

AEROSOLS CLIMATE POLICY

report of a hearing of experts,
about the role of aerosols in climate change,
and the potential implications for policy making
organized by the European Commission on behalf of the
European Union Climate Change Expert Group on Science
14 Sept 2004, Technical University, Vienna



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AEROSOLS & CLIMATE POLICY

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BOX 1

aerosol particles, aerosols, particulate matter, PM, ...

Aerosol particles in the atmosphere arise from *natural* sources such as wind-borne dust, sea-spray, natural fires and emission of biogenic volatile organic carbons. They also arise from a range of *anthropogenic* activities, in particular the combustion of fossil fuels and biofuels. Emitted directly as particles (primary aerosol) or formed in the atmosphere by (often photochemical) conversion of gaseous precursors (secondary aerosol), atmospheric particles range in size from a few nanometers to tens of micrometers.

Aerosol particles are denominated in a number of ways

An *aerosol* is a gas in which solid particles and/or droplets are suspended. Hence “aerosol” refers to both the gas phase and the particles and droplets.

With *aerosol particles* one clearly refers to the particles and droplets of the aerosol.

Often *aerosol(s)* is used in stead of “aerosol particles”, when it is clear from the context that aerosol particles are meant.

Particulate Matter is another way of referring to these particles. For one reason or the other, the climate effects community tends to use “aerosol particles”, whereas the health effects community prefers to use “particle matter” or PM.

PM_x then means the mass of all particles with an aerodynamic diameter lower than x micrometer.

Summary

A hearing was organized by the European Commission (DG Environment and DG Joint Research Centre) on behalf of the European Union Climate Change Expert Group on Science, with the aim to update non-expert policy-makers on the role of aerosols in the climate system. The focus was on new knowledge that came available since the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC TAR, 2001).

The present report does not pretend to provide information with the status of the IPCC. The experts anyway agreed that the following statements are robust, hence that they are not likely to change as scientific uncertainties are further reduced:

- the increase of the atmospheric aerosol concentration since pre-industrial times (1750) has resulted globally in a cooling, which magnitude is significant when compared with the warming due to greenhouse gases (GHG).
- the probability that the climate sensitivity is in the upper part of the range proposed by the IPCC TAR, i.e. larger than 2.5 °C for a doubling of the atmospheric CO₂ concentration, is therefore higher.
- reductions of black carbon and organic matter emissions from fossil fuel combustion (diesel in particular) would be beneficial for human health and would very likely counter-act partially the warming expected from ongoing reductions in sulfate and nitrate aerosols.
- in order to stabilize CO₂ equivalent concentrations there is an urgent need to reduce CO₂ emissions, however the potential of reducing non-CO₂ greenhouse gases, in particular CH₄ and tropospheric ozone, should be explored as well.

Policy relevant conclusions

The experts agree that within a few years the direct radiative forcing by reflective sulfate and nitrate aerosols will be known to a higher degree of accuracy than today. However estimating the effect of carbonaceous aerosols (reflective organic matter + absorbing black carbon, see Par. 2.2) will remain problematic for a longer time. It is however agreed that, *globally*, the cooling by all reflective aerosols is not completely compensated by the warming by absorbing black carbon. Hence, *globally*, the total *direct* radiative forcing by aerosols is negative and leads to global cooling.

The experts agree that, *globally*, the direct radiative forcing by black carbon aerosols from fossil fuel burning is likely to be larger than the central value mentioned in IPCC TAR, i.e. larger than +0.2 W/m². The experts note that black carbon (BC) is nearly always emitted together with organic matter (OM), and that it is more relevant to consider the effects of carbonaceous aerosols (= BC + OM).

There are now robust observations, at local scale, that an increase of aerosol concentrations in the atmosphere does enhance the reflective properties of low (warm) clouds as well as their lifetimes. Globally, these effects lead to a negative radiative forcing or global cooling. The uncertainty in the magnitude of this cooling will remain large, but the experts judge that *globally* the radiative forcing by the first and second indirect effect is probably in the range -1 to -1.5 W/m².

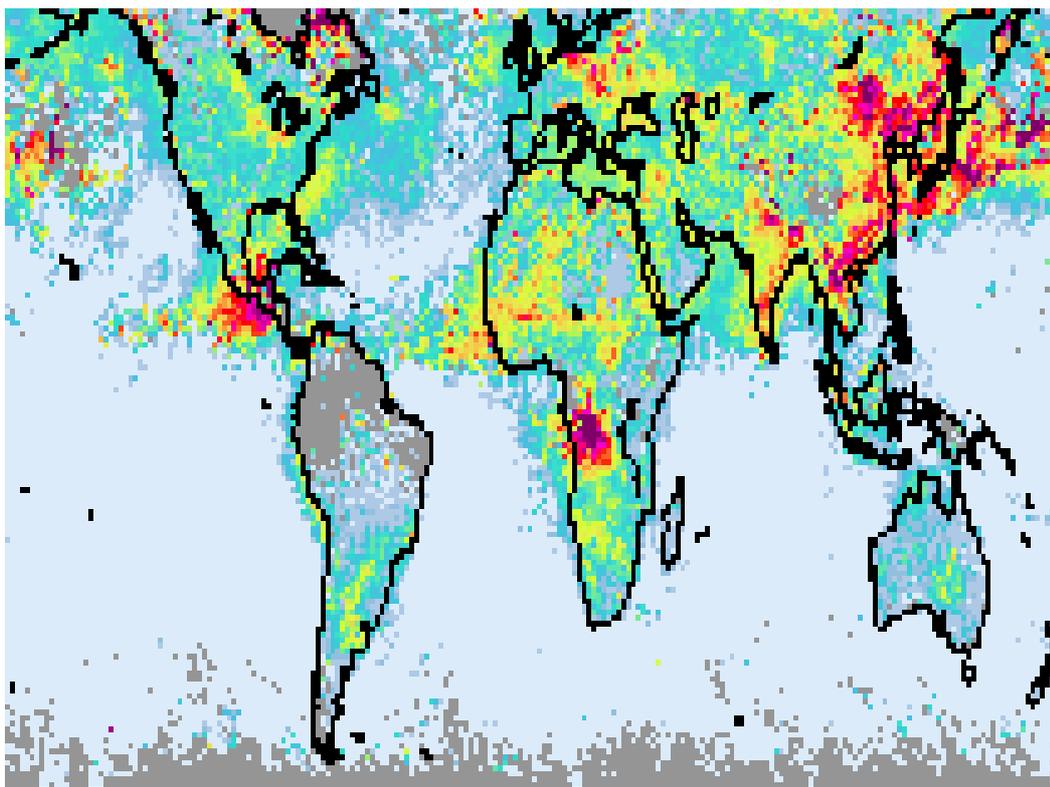


Fig.1 global aerosol distribution (May 1997)

Occurrence of aerosols (aerosol index) as seen from the space borne POLDER radiometer, during the month of May 1997. Clearly visible are major source areas such as deserts (Sahara, Gobi), urban/industrial regions and population centers and areas of vegetation burning.(CNES, France).

