Hadley Centre technical note 75

Olivier Boucher, Nicolas Bellouin, Bill Collins, Shekar Reddy, Jim Haywood, Colin Johnson, Fiona O'Connor

6 October 2008

Met Office

Met Office
Hadley Centre

Assessment of climate metrics for comparing the climate impacts of short-lived and long-lived chemical species.

Olivier Boucher, Nicolas Bellouin, Bill Collins, Shekar Reddy, Jim Haywood, Colin Johnson, Fiona O'Connor

Key outcomes/non technical summary

This report summarises the issues surrounding the climate change impacts of non-Kyoto gases and aerosols. The study stresses the need for a framework that allows comparing the climate effects of emissions of short- and long-lived atmospheric chemical species. Such a framework would enable a better integration of air quality and climate mitigation policies. We have performed a strength-weakness-opportunity-threat (SWOT) analysis of available climate metrics and argue that the Global Temperature change Potential (GTP) concept offers a promising way forward to overcome the issues and shortcomings associated with Global Warming Potentials (GWP). We suggest a possible extension of the GTP concept to the regional scale, with the construction of a database of climate responses to regional pulse radiative forcings.

1. Introduction: what are the issues?

Climate change is driven by a variety of climate forcings including
-changes in the atmospheric concentrations of long-lived greenhouse gases,
-changes in the atmospheric concentrations of short-lived species such as ozone and aerosols,
-changes in stratospheric ozone,
-changes in land use such as deforestation, afforestation, or irrigation,
-variability in the Sun output.

Most of the climate change mechanisms which have been studied so far and included in climate change experiments are quantified by their *radiative forcings*. Radiative forcings denote an externally imposed perturbation of the radiation balance of the Earth's system, either in the shortwave (solar) or longwave (terrestrial) spectrum. Radiative forcing is a commonly used measure of climate change because the climate response scales approximately linearly with radiative forcing irrespectively of the climate forcing that is considered. However there is an increasing number of potential climate change mechanisms that are *non-radiative forcings*. Non-radiative forcings affect climate in some other way, for instance through a modification of the surface energy budget, through cloud-aerosol interactions which influence cloud evolution (i.e. the second aerosol indirect effect), or through some indirect interaction with the carbon cycle**. A first issue is therefore to better understand non-radiative forcing climate change mechanisms and establish a framework where they can be compared with radiative forcings**.

Most of the short-lived species relevant to climate change are air pollutants and are regulated as such under national and European air quality legislations. Present and future air quality legislation is expected to have an impact on climate change. Given the complex nature of the interactions of short-lived species with climate, reduction in the emissions of short-lived species may result in either cooling or warming of the climate system system and complex changes in other features such as the location of the Intertropical Convergence Zone (ITCZ) and associated precipitation (e.g. Brasseur and Roeckner, 2005). An air quality regulation that results in a cooling of the climate system is referred to here as a *win-win* situation. In this case improving air quality could be made cheaper if it was possible to account for the climate benefit. An air quality regulation that results in a warming of the climate system is referred to here as a *trade-off*. In this case it is important that the optimal balance between the requirements for air quality and climate policies be established. Given the short lifetime of most air pollutants, their impact on climate is likely to have a regional component. It is also unclear by how much implementation of air quality policies would change the rate of climate change. **A second issue is therefore to understand the patterns and rates of climate change associated with the implementation of current and future possible air quality policies at UK, European and global scales.**

