Scientific issues in the design of metrics for inclusion of oxides of nitrogen in global climate agreements

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The Kyoto Protocol seeks to limit emissions of various greenhouse gases but excludes short-lived species and their precursors even though they cause a significant climate forcing. We explore the difficulties that are faced when designing metrics to compare the climate impact of emissions of oxides of nitrogen (NO_x) with other emissions. There are two dimensions to this difficulty. The first concerns the definition of a metric that satisfactorily accounts for its climate impact. NO_x emissions increase tropospheric ozone, but this increase and the resulting climate forcing depend strongly on the location of the emissions, with low-latitude emissions having a larger impact. NO_x emissions also decrease methane concentrations, causing a global-mean radiative forcing similar in size but opposite in sign to the ozone forcing. The second dimension of difficulty concerns the intermodel differences in the values of computed metrics. We explore the use of indicators that could lead to metrics that, instead of using global-mean inputs, are computed locally and then averaged globally. These local metrics may depend less on cancellation in the global mean; the possibilities presented here seem more robust to model uncertainty, although their applicability depends on the poorly known relationship between local climate change and its societal/ecological impact. If it becomes a political imperative to include NO_x emissions in future climate agreements, policy makers will be faced with difficult choices in selecting an appropriate metric.

climate change | climate metrics | Kyoto Protocol

The Kyoto Protocol to the United Nations Framework Convention on Climate Change aims to control emissions of relatively long-lived greenhouse gases. It excludes emissions of short-lived species, or their precursors, perhaps reflecting the difficulties policymakers would have faced had they tried to include them. Nevertheless, short-lived species are believed to contribute significantly to human-induced climate change (1). Their absence from the protocol could weaken efforts to mitigate climate change by weakening the "comprehensive" approach embodied in the United Nations Framework Convention on Climate Change; indeed, the U.S. administration has cited the absence of black carbon and tropospheric ozone from the protocol as one reason why they have not become signatories (see www.whitehouse.gov/news/releases/2001/06/20010611-2.html). The absence could also lead to a distortion of national priorities in emission reductions and discourage full engagement in the protocol if proper credit is not given to measures leading to reductions in climatically significant emissions.

The overall question that we pose here is whether there are fundamental barriers to the inclusion of short-lived species in climate treaties. We focus on the most important precursor to tropospheric ozone, oxides of nitrogen (NO_x) (1), which poses some unique difficulties. The discussion has wider applicability to other ozone precursors, aerosols, and contrails and contrail cirrus.

The operation of multigas climate agreements requires a metric that puts emissions on a common scale. The Kyoto Protocol uses the global-warming potential (GWP) (2) with a 100-yr time horizon. The GWP measures the time-integrated radiative forcing (RF) caused by a pulse emission of a gas; for each gas, the GWP indicates the (radiatively) equivalent mass emission of CO_2 that would have the same impact as a 1-kg emission of that gas. Recent Intergovernmental Panel on Climate Change reports have refrained from providing tabulated values for the GWP of NO_x.

The discussion in this article focuses on how NO_x could be included in a Kyoto-type multigas treaty, but we recognize that this is not the only option for future climate agreements; possibilities include individual treaties for each greenhouse gas (3), a specific agreement on short-lived species (4), or inclusion of short-lived species in regional agreements with a prime or cofocus of air quality (5). Our results will have relevance to all of these options.

We first discuss the unique difficulties in defining a GWP for NO_x. We then consider a range of metrics that use global-mean input, focusing on how the difference in climate impact of low- and high-latitude emissions depends on whether tropospheric ozone is considered on its own or in conjunction with methane change. To illustrate our considerations, we used model simulations that examined the impact of regionally constrained emissions of NO_x on concentrations of tropospheric ozone and methane, the resulting RF, surface-temperature response, and GWPs (6). Next, we explore possible metrics that use local input and are then aggregated to the global mean. We analyze what aspects of regionality in climate response are important for the determination of their value. After summarizing key conclusions, we discuss possible next steps and the decisions that policy makers need to make if they want to include NO_x in any climate agreements.

Difficulties in Defining a GWP for NO_x

Ozone–Methane RF Compensation. Although the Intergovernmental Panel on Climate Change gives a relatively high confidence to the RF caused by tropospheric ozone (1), this confidence level is deceptive for NO_x. In addition to increasing ozone, NO_x leads to increased concentrations of the hydroxyl radical (1) and hastens the destruction of several greenhouse gases including methane. Hence, NO_x emissions have suppressed the methane increase since preindustrial times, a fact that is not directly represented on the commonly used RF charts (1, 7), which are based on changes in abundance; emissions-based views of the RF caused by ozone precursors make this compensation more visible (8, 9).

