The science of the Kyoto protocol

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ECMWF seminar September 2005
Outline

- Kyoto protocol

- Observations relevant to Kyoto
  - Baseline analysis

- Modelling relevant to Kyoto
  - Earth system modelling
The targets cover emissions of the six main greenhouse gases, namely:

- Carbon dioxide (CO2);
- Methane (CH4);
- Nitrous oxide (N2O);
- Hydrofluorocarbons (HFCs);
- Perfluorocarbons (PFCs); and
- Sulphur hexafluoride (SF6)
CO₂ per capita emissions and population (2000)

Population (million)

Emissions (tonnes of carbon per capita)

USA
Canada, Australia, New Zealand
Russia
Japan
OECD Europe
Other EIT
Middle East
China
Latin America
Other Asia
Africa
India
The 1997 Kyoto Protocol

- Developed countries (38) agreed to reduce emissions of greenhouse gases below their 1990 levels by 2010
- Reductions average 5% (UK reduction 12%)
- Planting trees can offset emissions by absorbing CO2
- Countries can buy and sell carbon emissions reductions
- Even if all countries ratify, reduction in warming will be small
Effect of Kyoto Protocol on global temperature

- Business-as-usual
- Only Kyoto

Temperature rise °C

2000 2020 2040 2060 2080 2100
Negotiations on targets for the second commitment period are due to start in 2005, by which time Annex I Parties must have made “demonstrable progress” in meeting their commitments under the Protocol.
Baseline Analysis of Mace Head Observations

- Based on meteorological analyses
- NAME model derived air history maps - Darker shade means greater contribution from area
- All possible surface sources over previous 10 days
- Maps generated for each hour 1995-2004
- Sort Mace Head observations into ‘baseline’ (Atlantic) and ‘regionally polluted’ (European) based on air history maps
- Estimate Baseline trends of each GHG measured
GHG baseline trends from Mace Head data

Methane (CH4) (GCMD)
MONTHLY BASELINE
ppb

Nitrous oxide (N2O) (GCMD)
MONTHLY BASELINE
ppb

Carbon Dioxide
MONTHLY BASELINE
ppm

HFC-134a (GCMS)
MONTHLY BASELINE
ppt
Reasons for building an Earth System Model
- climate-carbon feedback
- climate-chemistry interactions
- climate-aerosol interactions
Development of the Hadley Centre Earth System Model beyond HadGEM1

Off-line model development

Strengthening colours denote improvements in models

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Importance of the baseline model

Relative humidity

HadGEM1

HadGEM1 - HadCM3

HadCM3 - ERA

HadGEM1 - ERA

Counts every 5.00 %

Counts every 4.00 %

Pressure (hPa)
Precipitation – coupled feedbacks

HadGEM1

HadGAM1 – HadGAM1

HadGAM1 – CMAP

HadGEM1 – CMAP
Earth system components

CLIMATE

AEROSOLS

Direct and Indirect Effects

ECHOSYSTEMS

ECOSYSTEMS

Greenhouse Effect

Online

Offline

Human Emissions

Oxidants: OH, H₂O₂, HO₂, O₃

CH₄, O₃, N₂O, CFC

CO₂

Human Emissions

Land-use Change

Human Emissions

Chemistry

Human Emissions
Earth system models for climate 2009

**CLIMATE**

- Greenhouse Effect
- Direct and Indirect Effects / Feedbacks on natural sources
- Heat island effect

**AEROSOLS**

- Human Emissions
- Oxidants: OH, H₂O₂, HO₂, O₃
- Fires: soot, Mineral dust

**GHGs**

- Human Emissions
- CH₄, O₃, N₂O, CFC
- CO₂

**ECOSYSTEMS**

- Biogenic Emissions: CH₄, DMS, VOC’s
- Dry deposition: stomatal conductance
- Land-use Change

**CHEMISTRY**

- N deposition: Ωₙ, UV radiation
- Dry deposition: stomatal conductance

**Online**

**Offline**
Interactive, on-line aerosols scheme (replacing climatological background aerosols):

- Sulphate, FF black carbon, biomass-burning aerosol (prognostic), sea-salt aerosol (diagnostic)
- Some chemistry associated with atmospheric aerosols is included (oxidants are specified).

Direct and indirect radiative forcings included.

Mineral dust scheme not yet included.

No interactive carbon-climate or chemistry-climate coupling in the standard HadGEM1 model. However, a version of HadGEM1 with on-line coupling to STOCHEM has been developed (which is much more expensive).
Column-integrated droplet numbers compare reasonably well with observations. (There is no mechanism for generating number concentration without aerosol.)

Droplet size is underestimated due to a lack of cloud water in sub-tropical oceanic regions.
Emissions of natural sulphate precursors depends on wind speed (exp 2xCO$_2$).