The experts point out that the largest uncertainties regarding aerosol effects on climate remain with those that are directly important for human well-being, i.e. the effects on the dynamics of the atmosphere, the water cycle and precipitation. These effects were not considered by the IPCC TAR. In order to compare them with the direct and indirect aerosol radiative effects, a metric different from radiative forcing is needed.

The experts agree that the man-made increase of the aerosol concentration has resulted in a negative radiative forcing, which is significant when compared with the positive *non*-aerosol radiative forcing. Hence the probability that the climate sensitivity is in the upper part of the IPCC TAR range, i.e. larger than 2.5 °C (2xCO₂), has increased.

The experts ascribe part of the accelerating trend in global warming during the last three decades to the success of air pollution policies which have led to a reduction of mainly sulfate and nitrate aerosols. The reductions in levels of particulate matter, required to protect human health, will further contribute to global warming.

The experts agree that controls of carbonaceous aerosol emission from fossil fuel combustion (diesel in particular) would be an absolute non-regret policy as it would be beneficial for human health and very likely help to partially counter-act the warming expected from further reductions in sulfate and nitrate aerosols.

The experts agree that because of a possibly higher climate sensitivity than initially thought, there might be a need to stabilize GHG concentrations at levels *below* 484 (^{note}) ppm CO_{2eq} in order to avoid that the global mean temperature exceeds its pre-industrial value by more than 2 °C. In order to do so, there is an urgent need to reduce emissions of CO₂. However the potential of reducing non-CO₂ greenhouse gases, in particular CH₄ and tropospheric ozone, should be further explored.

(^{note}) *the stabilization levels don't have the stated accuracy; the 3 significant figures are given to enable the reader to trace back the way the levels were calculated (see BOX 2 on page 20).*

	radiative forcing, W/m ² (IPPC TAR)		
	central	min	max
long-lived greenhouse gases (CO ₂ , CH ₄ , ...)	+2.43	+2.19	+2.67
stratospheric ozone	-0.15	-0.25	-0.05
tropospheric ozone	+0.35	+0.20	+0.50
sum non-aerosol forcings	+2.63	+2.14	+3.12
direct sulfate aerosols	-0.40	-0.80	-0.20
direct biomass burning aerosols	-0.20	-0.60	-0.07
direct fossil fuel aerosols (black carbon)	+0.20	+0.10	+0.40
direct fossil fuel aerosols (organic carbon)	-0.10	-0.30	-0.03
direct mineral dust aerosols		-0.60	+0.40
indirect aerosols		-2.00	+0.00
sum aerosol forcings		-4.20	+0.50

Table 1 radiative forcing by atmospheric changes (IPCC TAR)

Warming of the surface-troposphere system occurs when more radiation (expressed in W/m²) is entering the system than leaving it, i.e. when the net radiation flux at the top of the troposphere is positive.

The radiative forcing in the year 2000 is calculated as the difference between the 2000 net radiation flux and the 1750 net radiation flux.

Radiative forcing is mainly (but not solely) due to a change in the chemical composition of the atmosphere (changing concentrations of CO₂, CH₄, O₃, aerosols, ...).

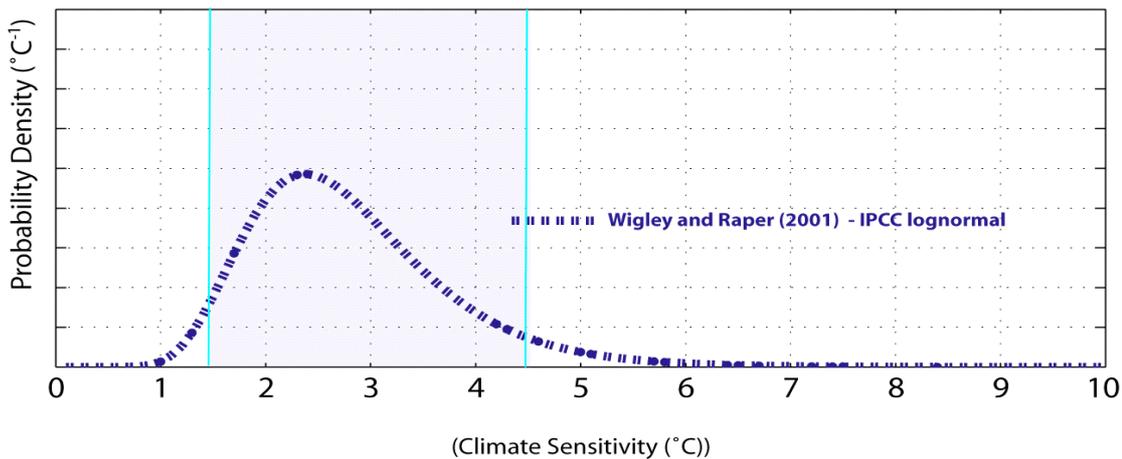


Fig. 2 climate sensitivity

The climate sensitivity is defined as the increase in global mean temperature when the CO₂ concentration is doubled from its pre-industrial concentration of 278 to 556 ppm.

The IPCC TAR gives a range from 1.5 to 4.5 °C (2xCO₂). Consistent with this range, Wigley and Raper have constructed, as one of many possibilities, a log-normal probability density function which suggests that the most probable value for the climate sensitivity is about 2.5 °C (2xCO₂).

1. Knowledge at the time of writing the IPCC TAR 2001

1.1 Aerosol direct and indirect radiative forcing

The Second and Third Assessment Report of the Intergovernmental Panel on Climate Change. (IPCC SAR, 1995 and IPCC TAR, 2001) recognized that climate change is not only due to increased levels of long-lived greenhouse gases (GHG), but that other anthropogenic factors also play a role. Among those factors are atmospheric aerosol particles stemming from anthropogenic activities. However, the SAR and TAR reported that the level of understanding of the effect of aerosols on the Earth's radiative balance is "low" to "very low".

