Atmospheric Environment 43 (2009) 182–195

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Impaired visibility: the air pollution people see

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A B S T R A C T

Almost every home and office contains a portrayal of a scenic landscape whether on a calendar, postcard, photograph, or painting. The most sought after locations boast a scenic landscape right outside their window. No matter what the scene – mountains, skyscrapers, clouds, or pastureland – clarity and vividness are essential to the image. Air pollution can degrade scenic vistas, and in extreme cases, completely obscure them. Particulate matter suspended in the air is the main cause of visibility degradation. Particulate matter affects visibility in multiple ways: obscures distant objects, drains the contrast from a scene, and discolors the sky. Visibility is an environmental quality that is valued for aesthetic reasons that are difficult to express or quantify. Human psychology and physiology are sensitive to visual input. Visibility has been monitored throughout the world but there are few places where it is a protected resource. Existing health-based regulations are weak in terms of visibility protection. Various techniques, including human observation, light transmission measurements, digital photography, and satellite imaging, are used to monitor visibility. As with air pollution, trends in visibility vary spatially and temporally. Emissions from the developing world and large scale events such as dust storms and wildfires affect visibility around much of the globe.

1. Introduction

Do you have views of distant hills, mountains, towers, skyscrapers, or fields in your daily routine? Are you conscious of day-to-day differences in the atmosphere through which you view these scenes? Is there a landmark that you see on some days and not on others? Have you ever gazed upon fluffy white clouds nested in a deep blue sky? Have you hiked to the top of a hill or mountain for a better view? Do you sometimes notice a layer of brown smog as your plane lands in an urban area? How is the visibility where you live?

Too often we neglect to take note of our surroundings, but consciously or unconsciously, they affect us. Life keeps most of us focused intently on the modern, constructed world. The majority of our lives is spent indoors, and many people are more familiar with the atmosphere of their office than their neighborhood. While most of us are distracted from it "there is not a moment of any day of our lives, when nature is not producing scene after scene, picture after picture, glory after glory" (Ruskin, 1906). When we take the time to experience nature, it can be harrowing and exhilarating, but even when we do not take the time, there is comfort in knowing that these events are occurring.

We are often most aware of our surroundings when we are on vacation - when we have the time to relax and enjoy the scenery. Vacations offer an escape from the routine and stress of our daily lives. Vacation destinations are often chosen based on their scenery; vacations are spent gazing at monuments, mountains, clouds, and oceans. Good visibility allows clear observation of distant features and appreciation of the inherent beauty of these scenes. Scenic photographs displayed in books, pamphlets, and advertisements depict the clearest atmospheric conditions and can set high expectations for the visitor. Artists and photographers are acutely aware of the importance of color contrast, saturation, and brightness. Air pollution, which is often present in both our cities and parks, interferes with these attributes and can ruin the views vacationers travel to enjoy.

Visibility refers to the clarity or transparency of the atmosphere and the associated ability to see distant objects. The terms haze and smog describe the effects of air pollution on visibility. Haze is defined as "an aggregation in the atmosphere of very fine, widely dispersed, solid or liquid particles, or both, giving the air an opalescent appearance that subdues colors" ("Haze", 2008). The opalescent appearance refers to the loss of contrast in a scene, which means a loss of ability to distinguish physical features, depth, and texture. Viewing distant landmarks offers the most straightforward measure of visual air quality. The visual range, or longest distance at which landmarks are visible, varies widely depending on the humidity and concentration of particles in the air. On clear days in remote areas of the world, visual range can be over 300 km in dry climates and over 100 km in humid climates; on the haziest days, visual range can be less than a few km in any climate. Not every

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1352-2310/$ – see front matter © 2008 Published by Elsevier Ltd.
doi:10.1016/j.atmosenv.2008.09.067

location provides landmarks needed to gauge visibility; sky color is an indicator of visual air quality that is accessible in flat terrain with no prominent landmarks and in natural or urban canyons where long-distance vistas are blocked. On a clear day, when particle concentrations are low, the sky is a deep azure color. Particles scatter sunlight which dilutes colors; therefore, on a hazy day, when particle concentrations are high, the sky appears light blue, white, or gray, depending on the concentration. The eyes can be calibrated by comparing the sky color before and after a rainstorm following a dry period. Once attuned to the differences, the eyes are effective instruments for assessing particulate air pollution.

Air pollutants can be roughly divided into two classes: gases and particles. Particles are composed of liquids or solids and are collectively referred to as particulate matter (PM). Most gaseous pollutants are invisible to the human eye including ozone, sulfur dioxide, and carbon dioxide. The individual particles in PM are so small that they are invisible (or nearly invisible) to the human eye but collectively they create haze. The visibility effects of haze are similar to the effects of fog; the main distinctions being that smog particles are smaller and are composed primarily of air pollutants not water. Examples of PM include diesel exhaust from motor vehicles, smoke from chimneys, and sulfuric acid droplets formed in the atmosphere. Although the PM from individual sources seems to disappear as it disperses in the atmosphere, it does not – it is merely diluted. In the process, the distinct plumes from individual sources merge into a featureless, uniform haze. PM can persist in the atmosphere for several days or weeks and be transported thousands of miles, affecting visibility locally, regionally, and globally.

Some level of air pollution is inevitable but it must be controlled to limit the aesthetic and health problems it causes. Establishing policies to protect visibility involves a complex mixture of philosophy, psychology, public policy, and science. Psychological research demonstrates that people are emotionally affected by visibility. Public policy research shows that people think it is important to protect visibility and are willing to pay for the protection. The causes of visibility reduction are known and visibility can be measured by several different techniques. Visibility is affected by global, regional, and local pollution sources. PM concentrations are regulated in many parts of the world for health protection but these regulations are lenient in terms of visibility. Visibility conditions have been studied throughout the world, and visibility trends vary by location.

2. Aesthetics

Aesthetics is defined as "1: a branch of philosophy dealing with the nature of beauty, art, and taste and with the creation and appreciation of beauty, 2: a particular theory or conception of beauty or art: a particular taste for or approach to what is pleasing to the senses and especially sight" ("Aesthetics", 2007). Aesthetics is not simply a matter of first impressions but is influenced by education, society, and individual beliefs. The aesthetic appreciation of art is highly subjective whereas views of oceans, mountains, clouds, pastures, lakes, and cityscapes are aesthetically pleasing to the vast majority of people. Visual clarity is essential to the aesthetic appreciation of these views. Air pollution has several deleterious effects on aesthetics including visibility reduction, soiling of materials, and destruction of vegetation.

Aesthetic appreciation of nature is arguably timeless but has only been documented in the last few centuries (Brady, 2003). Early Western aesthetic theories focused on art. Around the turn of the 18th century, the aesthetic appreciation of natural environments and phenomena was cultivated by English and French artists. The American Trancendentalists emphasized the appreciation of wild landscapes; they believed that "Nature is the incarnation of a thought…the world is mind precipitated." (Emerson, 1844). These authors recognized nature's ability to revitalize and renew the spirit and helped shift the attitudes of society. The Hudson River School of painters influenced the movement by sharing the grandeur of the American wildernesses with the world (Opie, 1983). Together these artists were pivotal in the creation and expansion of US National Parks.

National Parks often encompass the most spectacular landscapes in their respective nation. James Bryce, the British Ambassador to the US in 1912 said, "The national park is the best idea America ever had." National Parks can now be found throughout the world and are a source of national pride. Many national parks include wilderness areas that are at once tranquil and threatening, beautiful and sublime; they are sacred environments symbolizing freedom and independence as well as the antithesis of modern life (Brady, 2003). As populations increase and development continues to encroach on rural areas, parks will become more important. Citizens have fought hard to protect parks from development of all kinds: tourism, mineral extraction, timber harvesting, and damming of rivers. Although park management philosophies differ with regard to the role of humans, the importance of preserving the natural environment for the use, observation, health, and pleasure of the people is common to all philosophies (Ise, 1961). Maintaining the visual clarity of the atmosphere is essential to this goal. Unfortunately, on many days the visual ranges in National Parks are fractions of what they used to be.

Cities also tout their scenery to attract tourists and residents. The most expensive pieces of property are often the ones with the best views. Many urban areas have tall observation decks for viewing the surrounding scenery: Paris has the Eiffel Tower; Toronto has the CN Tower; Seattle has the Space Needle; Moscow has the Ostankino Tower, and London has the BT Tower just to name a few. The views of Mount Rainer and Puget Sound are spectacular from the Space Needle. Tourists are disappointed when the views are obscured by haze (Doyle and Dorling, 2002). Unfortunately, many urban areas routinely experience low visibility (below 20 km). Visibility has received little attention in most urban areas.

