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INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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SMR.780 - 34

FOURTH AUTUMN COURSE ON MATHEMATICAL ECOLOGY

(24 October - 11 November 1994)

"Causes and Consequences of Climate Change"

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These are preliminary lecture notes, intended only for distribution to participants.

What is Climate?

(a) Mean atmospheric conditions at the Earth's surface (traditional view)

(b) Means and higher moment statistics that characterize the structure and behavior of the atmosphere, hydrosphere, biosphere, and cryosphere.

Components of Climate System

Atmosphere:

0-10 km	Troposphere
10-50 km	Stratosphere
50-80 km	Mesosphere
80+ km	Thermosphere

Hydrosphere:
All water in liquid phase distributed on Earth (oceans, interior seas, lakes, rivers, subterranean waters)

Cryosphere:
Large masses of snow and ice on Earth's surface (extended ice fields of Greenland and Antarctica, other continental glaciers and snow fields, sea ice, and permafrost)

Biosphere:
Terrestrial vegetation, continental fauna, flora and fauna of oceans

Lithosphere:
Continents and ocean floor

The Atmosphere

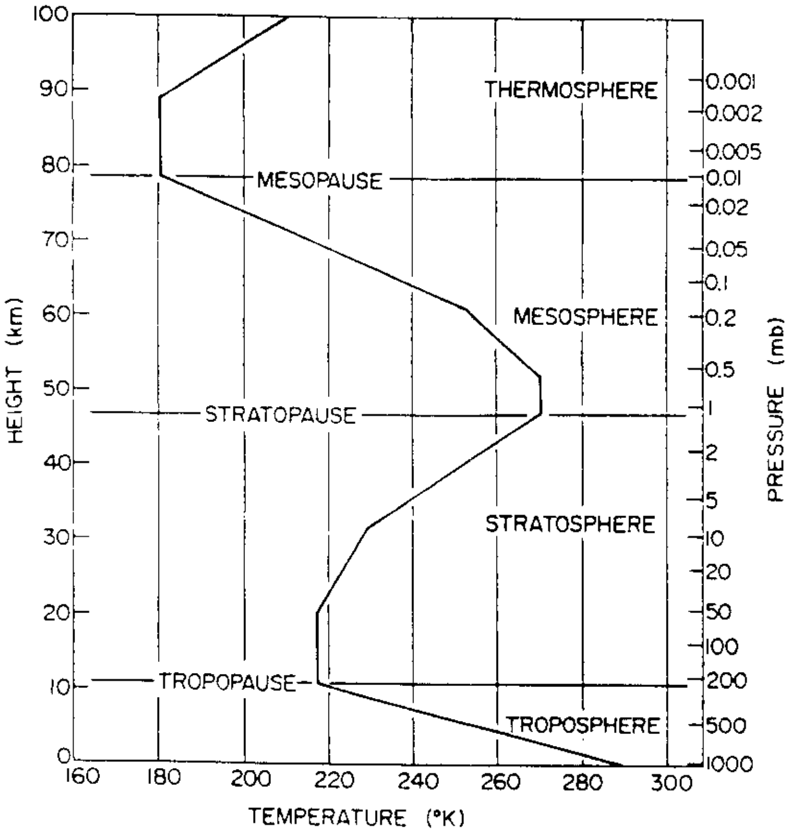


FIGURE 2.3. Idealized vertical temperature profile according to the U.S. Standard Atmosphere (1976). Also shown are the names commonly used for the various layers and pauses in the atmosphere from Wallace and Hobbs (1977).

Response Times of Climate System Components

Climate System Component	**Response Time**
atmospheric boundary layer	minutes to hours
free atmosphere	weeks to months
upper mixed layer of ocean	weeks to years
deep ocean waters	decades to millenia
sea ice	weeks to decades
inland waters & vegetation	months to centuries
glaciers	centuries
ice sheets	millenia
tectonic phenomena	millions of years

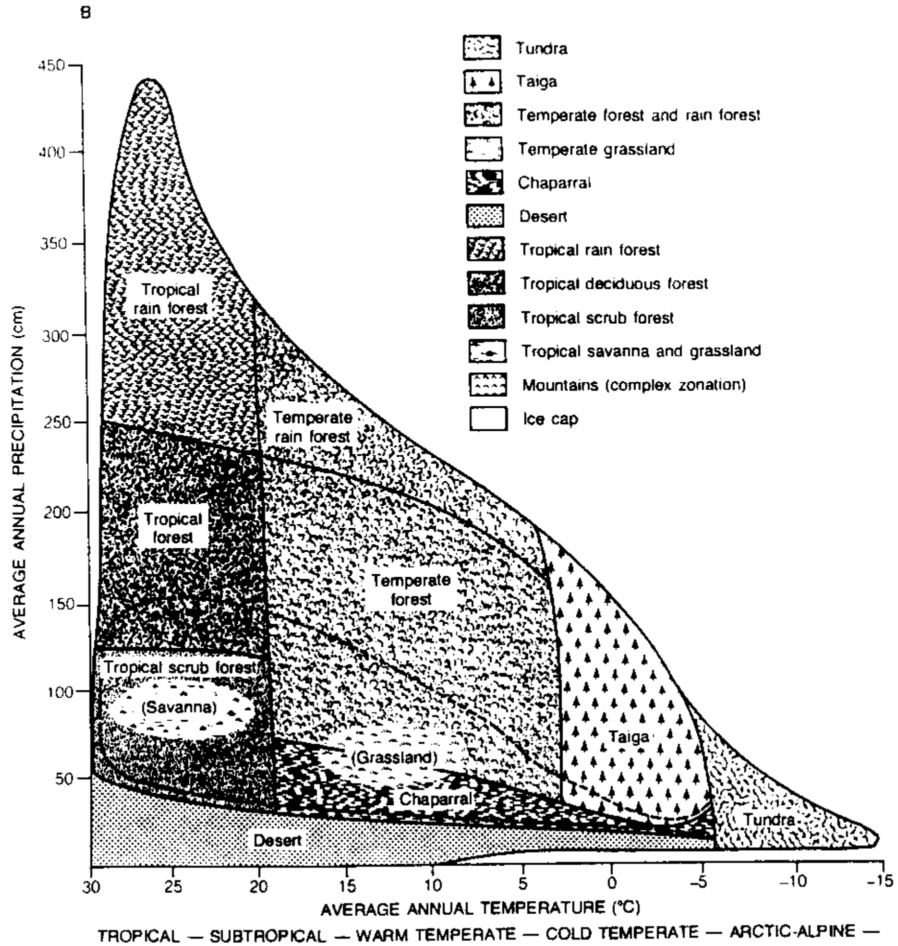
Why do we care?

(1) Climate has historically been a determining factor in

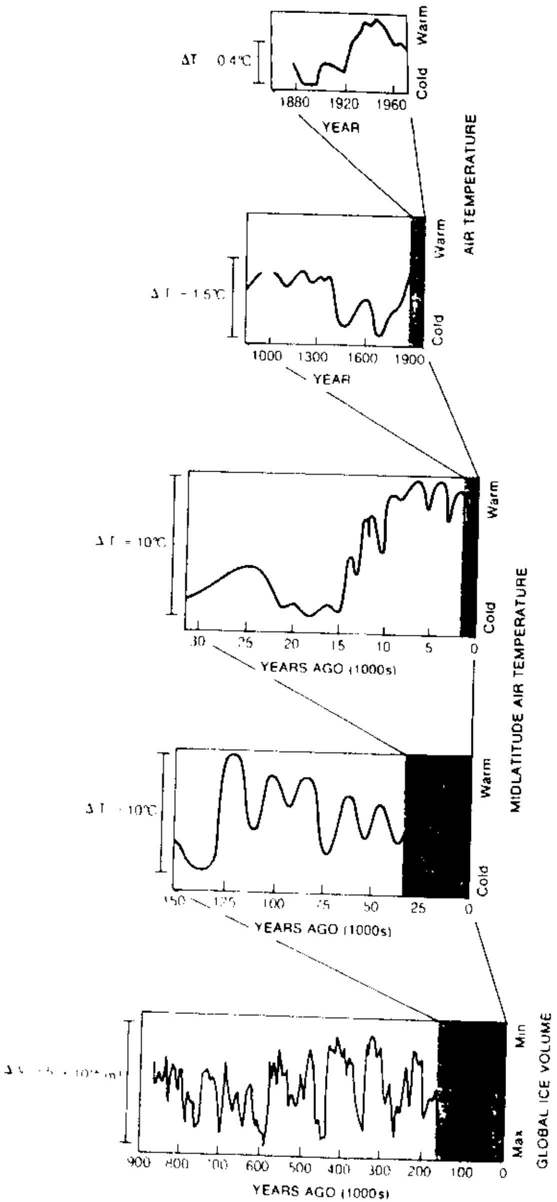
- distribution of biomes
- patterns of food production
- distribution of populations

(2) Humans are disrupting the atmospheric composition and thus the climate.

Biome-Climate Correlations



Climate Change over the Millennia

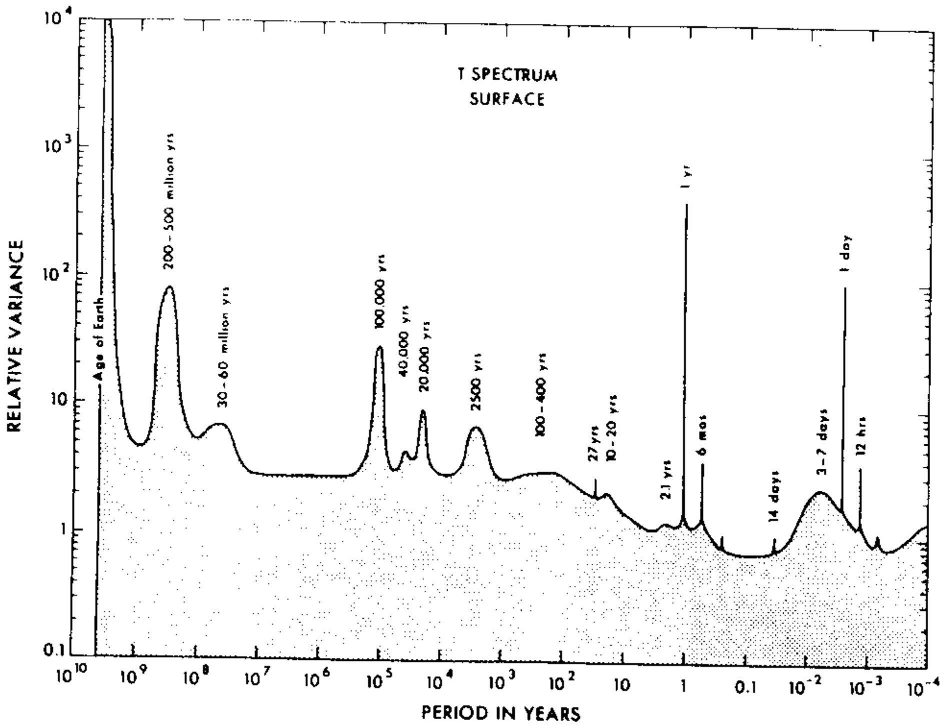


Climate changes due to . . .