One reason for this low level of understanding is that the aerosol particles remain in the atmosphere for short lengths of time, i.e. days to weeks. This is too short for them to be mixed homogeneously in the global atmosphere. Their geographical distribution is therefore complex and hard to capture by in-situ measurements or model calculation. Recently, the complex global distribution of aerosols has become apparent from satellite observations (see Fig. 1).

Another reason for the low level of understanding is that aerosols affect the Earth's radiative balance in a number of ways. The IPCC TAR considered only two such effects: the direct and the first indirect effect. The *direct effect* refers to reflection and absorption of light by aerosols, leading respectively to a cooling and a warming of the surface-troposphere system. The *first indirect effect* refers to the effect aerosol particles have on the cloud reflectivity: i.e. as each cloud droplet originates from water condensing on an aerosol particle, and assuming a fixed amount of water available, more particles will result in smaller droplets being formed. This results in clouds with a higher reflectivity, which results in cooling.

Taking the minimum and maximum values in Table 1 *at face value* and simply summing them up, one obtains a total radiative forcing by aerosols ranging between -4.2 to $+0.5$ W/m^2 . Although it must be remembered that these forcings may not be linearly additive, it indicates that the total aerosol forcing can be compared in magnitude with the forcings by long-lived GHG's, tropospheric ozone and stratospheric ozone, which together range from $+2.14$ to $+3.12$ W/m^2

Hence within the IPCC TAR range, the globally averaged total aerosol radiative forcing ranges from slightly positive to a negative forcing which can cancel completely the positive forcing by long-lived GHG's and ozone.

1.2. Climate Sensitivity

The climate sensitivity is defined as the increase in global mean temperature at equilibrium, when the CO_2 concentration doubles from its pre-industrial value of 278 to 556 ppm.

The wide range of possible values for the total aerosol radiative forcing poses a problem when trying to estimate the climate sensitivity to increasing GHG concentrations from the observed increase in global mean temperature. With a very small total aerosol forcing, the temperature increase of 0.6 $^\circ\text{C}$ since pre-industrial times could be mainly ascribed to GHG forcing. This would imply a low climate sensitivity of the order of 1 $^\circ\text{C}$. However, with an aerosol forcing large enough to almost cancel out the positive forcing by GHG's, the climate sensitivity would need to approach infinity to explain the same 0.6 $^\circ\text{C}$ warming.

Hence, the IPCC TAR did not provide an estimate of the climate sensitivity, based on the past temperature record since pre-industrial times. Instead, the IPCC TAR published climate sensitivities based on the temperature increase calculated with general circulation models when doubling the CO_2 concentration. These studies yield values ranging between $+1.5$ to $+4.5$ $^\circ\text{C}$ (Fig. 2).

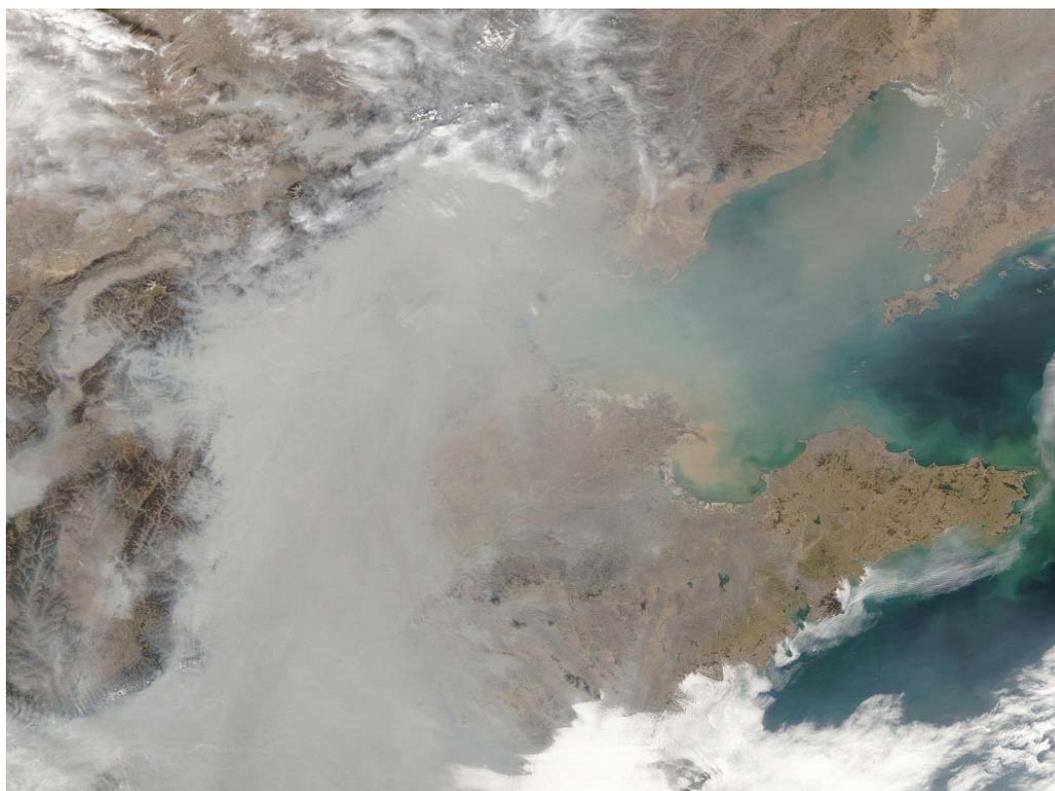


Fig. 3 the direct aerosol effect

The aerosol layer over the Beijing area, as seen from space, exemplifies the direct aerosol effect. The aerosol reflects and absorbs part of the incoming visible light, blurring the vision of the surface underneath.

	Total Carbon					
	Organic Carbon			Black Carbon		
	organic gaseous species	particulate organic matter	black carbon	pure elemental carbon		
Hydrogen/Carbon ratio	2	1.5	0.2	0.1	0.05	0
Aromaticity	0	0.1	0.8	0.8	0.9	1
Colour	none	yellowish		grey or black		

Table 2 carbonaceous aerosols

Co-variation of physical properties of Organic Carbon and Black Carbon aerosol particles (after Cachier, 1998).

