An introduction to metrics for climate change

Peter van Velthoven

KNMI

Koninklijk Nederlands Meteorologisch Instituut

• • • •

AK-CK Science meeting 25 March 2010

Overview

KNMI

Koninklijk Nederlands Meteorologisch Instituut

- Introduction: e.g. Why do we need a metric for climate change?
- Some concepts relevant to climate metrics:
  - Radiative forcing, RF
  - Climate sensitivity λ: relating RF and T
  - Backward & forward looking RF
  - Global warming potential, GWP
  - Alternative metrics: GTP etc.
  - Relevance versus uncertainty of metrics
  - A unified framework
- Typical problems in constructing climate metrics:
  - Dependence on time horizon
  - Climate efficacy of constituents (and domains)
  - Short-lived species (e.g. NO_x, CO)
- Conclusions and Outlook

Introduction: How did I get interested?

KNMI

Koninklijk Nederlands Meteorologisch Instituut

Climate metrics and associated problems were discussed in

- Bintanja et al., J.Clim. (1997)
- *EU project METRICS (~2003)*
- EU project QUANTIFY (2005-2010; Fuglestvedt, Shine)
- ICAO CAEP Assessment of climate, noise, air quality impact of aviation (Montreal, 29 Oct- 2 Nov 2007)
- KNMI colloquium Fuglestvedt, 3 April 2008
- *IPCC Expert Meeting on the Science of Alternative Metrics, Oslo, 18-20 March 2009*
- Transport, Atmosphere and Climate (TAC-2) conference 22-25 June 2009, Aachen-Maastricht

- Planning a dedicated workshop in 2010-2011 ..

Why do we need a metric for climate change?

KNMI

UNFCC: UN Framework Convention on Climate Change:

Art. 1: Objective: ".. stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."

Art. 3: Principles, 3: "The Parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures, taking into account that policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost. To achieve this, such policies and measures should take into account different socio-economic contexts, be comprehensive, cover all relevant sources, sinks and reservoirs of greenhouse gases and adaptation, and comprise all economic sectors."

....

UNFCC – Kyoto – EU – Copenhagen

KNMI

UNFCC and the Kyoto protocol do not define what the target of preventing dangerous interference with the climate system means ! e.g. limit temperature change to less than 2 degrees (as the EU proposes)

However, at Copenhagen the 2 degree target got widespread appreciation …

• • • •

The Kyoto protocol "basket"

KNMI

Koninklijk Nederlands Meteorologisch Instituut

Included in the Kyoto protocol (1997) "basket" :

- SF_6, N_2O, CO_2, CH_4, PFCs, HFCs

Not included :

- Ozone depleting compounds regulated by the Montreal protocol (CFC's …)
- Short-lived gases : ozone (CO, VOC's, NOx), aerosols (sulfate, nitrate, ammonium, carbonaceous)

Note that short-lived gases (OH) also affect the loss of CH_4 and HFCs!

Concepts: Radiative Forcing, RF
An element of most metrics for climate change

KNMI

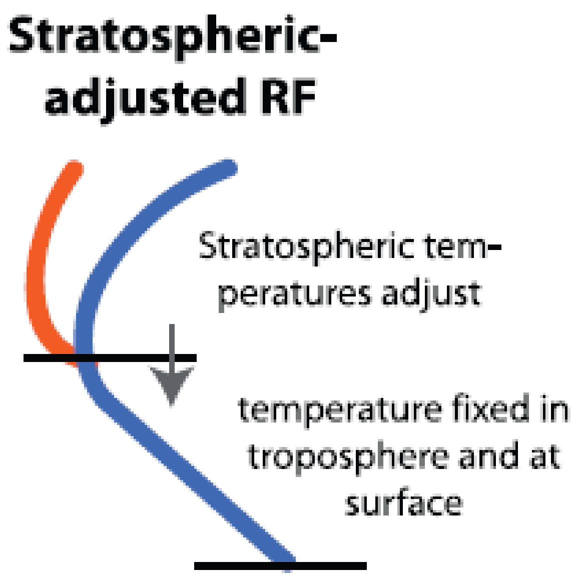
Koninklijk Nederlands Meteorologisch Instituut

Definition of RF frequently used by IPCC:

RF = the change in net (downward minus upward) irradiance (solar plus longwave) at the tropopause

- after allowing for stratospheric temperature to readjust to radiative equilibrium,
- but with surface and tropospheric temperature and state held fixed at the unperturbed values

RF is expressed in units of W/m^2



....

