

# metric<sup>°C</sup>

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## Metrics of Climate Change

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Oberpfaffenhofen, 21 December, 2001

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## 1. Management Report

Period covered: 03/2000 - 04/2001.

### Start of Project

The METRIC project started 1 March 2000, i.e., the end of the project is 28 February 2003.

### Workshops

The kick-off workshop was on 15 February 2000, assuming the project would start 1 February 2000. An additional workshop on CTM/GCM modelling was on 15 - 16 February 2001. Combined was a meeting of partner from natural and social sciences. Minutes of the workshops have been distributed. The first annual workshop was scheduled for May 2001.

### Activities Started / Completed

#### Task 2.1 Emission perturbations (for CTM simulations)

A base case and 2 perturbation scenarios were defined. Milestone M2.1 was achieved; the first phase of Task 2.1 is completed.

#### Task 2.2 CTM runs

CICERO and CNRS-DR5, both made several improvements to their CTMs, which will enable a better coupling to the CTM simulations to be performed in year 2 and allow a better computational performance. A first set of simulations has been performed. M2.3 was achieved.

#### Task 2.3 Calculation of RF

Due to a delay in Task 2.2 this task did not yet start during the reporting period.

#### Task 3.1 Perturbations of climate change agents (for GCM simulations)

A set of cases of idealised forcing perturbations (CO<sub>2</sub>, solar, ozone) were defined. M3.1 and M3.3 were achieved; the first phase of Task 3.1 is completed, the second phase started.

#### Task 3.2 (GCM) simulations for idealised forcing perturbations

DLR, UREAD and CNRS-DR5 have performed GCM simulations for the perturbations defined in Task 3.1. M3.5 was achieved. However a detailed inter-comparison is being made. Some ideas for causes of enhanced climate sensitivity have been analysed and published.

#### Task 4.1 Review of available metrics

This task started, a draft review is available. However, the review paper (M4.1) was not completed during the reporting period. The paper is more comprehensive than originally intended and will also cover some aspects of Tasks 4.2 and 6.1. It will be ready by the end of 2001.

#### Task 4.2 Calculation of metrics

A software tool for convenient calculation of GWP has been developed. Some metric (e.g., radiative forcing, climate sensitivity parameter) have been calculated for cases from Task 3.2. M4.2 is delayed.

#### Task 5.1 Development of refined metrics

This task has started, but still is in its infancy.

#### Task 5.2 Application of refined metric

This task has not yet started.

**Task 5.3 Scientific evaluation of metric**

This task has not yet started.

**Task 6.1 Political requirements**

This task has started. M6.1 is not yet achieved.<sup>1</sup>

**Task 6.2 Evaluation of existing metrics**

This task has started. First results are available.

**Task 6.3 Evaluation of refined metrics**

This task has not yet started.

**Task 6.4 Overall evaluation**

This task has not yet started.

**Problems**

The CTM simulations are delayed, the first set will be finished in summer 2001 Task 4.1 is delayed due to lack of personnel at DLR. (Several co-workers left DLR in order to take advantage of the good economic situation of software industry, which is able to offer better salaries and unlimited contracts.)

The Co-operation between Wuppertal Institut and CICERO need to be intensified. A further meeting is planned for September 2001 in Oslo.

**Deviation from Work Plan**

The management report for the next period will contain and up-dated work plan, depending on the outcome of the scheduled meeting in Oslo.

**Conclusions**

The METRIC project has made good progress, despite the above mentioned problems. The objectives of METRIC remain valid.

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<sup>1</sup> See forthcoming management report of the next period for more details.

## 2. Executive Summary

Using two different CTMs (OSLO CTM2 run by CICERO and LMDz-INCA run by CNRS) the response of the chemical composition of the atmosphere to 4 different localised emissions of CO and NO<sub>x</sub> was simulated. The emissions scenarios were:

1. CO fossil fuel surface emissions increased over Western Europe,
2. CO Fossil fuel surface emissions increased by over South East Asia,
3. NO<sub>x</sub> Fossil fuel surface emissions increased by over Western Europe,
4. NO<sub>x</sub> Fossil fuel surface emissions increased by over South East Asia.

Both models show that the NO<sub>x</sub> emissions much more efficiently (more than an order of magnitude) catalyses the ozone production than CO emissions do. The same amount of emissions results in a stronger ozone increase if the species (NO<sub>x</sub> or CO) are emitted in South East Asia.

The impact of geographically inhomogeneous perturbations of radiative active species was studied with two comprehensive GCMs (ECHAM4 run by DLR and LMDz run by CNRS) and one intermediate GCM (run by UREAD). In a first phase perturbations impacting the long wave radiation were inserted, all of the same global mean radiative forcing of 1 Wm<sup>-2</sup>:

1. a global homogeneous CO<sub>2</sub> increase,
2. a CO<sub>2</sub> increase confined to the tropics,
3. a CO<sub>2</sub> increase confined to the extra-tropics,
4. a CO<sub>2</sub> increase confined to the northern extra-tropics.

Despite the fact that the models have different climate sensitivity parameters for a homogeneous CO<sub>2</sub> perturbation, the normalised response in the global mean temperature, i.e., the temperature change normalised by the respective response for the homogeneous forcing, is astonishingly similar for all models. The tropical and extra-tropical perturbations result in smaller and larger temperature changes, respectively.

Available metrics of climate change, in particular radiative forcing and global warming potential have been reviewed. Their usefulness for "measuring" climate change was discussed and some limitations were shown. E.g. it was demonstrated that reductions in CO<sub>2</sub> emissions and equivalent CH<sub>4</sub> emissions (in terms of GWP) can result in quite different temperature responses.

Criteria for applicability of metrics for policy makers have been identified, e.g., regarding the procedural requirements at least three categories have to be considered:

- (1) Simplicity and transparency: The metric should be easily to understand and to use.
- (2) Flexibility: The methodology should be open to advancements in scientific knowledge and to changes in the negotiation process.
- (3) Political feasibility: Uncertainties should be reduced to the maximum extent possible.

So far, 7 papers were published or have been submitted.

### 3. Detailed Report

#### WP 2 Changes in atmospheric composition (CTM simulations)

##### Task 2.1 Emission perturbations (for CTM simulations)

###### Objectives

The main objective of Task 2.1 is to define a set of emission perturbations to be used in the chemistry transport models.

###### Methodology and scientific achievements related to Task including contribution from partners

###### *Base case*

The base case simulation for both models (OSLO CTM2 and LMDZ-INCA, see description below) is defined based on the IPCC (2001) OXCOMP intercomparison exercise. The protocol for model simulation is provided in Annex 2.1. Only a brief overview is provided here.

###### *Perturbation scenarios*

An initial set of 6 emission scenarios has been prepared for the METRIC chemical model simulations. The simulation will be conducted for 2 years and the second year will be used for intercomparison and as input for GCM perturbation studies. In order to test the sensitivity to emission pulse location, 2 regions have been retained with approximately the same area.

Region 1: Mid-latitude location corresponding to Western Europe and defined with the boundaries [40N-60N], [10W-20E].

Region 2: Tropical region corresponding to South-East Asia and defined with the boundaries [10N-30N], [100E-120E].

The 6 initial scenarios are:

5. CO Fossil fuel surface emissions increased by 40 Tg over Region 1 on an annual basis. The emissions are uniformly increased within the region in order to provide a total 40 Tg.
6. CO Fossil fuel surface emissions increased by 40 Tg over Region 2 on an annual basis.
7. NO<sub>x</sub> Fossil fuel surface emissions increased by 1 TgN over Region 1 on an annual basis.
8. NO<sub>x</sub> Fossil fuel surface emissions increased by 1 TgN over Region 2 on an annual basis.
9. NO<sub>x</sub> Aircraft Emissions increased over Region 1 on an annual basis.
10. NO<sub>x</sub> Aircraft Emissions increased over Region 2 on an annual basis.

###### Socio-economic relevance and policy implication

No direct socio-economic or policy implications are related to this work package.

###### Discussion and conclusion

An initial set of 6 scenarios has been defined in order to simulate the response of the chemistry (tropospheric ozone and OH burden) to emission perturbations of CO and NO<sub>x</sub> and to investigate the sensi-

tivity to perturbations applied at mid-latitudes and in the tropics. These scenarios have been provided to the CTM simulation WP (Task 2.2). At this stage, due to a delay in the definition of 2000 aircraft emissions only perturbations 1 to 4 have been simulated with the CTMs.

### Plan and objectives for next period

The aircraft emissions for 2000 conditions and the modified emissions (scenarios 5 and 6) will be prepared and provided to the CTMs. A second set of perturbations will also be defined depending on the outcome of the CTM result analysis. This new set of simulations will mainly aim at refining the analysis and understanding additional features and model discrepancies.

## Task 2.2 CTM runs

### Objectives

The objectives of Task 2.2 are

- to determine the change in tropospheric ozone and OH concentrations (and methane life-time) associated with selected perturbations of surface and free atmosphere emissions (e.g., from aircraft) of source gases (i.e., NO<sub>x</sub>, CO, NMHCs);
- to assess the dependence of changes in the O<sub>3</sub> and OH concentrations on the location of the perturbation in the emissions (e.g., mid-latitudes versus tropics, surface versus upper troposphere);
- to calculate the future levels of ozone associated with additional emissions in ozone precursors including aircraft, on the background of scenarios of future emissions (based on IS92 and the IPCC/SRES 2000).