2. Improved and new knowledge since the writing of the IPCC TAR

2.1 Direct radiative forcing by aerosols

Improved knowledge of the direct aerosol radiative effect, i.e the reflection and absorption of light by aerosols (Fig. 3), has been provided by new observational data and model studies.

There are longer and more homogeneous observational data on aerosol chemical and physical properties available from ground-based networks, e.g. EMEP in Europe and IMPROVE in the US. The AERONET network, on the other hand, provides global data on aerosol radiative properties.

Improved satellite-borne observations are also available from radiometers such as MODIS, MISR and POLDER-2. Through progress in instrumentation and algorithms it is now possible to retrieve the geographical distribution of aerosols over oceans *and* land with improved accuracy. It is also possible to retrieve the radiative properties of relevance to calculate the direct radiative effect.

These ground-based and satellite-borne measurements are being used to test global aerosol models that calculate emissions, transport, transformation, deposition of aerosols and eventually their radiative effect. Furthermore these models have a increased geographical resolution and contain more detailed physical and chemical schemes.

Most global models now calculate the global distribution and the direct radiative effect of the major aerosol chemical components: sulfate, black carbon (BC), primary organic matter, mineral dust, sea-salt and the water bound to these chemical species. Only a few global models however have nitrate, ammonium, and secondary organic matter.

conclusion 2.1

The experts agree that within a few years the direct radiative forcing by reflective sulfate and nitrate aerosols will be known to a higher degree of accuracy than today. However estimating the effect of carbonaceous aerosols (reflective organic matter + absorbing black carbon, see Par. 2.2) will remain problematic for a longer time. It is however agreed that, *globally*, the cooling by all reflective aerosols is not completely compensated by the warming by absorbing black carbon. Hence, *globally*, the total *direct* radiative forcing by aerosols is negative and leads to global cooling.

2.2 Direct radiative forcing by black carbon aerosols (and other carbonaceous aerosols)

In calculations of the direct effect of carbonaceous aerosols a distinction is usually made between absorbing black carbon (BC) and reflective organic material (OM). In reality, however, it is not straightforward to distinguish between BC and OM as their properties gradually between those of pure graphitic particles (pure elemental carbon) and those of particles including increasingly more non-carbon atoms such as hydrogen and oxygen (see Table 2). Robust measuring techniques to differentiate between various types of carbonaceous particles do not exist. Hence models of BC and OM are less supported by observations than models of inorganic aerosols such as sulfate and nitrate.

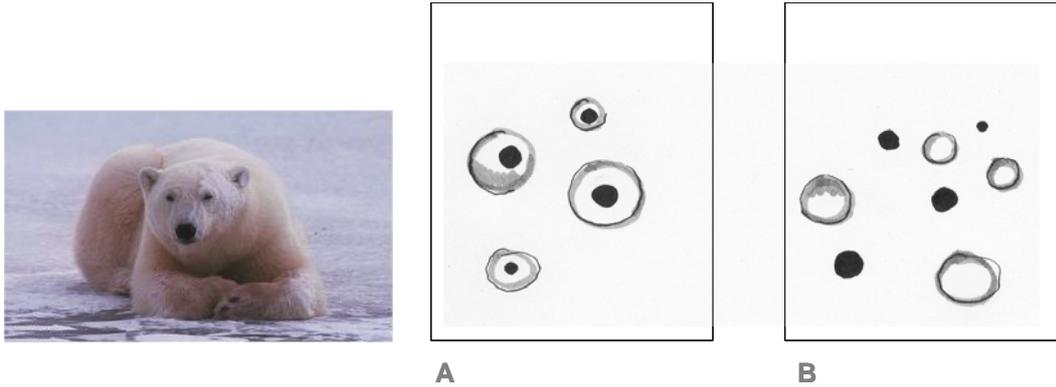


Fig. 4 ways of mixing different aerosol species

Pictorial presentation of carbonaceous aerosol particles A: assuming that organic carbon is forming a transparent film on black carbon particles, B: assuming that there is no interaction between organic and black carbon. With respect to absorption of light, coated particles (A) somehow act as polar bears ...

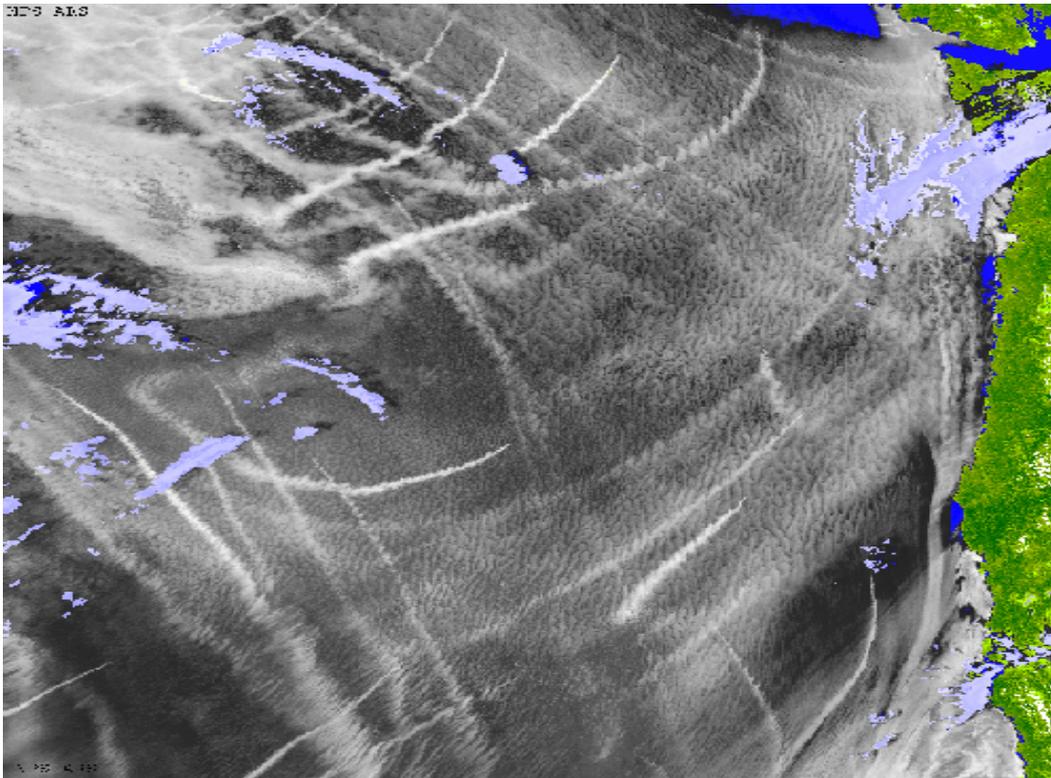


Fig. 5 the first indirect aerosol effect

“Ship tracks” off the west coast of the US exemplify the first indirect aerosol effect. A thin natural stratiform cloud is present over the ocean, which consist of large droplets formed on natural marine aerosol particles. The emissions of the ships, passing underneath, provide many more aerosols particles and hence centres for cloud droplet formation. They thus create more but smaller clouds droplets, and render the cloud locally more reflective.