(1) External forcing
- solar variability
- Earth orbit variations

(2) Internal forcing
- atmosphere-ocean interactions (inherent instabilities or oscillations of the system)

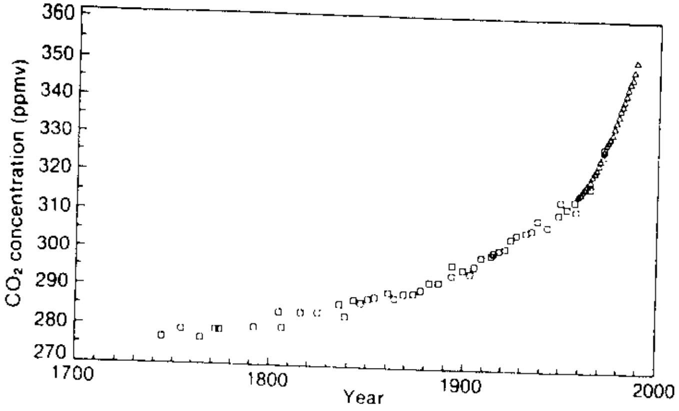
Climate Forcing

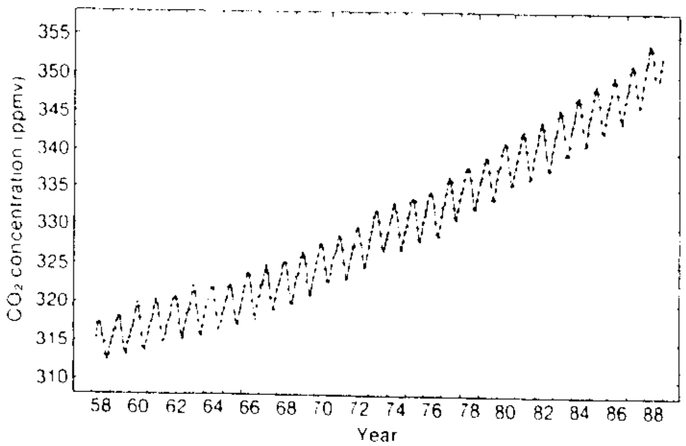


Humans are perturbing climate through emissions of . . .

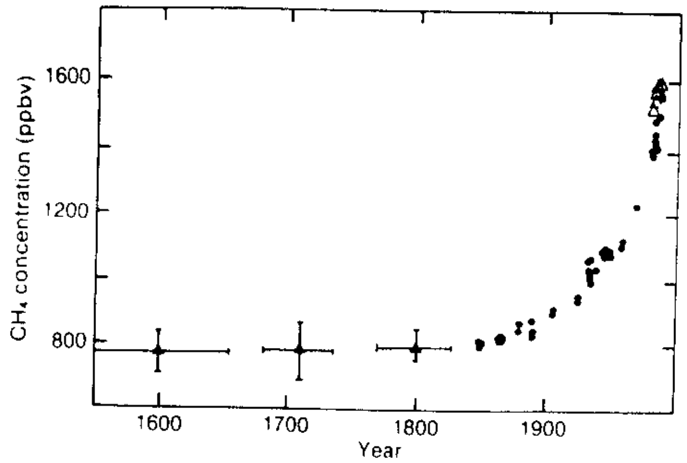
Gas	Rate of Increase	Anthropogenic Sources
CO_2	0.5% yr^{-1}	Fossil-fuel use, deforestation & other land-use changes
CH_4	0.9% yr^{-1}	Rice cultivation, domestic ruminants, natural gas use, biomass burning, landfills, coal mining
CFC-11 CFC-12	4% yr^{-1}	aerosol propellants, refrigerants, foam-blowing agents
N_2O	0.25% yr^{-1}	fertilizer use, land-use change, combustion, biomass burning

Human-induced increases in CO_2





Human-induced increases in Methane and Nitrous Oxide



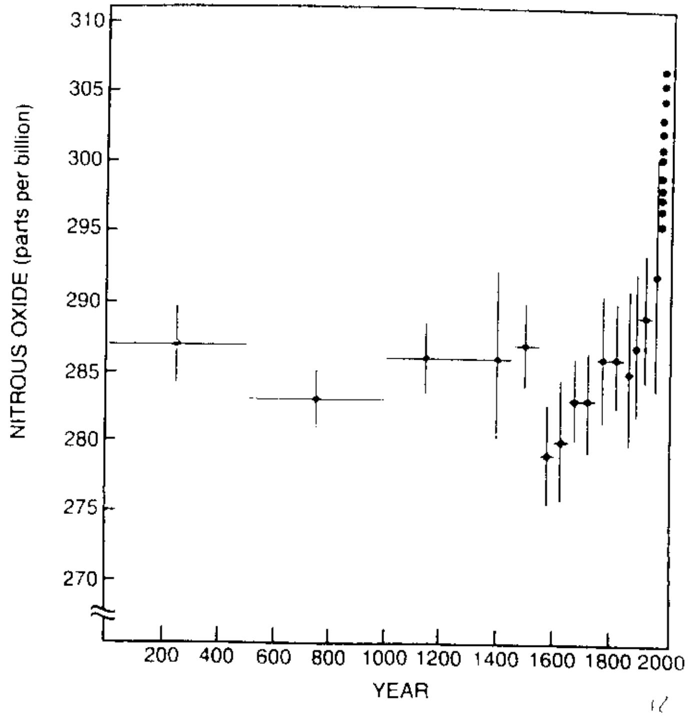


Table 1.1 [illegible] Greenhouse Gases [illegible] Human Activities

Parameter	CO_2	CH_4	CFC-11	CFC-12	N_2O
Pre-industrial atmospheric concentration (1750-1800)	280 ppmv[2]	0.8 ppmv	0	0	288 ppbv[2]
Current atmospheric concentration (1990)[3]	353 ppmv	1.72 ppmv	280 pptv[2]	484 pptv	310 ppbv
Current rate of annual atmospheric accumulation	1.8 ppmv (0.5%)	0.015 ppmv (0.9%)	9.5 pptv (4%)	17 pptv (4%)	0.8 ppbv (0.25%)
Atmospheric lifetime[4] (years)	(50-200)	10	65	130	150

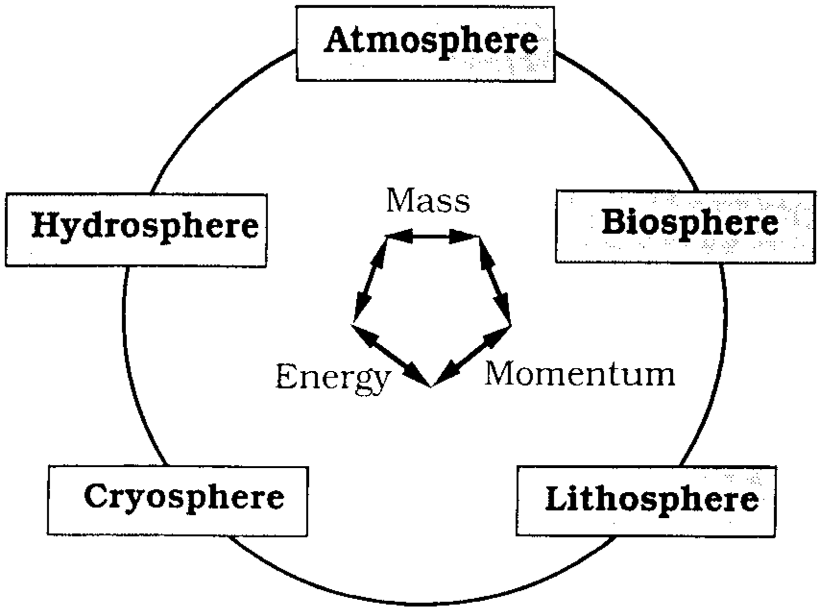
1 Ozone has not been included in the table because of lack of precise data.

2 ppmv = parts per million by volume; ppbv = parts per billion by volume; pptv = parts per trillion by volume.

3 The current (1990) concentrations have been estimated based upon an extrapolation of measurements reported for earlier years, assuming that the recent trends remained approximately constant.

4 For each gas in the table, except CO_2, the "lifetime" is defined here as the ratio of the atmospheric content to the total rate of removal. This time scale also characterizes the rate of adjustment of the atmospheric concentrations if the emission rates are changed abruptly. CO_2 is a special case since it has no real sinks, but is merely circulated between various reservoirs (atmosphere, ocean, biota). The "lifetime" of CO_2 given in the table is a rough indication of the time it would take for the CO_2 concentration to adjust to changes in the emissions (see section 1.2.1 for further details).

Interaction among climate components



- Solar radiation provides almost all of the energy that drives the climate system.

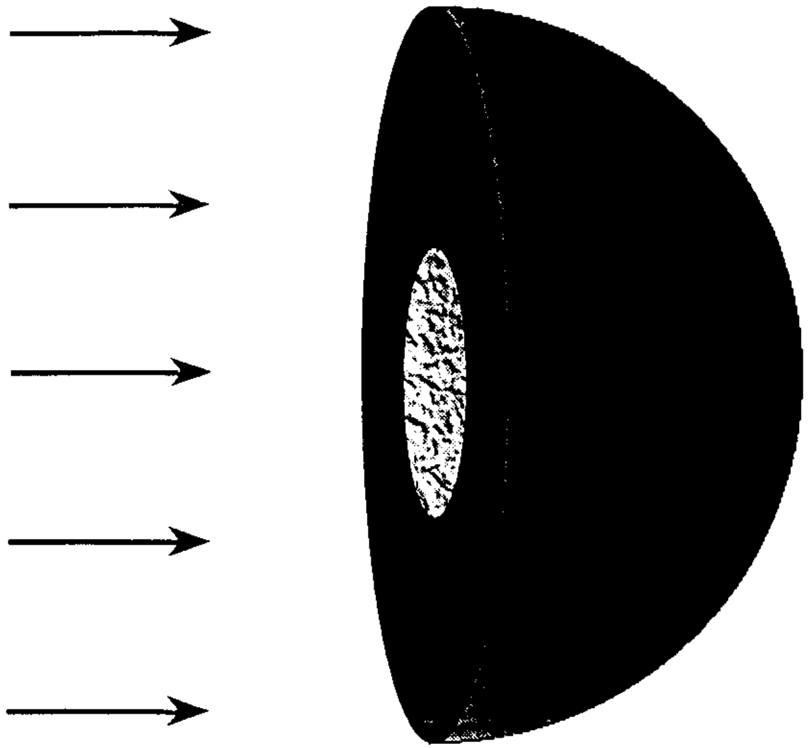
- Solar energy reaching top of atmosphere is...

(1) Partially transferred

(2) Partially transformed into other forms of energy that are eventually dissipated by general circulations of the atmosphere and oceans

(3) Partially used in chemical and biological processes

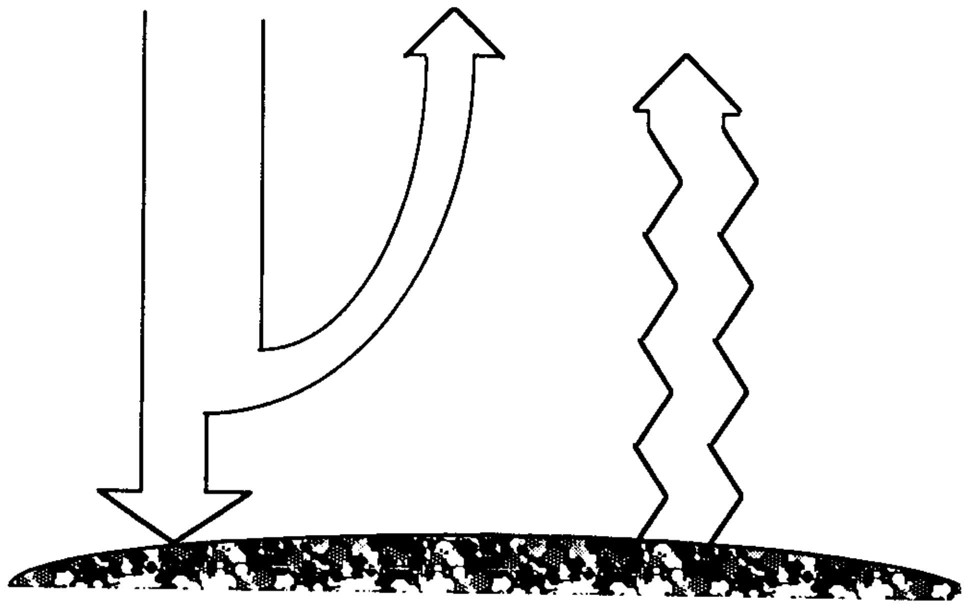
Earth's interception of solar radiation



Average solar flux reaching the top of the atmosphere

$$= \frac{\Omega}{4 \pi R_E^2} \bullet \pi R_E^2 = \frac{\Omega}{4} = 340 \frac{W}{m^2}$$

