Chapter 4: Atmosphere

- 4.1 Composition
- 4.2 Climate
- 4.3 Greenhouse gases
- 4.4 Ozone

Some figures and tables in this chapter are taken from the personalized textbook Environment (Pearson)
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4.1 Composition

- Atmospheric composition has evolved since the beginning of the earth
- Primitive atmosphere was composed of N_2, H_2O and CO_2 with some NH_3 and CH_4.
- Atmosphere underwent a dramatic change with the appearance of photosynthetic organisms: production of O_2 and organic carbon

Photosynthesis:
$6CO_2 + 6H_2O = C_6H_{12}O_6 + 6O_2$

Great Oxygenation Event (2.3 billion years ago)

- Appearance of photosynthetic organisms
  - Cyanobacteria appeared maybe 3.5 billion years ago (definitely by 2.7 billion years ago)
  - Photoautotrophs
    - Use sunlight to convert CO_2 & water into organic carbon for cell
    - Also produces O_2

Banded iron formations

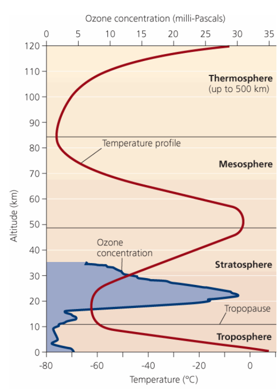
Composition (Table 3.1)

component	% (vol/vol)
Nitrogen	78.08
Oxygen	20.95
Argon	0.93
Carbon dioxide	0.035

- The current earth's atmosphere is essentially composed of N_2 and O_2.
- O_2 is consumed during organic carbon degradation (respiration) and produced during photosynthesis

Thermal structures

- Thermal boundaries between layers called pauses



Thermosphere:
- low density and pressure (< 10^{-5} atm.)
- composed of atoms and ions
- altitude > ~ 85 km

Mesosphere: ~ 50-85 km
- absorption of solar radiation: warming phenomenon

Stratosphere: ~12-50 km
- less solar radiation, temperature decreases with decreasing altitude
- contains ozone (O_3)

Natural formation of ozone

Ozone continuously created and destroyed in the stratosphere, by UV radiation

Ozone production
- UV-C radiation splits O_2 (photodissociation) :

$$O_2 + h\nu \rightarrow 2O \qquad (\lambda < 240 \text{ nm})$$

- Oxygen atom can then recombine with O_2 to form ozone:

$$O + O_2 + M \rightarrow O_3 + M \text{ (M = third body)}$$

Natural destruction of ozone

Ozone absorbs UV-B radiation, and is destroyed in the process (how it shields us)

Ozone destruction
- UV-B radiation splits ozone (photodissociation):

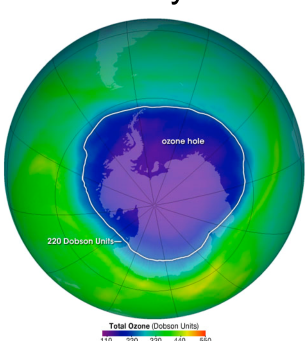
$$O_3 + h\nu \rightarrow O_2 + O \qquad (\lambda = 280 – 320 \text{ nm})$$

- Oxygen atom produced can then split another ozone molecule :

$$O + O_3 \rightarrow 2O_2$$

Imaging the ozone layer

- Ozone is measured in Dobson units (DU)
- Measure of thickness of the ozone layer if present at ground level
- 100 DU = 1 mm thick at ground level
- Presently, usually measured by satellites



Troposphere

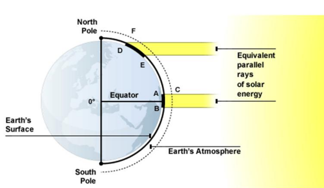
- contains 75-90% of the mass of the atmosphere and the majority of trace gases
- Can reach 8-17 km
- within the troposphere, absorption of terrestrial radiation (by CO_2, H_2O and CH_4) causes warming near the surface. This is called the **greenhouse effect**
- without the greenhouse effect, the mean temperature of the atmosphere at the surface of the earth would fall from the current 15 °C to -18 °C

4.2 Climate

- Weather is the physical condition of the atmosphere at a specific time and place. Weather is highly variable and unpredictable
- Climate is the long term view of weather patterns of a particular locality
- The earth is bathed in short-wave electromagnetic radiation from the sun.
- Earth receives 8.4 joules/cm^2 minute as electromagnetic radiations