3. Human perception of air pollution

Sight dominates the way we 'see' the world. It even dominates our descriptive vocabulary; thinking is often associated with visual metaphors: observe, insight, illuminate, enlighten, reflect, clarify, speculate, perspective, point of view, and bright. A large fraction, 25–35%, of our brain is dedicated to processing visual images (Gilbert and Walsh, 2004). Researchers have suggested that visual input has played a major role in human brain evolution, and positive correlations exist between the size of the optical nerve and the brain (Kirk, 2006). Therefore, it is not surprising that our visual intake has an effect on our physiology and psychology.

The scientific study of therapeutic landscapes is relatively new but the concept is old (Gesler, 2005). The trip to the countryside to escape the pollution in the city and recover from an illness is common in 18th century European literature. Recreational researchers have found that a primary reason for visiting a national park, wilderness area, or forest is to escape the stressors found in urban areas (McHenry, 1983). Numerous studies have documented benefits of viewing natural scenes including short-term recovery from stress or mental fatigue, faster physical recovery from illness, and long-term overall improvement in people's health and well-being (Velarde et al., 2007). Environmental psychologists have discovered that viewing natural scenes reduces physiological indicators of stress, including blood pressure, skin conductance, and muscle tension, whereas viewing urban scenes does not (Velarde et al., 2007). Perception of pollution is correlated with stress, annoyance, and symptoms of depression (Mace et al., 2004; Evans and Jacobs, 1982). For natural places to retain their ability to calm and soothe, they must have minimal visual pollution.

Humans can visually detect low levels of pollution (Malm et al., 1983). As shown in Fig. 1, people's perception of air quality is very sensitive to increases in PM concentration at low concentrations and becomes less sensitive as concentrations increase (non-linear response). Therefore, even low levels of air pollution in relatively clean National Parks are noticeable, particularly if the pollution is present in a distinct layer or plume. Air pollution detracts from the enjoyment of the visitor experience (Bell et al., 1985). US National Park rangers substantiate these findings with personal accounts of visitor complaints about poor visibility (McHenry, 1983). Fig. 2 shows pictures of a Glacier National Park vista under four different PM concentrations. Visibility also affects the night sky; even moderate levels of PM make astronomical observations unfeasible (Joseph et al., 1991).

Despite the above evidence supporting the importance of visibility, community opinion surveys find that few people spontaneously express concern about air pollution even if they live in heavily polluted areas (Bickerstaff and Walker, 2001). Not surprisingly, more immediate social problems (e.g., crime) in a neighborhood can lead to a lower relative importance being ascribed to air pollution. This raises the question of whether people know what to look for in terms of air pollution and visibility. A research survey in Birmingham, UK, examining public perceptions of air pollution found that only 13.5% of the respondents identified visual evidence as a means by which they became aware of air pollution (Bickerstaff and Walker, 2001). Conversely, when participants were asked to evaluate the visibility in photographs and outdoor scenes, researchers found that the perceived levels of air pollution relate well to physically measured levels (Day, 2007; Malm et al., 1983).

People's awareness of air pollution is often linked to publicity about the pollution. Public opinion polls have documented an

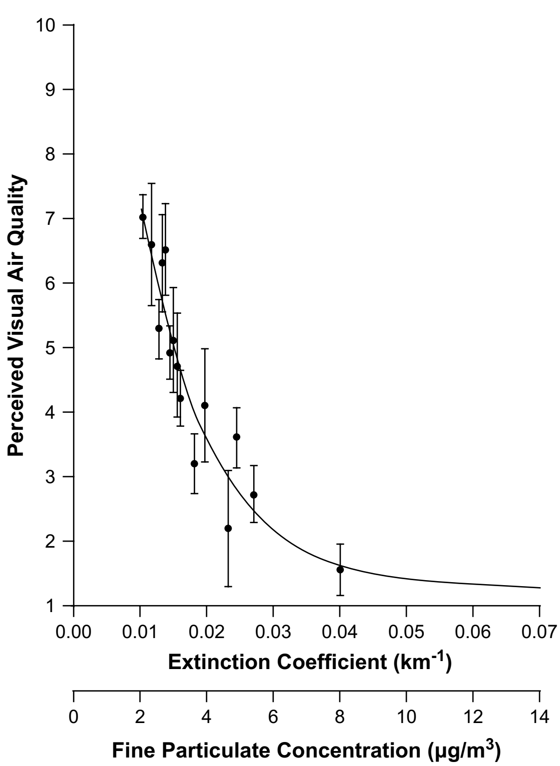

Fig. 1. The perceived visual air quality values are based on survey responses, and the error bars represent the variation in individuals' responses (Malm, 2008). A given increase in particle concentration is more noticeable when the air is clean (e.g., concentration/extinction is low).

increase in awareness since the 1960s in the US, while over that same period air pollution has improved in almost every major city (Brody et al., 2004; Bickerstaff and Walker, 2001). Higher levels of measured air pollution are not always associated with an increase in public awareness, particularly when the changes take place over long periods of time. Perceptions are influenced by setting, access to information, and socioeconomic characteristics. Newspaper and television weather reports throughout the world now include air pollution predictions. In addition, several urban and rural locations in the US operate digital cameras that send real-time images directly to the Internet (http://www.airnow.gov/index.cfm?action=airnow.webcams, http://www2.nature.nps.gov/air/webcams/index.cfm). The cities of Phoenix, Arizona, and Denver, Colorado, which both have spectacular mountain ranges within their view, have conducted measurements and surveys to understand and alleviate visibility problems in their areas. Together these efforts raise people's awareness of the problem.

Despite this increase in awareness, there is at least one common misconception about air pollution: the belief that air pollution enhances the beauty of sunrises and sunsets (Corfidi, 1996). PM does alter the appearance of sunrises and sunsets - whether or not these alterations are for the better may be a matter of personal aesthetics or awareness. PM increases the amount of orange and red color in a sunset but it also dulls the colors and diminishes the contrast between colors, just as it does to the daytime sky. Once you know what you are looking at, it may be difficult to find beauty in a glowing red layer of haze spread across the horizon at sunrise or sunset. The misconception that pollution creates more beautiful sunrises and sunsets likely results from the fact that following major volcanic eruptions sunrises and sunsets become more colorful throughout the world (Zerefos et al., 2007). The major difference between natural volcanic and anthropogenic particulate emissions is where they exist in the atmosphere: volcanoes inject ash and sulfuric acid particles into the upper atmosphere (stratosphere) not into the lower atmosphere (troposphere) where most PM pollution exists. Because volcanic particles exist in an elevated layer they produce a different visual effect than tropospheric particles. Volcanic particles in the stratosphere catch the first and last rays of sunlight, similar to high-level clouds, causing the sky to have more orange and red colors (Corfidi, 1996; Zerefos et al., 2007). Under certain circumstances PM can create unusual and beautiful optical phenomena, but in most situations, PM results in duller skies. Locations with the most spectacular sunrises and sunsets, such as the tropics, typically have low levels of pollution (Corfidi, 1996).

4. Value of visibility

The value of any intangible such as visibility, health or comfort is a philosophical question. The repercussions of poor visibility are difficult to identify and quantify. In addition, the relationships between emissions and visibility (or health) are complex. The costs associated with reducing air pollution are not linearly related to the reductions, and reductions in air pollution are not linearly related to improvements in visibility. Despite the difficulties, estimates of the monetary value of visibility have been used to establish regulations. In fact, the United States Environmental Protection Agency is required to evaluate both the potential benefits to society and the costs of any new regulation (The White House, 1994). Opponents of this approach argue that laws that protect the natural environment are intended to do just that – not to balance interests, internalize externalities, maximize benefits, or increase social wealth (Sagoff, 1988). Nevertheless, air pollution is inevitable and acceptable levels must be determined; this is a complex task that requires a combination of information about science, sociology, policy, and commerce.