Table 2.1: Globally and annually averaged ozone and OH changes as calculated by the 2 models [LMDz-INCA](#) (first row each) and [OSLO CTM2](#) (second row each).

	Base Case	Scenario 1 CO, region 1	Scenario 2 CO, region 2	Scenario 3 NO <sub>x</sub> , region 1	Scenario 4 NO <sub>x</sub> , region 2
Methane Lifetime (years)	11.534 8.532	0.072 0.032	0.069 0.031	-0.014 -0.031	-0.054 -0.097
OH density (10 <sup>5</sup> molec./cm <sup>3</sup> )	7.624 10.306	-0.053 -0.039	-0.058 -0.047	0.010 0.033	0.043 0.110
O3 burden (Tg)	388.399 316.995	0.796 0.394	0.885 0.547	0.179 0.884	1.232 2.842
Normalized O3 change (x100)		1.991 0.985	2.213 1.368	17.896 22.100	123.157 71.050
Normalized OH change (x100)		-0.132 -0.098	-0.146 -0.118	0.981 0.825	4.333 2.750

### Methodology and scientific achievements related to Task including contribution from partners

The 2 CTMs used in this task are LMDz-INCA for CNRS and Oslo CTM2 for CICERO. A description of the models is provided in Annex 2.2. Table 2.1 provides a summary of the various perturbations and gives the globally and annually averaged ozone and OH change for the 2 models and for scenarios 1-4. The results for LMDz-INCA are given in blue (first line) and for Oslo CTM2 in green (second line). Please note that the simulations 3 and 4 for Oslo (shaded area) have been performed for different conditions (4 TgN perturbation instead of 1 TgN) in order to provide some insight into the non-linear behaviour of the system. Even if the model results differ in terms of magnitude of the response, several basic features emerge from the results.

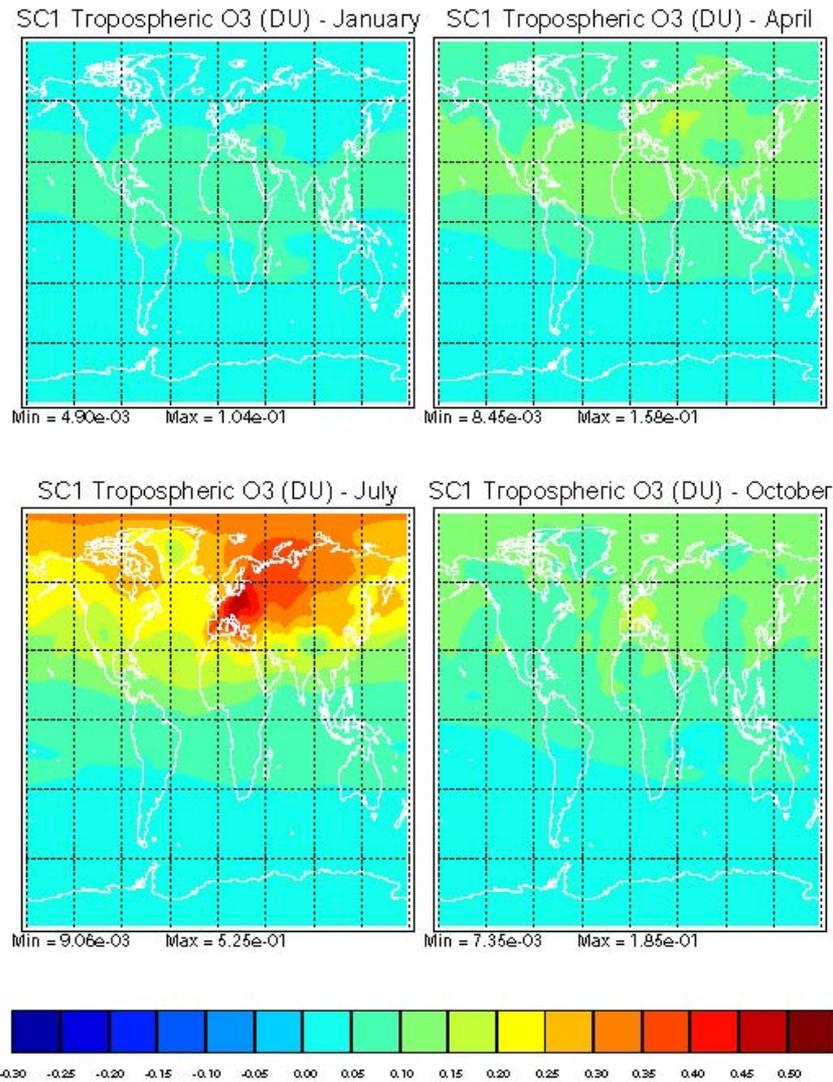


Figure 2.1: Change in total ozone (DU) calculated for scenario 1 (CO perturbation applied over Europe) as simulated by LMDz-INCA.

In particular, both models show that NO<sub>x</sub> much more efficiently catalyses the ozone production than CO as can be noticed from the much higher normalised ozone response (global change in ozone relative to the perturbation in precursors for scenario 3 and 4). An important feature is the dramatically higher efficiency in producing ozone in the case of a perturbation in the tropics. This finding is associated with a more efficient chemistry in the tropics and different mixing regimes between the 2 regions. Due to a shorter lifetime, the NO<sub>x</sub> distribution is more affected by dynamics than in the case of CO. The annual and geographical distribution of the perturbation is similar in both models. In the case of

perturbation at mid-latitudes of the northern hemisphere a strong seasonal cycle is calculated peaking in summer when photochemistry is more intense (Figure 1). In contrast (not shown), the seasonal cycle is weaker if the perturbation is located in the tropics.

Results in Figure 2.1 are given for LMDz-INCA. The results by OSLO CTM2 show a very similar pattern for both the seasonal and geographical distribution. Again, the magnitude of the perturbation is different in the two models. In the case of LMDz-INCA, the ozone change reaches 0.5 DU in NH summer over Europe, while the respective signal in the case of Oslo CTM2 is only 0.25 (see also Table 2.1). This discrepancy is currently being investigated and has been tentatively attributed to differences in the simulated background NO<sub>x</sub> conditions.

An important difference between the two types of perturbations (Europe versus South East Asia) is the difference in dynamic regimes. In the tropics, rapid upward transport prevails and the precursors are vigorously redistributed in the vertical. Figure 2.2 illustrates this feature and shows the change in ozone (ppbv) calculated for scenario 4 (change in NO<sub>x</sub> in SE Asia). In this case, the ozone perturbation peaks clearly in the upper troposphere during July and reaches about 1 ppbv. Since the radiative forcing of ozone is the most sensitive to perturbations occurring in this region, we anticipate a higher radiative forcing when the change in emissions is applied in the tropics.

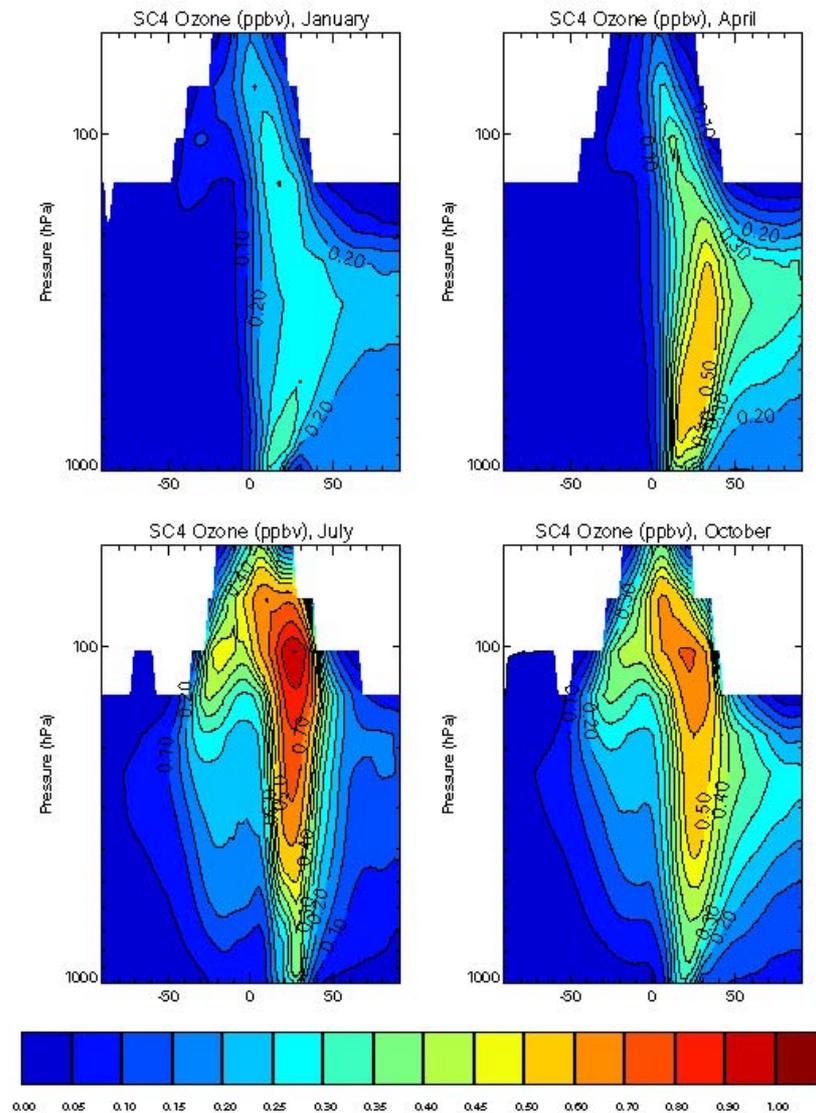


Figure 2.2: Change in ozone (ppbv) calculated for scenario 4 (NO<sub>x</sub> perturbation in SE Asia) and for January, April, July, and October conditions as simulated by LMDz-INCA.