Solar energy and temperature

- Polar regions receive less solar energy than equatorial
  - Sunlight spread over large surface area closer to poles
  - Travels longer through atmosphere at poles



Atmospheric circulation – driven by solar energy

- Circulatory systems allow energy to move from equatorial regions to the poles
- Solar energy warms air, evaporates water, creates convection cells
  - Warm, moist air is less dense, so rises
  - As air rises, it expands, loses its moisture and cools
  - Cooling → Air descends, closing convection current

Incident solar radiation

- 30% of the incident solar energy is reflected back to the outer space
- 25% of the incident solar radiation is absorbed by gases, vapours and particulates in the atmosphere
- 45% of the incoming solar radiation passes through the atmosphere and is absorbed by the Earth's surface, plants, organisms, etc.
- The earth-atmosphere system not only absorbs radiation, but emits electromagnetic radiation: over a long period of time, the energy budget of the globe is seen in balance

Continued

- Solar radiation is absorbed by the greenhouse gases, which include water vapour (H_2O), carbon dioxide (CO_2), nitrous oxides (NOx), methane (CH_4), etc.. This is the natural greenhouse effect
- These gases re-emit energy at a longer wavelength: infrared
- Earth's surface temperature is determined by the equilibrium rates at which (a) solar energy is absorbed by the surface and (b) the absorbed energy is re-radiated in a longer wavelength form

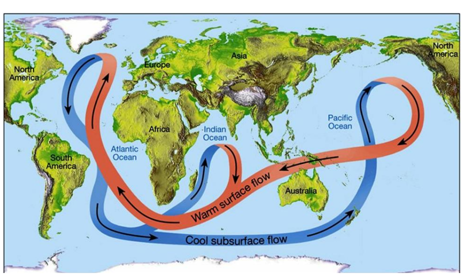
Circulatory systems

- Circulatory systems allow the energy to move from equatorial regions to the poles
- There are prevailing winds known as trade winds (tropical airflows that blow from the northeast in the northern hemisphere and from the southeast in the southern hemisphere), westerlies (mid-latitude winds) and polar easterlies

Climate and oceans

- Climate is also influenced by oceans
- Water has high heat capacity
  - Can absorb a lot of heat from the atmosphere and move this heat around the globe
- Oceanic conveyor belt or **thermohaline** circulation plays an important role in regulating climates
  - Cold water more dense than warm water
  - Water density increase with salinity
  - Both these properties drive global ocean circulation patterns

Thermohaline circulation



Driven by sinking of water in north Atlantic (North Atlantic Deep Water)

- Cold water (made saltier by formation of sea ice) sinks
- Cold , deep water resurfaces as it warms passing through the Pacific & Indian ocean
- Returns to north Atlantic

Effect of winds

- Winds blowing across the North Atlantic transfer a significant degree of warmth to the surrounding countries. The annual amount of heat absorbed from the conveyor belt is almost one-third as a much as that received from the sun in this location. North America is 6 °C warmer because of this effect.
- **The Atlantic conveyor belt has decreased by 30% since 1957 because of glacier melting and lower salinity: decrease in T of 1-2 ° C in Europe in the next 20 years**
- Winds blowing across the oceans create surface currents. The rotation of the earth influences the path of the currents.

Winds

- south of the equator, movement is essentially anti-clockwise
- movement is clockwise in the north hemisphere
- Air circulates in the atmosphere under 3 forces:
  - pressure gradient force
  - frictional force
  - Coriolis force : force that operates to the right over a surface that is rotating anti-clockwise and to the left, over a clockwise rotating surface
- the pressure gradient is the principal driving force producing horizontal airflow

Climates

tropical: no discernible winter/summer seasonal change in temperature

(latitudes of 30° N and 30° S)

Mid-latitude: (30-60° N, 30-55° S)

Polar: the average temperature of the warmest month does not exceed 10° C

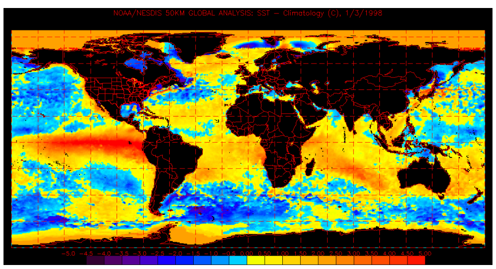
(latitudes > 60° N, and 55° S)