Current legislation related to the Kyoto protocol only regulates a small basket of long-lived greenhouse gases (CO_2, CH_4, N_2O, HCFC, PCF, SF_6). In addition the Montreal protocol for the protection of the stratospheric ozone layer regulates a range of chlorofluorated gases which are also greenhouse gases. Short-lived species are known to affect climate but are not regulated under current climate change legislation. Changes in land use are also a main driver of climate change at the regional and global scales but again are not regulated under the Kyoto protocol. The issue of land use has now been put on the table of the post-Kyoto negotiations. It has also been suggested that there is some potential to mitigate climate change by reducing the radiative forcing of short-lived species. Hansen et al. (2000) proposed that in order to reduce the risk of dangerous climate change the emphasis on emission reduction could be put on methane, black carbon (BC) and ozone precursors over the next 50 years although they argue too that a reduction in CO_2 emissions is also needed. Although there are still large uncertainties on the present-day radiative forcing by black carbon, it is clear that there is potential to mitigate some of the anticipated global warming by tackling emissions of black carbon (Ramanathan and Carmichael, 2008). Ground-level ozone is also a hemispheric-scale air quality pollutant. A particular abatement measure proposed (West et al. 2007; Fiore et al. 2002) is to control northern hemispheric methane emissions. This would have the added benefit of reducing the climate impacts of methane and ozone. Although methane is included in the Kyoto basket based on its 100 year GWP, it is sufficiently short lived (~12 years) that its climate impact relative to CO_2 is strongly dependent on the metric and timescale chosen. Current climate metrics for methane ignore its contribution to the ozone forcing (which Sitch et al. (2007) have shown may itself be underestimated). The above-mentioned examples show that there is a strong economical rationale to consider as many pollutants as possible in climate change policies. The more flexibility there is across sectors and species to reduce emissions of pollutants responsible for climate change, the cheaper it will be to mitigate climate change. However this has to rely on sound scientific results. If a particular pollutant is valued at too high a price in comparison to carbon dioxide, then too much effort will be put in reducing its emission at the expense of more efficient reductions of carbon dioxide emissions. Reducing emissions of short-lived species in the short-term may also allow a somewhat later intervention for long-lived species, thus buying in time for new technologies to become available. **A third issue is therefore to investigate how emissions of long-lived species and short-lived species can be traded against each other in order to achieve the most cost-effective mitigation of climate change.**

In conclusion there is a pressing need for devising a framework which allows comparison of the climate effects of emissions of short- and long-lived atmospheric chemical species. The framework should encompass radiative as well as non-radiative climate change mechanisms. Such a framework (or climate metric) would allow development of more efficient climate mitigation policies and achieve better trade-offs between air quality and climate policies. The robustness of such a climate metric to uncertainties and to the choice of socio-economic scenario needs to be understood. It also has to be practical and accepted by policy-makers and other stakeholders in order to be used.

2. Assessment of available climate metrics

2.1 Climate metrics

A limited number of climate metrics have been proposed in the literature.

2.1.1 Radiative forcing

A radiative forcing is an externally imposed perturbation of the radiation balance of the Earth's system, either in the shortwave (solar) or longwave (terrestrial) spectrum. Radiative forcing is defined against a baseline (usually taken as the pre-industrial atmosphere) and has a unit of Wm^{-2}. Radiative forcing is a popular measure of climate change because modelling studies suggest that the global-mean equilibrium near-surface temperature change scales approximately linearly with radiative forcing irrespectively of the climate forcing that is considered. There are however small variations for some climate forcings (Hansen et al., 2002). Radiative forcing is widely used by IPCC to show the relative contributions of past and future forcing mechanisms to climate change.

Radiative forcing also underlies the concept of equivalent carbon dioxide concentrations. Equivalent carbon dioxide (CO_2e) is the concentration of CO_2 that would cause the same level of radiative forcing (relative to 1750) as a given mix and concentrations of greenhouse gases. A concentration of say 550 ppm CO_2e can correspond to different atmospheric mixes of carbon dioxide, methane and nitrous oxide. There is sometimes confusion around the concept of equivalent carbon dioxide because some authors include some short-lived species (sulphate aerosols in particular) in its definition while others restrict the concept to long-lived and therefore well-mixed greenhouse gases.

2.1.2 Radiative forcing index

Radiative forcing underlies the concept of Radiative Forcing Index (RFI). The RFI is the ratio of the total RF due to an economical sector to the RF due to carbon dioxide alone. It is also defined relative to pre-industrial times.