Climate sensitivity parameter, λ

KNMI

$$\Delta T_s = \lambda \,.\, RF$$

λ : climate sensitivity parameter
ΔT_s : change in (equilibrium) surface temperature

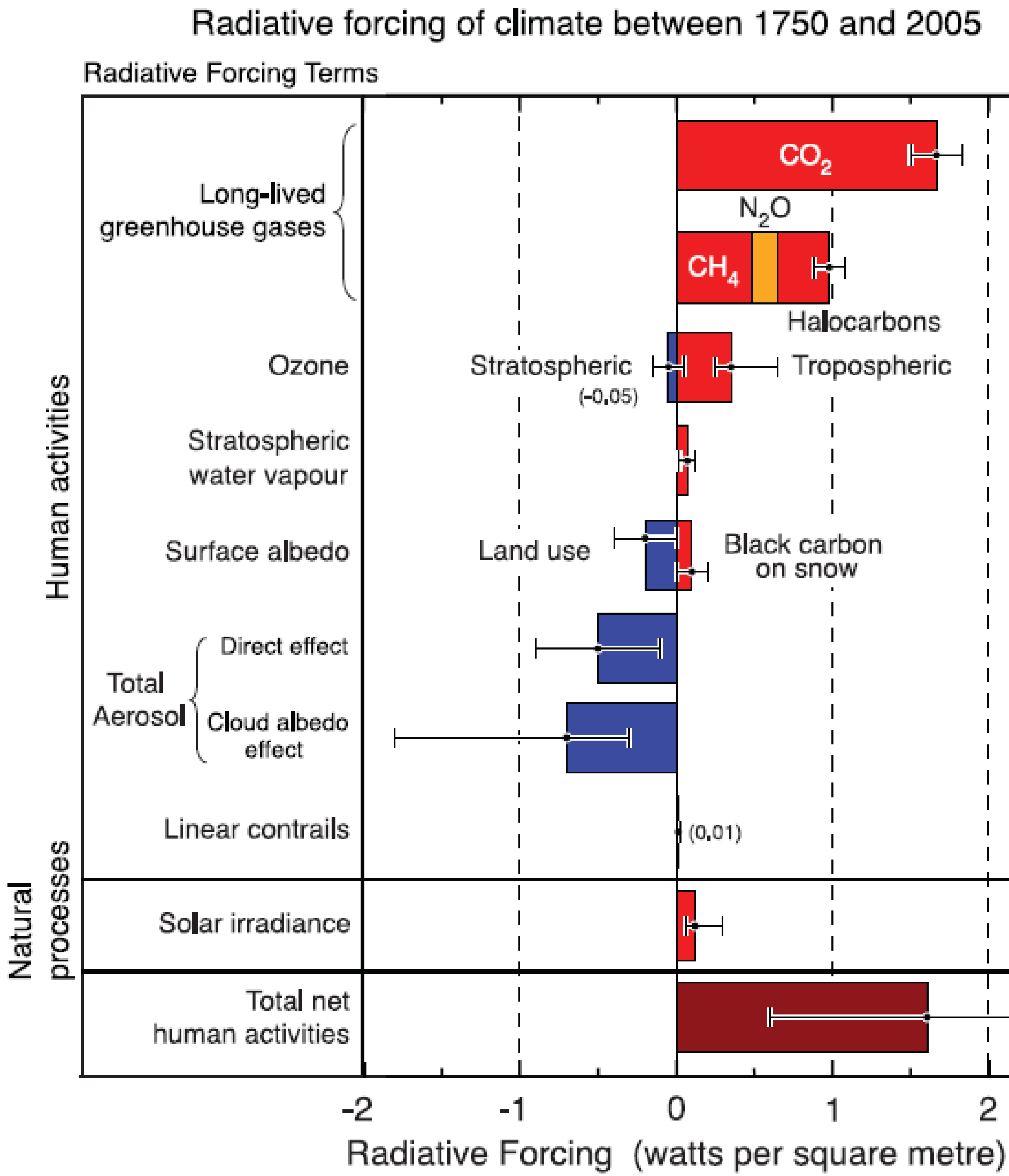
IPCC 4AR (2007): $\lambda = 0.54 - 1.2$ K / (W/m^2)

Unlikely to be less than the lower limit

Values substantially higher than the upper limit cannot be ruled out !

Note that λ is model-dependent and constituent-dependent !