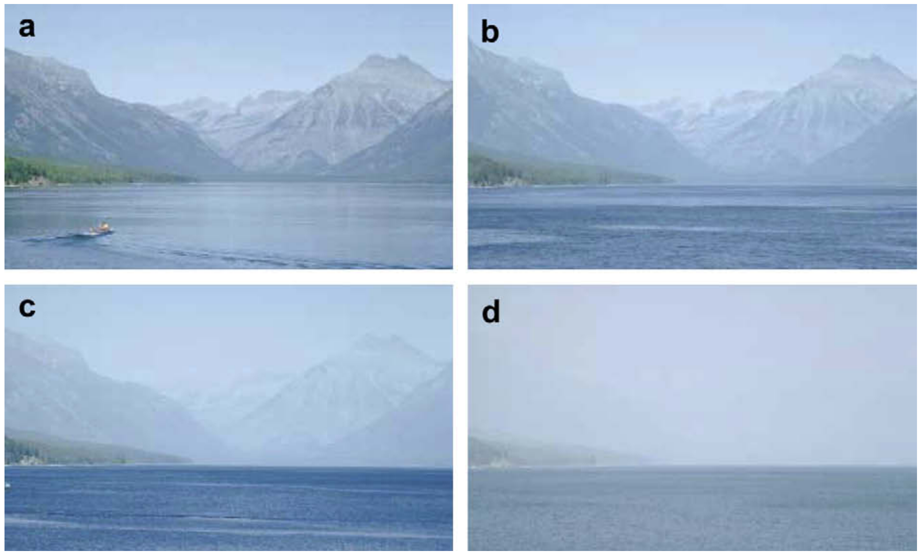

Fig. 2. The effect of haze on a Glacier National Park vista. Atmospheric fine PM concentrations associated with photographs are a) 7.6, b) 12, c) 21.7, and d) 65.3 $\mu g\, m^{-3}$. Figure is from Malm (1999).

Several surveys have attempted to establish the value of visibility in monetary terms (McClelland et al., 1993; Chestnut and Rowe, 1990; Delucchi et al., 2002). Survey results have consistently found that visibility in both urban and rural areas is important to citizens. Visibility is regulated in US National Parks so several studies have focused on these locations. Very few studies are available to set a value for urban visibility benefits (Krupnick and Morgenstern, 2002; Cropper, 2000). Two approaches commonly used in cost-benefit analyses are based on bidding or property values. The bidding method asks participants to estimate their willingness to pay (WTP) for an increase in visibility or willingness to accept (WTA) payment for a decrease in visibility. The property value approach uses relationships between property values and air quality to estimate the value of air quality. The weaknesses associated with these attempts are many.

The most important weakness associated with the bidding method is the absence of an existing market to establish a baseline value for visibility. As a result, many people refuse to provide an estimate. In addition, it is difficult to establish a consistent measure of visibility among human subjects and to disentangle visibility from the other effects of air pollution, particularly health. WTP values differ greatly depending on the payment vehicle: higher entrance fee, an addition to a monthly utility bill, or an annual tax. Surveys in general suffer from problems associated with the order and phrasing of the questions. Despite these shortcomings, surveys play a pivotal role in establishing public policy, particularly in the US.

Surveys have decisively shown that Americans are willing to pay for better visibility in their cities and parks (Mace et al., 2004). Remarkably, some surveys have shown that people's WTP for better visibility in parks is regardless of whether they live near the park, have visited the park, or plan to ever visit the park. Estimates for improving visibility in a single park range from $40 to $166 (in 2007 U.S. dollars) per person per year (Chestnut and Rowe, 1990).

At least one researcher has taken a different approach to estimating a monetary value for air pollution. Heinz Welsch (2002, 2006) used subjective well-being (happiness) data along with pollution data from several countries to explore the value of air pollution. Psychologists and sociologists have compiled data on average well-being by country for over a decade. Welsh found that air pollution plays a statistically significant role as a predictor of both inter-country and inter-temporal differences in subjective well-being. The two studies did not specifically address visibility but did address PM. A reduction of 1 $\mu g\, m^{-3}$ in PM concentration was found to be worth $21 to $337 (in 2007 U.S. dollars) per person per year; this is a large sum of money for a rather small reduction in concentration. This approach may prove useful for estimating the value of visibility.

5. Visibility physics

Air pollution affects what we see by interfering with light. Objects are visible when light bounces (reflects) off their surfaces and is redirected into our eye. For example, when we aim a flashlight at an object, light hits the object and is reflected back into our eye. We do not need to light up the sight path between the object and ourselves to see the object; in fact, it is easier to see the object if the sight path is not illuminated, as with a spotlight shining from above. If the sight path is illuminated, the atmosphere in the intervening path interferes with the light (e.g., dust is often visible in the air under bright rays of sunlight through a window). The atmosphere is primarily composed of gases, with small amounts of suspended PM. PM affects visibility in multiple ways: particles scatter light coming from an object which diminishes the contrast, absorb light which gives the scene a grayish cast, and scatter sunlight which subdues colors.

Both particles and gases interact with light, and the interactions consist of light absorption and light scattering. The amount of light redirected from its original path is referred to as total light extinction (b_{ext}) and is equal to the sum of these four interactions as shown in Equation (1): light scattering by particles ($b_{scat,p}$) and gases ($b_{scat,g}$) and light absorption by particles ($b_{abs,p}$) and gases ($b_{abs,g}$).

$$b_{ext} = b_{scat,p} + b_{scat,g} + b_{abs,p} + b_{scat,g} \tag{1}$$

Light scattering by particles is the dominant cause of reduced visibility in most areas because particles scatter light more efficiently than gases (van de Hulst, 1957; White, 1990). The difference in scattering efficiencies is best illustrated by clouds that suddenly form "out of nowhere." The same amount of water is present in the air mass before and after the clouds appear but the size of the water droplets increased through condensation to a point where they efficiently scatter light and become visible. These large water drops scatter all wavelengths of visible light making the air mass (cloud) appear white.

There are straightforward relationships between b_{ext}, particle concentration, and visual range (VR). Visibility is often quantified by the VR which is the longest distance that a large, black object can be seen against the sky at the horizon. VR and b_{ext} are inversely related by the Koschmieder equation, $VR = -\ln(C_L)/b_{ext}$, where C_L is the minimum observable contrast; contrast is a ratio of the difference in brightness of the black object and the horizon to the brightness of the horizon, and is equal to 0.02 – 0.05 for most observers. VR has units of length, and the Koschmieder equation illustrates that b_{ext} has units of inverse length. VR varies from a few kilometers in heavily polluted areas to hundreds of kilometers in pristine environments. The Koschmeider equation is inaccurate if illumination is non-uniform and for very clean atmospheres where the curvature of the earth becomes a factor. For a given mix of particles, b_{ext} is directly proportional to the number of particles encountered in the sight path between the observer and the object. This relationship is complicated by the fact that particle chemical composition and size vary in the real atmosphere, but the variations are relatively minor (Chow et al., 2002; Delene and Ogren, 2002; Omar et al., 2005); a recent review of estimates from several locations found that $PM_{2.5}$ scattering efficiencies varied from 3.1 to 4.3 $m^2\,g^{-1}$ (Hand and Malm, 2007). Simply stated, b_{ext} is directly related to PM concentration and inversely related to VR.

The term particle refers to an agglomeration of liquid- or solid-phase molecules that range in size from $\sim$0.001 μm (a few molecules adhered together) to $\sim$30 μm (soil dust) (Seinfeld and Pandis, 1998). Individual molecules do scatter light but are too small to efficiently scatter light; when individual molecules agglomerate to the point where their collective size is similar to the wavelength of visible light (0.380–0.780 μm) they can scatter light very efficiently. Fig. 3 shows the dependence of mass scattering efficiency on particle diameter for homogeneous spheres of water, carbon, silicon dioxide, and iron. Chemical compounds have different refractive indices and thus different scattering efficiency curves (Hand and Malm, 2007; Tang, 1981).

Scattered light is redirected from its original path resulting in a loss of contrast (indistinct images). Scattering interferes with the light coming from both the object and the sun. Image-forming light coming from the object of interest is scattered out of the path resulting in a less vivid image (i.e., the signal is attenuated). In addition, sunlight is scattered into the sight path of the observer (i.e., noise is added to the signal). When the sun is in front of the observer, this added air light (noise) can overwhelm the light coming from the object (signal). The end result of these effects is reduced contrast, making details in the image difficult to discern.

Particles do not scatter light uniformly in all directions; the scattering phase function describes the angle-dependent scattering of light incident on a particle (van de Hulst, 1957; Seinfeld and Pandis, 1998). Particles with diameters at or above the wavelengths of visible light (the most efficient scatterers) preferentially scatter light in the forward direction; therefore, haze appears bright in the forward-scatter mode (sun in front of observer) and dark in the backscatter mode (sun behind observer).

