

Implications of climate change for air quality

by Guy P. Brasseur*

Introduction

Changes in the chemical composition of the atmosphere, which have resulted from massive industrialization, intensive agriculture and urbanization, as well as road, maritime and air traffic, have led directly and indirectly to enhanced radiative forcing with, as a result, future changes in the Earth's temperatures and hydrological cycles.

The largest contribution to radiative forcing is caused by increasing atmospheric concentrations of carbon dioxide, a product of fossil fuel combustion. The emissions of other greenhouse gases, including methane and nitrous oxide, have also increased as a result of human activities. Ozone is a reactive gas that is not only important in protecting us from harmful ultraviolet radiation but is also a greenhouse gas and, at high smog-level concentrations, harmful to human health and vegetation. Finally, the release into the atmosphere of sulphur dioxide, a precursor of sulphate aerosol particles, of black carbon and organic particles has also affected radiative transfer in the atmosphere with impacts on the climate system. Submicron sulphate aerosol particles tend to scatter a fraction of the incoming solar radiation back to space, while black carbon

particles absorb a significant amount of shortwave solar radiation and affect the flux of terrestrial longwave radiation.

In addition, aerosols provide the condensation nuclei that facilitate the formation of cloud droplets. Their presence in the atmosphere leads to noticeable changes in the cloud albedo and lifetime with indirect effects on the Earth's climate. The presence of large amounts of aerosols may also affect the vertical stability of the atmosphere and, when deposited on the surface, particles may reduce the albedo of snow, again with impacts on climate.

These processes are quite difficult to quantify, since they involve complex microphysical and chemical processes. The climate impact of chemical compounds, and specifically of air pollution, is therefore difficult to estimate. Even more difficult to assess is the impact of climate change on the chemical composition and, specifically, on air quality.

In this article, we briefly review the processes that determine the interactions of the climate system and the chemical composition of the atmosphere at different scales. In particular, we examine the different processes by which

expected changes in temperature and precipitation resulting from human enterprise could affect air quality in the future.

Impact of climate change on the chemical composition of the background atmosphere

Climate models (IPCC, 2007) have been used to project the evolution of the mean temperature and precipitation rate during the coming centuries. When a "business-as-usual" scenario is adopted for the simulations, the projected increase in the global surface mean temperature at the end of the 21st century is 2.8°C, with an average warming of 3.5°C on land and of as much as 7°C in the Arctic. These changes, which are expected to occur unless drastic measures are adopted to reduce emissions of greenhouse gases, will have substantial effects on the coupled physical-chemical-biological-hydrological system that drives the evolution of the planet on timescales of decades to centuries.

As highlighted by Figure 1, the interactions of continental and oceanic ecosystems, the hydrological, biogeochemical, photochemical, microphysical and climate systems are complex, so that understanding of them requires laboratory investigations, observations and modelling.

