mast602

Lecture 2

Earth's heat balance

Air-sea transfer of heat
Solar radiative energy
Back radiation
Latent & sensible heat fluxes
The greenhouse effect
The carbon cycle

MAST 602

Lecture 2
Earth’s heat balance

Air-sea transfer of heat

Ref.: KNAUSS, Chapter 3

Heat enters the ocean across the sea surface.
(except for imperceptible flow
from the center of Earth)

The ocean is in steady state.
It doesn't change with time (approximately).

So…
…heat entering ocean = heat leaving ocean.

Major sources (and sinks) of heat
for Earth, and thus for the ocean, are:

Radiation from the sun
(shortwave) Q_s

Radiation to the atmosphere
(longwave) Q_b

Evaporation
(latent heat) Q_e

Sensible exchange
(conduction) Q_h

Heat gain
(surface layer storage) Q_T

Advection of heat
(ocean currents) Q_v

Steady state thus implies that globally:

$$Q_s = Q_b + Q_e + Q_h$$

(Q_v and Q_T average out to zero, globally.)

Locally, these terms *don't* need to balance.

Why don't Q_v and Q_T need to balance locally, but do average out to zero, globally?

Let Q_T be the storage or release of heat in the surface layer.

Then,

$$Q_T = Q_s - Q_b - Q_e - Q_h - Q_v$$

We will, in turn, look at each of these individual terms.

Solar radiative energy, Q_s

All bodies radiate heat

The sun is a gray body, with an emission temperature ~ 5780K.

The radiative emission per unit area is

$$Q = c_S K^4 \qquad \text{(Stefan-Boltzmann Law)}$$

where $c_S = 5.6707 \times 10^{-8}$ W m^{-2} K^{-4}

(K = °C + 273°) [absolute temperature]

The wavelength of maximum emission is

$$\lambda_{max} = \frac{c_w}{K} \qquad \text{(Wien's Law)}$$

where $c_w = 2.8978 \times 10^6$ nm K

For the sun, $K = 5780$K
so λ_{max} =501 nm.
(~ 0.5 μm
or 0.5 x 10^{-6} m)

So, at the top of the atmosphere, the solar irradiance according to Stefan-Boltzmann is

$s = 1.487$ kW m^{-2}

i.e.,

$$s = c_s K^4 \frac{R_s^{\ 2}}{R_{es}^{\ 2}}$$

where R_s = radius of sun
= 6.96×10^8 m

and $R_{es} = 1.49598 \times 10^{11}$ m
= 1 astronomical unit
= earth-sun distance

But the sun is *gray*, not *black*,
so in reality, the solar irradiance
at the top of the atmosphere is:

$s = 1.360$ kW m^{-2}

The total energy received by Earth is
$\pi R_e^2 s$

But Earth's surface area is

$4 \pi R_e^2$ [PPT 1]

So the amount arriving on average
is 340 W m^{-2}

But some energy is
reflected back to space (~30%)

So the average value absorbed by Earth
(including the atmosphere) is
241 W m^{-2}.

Maximum of radiation ~ 500nm. "shortwave" radiation

49% of energy is in visible,
400 ⇒ 700 nm 1 nm = 10^{-9} m

Fig 2- 1 Spectral distribution curves for the sun (Peixoto and Oort 1992), Fig. 6.1

> Which atmospheric gas absorbs the most
> solar irradiation over this spectrum?

9 %	is in the ultraviolet
42 %	is in the infrared
99 %	< 4000nm

Fig 2- 2 Solar radiation varies with season. **Knauss, Fig. 3.2**

> Why does there seem to be more radiation in the southern summer than in the northern summer?
>
> Notice that there are two annual maxima in equatorial regions.

In the atmosphere, radiant energy is
—scattered ⇒ becomes diffuse
—absorbed

~ 75% reaches Earth's surface,

giving typical values of $Q_s \sim 180$ W m^{-2}

Scattering

Scattering takes place through interactions with molecules, aerosols, dust, water vapor,…
It's selective, according to wavelength.

Rayleigh scattering,
is proportional to λ^{-4} where λ = wavelength

e.g., for blue light, $\lambda_{blue} = 400$nm
this is 10 × more effective than red light,
where $\lambda_{red} = 700$nm

∴ the sky is blue.
we find the same effect in the ocean.