Different wavelengths of light are scattered more or less depending on the size of the particles (van de Hulst, 1957; Finlayson-Pitts and Pitts, 2000). Gases and small particles preferentially scatter short-wavelength blue light, scattering is proportional to λ^{-4}, where λ is wavelength; this is referred to as Rayleigh scattering. Light scattering by gases gives the sky its blue color and is essentially constant at a given altitude (air pressure). Lord Rayleigh observed that the sky is bluest when the air is cleanest (i.e., having the fewest number of particles). In the cleanest possible atmosphere with only Rayleigh scattering, the visual range is over 350 km (Middleton, 1952). Particles with diameters similar to the range of visible light (380–780 nm) scatter light most efficiently as shown in Fig. 3; scattering in this size range is referred to as Mie scattering. Under all but the clearest conditions, Mie scattering exceeds gas scattering. Mie scattering is not as wavelength dependent as Rayleigh scattering, it is proportional to λ^{-1}; therefore, Mie scattering makes the sky look whiter. This whitening of the sky is obvious at the horizon compared to the sky color directly overhead because when an observer looks at the horizon, the sight path is tangential to the earth's surface and thus passes through a longer atmospheric path and intersects more particles than looking straight up. As shown in Fig. 3, the mass scattering efficiency decreases as the particle size increases beyond the visible wavelengths. Scattering in this regime is referred to as geometric scattering and is highly dependent on particle shape and orientation relative to the incoming beam. Fog droplets are larger particles, 2–70 μm, and thus instigate geometric scattering. Although large fog droplets are less efficient scatterers, they can exist at very high concentrations and thus cause poor visibility. Fog typically has a liquid water content of >1000 $\mu g\,m^{-3}$, whereas $PM_{2.5}$ concentrations exceed 100 $\mu g\,m^{-3}$ only in the most polluted locations and conditions.

Some particles absorb water (hygroscopic), particularly particles containing sulfate and nitrate. As relative humidity (RH) increases, these particles grow in diameter and as their cross sections increase, their ability to scatter light increases (Tang, 1996). Fig. 4 shows the ratio of wet to dry light scattering as a function of relative humidity (RH). The presence of hygroscopic particles in the atmosphere may increase the likelihood of visibility-reducing fog exacerbating the visibility problem in polluted atmospheres (Bréon, 2006; Kaufman and Koren, 2006; Kokkola et al., 2003; Kulmala et al., 1997).

Unlike light scattering, light absorption results in the loss of visible light; absorbed light is converted to longer-wavelength energy (heat). In terms of visibility, light absorption causes both darkening and discoloring of the atmosphere. Only colored gases and particles absorb light. Most atmospheric gases are transparent. NO_2 is the only notable exception but NO_2 is reactive so it is generally at negligible concentrations except close to sources (furnaces, motor vehicles). When present at high concentrations, NO_2 gives the air a brown, red, or yellow tint because it

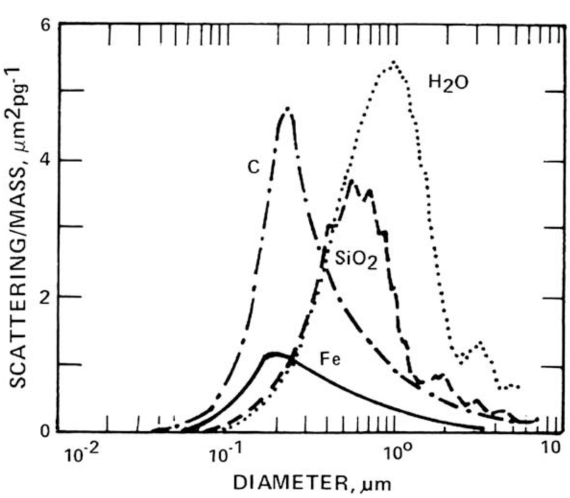

Fig. 3. Light scattering cross section per unit mass as a function of particle diameter for spherical particles of carbon, SiO_2, Fe, and H_2O. Figure is from EPA, 1979.

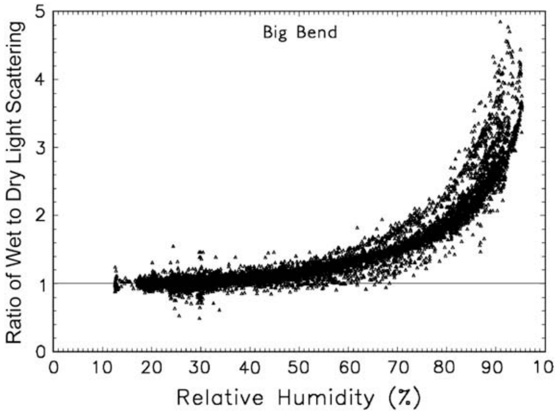

Fig. 4. Ratio of wet to dry particle scattering ($b_{scat,p}$) as a function of RH. Particle scattering increases with RH because the particles take up water. Measurements are from Big Bend National Park in Texas. Figure is from Day and Malm (2001).

preferentially absorbs blue light. Plumes from large industrial sources such as power plants often have a brown tint as a result of high NO_2 concentrations. Atmospheric particles vary in color but most are lightly colored except black carbon (also referred to as elemental carbon or soot). Black carbon particles strongly absorb all wavelengths of light and are thus the dominant light absorbers when present. Organic carbon and soil particles weakly absorb light. In most rural locations (in the absence of fires), light absorption accounts for 5–10% of total light extinction; in urban areas, elemental carbon accounts for 20-30% of total light extinction (White, 1990; Jacobson, 2002).

6. Particles in the atmosphere

Atmospheric PM mass, size distribution and chemical composition vary by location and time. PM is typically divided into a few major groups based on chemical composition: sulfate, nitrate, black carbon, organic carbon, and mineral-based (soil) particles. Fig. 5 shows examples of $PM_{2.5}$ chemical compositions for several locations in North America. There are two major pathways whereby PM enters the atmosphere: various sources directly emit particles (primary) and gases are converted into particles via processing in the atmosphere (secondary) (Donahue et al., 2008).

A wide range of natural and anthropogenic sources emit both primary particles and gaseous pollutants that are converted into secondary particles. Table 1 lists the major sources of particulate matter; these estimates are rather old but provide order of magnitude estimates of the various sources. According to Table 1, the world-wide natural sources of particles exceed the anthropogenic sources, although a large fraction of the anthropogenic emissions are in the coarse mode, which is not as relevant to visibility. The majority of primary particles are carbon- or mineral-based. Major sources of primary PM include fires, windblown dust, burning of fossil fuels, agricultural activities, and open fire cooking. Primary particles are visible in exhaust from motor vehicles, particularly diesel-fueled vehicles; these particles are composed of unburned or partially burned fuel. The majority of secondary particles are composed of ammonium sulfate, ammonium nitrate, and organic carbon species.

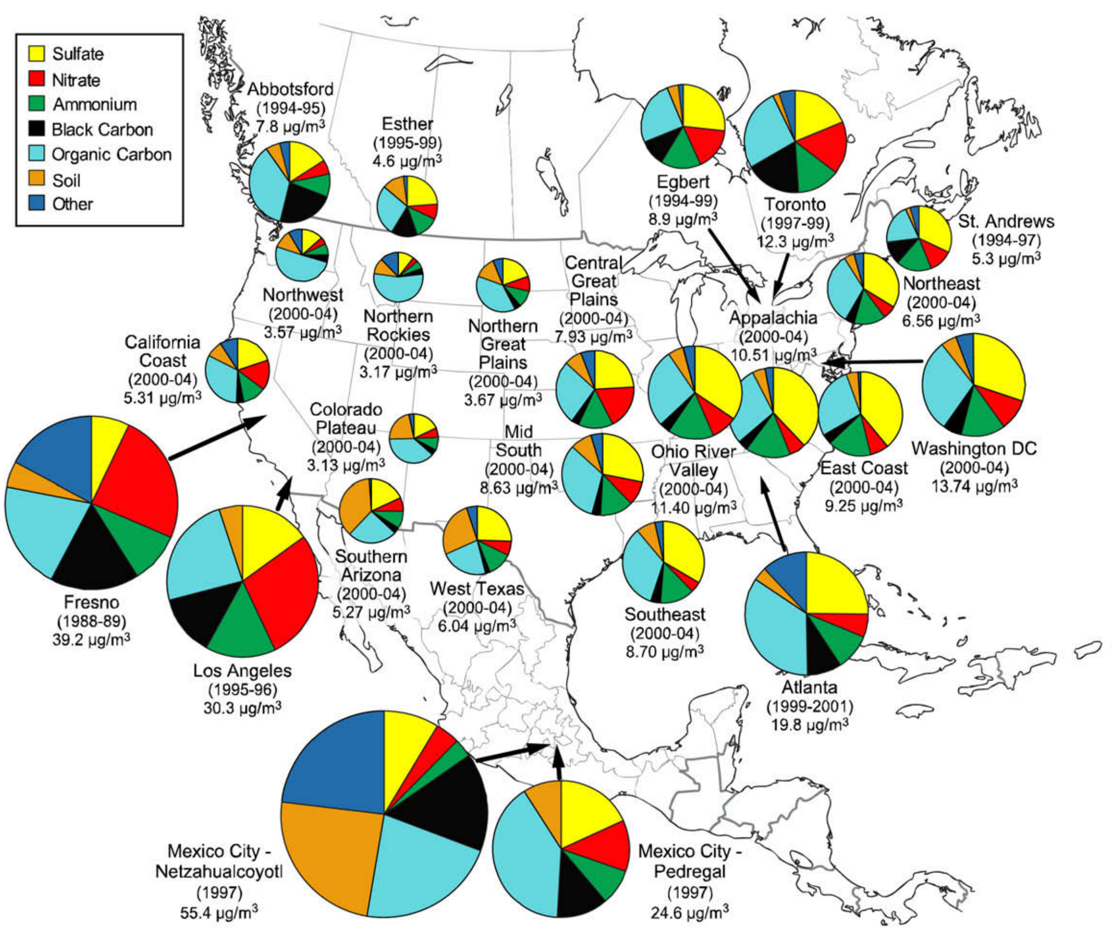

Fig. 5. Chemical composition of $PM_{2.5}$ at several urban and rural locations. Figure is adapted from McMurry et al. (2004).