As BC is never emitted alone but together with OM, it is more relevant to discuss the radiative effect of carbonaceous aerosols (i.e. the mixture of BC + OM) rather than that of BC alone. In emissions from fossil fuel burning the ratio of BC mass to OM mass is initially high (BC/OM>1). In diesel emissions the aerosol is nearly pure BC. In emissions from open vegetation fires BC/OM is initially low (<1). During their residence in the atmosphere, the BC/OM ratio of the particles will decrease due to condensation of gaseous organic species. These differences in the BC/OM ratio change the radiative properties of the carbonaceous aerosol (see also Par. 3.2).

In most models the aerosol species are described independently of one another, because few models have the necessary physical and chemical schemes to describe interactions between species (e.g. condensation of sulfate and OM on BC particles, Fig. 4).. Modeling aerosol species independently from one another will not have a large effect on the estimates of the reflection by the aerosol. It will however underestimate the absorption by black carbon. The latter is explained by the fact that a transparent coating around a black carbon particle will intercept more light (the particle is bigger) and subsequently focus that light on the black carbon core (a lens effect), where it will be absorbed.

The experts agree that in the real atmosphere BC particles are generally coated with OM and other materials, and hence they will absorb more (per gram of BC) than if they would exist as pure BC particles.

Two more effects, which were not taken into account in the IPCC TAR, are now being considered when calculating the radiative effect of BC particles:

- *the semi-direct effect*: the fact that absorbing particles in and around clouds heat up the atmosphere and lead to the evaporation of the cloud.
- *the ice-snow albedo effect*: the deposition of absorbing particles on snow and ice, reducing their reflectivity, and potentially leading to earlier melting.

These effects are not well quantified yet. They will in any case enhance the warming effect of BC, as they reduce the reflectivity by clouds and by part of the Earth's surface.

Finally, large uncertainties still exist regarding the global emission inventories of BC and OM. These uncertainties might be significantly reduced in the next couple of years through coupled modeling and measurement studies.

conclusion 2.2

The experts agree that, *globally*, the direct radiative forcing by black carbon aerosols from fossil fuel burning is likely to be larger than the central value mentioned in IPCC TAR, i.e. larger than + 0.2 W/m². The experts note that black carbon is nearly always emitted together with organic matter, and that it is more relevant to consider the effects of carbonaceous aerosols (= BC + OM).

2.3 Indirect radiative forcing by aerosols

In the IPCC TAR only one indirect effect was considered:

- *the first indirect effect*: more aerosol particles resulting in smaller cloud droplets, leading to clouds with a greater reflectivity, hence to cooling (see Fig.5).

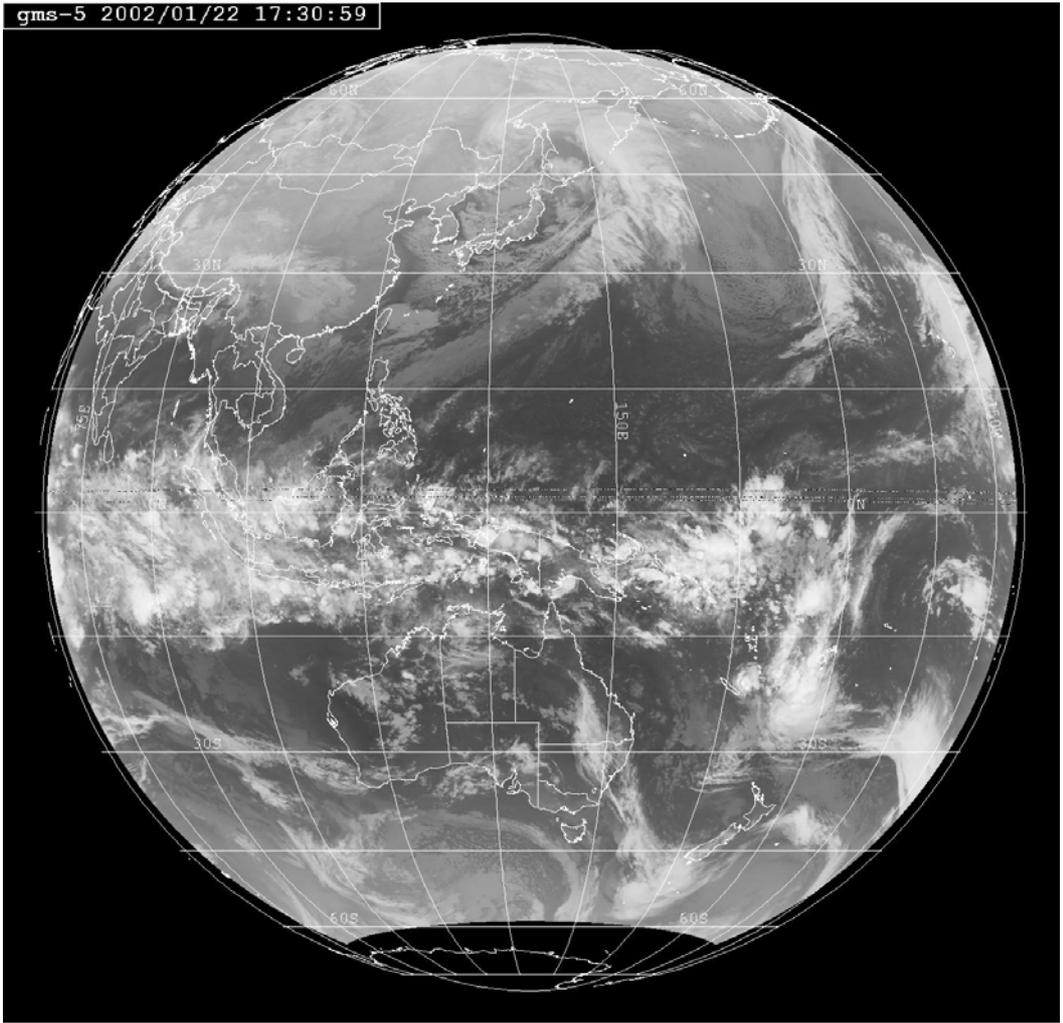


Fig. 6 tropical clouds: engines of general atmospheric circulation

The Earth seen by a weather satellite. The white patches around the equator are convective clouds that develop over the hot tropical oceans and humid continents. They set in motion the general atmospheric circulation: they pump up air from the tropics, which subsequently sinks in the (cloud-free) sub-tropics.