**Socio-economic relevance and policy implication**

No direct socio-economic or policy implications are related to this work package.

**Discussion and conclusion**

The simulations show that ozone is most sensitive to perturbations in NO<sub>x</sub> applied in the tropics. Even if the two model results differ in terms of the magnitude of the ozone change, the seasonal and geographical distributions are quite similar. A strong seasonal cycle is predicted for a mid-latitude perturbation peaking in summer. In the tropics, a maximum ozone perturbation is calculated in the upper troposphere where the impact on the radiative forcing is the largest.

**Plan and objectives for next period**

Over the next period, the analysis of the CTM results for simulations 1 to 4 will be continued and differences between the models explored. Scenarios 5 and 6 will be performed and results analysed. Additional simulations will be performed as specified by Task 2.1.

**Task 2.3 Calculation of RF****Objectives**

The objectives of this task are

- to quantify the indirect RF associated with changes in ozone and CH<sub>4</sub> concentrations;
- to calculate RF for various other perturbations.

**Methodology and scientific achievements related to Task including contribution from partners**

Due to a delay in the CTM simulations (Task 2.2) this task has not started yet.

**Socio-economic relevance and policy implication**

n.a.

**Discussion and conclusion**

n.a.

**Plan and objectives for next period**

This task will start with a delay of 4 month. Apart from this no changes to the plan are necessary.

## WP 3 Changes in climate (GCM simulations)

### Task 3.1 Perturbations of climate change agents

#### Objectives

The objective of this task is

- to define sets of perturbations of climate change agents.

#### Methodology and scientific achievements related to Task including contribution from partners

This task requires the definition of General Circulation Model (GCM) experiments that are performed by the three METRIC groups running GCMs (i.e. DLR, LMD and UREAD). All model calculations use mixed-layer oceans run to equilibrium with the forcing.

The purpose of these experiments is to test the validity of radiative forcing as a concept by comparing results for identical calculations in the three models. The work was envisaged to progress in two phases:

- A. Use highly idealised forcings that test the dependence of the relationship between radiative forcing and climate response, by for example, varying the latitudinal distribution of forcings or the relative importance of the solar or thermal infrared radiation streams in contributing to that forcing. The philosophy broadly follows that adopted by Forster et al. (2000)<sup>2</sup>.
- B. Using results from Work Packages 4 and 5, compare the forcing-response relationship for more realistic changes in constituents.

This task is progressing to schedule. Three sets of idealised experiments were defined (which, including a control run, amount to 13 individual GCM integrations per group) and circulated by email between February 2000 and March 2001. All GCM experiments were run with a global and annual averaged radiative forcing of  $1 \text{ Wm}^{-2}$ , as determined using the radiation scheme in each GCM, and using the fixed dynamic heating parameterisation to determine the stratospheric temperature changes. Common output was requested to allow easier intercomparison.

1. *Changes in carbon dioxide.* 4 experiments were requested from each group: (a) CO<sub>2</sub> changed at all latitudes, (b) CO<sub>2</sub> changed in the tropics (latitudes less than 30 degrees), (c) CO<sub>2</sub> changed in the extra-tropics (latitudes greater than 30 degrees), and (d) CO<sub>2</sub> changed in northern extra-tropics only.
2. *Changes in solar constant.* 3 experiments, following 1(a) to 1(c) above.
3. *Changes in ozone.* The experiments follow those reported by Stuber et al. (2001a, 2001b) which indicated significant departures from a constant forcing-response relationship. Five experiments were requested: (a) changes in lower stratospheric ozone, globally on fixed pressure levels, (b) changes in upper tropospheric ozone globally, following local tropopause, (c) as (b) but tropical ozone change only, (d) as (b) but extra-tropical ozone change only, (e) as (b) but northern extra-tropical ozone change only.

#### Socio-economic relevance and policy implication

No direct socio-economic or policy implications are related to this work package.

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<sup>2</sup> Forster P. M. de F., M. Blackburn, R. Glover, K.P. Shine, 2000: An examination of climate sensitivity for idealised climate change experiments in an intermediate general circulation model. *Climate Dynamics* 16, 833-849.

## Discussion and conclusion

The definition of the idealised experiments was quite straight forward. The well defined simulations will allow for a better intercomparison.

## Plan and objectives for next period

The definition of experiments for the more realistic calculations will be done early in year 2 as anticipated.

## Task 3.2 Simulations for idealised forcing perturbations

### Objectives

The objective of Task 3.2 is

- to perform GCM simulations for idealised perturbations designed in Task 3.1.

### Methodology and scientific achievements related to Task including contribution from partners

The experiments designed under Task 3.1 are being performed by the three groups running GCMs: DLR, LMD (CNRS) and UREAD. The inter-model comparison is performed mainly at UREAD.

The current status of this task is that it is on schedule. The carbon dioxide experiments have been completed and the initial analysis completed; the solar constant experiments are largely completed and analysis has started; and the ozone perturbation calculations have now been initiated and should be complete by the summer of 2001.

Table 1: Overview of the CO<sub>2</sub> experiment results from the three GCMs (DLR, LMD and UREAD). The columns indicate the particular experiment (i.e. where the CO<sub>2</sub> is perturbed). For each GCM, the first row indicates the CO<sub>2</sub> (in ppmv) required to achieve a 1 Wm<sup>-2</sup> forcing for the relevant region. The second row gives the global mean surface temperature change (in K) and the third row gives the ratio of the global-mean surface temperature change with respect to the global CO<sub>2</sub> change (i.e. row 2).

	<b>Control</b>	<b>CO<sub>2</sub> global</b>	<b>CO<sub>2</sub> tropics</b>	<b>CO<sub>2</sub> extra-trop.</b>	<b>CO<sub>2</sub> northern extra-tropics</b>
<b>DLR</b>					
CO <sub>2</sub> (ppmv)	335	428.8	503.0	536.0	823.0
$\Delta T$ (K)		+0.81	+0.67	+0.99	+1.12
$\Delta T / \Delta T^*$		1.00	0.83	1.22	1.38
<b>LMD</b>					
CO <sub>2</sub> (ppmv)	330	407.93	469.3	553.4	885.6
$\Delta T$ (K)		+1.07	+0.65	+1.54	+1.13
$\Delta T / \Delta T^*$		1.00	0.61	1.44	1.06
<b>UREAD</b>					
CO <sub>2</sub> (ppmv)	360	428.4	504.7	511.2	712.8
$\Delta T$ (K)		+0.38	+0.31	+0.45	+0.46
$\Delta T / \Delta T^*$		1.00	0.83	1.19	1.22

The basic scientific point being addressed by this task is the extent to which the nature of the radiative forcing impacts on the climate response. Importantly, we wish to establish whether conclusions drawn from one model are supported by the other GCMs. The basic conceptual framework is as follows: The global-mean radiative forcing  $RF$ , can be related to the global-mean surface temperature response  $\Delta T$ , by  $\Delta T = \lambda \cdot RF$ , where  $\lambda$  is a climate sensitivity parameter. It is well known that there is much inter-model difference between the absolute value of  $\lambda$  amongst climate models, ranging from around 0.4 to 1.1 K/Wm<sup>2</sup>. Most of this uncertainty is due to problems in modelling cloud feedbacks, and as reported by IPCC (2001) there has been little progress in reducing this uncertainty in recent decades; indeed, this is one reason for using radiative forcing, rather than surface temperature response, as a metric. For a wide range of forcings, GCMs indicate that the value of  $\lambda$  is approximately independent of the nature of the forcing, but there is concern over the generality of this result. The particular question we address is whether the departure of the value of  $\lambda$  from its value for a globally homogeneous forcing is similar for all three GCMs.

Table 1 indicates our initial results. Concentrating first on the column labelled "CO2 global", this shows the climate sensitivity for a global change in carbon dioxide. By coincidence, the range of climate sensitivity parameters  $\lambda$  amongst the three different GCMs spans the range from 0.38 to 1.1 K/Wm<sup>2</sup>, which is found in the wider community. This is of importance; we will be able to establish whether the dependence of  $\lambda$  on the nature of the forcing depends on the model's own absolute value of  $\lambda$ .