On a global-mean level, the negative RF caused by methane loss is of the same order as the positive RF caused by the ozone increase (6, 8–12); thus, even the sign of the net RF caused by NO_x emissions is uncertain. Hence, confidence in the tropospheric ozone RF does not translate into confidence in the total climate impact of emissions of ozone precursors, which has consequences for the design of metrics to measure the relative climate impacts of NO_x. NO_x emissions also impact the forma-

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Abbreviations: NO_x, oxides of nitrogen; GWP, global-warming potential; RF, radiative forcing; GTP, global temperature-change potential; CTM, chemical-transport model; GCM, general-circulation model; LDP linear damage potential; SDP, square damage potential; ALDP, absolute LDP; VOC, volatile organic compound.

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tion of nitrate aerosols and the concentrations of other greenhouse gases (such as hydrofluorocarbons) (1); these effects will not be considered here. Estimates of nitrate aerosol RF (13, 14) disagree on whether it contributes significantly; its omission here should not affect our main conclusions.

Regional Dependence of Ozone Production. Ozone production from NO_x emissions highly depends on the state of the atmosphere into which NO_x is emitted (1, 9). The regional differences are determined by latitudinal differences in solar flux, the background NO_x levels, and the regional emissions and chemistry of hydrocarbons (15, 16). Hence, equal NO_x emissions in different regions can lead to quite different globally averaged ozone changes depending on their temporal, geographical, or vertical (in the case of aircraft) location. Emissions from low-latitude (and generally less developed) nations have a larger RF and GWP than equal emissions from midlatitude (and generally more developed) nations (6, 12, 17), which is also a complicating factor for policy makers (5).

Geographical Distribution of Climate Change. There is another distinct aspect of this regionality: even if equal emissions from different locations were to lead to the same global-mean RF, the geographical distribution of this RF and climate response could be quite different, because NO_x and ozone are relatively short-lived. Although this problem of regionality of RF is shared in the characterization of climate metrics for all short-lived emissions, it is uniquely complicated for NO_x. Although the ozone RF is inhomogeneous, the associated methane-negative RF is much more homogeneous because of its decadal lifetime (9). Hence, even if the positive ozone and negative methane RFs (or indeed the resulting surface-temperature change) were fortuitously to cancel in the global mean, it would not mean that the local climate impact would be zero. In addition, even the global-mean temperature response may depend on the regional distribution of the RF, a fact that recently has begun to be considered in metric design (6, 18).

Geographical Distribution of Climate Impact. Following the original definition, the GWP uses global-mean inputs, as do several proposed alternatives. We will refer to these as $M([x])$ metrics, where the square brackets denote the global mean, and x denotes any input required by the metric. Note that the global-mean inputs themselves may be calculated locally and averaged globally (as is the case for the ozone RF here), but the GWP only uses the global-mean input. In principle, metrics could be designed that are calculated locally, using local inputs, and then averaged globally; we refer to these as $[M(x)]$ metrics. If $M(x)$ is a nonlinear function of x, then $M([x]) \neq [M(x)]$. Here we explore two metrics that, by their definition, are strongly nonlinear. These choices are motivated by the fact that it is likely that the ecological and societal impacts of climate change depend on its geographical distribution; the impacts may also have a nonlinear dependence on climate change. One possible metric could assume that any climate change has an impact, and thus the absolute value of temperature could be used, so that cancellation in the global mean cannot occur. Another possible, and crude, impact metric assumes that climate "damage" varies as the square of local temperature change, a damage function that has been applied in global-mean calculations (19–22).

The above discussion leads to more focused questions. How does the methane–ozone RF compensation and the regionality of ozone production, climate response, and climatic impact affect different metrics? Is the GWP formulation itself part of the barrier to the incorporation of short-lived species? Do other metrics show the same degree of regional or intermodel dependence?

It is unlikely that a perfect metric for short-lived species can be found and agreed on. There is a delicate balance between metrics that adequately include our understanding of the relevant climate-impact parameters (e.g., sea-level rise, ecosystem change, economic consequences, etc.) and those with a level of scientific uncertainty and controversy low enough to be perceived as acceptable by policy makers; this may be one reason the GWP, despite its shortcomings (4, 23, 24), has retained favor in terms of its use in the Kyoto Protocol (18).