Greatest factor influencing Q_s is cloud cover.
— clouds normally cut off ~ 25%
— can reach 80%

Fig 2- 3 Total solar, annual Q_s **(Budyko 1974), Fig. 23**

> Watch out for the strange units in this series of charts! Annual values are 12× monthly.
>
> Why are the highest values over deserts?
>
> Why are there such low values south of Greenland and west of the Aleutians?

Albedo

Albedo is the percent of radiation reflected from a surface

Because it is reflected, it has the same frequency as the incoming radiation, i.e., shortwave radiation

For the ocean:

minimum	~ 3%
average	~ 6%
maximum	~ 30%

For sea ice, albedo is 30 ⇒ 40%

For fresh snow, albedo is ⇒ 90%

Albedo changes with season: [PPT 2]

- increases in N hemisphere winter due to increased snow cover
- increases in S hemisphere winter due to increased sea ice

Reflected energy is sometimes called Q_r [shortwave]

Do not confuse with back radiation, Q_b [longwave]

Incoming radiation is higher in the tropics than at the poles [PPT 3]

The imbalance is accentuated by the higher albedo found in high latitudes

Back radiation, Q_b

Average surface temperature of Earth, $T_e = 288\text{K}$

From Wien's law, $\lambda_{max} \sim 10{,}100\ \text{nm} = 10.1\ \mu\text{m}$

Recall that for the sun, $\lambda_{max} \sim 500$ nm ⇒ shortwave

But for Earth, $\lambda_{max} \sim 10{,}100$ nm ⇒ longwave

Fig 2- 4 Solar spectral irradiances **(Apel 1987), Fig. 2.2**

Note how much more of the back radiation is absorbed by atmospheric gases.

From Stefan-Boltzmann, back radiation from Earth is $c_s K^4$
~ 400 W m^{-2}

Compare this with the average received,
~ 241 W m^{-2}

Thus, the ocean's back radiation is nearly twice the incoming solar radiation.

If back radiation is 2× the incoming, why doesn't the ocean (Earth) lose all its heat?

Answer: clouds, water vapor:
…they absorb energy
…then they re-radiate some of
that energy back to Earth
} the "greenhouse effect"

the *effective* back radiation is
~ 40 - 60 W m^{-2}

Again, let's look at Budyko's charts:

Fig 2- 5 Radiation balance at surface, annual Q_s - Q_b **(Budyko 1974), Fig. 26**

Why are oceanic values generally greater than terrestrial values at the same latitude?

Evaporation, Qe (latent heat)

$Q_e = F_e L_t$

L_t is the ***latent heat of evaporation***

It takes $L_t \sim 2.453 \times 10^6$ Joules
to evaporate 1 Kg of water @ 20°C

F_e is the rate of evaporation of water,
in units of Kg s^{-1}
per m^2 of sea surface

On average, the ocean loses
~ 1.26 m of water per year (according to Budyko)

This corresponds to a typical value
for Q_e of 83 ⇒ 120 W m^{-2} (in tropics)

Thus, Q_e is the largest of the 3 heat-loss terms

To measure Q_e, we need to measure F_e.

Alas!
Estimates of Q_e aren't reliable.

A factor of two uncertainty
in measuring Q_e could be good.

Evaporation depends on:

- wind & mixing
- atmospheric stability
- air humidity

It can't be measured directly
over the sea; only approximate
techniques are available

The rate of transfer of moisture
depends on the wind speed

Transfer is related to shear:
that is, the difference in
wind speed between 10 m height
and the sea surface.

Evaporation, F_e, can be roughly
estimated by what is called
a "bulk formula":

$$F_e = c_e \, \rho_a \, W \, (e_w - e_a)$$

where:

e_a = vapor pressure in the air at a standard level
e_w = saturated vapor pressure at the sea surface
W = wind speed
(at standard level, ~ 10m height)
ρ_a = air density
c_e = dimensionless coefficient (Dalton number)
$\approx 1.5 \times 10^{-3}$

In practice, the bulk formula
is often simplified:

$F_e = 1.44\,(e_w - e_a)\,W$ units of W Kg

Using a bulk formula,
Budyko has produced charts of Q_e:

Fig 2- 6 Latent heat flux, annual Q_e (Budyko 1974), Fig. 29

Notice the extremes in the western Atlantic.
What processes may be responsible?