All three models show a broadly similar response. The row labelled  $\Delta T / \Delta T^*$  shows the ratio of the global mean surface temperature response for the particular case relative to the global case. All three models show that a 1 Wm<sup>-2</sup> forcing concentrated in the tropics causes a smaller response than the global mean forcing. The LMD model is rather more sensitive to this than the DLR and UREAD results which are in good agreement.

As anticipated, the extra-tropical runs show enhanced sensitivity, again with good agreement between DLR and UREAD, although this agreement is diminished for the perturbation solely in the northern hemisphere.

Figure 3.1 shows the zonal mean surface temperature response. This shows the degree to which the location of the forcing influences the response. This is most marked in the extra-tropical NH case where most of the response is also in the northern hemisphere. It can be seen in all cases that the response of the LMD model at around 60 S is distinct from DLR and UREAD and is believed to be related to the form of the sea-ice parameterisation in the LMD model.

### **Socio-economic relevance and policy implication**

No direct socio-economic or policy implications are related to this work package.

### **Discussion and conclusion**

The overall conclusions of the work so far under this task is that there is encouraging agreement between the models on the degree to which the global (and hemispheric) response depends on the geographical distribution of the forcing. If this result were confirmed by the other experiments, it would indicate that it may be possible to improve the concept of radiative forcing and global warming potential (GWP). It might be possible to improve the precision with which forcings and GWPs can be compared by taking into account the nature of the individual forcing, by, for example, applying a simple weighting which accounts for this weighting.

Another issue, less significant for the purposes of this task, which is identified here, is the differences amongst the radiation codes. Our experimental design was such that each model applied a 1 Wm<sup>-2</sup> global mean forcing, with each group establishing the change in constituent necessary to achieve this

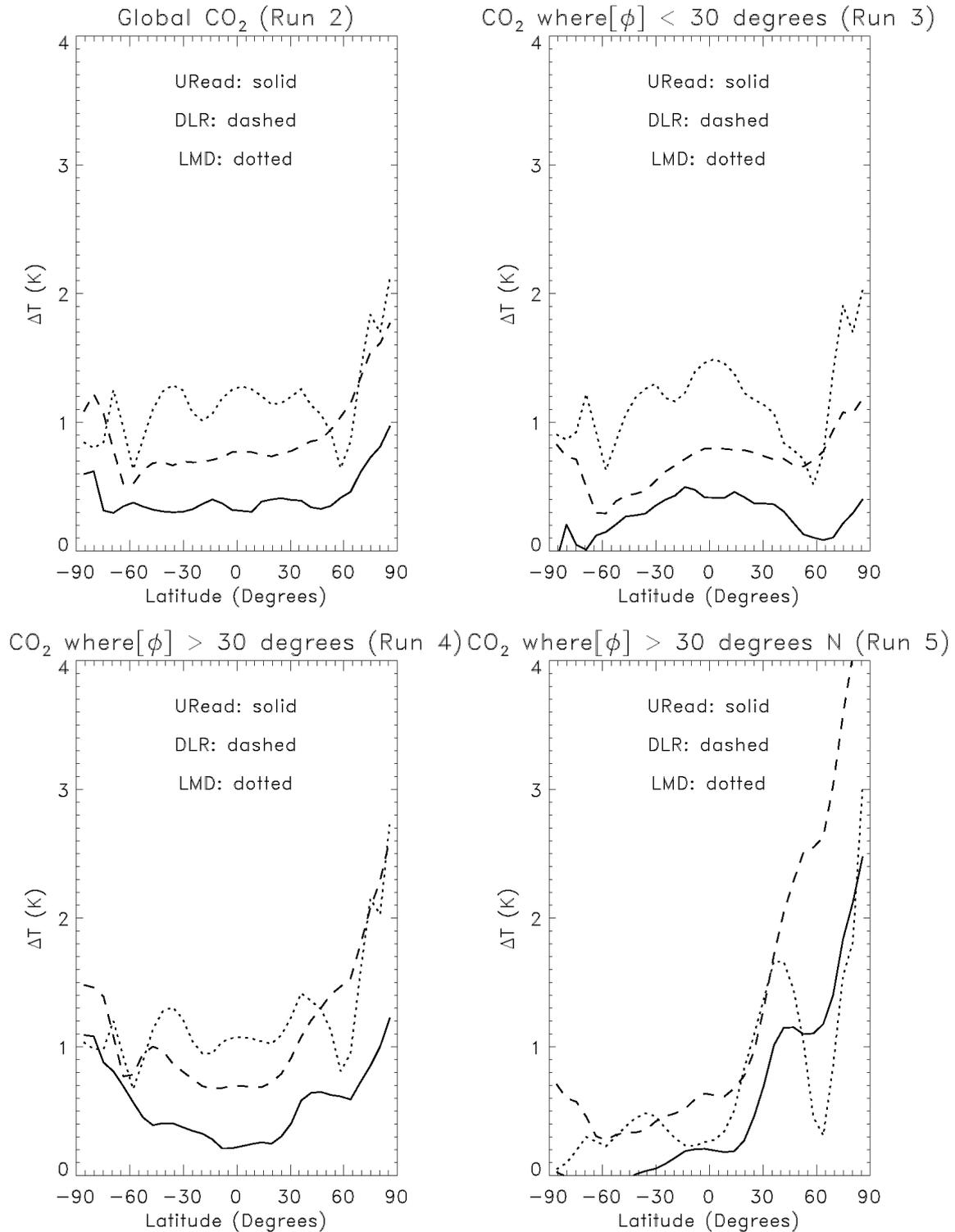


Figure 3.1: Zonal mean surface temperature change (in K) for the four  $\text{CO}_2$  experiments using the three GCMs (DLR, LMD, and UREAD).  $\phi$  is the latitude.

in their model. It can be seen that, particularly for the extratropical NH case, significantly different  $\text{CO}_2$  perturbations are required.

**Plan and objectives for next period**

Further perturbations as designed in Task 3.1 will be studied.

**Task 3.3 Simulations for realistic forcings**

This Task has not yet been started.

**Plan and objectives for next period**

We plan to perform GCM simulations for realistic perturbations of radiative forcing agents.

## WP 4 Existing metrics

### Task 4.1 Review of available metrics

#### Objectives

The objective of this task is

- to review existing metrics of climate change.

#### Methodology and scientific achievements related to Task including contribution from partners

Based on an extensive literature review and our own research in this field we are assessing the various existing metrics of climate change. The main focus is on radiative forcing (RF) and GWP since these form the basis for present climate policy. But GWPs and their application in policy making have been debated, and several other alternative concepts have been suggested by both natural and social scientists. There has been relatively little discussion of which purpose and functions alternative metrics *serve*, and which purpose and functions metrics of climate change *should* serve. We address the question of which functions metrics of climate change can serve, and which trade-offs that may be associated with alternative metrics. Our work gives an overview of how cost issues are dealt with, the climate impact (end point) against which gases are weighted, and the extent to which and how temporality is included, both with regard to emission control and with regard to climate impact. A list of criteria and "check points" is also developed. The question of purpose and function of the metrics is discussed in order to evaluate the metrics according to this. The results of the literature review are synthesized in Fuglestad et al. (2002).

We evaluated how sensitive climate policy is to use of various metrics. This is done with Norway as a case (Godal and Fuglestad, 2002): The comprehensive approach adopted in the Kyoto Protocol relies on the use of 100-year Global Warming Potentials (GWPs) to convert emissions of various gases to "carbon dioxide (CO<sub>2</sub>) equivalents". This particular set of weights, or metric, has a limited capacity to handle the large variations in atmospheric adjustment times, and emissions of various gases that are equal in terms of "CO<sub>2</sub> equivalents" will not result in equal climatic effects. In this study, the 100-year GWP metric is assessed in the context of implementing the Kyoto Protocol. Using data from Norway, we explore how abatement policy formulated on the basis of 100-year GWPs compares to policies based on other metrics in terms of compliance costs and abatement profile, that is, the composition of the basket of gases reduced. We found that the costs for Norway change significantly when other metrics are used, but changes in the composition of the basket of gases are moderate. However, since compliance costs can be controlled through other mechanisms for post-Kyoto Protocols, the use of 100-year GWPs versus other metrics has little impact on the general formulation of Norwegian climate policy.

We tested how GWPs can be used in economic analyses of damages of climate change and the degree of equivalence that is obtained when damages of climate change are taken into consideration (Sygna et al., 2002). We look at the capacity of Global Warming Potentials (GWPs) to act as indicators of equivalence for temperature development and damage costs. We look at two abatement scenarios that are equivalent when using a 100-year GWP metric: one scenario reduces short-lived gases, mainly methane; the other scenario reduces CO<sub>2</sub>. Model calculations show that, despite their equivalence in terms of CO<sub>2</sub> equivalents, the scenarios do not result in equal rates or levels of temperature change. The disparities become more prominent the further we move down the chain of consequences towards damage costs, measured either in respect to rate of climate change or level of climate change. Compared to the methane mitigation scenario, the CO<sub>2</sub> mitigation scenario showed present-value costs 1.3 and 1.4 times higher for level- and rate-dependent damage costs, respectively. This implies that the adequacy of using 100-year GWP as an index to reflect equivalent climate effects and damage costs from emissions is questionable.