Drylands cover about 43% of the world's land surface and are particularly concentrated in Africa and Asia (UNEP, 2001). When high winds pass over these areas, blinding amounts of dust can be swept into the air, entrained in the free troposphere, and transported thousands of miles. Desertification, the process whereby desert areas are expanding, is leading to increasing dust events in several areas of the world. Table 1 classifies all soil dust as "Natural", which is disputable. Dust particles may be transported at altitudes of up to 6 km and move over distances of up to 6000 km. Fig. 7 shows a satellite image of two distinct dust plumes blowing off Libya.

Secondary particles are formed via oxidation and condensation of gaseous species. The vast majority of the sulfate and nitrate particles found in the atmosphere are formed through the oxidation of sulfur dioxide (SO_2) and oxides of nitrogen (NO_x). Combustion of fossil fuels is the major source of both SO_2 and NO_x (Benkovitz et al., 1996). Anthropogenic SO_2 emissions from North America and Europe have decreased over the last two decades but have increased across Asia (Manktelow et al., 2007; Prospero and Savoie, 2003; Streets and Waldhoff, 2000).

Carbon-based PM is divided into two categories: black and organic carbon. Black carbon is emitted by combustion processes: fossil fuel, biofuel, and open burning (Bond et al., 2004). Organic carbon PM is both primary and secondary and has both natural and anthropogenic sources. The Great Smoky Mountains in the Eastern US are named for the blue haze that is formed by organic carbon emissions from vegetation (Rasmussen and Went, 1965; Went, 1964). The ratios of primary-to-secondary and biogenic-to-anthropogenic organic PM vary over time and space (Weber et al., 2007; Schichtel et al., 2008). Over 10,000 unique compounds have been found in organic PM. The relative contributions to organic carbon from anthropogenic versus natural sources are not well known (Heald et al., 2008).

Not only does PM chemical composition vary in the atmosphere, the size distribution of PM varies over time and location. The size distribution typically has two modes referred to as fine and coarse. An example of a size distribution is shown in Fig. 6. In general, different sources are responsible for the two modes of particles but there are many exceptions as shown in Table 1. Soil particles are often the major contributor to the coarse mode while carbon-based, ammonium nitrate, and ammonium sulfate particles dominate the fine mode. Monitoring is necessary to characterize the chemical composition and size distribution of PM in a particular area.

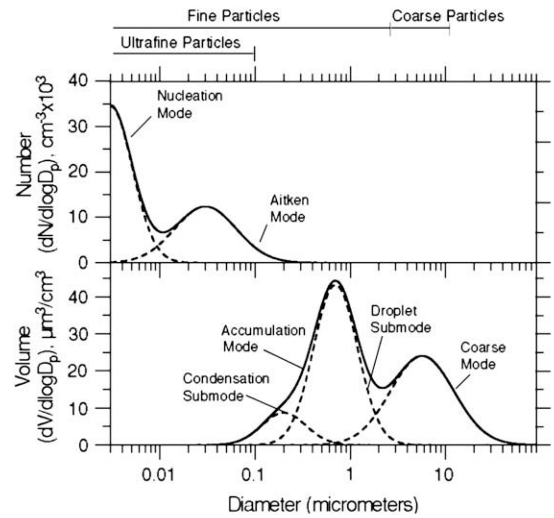

Fig. 6. Typical number and volume distributions of atmospheric particles. The mass distribution is similar to the volume distribution. Figure is from McMurry et al. (2004).

Table 1
Global emission estimates for major particle types in the 1980s (adapted from Seinfeld and Pandis, 1998).

Category	Source	Estimated flux ($Tg\ yr^{-1}$)	Particle size mode
Natural			
Primary	Soil dust	1500	Fine and coarse
	Sea salt	1300	Mainly coarse
	Volcanic dust	30	Coarse
	Biological debris	50	Coarse
Secondary	Sulfates from biogenic gases	130	Fine
	Sulfates from volcanic SO_2	20	Fine
	Organics from biogenic gases	60	Fine
	Nitrates from NO_x	30	Fine
	Total natural	3100	
Anthropogenic			
Primary	Industrial dust (except soot)	100	Fine and coarse
	Soot	10	Fine
Secondary	Sulfates from SO_2	190	Fine
	Biomass burning	90	Fine
	Nitrates from NO_x	50	Fine and coarse
	Organics from anthropogenic gases	10	Fine
	Total anthropogenic	450	

7. Visibility monitoring

Several techniques are available for monitoring visibility including human-based, optical, and PM measurements. None of these techniques captures the entire human visual experience because the complex processing of visual images performed by the eye-brain system is not well characterized (Henry, 1987; Henry, 2006; Mahadev and Henry, 1999). Nonetheless, several measurement techniques provide useful estimates of visibility. Phenomenological relationships – simplified empirical relationships consistent with theory – are well established between several of the measurements.

7.1. *Visual range*

The simplest approach to assessing visibility is a human observation of the farthest distance at which a large, black object can be seen against the sky at the horizon. This distance estimate is referred to as the visual range (VR). Multiple factors influence VR including properties of the atmosphere, the intensity and distribution of light, characteristics of the observed objects, and properties of the human eye.

Human observers at airports around the world routinely report VR for transportation safety. Large buildings or hills at known distances are used as targets to estimate the VR. Under many conditions, VR estimates correlate well with optical instrumentation measurements. Real-world VR estimates have many limitations though. The lower contrast of the real targets compared to black objects imposes a systematic underestimate of visual range. Also, VR is reported in quantized units, dependent on the available targets. Often long-range targets are not available or assessed because they are not relevant to aviation (i.e., air traffic is most concerned that visibility is above a particular threshold value but isn't necessarily concerned with the details of good visibility). As a result of these non-ideal conditions, empirical research suggests the log of the contrast ratio in the Koschmieder equation is 1.9 ± 0.4, $VR = 1.9 \pm 0.4/b_{ext}$ (Griffing, 1980). Lastly, as with any human-based measurement, VR is subjective. In the 1990s, many human VR observations were replaced by instrumentation.

7.2. Optical instrumentation

Several different techniques are used for visibility monitoring. Transmissometers measure b_{ext} by aiming a light source (transmitter) at a transceiver located some distance away that measures the radiance of the received light (Watson, 2002; Horvath, 1981). The transmittance of the path is calculated by dividing the measured radiance by the calibrated initial intensity of the light source. The average b_{ext} of the path is calculated from the transmittance and length of the path. The relationship between human perception of visual air quality and contrast transmittance is linear (Malm et al., 1983).

Nephelometers measure b_{scat} by illuminating an air-filled chamber and detecting the scattered light. Particle scattering is usually the most significant component of extinction; therefore, nephelometers provide valuable information with very simple instrumentation. Average Rayleigh scattering values can be subtracted from the b_{scat} measurement to determine particle scattering ($b_{scat,p}$). One disadvantage of the nephelometers is that heating by the light source may inadvertently modify hygroscopic and volatile particles as they pass through the chamber.

Teleradiometers are used to measure contrast transmittance which is the ratio of the apparent contrast at a known distance away from the object to the inherent contrast of the object. Teleradiometers focus a telescope on a distant target and background and measure changes in radiance (Watson, 2002; Horvath, 1981; Seigneur et al., 1984; Middleton, 1952). Contrast measurement methods are sensitive to non-uniform illumination conditions (e.g., clouds behind target or in sight path). Various techniques involving photographic equipment have also been used to assess visibility (Bäumer et al., 2008; Kim and Kim, 2005). These photographic techniques may prove to be very useful given the cost effectiveness of digital cameras.