Both natural and anthropogenic sulphate responds to change in precipitation (exp 2xCO$_2p$).
Emissions and sinks of sea-salt will respond to climate change through changes in wind speed, transport, and precipitation.

Less cooling in the NH, more cooling in the SH, leading enhanced hemispheric contrast.
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Met Office Surface Exchange Scheme (MOSES)

Land surface type prescribed – land use changes can be included
TRIFFID-GCM coupling

Photosynthesis, respiration, transpiration (30 minutes)

Litter (1 day)

Leaf Area Index, albedo, roughness (1 day)

Competition (10 days)
Simulated changes in the global total soil and vegetation carbon content

Can changes to the carbon cycle speed up climate change?
Can changes to the carbon cycle speed up climate change?

Simulated changes in the global total soil and vegetation carbon content

![Graph showing changes in total soil and vegetation carbon content over years](image-url)
Change to carbon stored in soils (1860–2100)

Increased Respiration as warmer soil

No litter input

Change to carbon stored in vegetation (1860–2100)
Precipitation changes in 2080 relative to 2000

- Non-interactive CO₂

-Further precipitation changes with CO₂-climate feedback

mm day⁻¹
30-year means
Can changes to the carbon cycle speed up climate change?

The answer appears to be YES

- Climate-carbon cycle feedbacks significantly accelerate CO2 increase and climate change – large positive climate feedback in HadCM3

- Temperature rise over land
  - Without carbon feedback 5°C
  - With carbon feedback 8°C

- Land becomes source of CO2
  - Amazon dieback
  - Loss of soil carbon
  - Ocean continues take up of carbon
WRE scenarios

- WRE are a family of scenarios of CO$_2$ level, stabilising at 450, 550, 650, 750 and 1000 ppmv
  

- We run the carbon cycle GCM with these prescribed CO$_2$ levels and infer the emissions required to achieve them

- Results shown in detail for 550 ppm

- Summary of results for all levels
Other stabilisation levels

Cumulative CO\textsubscript{2} emissions (GtC) 2000–2300

- **without climate feedback**
- **with climate feedback**

Levels:
- 450
- 550
- 650
- 750
- 1000
- Forests are typically much darker than grasslands and croplands, especially in snow-covered areas.

- They therefore absorb more sunlight which tends to warm the climate.

- This warming effect offsets the cooling effect of carbon sequestration.

- Reforestation would have a net warming effect on climate in some (snowy) regions.
Runoff increase under climate change is greater when physiological forcing by CO$_2$ (causing plant stomatal closure) is included.
Climate impacts on chemistry

Only changes within troposphere included.

Increased water vapour and temperature in the future will lead to greater destruction of methane and ozone – red versus black lines.

However this will be offset by increases in natural emissions.

Not yet clear which will win.

Methane

Ozone

Johnson et al. GRL 2001
Increasing temperature increases hydrocarbon emissions from vegetation (e.g. isoprene)
Simulated annual mean wetland fraction

Off-line:

Modelled Natural Wetlands

Natural Wetland: Azelmann and Crutzen

On-line:

Modelled Natural Wetlands

Natural Wetland: Azelmann and Crutzen
Effect of predicted wetland CH$_4$ emissions

1990→2100: 25% increase in CH$_4$
3-5% increase in total radiative forcing
Coupling chemistry to ecosystems

Ozone causes damage internally after passing through stomata

- By coupling chemistry and ecosystem models we can model the flux through stomata
- Increasing ozone will reduce the ability of plants to soak up CO₂
Ozone affects GPP. Ozone concentrations are expected to increase by 2100. Results indicate a potential loss of veg+soil carbon of 130 PgC (corresponding roughly to an extra 50 ppm in the atmosphere, to be compared to an increase of about 350 ppm due to CO₂ emissions – IS92a scenario, no carbon feedback)
Conclusions 1

Kyoto protocol

- Science?

Observations relevant to Kyoto

- Baseline analysis – results depend on method
Modelling relevant to Kyoto

- Atmospheric concentrations depend on
  - Man-made emissions
  - Changes to natural emissions due to climate change
    - Isoprene etc
    - Methane from wetlands
  - Earth system feedbacks
    - Carbon cycle
    - Climate effect on methane, ozone
    - Ozone effect on plants/ carbon storage
- Are all greenhouse gases equivalent?
  - Physiological effects of CO₂
- Planting trees may not be an effective strategy
Precipitation – coupled feedbacks

- Lack of convection over Indonesian subcontinent allows SSTs to warm
- Excessive easterly wind stresses over the Pacific promote upwelling and cooling.
- New balance shifts rainfall over maritime subcontinent.
- Drives stronger Walker circulation alters wind stresses
- Similar process in HadCM3 and HadGEM1
- HadGEM1 bigger cooling error and very small warming error
- Locks in to a La Nina type phase