2.1.3 Global warming potential

Global warming potential (GWP) is a measure of how much a given mass of greenhouse gas emitted today is estimated to contribute to global warming in the future. The absolute GWP is defined as the integral of the radiative forcing caused by the pulse emission of 1 kg of a chemical species over a time horizon T, which results in a unit of W m^{-2} kg^{-1} yr. GWP is a relative scale which compares the emission of 1 kg of the gas in question to that of the same mass of carbon dioxide (whose GWP is by definition 1). Both absolute GWP and GWP depend on the atmospheric decay time and radiative efficiency of the chemical species. GWP are usually reported for periods of 20, 50, 100 and 500 years. GWP is sometimes quoted without a time horizon, which strictly speaking is meaningless, although in practice a time horizon of 100 years is generally assumed. Although GWPs can technically be defined for short-lived species as well, their usage is not well established and there is little scientific literature on GWPs for short-lived species.

GWPs are used to weight the emissions of different long-lived greenhouse gases and trade them against each other under the Kyoto protocol as it underpins the concept of carbon dioxide equivalent. Carbon dioxide equivalent is a quantity that describes, for a given mixture and amount of greenhouse gas emissions, the amount of CO_2 emissions that would have the same absolute GWP when measured over a specified time horizon (generally, 100 years). It is important to note that carbon dioxide equivalent is different from equivalent carbon dioxide concentrations. Carbon dioxide equivalent reflects the time-integrated radiative forcing of emissions, rather than the instantaneous value described by CO_2e.

2.1.4 Global temperature change potential

Shine et al. (2005) introduced the concept of a global temperature change potential (GTP), which is further discussed in Shine et al. (2007). The absolute GTP is defined as the change in global surface temperature at a given time horizon induced by a pulse emission. It has unit of K.kg^{-1}. GTP is a relative scale which compares the gas in question to that of the same mass of carbon dioxide. GTP can be reported for a period of 100 years although Shine et al. (2007) proposed to use a variable time horizon as we approach a particular target year.

2.2 SWOT analysis of available climate metrics

We now present a strength-weakness-opportunity-threat (SWOT) analysis of the four different climate metrics discussed above. It is clear from the SWOT analysis that Global Temperature change Potential metric offer a promising alternative to Global Warming Potentials in order to compare different climate change mechanisms. However further work is needed to establish GTPs on a more robust footing to obtain a wider acceptance of the concept in the scientific and policymaking communities. In particular GTPs are sensitive to the adjustment time scales of the climate system which are climate model dependent. For instance the HadCM3 climate model responds with a short time scale of 8 years and a longer time scale of 400 years. These timescales were derived from more than 1000 simulated years of an experiment in which atmospheric CO_2 concentrations were quickly ramped up to four times the pre-industrial levels before being held constant. It would be more appropriate to derive these time scales from pulse radiative forcing rather than equilibrium experiments.

2.2.1 Radiative forcing

Strengths	**Weaknesses**
Is a well-established quantity. Is well understood by policy-makers. Is a useful quantity to compare the role of different forcing agents in observed climate change. Relates approximately linearly to equilibrium global surface temperature change.	Does not factor in the climate efficacy of different climate forcing agents. Is a cumulative measure of past emissions for long-lived species but a measure of present-day emissions for short-lived species. Does not mean much for non-monotonic forcings (such as for increasing then decreasing emissions and concentrations of sulphate aerosols). Cannot be used for non-radiative forcings. Cannot be used to weight emissions of different species. Cannot be regionalised in a meaningful way. As it is defined as the change since pre-industrial times, the future importance of radiative forcings that have appeared only recently (such as contrails) can be underplayed.
Opportunities Can be extended to the future for particular socio-economic scenarios. Climate models can be used to investigate the regional climate response to regional radiative forcing.	**Threats** Is so well established that it may be difficult to move away from it even if there is consensus for a better concept.