Fig 2- 7 Latent heat flux, December Q_e (Budyko 1974), Fig. 30

Note large values off Delaware in winter.
Why are these the largest values in the world? What processes are at work?

Fig 2- 8 Latent heat flux, June Q_e (Budyko 1974), Fig. 31

Why have the large values of December
virtually disappeared in June?

Sensible heat flux, Q_h

Sensible heat flux is due to
convection, conduction

i.e., the ocean gives heat directly
to the atmosphere. It increases
with wind speed, due to turbulent transfer

Again, this term is hard to measure.
But, values are ~ 10 - 15% of Q_e

This gives typical values for Q_h
of about 10 W m^{-2}

Q_h is much smaller than Q_e , so the
uncertainty in Q_h is not so critical

Sensible heat flux can be estimated
using a bulk formula:

$$Q_h = c_h \, \rho_a c_p W (T_w - T_a)$$

where:

Q_h = upward heat flux

$\rho_a c_p$ = heat capacity per unit volume of air

W = wind speed at standard level

T_w = sea-surface temperature

T_a = air temperature @ standard level

c_h = dimensionless coefficient

~ 0.83×10^{-3}	under stable conditions
~ 1.10×10^{-3}	under unstable conditions

The bulk formula for Q_h can be expressed more simply, as approximately

$$Q_h = 1.88 \, W (T_w - T_a) \qquad \text{in units of W m}^{-2}$$

Can we relate Q_h and Q_e, assuming the controlling processes are similar?

That assumption is the basis of the *Bowen ratio*:

$$R = \frac{Q_h}{Q_e} = 0.5 \frac{T_w - T_a}{e_w - e_a}$$

This ratio assumes identical vertical eddy diffusion coefficients for heat and water vapor

Q_e is estimated using the principal Q-terms:

$$Q_e = \frac{Q_s - Q_b - Q_T}{1 + 0.5\left(\dfrac{T_w - T_a}{e_w - e_a}\right)}$$

$$= \frac{Q_s - Q_b - Q_T}{1 + R}$$

Again, Budyko has estimated Q_h:

Fig 2- 9 Sensible heat flux, Q_h annual **(Budyko 1974), Fig. 32**

In general, values are higher over land than over the ocean. Why?

Fig 2- 10 Sensible heat flux, Q_h December **(Budyko 1974), Fig. 33**

Why large winter values off Delaware?

Fig 2- 11 Sensible heat flux, Q_h June **(Budyko 1974), Fig. 34**

Why is nothing apparently happening in the ocean off Delaware in summer?

To summarize, Budyko has prepared an annual chart, showing the balance of terms:

Fig 2- 12 Radiation balance, annual **(Budyko 1974), Fig. 37**

How do you generalize regions of positive and negative net radiation? Should the average over the whole Earth be zero?

Variations in incoming radiation

Over geologic time, there have been small changes in the pattern of the sun's radiation

a) Wobble in the axis of rotation

The axis today is inclined by 23.5° to the plane of rotation of Earth (giving the seasons) [PPT 4]

The tilt of the axis varies, from about 22.2° to about 24.5° with a period ~ 41,000 years

Greater axial tilt has the effect of increasing the amplitude of seasonal differences at high latitudes

At higher tilt, the summer-hemisphere pole is more directly pointed to the sun, increasing the solar radiation received

b) Precession of the elliptic

Earth's orbit is an ellipse, rather
than a circle

The major and minor axes of the ellipse
slowly shift through time [PPT 5]

This *precession* in the elliptical path
around the sun has a period ~ 23,000 yr

Currently, Earth is closer to the sun
in the Southern Hemisphere summer;
in 11,500 years, it will be closer
during the Northern Hemisphere summer

c) Eccentricity of the ellipse

The eccentricity of the ellipse describes
the degree of departure from a
perfectly circular orbit

Earth's eccentricity variations are concentrated
at two (irregular) periods,
one with a period ~ 100,000 yr
the other, at about 413,000 years [PPT 6]

These variations will alter the amount of
solar radiation received by Earth

Milankovitch cycles

Collectively, Earth's long-term orbital
variations produce variations in
solar radiation received by season
and by hemisphere

They are known as the *Milankovitch cycles*,

The tilt in the axis of rotation (~ 41,000 yr)
and the precession of the elliptic (~ 23,000yr)
are modulated by the eccentricity of
the ellipse