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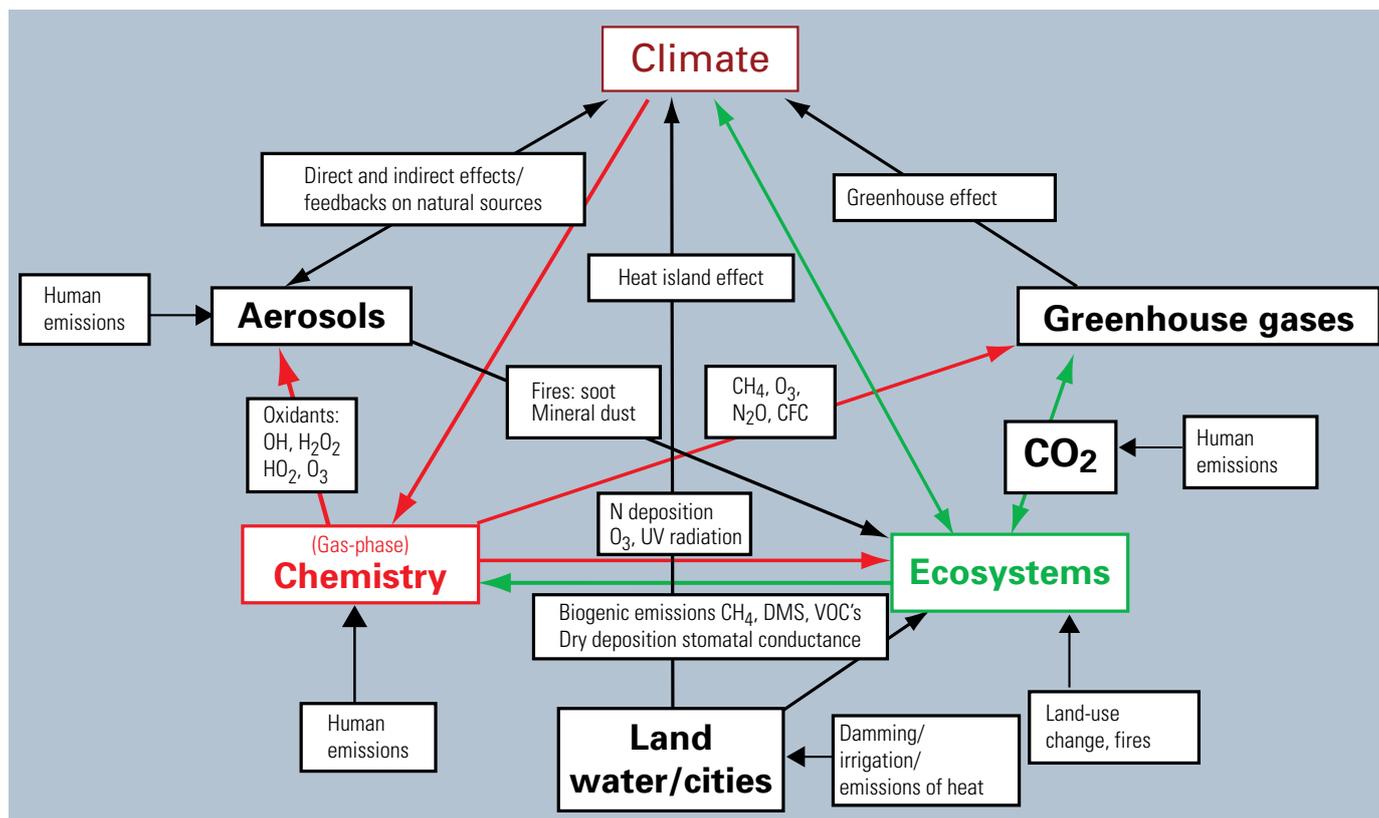


Figure 1 — Schematic representation of the interactions of climate, atmospheric reactive gases, greenhouse gases, aerosols, ecosystems and the water system (from Cox, personal communication)

Specifically, the development of comprehensive monitoring systems, data-assimilation tools and predictive models that integrate a diverse set of data into a coherent framework is a priority for the international research community. Humans perturb the Earth system, not only by emitting greenhouse gases but also by producing and releasing reactive compounds and aerosols and by changing land use (e.g. through deforestation, irrigation and urbanization). All these anthropogenic changes and the resulting climate change have the potential to modify the chemical composition of the atmosphere.

The impact of climate change on the atmospheric abundance of reactive gases and aerosols can occur through different mechanisms:

- Changes in atmospheric temperature affect the rates at which chemical reactions take place;
- Changes in atmospheric humidity affect the chemical production and destruction of chemical species and, specifically, the loss rate of tropospheric ozone;
- Changes in the frequency and intensity of lightning affects the atmospheric production of nitric oxide with direct impact on the ozone budget in the upper troposphere;
- Changes in atmospheric cloudiness affect the atmospheric composition by modifying the penetration of solar radiation and, hence, the photochemical activity in the atmosphere; aqueous and heterogeneous chemistry associated with the presence of clouds is also modified;
- Changes in the frequency and intensity of precipitation resulting from climate change affect the rate at which soluble species are scavenged and therefore removed from the atmosphere;
- Changes in surface temperature and precipitation affect the emission and deposition of chemical compounds and the surface deposition by vegetation and soil;
- Changes in ocean temperature affect the atmosphere-ocean exchanges of compounds such as dimethyl sulphide, which are a source of sulphate aerosols;
- Changes in the frequency and intensity of prolonged stagnant air conditions affect the dispersion of pollutants and enhance the frequency and intensity of pollution events with severe consequence for human health;
- Changes in the general circulation of the atmosphere affect the long-range transport of pollutants from continent to continent;



Finally, climate-generated increases in lightning frequency could produce a larger number of natural fires, especially in boreal regions with enhanced emissions of pyrogenic chemical compounds to the atmosphere. In each case, not only is the air quality affected, but also the radiative forcing and, hence, the climate system. Positive feedbacks between the chemical and climate systems can be identified, but their role in the overall Earth system may be overshadowed by other, more intense negative feedbacks that maintain the climate within acceptable bounds, at least for the foreseen future.