7.3. Satellite platforms

Several satellites orbit the earth measuring atmospheric optical properties. Satellite data have not been fully utilized for assessing visibility but some analyses do exist. Satellite data are particularly useful for obtaining visibility estimates in areas without ground-based measurements and identifying large-scale PM emission events. Stunning images of dust sweeping out of Africa and Asia have been published (Fig. 7). There are several problems with using satellite data for visibility estimates. Satellites most often measure the total aerosol loading in the air column and cannot distinguish between particles at the ground level and in the upper atmosphere, and particles are not homogenously distributed. Satellite-based Lidar measurements can provide vertical profiles of PM but are not as common as radiometric measurements (Li and Philbrick, 2003; Philbrick and Mulik, 2000). Separating atmospheric reflectance from surface reflectance is possible over dark and uniform ocean surfaces but difficult over land. Estimates of aerosol extinction over oceans have been available for several years (Husar et al., 1997; Deuzé et al., 1999). Estimates of aerosol extinction over continents have been published but are not consistent and are riddled with holes (Engel-Cox et al., 2004; Kokhanovsky et al., 2007; Deuzé et al., 2001). Satellite radiometric data are useful for assessing major PM events and gaining knowledge in areas where no other measurements are available, but at this time, they cannot provide measurements of ground-level visibility at any desired location and time.

7.4. PM speciation monitoring

Chemical speciation of atmospheric particles is useful for determining the sources of the PM. The most common approach is to collect the particles on filters and then subject the filters to various analytical techniques. For example, the Interagency Monitoring for Protected Visual Environments (IMPROVE) network collects $PM_{2.5}$ samples and analyzes the samples using ion chromatography for the major cations, thermal-optical reflectance for carbon, and x-ray fluorescence spectroscopy for elements. Several techniques exist for performing real-time analyses of PM including mass spectrometry, ion chromatography, and thermal-optical transmittance or reflectance; real-time chemical speciation samplers are utilized in special studies but are rarely utilized in routine networks because they require extensive maintenance and operator training. The disadvantages of these measurements include modification of the particles when they are removed from their native media (air) and long averaging times. For example, the attenuation of light by particles collected on a filter is usually enhanced over that of suspended particles (Horvath, 1993). PM speciation samples are often collected over 24 h; visibility often displays a diurnal pattern which is impossible to observe with 24-h averaging times. Therefore, PM speciation monitoring is often performed in conjunction with real-time optical visibility measurements.

Fig. 7. Two-toned dust plumes blew northward off the coast of Libya on October 26, 2007, as the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite took this picture (http://earthobservatory.nasa.gov).

PM chemical speciation measurements can be used to reconstruct b_{ext} (or b_{scat}) and identify the sources responsible for visibility impairment. Reconstructed b_{ext} (b_{scat}) is calculated by multiplying the chemical concentrations by their respective extinction efficiencies (Ouimette and Flagan, 1982). For hygroscopic species, nitrate and sulfate, the extinction efficiencies are scaled by a function that increases with increasing RH (Fig. 4). The agreement between reconstructed light extinction and transmissometer measurements is reasonably consistent from site to site and time to time, and the agreement between reconstructed light scattering and nephelometers measurements is even better (Watson, 2002).

8. Legislation and regulations

Legislation and regulations for the control of PM do exist throughout the world, but visibility is rarely addressed. The first priority of PM regulations is to protect human health. Secondary priorities such as visibility are often not addressed until first priorities are met. In many urban areas throughout the world, PM concentrations exceed the regulated levels. Visibility has not been addressed by legislation in most places. Multiple versions of legislation and regulation have been passed in the US to protect visibility in National Parks and Forests.

Many countries throughout the world have limits on $PM_{2.5}$ concentrations designed to protect human health. The best empirical evidence suggests that the PM concentration-health response relationship can be modeled as linear (Pope and Dockery, 2006). Table 2 lists VR estimates corresponding to several $PM_{2.5}$ concentration standards. The VRs were estimated from the Koschmieder equation assuming a $PM_{2.5}$ mass scattering efficiency of 3.6 $m^2\,g^{-1}$ (Hand and Malm, 2007), scattering to extinction ratio of 0.8, and gas scattering value of 13.2 Mm^{-1}. The actual VRs could be much lower than the estimates under moderate or high humidity conditions. Although the regulations have been tightening over the years, $PM_{2.5}$ concentration limits do little to protect visibility.

The 1970 US Clean Air Act (CAA) focused on air pollution in urban areas and led to the USEPA establishing National Ambient Air Quality Standards (NAAQS) designed to protect human health. These regulations made it more difficult to construct large industrial sources in urban areas and lead to the construction of several coal-fired power plants in non-urban areas in the 1970s (Watson, 2002). Several of these new facilities were located close to national parks; stack plumes could be clearly seen from some parks. This trend precipitated concerns that air quality in remote areas would degrade to the levels found in urban areas without further legislation. In 1977, Congress declared "as a national goal the prevention of any future and remedying of any existing, impairment of visibility in [National Parks and Forests]" (U.S.C, 1977). The implementation of this legislation propelled the scientific investigation of reduced visibility. Scientific studies led to better understanding of the regional nature of haze, conversion of primary gaseous emissions into particles, and transport of pollution in complex terrain (Crawford, 1990). The CAA was amended in 1990 to address these new findings. The USEPA created the Regional Haze Rule (RHR) in response to the 1990 CAA amendments. The RHR mandates that air quality in the National Parks and Forests be returned to background conditions by 2065. Progress will be evaluated every five years and emission reduction strategies will be revised every ten years. The individual states are currently in the process of establishing background conditions and developing plans to improve the visibility in their Class I areas. The efficacy of the RHR has yet to be tested.

Visibility has not been regulated in Europe, and concerns have been raised about the lack of visibility regulations (Colls, 2002). Similar to the concerns expressed in the US in the 1970s, Colls (2002) laments that concentrations in remote European areas will either never fall to the low values that are appropriate or will increase towards the standard values (Table 2). A review of air pollution policies in the UK over the last fifty years did not even mention visibility (Williams, 2004).

Table 2
Visual range estimates corresponding to $PM_{2.5}$ concentration standards.

$PM_{2.5}$ measurement	Agency	Concentration ($\mu g\,m^{-3}$)	VR estimate (km)
Annual average	USEPA	15	48
Annual average	WHO	10	67
Daily average	USEPA	35	23
Daily average	EU/WHO	25	31

EU = European Union (Europa, 2007), WHO = World Health Organization (WHO, 2005).

9. Current conditions and trends

Visibility trends tend to track air pollution trends. As a result of dramatic improvements in air pollution control technologies for industrial and vehicular sources, visibility has improved in most cities in the developed world over the last 50 years. Rural areas of the developed world have not seen similar improvements as development has often spread into these areas. Visibility has gotten worse in many developing countries and may continue to degrade as populations and energy usage increases.

Visibility measurements and analyses have been made at locations all over the world: Mexico (Márquez et al., 2005), Chile (Trier and Firinguetti, 1994), Canada (McDonald and Shepherd, 2004), the UK (Eggleton, 1969), the Netherlands (Diederen et al., 1985), Hungary (Molnár et al., 2008), Hong Kong (Lai and Sequeira, 2001), Taiwan (Cheng and Tsai, 2000), China (Yang et al., 2007; Cheung et al., 2005), Nigeria (Anuforom et al., 2007), New Zealand (Senaratne and Shooter, 2004), and Australia (Gras et al., 2001) to name a few. UK visibility data from 1950 to 1997 showed major improvements at many sites after 1973 (Doyle and Dorling, 2002). Improvements in visibility at the less populated and less polluted Scottish sites were much less than at the other sites. Molnár et al. (2008) found that visibility improved throughout Hungary from 1996 to 2002, but also noted that the improvements were smaller in less polluted areas than in more polluted areas. Visibilities in Europe outside population centers are 40–50 km on average. Horvath (1995) used visibility measurements and a box model to show that these poor visibilities are a consequence of anthropogenic emissions and high population density in Europe. A visibility trend analysis for China found significant decreases in visibility since the 1990s (Che et al., 2007). The decreases in visibility track energy consumption trends and are the most severe in the eastern regions which have large populations and rapidly developing economies. Visibility has been studied extensively in the Arctic and US.

9.1. Arctic and Antarctic regions

In the 1950s pilots flying over the Arctic observed widespread haze in the winter and spring. In the 1970s scientists determined the chemical composition of the haze and realized that it was caused by air pollutants transported from the middle latitudes. Arctic haze highlights the impact of transported PM (Quinn et al., 2007; Tomasi et al., 2007). Arctic haze is predominantly caused by sulfate and organic carbon particles and to a lesser extent ammonium, nitrate, black carbon, and dust particles (Law and Stohl, 2007; Sharma et al., 2004; Barrie and Barrie, 1990). The vast majority of the PM responsible for Arctic haze is transported to the Arctic from Asia, Europe, and North America. The particles are well aged and have a mass median diameter of about 0.2 µm, which makes them very efficient at scattering light (Quinn et al., 2007).