They appear to correlate with long-term
variations in climate

Earth’s surface temperature

Fig 2- 13 Global surface temperatures **Ref. NASA**

Top: January, 1989
Middle: July, 1989
Bottom: Temperature differences between
July & January

Here are some points to note:

January:

- Extreme cold over Siberia & northern Canada
- Southern hemisphere summer
- Hottest temperatures over Australia

July:

- Northern hemisphere summer
- Hottest temperatures ~ 30°N

July - January:

- Greatest differences in temperature over land
- Ocean temperatures rarely differ by more than 10°C
- Least temperature difference over equatorial ocean

Conclusions: The ocean shows the effect of its higher heat capacity

The greenhouse effect

The results described in this section assume that Earth’s heat is in steady state.
If the earth is not in steady state, there will be long-time changes

There is concern that such changes are now taking place

The *enhanced greenhouse effect*: raising of Earth's temperature by atmospheric gases and water vapor may be causing global warming.

Atmospheric trace gases are largely transparent to incoming shortwave radiation
But some of those same gases absorb longwave outgoing (back-)radiation.

For equilibrium, upward & downward fluxes must balance.

Let's look at a simple model that might help show this

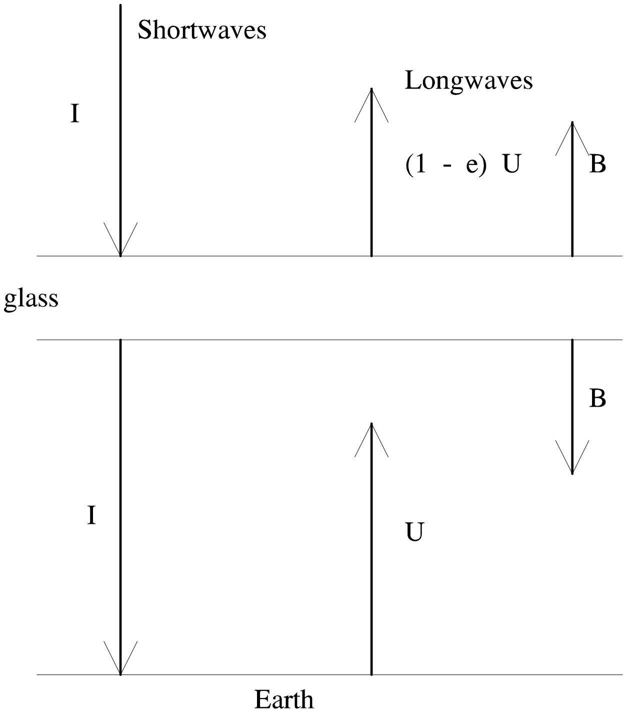

Fig 2- 14 A simple "greenhouse" model

Consider the radiation balance, in the above diagram, in which the atmosphere is represented as a sheet of glass which may absorb some longwave radiation:

$$I = (1-e)\, U + B = U - B$$

where

I is the incoming radiation,
U is the longwave upward radiation
B is the back longwave radiation from the glass
e is the percent of the outgoing longwave radiation absorbed by the glass
(the glass is transparent to incoming shortwave radiation)

Solving,

$$c_s T_G^4 = U = \frac{I}{1-\frac{e}{2}} \qquad \text{(using Stefan-Boltzmann)}$$

T_G , the ground temperature, is higher according to the absorption, *e*, of the glass.

If $e = 0$, all longwave radiation passes so that $B = 0$

If $e = 1$ all longwave radiation is absorbed) then $I = B$,

and the ground receives a flux of $I + B = 2I$

In the real atmosphere, “greenhouse” gases are continuously distributed, e.g., CO_2, methane, water vapor, …

These greenhouse gases could be considered to act as a sort of “glass” (though don’t push this simple sheet-of-glass model too far!)

However, increasing the concentration of greenhouse gases:

- closes the longwave (infrared) window (i.e., increases e in our model)
- thereby raising temperatures (i.e., T_G in our model)

Greenhouse gas concentrations in the atmosphere are increasing:

Fig 2- 15 Atmospheric CO_2 concentrations (Houghton, Meira Filho et al. 1996), Fig. 1

Exponential growth. Is this is likely to continue?