Backward looking radiative forcing



IPCC 4AR

• • • •

Forward vs. backward looking RF

KNMI

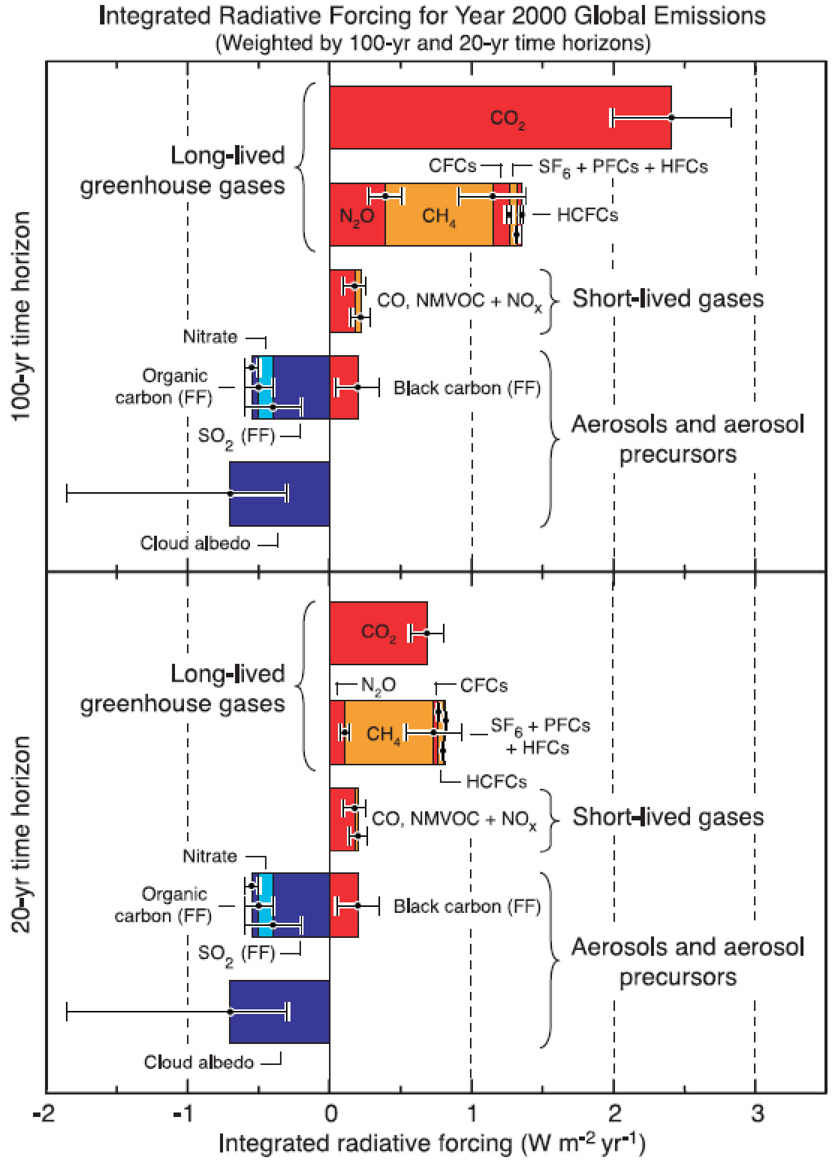
Backward looking RF:

- to quantify the (current) impact of past emissions
- relevant for attribution purposes
- usually considers (emission) changes since 'pre-industrial times' ~1750

Forward looking RF

- to quantify the future impact of current emissions .e.g. a pulse of annual emissions
- relevant for mitigation purposes
- dependence on chosen time horizon

100 & 20 yr forward looking **integrated** RF of year 2000 emissions



IPCC 4AR

• • • •

AK-CK Science meeting 25 March 2010

KNMI Koninklijk Nederlands Meteorologisch Instituut

Global warming potential, the GWP metric

GWP= the time-integrated global mean RF of a pulse emission of 1 kg of some compound (i) relative to that of 1 kg of the reference gas CO_2:

$$GWP_i \equiv \frac{\int_0^{TH} RF_i(t)\,dt}{\int_0^{TH} RF_r(t)\,dt} = \frac{\int_0^{TH} a_i \cdot [C_i(t)]\,dt}{\int_0^{TH} a_r \cdot [C_r(t)]\,dt}$$

• • • •

Alternative metrics for climate change

- Temperature change < 2° C (EU)
- Rate of temperature change < max
- $<(\Delta T)^2>$ or $<|\Delta T|>$ for nitrogen oxides: ΔO_3 warms, ΔCH_4 cools (Shine et al., PNAS, 2005)
- Minimize damage costs (ΔT), e.g. $D(t)=a\,\Delta T+b\,(\Delta T)^2$ (Marais et al., Met.Z. 2008)
- Sea level change (e.g. limit flooding to once every 1000 years)
- Ecosystem change
- Water supply shortages
- Cost-benefit analysis (take into account mitigation and damage)

- Take into account multiple environmental issues, e.g. for aviation noise, air quality, ozone depletion and climate change (Marais et al., Met.Z. 2008)

The choice of metric depends upon the target !