- in polar regions, much of the ground is permanently frozen: permafrost

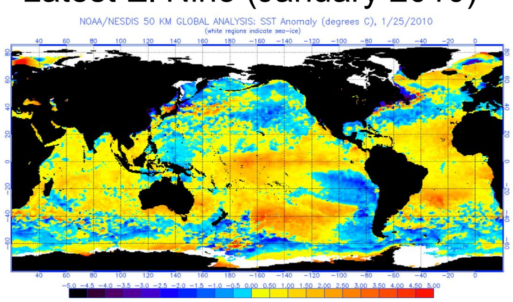
El Nino

- is a disruption of the ocean-atmosphere system in the Tropical Pacific having important consequences for weather and climate around the globe
- It occurs every 2 to 7 years. Recent events were in 1982-1983, 1986-1987, 1991-1993, 1994-1995, 1997-1998 (strong event), 2002 (weak event), 2004-2005 (weak event), 2006-2007, 2010
- this phenomenon is thought to be triggered when the steady westward blowing winds over the Pacific ocean weaken and reverse direction
- it allows a large mass of warm water (that is normally located near Australia) to move eastward along the equator, near the coast of south America
- http://www.elnino.noaa.gov/

El Nino January 1998
(strong event)



Latest El Nino (January 2010)



The impacts

- It affects evaporation patterns and can cause floods, droughts, etc.
- It also affects fish populations by changing their migration patterns (change of T°, decrease of primary production caused by limited nutrients)
- El Nino is also blamed for coral bleaching (higher T° and lower salinity)

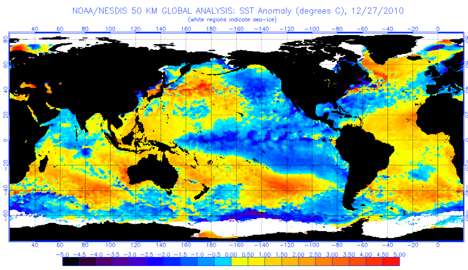
continued

- 1982-1983, severe droughts in Australia, Indonesia, India and South Africa. In Australia alone, 2 billion dollar loss in crops
- 1997-1998, heavy rains in California, snow in Mexico, field fires in the Prairies, unusual warm winter in Canada. $34 billions in damage worldwide, 24 000 people died.
- Temperature of the water off the coast of BC was 2 to 3 °C above average in 1997-1998

La Nina

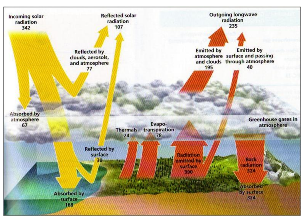
- Characterized by unusually cold ocean temperatures in the eastern equatorial Pacific, as compared to El Niño, which is characterized by unusually warm ocean temperatures in the Equatorial Pacific.
- Usually follows El Nino episodes
- Responsible for cooler temperatures in the Northeastern parts of US and Canada
- El Nina episodes in 1987, 1995 and 1999 and 2008
- http://www.elnino.noaa.gov/lanina.html

La Nina, Dec. 2010



4.3 Greenhouse gases

- Greenhouse gases include
  - CO_2, water vapour, nitrous oxide (N_2O), methane (CH_4) etc
- Solar radiation re-emitted by Earth's surface at longer wavelength [infrared (heat)]
- Greenhouse gases absorb some of this and re-radiate it back to the Earth's surface ➡



This is the natural greenhouse effect (without it, surface would be 33 °C cooler)

Natural greenhouse effect

- The magnitude of greenhouse warming depends on the quantities of the various greenhouse gases in the atmosphere and their relative efficiencies as absorbers and emitters of radiation.
- Water vapour is the most abundant
  - Contributes about 21°C of warming to the natural greenhouse effect

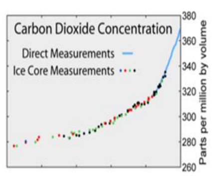
Natural greenhouse effect

- CO_2
  - Less abundant than water vapour, but much more efficient absorber of radiation
  - Accounts for another 7°C of natural warming
- Ozone, methane, and nitrous oxide
  - Much less abundant
  - Responsible for the remaining 5°C

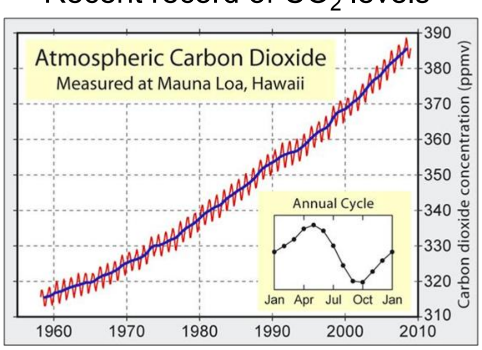
Greenhouse gas	Relative heat-trapping ability
CO_2	1
CH_4	21
N_2O	310