The increase of greenhouse gases is about: [PPT 7]

CO_2 ~ 0.5% /year
CFCs ~ 5% /year
CH_4 (methane) ~ 1% /year

Carbon emissions will likely continue to increase since they are linked to world population

Fig 2- 16 World Population (National Academy of Sciences 1992) Fig. 2.1

Exponential growth. Is this likely to continue?

[PPT 8]

Fig 2- 17 CO_2 emissions from long-range energy projections (Houghton, Meira Filho et al. 1996), Fig. 5

All estimates are that the concentration of radiatively important (greenhouse) gases in the atmosphere will continue to increase.

On the following page, we can see the details of increasing concentrations of atmospheric CO_2 for 3 stations (in parts per million by volume):

1. Barrow, Alaska, U.S.A., on the coast of the Arctic Ocean, 71°19' N, 156°36' W, 11 m above mean sea level
2. Mauna Loa, Hawaii, U.S.A., a barren lava field of an active volcano, 19°32' N, 155°35' W, 3397 m above mean sea level
3. South Pole, Antarctica, an ice- and snow-covered plateau, 89°59' S, 24°48' W, 2810 m above mean sea level

The annual series shows the steady increase in CO_2 concentrations due to the burning of fossil fuels.

Why do the highest values of annual variation occur on the North American continent at Barrow?

Why does the lowest annual variation occur at the South Pole?

Note the phase inversion between the Northern and Southern hemispheres.

(The Mauna Loa data series has breaks near the beginning because the funding agencies couldn't see value to such measurements.)

These data were produced by C.D. Keeling and T.P. Whorf, Scripps Institution of Oceanography, University of California, La Jolla, California 92093-0220, U.S.A. The data are kept up to date and may be obtained from the Carbon Dioxide Information Analysis Center at http://cdiac.esd.ornl.gov/trends/trends.htm

The monthly series show the influence of the annual cycle of vegetation, with winter increases due to respiration and summer decreases due to photosynthesis.

Fig 2- 18 Respiration and gross photosynthesis (Carbon Dioxide Assessment Committee 1983), Fig. 1.9