Since the IPCC TAR three further indirect effects have been studied:

- the *second indirect effect*: more aerosol particles lead to smaller cloud droplets, which less easily transform into rain droplets, leading to an increased cloud lifetime and cloud abundance. This effect adds to the cooling ascribed to the first indirect effect.
- the *third indirect effect (occurring in convective clouds)*: more aerosol particles lead to smaller droplets and delay the formation of rain droplets at lower altitudes. These then form at higher, often freezing altitudes in the troposphere. Latent heat is therefore released at higher altitudes, and in case of ice formation more heat is released, leading to more vigorous clouds, thunderstorms and heavy precipitation. Hence the third indirect effect has an effect on air circulation and the water cycle rather than on the radiative balance and is therefore difficult to compare with the two other indirect effects.
- the *glaciation indirect effect (occurring in mixed-phase clouds between 0 and -40 °C)*: more aerosol particles leading to an increase in a certain type of ice nuclei lead to more frequent glaciation of super-cooled clouds and increase the amount of precipitation via the ice phase. This would decrease the global mean cloud cover and lead to a warming

These additional indirect effects are not well quantified yet.

The IPCC TAR did not assign a specific radiative forcing value to the first indirect effect. However it did provide a range from 0 to -2 W/m^2 for this effect. The uncertainties on all indirect effects are still large and, given the complexity of the problem it is not expected that these uncertainties will be reduced to levels comparable to that of the long-lived GHG's in the near future. However the various indirect effects are being observed by remote sensing and by in-situ (e.g. aircraft) measurements. All physics based models also predict a negative forcing. The experts, from their part, judge that the sum of the first and second indirect effect is negative and probably in the range of -1 to -1.5 W/m^2 .

conclusion 2.3

There are now robust observations, at local scale, that an increase of aerosol concentrations in the atmosphere does enhance the reflectivity of low (warm) clouds as well as their lifetimes. Globally, these effects lead to a negative radiative forcing or global cooling. The uncertainty in the magnitude of this cooling will remain large, but the experts judge that *globally* the radiative forcing by the first and second indirect effect is probably in the range of -1 to -1.5 W/m^2 .

2.4 Aerosols, the water cycle and precipitation

Considerable scientific debate exists on the effect of aerosol pollution on precipitation, i.e. the second, third and glaciation indirect effect. Although a suppression of precipitation by aerosols is observed in individual clouds, there is no indication whether such effects can be extrapolated to the regional scale. The third indirect effect has been observed in tropical convective clouds impacted by aerosols from biomass burning. Since tropical clouds are the engines of the general atmospheric circulation, changes in their vigorousness might have widespread global effects (see Fig. 6).

The IPCC TAR considered radiative forcing as a change in the radiative balance *at the top of the atmosphere* (see Table 1). However, an increased reflection and absorption of incoming radiation by aerosols and clouds also leads to a reduction of the radiation arriving at the surface. (This reduction has been observed by surface radiation networks and has been termed “global dimming”). The potential effects of this modification of the energy balance *at the bottom of the atmosphere* were not

considered in the IPCC TAR. They include a reduction in evaporation, often over large regions, with a resulting reduction in precipitation, within the region or elsewhere.

conclusion 2.4

The experts point out that the largest uncertainties regarding aerosol effects on climate remain with those that are directly important for human well-being, i.e. the effects on the dynamics of the atmosphere, the water cycle and precipitation. These effects were not considered by the IPCC TAR. In order to compare them with the direct and indirect aerosol radiative effects, a metric different from radiative forcing is needed.

2.5 Climate Sensitivity

The experts recall that general circulation models can produce a wide range of climate sensitivities by altering model parameterizations, in particular those related to representations of clouds. Hence each of these models is “calibrated” using the past temperature record, assuming either a low climate sensitivity and a weak aerosol cooling, or a high climate sensitivity and a strong aerosol cooling. The assumptions made are evidently reflected in the climate sensitivity which is subsequently calculated in a doubling CO₂ experiment.

Based on the discussions in the previous paragraphs, the experts consider that the total aerosol radiative forcing is likely to be between -1 and -2 W/m². Although this range is narrower than that derived from the IPCC TAR. (+0.5 to -4.2 W/m²), the experts stress that the new range should only be taken as an indication that, globally, total radiative forcing by aerosols is *negative* and that it is *significant* when compared with the total *non-aerosol* radiative forcing of + 2.63 W/m².

The experts therefore agree that warming due to increased atmospheric GHG levels has been partially offset by aerosol cooling. This hints towards the possibility that current observed temperatures arise from a high climate sensitivity to an increase in GHGs in combination with significant aerosol cooling, rather than a low climate sensitivity in combination with weak aerosol cooling. The modeling studies, available to the experts, suggest that the climate sensitivity is therefore more likely to be near the upper end of the IPCC TAR range: i.e. 2.5 °C *or larger*. This is in agreement with other studies, e.g. based on the paleo-climatological record.

conclusion 2.5

The experts agree that the man-made increase of the aerosol concentration has resulted in a negative radiative forcing, which is significant when compared with the positive *non-aerosol* radiative forcing. Hence the probability that the climate sensitivity is in the upper part of the IPCC TAR range, i.e. *larger than 2.5 °C (2xCO₂)*, has increased.