2.2.2 Radiative forcing index

Strengths	**Weaknesses**
Can be easily computed from radiative forcing calculations.	Relies on the concept of radiative forcing and therefore shares its weaknesses. Has not been applied to many socio-economic sectors.
Opportunities Can be extended to the future for particular socio-economic scenarios.	**Threats** Credit given by IPCC (1999) and media attention makes it a popular concept despite its many weaknesses.

2.2.3 Global warming potential

Strengths Is a well-established quantity. Can be computed accurately for long-lived species. Is well understood by policy-makers and other stakeholders. Is a useful quantity to compare future climate change induced by present-day emissions of long-lived species.	**Weaknesses** Somehow depends on the underlying emissions scenarios (e.g. CO_2 RF per unit emission depend on CO_2 atmospheric concentrations and CO_2 airborne fraction depends on ocean uptake). Is not very appropriate for short-lived species as it does not factor in the memory of the climate system. Does not factor in the climate efficacy of different climate forcing agents.
Opportunities Can be used as a starting point to introduce more appropriate climate metrics such as global temperature change potential.	**Threats** Is often used for an arbitrary time horizon without understanding of the sensitivity to time horizon. Can be misused if extended to short-lived species. Is so well established that it may be difficult to move away from it even if there is consensus for a better concept.

2.2.4 Global temperature change potential

Strengths Is formulated in terms of global surface temperature change which is a more relevant quantity to policy-makers. Is a more appropriate metric than global warming potential to compare the climate impact of long-lived and short-lived species. Can factor in the climate efficacy of different climate forcing agents. Can handle non-radiative forcings. Is traceable to GWP for long-lived greenhouse gases.	**Weaknesses** Is not as robust as the global warming potential as it is dependent on the adjustment timescales and the climate sensitivity of the climate model used. Is not widely accepted and has received little support from IPCC so far.
Opportunities Climate models can be used to investigate the global temperature change potential to pulse regional radiative forcing. Can be parametrised. Can be extended to regional temperature change potential for short-lived species. Can be used to assess the climate impact of complicated options involving radiative and non-radiative forcings in a comprehensive and integrated way (e.g. avoided deforestation and fossil-fuel use versus deforestation and biofuel production with associated changes in surface albedo and use of fertilisers).	**Threats** May be used for an arbitrary time horizon without understanding of the sensitivity to time horizon.

3. Two examples where an appropriate climate metric matters

3.1 Black carbon and carbon dioxide

Hansen et al. (2000) were the first authors to propose that reduction of black carbon (BC) emissions should be considered to mitigate global warming in the near-term. Streets and Aunan (2005) further highlighted the potential of BC emission reduction in the household sector in China. Recently Bond and Sun (2005) estimated that, despite its very short lifetime as compared to CO_2, the 100 year GWP for BC is 680. While such a GWP for BC appears very high on the face of it, it should be kept in mind that the global emissions of CO_2 and BC are very disparate: current estimates of emission of CO_2 are around $2x10^{16}$ g CO_2 yr^{-1}, while those for BC are around $7x10^{12}$ g BC yr^{-1} (Forster et al., 2007). However Bond and Sun argued that such a large GWP implies that there would be a climate benefit to cut BC emissions for a range of super-emitters even with a fuel penalty of 10%. Reddy and Boucher (2007) further investigated how the direct GWP for BC depends on the region of emission. They found that the 100-year GWP for BC ranges from 374 for BC emitted in Europe to 677 for BC emitted in Africa. The regional differences in BC GWP mainly reflect differences in the BC atmospheric lifetime. Reddy and Boucher (2007) also pointed out that the snow-albedo effect of BC is associated with an indirect BC GWP that would present even larger regional differences. In particular it was argued that the total (direct and indirect) GWP for European BC could be as large as 1600 for a time horizon of 100 years. This argues for BC emission reduction as part of a portfolio of climate mitigation policies. However it should be kept in mind that i) the radiative forcing (RF) and GWP by BC are still fairly uncertain and therefore climate policies should rely on a conservative estimate if a trade-off with CO_2 is involved, and ii) GWPs do not factor in the fact that a RF concentrated at the beginning of a time period is less effective in inducing climate change at the end of the time period as compared to a RF that decays more slowly over time such as that of a CO_2 pulse (see e.g. Fig. 1 in O'Neill (2000)). Rypdal et al. (2004) also acknowledged that GWPs are not well suited for short-lived species and suggested that, because of the regional nature of the forcings, aerosol emissions could be regulated as part of regional climate agreements linked to a global climate agreement. There are also co-benefits to further regulate aerosols and other short-lived species because of their impact on air quality, human health and ecosystems.