The quantification of coupling mechanisms between atmospheric chemistry and climate requires the development of complex Earth system models that take into account the known interactions of chemical and climate processes. Several groups in the world are currently using such models, for example to assess the rate of stratospheric ozone recovery (after the phase-out of manufactured halocarbons) under a changing climate. A major expectation of these models is that they will also provide information on the response of the troposphere, specifically of ozone and aerosols, to future climate change.

Several chemical transport models have been used to assess the response of tropospheric ozone to climate changes during the 21st century (see, for example, Brasseur et al., 2006; Stevenson et al., 2006). In the study of Stevenson et al., nine global models were used to assess how climate change would affect tropospheric ozone by the year 2030. Although significant differences characterize the models, they suggest that, in a warmer climate, ozone concentration should decrease in the lower troposphere as the water-vapour concentration increases, due to enhanced evaporation at the surface.

At the same time, ozone should increase in the upper troposphere as

- Changes in convective activity lead to changes in vertical transport in the chemical composition of the upper troposphere;
- Changes in stratosphere-troposphere exchange affect the abundance of chemical species, including ozone, in the upper troposphere;
- Changes in surface wind intensity over the continent modify the mobilization of dust particles in arid regions and, therefore, the aerosol burden in the troposphere;
- Changes in surface wind intensity over the ocean modify the exchanges of trace gases at the ocean-atmosphere interface, and affect the emission of sea-salt particles to the atmospheric boundary layer.

of the leaves. Once released in the atmosphere, isoprene is oxidized, which contributes to the formation of secondary organic aerosols and, when the level of nitrogen oxides is high, to the production of ozone. Most of the nitrogen oxides present in the atmosphere are released as a result of combustion processes.

Thus, climate warming is expected to enhance the release to the atmosphere of biogenic hydrocarbons such as isoprene, which will contribute to the worsening of regional air quality; additional ozone and aerosols will be produced with impacts on health and climate forcing.

A second example of climate-atmospheric chemistry interaction is provided by emissions of nitric oxide by bacteria in soils; these emissions are sensitive to temperature and soil moisture and will be affected by climate change. The increasing number of wildfire outbreaks in regions where droughts are becoming more frequent or intense will lead to substantially larger emissions of combustion products such as carbon monoxide, nitric oxide, soot and other compounds, with large impacts on regional and even global air quality.

An example of interactions of the climate and atmospheric chemical systems is provided by the action of isoprene, a biogenic hydrocarbon released in large quantities by vegetation. These emissions increase considerably with the temperature

a result of enhanced ozone influx from the stratosphere. In spite of recent advances made from these model studies, no definite conclusions on the magnitude or even the sign of the ozone-climate feedback currently exist. Similarly, the changes in the probability of occurrence of ozone episodes in response to climate change remain a matter of debate.

Coupled chemistry-climate models must also take into account the role of aerosol particles. The problem is complex because, apart from the effects of sulphate aerosols, the role of soot and organic aerosols must be considered. Organic aerosols are produced in large part by the oxidation of biogenic organic gases, followed by the condensation of semi-volatile oxygenated organic molecules. As indicated above, a large fraction of gaseous organic compounds are released by vegetation and the corresponding emissions are a strong function of temperature. Climate warming is therefore expected to enhance the emissions of biogenic hydrocarbons and, hence, will produce additional organic aerosols.

Modern climate models include a simplified representation of aerosol processes; they are far from realistic when treating aerosol processes and, specifically, the formation of secondary organic aerosols. Climate change will affect the emissions of aerosol precursors, in particular, biogenic volatile organic compounds. Shifts in the period and intensity of climate modes such as El Niño/Southern Oscillation (ENSO) in the tropical Pacific will affect the precipitation regimes in different parts of the world. During El Niño events, in regions such as Indonesia, where precipitation is suppressed and biomass burning is intense, the amounts of particle and gas emissions are enhanced.

Many unknowns remain in our understanding of changes in global air quality resulting from climate change. They include the potential changes that could be expected from the