Earth's Blackbody Temperature

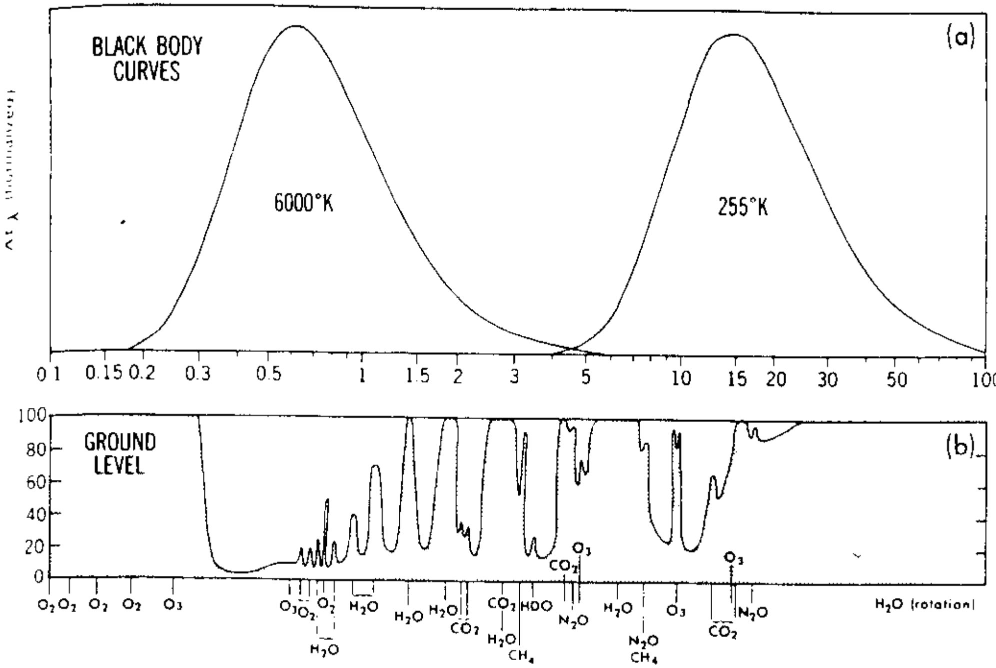


$$F_{in} = \frac{\Omega}{4} \qquad F_{out} = \frac{a\,\Omega}{4} + \sigma T^4$$

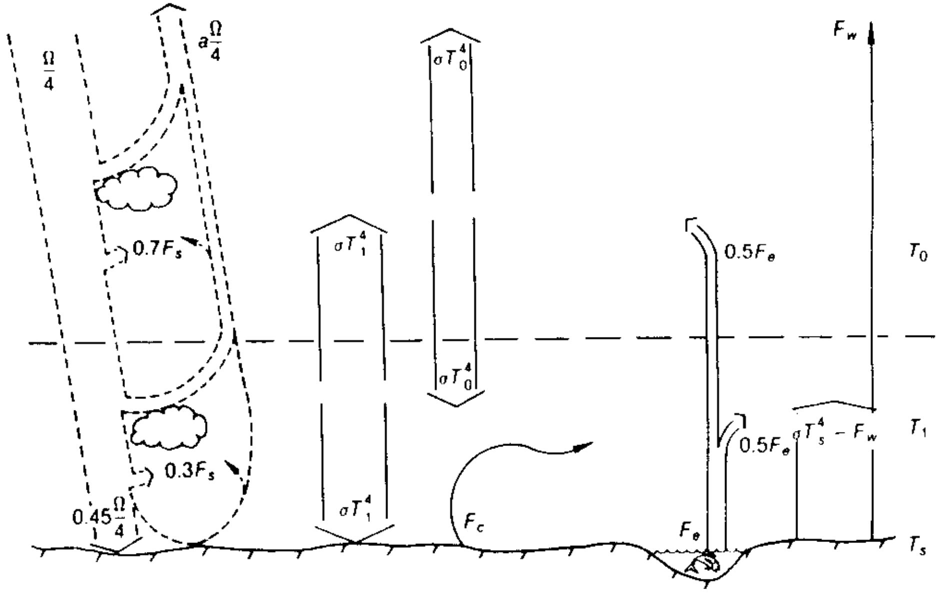
$$F_{in} = F_{out} \quad \text{or} \quad T^4 = \frac{(1 - a)\,\Omega}{4\,\sigma}$$

$$T = 255\ K = -18\ ^\circ C$$

Absorption spectra for greenhouse gases



Earth's Average Surface Temperature



a = albedo of Earth system ≈ 0.3
T_0 = temperature of upper layer of atmosphere
T_1 = temperature of lower layer of atmosphere
T_s = temperature of Earth's surface
F_s = portion of solar fluxed absorbed in atmosphere ≈ 86 W/m^2
F_c = convective heat transfer from surface to atmosphere ≈ 17 W/m^2
F_e = flow of latent heat from evaporating surface water ≈ 80 W/m^2
F_w = IR flux that goes directly from surface to space ≈ 20 W/m^2

Earth's Average Surface Temperature

Energy balance for the whole system:

$$\frac{\Omega}{4} = \frac{a\,\Omega}{4} + \sigma T_0^4 + F_w$$

Energy balance for the top layer of the atmosphere:

$$2\sigma T_0^4 = \sigma T_1^4 + 0.5\, F_e + 0.7\, F_s$$

Energy balance for the bottom layer of the atmosphere:

$$2\sigma T_1^4 = \sigma T_0^4 + \sigma T_S^4 - F_w + F_c + 0.5\, F_e + 0.3\, F_s$$

Solutions:

$T_0 = 250$ K $= -23$ °C

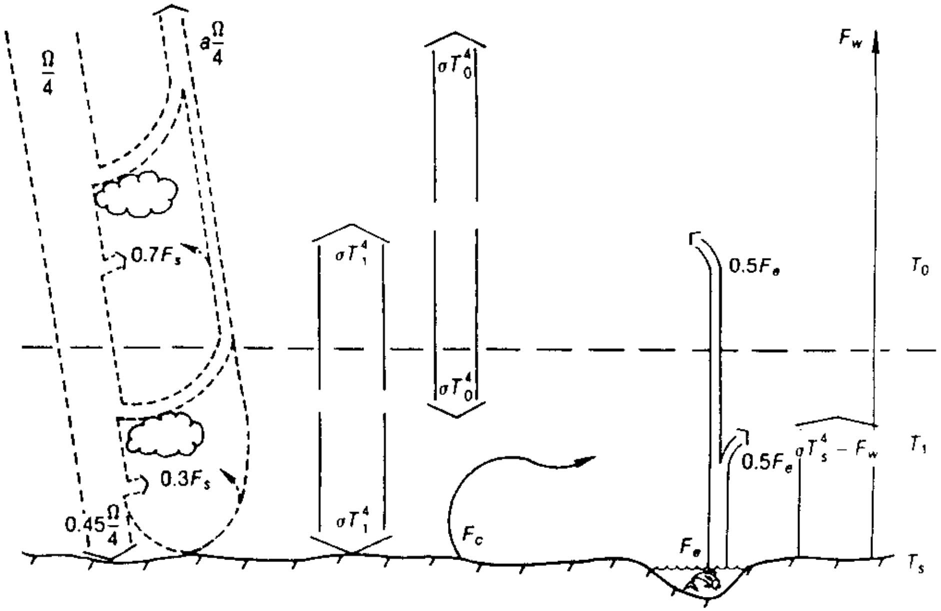
$T_1 = 278$ K $= +5$ °C

$T_S = 289$ K $= +16$ °C

- Human induced increases in greenhouse gases lead to increases in *radiative forcing* on the Earth's surface.

- Radiative forcing is any increase in downward radiation reaching the Earth's surface that perturbs the balance between received and emitted energy.

Earth's perturbed surface temperature



Unperturbed: ≈ 494 W/m^2 reaching surface
≈ 397 W/m^2 emitted by surface infrared fluxes ($\sigma T_S{}^4$)

Doubled CO_2: additional 4 W/m^2 reaching surface

$F_{in} > F_{out}$ so Earth's surface will warm until fluxes of energy balance:

$\Delta T_S{}^0 \approx 1\ ^\circ C$

• In the absence of feedbacks, increased downward infrared radiation at the Earth's surface would result in warmer surface temperatures.

But

$\Delta T_S{}^* = \mathcal{F}\, \Delta T_S{}^0$

$\mathcal{F}$ = Feedback effect

If $\mathcal{F} > 1$, positive feedback (amplify initial change)

$\mathcal{F} < 1$, negative feedback (reduce or reverse initial change)

Potential Feedbacks:

$\Delta T_S^0 > 0$ will	Resulting in
↑ evaporation of water, stock of water in atmosphere	$\mathcal{F} > 1$ (vapor) $\mathcal{F} > 1$ or (clouds) $0 < \mathcal{F} < 1$
↓ in ice caps, ↓ in albedo in polar regions	$\mathcal{F} > 1$
↑ ocean temperature, ↑ in outgassing of CO2	↑ in atmospheric CO2 ($\mathcal{F} > 1$)

$\Delta T_S^0 > 0$ = an initial increase in the Earth's surface temperature

$$\Delta T_S^* = \mathcal{F}\,\Delta T_S^0$$

ΔT_S^* = 2.0 to 5.2 for various climate models ($\mathcal{F}$ = 2.0 to 5.2)

Cloud Feedbacks

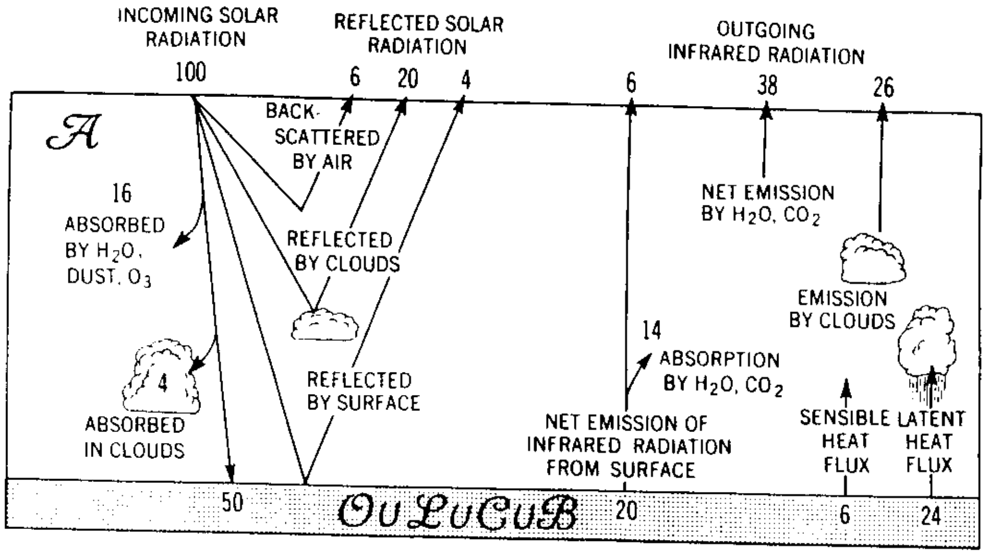


FIGURE 6.3. Schematic diagram of the global radiation budget in the climatic system. A value of 100 units is assigned to the incoming flux of solar energy.