Arctic haze exhibits a definite seasonal pattern with a maximum in late winter and early spring; strong south to north transport combined with weak pollutant removal mechanisms (e.g., low rainfall) in the winter/spring lead to this temporal pattern. As shown in Fig. 8, the daily average extinction due to particles exceeds 15 Mm^{-1} in winter/spring; this level is similar to the magnitude of Rayleigh scattering by gases, and thus reduces the visual range by approximately one-half. The summertime visibility conditions are excellent; scattering and absorption drop to almost zero (Fig. 8).

Although trends vary by site, many Arctic sites have shown improvements in visibility since the 1970s. Throughout the 1990s, several measures of haze (e.g., sulfate, black carbon, light extinction) decreased (Sharma et al., 2004; Quinn et al., 2007). In the

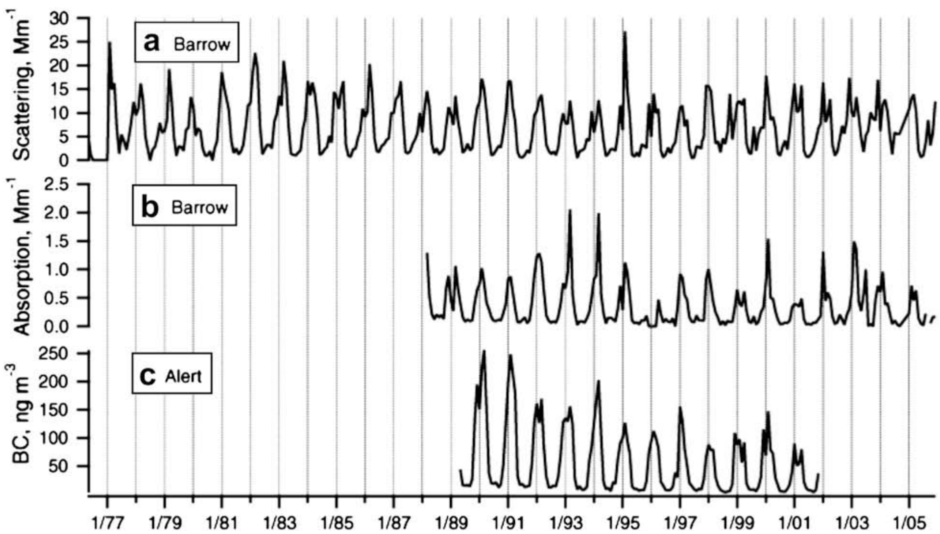

Fig. 8. Monthly averaged (a) light scattering and (b) absorption at 550 nm by PM_{10} aerosol at Barrow, Alaska (Mm^{-1}) and (c) black carbon mass concentration (ng m^{-3}) at Alert, Canada. Figure is from Quinn et al. (2007).

2000s, these measures of haze appear to be stabilizing or increasing. Melting Arctic ice is resulting in increased summertime ship traffic, and ship emissions contain high concentrations of black carbon and sulfur (Law and Stohl, 2007). Particle nitrate concentrations increased throughout the last two decades at the Canadian Alert site; the increases may be the result of increasing offshore oil and gas drilling activities in the Arctic.

The Antarctic, on the other hand, continues to experience excellent visibility. The Antarctic does not appear to be influenced by anthropogenic emissions because it is more remote than the Arctic and the Southern Hemisphere has much lower anthropogenic emissions than the Northern Hemisphere. No trends in Antarctic visibility were observed over the last 30 years (Tomasi et al., 2007).

9.2. United States

Visibility has been studied extensively in both urban and rural areas of the US. Legislation and regulations addressing visibility in the US National Parks and Forests have resulted in the creation of the IMPROVE program. IMPROVE currently operates over 170 sites. Every IMPROVE site operates a PM sampler to measure PM mass and chemical speciation; select sites operate a nephelometer, transmissometer, and automatic camera system. Fig. 9 shows a contour map of the annual average haziness, expressed in termed of VR, based on the IMPROVE and STN data from 2004. These VR estimates are reconstructed from PM chemical speciation measurements. More heavy industry, higher population density, and higher humidity contribute to poorer visibility in the eastern

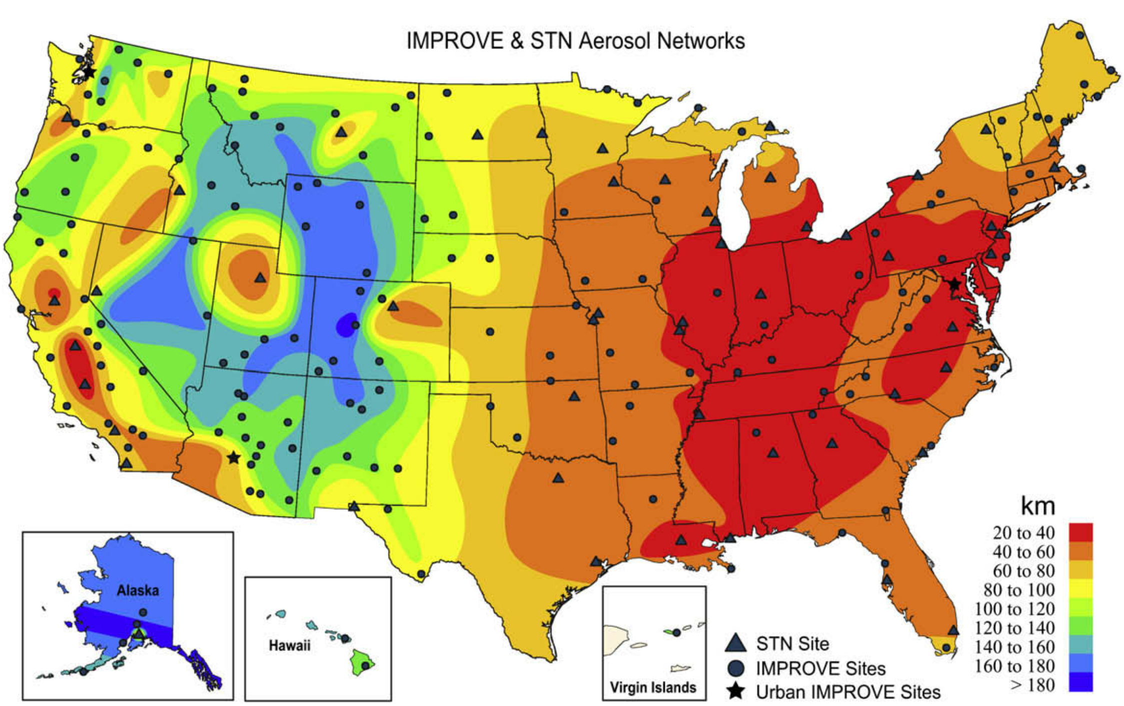

Fig. 9. Average haziness expressed as visual range based on 2004 measurements from IMPROVE and Speciation Trends Network (STN) air quality monitoring sites in the US.