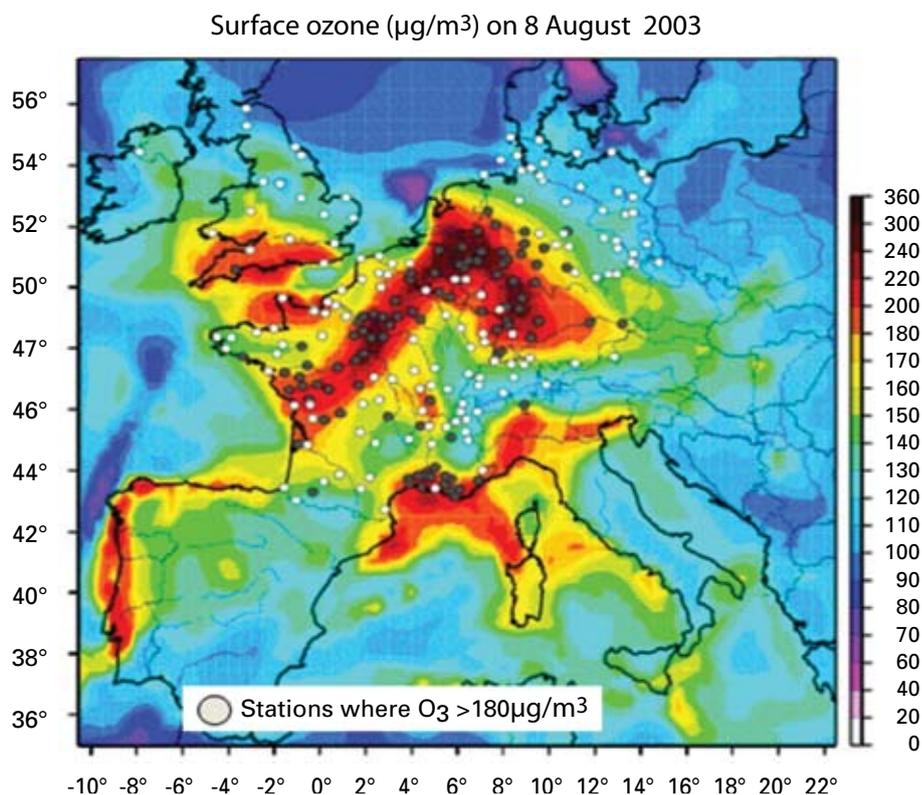


Figure 2 — Surface ozone concentration (in $\mu\text{g}/\text{m}^3$) on 8 August 2003 (during the European heatwave of 2003) calculated by Vautard et al., 2005. Stations which report ozone concentrations larger than $180 \mu\text{g}/\text{m}^3$ are indicated (from Vautard et al., 2005).

modification of long-range transport, boundary-layer ventilation and cross-tropopause exchanges. Potential changes in surface emissions and deposition in response to climate change also need to be better assessed. Experimental studies in the laboratory and in the field, as well as satellite and modelling studies, will help resolve several of these outstanding questions.

Effects of heatwaves on regional air quality

Heatwaves provide a way of estimating how air pollution could evolve under future climate change. In this regard, the heatwave that took place in western and central Europe in August 2003 constitutes an interesting test case. During the first two weeks of August, the temperature was particularly high in these regions of Europe, with daily maxima reaching between 35°C and 40°C in Paris, i.e. more than 10°C above the climatological average

temperature for this period of the year. Excessive mortality rates of 50–100 per cent were reported in several countries of Europe. In total, more than 30 000 additional deaths (15 000 in France, 5 000 in Germany, 6 000 in Spain, 5 000 in Portugal, and 5 000 in the United Kingdom) were recorded (Trigo et al., 2005). Crop damage, slides associated with tundra thawing at high latitudes, forest fire outbreaks, etc., led to considerable damage to the economy.

During this period of exceptionally high temperatures, high levels of photochemically produced ozone were observed, especially in the central part of France and south-western Germany. On 8 August, for example, many stations reported ozone concentrations exceeding $180 \mu\text{g}/\text{m}^3$, which is considerably above air-quality standards (see Figure 2). It is believed that about one-third of the deaths reported during this period were associated with health problems caused by these excessive ozone concentrations.