### **Socio-economic relevance and policy implication**

The results from our studies are relevant for the assessment of the application of GWPs and other metrics in the formulation of climate policy and also in economic analyses of climate change. A commentary article about IPCC's structure and work on GWPs and the need for a multi-disciplinary approach to this issue was submitted (Godal, 2002).

### **Discussion and conclusion**

We have gained a good overview of existing metrics of climate change and useful insight to the problems related to the various metrics; both in terms of scientific limitations and shortcomings, the problems related to their application and the formulation of metrics in light of what function and purpose they should serve. Our multidisciplinary approach (political science, economics, natural science) enables us to understand the different aspects of the various alternative metrics and how they may function in policy-making and in the development of climate regimes.

### **Plan and objectives for next period**

D4.1 and M4.1. are delayed. The paper Fuglestad et al. (2002) will be submitted by the end of 2001.

## **Task 4.2      Calculation of metrics**

### **Objectives**

The objective of Task 4.2 is

- to calculate the old metrics for the climate simulations of WP 3.

### **Methodology and scientific achievements related to Task including contribution from partners**

We completed a FORTRAN program for routine calculation of GWPs for 88 gases for any chosen time horizon, and a set of GWPs was calculated.

No detailed documentation of the GWP values given by the IPCC in The Second Assessment Report (SAR) is, to our knowledge, available. This is remarkable since these GWP values form the basis for the implementation of the Kyoto Protocol. In Godal and Fuglestad (2002) we have given a quite detailed documentation of how these GWPs are calculated and which parameter values that are chosen (lifetimes, forcing parameters, concentrations, etc).

We also developed a method for relating GWPs for various time horizons (H) to metrics based on damage functions and discounting of future damages. These "backward calculations" give us insight to what the use of GWPs for the different gases and different time horizons means in terms of the nature and shape of the damage function and the rate for discounting future damages climate change.

### **Socio-economic relevance and policy implication**

It is important that it is possible to understand how the GWP values given by the IPCC are calculated and to reproduce these calculations. Thus, a clear and detailed documentation is required. This is not given by the IPCC, but the appendix in Godal and Fuglestad (2002) gives an outline of how the GWPs can be calculated in order to reproduce the values given by the IPCC. It also allows the calculation of GWPs for other time horizons or other choices of parameters or for updating the GWPs.

Our work on this WP has also formed the basis for several comments and input to the Third Assessment Report from the IPCC during the review process (Expert review and Government review).

## **Discussion and conclusion**

M4.2 is delayed.

### **Plan and objectives for next period**

We plan to use input from WPs 2 and 3 to calculate a set of metrics. We have the tools ready to start the work in this WP as soon as the input is available.

## **Task 4.3 Scientific evaluation of metrics**

### **Objectives**

The objective of this task is

- to evaluate the existing metrics from the view point of natural sciences.

### **Methodology and scientific achievements related to Task including contribution from partners**

In this WP we have discussed for which climate parameter equivalence can be and should be expected (RF, integrated RF,  $\Delta T$ , integrated temperature change,  $\Delta SL$ , Damage (Euro), etc.).

A test was performed: The temperature effect ( $\Delta T$ ) of CO<sub>2</sub> equivalent reductions in emissions (15 years), implemented for CO<sub>2</sub> and methane using GWPs for time horizons of 20, 100 and 500 years has been calculated (Figure 4.1). Obviously there is no equivalence in  $\Delta T$ , which is no surprise to scientists. but probably to policy makers and users from other disciplines. This may be a matter of communication about expectations.

Equivalence further down the cause-effect chain has been tested (Sygna, et al., 2002). We use scenarios (from Fuglestad et al., 2000<sup>3</sup>) that are equivalent based on 100-year GWPs:

- S1: CO<sub>2</sub> reductions
- and
- S2: Reductions of short-lived gases (mainly CH<sub>4</sub>)

The calculation show large differences in rates and levels of temperature change between the scenarios (i.e., no equivalence). Damage costs are calculated based on level of temperature change or rate of temperature change. Large disparities between the scenarios in terms of development of damage costs

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<sup>3</sup> Fuglestad, J.S., T. Berntsen, O. Godal and T. Skodvin, 2000: Climate implications of GWP-based reductions in greenhouse gas emissions. *Geophysical Research Letters* 27, 409-412.

over time are found. But in terms of present value (PV) costs the scenarios did not show very large differences.

Ratio of PV costs between scenarios (S1/S2)	Discount rates				
	1%	2%	3%	7%	10%
Level dependence	0.81	1.05	1.26	1.76	1.74
Rate dependence	0.77	1.10	1.37	1.64	1.50

### Socio-economic relevance and policy implication

The fact that emissions may be equivalent in terms of GWP but not in terms of other metric like temperature change, rate of temperature change or damage costs, might have an impact on design and choice of metrics in a follow-up treaty to the Kyoto Protocol.

### Discussion and conclusion

Our calculations illustrate that emissions that are equal in terms of CO<sub>2</sub> equivalents will not produce equivalent climatic effects. The results from our work also imply that the adequacy of using GWP<sub>100</sub> as an index to reflect equivalent climate effects and damage costs from emissions is questionable. On the other hand, the limitations and inaccuracies in the GWP metric have to be weighted against the advantage of having transparent and simple tools.

Regarding possible refinements of metrics: Several different metrics with various key parameters ( $\Delta T$ ,  $\Delta T/dt$ ,  $\Delta SL$ , etc.) can be constructed. But although a climate convention is established and a protocol for reductions of GHGs has been negotiated, there is so far no common conception or agreement regarding what aspects of climate change are most important. According to Article 2 of the UNFCCC, "the ultimate objective of the convention is to achieve stabilization of GHG concentrations in the at-

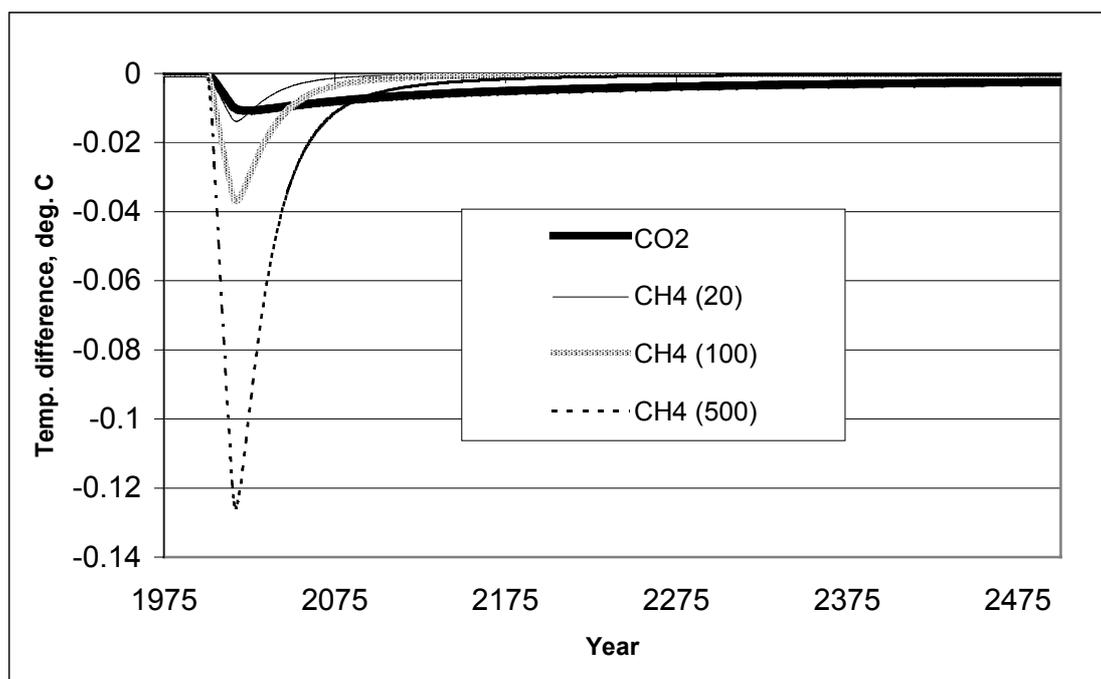


Figure 4.1: Temperature responses to changes in emissions of CO<sub>2</sub> and CH<sub>4</sub> in terms of CO<sub>2</sub> equivalents for various time horizons.

mosphere at a level that would prevent dangerous anthropogenic interference with the climate system." A reasonable interpretation given the comprehensive approach principle in the Convention is that *radiative forcing* is to be stabilized at a level that prevents a dangerous interference with the climate system and that a suite of GHGs can be reduced according to the comprehensive approach to meet the forcing target. But since "dangerous" can be interpreted in several ways, this goal formulation does not provide any guide to evaluation criteria for existing metrics or for a new metric concept.

**Plan and objectives for next period**

We plan to evaluate the metric calculated for the runs performed in WPs 2 and 3.

## **WP 5 Refined metrics**

### **Task 5.1 Development of refined metrics**

#### **Objectives**

The objective of this task is

- to develop refined metrics of climate change.