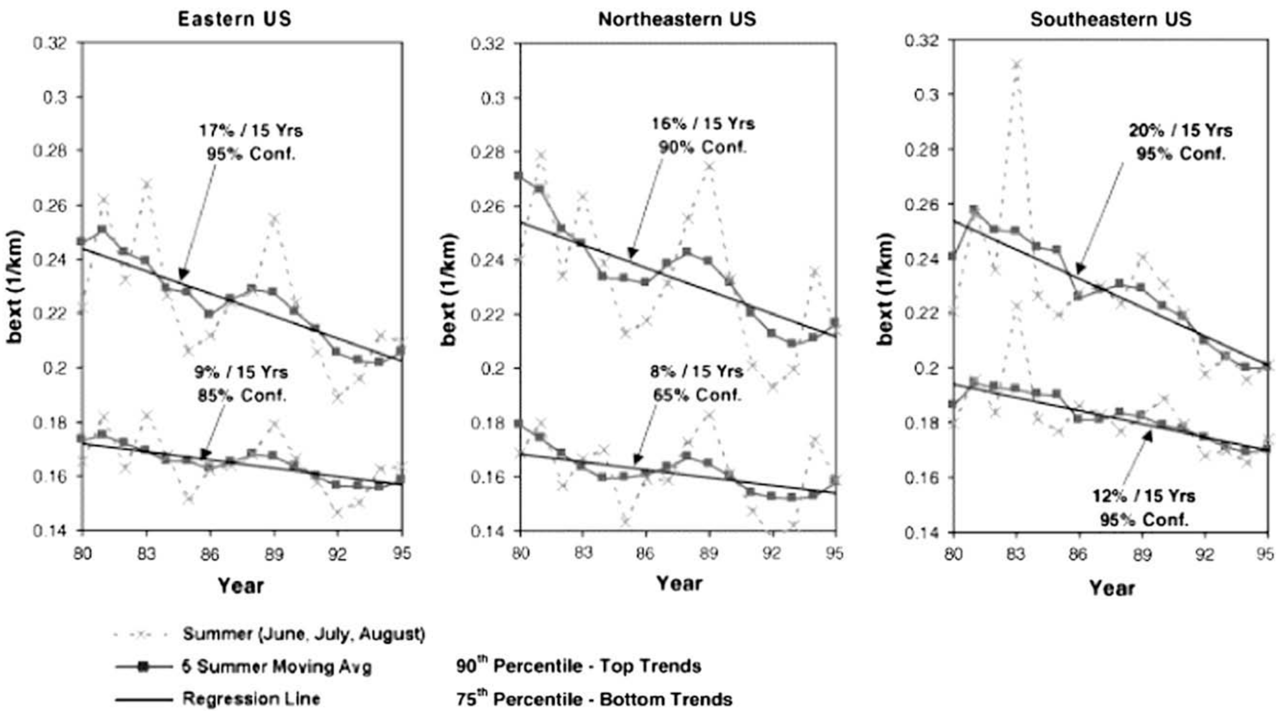

Fig. 10. Trends in extinction coefficient on the 90th and 75th percentile days from 1980 to 1995. Figure is from Schichtel et al. (2001).

US. Fig. 10 shows the trends in the 75th and 90th percentile extinction coefficients for different regions of the US. The extinction coefficients decreased which means that the hazy days became less hazy over this time period.

Urban visibility trend analyses have shown mixed results over the last 50 years. Emissions reductions have resulted in improved visibility in many areas while increasing populations have resulted in decreased visibility in some areas. Husar and Wilson (1993) analyzed airport visibility data from 1948 to 1983 and found evidence of improving visibility in the northeast and degrading visibility in the southeast. Schichtel et al. (2001) extended that trend analysis from 1980 through 1995 and found significant improvements in visibility throughout the eastern US and in California. Reductions in sulfur dioxide emissions correspond to the improvements in visibility.

9.3. Global assessments

Continental visibility was assessed by Husar et al. (2000) using VR estimates from 7000 airports around the world. The coverage of VR data is good in most parts of the world, excluding the Sahara region, northern Brazil, and southern Peru. The VR data were used to estimate aerosol extinction coefficients. They found that the aerosol extinction levels vary by a factor of 2–5 within each continent. In general, the worst visibility conditions are centered on the most populated areas, particularly in developing regions. The extinction levels also vary seasonally although different areas showed different seasonal trends depending on the sources, climate, and chemistry. Fig. 11 shows a map of the extinction coefficients for the five year period 1994–1998 in (a) December, January, February and (b) June, July, August.

Husar et al. (2000) summarized the extinction levels throughout the world as follows. The Southwestern region of Asia stands out as the haziest location throughout the year. The 75th percentile daily extinction coefficient is consistently above 0.5 km^{-1} which corresponds to <4 km visibility. This region is plagued with a high concentration of industrial and domestic sources of pollution. There is an abrupt change in the visibility moving north across the Himalayas, the visibility becomes excellent, demonstrating the importance of mountain ranges in trapping air masses. Southeast Asia contains two extinction hot spots. In the low-lying valleys of northern Thailand and Laos, the extinction levels peak (above 0.5 km^{-1}) between December and May; these high extinction values likely result from agricultural burning, which is common in the area in spring. High extinction coefficients are also found over Indonesia and Malaysia; in the fall season, this area has some of the highest extinction levels in the world due to forest fires. The forest fires were particularly bad in 1997 and drew international attention when the smoke reduced visibility in several surrounding countries. Africa has a couple hazy regions. Unfortunately, the VR coverage is poor over the Sahara region, which is the largest hot spot. The Sahara region has the highest extinction coefficients in spring and summer resulting from windblown dust. Saharan dust events are known to transport dust over long distances and can degrade the visibility in Europe and even the Americas. There is another hazy region of Africa located just south of the Sahara in the Sahel region. This region experiences the worst visibility in the summer season. The extinction coefficient is generally low throughout the year in South America except over the central region of western Brazil and Bolivia. Unfortunately, the spatial coverage is poor in this central region. Similar to the Himalayas in Asia, the Andes present a formidable barrier to the dispersion of pollution and cause distinct gradients in visibility. Comparatively, North America has low levels of haze throughout the year. Only Australia has lower extinction coefficients. Slight increases in the extinction coefficients are observed in Central America during the spring and the Eastern United States during the summer. Europe exhibits the most extreme spatial variations in haziness. The Po River Valley in northern Italy is the haziest area of Europe; it is confined by the Alps and thus has poor circulation. The Iberian Peninsula and the British Isles have moderate extinction

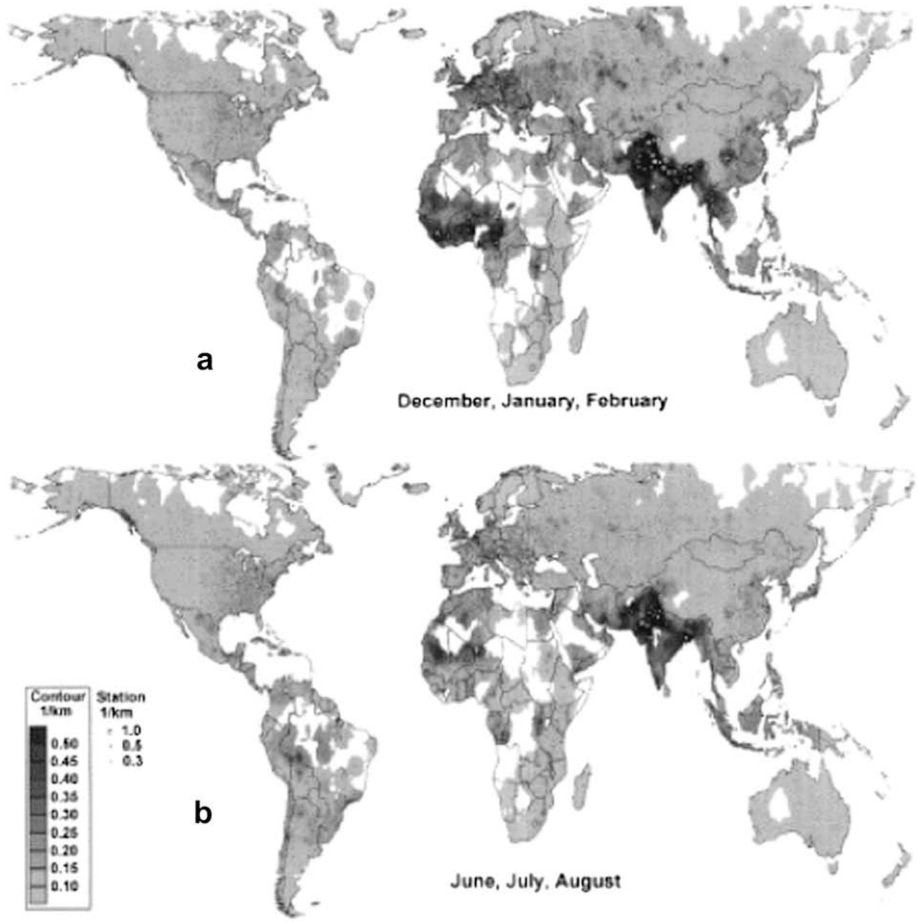

Fig. 11. Global extinction coefficient for the five year period 1994–1998 in (a) December, January, February and (b) June, July, August. Figure is from Husar et al. (2000).

coefficients. The highest extinction coefficients in Europe are observed in the winter months. Worldwide trends in visibility have yet to be addressed.

10. Concluding remarks

The last several sections have summarized ways to quantify visibility in various terms: currency, distance, brightness, etc. Quantification is important for establishing policies, but non-quantifiable considerations such as aesthetics are an important motive for preserving visibility. People are sensitive to their surroundings on both a conscious and subconscious level. Maybe once people are aware of the signs of pollution on a conscious level, they will be more interested in protecting visibility. Take note of the deep blue color of the sky following the next rainstorm in your area. Pick out a landmark that you can use to gauge the status of the air quality from day-to-day. Next time you visit a park, compare the current visibility to some photos of the location. Take advantage of the vantage point offered by your next plane ride to look for the layers of haze that often envelop our urban areas.

Acknowledgments

The author would like to acknowledge the guidance provided by Warren White on this paper; his input, feedback, and encouragement has been invaluable. The author would also like to acknowledge the reviews provided by Bill Malm, Chuck McDade, Professor John E. Thornes, and one anonymous reviewer.

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