Whether clouds are a positive or negative feedback depends on

- cloud amount

clouds reflect incoming solar radiation (– feedback)
" " infrared radiation (+ feedback)

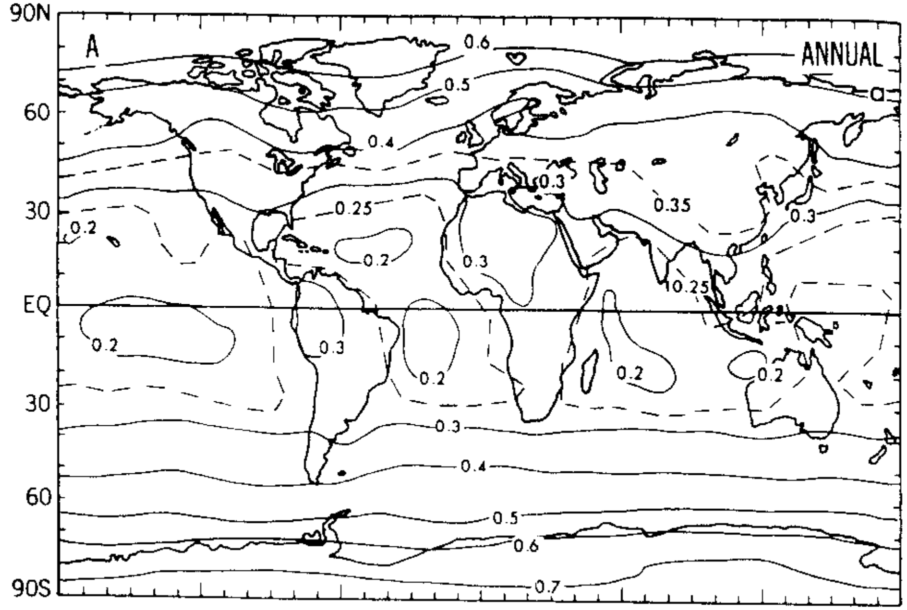
- cloud altitude

displaced to higher, colder region (+ feedback)
" " lower, warmer region (– feedback)

- cloud water content

increased, brighter clouds (– feedback)

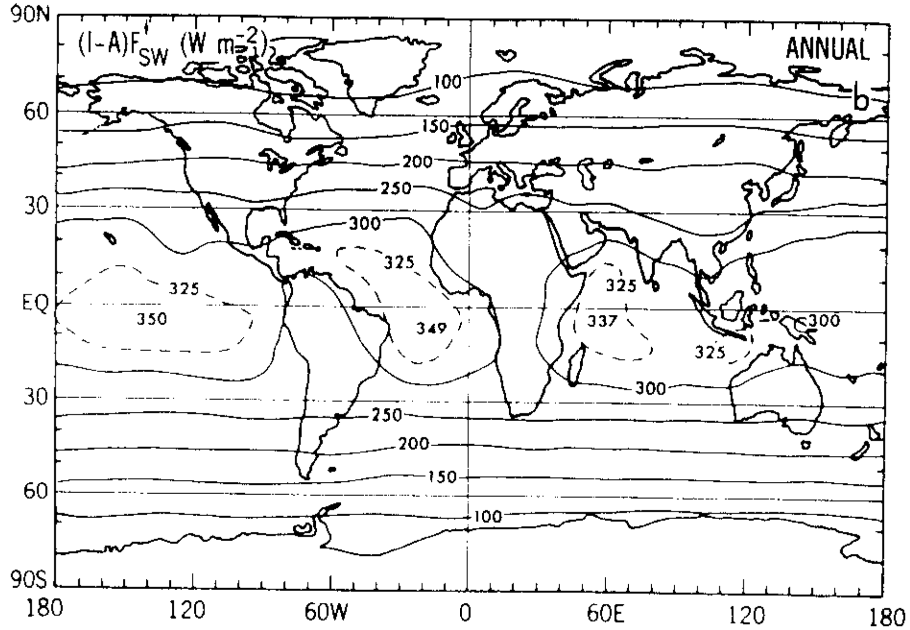
Earth's Albedo

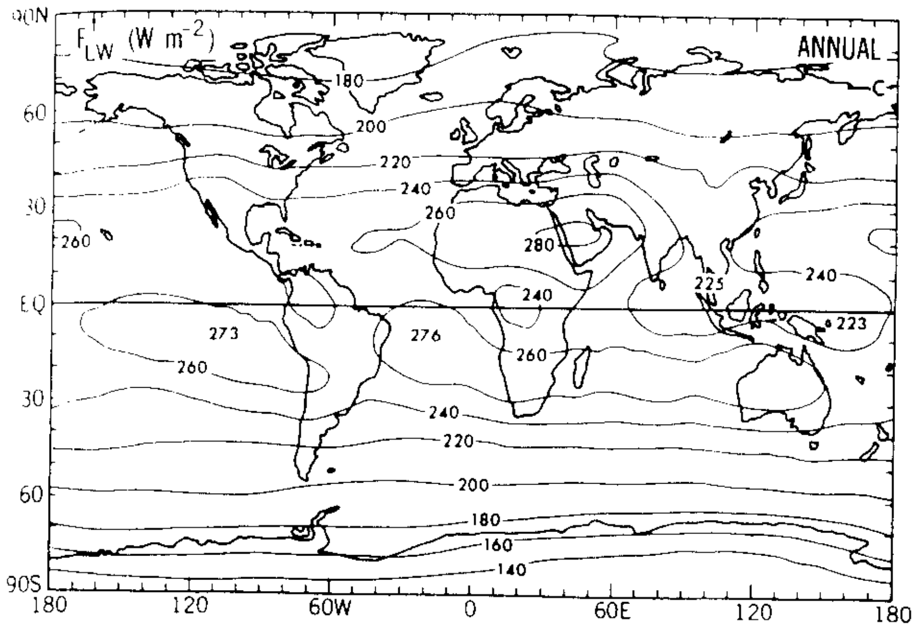


Albedo depends on surface and incident angle of radiation

snow	0.7 ± 0.2
sand	0.25 ± 0.05
grasslands	0.23 ± 0.03
bare soil	0.2 ± 0.05
forest	0.15 ± 0.1
water	0.2 + 0.6
	− 0.2

Absorbed and Emitted Radiation





Atmospheric and ocean currents transfer energy from the Equator to the Poles

The equations describing the circulation patterns of the atmosphere and the oceans are derived from the

- conservation of mass
- conservation of momentum (Newton's 2nd Law)
- conservation of energy

Conservation of mass

$$m = \int \rho \, dV$$

$$\frac{\partial m}{\partial t} = \frac{\partial}{\partial t}\int \rho \, dV = -\oint \rho \, \vec{c}\cdot\vec{dS}$$

By Green's theorem

$$\oint \rho \, \vec{c}\cdot\vec{dS} = \int \nabla\cdot(\rho \, \vec{c}) \, dV$$

Giving

$$\int \left[\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho \, \vec{c})\right] dV = 0$$

or

Equation of Continuity

$$\frac{\partial \rho}{\partial t} + \rho \nabla \cdot \vec{c} + \vec{c} \cdot \nabla \rho = 0$$

where

ρ = density

$\vec{c}$ = wind velocity

Equations of Motion

$$\underbrace{\frac{d\vec{c_a}}{dt}}_{\text{velocity in absolute, non-rotating reference frame}} = \underbrace{-\frac{\nabla p}{\rho}}_{\text{force due to changes in pressure}} \underbrace{-\nabla \Phi}_{\text{gravitational force}} \underbrace{+\vec{F}}_{\text{frictional force}}$$

To move to a rotating frame on the surface of the Earth:

$$\frac{d\vec{c_a}}{dt} = \frac{d\vec{c}}{dt} \underbrace{+ 2\,\vec{\Omega} \times \vec{c}}_{\text{Coriolis force}} \underbrace{+ \vec{\Omega} \times (\vec{\Omega} \times R)}_{\text{Centripetal force}}$$

where

$\vec{\Omega}$ = angular velocity of the Earth

Table 3.2(a): *Summary of results from global mixed-layer ocean-atmosphere models used in equilibrium 2 x CO_2 experiments*

ENTRY	Group	Investigators	Year	RESOLUTION No. of waves, or °lat. x °long.	No. of Vertical Layers	Diurnal Cycle	Convection	Ocean Heat Transport	Cloud	Cloud Properties	ΔT (°C)	ΔP (%)	COMMENTS
A.	**Fixed, zonally averaged cloud; no ocean heat transport**												
1.	GFDL	Manabe & Stouffer	1980	R15	9	N	MCA	N	FC	F	2.0	3.5	Based on 4 x CO_2 simulation
2.		Wetherald & Manabe	1986, 8	R15	9	N	MCA	N	FC	F	3.2	n/a	
B.	**Variable cloud; no ocean heat transport**												
3.	OSU	Schlesinger & Zhao	1989	4° x 5°	2	N	PC	N	RH	F	2.8	8	
4.			1989	4° x 5°	2	N	PC	N	RH	F	4.4	11	As (3), but with revised clouds.
5.	MRI	Noda & Tokioka	1989	4° x 5°	5	Y	PC	N	RH	F	4.3 *	7 *	* Equilibrium not reached.
6.	NCAR	Washington & Meehl	1984	R15	9	N	MCA	N	RH	F	3.5 *	7 *	* Excessive ice. Estimate ΔT = 4°C at equilibrium.
7.			1989	R15	9	N	MCA	N	RH	F	4.0	8	As (6), but with revised albedos for sea-ice, snow.
8.	GFDL	Wetherald & Manabe	1986, 8	R15	9	N	MCA	N	RH	F	4.0	9	As (2), but with variable cloud.
C.	**Variable cloud; prescribed oceanic heat transport**												
9.	AUS	Gordon & Hunt	1989	R21	4	Y	MCA	Y	RH	F	4.0	7	
10.	GISS	Hansen et al.	1981	8° x 10°	7	Y	PC	Y	RH	F	3.9	n/a	
11.		Hansen et al.	1984	8° x 10°	9	Y	PC	Y	RH	F	4.2	11	
12.		Hansen et al.	1984	8° x 10°	9	Y	PC	Y	RH	F	4.8	13	As (11), but with more sea-ice control.
13.	GFDL	Wetherald & Manabe	1989 †	R15	9	N	MCA	Y	RH	F	4.0	8	
14.	MGO	Meleshko et al	1990	T21	9	N	PC	Y	RH	F	n/a	n/a	Simulation in progress.
15.	UKMO	Wilson & Mitchell	1987	5° x 7.5°	11	Y	PC	Y	RH	F	5.2	15	
16.		Mitchell & Warrilow	1987	5° x 7.5°	11	Y	PC	Y	RH	F	5.2	15	As (15), but with four revised surface schemes.
17.		Mitchell et al.	1989	5° x 7.5°	11	Y	PC	Y	CW	F	2.7	6	As (16), but with cloud water scheme.
18.			1989	5° x 7.5°	11	Y	PC	Y	CW	F	3.2	8	As (17), but with alternative ice formulation.
19.			1989	5° x 7.5°	11	Y	PC	Y	CW	V	1.9	3	As (17), but with variable cloud radiative properties.
D.	**High Resolution**												
20.	CCC	Boer et al	1989	T32	10	Y	MCA	Y	RH	V	3.5	4	* "Soft" convective adjustment.
21.	GFDL	Wetherald & Manabe	1989 †	R30	9	N	MCA	*	RH	F	4.0	8	* SSTs prescribed, changes prescribed from (13).
22.	UKMO	Mitchell et al.	1989	2.5°x3.75°	11	Y	PC	Y	CW	F	3.5	9	As (18), but with gravity wave drag.

All models are global, with realistic geography, a mixed-layer ocean, and a seasonal cycle of insolation. Except where stated, results are the equilibrium response to doubling CO_2.