#### **Methodology and scientific achievements related to Task including contribution from partners**

Based on the results of Task 3.2 we are considering a modified radiative forcing  $RF^*$  for inhomogeneously distributed forcing agents:

$$RF^* = \frac{\lambda}{\lambda_{CO_2}} \cdot RF$$

where  $RF$ ,  $\lambda$  and  $\lambda_{CO_2}$  are the radiative forcing of given perturbation, the associated climate sensitivity parameter and the climate sensitivity parameter associated with a homogeneous  $CO_2$  forcing.

#### **Socio-economic relevance and policy implication**

A refined metric may have an impact on future climate negotiations.

#### **Discussion and conclusion**

So far on preliminary studies have been made.

#### **Plan and objectives for next period**

A more intense phase of this task is about to start.

### **Task 5.2 Application of refined metrics**

This Task has not yet been started.

#### **Plan and objectives for next period**

We plan to calculate the refined metrics for the climate simulations of WP 3.

### **Task 5.3 Scientific evaluation of metrics**

This Task has not yet been started.

#### **Plan and objectives for next period**

We plan to evaluate the refined metrics from the view point of natural sciences.

## WP 6 Political evaluation of metrics

### Task 6.1 Political requirements

#### Objectives

The objective of Task 6.1 is

- to discuss and formulate requirements for climate metrics to be applicable by policy makers, both as a tool for decision making and as a tool for generating environmentally adequate solutions.

#### Methodology and scientific achievements related to Task including contribution from partners

Metrics for comparing GHGs should not only be evaluated in terms of their scientific robustness and performance, but should also be evaluated in terms of its political feasibility. At a general level, the political applicability of an index or methodology for the comparison of different GHGs can be evaluated in terms of at least four main functions, which all prompt different requirements to the metric (see also Skodvin and Fuglestedt, 1997):

- (1) The methodology or index should serve as a tool for communication between scientists and policy makers. This function primarily prompts one requirement, namely simplicity.
- (2) It should serve as a tool for decision-making. This prompts at least two requirements: That it can be employed by policy makers in relative independence of scientific input, and that policy makers can employ the metric in confidence of its scientific quality. This essentially implies that the metric, to the extent possible, should be scientifically uncontroversial. While scientific agreement regarding the quality of the metric certainly does not guarantee political agreement on policy decisions, scientific controversy regarding this aspect could hamper political decision-making to the extent that the metric in practice becomes inapplicable as a tool for decision-making.
- (3) The metric should be flexible in the sense that new knowledge can be incorporated as it is developed. This is not only a requirement to the metric itself, but also to the policy framework within which the metric is applied.
- (4) Perhaps encompassing all of the above, the metric should be evaluated in terms of the extent to which it allows for policy options otherwise not available.

#### *Methodological issues*

In WP 6.1, four approaches to the objectives are applied:

- (1) Literature review (role of scientific and policy making models) and own analysis of climate negotiations focusing on the political discussion and adoption of
  - commitments for Annex I Parties and their relevance regarding the choice of metrics,
  - GWP as a decision making tool in order to implement the „comprehensive approach“,
  - proposals of Parties currently discussed and implications for the choice of metrics.
- (2) Legal text review (Kyoto Protocol) to distinguish the different functions metrics of climate change have to fulfil.
- (3) Two phases of complementary interviews: These are held with experts in international climate change negotiations and multilateral environmental agreements (MEA) in general. The development of an interview guide assures to held interviews in a common frame.
  - Phase 1: testing the initial thoughts about political requirements to metrics of climate change and testing the interview guide in order to revise the guide if found necessary.
  - Phase 2: investigate on political requirements as observed by negotiators and experts on the basis of the revised interview guide.
- (4) A first review of the design and application of metrics in other MEAs. Background: interview partners of the first phase indicated that the climate negotiations would considerably profit from

the experiences with metrics in other MEA. Two regimes considered are the stratospheric ozone regime and the LRTAP regime.

### *Achievements*

A draft working paper on „Political requirements of metrics of climate change“ has been developed. Two basic categories of requirements have been distinguished: First, those that stem directly from legal texts (UNFCCC, the Kyoto Protocol), and second, those procedural ones that may be derived from the negotiation context. Generally, environmental and political effectiveness are criteria for successful negotiations and decision-making. Negotiation processes are regularly confronted with tensions and trade-offs between these two criteria. As regards revised or new metrics of climate change, effectiveness can be interpreted as follows:

- Environmental effectiveness: find a metric that is the adequate instrument regarding the ultimate goal of the climate regime and its more specific commitments (scientific criteria).
- Political effectiveness: find a metric that is the adequate instrument regarding the generation of successful negotiations and political decision making, which means it allows to mobilise sufficient political support to generate agreement in a suitable tailored political process (political criteria).

This implies that „adequacy“ is a central issue. Whether or not a metric is adequate depends on both of these criteria. Hence, both the metric and the political process have to be judged together.

Based on the assessment of legal text and procedures, a working list of political requirements was developed, building on the work of Skodvin and Fuglestvedt (1997)<sup>4</sup> and Fuglestvedt et al. (2002).

Regarding the legal text requirements, particularly relevant are three functions of metrics:

(1) Scientific assessments:

- Definition of the ultimate objective in Art.2 UNFCCC.
- Review adequacy of measures taken and of compliance with regard to commitments.

(2) Negotiations:

- Enable for the implementation of the comprehensive approach
- Enable for the inclusion of other than the „Kyoto basket greenhouse gases“
- Enable for burden sharing

(3) Trading:

- Enable for the application of instruments (flexible mechanism).

Regarding the procedural requirements at least three categories have to be considered:

(1) Simplicity and transparency: The metric should be easily to understand and to use.

(2) Flexibility: The methodology should be open to advancements in scientific knowledge and to changes in the negotiation process.

(3) Political feasibility: Uncertainties should be reduced to the maximum extent possible.

### **Socio-economic relevance and policy implication**

Task 6.1 generates background material that will be used in Task 6.2 and later for the assessment of new or refined metrics of climate change. The preliminary checklist to assess the political applicability of any metric of climate change already provides important insights in how metrics might be further developed in the climate negotiations.

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<sup>4</sup> Skodvin, Tora and Jan S. Fuglestvedt, 1997: A comprehensive approach to climate change: Political and scientific considerations. *Ambio* 26, 351-358.

## Discussion and conclusion

An important result is the recommendation that a more thorough assessment of the design and use of metrics in other than the climate regime would be extremely fruitful. In particular, experiences with the role that the RAINS-model, an "Integrated Assessment Model", played in the negotiations for the Gothenburg Protocol appeared to be helpful for understanding the particular circumstances in which metrics are more or less useful in environmental regimes. This investigation aims at improving the applicability of a metric under the climate regime, in particular with respect to the procedural requirements that have so far been developed. A first but short overview on the ozone and LRTAP regime with regard to the metrics and decision making tools applied has been elaborated. As a conclusion from these works, three concepts of how metrics fulfil their functions in multilateral environmental regimes are distinguished.

## Plan and objectives for next period

(1) The working paper in Task 6.1 is close to a final version. Three tasks are currently carried out in order to complement the current draft:

- Carry out a few (1-2) additional interviews.
- Revise the draft working paper in order to further develop the "checklist" for new and revised metrics of climate change. Revisions should particularly consider the results obtained from the first, general assessment of other multilateral environmental regimes.

(2) The working list of political requirements will iteratively be developed further if necessary, particularly if

- new results arise from WPs 4 and 5.
- new results arise during the finalisation of Task 6.1
- new results arise from the comparative work on other environmental regimes,

(3) The inclusion of a new Task is strongly suggested and has been discussed within the consortium. The consortium agrees that an assessment of the role and application of metrics in other environmental regimes would be a promising objective to integrate a greater amount of political experiences with metrics in multilateral environmental regimes. A proposal for the integration of this new task at no additional cost is currently developed.

## Task 6.2 Evaluation of existing metrics

### Objectives

The objectives of this task are

- to assess existing metrics according to requirements formulated in 6.1;
- to compare alternative existing metrics with respect to their capacity to serve these functions;
- to evaluate alternative existing metrics in terms of the extent to which they are associated with a trade-off between scientific accuracy and political applicability and feasibility;
- to evaluate existing metrics in terms of the extent to which they serve to include or exclude policy options.

## **Methodology and scientific achievements related to Task including contribution from partners**

### *Methodological issues*

WP 6.2 basically relies on a review of available metrics and their scientific evaluation (from WP 4) and the list of requirements (from Task 6.1).

### *Achievements*

Work on WP 6.2 concentrated on a partial assessment of the currently used metric CO<sub>2</sub> equivalents and GWP on the basis of the evolving list of requirements. This assessment will be complemented and revised as the list develops.

## **Socio-economic relevance and policy implication**

The assessment will perform a thorough evaluation of existing metrics, notably the GWP methodology, according to requirements formulated in 6.1. It will also evaluate some of the major existing proposals for refinements of the GWP methodology in terms of the same requirements. This will provide prominent input for the climate negotiations, as methodological issues are currently on the Agenda of the Subsidiary Body on Scientific and Technological Advice (SBSTA). Furthermore the inclusion of other than the six „Kyoto basket“ source gases will be a prominent issue in the climate negotiations not least subsequent to the fundamentally altered positions of the USA.