Boucher and Reddy (2008) showed how GTPs can be used in the context of black carbon and carbon dioxide emissions to alleviate some of the issues discussed above. Boucher and Reddy illustrate their methodology with two concrete examples. In particular they discuss a trade-off situation where a decrease in BC emissions is associated with a fuel penalty and therefore an additional CO_2 emission. A parameter X -which depends on the BC radiative effects, the BC emission reduction and the additional CO_2 emission- is defined and can be compared to a critical parameter to assess whether or not the BC emission reduction wins over the fuel penalty for various time horizons (see Figure 1). This tool is particularly appropriate to estimate the climate benefit of particle trap on diesel cars or to compare the integrated climate effects of gasoline versus diesel cars. Their concept can be generalised to compare the climate effects of carbon dioxide against a set of short-lived species and to account for differences in climate efficacy. The readers are directed to Boucher and Reddy (2008) for more details.

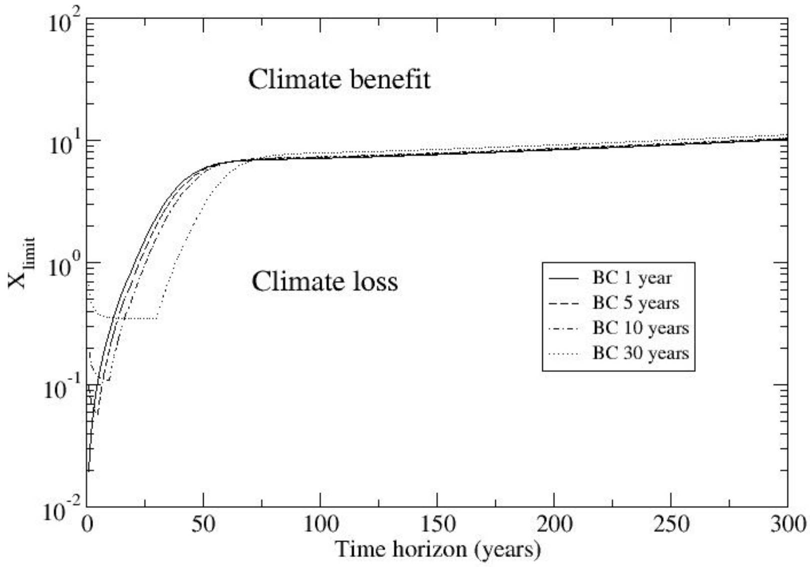

Figure 1: A parameter X is defined as X = GWP_{BC}(T=100years) Δx_{BC} / Δx_{CO2} *with* GWP_{BC}(T=100years) *the 100 year GWP for black carbon,* Δx_{CO2} *the average additional CO_2 emissions (in kg CO_2) for a BC emission reduction of* Δx_{BC} *(in kg BC). The figure shows the critical X_{limit} parameter as a function of time horizon. If X is larger than X_{limit}, there is a climate benefit for this time horizon to reduce BC emissions despite the associated CO_2 penalty.*