➔ Interaction between science and policymaking required

A generalized climate scenario metric

$$AM_i = \int_0^{\infty} [(I(\Delta C_{(r+i)}(t)) - I(\Delta C_r(t))) \times g(t)]dt$$

$I(\Delta C_i(t))$: describes the impact (damages and benefits) of a climate change (ΔC) at time t

g(t): a weighting function over time, e.g. e^{-kt}

r : refers to a baseline emission path

i: en emission perturbation

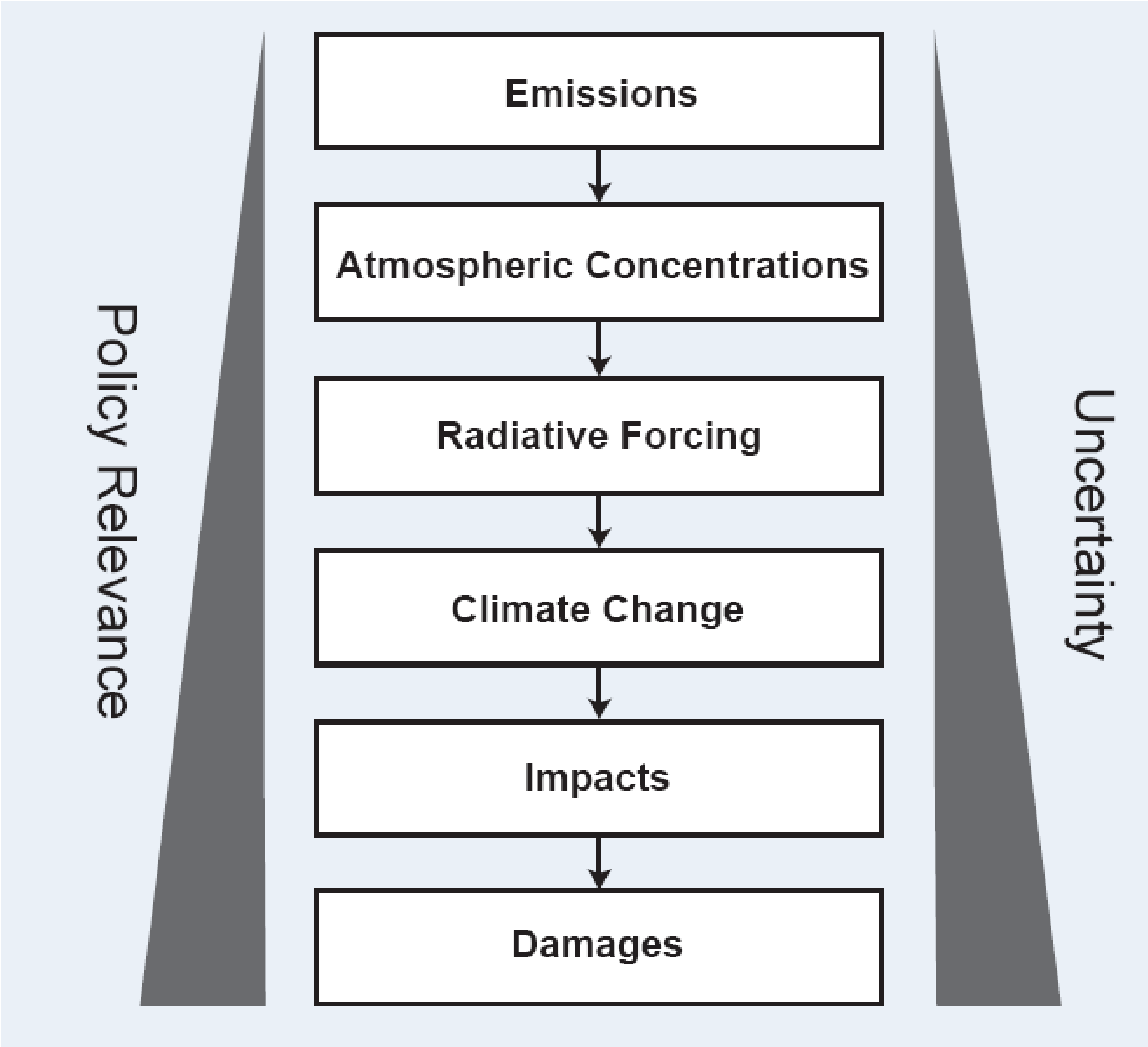
Kandlihar (1996)

Relative metric: $RM_i = AM_i / AM_{CO2}$

$\Delta C(t)$ requires extensive climate model calculations !