Metrics Using Global-Mean Inputs

Metric Choices. A number of choices have to be made when selecting and evaluating metrics, some of which are illustrated schematically in Fig. 1. One choice is whether comparison is made between a pulse emission or a sustained emission change. Another choice is the "end point." The traditional GWP uses the time-integrated RF caused by a pulse emission (which we denote GWP_P), which has been extended (6, 25, 26) to the time-integrated RF caused by a sustained emission change (which we call the sustained GWP or GWP_S). Another possibility for an end point is RF or ΔT_s at a particular time. The global temperature-change potential (GTP) (27) compares temperature change at a given time for either a pulse or a sustained emission change; we consider the sustained version here and label it GTP_S. Another choice for the GWP_P, GWP_S, or GTP_S is the time horizon, H, at which the metric is computed; because the Kyoto Protocol adopted 100 yr, we will use the same value here.

Any chosen metric can have an absolute value or be relative to some reference value; the latter is generally of greater utility. For example, the Intergovernmental Panel on Climate Change (1) presents ratios of the absolute GWP of a given gas to the absolute GWP of CO_2. In the following, absolute metrics will be denoted by the initial "A." To be acceptable for policy makers, metrics must be robust (i.e., not too model-dependent). Our main concern here is to measure the relative effect of subtropical compared with midlatitude NO_x emissions rather than their impact relative to CO_2. Robustness in this ratio is a necessary but not sufficient requirement for a metric. Because we will see that this ratio depends less on model uncertainties than the absolute metric values, we will use it to evaluate the prospects of the proposed metrics. However, in normal policy usage, the ratio of the absolute NO_x metric to that of a reference gas is of greater utility.

We also account for the fact that, depending on their nature and geographical distribution, the same global-mean RF could lead to a different ΔT_s. This "efficacy" can be included by multiplying the absolute metrics by the appropriate climate sensitivity parameter, λ, which measures ΔT_s for a unit RF (6, 18). Although the absolute value of λ is poorly known (1), the relative dependency of λ on the nature of the RF seems more robust (28, 29). To illustrate the possible impact of this dependency, for the GTP_S we will present values (denoted GTP^*_S) to indicate that climate efficacy has been taken into account.

There are many additional nuances that can be added to metrics that we do not pursue; for example, some have argued for the inclusion of a discount rate, e^{-rt}, where r is a constant and t is time, such that near-term changes are deemed more important than distant future changes (18, 30).

Results

The equilibrium effects of sustained mass emissions of NO_x [of 1 Teragram(N) yr^{-1}] from "Europe" (40–60°N, 10°W–20°E) and from southeast Asia (henceforth "Asia") (10–30°N, 100–120°E) have been calculated (6). Because of model uncertainties, calculations were presented from two chemical-transport models (CTMs), three RF codes, and two general-circulation models (GCMs) to generate a range of results.‖

These calculations form the basis of the metric calculations here. The O_3 RF has two components of opposing signs. One is short-

‖Additional details of the models are given in ref. 6 and references therein. Here, the two CTMs are labeled LMD and UiO, and the two GCMs are labeled ECHAM4 and UREAD. Because of computer-time restrictions, only a subset of the CTM-derived ozone changes are used in the GCM calculations.