R, T = Rhomboidal/Triangular truncation in spectral space;
N = Not included;
PC = Penetrative convection;
FC = Fixed cloud;
F = Fixed cloud radiative properties;
GFDL = Geophysical Fluid Dynamics Laboratory, Princeton, USA;
MGO = Main Geophysical Observatory, Leningrad, USSR;
AUS = CSIRO, Australia;
ΔT = Equilibrium surface temperature change on doubling CO_2;
Y = Included;
CA = Convective adjustment;
RH = Condensation or relative humidity based cloud;
† = Personal communication.
NCAR = National Center for Atmospheric Research, Boulder, CO, USA;
CCC = Canadian Climate Center;
ΔP = Percentage change in precipitation;
MCA = Moist convective adjustment;
CW = Cloud water;
V = Variable cloud radiative properties;
n/a = Not available
MRI = Meteorological Research Institute, Japan;
UKMO = Meteorological Office, United Kingdom;

$$\frac{d\vec{c}}{dt} + 2\vec{\Omega} \times \vec{c} = -\frac{\nabla p}{\rho} - \nabla\Phi' + \vec{F}$$

where

$\nabla\Phi'$ includes centripital force

In the horizontal direction. . .

$$\left\{2\,\vec{\Omega} \times \vec{c}\,,\, -\frac{\nabla p}{\rho}\right\}_{hor} > \left\{\frac{d\vec{c}}{dt},\, -\nabla\Phi'\,,\, \vec{F}\right\}_{hor}$$

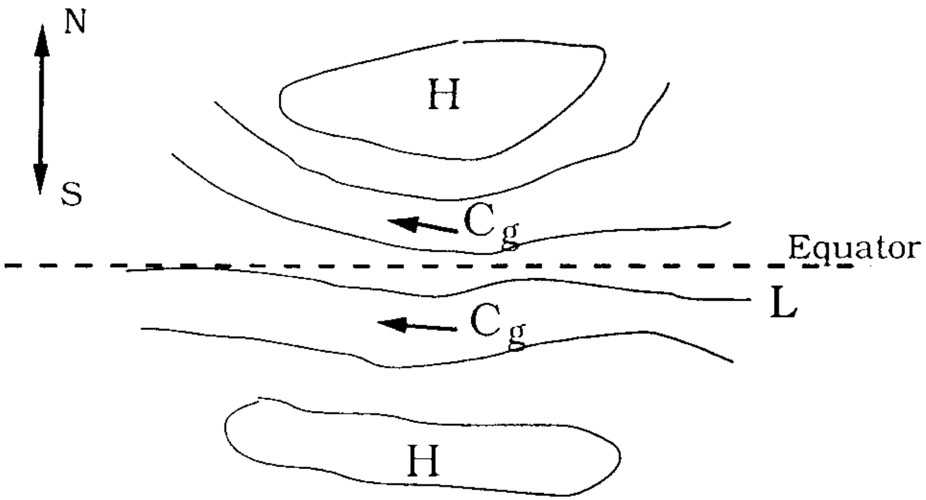
so

$$\left(2\,\vec{\Omega} \times \vec{c}\,\right)_{hor} \approx \left(-\frac{\nabla p}{\rho}\right)_{hor}$$

This is the *Geostrophic Balance*

Winds in the horizontal direction tend to blow parallel to lines of constant pressure (isobars)

Geostrophic Balance



General Circulation of the Atmosphere

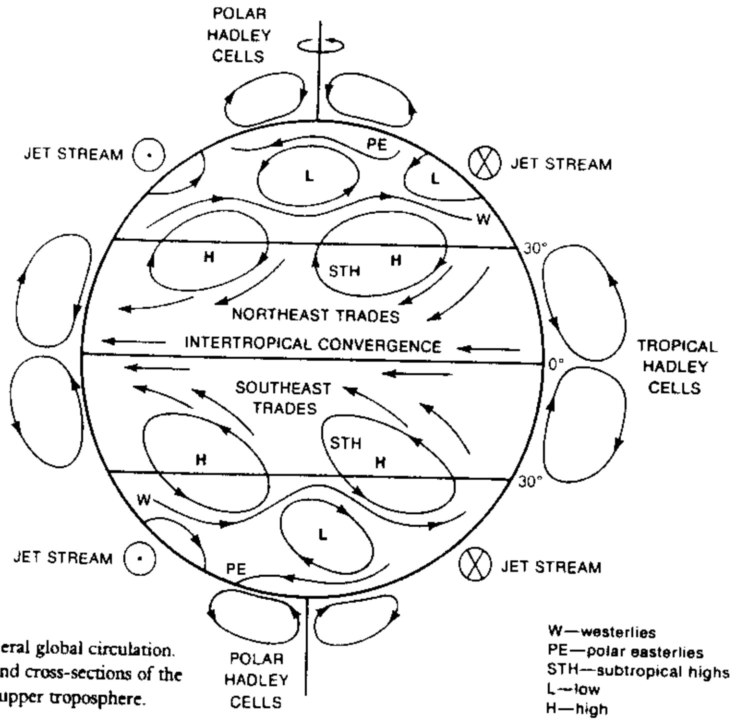


FIGURE 2-21

Main features of the general global circulation. Flows near the surface and cross-sections of the main circulations in the upper troposphere.

Models that simulate atmospheric circulation are known as "General Circulation Models of the Atmosphere" (GCMA's)

Atmosphere is divided

- vertically into discrete layers (2-11)
- horizontally into cells $(4^\circ - 8^\circ)_{latitude} \times (5^\circ - 10^\circ)_{longitude}$

Equations describing conservation of mass, energy, momentum solved within each grid cell.

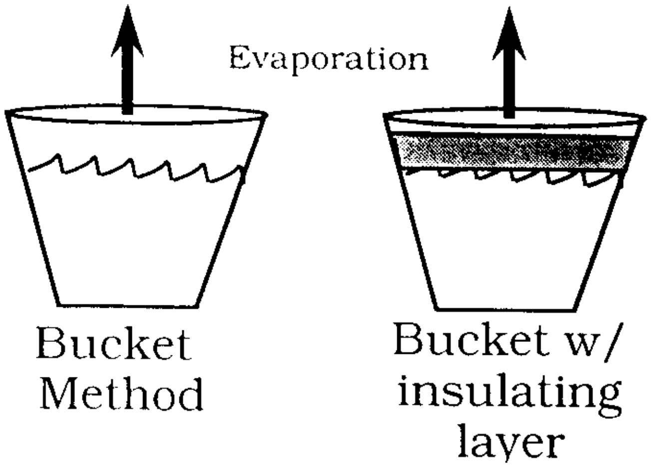
GCMA's treatment of Oceans

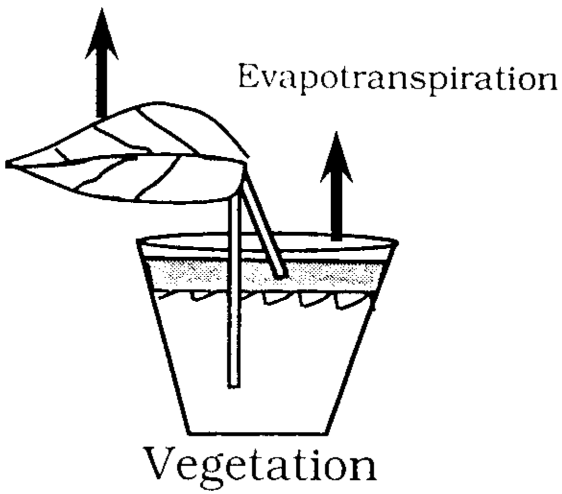
- Slab ocean, mixed layer only
- Heat transport vs. no heat transport

Treatment of oceans in GCMA's means

- Time lags between radiative forcing and change in surface temperatures (due to high oceanic thermal mass) are not well simulated.
- Regional differences in climate change due to ocean transport of heat are not well simulated.

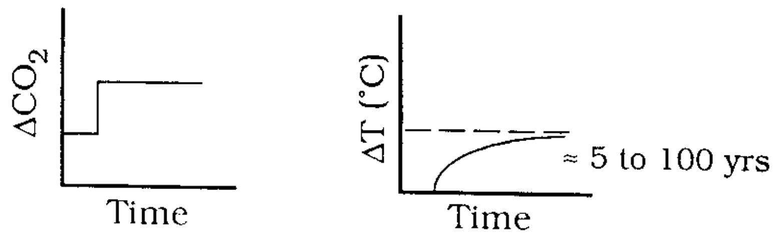
Soil Moisture and Vegetation



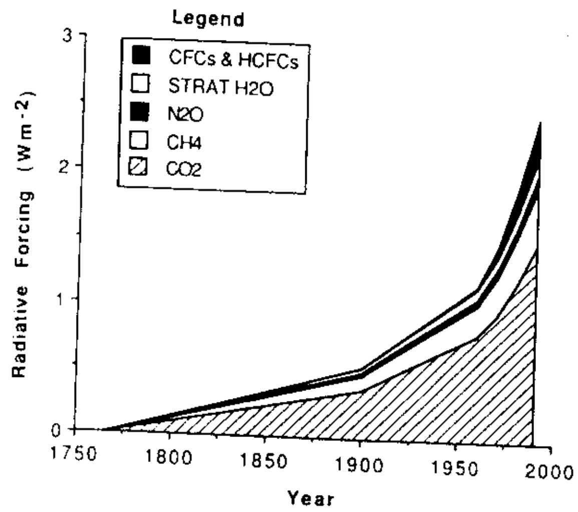


Types of Models and "Experiments"

- GCMA's



Equilibrium Response



Global Warming Potentials (GWP's)

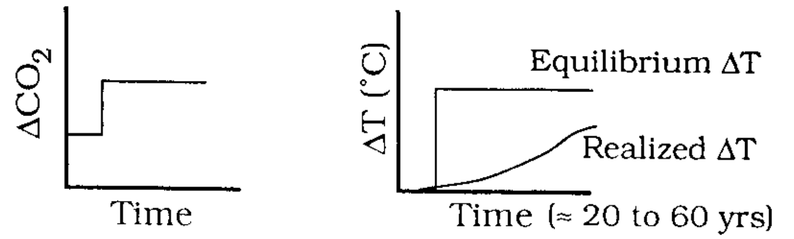
GWP's depend on

- position and strength of the absorption bands of the gas
- lifetime in atmosphere
- time period over which climate effects are of concern

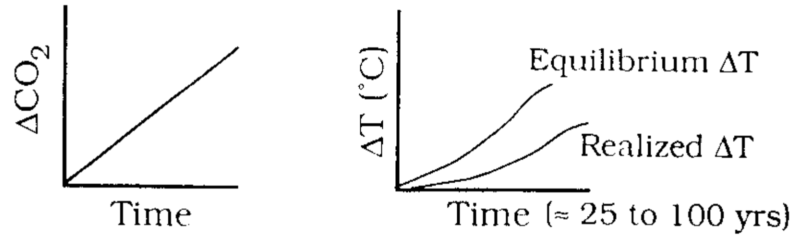
GWP's for release of 1 kg of each trace gas, relative to CO_2

Trace Gas	Estimated Lifetime, years	Global Warming Potential Integration Time Horizon, Years: 20	100	500
Carbon Dioxide	*	1	1	1
Methane - inc indirect	10	63	21	9
Nitrous Oxide	150	270	290	190
CFC-11	60	4500	3500	1500
CFC-12	130	7100	7300	4500

- Coupled Atmosphere-Ocean Models (GCMA's & GCMO's)



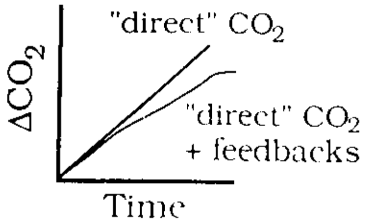
Transient Response

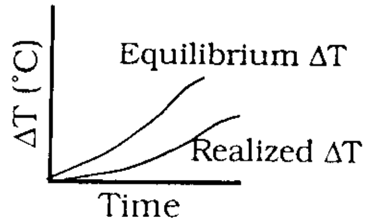


Time-dependent Response

(Reaching equilibrium for coupled ocean-atmosphere models would take hundreds to thousands of model years, and is beyond the capacity of current computers)

GCMA's and GCMO's with Carbon Budget Models (Ocean and Terrestrial)





Only about 50-60% of the carbon emitted each year from fossil-fuel use and deforestation remains in the atmosphere (airborne fraction). Rest is dissolved in the ocean or taken up by the biosphere.