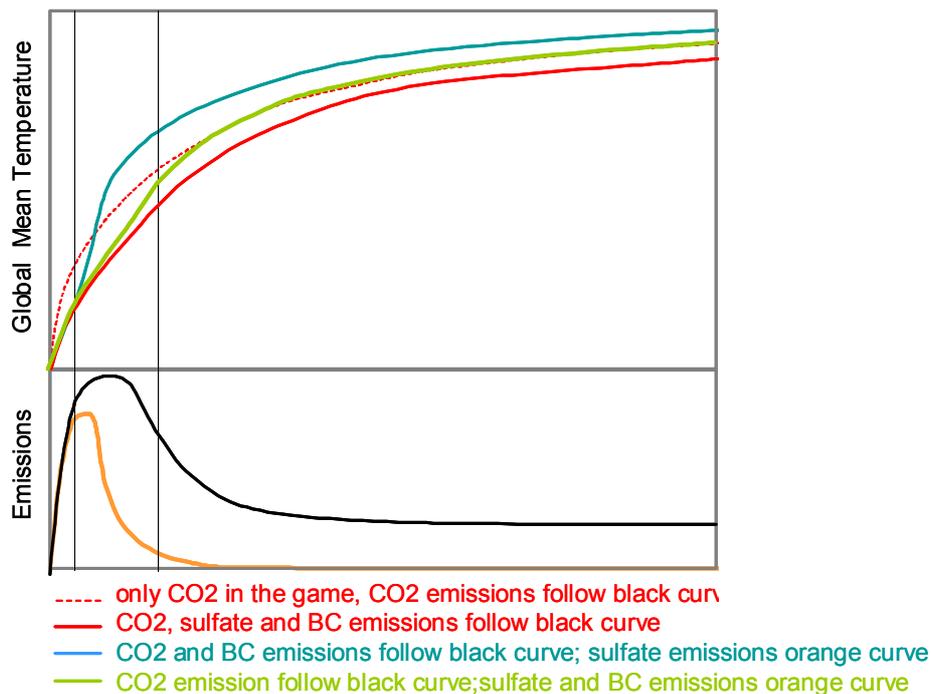


Fig. 7 emission reductions and climate change

Pictorial representation of the effects of emission reductions of long-lived GHGs (“CO₂”), scattering aerosols (“sulfates”) and absorbing aerosols (“BC”).

Two emission pathways are considered:

- black curve: slow pathway that is achieved by structural/behavioral changes, which is typical for climate change policies and which would reduce GHGs and aerosols at the same time.
- orange curve: a fast pathway that is achieved by end-of-pipe technologies, which is typical for air pollution policies and which would reduce some or all of the aerosols, but not GHGs.

Because of the long atmospheric lifetime of GHGs (decades - centuries), their concentrations in the atmosphere react only slowly to reductions in their emission. On the contrary, the short lifetime of aerosols (days-weeks) make their concentrations in the atmosphere react “immediately” to their emission reductions. Finally, the global mean temperature reacts with a time constant of several decades to changes in the atmospheric concentrations of GHGs and aerosols.

Since the beginning of industrial times the global mean temperature (red curve) remained below the temperature expected when considering only long-lived GHGs (red dashed curve), due to the overall cooling effect of the aerosols that were co-emitted with the GHGs. This situation cannot be maintained since the concentrations of aerosols in the atmosphere must necessarily be reduced because of their negative effect on human health.

During the past few decades the sulfate and nitrate aerosols have been effectively reduced in the developed world, but less so the carbonaceous aerosols from fossil fuel burning. This has led to an accelerated increase of the global mean temperature (blue curve).

A specific policy to reduce carbonaceous aerosols from fossil fuel burning, would help to partially counter-act the warming expected from further reductions in sulfate and nitrate aerosols (green curve).

3. Potential implications for policy making

3.1 Effect of particulate matter reductions on global warming

In Europe and the US air pollution policies have been implemented during the past decades to protect the health of humans and ecosystems. They require the reduction of the emissions of acidifying substances, eutrophying substances and the precursors to tropospheric ozone. These policies, implemented by end-of-pipe technologies, have strongly effected the emissions of the precursors to sulfate and nitrate particles, and less so the emissions of carbonaceous particles.

The experts agree that the success of air pollution policies in Europe and the US, and in particular the resulting reduction of the atmospheric concentrations of reflective aerosols, is partly responsible for the accelerating warming trend observed during the last two decades.

More recently, policies are being implemented to reduce the bulk mass concentration of aerosols (i.e. particulate matter, PM) in order to protect more specifically human health. Because of the overall cooling effect of aerosols, these policies are expected to lead to further warming.

In the developed world reductions of aerosol emissions will be mainly obtained by end-of-pipe control technologies, which have no major effect on CO₂ emissions. On the other hand, in developing countries there is still large scope to reduce aerosol emissions by shifting to more efficient energy production systems, which will also reduce CO₂ emissions. In any case, the reduction of aerosol emissions, or of their precursors, will have an “immediate” effect on the radiative balance, because of the short atmospheric lifetime of aerosol particles (see Fig. 7).

conclusion 3.1

The experts ascribe part of the accelerating trend in global warming during the last three decades to the success of air pollution policies which have lead to a reduction of mainly sulfate and nitrate aerosols. The reductions in levels of particulate matter, required to protect human health, will further contribute to global warming.

3.2 Options for mitigation global warming by reducing carbonaceous aerosol emissions

Reducing the bulk mass concentration of aerosols (PM) is not considered optimal in relation to health, as not all aerosol components might have the same effects. According to the World Health Organization, toxicological studies indicate that primary combustion-derived particles (i.e. carbonaceous particles) have a higher toxic potential than e.g. sulfates and nitrates.

On the other hand, the positive forcing by BC aerosol mentioned by the IPCC TAR, has lead to the idea of reducing global warming by controlling BC emissions. It was made clear in Par. 2.2 that the issue is not straightforward, as BC is emitted together with other species, in particular OM. In the case of diesel vehicles, however, BC emissions largely dominate.

Considering the following effects: absorption by BC, scattering by OM, the semi-direct effect, the snow-ice albedo effect and the indirect effect, the experts agree that

BOX 2

CO₂ equivalent concentrations

In this report the CO₂ equivalent concentration (CO₂eq) is defined as the CO₂ concentration that would result in the same radiative forcing as the one due to all forcing agents: long-lived greenhouse gases, ozone and aerosols.(see Table 1).

CO₂eq concentrations are calculated using Eq. 2 below.

Since radiative forcing is defined as a difference in net radiation flux between *present* and *pre-industrial times*, the pre-industrial CO₂eq concentration equals the CO₂ concentration by definition.