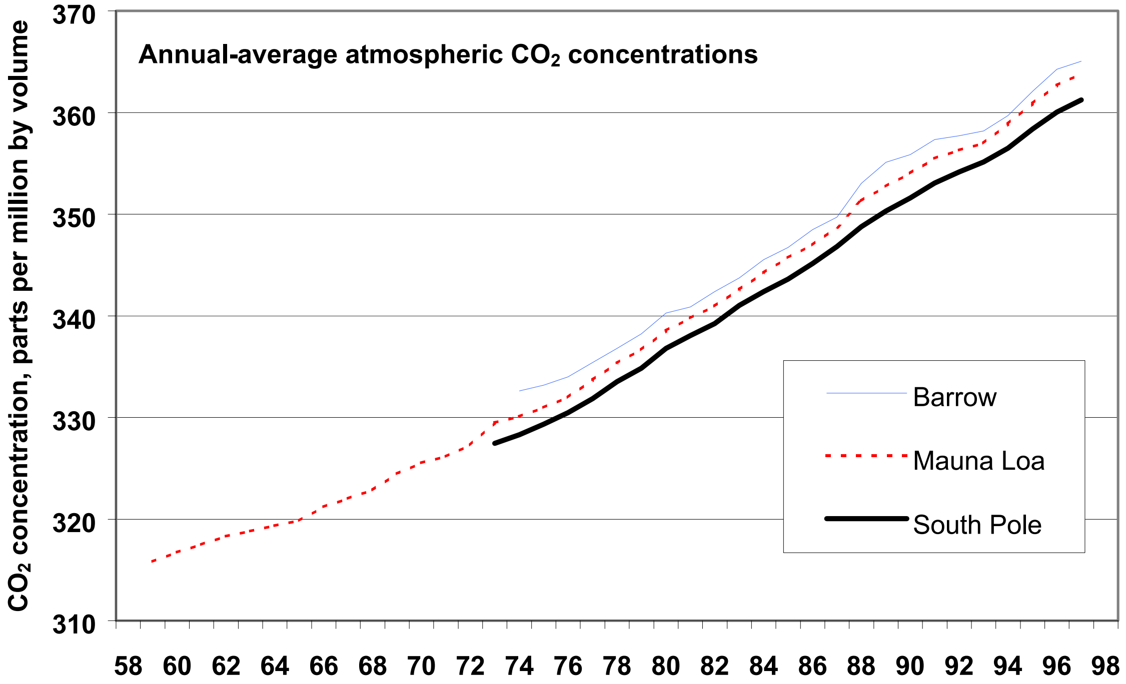

Fig 2- 19 Annual-average atmospheric CO_2 concentrations

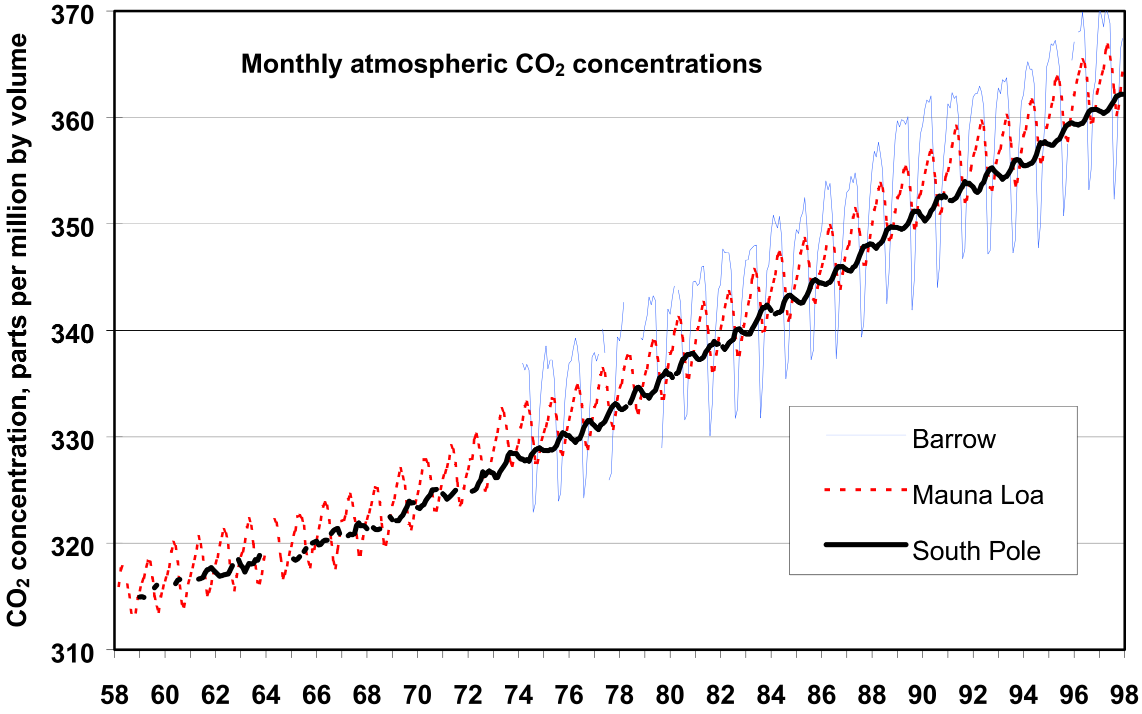

Fig 2- 20 Monthly atmospheric CO_2 concentrations

Other atmospheric constituents
also have a radiative influence.

Temperature effects of atmospheric constituents
((Carbon Dioxide Assessment Committee 1983), Table 1.4)

Constituent	**Mixing-ratio change (ppb)**		**Surface temperature change (°C)**
	From	**To**	
Carbon dioxide	300	600	2.0 - 3.0
Nitrous oxide	300	600	0.3 - 0.4
Tropospheric ozone	F (lat., ht.)	2F (lat., ht)	0.9
Water vapor	3000	6000	0.6
Methane	1500	3000	0.3
CFC-11	0	1	0.15
CFC-12	0	1	0.13
CFC-22	0	1	0.04
Carbon tetrachloride	0	1	0.14
Carbon tetrafluoride	0	1	0.07
Methyl chloride	0	1	0.013
Methylene chloride	0	1	0.05
Chloroform	0	1	0.1
Methyl chloroform	0	1	0.02
Ethylene	0.2	0.4	0.01
Sulfur dioxide	2	4	0.02
Ammonia	6	12	0.09

The Carbon cycle

The ocean is the largest reservoir of carbon

Reservoirs:

Atmosphere	~ 750 × 10^{15} Kg of Carbon
Oceans	~ 38,100 × 10^{15} Kg of Carbon
Terrestrial ecosystems	~ 2,190 × 10^{15} Kg of Carbon

The ocean plays a critical role
in the carbon cycle

Fig 2- 21 The global carbon cycle (Houghton, Meira Filho et al. 1995), Fig. 1.1

Note the relatively large exchanges between reservoirs, with much smaller net values.