• • • •

Uncertainty and Relevance of metrics



• • • •

adapted from Fuglestvedt et al., Climatic Change, 2003

KNMI
Koninklijk Nederlands Meteorologisch Instituut

A unified framework for metrics

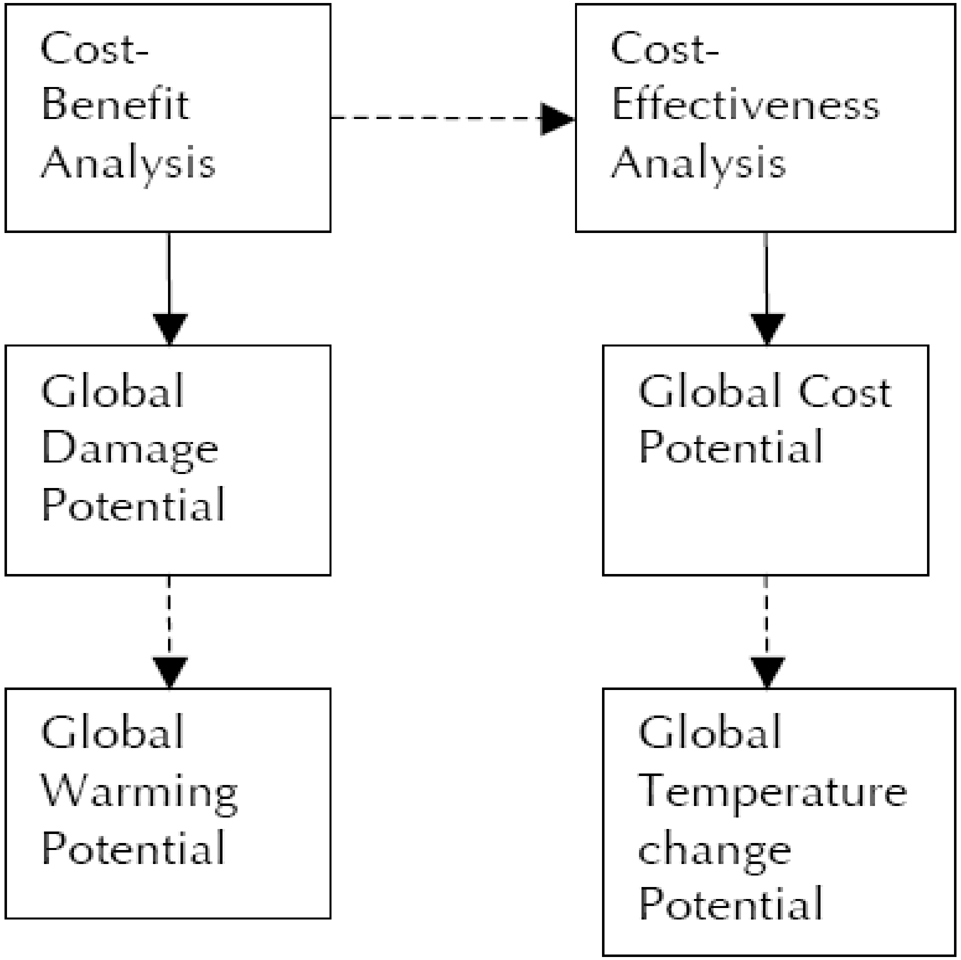


Figure 1. Relationship among equivalences and analytic approaches. Arrow represent derivations, with dashes indicating simplifications.

Richard Tol et al., ESRI working paper 257 (2008)

A unified framework for metrics

Tol et al., ESRI working paper 257 (2008):

GWP is a special case of cost-benefit analysis with:

- Zero discount rate
- Arbitrary and finite time horizon
- Assumes costs of climate change are proportional to integrated RF
- Neglects the time evolution of greenhouse gas (Boucher, 2009)

Metric "problems": dependence on time horizon

Example: Methane

KNMI

Koninklijk Nederlands Meteorologisch Instituut

Time horizon (years)→ Metric↓	20	50	100	500
GWP (Forster et al, AR4, 2007)	72		25	7.6
GTP (Fuglestvedt et al. 2009)	57	12	4	

For longer time horizons CH_4 reductions become relatively less attractive compared to CO_2 reductions

Impact of CH_4 reductions decreases faster for GTP than for GWP with increasing time horizon

Discount rate (%/year)	1	3
GDP (Boucher, 2009)	16	38

For higher discount rates

CH_4-reductions become more attractive !