The increase, since pre-industrial times, of the concentration of long-lived greenhouse gases, ozone and aerosols has lead to a radiative forcing of about 1.13 W/m² (see Table 1, and assuming a total aerosol forcing of - 1.5 W/m², i.e. between -1 and -2 W/m as derived in Par. 2.5). An increase of just CO₂ from its pre-industrial level of 278 ppm to 343 ppm would lead to the same radiative forcing of 1.13 W/m². The year 2000 CO₂ equivalent concentration is therefore 343 ppm. (Excluding the forcing by ozone and aerosols would give a forcing of 2.43 W/m² and a CO₂ equivalent concentration of 438 ppm.)

stabilization levels

A radiative forcing ΔF will lead to a temperature increase ΔT which is proportional to ΔF

$$\Delta T = \lambda \Delta F \quad (1)$$

According to the IPCC TAR the radiative forcing due to an increase in the atmospheric CO₂ (or CO₂eq) concentration from C_0 to C equals

$$\Delta F = \alpha \ln(C/C_0) \quad \text{with } \alpha = 5.35 \quad (2)$$

It follows from Eqs. 1 and 2 that the climate sensitivity, CS, defined as the temperature increase resulting from a doubling of the CO₂ concentration, equals

$$CS = \lambda \alpha \ln 2 \quad (3)$$

Using Eqs. 1,2 and 3, the CO₂ (or CO₂eq) concentration resulting in a global temperature increase of X °C since pre-industrial times can be calculated as follows:

$$CO_2eq(X) = CO_2eq(0) \exp\left(\frac{X \ln 2}{CS}\right) \quad (4)$$

where $CO_2eq(0) = CO_2(0) = 278$ ppm

For example:

- for $X = 2$ °C and $CS = 1.5$ °C, $CO_2eq = 701$ ppm.
- for $X = 2$ °C and $CS = 2.5$ °C, $CO_2eq = 484$ ppm.
- for $X = 2$ °C and $CS = 4.5$ °C, $CO_2eq = 378$ ppm.

- carbonaceous aerosols from fossil fuel burning probably lead to a small positive radiative forcing, globally.
- carbonaceous aerosols from biomass burning lead to negative radiative forcing, globally.

Hence, a focus on reducing carbonaceous aerosols from fossil fuel burning, and from diesel in particular, would not only be beneficial for human health, but it would also help to counteract the warming from the ongoing reduction of sulfate and nitrate aerosols (see Fig. 7). In other words, there might be an opportunity to optimize aerosol reduction policies in order to more effectively protect human health, while minimizing the effect on climate.

conclusion 3.2

The experts agree that controls of carbonaceous aerosol emission from fossil fuel combustion (diesel in particular) would be an absolute non-regret policy as it would be beneficial for human health and very likely help to partially counter-act the warming expected from further reductions in sulfate and nitrate aerosols.

3.3 Climate sensitivity and long term climate policy

The long-term objective of the UN Framework Convention on Climate Change is to “stabilize GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interferences with the climate system”. Since the IPCC SAR and IPCC TAR there is a growing consensus that “dangerous anthropogenic interferences” might occur when global mean temperature exceeds its pre-industrial value by more than 2 °C.

Keeping the global mean temperature increase below 2 °C would require to stabilize GHG concentrations at about 701, 484, 378 ^(note) ppm CO_{2eq}, depending on whether the IPCC TAR 1.5, 2.5, or 4.5 °C (2xCO₂) climate sensitivity is used. (see BOX 2 for an explanation of the CO_{2 equivalent} concentration concept and calculation of GHG stabilization levels)

Having advocated a climate sensitivity possibly in the upper part of the IPCC TAR range, 2.5 °C (2xCO₂) or more, the experts conclude that long term climate policies might have to aim at stabilizing GHG levels *below* 484 ppm CO_{2eq}.

Since pre-industrial times the CO_{2eq} concentration has increased from 278 to 343 ppm, due to an increase in the net radiative forcing by roughly 1.13 W/m² (see BOX 2). This increase in net radiative forcing is in fact made up by a much larger increase of 2.43 W/m² due to long-lived GHG's (which lead to warming) *compensated* by -1.30 W/m² due to short-lived ozone and aerosols (the sum of which leads to cooling)

Of the 2.43 W/m² increase due to long-lived GHGs, 60% has been due to the increase in CO₂, the remainder due to increases in CH₄, N₂O, CFC's and HFC's. The growth rate of CO₂, i.e. the amount that is added each year to the already existing level, is still increasing. During the past decade, however, the growth rate of N₂O has remained constant, whereas the growth rates of CH₄ and CFC's have decreased.

^(note) *the stabilization levels don't have the stated accuracy; the 3 significant figures are given to enable the reader to trace back the way the levels were calculated.*

According to the discussion in Par. 3.1 and 3.2, aerosol (and ozone) concentrations will be reduced much faster than the CO₂ concentration, hence the compensating cooling effect mentioned before will become smaller and will lead to an increase of the CO_{2eq} concentration. (This is saying the same as what is shown in Fig. 7, but using the CO_{2eq} concept rather than the global mean temperature).

From the last two paragraphs the experts conclude that: because CO₂ is the main long-lived GHG and the one which growth rate is still increasing, efforts to keep CO_{2eq} concentrations below 484 ppm must urgently focus on emissions of CO₂. However, given the difficulty of halting CO₂ emissions in the short term, a practical way to remain below 484 ppm may consist of *simultaneous* efforts to reverse the growth rates of non-CO₂ GHG's. Reductions of emissions of the relatively short-lived CH₄ and tropospheric ozone are particularly appealing as it would partially counteract the increase in CO_{2eq} concentrations caused by the reduction of atmospheric aerosol concentrations.

conclusion 3.3

The experts agree that because of a possibly higher climate sensitivity than initially thought, there might be a need to stabilize GHG concentrations at levels *below* 484 ppm CO_{2eq} in order to avoid that the global mean temperature exceeds its pre-industrial value by more than 2 °C. In order to do so, there is an urgent need to reduce emissions of CO₂. However the potential of reducing non-CO₂ greenhouse gases, in particular CH₄ and tropospheric ozone, should be further explored.

Mission of the JRC

The mission of the JRC is to provide customer-driven scientific and technical support for the conception, development, implementation and monitoring of EU policies. As a service of the European Commission, the JRC functions as a reference centre of science and technology for the Union. Close to the policy-making process, it serves the common interest of the Member States, while being independent of special interests, whether private or national.