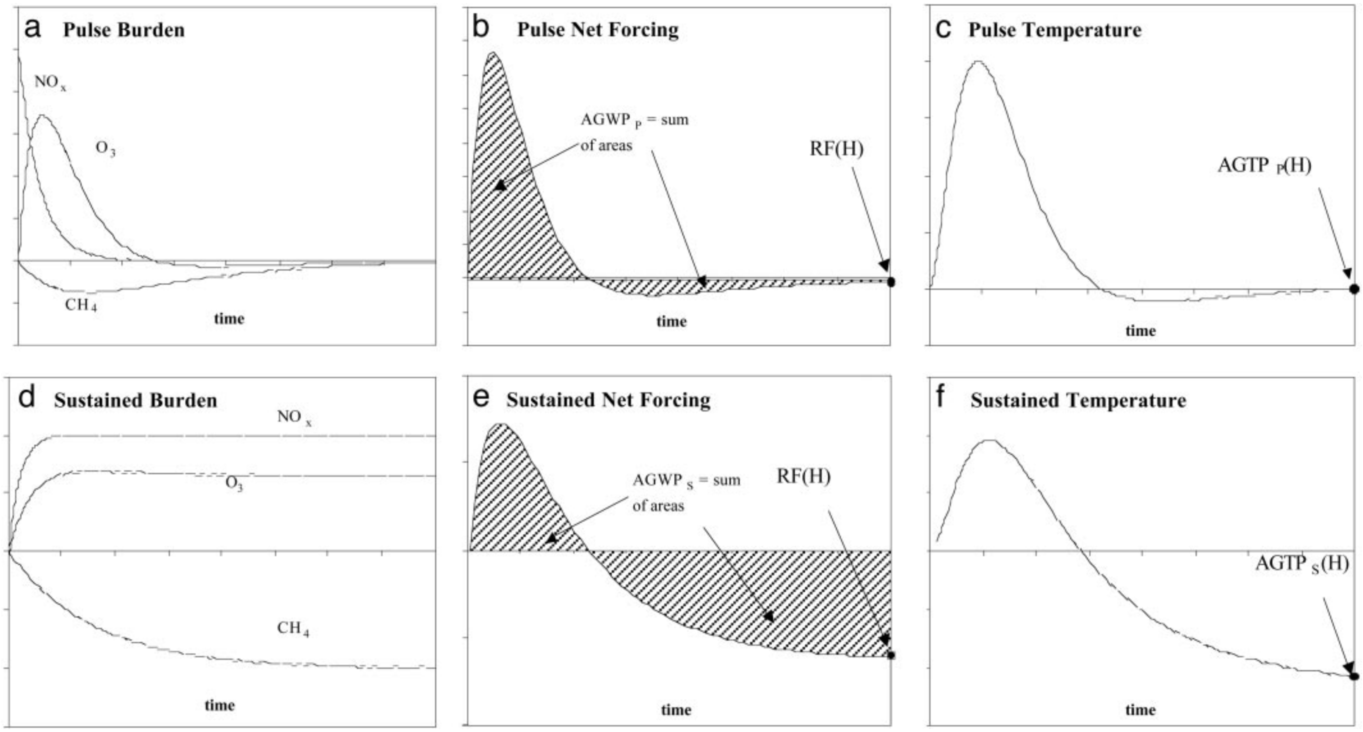

Fig. 1. Schematic illustrating possible metrics for NO_x emissions that lead to perturbations of both ozone and methane. Shown are the cases of a discrete pulse emission of NO_x (*a*–*c*) and a sustained emission change (*d*–*f*). (*a* and *d*) The evolution of the concentrations of NO_x, ozone, and methane. (*b* and *e*) The net (ozone plus methane) RF (the individual ozone and methane RFs follow the curves for the burden in *a* and *d*) and the parameters that can be used for climate metrics. The absolute GWP (AGWP) is the time-integrated RF over some time horizon (H). The degree of compensation between the ozone and methane RFs depends on the value of *H*. The RF at some time *H* could also be used in a metric. (*c* and *f*) The global-mean surface-temperature change in response to the RF from *b* and *e*. The absolute global temperature potential (AGTP) at some time *H* is another possible metric.

lived and driven by the direct effects of NO_x on O_3 chemistry; the other is long-lived, controlled by slower changes in methane, and included using the approach described in ref. 6. The change in methane adjustment time caused by the effects of NO_x is also taken into account. The GWP_P was calculated by assuming a 1-yr pulse. During this year the concentrations change according to their adjustment times; after 1 yr the perturbations decay according to their adjustment times.

Table 1 presents the Asia/Europe ratios as ranges for the metrics using the model outputs from ref. 6. The Asia/Europe ratio of the steady-state change in global-mean ozone burden is in the range of 3.6–6.1, showing that the Asian emissions are, per kilogram, much more effective at changing ozone. The Asia/Europe ratio is enhanced when considering ozone RF, because the low-latitude ozone change interacts more effectively with radiative fluxes. This interaction results in a ratio for the other metrics in the ozone-only case being higher, with approximate values of 4–13; the similarity between metrics is expected when H is much greater than the lifetime τ of the gas involved. The GCMs indicate that the climate sensitivity for the Asian ozone perturbations is 20% lower than for the European emissions, which reduces the GTP_S^* ratio compared to the GTP ratio, giving values of 3.6–11. In summary, there is large model dependence in the values but relatively little difference between metrics.

Table 1. Values of various indicators and metrics for the effect of emissions of NO_x, presented as ratios of the impact of equal mass emissions from Asia and Europe

Quantity (with time horizon in years)	Ozone	Methane	Ozone and methane
Global-mean burden for sustained emissions	3.6–6.1	3.6–3.8	Not applicable
RF for sustained emissions	4.6–13.5	3.6–3.8	3 to 0.9
GWP_P (100)	4.6–12.3	3.6–3.8	−9.4 to 0.7
GWP_S (100)	4.6–11.7	3.6–3.8	−5.8 to 37
GTP_S (100)	4.6–13.6	3.6–3.8	−3.2 to 0.8
GTP_S^* (100)	3.6–10.7	3.6–3.8	−0.1 to 14.7

The values are presented as ranges derived from simulations of two CTMs, three RF codes, and two GCMs.