3.2 Aviation

The impacts of aviation on climate are very topical and it is often read that a *multiplier factor* should be used to take into account emissions other than carbon dioxide. The multiplier factor finds its origin in the radiative forcing index (RFI) and has been suggested to be around 2.7 as estimated for aviation by IPCC (1999). The multiplier factor is thought not to be scientifically robust (Forster et al., 2006, 2007a) but this does not mean that a more appropriate climate metric should not be used to quantify the overall impact of aviation on climate. Aviation is an interesting case study because there are a large variety of climate agents contributing to climate change (carbon dioxide, methane, tropospheric ozone, aerosols, linear persistent contrails, induced cirrus, stratospheric ozone, stratospheric water vapour) with a large range of time scales. We suggest that we should move towards estimating the climate impact of individual flights as this would provide more leverage to minimise their climate impacts. There are many factors why two different flights can have different climate impacts: technological factors (optimum flight altitude, engine efficiency, NOx emission factor), operational factors (flight latitude and altitude, time in the year, time in the day) and environmental factors (temperature, humidity, tropopause height). The GTP offers a promising framework to aggregate the climate impacts of individual flights due to carbon dioxide emissions, changes in methane and ozone and contrails. Quantifying the overall impact of aviation on climate is quantified is a prerequisite to minimising it. A more precise knowledge of the climate impacts of individual flight types can inform how to optimise the use of a fleet to meet the air travel requirements (e.g. by encouraging day flights in regions prone to contrail formation or by adjusting the flight altitude in order to minimise contrail formation at little or no fuel penalty).

4. Conclusions

Air quality and climate issues are intricately related, especially on decadal time scales. There is a pressing need for devising a framework which allows comparing the climate effects of emissions of short- and long-lived atmospheric chemical species. The framework should encompass radiative as well as non-radiative forcings. Such a framework would enable a better integration of air quality and climate mitigation policies. It is particularly timely to look into the climate effects of short-lived species because i) the tools are available to do so and ii) there is more and more emphasis on the economics of climate change, which requires appropriate metric to support decision-making.

We have performed a strength-weakness-opportunity-threat analysis of available climate metric and argue that in the current context the Global Temperature change Potential concept (initially proposed by Shine et al.) offers a promising way forward. We suggest a possible extension of the concept to the regional dimension. More specifically it is proposed here to build a database of climate responses to regional pulse radiative forcings. A set of "climate responses to regional pulse radiative forcings" can be combined with a set of "radiative forcing response to regional pulse emissions" (e.g. Derwent et al. (2008)) to provide an end-to-end database of climate responses to pulse emissions. Such a database would be very valuable ad-hoc tool to assess the climate impacts of air quality control policies.

However a temperature-based climate metric should not be seen as the final answer to the issue of comparing greenhouse gases with other atmospheric pollutants. A global- or regional-mean temperature change may not be sufficient as a metric for climate change. Precipitation changes show complex relationship to temperature changes which are spatially and forcing dependent. Although many climate impacts are temperature-mediated, this is not always the case and other impacts can be related to the carbon dioxide concentration itself (such as ocean acidification) or to the toxic nature of some of the pollutants. For instance aerosols and ozone are both known to affect ecosystems, which can feedback onto the carbon cycle and impact ecosystem services (such as vegetation productivity and carbon storage). It is important that research continues on how to better integrate these different impacts in our modelling of climate change and climate mitigation.

5. Acknowledgements

This work was supported by the Joint Defra and MoD Integrated Climate Programme - GA01101, CBC/2B/0417_Annex C5.

6. References

Bond, T. C. and H. L. Sun, Can reducing black carbon emissions counteract global warming? *Env. Sci. & Technol.*, 39, 5921-5926, 2005.

Boucher, O. and M. S. Reddy, Climate trade-off between black carbon and carbon dioxide emissions, *Energy Policy*, 36, 193-200, doi:10.1016/j.enpol.2007.08.039, 2008.

Brasseur, G. P., and E. Roeckner, Impact of improved air quality on the future evolution of climate, *Geophys. Res. Lett*., 32, L23704, doi:10.1029/2005GL023902, 2005.