Anthropogenic contributions to greenhouse effect

- Since industrial revolution, concentrations of greenhouse gases have increased substantially from 280 ppm to 385 ppm in 2007
- 60% of this increase has occurred since 1958, mirroring the rapid growth of a postwar global economy powered by fossil fuels

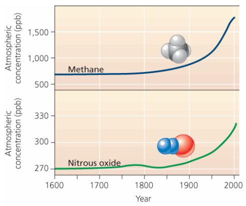


Recent record of CO_2 levels



Other greenhouse gases

- Methane (CH_4) concentration have more than doubled
  - Tapping fossil fuel deposits
  - Livestock emissions
  - Enhanced fermentation in soils, sediments, wetlands etc
    - Landfills, rice production
- Nitrous oxide (N_2O) levels have also increased markedly
  - Auto emissions
  - Chemical manufacturing
  - Nitrogen fertilizers
- Also, synthetic greenhouse gases have been added to atmosphere
  - HFC, CFC (high heat trapping ability)

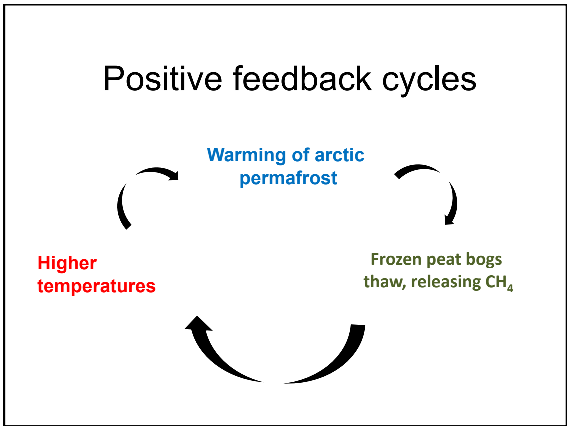


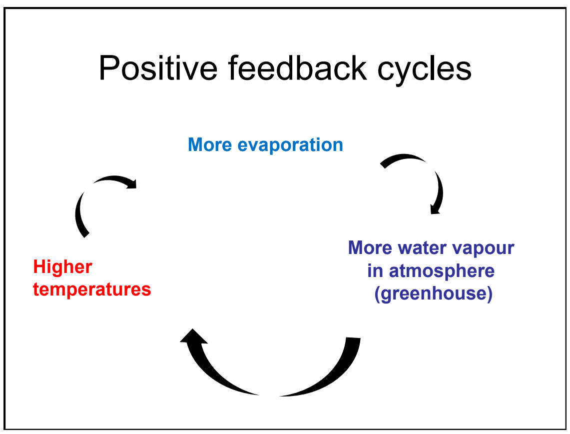
CO_2 budget

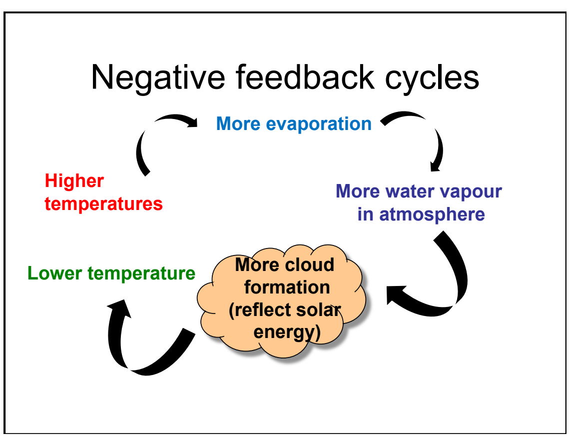
- ~40% of CO_2 from fossil fuel combustion is present in atmosphere
- Remaining 60% absorbed by forests & oceans
- Forests
  - Deforestation may lead to increased levels of CO_2 since it is not assimilated by the plants
    - Before widespread deforestation, the global terrestrial vegetation stored 900 billion tons of organic carbon (50% in tropical forests)
    - Now, only 560 billion tons of carbon are stored.
- Oceans
  - Immobilize large quantities of CO_2 (by precipitating $CaCO_3$), but their retention capacity is limited