• • • •

Metric "problems": Climate sensitivity parameter λ
Different for stratospheric ozone layer perturbations

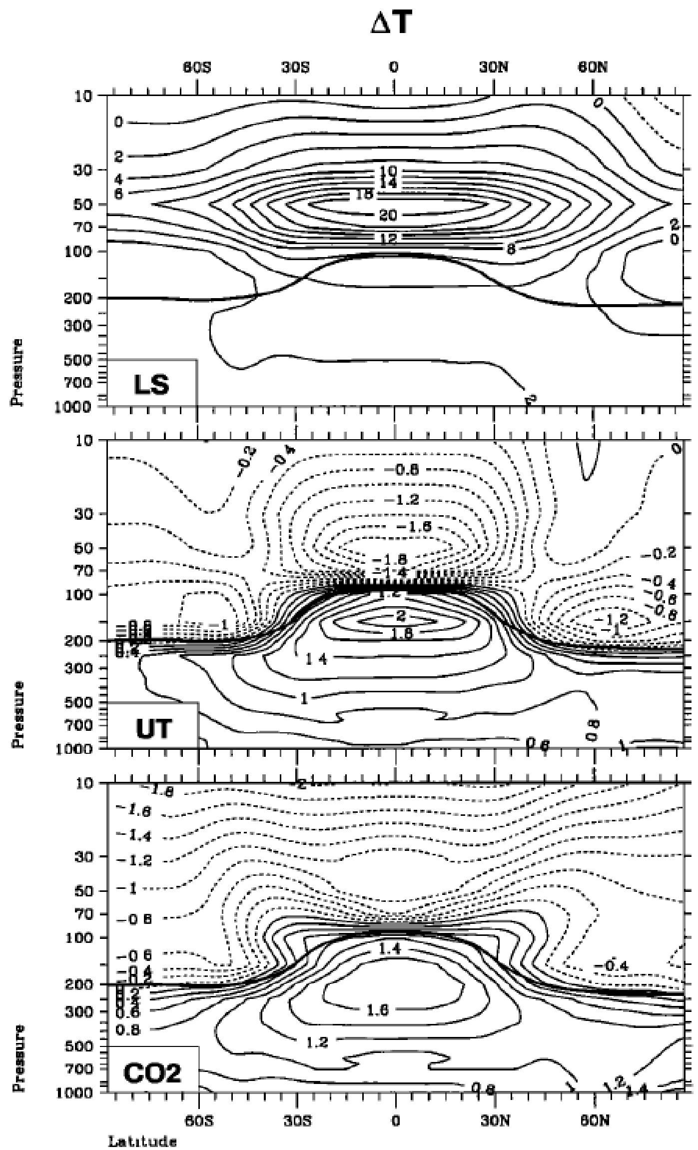
KNMI

lower stratospheric ozone

upper tropospheric ozone

carbon dioxide, CO_2

....



Stuber et al. GRL 2001 & Clim.Dyn. 2005 , Bintanja et al. J.Clim. 1996

Partial "solution": climate efficacy, ε

KNMI

$$\varepsilon_i = \lambda_i / \lambda_{CO2}$$

Effective RF = $\varepsilon_i \, RF_i$:

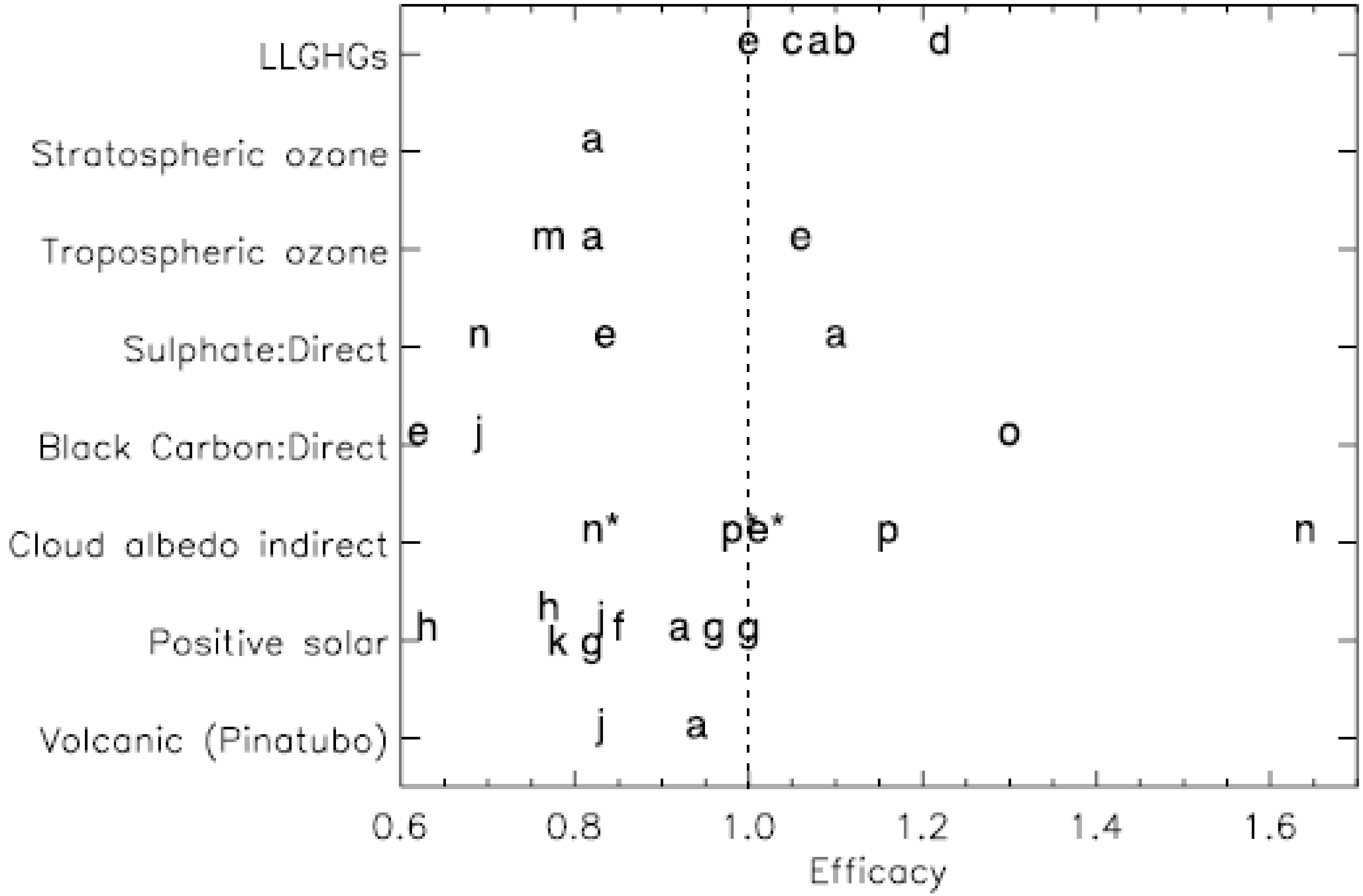
$$\Delta T_s = \lambda_{CO2}\, \varepsilon_i\, RF_i = \lambda_{CO2}\, RF$$

Joshi et al., 2003

- Effective RF is a better estimator of the likely surface temperature response than RF !
- However, ε depends on the 3D structure of forcing and the way it projects on feedbacks

• • • •

Metric "problems": model dependence of climate efficacy



• • • •

Metric "problems" with short-lived gases, aerosols and contrails

KNMI

Koninklijk Nederlands Meteorologisch Instituut

1. Chemical perturbation depends on location and time of emission
2. Large chemistry model uncertainties & also inherent uncertainty due to non-linear chemistry
3. RF (radiative perturbation) depends on the 3D-location and time of the chemical perturbation : perturbations in the tropics and near the tropopause usually have a larger RF
4. Same RF can have different climate impacts (different climate sensitivity parameter)

Solutions?:

1,3 : Take into account emission/perturbation location and time …. this may include replacing ΔT by e.g. ΔT^2 and performing 'spatial averaging'

2: Model ensemble approach, consensus approach

4: Climate efficacy

→Solution seems to require application of chemistry-climate models (CCMs)

Metric problem with short-lived gases (NO_x, CO)

Chemical perturbation depends on location of emission and on model !

Table 1. Description of emission perturbations used in the CTMs

Perturbation	Region	Emission (fossil fuels)
CO-Europe	Europe (40°–60°N, 10°W–20°E)	+40 Tg yr^{-1} of CO
CO-Asia	SE Asia (10°–30°N, 100°–120°E	+40 Tg yr^{-1} of CO
NOx-Europe	Europe (40°–60°N, 10°W–20°E)	+1 Tg(N) yr^{-1} of NOx
NOx-Asia	SE Asia (10°–30°N, 100°–120°E	+1 Tg(N) yr^{-1} of NOx

Table 2. Calculated increase in tropospheric ozone mass (Tg) below levels with background ozone concentrations less than 200 ppbv for the two CTMs