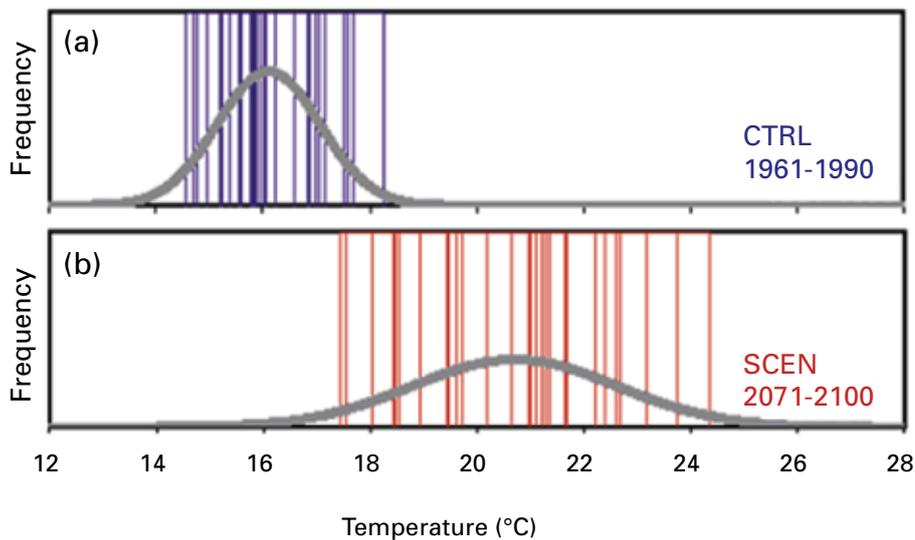


Figure 3 — Simulation by the regional climate model of Schär et al. (2004) of the mean temperature and its variability in northern Switzerland for the period 1961-1990 and 2071-2100 (scenario SRES A2), respectively. The probability for the occurrence of heatwaves increases in the future.

Several factors are believed to explain the high ozone concentrations during the August 2003 heatwave. First, temperature increases favoured the chemical production of ozone in the troposphere. Second, low atmospheric humidity reduced ozone destruction, as well as the production of the hydroxyl radical, which destroys several air pollutants, including those which are ozone precursors. Third, the vegetation was affected by high temperature and the lack of precipitation, which led to a substantial reduction in the removal by dry deposition to the Earth's surface of ozone and other compounds. Fourth, the emission of biogenic ozone precursors such as isoprene was considerably enhanced under high temperature conditions. Increases of 60-100 per cent in isoprene emissions were reported (Solberg et al., 2008). Finally, a stable meteorological situation with cloudless skies that persisted for two weeks created favourable conditions for the containment of pollutants in the boundary layer and for active photochemistry.

In addition to these local conditions, the extreme drought that occurred in southern Europe during August favoured the outbreak of wildfires.

Portugal, for example, witnessed one of its worst fire seasons. Hodzic et al. (2007) estimated that some 130 kilotonnes of fine aerosol particles ($PM_{2.5}$) were emitted as a result of European fires during the heatwave period, which led to an average $PM_{2.5}$ ground concentration of 20-200 per cent (up to $40 \mu g/m^3$) over Europe. These tiny aerosol particles, composed mainly of organic matter and black carbon, can penetrate deep into the respiratory systems of humans and, therefore, represent a serious health hazard. Hodzic et al. (2007) also reported that the presence of elevated smoke layers over Europe had significantly altered atmospheric radiative properties: the model results suggested a 10-30 per cent decrease in photolysis rates and an increase in atmospheric radiative forcing of 10-35 W/m^2 during the period of strong fire influence throughout a large part of Europe.

Air-pollution episodes could become more frequent and more acute under future climate change. Climate models show that the probability of heatwaves occurring could increase significantly during the present century. Models applied to Switzerland suggest, for example, that

not only would the mean temperature in the country increase significantly but the standard variation of the temperature would double by the end of the 21st century (see Figure 3 and Schär et al., 2004). Thus, dry and warm summers should become more frequent and, on average, heatwaves such as the heatwave of 2003 could occur every second year in Europe. Global models (IPCC, 2007) show that the standard deviation in temperature and hence the probability of heatwave occurrence would increase in many parts of the world. As a result, more frequent ozone events would be expected not only in the urbanized regions of the northern hemisphere but also in emerging countries (e.g. China and Brazil) affected both by rapid industrialization and intense biomass burning. As countries in Europe and North America attempt to reduce anthropogenic emissions of pollutants, air pollution may become more resilient than expected because of climate change.

Conclusions

In summary, the high ozone concentrations observed in Europe during the heatwave of 2003 resulted from a combination of meteorological, chemical and biological factors. It is likely that such events will become more frequent in the future. A better understanding of the links that exist between climate, ecosystems and biogeochemical cycles is required, since the coupling between these different systems directly affect air quality.

As we consider regional, as well as global, aspects of these interactions, it is important to address air pollution in an Earth system perspective. Models of the future will have to capture processes related to:

- The physical climate, including across-scale dynamics and microphysics;
- Atmospheric chemistry (reactive gases and aerosol particles) and

biogeochemical cycles (including the carbon and nitrogen cycles);

- Terrestrial ecosystems and hydrological processes (managed and unmanaged ecosystems); and
- Interactions of natural and social systems (energy, agriculture, coastal systems and other human systems).

One of the intellectual challenges for the future is not only to better understand the behaviour of the different components of the Earth system, but also to develop a science of coupling, so that the fate of our planetary system will be better simulated by comprehensive numerical models.

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