The CO_2 numbers don't seem to balance, though...
Is there an "oceanic sink" for CO_2?

Emission from fossil fuels	4.7 GT C/yr
Emission from deforestation	1.7 GT C/yr
Total emission	6.4 GT C/yr
Ocean uptake	1.8 GT C/yr
Atmospheric accumulation	2.8 GT C/yr
Total uptake	4.6 GT C/yr

Is the "missing" 1.8 gigatons of carbon/year an oceanic sink?

Climate trends

[PPT 9

Fig 2- 22 Summary of observed climatic trends (Houghton, Ding et al. 2001) **[PPT 10, 11]**

The pattern of climate trends can be fit to models. Though some of the indicators don't have high confidence, the complexity of the pattern provides valuable model constraints.

Most models predict global warming , also a wetter world [PPT 12]

Is Earth warming?
= it seems to be:
~ 0.5˚C over the past 120 years:

Be cautious with the data used in plots like the one on the next page! The measurements may not be consistent over the period of observation due to:

- changes in measurement techniques (e.g., buckets ⇒ injection, for sea-surface temperature)
- increasing urbanization
- expansion of population into more hostile climatic regions

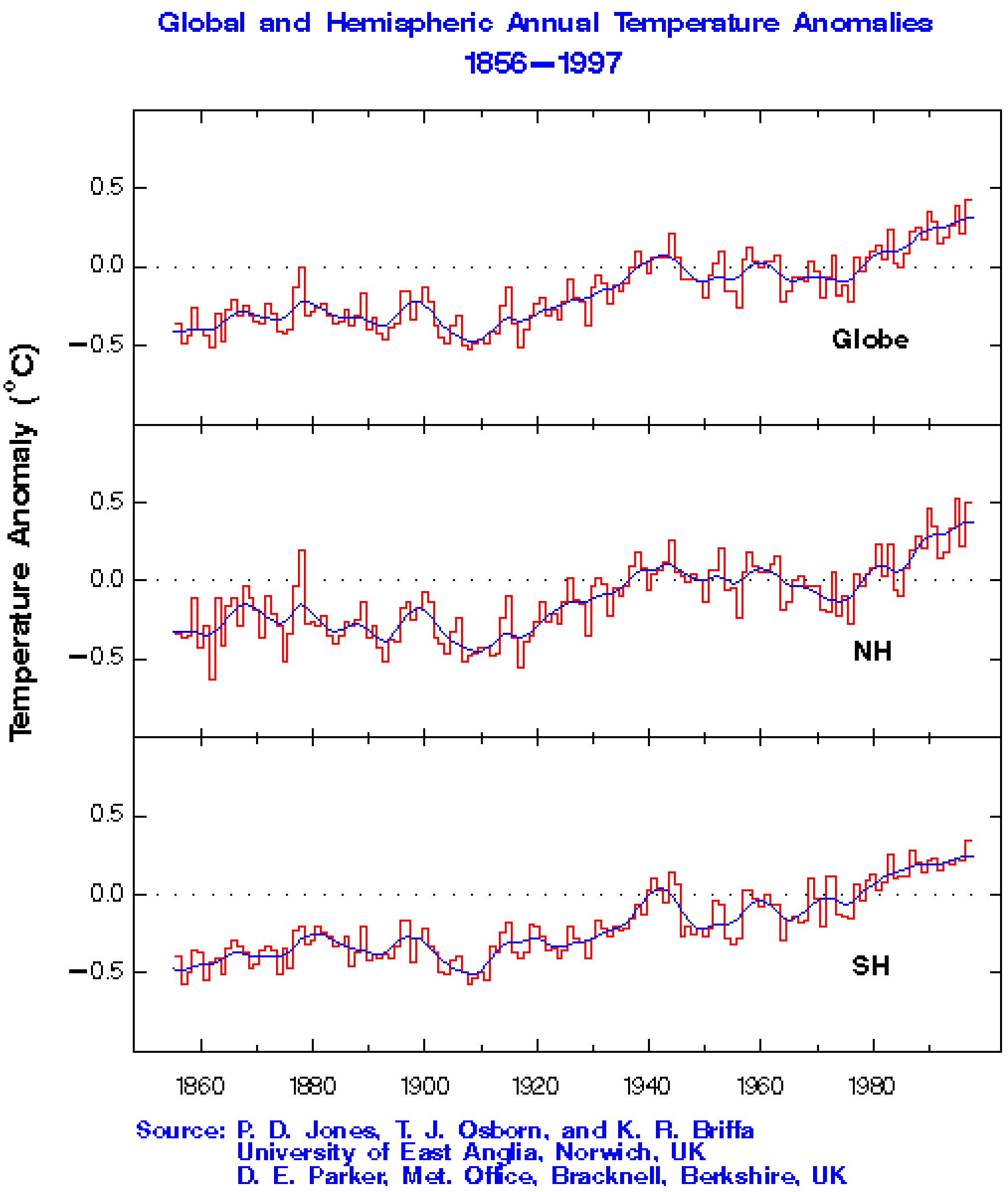

Fig 2- 23 Global and hemispheric annual temperature anomalies over the past century
(This figure from: http://cdiac.esd.ornl.gov/trends/temp/jonescru/jones.html)

Summary: what we know for sure

What do we know for sure
about greenhouse warming?

1. Concentrations of greenhouse gases are increasing.
2. The release of CO_2, methane,… will continue.
3. Most models predict a warmer, wetter world.
4. Observed warming:
   - Global-average surface temperature has increased over the 20th century by about 0.6° [PPT 13]
   - Snow cover and ice extent have decreased

The "official" word

According to the 2001 report of the Intergovernmental Panel on Climate Change (IPCC) [http://www.ipcc.ch/] (Houghton, Ding et al. 2001):

- There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities
- Human influences will continue to change atmospheric composition throughout the 21st century
- Global average temperature and sea level are projected to rise
- Anthropogenic climate change will persist for many centuries

The IPCC conclusion:
"In the light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations."

A "contrarian" view

In the views of S. Fred Singer, (Singer 1997)