Components of a coupled atmosphere-ocean-biosphere model

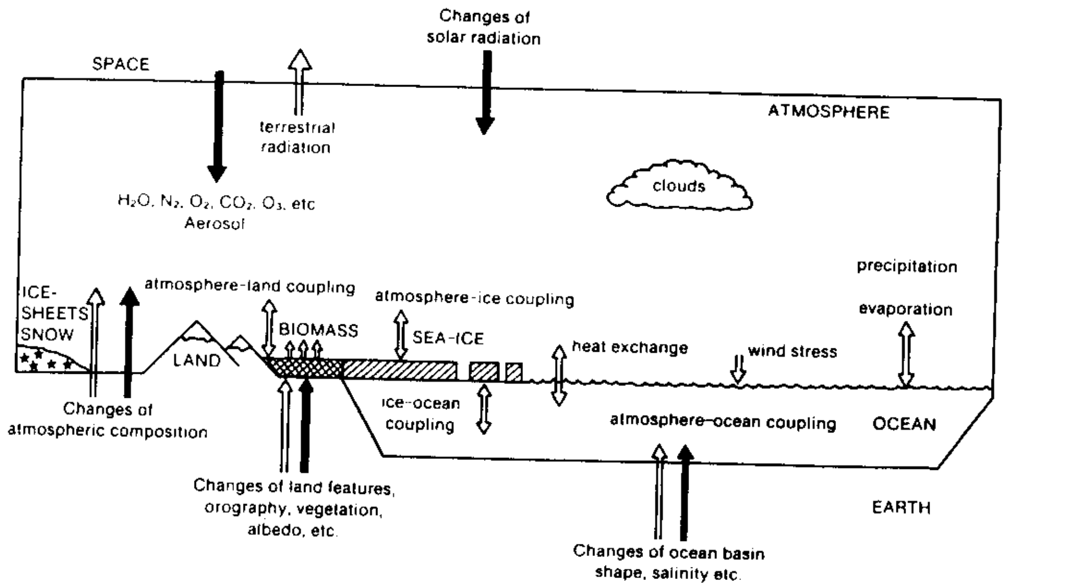
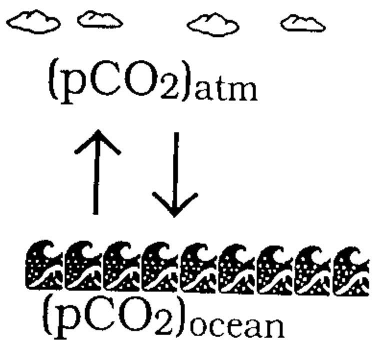


Figure 3.1: Schematic illustration of the components of the coupled atmosphere-ocean-ice-land climatic system. The full arrows examples of external processes, and the open arrows are examples of internal processes in climatic change (from Houghton, 1984)

Ocean Storage of Carbon



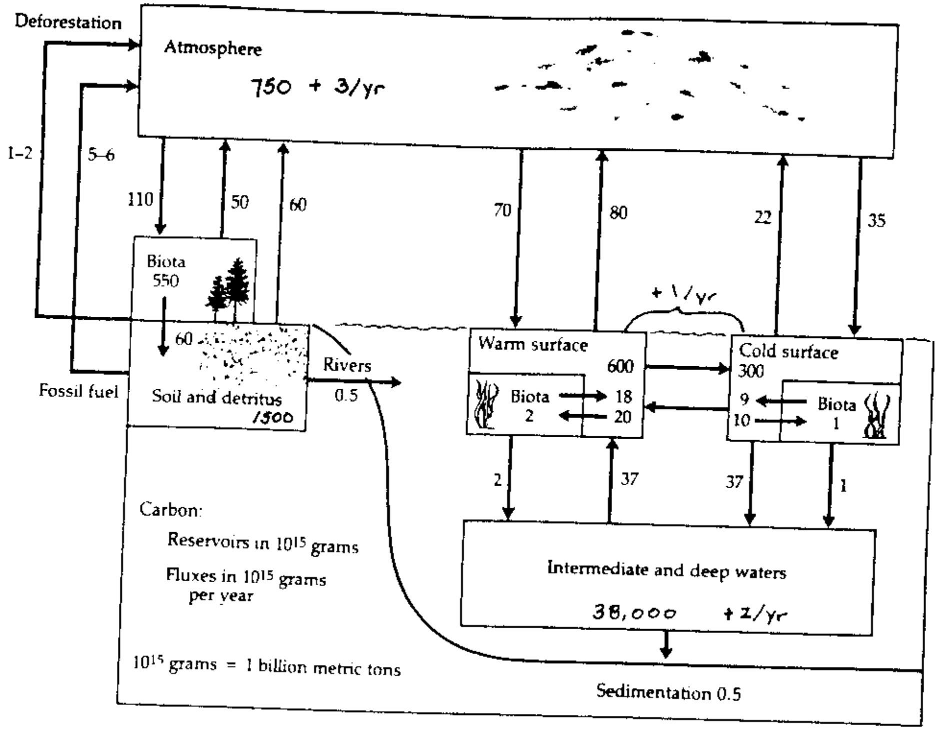
$CO_2(g) + H_2O \Leftrightarrow H_2CO_3\ (aq)$ (dissolved CO_2)

$H_2CO_3\ (aq) \Leftrightarrow H^+ + HCO_3^-$ (carbonate)

$HCO_3^- \Leftrightarrow H^+ + CO_3^{2-}$ (bicarbonate)

Total Dissolved Inorganic Carbon (DIC) =
$[H_2CO_3]$ + $[HCO_3^-]$ + $[CO_3^{2-}]$
(0.5%) (88.8%) (10.7%)

The Global Carbon Cycle



Units are gigatons of carbon (GtC: 1 Gt = 10^9 metric tonnes = 10^{12} kg)

- Oceans have 98% of the total ocean + atmosphere stock of CO_2

<u>Distribution of DIC in the Oceans</u>

DIC ≈

2050 - 2080 mmol/kg mixed layer

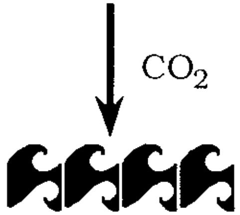
2160 - 2360 mmol/kg deep ocean

Differences in DIC between shallow and deep ocean due to

- "Solubility pump" (≈10% of difference)
- "Biological pump" (≈90% of difference)

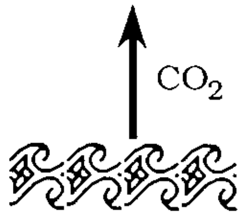
Solubility pump

Cold, dense water
High solubility of CO_2



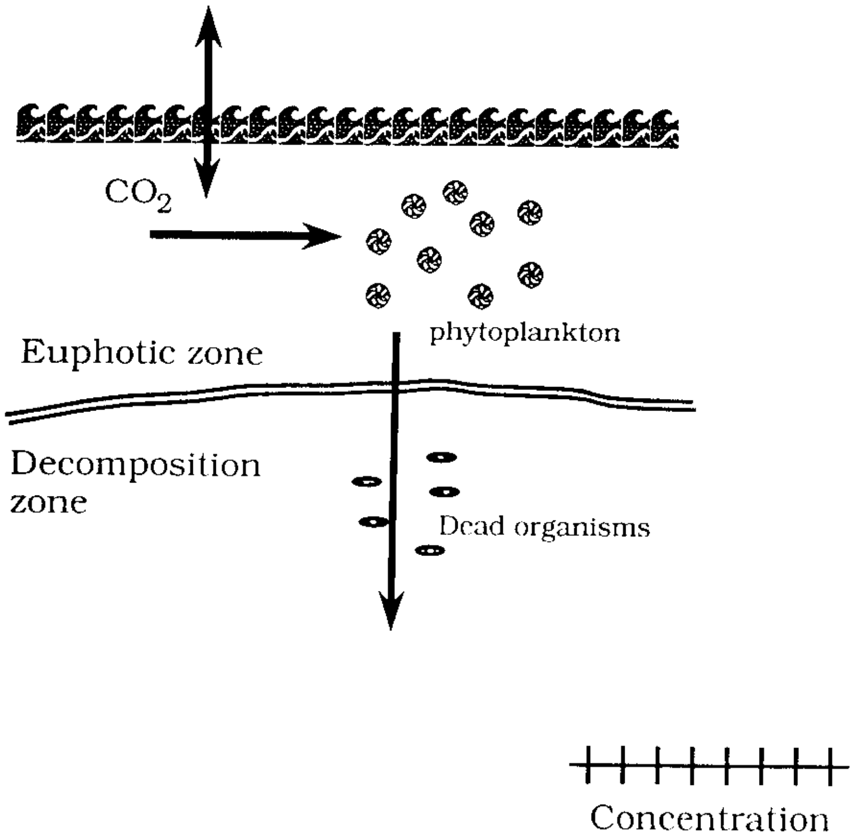
North Atlantic

Warm water
Low solubility of CO_2



Equatorial Pacific,
northern Indian Ocean

The Biological Pump

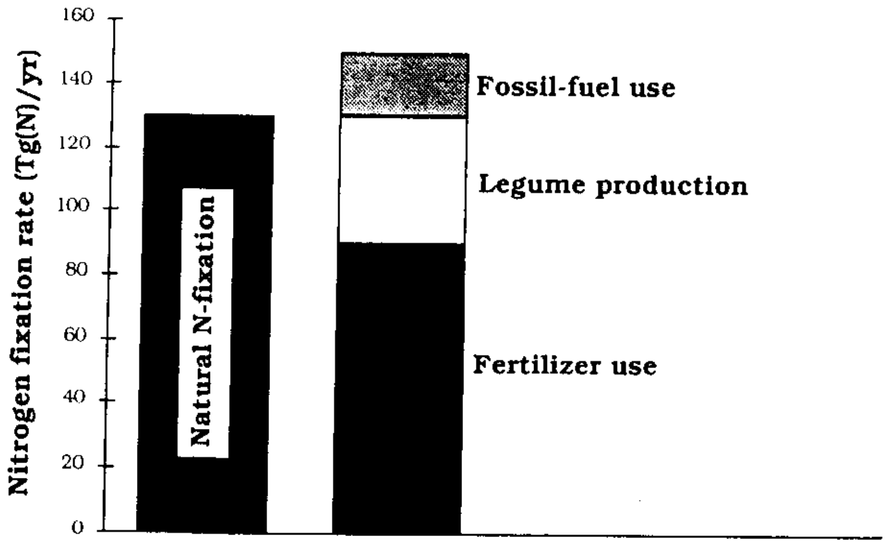


The Biological Pump could change due to . . .

- Changes in upwelling, ocean currents

- Anthropogenic effects on phytoplankton (e.g., ozone, nitrogen fertilization)

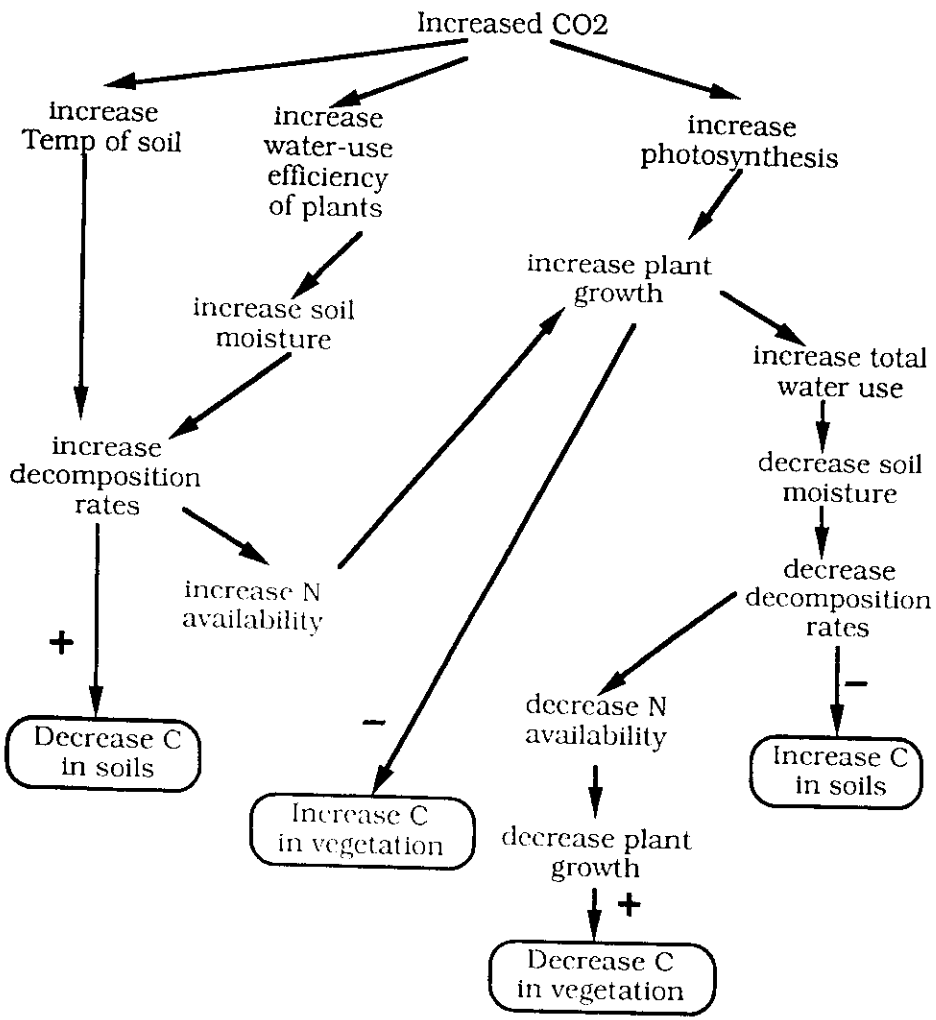
Anthropogenic Nitrogen Fertilization



Biological Pump Feedback

	pCO_2 (ppmV)
IPCC "Business as Usual" Scenario	785
Biological pump "off" in Southern Ocean (south of 31.12 °S)	955
Biological pump at full strength	670

Terrestrial Carbon Cycle Feedbacks



The terrestrial biosphere may be sequestering additional carbon due to. . .