Because methane has a longer adjustment time, its perturbation is distributed more homogeneously. Hence, there is no difference in climate sensitivity for the Asian and European NO_x emissions, but still $H \gg \tau$ and all of the metrics shown in Table 1 are $\approx$3.7.

The RF caused by NO_x-induced methane change was found, on a global mean, to be similar in size but opposite in sign to the ozone RF; the net RF (and hence ΔT_s) is then a small residual of two much larger numbers. Hence, when both are considered together, the net RF can vary between positive and negative depending on the model combination used, and the Asia and Europe values are not necessarily of the same sign. Therefore, the Asia/Europe ratio can be negative. The ratios now vary widely between models and between metrics. The equivalence between the metrics found for ozone and methane separately is not found for the net effect, first because the net effect is a small residual of two larger numbers, and hence subject to larger error, and second because the effect of the ozone–methane offset in RF depends on the nature of the metric.

Potential for a Metric Using Local Inputs

We explore the potential role of spatial variations of surface-temperature change in assessing the impact of regionally constrained RFs. Regionality in response can only influence a global-mean metric if there is some nonlinear relationship between climate

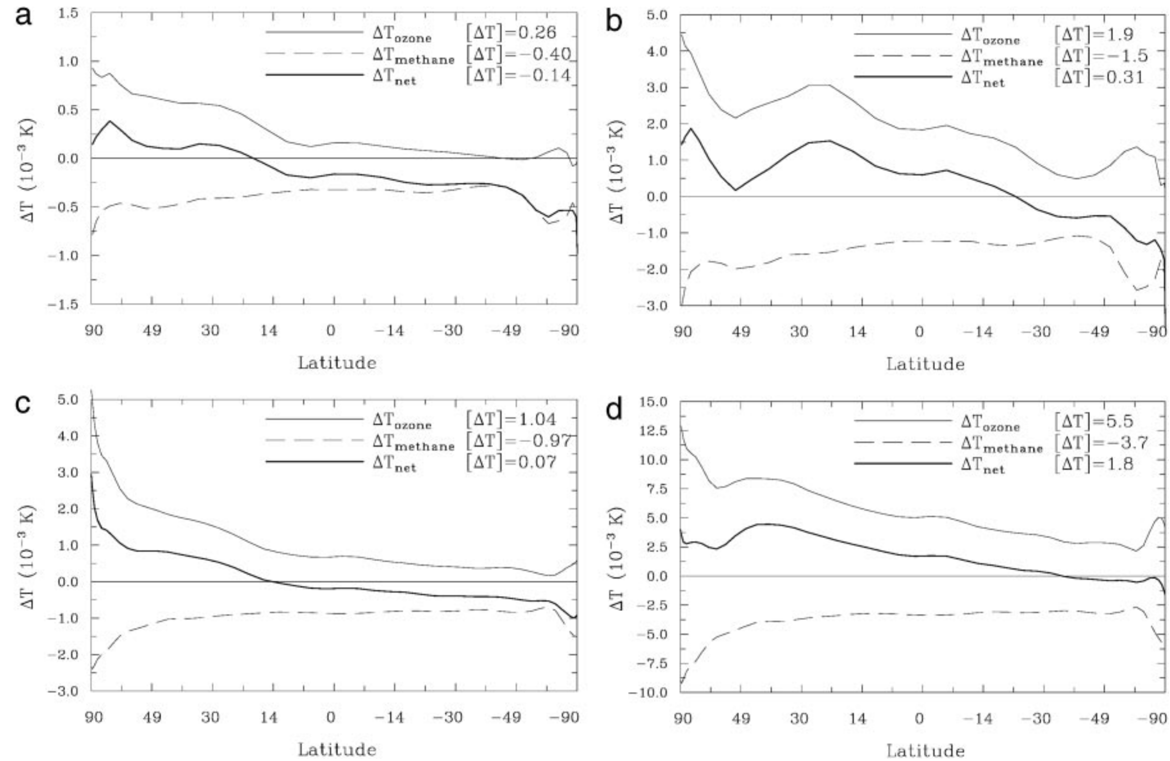

Fig. 2. Zonal and annual mean surface-temperature change (in milli-Kelvin) in the two GCMs (*a* and *b*, UREAD; *c* and *d*, ECHAM4) for the NO_x Europe (*a* and *c*) and the NO_x Asia (*b* and *d*) cases using the LMD CTM ozone. Note that the *x* axes are linear in the sine of latitude such that they are linear in surface area. The global-mean change (in milli-Kelvin) is shown.