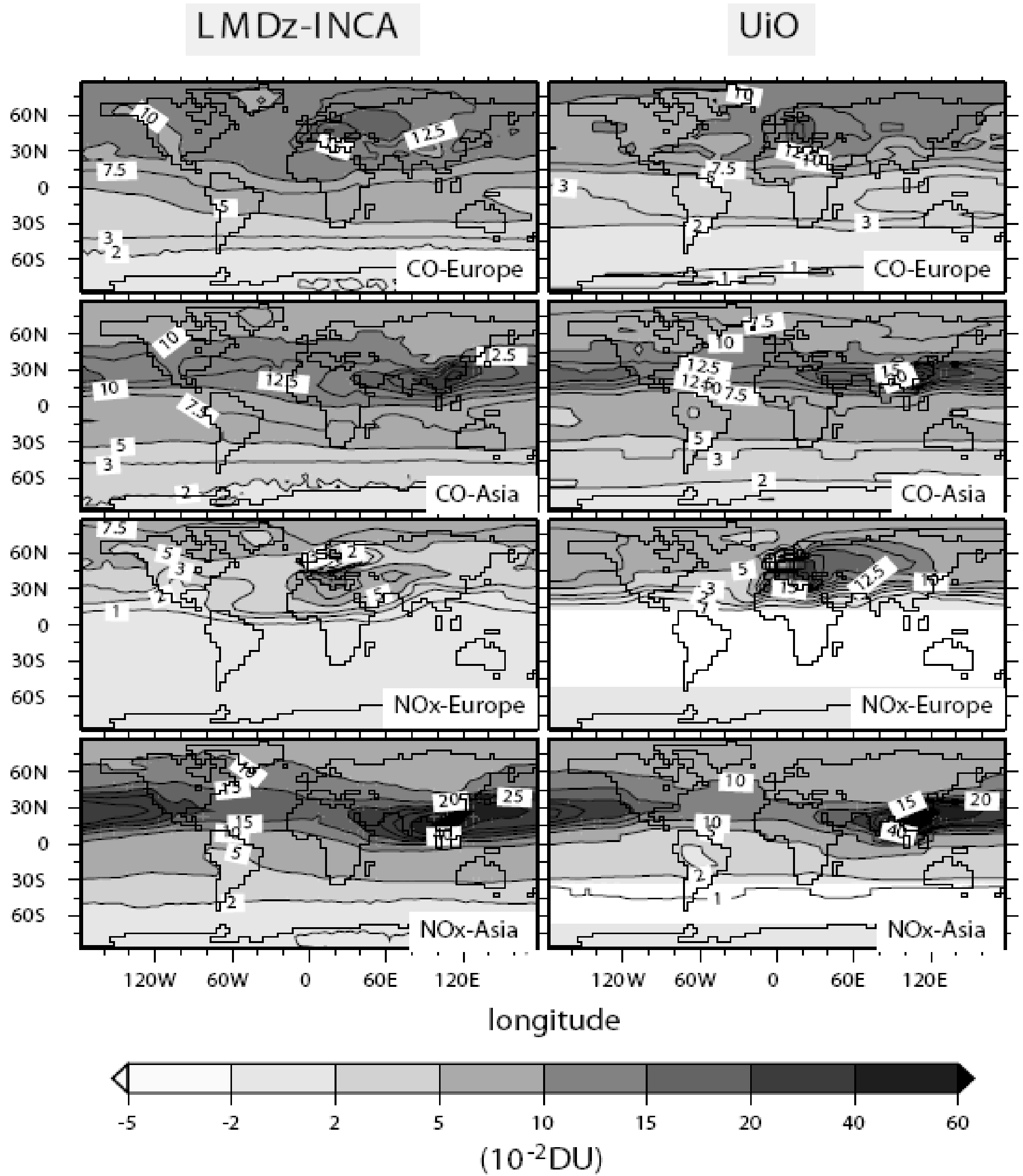
	UiO, ΔO_3 (Tg)	LMDzINCA, ΔO_3 (Tg)
CO-Europe	0.59	0.78
CO-Asia	0.83	0.84
NOx-Europe	0.26	0.19
NOx-Asia	0.93	1.16

• • • •

Berntsen et al. Tellus 57B, 2005

Metric problem with short-lived gases (NO_x, CO)

KNMI



• • • •

Koninklijk Nederlands Meteorologisch Instituut

Berntsen et al. Tellus 57B, 2005

Conclusions

KNMI

- A climate metric is needed for defining/negotiating emission reductions (emission trading) and for estimating adaptation and mitigation costs
- Choice of metric depends on the target (to be specified in protocols):
  ➔ requires interaction between science and policy
- Several problems have been identified for (extension to more gases of) climate metrics !

Outlook

- More research and discussion of metrics needed !
- A workshop on metrics for scientists and policymakers is planned in NL in 2010/2011

• • • •