- increased availability of CO_2
- increased availability of fixed nitrogen
- increased temperatures

The GEM model

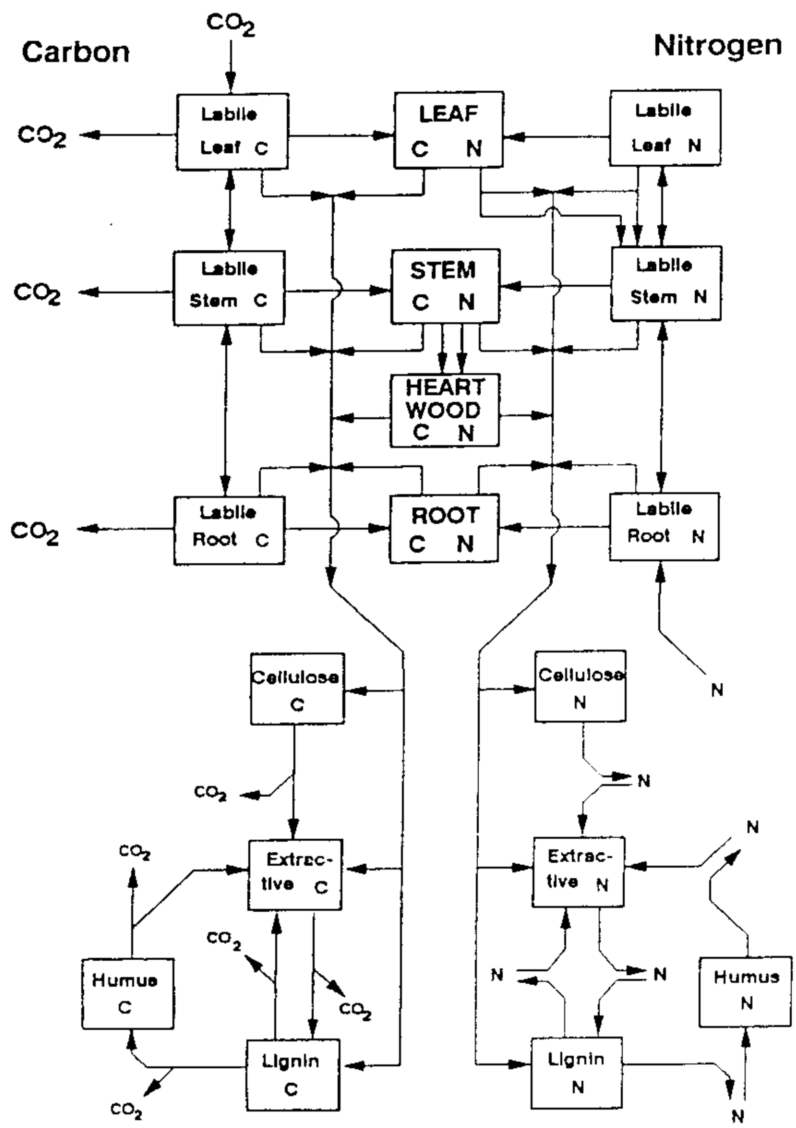


Figure 1. Schematic diagram of a general model of carbon and nitrogen cycles within terrestrial ecosystems. Equations for the model processes are given in Appendix 3.

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Results of the GEM analysis

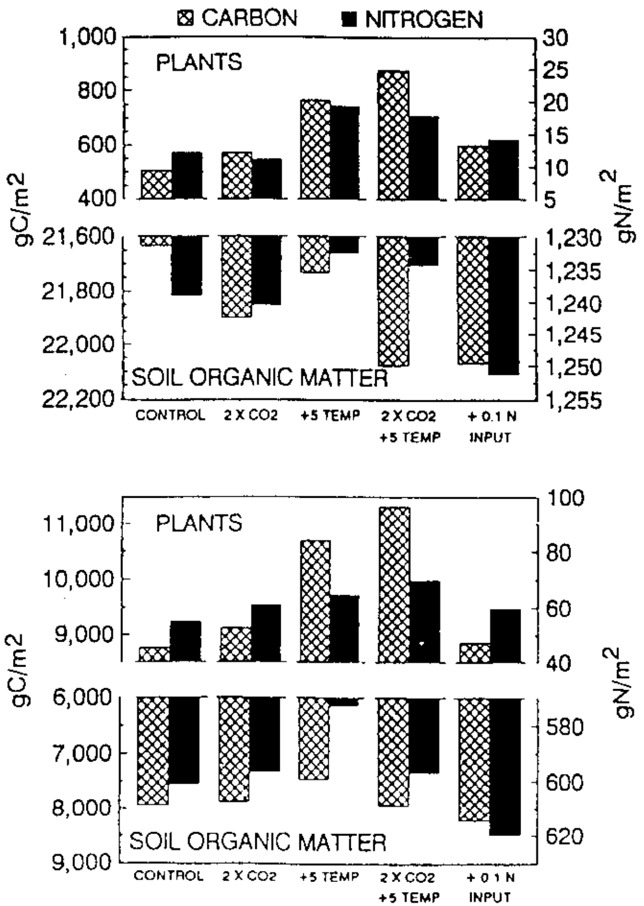


Figure 4. Simulated plant and soil stocks of carbon and nitrogen in arctic tundra (upper graph) and temperate hardwood forest (lower graph) after exposure for 50 years to a doubling of CO_2 concentration, a 5 °C increase in temperature, a combined CO_2 and temperature increase, and an increase in nitrogen deposition of 0.1 N m^{-2} $month^{-1}$ over the growing season.

Estimated Sources and Sinks of Methane (CH_4)

	Tg (10^{12} g) CH_4 per year
Sources	**475**
Natural	*155*
• Wetlands	115
• Termites	20
• Ocean	10
• Freshwater	5
• CH_4 Hydrate	5
Anthropogenic	*360*
• Coal mining, natural gas, & petroleum industry	100
• Rice paddies	60
• Enteric fermentation	80
• Animal wastes	25
• Domestic sewage treatment	25
• Landfills	30
• Biomass burning	40
Sinks	**500**
Atmospheric removal	470
Removal by soils	30
Sources - Sinks	**– 25**
Atmospheric Increase	**32**

Estimated Sources and Sinks of Nitrous Oxide (N_2O)

	Tg (10^{12} g) N per year
Sources	**5.2-14.2**
Natural	*4.2-8.5*
• Oceans	1.4-2.6
• Wet Tropical Forests	2.2-3.7
• Dry Tropical Savannas	0.5-2.0
• Temperate Forests	0.05-2.0
• Grasslands	?
Anthropogenic	*1.0-5.7*
• Cultivated Soils	0.03-3.0
• Biomass Burning	0.2-1.0
• Stationary Combustion	0.1-0.3
• Mobile Sources	0.2-0.6
• Adipic & Nitric Acid Production	0.5-0.8
Sinks	**7-13**
Removal by soils	?
Photolysis in Stratosphere	7-13
Sources - Sinks	**-0.3**
Atmospheric Increase	**3-4.5**

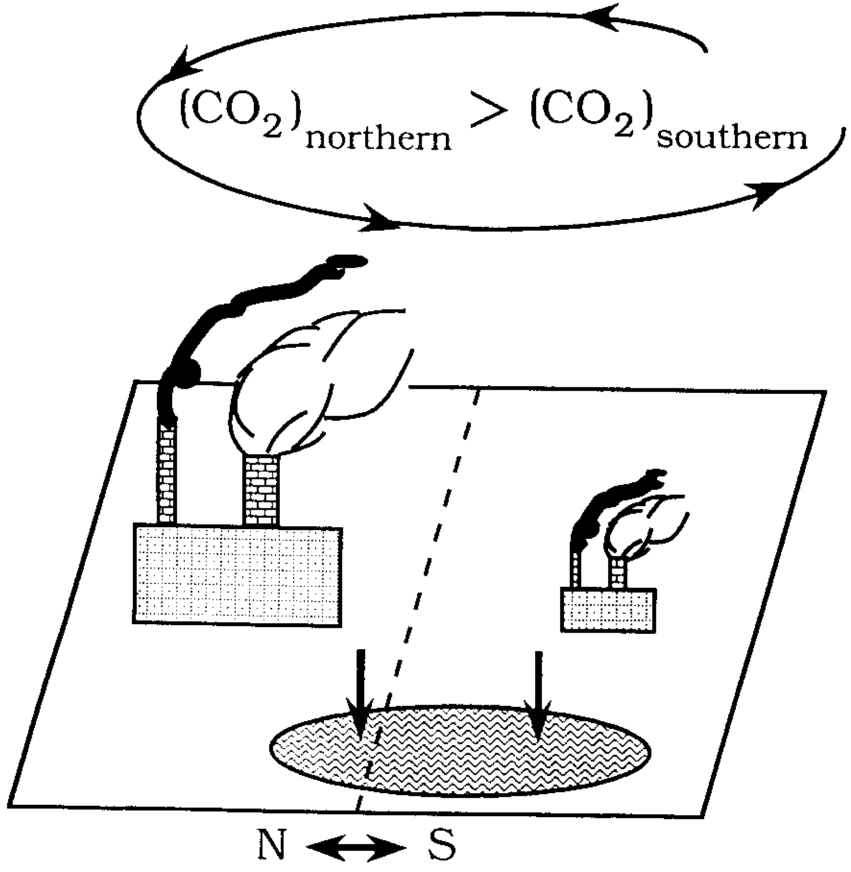
Estimated Sources and Sinks of Anthropogenic CO_2

	Pg (10^{15} g) C per year
Sources	**7.0 ± 1.2**
• Fossil-fuel burning	5.4 ± 0.5
• Changes in land use	1.6 ± 1.0
Sinks	**5.2 ± 0.6**
Atmosphere	3.2 ± 0.1
Oceans	2.0 ± 0.6
Missing Sink	**1.8 ± 1.3**

How do we "balance" the CO_2 budget?

- Interhemispheric differences in CO_2
- Carbon Isotopes
- Oxygen content of atmosphere

Interhemispheric differences in CO_2



• N-S difference in CO_2 is only about 3 ppm, smaller than would be expected with known sources and sinks.