change and its impact. Our purpose here is to illustrate how nonlinearities may influence the metrics. Hence, we use highly simplified representations of "damage" caused by climate change; we simply assume that the local climate impact depends on either the absolute value of the local temperature change [which we call the linear damage potential (LDP)] or the square of the local temperature change [the square damage potential (SDP)]. The representation of damage as the square of the temperature change has been used in a number of climate-change–impact studies, often applied at a global-mean level (19, 21, 23, 31). There is considerable debate and uncertainty regarding the nature of the dependence of impacts on climate change and how to quantify these impacts, especially in the case of nonmarket impacts (22, 32–35); ref. 35 describes existing functional forms as "highly speculative." There is likely to be considerable regional variation in any functional dependence, ΔT_s will not be the only controlling variable, and in some regions, impacts may be beneficial for small climate changes (33, 34). Our results are only intended to be illustrative, but they will serve the purpose of exploring whether some of the problems in using an $M([x])$ metric could be modified significantly when local climate impacts are taken into account.

In general, emission-based metrics need to account for the time dependence of concentration change of the emitted species (or their products), as well as the climate response. Here we neglect the time dimension and use equilibrium responses to focus on metric design issues.

The LDP and SDP have basic properties that differ from $M([x])$ metrics. For both, negative and positive local temperature changes are equally harmful. For the NO_x emission perturbations in Asia or Europe, the net warming (dominated by increased ozone) mainly in the northern hemisphere will not be cancelled by the net cooling (dominated by reduced methane) mainly in the southern hemisphere. In addition, the SDP has the property that it increases as the degree of spatial heterogeneity increases. For two climate perturbations with equal global-mean temperature change, the perturbation with the largest spatial variance in temperature change would give the largest SDP. We assume here that ΔT_s from the ozone and methane RFs can be added linearly, an assumption that is justified by several GCM studies (36–38).

Fig. 2 shows how adding the inhomogeneous ΔT_s caused by ozone to the more homogeneous ΔT_s caused by methane gives a net effect that is zonally (and thus regionally) significantly different from zero. This is a robust feature in both GCMs even though the global-mean net ΔT_s is quite small and can be of either sign. In both GCMs, despite their significantly different climate sensitivities, the latitude with zero net ΔT_s is in the northern hemisphere (≈20°N) for the Europe emissions and in the southern hemisphere (20–35°S) in the Asia case. In the ECHAM4 model there is a stronger feedback (through the ice/snow–albedo feedback) at high latitudes, in particular when the largest part of the RF is constrained to high latitudes as with ozone in the Europe case. In the UREAD model, the temperature response to the ozone RF in the Asia case shows a wide maximum, centered at ≈25°N, which is closer to the latitude of maximum RF (≈15°N) than in the ECHAM4 model, which shows only a small maximum in the response at ≈45°N.

Fig. 2 reveals that NO_x emissions in either Asia or Europe give a robust zonal-mean ΔT_s, which may indicate that the LDP and SDP are less model-dependent because they will not be influenced by cancellation in the same way as the $M([x])$ metrics considered above. We consider first the LDP. For emissions of component *i* we define the LDP, relative to a reference gas *r*, as

$$\mathrm{LDP}_i = \frac{\frac{1}{A}\int|\Delta T_i(x, y)|dA}{\frac{1}{A}\int|\Delta T_r(x, y)|dA},$$

where (x, y) indicates geographical location, and A is area. Here we need only be interested in the absolute value of the metric [i.e., the

Table 2. Values of the ALDP metric for the NO_x-Asia and the NO_x-Europe experiments for net temperature change (including ozone and methane changes) and for the ozone-only case

	ECHAM4, net	UREAD, net	ECHAM4, ozone only	UREAD, ozone only
$ALDP_{Asia}$, mK	2.3	2.0	5.5	2.5
$ALDP_{Europe}$, mK	0.55 (0.80)	0.35 (0.43)	1.0 (1.3)	0.34 (0.45)
Asia/Europe ratio	4.1	5.7	5.3	7.3

The results are mostly from the LMD CTM, with UiO CTM results indicated in parentheses when available.

Table 3. Values of the ASDP metric for the NO_x-Asia and the NO_x-Europe experiments for net temperature change (including ozone and methane changes) and for the ozone-only case

	ECHAM4, net	UREAD, net	ECHAM4, ozone only	UREAD, ozone only
$ASDP_{Asia}$, 10^{-6} K^2	11	11	45	14
$ASDP_{Europe}$, 10^{-6} K^2	0.62 (1.7)	0.24 (0.38)	2.2 (3.8)	0.28 (0.5)
Asia/Europe ratio	17	47	20	49

The results are mostly from the LMD CTM, with UiO CTM results indicated in parentheses when available.

numerator of this expression [the absolute LDP (ALDP)] and the Asia/Europe ratio of the ALDPs].