## **Discussion and conclusion**

Preliminary work shows that the differentiation of functions suggested in Task 6.1 which metrics of climate change have to fulfil leads to the conclusion that a phased approach to metrics of climate change is expected to be fruitful: depending on the function (for scientific assessments, negotiations or trading), different metrics may be most adequate. Or, depending on the functions, it might be most adequate to consider the choice of metrics within specific context. This would imply the need to consider metrics with regard to their applicability and their integration in more or less complex decision making tools, especially with respect to the science/policy interface.

## **Plan and objectives for next period**

We plan to application of the final checklist (from Task 6.1) to the summary of existing metrics provided by WP 4.

## **Task 6.3 Evaluation of refined metrics**

This Task has not yet been started.

## **Plan and objectives for next period**

We plan

- to assess refined metrics according to requirements formulated in 6.1;
- to compare alternative refined metrics (and existing metrics) with respect to their capacity to serve these functions;

- to evaluate alternative refined metrics in terms of the extent to which they are associated with a trade-off between scientific accuracy and political applicability and feasibility;
- to evaluate refined metrics in terms of the extent to which they serve to include or exclude policy options.

#### **Task 6.4 Overall evaluation**

This Task has not yet been started.

#### **Plan and objectives for next period**

We plan to perform an overall evaluation of the metrics, both existing and refined (jointly from the view points of natural sciences, economics and political science).

## WP 7 Publications

### Objectives

The objectives of this WP are

- to publish results in scientific journals, in reports more accessible to policy makers, and on the internet;
- to publish selected model output on the internet.

### Methodology and scientific achievements related to Task including contribution from partners

During the first year of the METRIC project several papers on the topics of METRIC have already been published by the partners or are in the review/print process. Various presentations have been made in conferences, workshops or seminars. The basis for a web site was made.

Furthermore, the participants have been Contributing Authors and Reviewers to Chapter 4 (Atmospheric Chemistry and Greenhouse Gases) and Chapter 6 (Radiative Forcing of Climate Change) of the IPCC Third Assessment Report.

#### *Publications in peer reviewed journals*

1. Fuglestedt, J.S., T.K. Berntsen, O. Godal, R. Sausen, K.P. Shine and T. Skodvin, 2002: Assessing metrics of climate change: Current methods and future possibilities. *Climatic Change*, submitted.
2. Godal, O. and J. Fuglestedt, 2002: Testing 100-year global warming potentials: Impacts on compliance costs and abatement profile. *Climatic Change*, in press.
3. Godal, O., 2002: IPCC's Third Assessment Report and global warming potentials: Avoiding the road less travelled, *Climatic Change*, submitted.
4. Jourdain, L. and D. A. Hauglustaine, 2001: The global distribution of lightning NO<sub>x</sub> simulated online in a general circulation model, *Physics and Chemistry of the Earth*, in press.
5. Stuber, N., R. Sausen and M. Ponater, 2001a: Stratosphere adjusted radiative forcing calculations in a comprehensive climate model. *Theor. Appl. Climatol.* 68, 125-135.
6. Stuber, N., M. Ponater and R. Sausen, 2001b: Is the climate sensitivity to ozone perturbations enhanced by stratospheric water vapor feedback? *Geophys. Res. Lett.* 28, 2887-2890
7. Sygna, J.S. Fuglestedt and Aaheim, 2002: The adequacy of GWPs as indicators of damage costs incurred by global warming. *Mitigation and Adaption Strategies for Global Change*, submitted.

#### *Further publications*

1. Fuglestedt, J.S., 2000: Looking for a better way to measure the effects of GHGs: CICERO in a new EU project to refine GWPs and radiative forcing *Cicerone 1/2000*. <http://www.cicero.uio.no/cicerone/00/1/en/jansf2.pdf>

#### *Oral presentations*

1. Joshi, M., E. Highwood and K.P. Shine K: Radiative forcing, climate sensitivity and the tropopause. AGU 2000 Fall Meeting, San Fransisco, USA, 7-13 December 2000.
2. Ponater, M.: Klimawirkung von Spurengasen – Möglichkeiten und Grenzen des "radiative forcing"-Konzeptes, Colloquium of the Meteorological Institute of the Munich University (LMU). 23.1.2001.

3. Ponater, M.: Radiative Forcing – ein verlässlicher Parameter zur Klimavorhersage ?, German-Austrian-Swiss meteorological congress (DACH-Meteorologentagung). Wien, Austria, 18.-21.9.2001.
4. Ponater, M., M. Dameris, N. Stuber, C. Schnadt, R. Hein, and B. Steil: On the contribution of ozone and stratospheric water vapour to the global warming, EGS XXVI General Assembly, Nice, France. 25.-30. March 2001.
5. Sausen, R., N. Stuber and M. Ponater: Climate response to inhomogeneously distributed forcings. Seminar at the Department of Earth System Sciences, University of California, Irvine, USA, 2.5.2001.
6. Sausen, R., N. Stuber and M. Ponater: Climate response to inhomogeneously distributed forcings. Seminar at the SCRIPPS Institution of Oceanography, La Jolla, CD, USA, 5.6.2001.
7. Sausen, R.: Die Antwort der Atmosphäre auf räumlich inhomogen verteilte Störungen. Kolloquium des Instituts für Chemie und Dynamik der Geosphäre, Teilinstitut Stratosphäre, Forschungszentrum Jülich, 9.6.2001.
8. Sausen, R., N. Stuber and M. Ponater: Climate response to inhomogeneously distributed forcings. Seminar at the Program for Climate Model Diagnostics and Intercomparison (PCMDI), Lawrence Livermore National Laboratory (LLNL), Livermore, USA, 24.6.2001.
9. Shine, K.P.: Radiative Forcing of Climate Change: The certainties and uncertainties. Seminar at Department of Chemistry, University of Cambridge, 5 June 2001
10. Skodvin, T.: Making climate change negotiable: The development of the global warming potential index. Worlds in Transition: Technoscience, Citizenship and Culture in the 21<sup>st</sup> Century. Conference co-sponsored by the Society for the Social Studies of Science (4S) and The European Association for the Study of Science and Technology (EASST). Wien, Austria, 27.-30.9.2000.
11. Stuber, N., M. Ponater, and R. Sausen: Enhanced climate sensitivity due to stratospheric water vapour feedback ?, EGS XXVI General Assembly, Nice, France. 25.-30.3.2001.
12. Stuber, N., M. Ponater, and R. Sausen: Enhanced climate sensitivity due to stratospheric water vapour feedback ?, IAMAS congress, Innsbruck, Austria, 10.-18.8.2001.

*Poster presentations*

none.

## 5. Annex

### Annex 2.1 Protocol for model simulations based on IPCC intercomparison.

#### BOUNDARY CONDITIONS

FIXED GASES based on 1998 values: CH<sub>4</sub> and N<sub>2</sub>O

CH<sub>4</sub>: Global mean = 1745 ppbv, assume NH=1790 and SH=1700 ppbv. Choose a reasonable stratospheric profile based on your model.

N<sub>2</sub>O: global mean = 314 ppbv (should not impact these calculations)

CO<sub>2</sub>: global mean = 365 ppmv (should not impact these calculations)

SURFACE DEPOSITION: O<sub>3</sub>

We are interested in the modeled O<sub>3</sub> distribution, and thus it is recommended that all participants use as-similar-as-possible surface "deposition velocities" for this species:

For O<sub>3</sub>: Land (0.60 cm/s), Sea (0.00 cm/s), Poleward of 60 degrees (0.00 cm/s)

Other wet and dry deposition rates up to individual participants.

EMISSIONS-BASED GASES: NO<sub>x</sub>, CO, NMHC

The year-2000 emissions data set considers separate source categories per component based on existing standards or an extrapolation of EDGAR data (1x1 degree inventory). The interpolation to model grid is the responsibility of the participant.

#### Summary of Year-2000 emissions of NO [Tg N]:

Industry = fossil & bio fuels (~30 + 1.8)	31.8
BB = savannah & ag-waste burning/deforest (3.2+1.2+2.7)	7.1
Aircraft ANCAT 2000	0.6
Soils	5.5
Lightning	5.0
<b>TOTAL</b>	<b>50.0</b>

Fossil fuel/industrial and biofuel emissions (IND). These emissions are provided as aggregated 1x1 gridded emissions. Assume no seasonal dependence.

Aircraft emissions (AV). ANCAT emissions updated for 2000 conditions.

Biomass burning emissions (BB). Use the model emissions for seasonal and geographical distributions and normalize to the global-annual value.

Soil emissions. Use the geographical and temporal distribution of soil emissions specified by Yienger and Levy (1995) of 5.5 Tg N for 1990; or use your model emissions scaled to 5.5 Tg(N)/yr.

Lightning. Scale your model lightning NO<sub>x</sub> to 5 Tg(N)/yr.

Stratospheric influx. Models should use their own current method.