(Interhemispheric mixing time for gases ≈ 1 year)

Carbon Isotopes

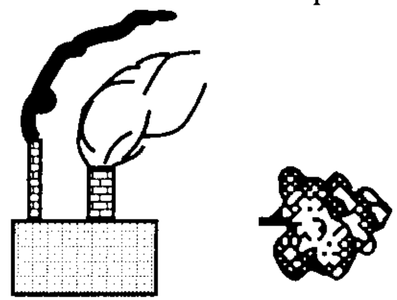
Increases $^{13}C/^{12}C$
in the atmosphere

⇓ CO_2

$^{13}C/^{12}C$ in the
atmosphere **unchanging**

⇑ ⇓ CO_2

Lowers the $^{13}C/^{12}C$ ratio
in the atmosphere



Oxygen content of atmosphere

Increases O_2 content
of the atmosphere

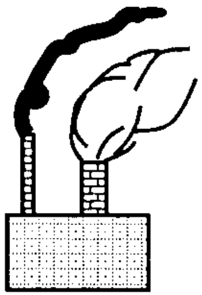
⇓ CO_2

$CO_2 + H_2O$ -->
$CH_2O + O_2$

O_2 content of the
atmosphere **unchanging**

⇑ ⇓ CO_2

Lowers O_2 concentration in atmosphere



$CH_y + (1 + y/4)O_2$ -->
$y/2\ H_2O + CO_2$

$CH_2O + O_2$ -->
$CO_2 + H_2O$

Oxygen Content of the Atmosphere

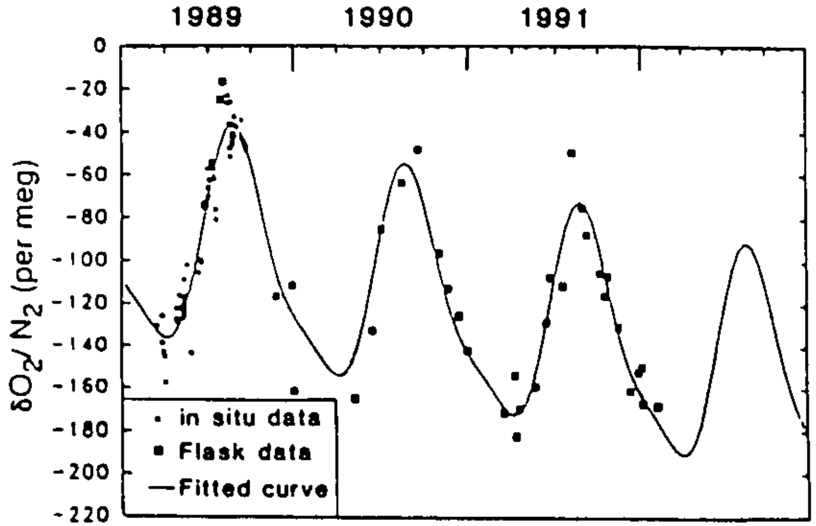


Fig. 16. O_2/N_2 ratio in air at La Jolla, California vs. time from 1989–1992. Units of per meg are defined in the text. The ratio increase in the summertime as land and marine plants grow, producing O_2, and falls in the winter due to respiration. Note the long term decrease in the O_2/N_2 ratio of air, which mainly reflects anthropogenic consumption of O_2 due to the burning of fossil fuels.

What are the causes and consequences of climate change?

• Scientists are certain that human activities are increasing greenhouse gas concentrations in the atmosphere.

• Scientists are reasonably certain that these increases in greenhouse gases will on result on average in additional warming of the Earth's surface (above and beyond the "natural" greenhouse effect)

How much warming can we expect?

• IPCC "Business-as-Usual" scenario results in warming of 0.3 °C per decade over the next century (0.2 °C to 0.5 °C per decade) greater than any rate of warming seen over the past 10,000 years.

• Even with relatively draconian measures (shift to renewables and nuclear reduced CO_2 emissions to 50% of 1985 levels by 2050) we can expect a warming of about 0.1 °C per decade.

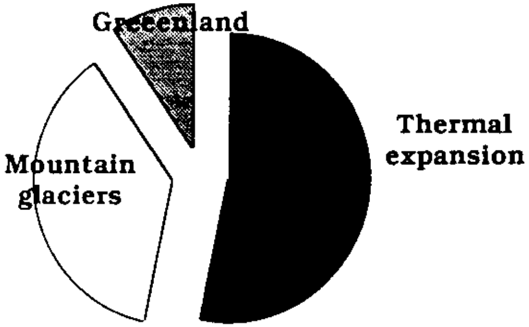
• Land surfaces warm more rapidly than oceans, high northern latitudes warm more than global mean in winter.

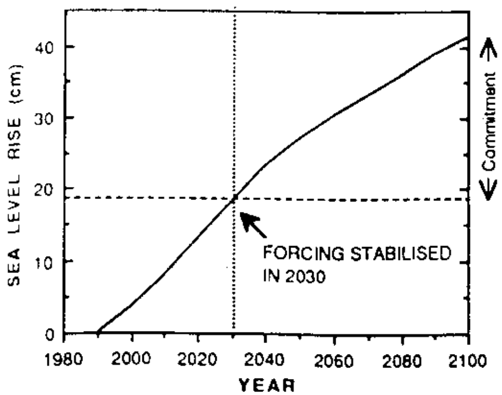
• Faith in regional predictions of climate change is low

Sea Level Rise

• Scientists are nearly certain that warming of the Earth's surface will lead to a rise in sea level

•≈ 20 cm rise in sea level by 2030 under "Business as Usual" IPCC scenario, 65 cm rise by end of next century.





Other potential consequences of an increase in Earth's surface temperature include. . .

• Regional changes in precipitation and soil moisture

• Increased variability of climate

• Increased frequency of tropical storms (develop over warm seas)

• Decreased frequency of mid-latitude storms (depend on equator to pole temperature contrast)

• Changes in ecosystems

Some difficulties in predicting changes in ecosystems. . .

- Difficulty of obtaining direct field evidence of effects on entire ecosystems of elevated CO_2 and/or temperature (most studies have been carried out on single trees or seedlings)

- Potential for disruption of community composition affecting ecosystem response

- Mismatch between scale of ecological studies and climate models (most ecological studies carried out on area the size of a tennis court, resolution of most climate models approximately the size of Senegal)

Major Uncertainties?

- Sources and sinks of greenhouse gases

- clouds (feedback effects)

- oceans (timing and pattern of climate change)

- polar ice sheets (sea-level rise)

Future Emissions of CO_2

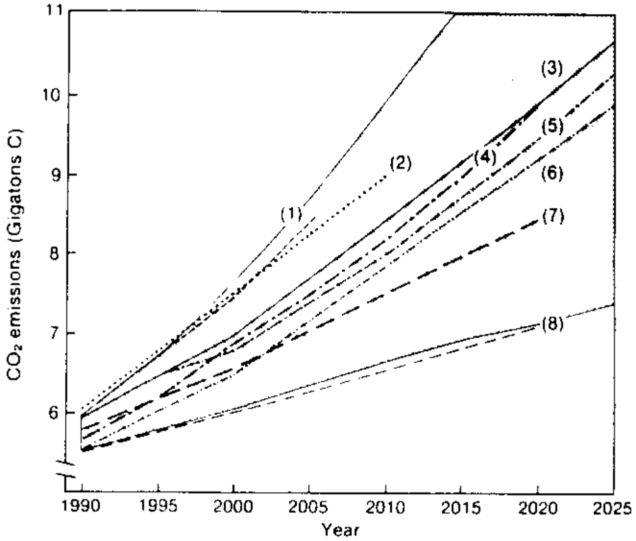


Figure A3.3: Comparison of CO_2 emissions from fossil fuels out to AD 2025 according to: (1) IEA; (2) CEC; (5) IS92b; (6) SA90; (7) the World Energy Conference (WEC) "moderate" and (8) "low" scenarios. The shaded range of the IS92 scenarios

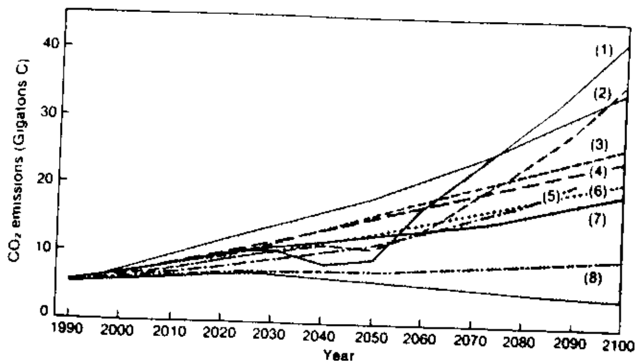


Figure A3.4: Comparison of CO_2 emissions from fossil fuels according to longer-range scenarios: (1) CETA; (2) CRTM-RD; (3) Manne & Richels; (4) EPA (RCW); (5) Edmonds/Reilly; (6) SA90; (7) IS92a, and (8) EPA (SCW). The shaded area indicates the range of the IS92 scenarios.

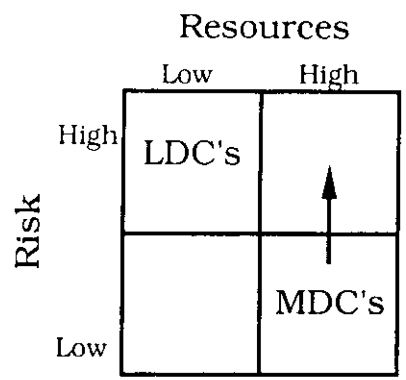
Coming to the Table? Risks, Priorities, and Resources

More-Developed Countries

- The role of service economies and capital in mitigating the impacts of climate change

Less-Developed Countries

- Development as a priority
- Lack of resources



At the Table. . .

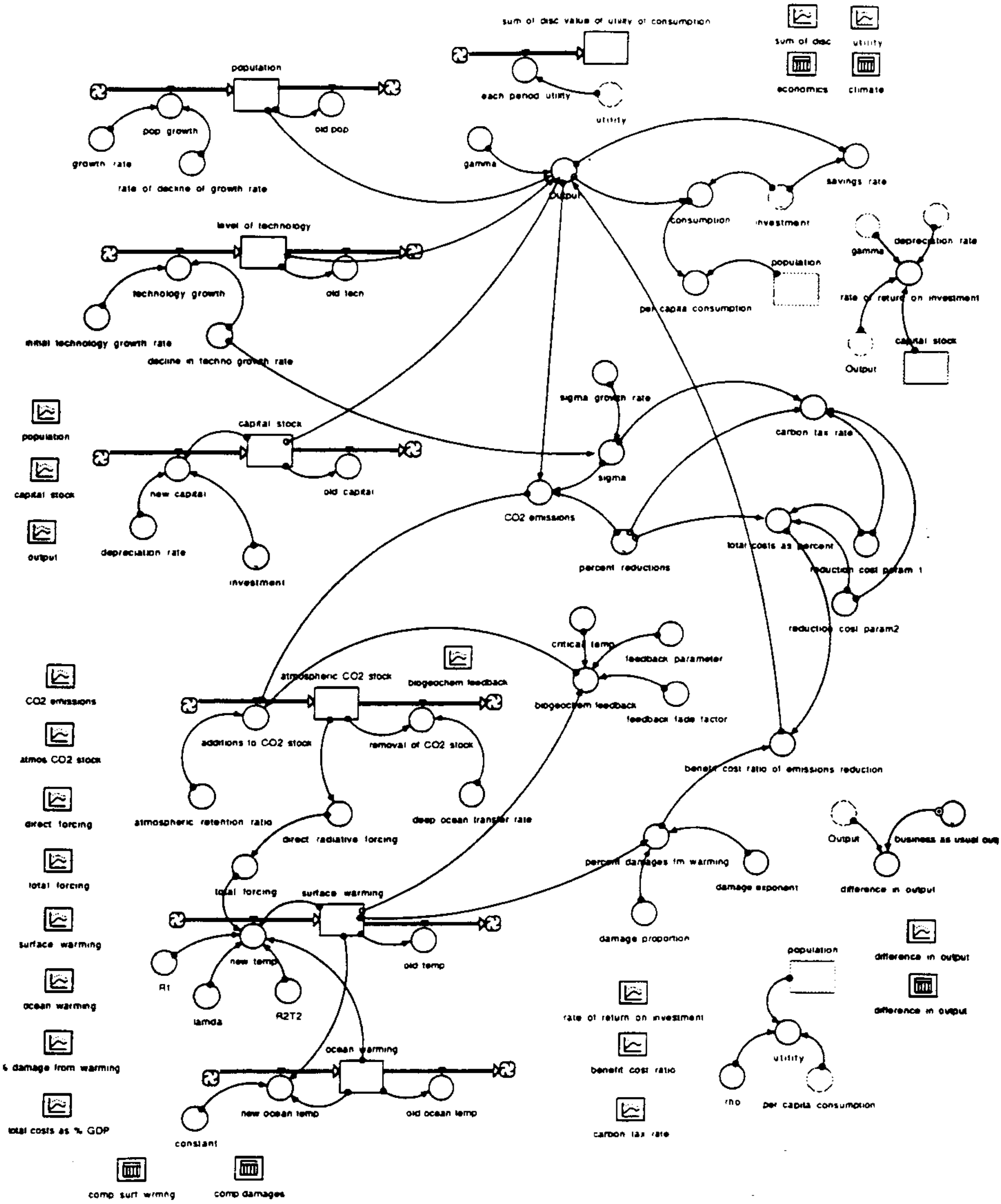
• Who is responsible: past vs. future emissions

Is it "worth it" to reduce greenhouse gas emissions?

• "No-cost" policies to reduce greenhouse gas emissions (e.g., energy efficiency, land reform)

• Pay now vs. pay later

DICE Model



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How much do we value the future and what do we value about it?