- "…the evidence is neither settled, nor compelling, nor even convincing. On the contrary, scientists continue to discover new mechanisms for climate change and to put forth new theories to try to account for the fact that global temperature is not rising, even though greenhouse theory says it should."
- "…there are some half-dozen plausible mechanisms that could account for the fact that—despite computer predictions of a major warming trend—no significant global warming has been observed in the last half-century, and none at all in the last two decades. No one knows which of these mechanisms, if any is correct…"

Sea-level rise

Fig 2- 24 Sea level during the past 160,000 years (Carbon Dioxide Assessment Committee 1983) Fig. 8.1

Sea level has risen more than 100 m over the last 160 centuries.

Sea level has been rising
  - about 1-2 mm/yr over the last century
  - there's no clear sign of acceleration

Sources of sea-level rise
  1. glacier melting
  2. upper ocean expansion

Greenland will have a mixed effect :
there will be some melting,
but there will also be
increased accumulation in higher regions

Antarctica probably will have a negative effect:
increased accumulation due to warming?

Sea-level rise over the next century could be:

Alpine glaciers & Greenland	~40cm
Upper ocean expansion	~30cm
Total	~70cm

Thus, the increase in sea level
over the next century
could likely be < 1m.

What about other sources of sea-level rise
that aren't included in the above estimate? [PPT 14]

There is concern over possible instability
of the West Antarctic Ice Sheet

Fig 2- 25 West Antarctic Ice Sheet

Floating ice is "pinned" by rock below sea level.

Global warming might eventually
cause enough melting to make the
ice sheet unstable and break up.

The melting of the West Antarctic Ice Sheet
⇒ several meters (maybe 3 - 6m rise?)

Such a cataclysmic rise could occur
over the next century or two, … if at all
(current thinking is that it's unlikely)

Percent coverage for a 15-ft. rise in sea level	
Louisiana	27.5%
Florida	24.1%
Delaware	16%
District of Columbia	15.0%
Maryland	12.3%
North Carolina	7.9%
California	1.0%
New York	0.6%

Sea-level rise could be hard on Delaware!
A 15 ft. (4.6m) rise could flood 15% of state.

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