The ALDP is generally lower for the net ΔT_s for ozone and methane compared with the ozone-only cases except for the Europe case in the UREAD model, in which the cooling by methane dominates in the combined case. For both GCMs (Table 2) the Asia/Europe ratio is typically 5 in both the ozone-only and net cases. Compared with the $M([x])$ metrics considered in Table 1, the agreement between the ALDPs is much better; in addition, Table 2 indicates that by applying the ALDP, the model dependency decreases when both ozone and methane effects are considered. However, this last feature seems to be a coincidence, because it can be explained by the fact that in the UREAD model there is a larger sensitivity at high southern latitudes to RF in that hemisphere (see the methane lines in Fig. 2 *a* and *b*), whereas in the ECHAM model there is a larger sensitivity at high northern latitudes to a northern-hemisphere RF. In the UREAD model this sensitivity leads to a significant cooling signal at high southern latitudes in the net case that compensates for the reduced warming in the northern hemisphere. Thus, there is only a small reduction in the ALDP from the ozone-only to the net case for Asian emissions, whereas there is even a small enhancement for European emissions. By contrast, the ECHAM ALDPs change by a factor of 2 between the ozone and the net cases. Another contribution to the small changes in ALDP between the ozone-only case and the net case is the fact that there is a lower RF for the ozone perturbations in the UREAD model compared to the ECHAM model.

The Asia/Europe ratio of the ALDPs also shows relatively small model dependency. This dependency is certainly not a coincidence; it is mainly reflecting the regional differences in chemical and radiative response (6) because there is not a large difference between the climate sensitivities for ozone and methane perturbations within either model.

The SDP is defined as

$$SDP_i = \frac{\frac{1}{A}\int \Delta T_i(x, y)^2 dA}{\frac{1}{A}\int \Delta T_r(x, y)^2 dA}.$$

The ASDP values listed in Table 3 show many of the same features as the ALDP values, in particular the reduced model dependency in the net case compared with the ozone-only case. For the SDP the Asia/Europe ratio is enhanced (in both GCMs) compared with the LDP because of the assumption that the damage is proportional to the square of ΔT_s, which means that the higher chemical efficiency of NO_x in Asia is amplified in the Asia/Europe SDP ratios.

Both the LDP and the SDP include a damage function that is symmetric about zero, whereas only the SDP includes the spatial variance of the geographical distribution of ΔT_s. The fact that the ratio of the square root of the ASDP to the ALDP for both the Asia and Europe cases is larger than unity (1.4–1.7) is a manifestation of this property of the SDP metric. The spatial variability is quite similar in both GCMs. They show a consistent picture that in the ozone-only case the spatial variance is higher for Europe than for Asia (as might be expected because the more localized high-latitude RF can trigger a regional sea-ice–albedo feedback), but the opposite is true for the net case. The largest impact of spatial variance is found in the net Asia case with the UREAD model probably because of the triggering of the southern-hemisphere sea-ice–albedo feedback by the methane RF as discussed above.

When both ozone and methane effects are included, the global-mean ΔT_s is reduced (compared with the ozone-only case), whereas there are still significant and robust spatial differences in ΔT_s. For such climate perturbations, $M([x])$ metrics can give a misleading picture and can be very model-dependent. In the Europe case as simulated in ECHAM4, $[\Delta T_s]$ is only 0.07 mK, whereas in the Asia case it is 1.8 mK. A metric that is linear in $[\Delta T_s]$ would be a factor of 26 higher for NO_x emissions in Asia. Based on the UREAD model the linear metric would even have different signs for NO_x emissions in the two regions. A metric based on $[\Delta T_S^2]$ would yield a factor of $\approx$700 larger impact for the Asia case in the ECHAM model. However, for the new metrics proposed here (the LDP and SDP), the enhancement of the impact of NO_x emissions in Asia relative to Europe is more reasonable and less model-dependent (4.1 and 5.7, respectively, for the two GCMs for the LDP, and 17 and 47 for the SDP).

Next Steps: Implications for Policy Makers and Climate Agreements

The previous sections can be summarized as indicating that when the net (ozone plus methane) effect of NO_x emissions is taken into account, the GWP and the other $M([x])$ metrics considered here do not produce a consistent picture of the difference between European and Asian emissions, and the values of $M([x])$ ozone metrics show significant model dependence. The two $[M(x)]$ metrics explored here seem to be in better shape and offer a prospect of a more robust metric. Nevertheless, if policy makers require a metric to include NO_x in a climate agreement, they will face clear challenges and decisions. There are (at least) two distinct dimensions to the problem: (*i*) differences among metrics and (*ii*) differences among model results used to generate the metrics.