#### Summary of Year-2000 emissions of CO [Tg CO]:

Industry = fossil fuel/domestic burning	650
BB = deforestation/savannah burning/waste burning	700
BIO = vegetation (150) + oceans (50)	200
<b>SUB-TOTAL</b>	<b>1550</b>

(If the model do not account for NMHC use the following CO production)

CH4 oxidation	800
Isoprene oxidation	165
Terpene oxidation	Included in BIO
Industrial NMHC	110
Biomass burning NMHC oxidation	30
Acetone oxidation	20
<b>TOTAL (including model derived emissions)</b>	<b>2675</b>

Fossil fuel/domestic burning (IND). Gridded 1x1 industrial source supplied. Assume no seasonality.

Vegetation & ocean (BIO). Gridded 1x1 emissions are supplied. The vegetation 150 Tg CO includes potential terpene source. The oceanic 50 Tg CO is consistent with Bates.

Deforestation/savannah burning/waste burning (BB). Model emissions scaled to global-annual value.

The other components of the CO budget need to be calculated internally to each model. We include some approximate numbers above for reference. If possible, please try to keep your total CO sources close to this approximate budget. A CO yield of 35 % C/C per molecule of hydrocarbon oxidized is assumed for isoprene and industrial/biomass-burning NMHC in these estimates.

If NMHC are considered in the simulation:

#### Summary of Year-2000 emissions of NMHC [Tg C]:

Industry = fossil fuel/domestic burning	161
BB = deforestation/savannah & waste burn	34
Isoprene	220
Terpene	127
Acetone	30
<b>Total</b>	<b>572</b>

Fossil fuel/domestic burning (IND). A 1x1 EDGAR-based set of gridded emissions is provided along with NMHC breakdowns into 24 compounds/classes. It includes sectors such as power generation, industry, fossil fuel production.

Deforestation / savannah burn / waste burning (BB). A 1x1 EDGAR-based set of gridded emissions is provided along with NMHC breakdowns into 24 compounds/classes. Apply same seasonality as for biomass burning NO<sub>x</sub>.

Isoprene. Total is based on Hauglustaine & Brasseur work. For gridded emissions use the GEIA data of Guenther et al (1995) scaled to 220 Tg C (i.e., by 43.7%).

Terpenes. Use the GEIA recommendations.

Acetone. Rough estimate is based on Singh et al. Models should use their own distributions if this source can be included.

## STRATOSPHERE:

It is impossible to specify a consistent stratosphere for the range of 3-D models involved in tropospheric studies, and thus we ask all participants to use their 'best, current stratosphere' and to keep this unchanged for ALL simulations.

The diagnostics for these simulations are:

Change in CO, O<sub>3</sub>, and NO<sub>x</sub> mixing ratio for January and July conditions (surface, 200 mb, and zonal-mean cross sections).

Change in ozone tropospheric column (DU) as a function of season.

Change in globally averaged OH concentration, methane lifetime, ozone burden as a function of the season.

## Annex 2.2 CTM descriptions

### LMDz-INCA

INCA (Interactions with Chemistry and Aerosols) is a new emission/chemistry model coupled to the LMDz (Laboratoire de Météorologie Dynamique) general circulation model. LMDz-INCA accounts for emissions, transport (resolved and sub-grid scale), photochemical transformations, and scavenging (dry deposition and washout) of chemical tracers interactively in the GCM. Several versions of the INCA model are currently used depending on the envisaged applications. The standard model resolution is 3.75x2.5 degrees with 19 sigma-p hybrid levels. The GCM also offers the possibility to zoom over specific regions, reaching typical horizontal resolutions of 50x50 km<sup>2</sup>. The numerics used to solve the time evolution of chemical species is based on a pre-processor. The model can be run in a nudged mode, relaxing to ECMWF winds and temperature. An off-line version of the GCM has also been developed in order to minimize the required computing time for transport simulations. This model is still under development and constitutes the atmospheric component of the IPSL coupled atmosphere-ocean-biosphere model.

Four versions of INCA are currently being used for gas phase chemistry.

INCA.0. This version is used for the transport of "inert" tracers and does not account for chemical transformations. The typical version of INCA.0 accounts for Rn<sup>222</sup>, Pb<sup>210</sup>, SF<sub>6</sub> and CO<sub>2</sub>. This version is specifically designated for the transport of radioactive tracers, and CO<sub>2</sub>.

INCA.1. Version 1 is designed to simulate the time evolution of tracers using fixed oxidant (i.e., OH, O<sub>3</sub>, NO<sub>3</sub>, H<sub>2</sub>O<sub>2</sub>) distributions. The three-dimensional distributions of oxidants are prescribed at each time-step according to monthly mean distributions pre-calculated with a more complete version of the model including chemistry. The evolution of long-lived greenhouse gases or chlorine/bromine reservoir species like CH<sub>4</sub>, N<sub>2</sub>O, CH<sub>3</sub>CCl<sub>3</sub>, CFCs, and HCFCs/HFCs can be calculated with INCA.1. By default this version includes 22 tracers and 39 photochemical reactions.

INCA.2. In this version of INCA, a methane oxidation scheme has been implemented in order to calculate interactively the distribution of tropospheric ozone and OH. This version includes the emissions and chemistry of CH<sub>4</sub>, CO, and NO<sub>x</sub>. A standard version of INCA.2 includes 43 tracers and about 100 photochemical reactions.

INCA.3. This more complete version of the model accounts for NMHCs. The oxidation schemes of C<sub>2</sub>H<sub>6</sub>, C<sub>3</sub>H<sub>8</sub>, C<sub>2</sub>H<sub>4</sub>, C<sub>3</sub>H<sub>6</sub>, C<sub>2</sub>H<sub>2</sub>, isoprene, and terpenes (as alpha-pinene) are considered. All other heavier than C<sub>4</sub> hydrocarbons are represented as six generic species (ALKANE, ALKENE, AROMATIC, C<sub>2</sub>H<sub>5</sub>OH, MEK, and C<sub>2</sub>H<sub>2</sub>). A standard version of INCA.3 includes 99

tracers and about 300 photochemical reactions.

Photolysis rates in INCA are determined based on a pre-calculated multiple entry look-up table. This table is generated using version 4.01 of the Tropospheric Ultraviolet and Visible (TUV) model. The pseudo-spherical discrete ordinates method has been used. The photorates are tabulated for 8 solar zenith angles, 7 ozone columns, 4 surface albedos, 3 temperatures at 500mb, and 2 temperatures at 200 mb. The  $j$  values are then multi-interpolated on-line depending on local conditions prevailing in the gridcell and corrected for the effect of cloud cover and optical depth as calculated by the GCM.

Surface emissions of precursors and in-situ aircraft emissions are prepared based on emission inventories using the INCAsflx pre-processor. This processor collects the various emissions on different resolutions, interpolates on the GCM horizontal grid, allows for re-scaling of global inventories if needed, and generates a netCDF input file for INCA with monthly mean emissions.

Lightning NO<sub>x</sub> emissions are calculated in the GCM based on empirical parameterizations. At each time step these emissions are recalculated interactively and show a strong seasonal and diurnal cycles (Jourdain and Hauglustaine, 2001).

#### Reference:

Jourdain, L., and D. A. Hauglustaine, 2001 : The global distribution of lightning NO<sub>x</sub> simulated on-line in a general circulation model, *Physics and Chemistry of the Earth*, in press.

## OSLO CTM2

The OSLO-CTM2 is a global 3-dimensional chemical transport model that uses pre-calculated fields of winds and other physical parameters to simulate the chemical turnover and distribution of chemical species in the troposphere (Sundet, 1997). The meteorological input data for the model have been generated specifically for this model by running a series of 36 hours forecasts, with the ISF model at the ECMWF at T63 resolution for the year 1996. A new forecast is started every 24 hours from the analysis, allowing 12 hours of spin-up. An extensive set of data is sampled every three hours, including convective mass fluxes, which is not a part of the standard ECMWF archives. Also the temporal resolution (3 hours) is better than the standard ECMWF archives which uses 6 hours. The CTM can be run variable resolution up to T63 (1.87° x 1.87°), however, to limit the amount of CPU-time needed, in this study a horizontal resolution of T21 (5.6° x 5.6°) is used. The vertical resolution is also determined by the input data and the current model version includes 19 levels from the surface up to 10 hPa.

The advection of chemical species is calculated by the Prather scheme, a second order moment method (Prather, 1986). Convection is based on the Tiedtke (1987) mass flux scheme, where vertical transport of species is determined by the surplus or deficit of mass flux in a column. A comprehensive chemical scheme, including NMHC chemistry, is used. It includes 55 chemical compounds and 120 gas phase reactions in order to describe the photochemistry of the troposphere (Berntsen and Isaksen, 1997; Berntsen and Isaksen, 1999). The scheme is solved using the quasi-steady state approximation (QSSA). Photodissociation rates are calculated on-line, following the approach described in Wild et al. (2000). NO<sub>x</sub> emissions from lightning are coupled on-line to the convection in the model using the parameterisation proposed by Price and Rind (1993) and the procedure given by Berntsen and Isaksen (1999). Mixing in the planetary boundary layer is treated according to the Holtslag K-profile scheme (Holtslag et al., 1990). Influence of stratospheric ozone is estimated using a synthetic ozone approach where the ozone flux from the stratosphere is prescribed, but the model transport generates an ozone distribution that varies with time and space.

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