Derwent, R. G., D. S. Stevenson, R. M. Doherty, W. J. Collins, M. G. Sanderson, and C. E. Johnson, Radiative forcing from surface NOx emissions: spatial and seasonal variations, *Climatic Change*, doi:10.1007/s10584-007-9383-8, 2008.

Fiore A. M., D. J. Jacob, B. D. Field, D. G. Streets, S. D. Fernandes, and C. Jang, Linking ozone pollution and climate change: The case for controlling methane, *Geophys. Res. Lett.*, 29 (19), 1919, doi:10.1029/2002GL015601, 2002.

Forster, P. M. de F., K. P. Shine, and N. Stuber, It is premature to include non-CO_2 effects of aviation in emission trading schemes, *Atmos. Env.*, 40, 1117-1120, 2006.

Forster, P. M. de F., K. P. Shine, and N. Stuber, Corrigendum to “It is premature to include non-CO_2 effects of aviation in emission trading schemes”, *Atmos. Env.*, 41, 3941, 2007a.

Forster, P. M. de F., V. Ramaswamy, P. Artaxo, T. Berntsen, R. A. Betts, D. W. Fahey, J. A. Haywood, J. Lean, D. C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz, and R. Van Dorland, *Changes in atmospheric constituents and in radiative forcing*, In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, pp. 129-234, 2007b.

Hansen, J., M. Sato, R. Ruedy, A. Lacis, and V. Oinas, Global warming in the twenty-first century: An alternative scenario, *Proc. Nat. Acad. Sciences*, 97 (18), 9875-9880, 2000.

Hansen, J., et al., Efficacy of climate forcings, *J. Geophys. Res.*, 110, D18104, doi:10.1029/2005JD005776, 2007.

IPCC, *Aviation and the Global Atmosphere*, J.E. Penner et al. (Eds.), Cambridge University Press, Cambridge, UK, 1999.

O’Neill, B. C., The jury is still out on global warming potentials, An editorial comment, *Climatic Change*, 44, 427-443, 2000.

Ramanathan, V., and G. Carmichael, Global and regional climate changes due to black carbon, *Nature Geoscience*, doi:10.1038/ngeo156, 2008.

Reddy, M. S., and O. Boucher, Climate impact of black carbon emitted from energy consumption in the world’s regions, *Geophysical Research Letters*, 34, L11802, doi:10.1029/2006GL028904, 2007.

Rypdal, K., T. K. Berntsen, J. S. Fuglestvedt, A. Torvanger, K. Aunan, F. Stordal and L. P. Nygaard, Tropospheric ozone and aerosols in climate agreements: Scientific and political challenges, *Environ. Sci. Policy*, 8, 29-43, 2004.

Shine, K. P., J. S. Fuglestvedt, K. Hailemariam, and N. Stuber, Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases, *Climatic Change*, 68, 281-302, 2005.

Shine, K. P., T. K. Berntsen, J. S. Fuglestvedt, R. B. Skeie and N. Stuber, Comparing the climate effect of emissions of short and long lived climate agents, *Phil. Trans. R. Soc. A*, 365, 1903-1914, doi:10.1098/rsta.2007.2050, 2007.

Sitch, S., P. M. Cox, W. J. Collins, C. Huntingford, Indirect radiative forcing of climate change through ozone effects on the land-carbon sink, *Nature*, 448, 791-794, doi: 10.1038/nature06059, 2007.

Streets, D.G., and K. Aunan, The importance of China's household sector for black carbon emissions, *Geophys. Res. Lett.*, 32, L12708, doi :10.1029/2005GL022960, 2005.

West J. J., A. M. Fiore, V. Naik, L. W. Horowitz, M. D. Schwarzkopf, D. L. Mauzerall, Ozone air quality and radiative forcing consequences of changes in ozone precursor emissions, *Geophys. Res. Lett*., 34, L06806, doi:10.1029/2006GL029173, 2007.