Differences Among Metrics. One part of this dimension is whether the metric takes into account the dependence on the region from where NO_x is emitted. Also, would that metric incorporate the fact that GCMs indicate that the efficacy of RFs vary with both the geographical distribution of the RF and the nature of that RF? This is not a significant issue for the Kyoto gases.

Another difficult issue is how to account for the impact of NO_x emissions on methane. In many of our calculations, the negative methane RF from European emissions is so strong that, for the global mean, it overwhelms the positive ozone RF. Would "credit" be given to nations with emissions that cause a net cooling? Even if there were perfect compensation in the global mean, the simulations here indicate that significant regional-scale ΔT_s, with the warming generally associated with the hemisphere in which the NO_x is emitted, and cooling associated with the other hemisphere. Would only the global-mean response be accounted for, or would the regionality be incorporated in some way? Would any temperature perturbation, whether negative or positive, be regarded as dangerous anthropogenic interference with the climate system? The result then becomes sensitive to whether the metric is calculated by using global-mean or regional changes. Also, because NO_x emissions do not occur in isolation from other emissions, in reality any cooling from NO_x emissions would more likely be manifested as a reduction in an overall warming; currently the Kyoto GWP values do not account for varying atmospheric composition and climate changes, so the neglect of the changing "baseline" for metric calculation is a wider issue.

Intermodel Differences. This dimension is secondary to the first because, in principle, it can be improved by better knowledge; nevertheless, at the present time there are serious concerns about the robustness of values given to any metric for NO_x emissions. The net (global-mean) impact of NO_x emissions is the sum of two similarly sized effects with opposite signs, and even with our small sample of CTMs and GCMs, there is no consensus on the sign, let alone the size, of the net impact. In addition, as noted earlier, other NO_x impacts, and in particular the effect on nitrate aerosol formation, have not been considered here, which adds additional uncertainty. Policy makers would have to decide on a strategy to cope with the likely volatility in results and, in effect, would have to do a risk–benefit analysis: do the benefits of incorporating NO_x in a protocol outweigh the complications that might accompany any significant changes in the adopted metric and the risk of adopting policies that may not turn out to be cost-effective? To some extent the issue of volatility is not new, because the ozone depletion potentials of the Montreal Protocol gases and the GWPs of the Kyoto gases have been subject to revision; however, revisions have been relatively small, and to date, policy makers have chosen to ignore them (18). The indication here of an increased robustness in the case of the LDP and SDP would need to be tested for other model outputs, cases, and damage functions.

From a climate science perspective, there remains a clear need for continued development, assessment, and intercomparison of CTMs and GCMs and the observational data used to drive and evaluate these models. Our work also highlights the need for the impacts community to advance understanding of damage functions; such functions seem more critical for the development of metrics for short-lived species than for the Kyoto gases because of the more regional nature of the resulting RF and response and the issue of compensation between climate responses of opposite signs but differing regionality.

Implications for Other Short-Lived Species. Among the short-lived species, NO_x may be the most difficult case to consider because it captures several complicated characteristics of other short-lived RF agents. However, our approach, with a focus on the spatial dimensions of the issue of comparing gases, may be relevant for emissions of CO, volatile organic compounds (VOCs), black and organic carbon, and SO_2.

Among these species, CO may be the one with the lowest hurdles, mainly because it does not initiate responses of opposite signs. This was recognized by the Intergovernmental Panel on Climate Change (1), which presented tabulated values for the GWP of CO. Intermodel differences and the variation in the impact of emissions from different regions on the metrics is much smaller than for NO_x (6). The VOCs also generally give responses of the same sign, but the regional variation in responses to emissions may be larger than for CO because of the generally shorter lifetimes. For individual VOCs and CO, the hurdles along the two dimensions (type of metric and model dependence) are smaller than for NO_x; VOCs have the added complication that there are many different types of VOCs, and different species can behave distinctly differently (15).

The climate impact of black-carbon aerosols has many similarities with NO_x. There are considerable regional differences and uncertainties in the relationship between emissions and RF, and RF is spatially inhomogeneous. An additional complexity with black carbon is that because of the so-called semidirect effect there may be a much more complex relation between RF and climate response (28, 39). All of these factors indicate that for black carbon, $[M(x)]$-type metrics (based on simulations with coupled aerosol–climate models) might also be more appropriate.

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