Feedback cycles in climate system

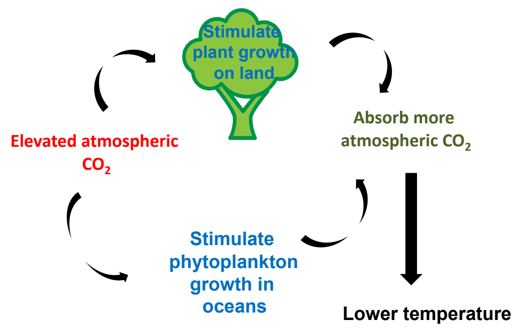
- Feedback cycles/loops
  - Output from cycle is fed back into cycle
    - **Positive** feedback = self-reinforcing
    - **Negative** feedback = self-limiting
- Climate system is filled with such examples of positive and negative feedback


Positive feedback cycles
Warming of arctic permafrost
Frozen peat bogs thaw, releasing CH_4
Higher temperatures


Positive feedback cycles
More evaporation
More water vapour in atmosphere (greenhouse)
Higher temperatures


Negative feedback cycles
More evaporation
More water vapour in atmosphere
More cloud formation (reflect solar energy)
Lower temperature
Higher temperatures

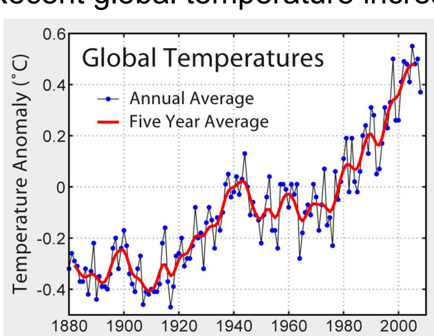
Negative feedback cycles



CO_2 and climate

- One of the most important indicators of climate change is the temperature of the surface atmosphere
- Thermometer temperature data go back to 1880
- Air-temperature data can be biased by the fact that air T° can vary between cities and rural areas, that it can be affected by cooling effects caused by volcanic eruptions
- Recent analyses suggest a definite warming trend since the mid-19th century in some parts of the world.

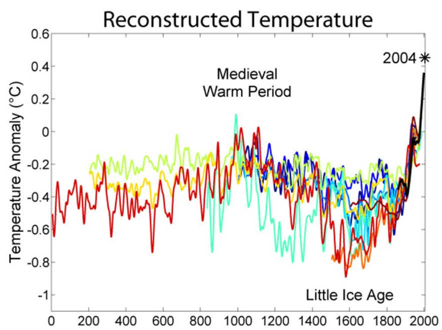
Recent global temperature increase



Earth surface temperatures further back in past

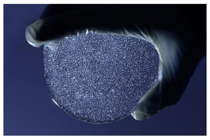
- We know from thermometer measurements that global temps have risen in past 130 years
- Is this anomalous (and so worrying) or just a fluctuation when viewed over longer timescales?
- We need temperature data further back in time
  - Use proxies (surrogates) for temperatures
    - Human records (e.g. extent of sea ice)
    - Natural records (e.g. tree rings, coral reefs, pollen grains in sediments, ice cores)

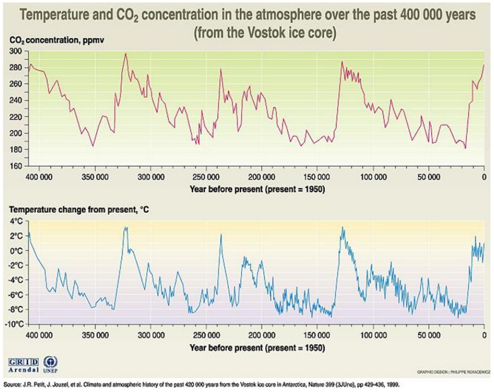
Global surface temperatures over past two millennia



Ice cores: A window to distant climates

- Air bubbles trapped as snow falls and is compressed into ice at the poles
  - Melt ice to recover air bubbles and analyze its CO_2 concentration
- Measure isotopic composition of H & O in ice to determine past temperature
  - Warmer temperatures: higher levels of heavier isotopes (^{2}H, ^{18}O)
- Collect deep ice cores to recover information on past atmosphere (ice core in Antarctica: 800 000 yrs



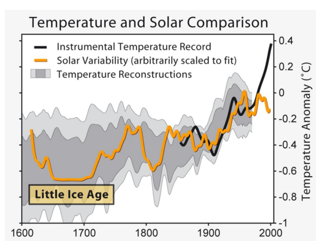


What about the Sun?

- Changes in Earth's orbit and its rotational axis alter the amount of solar energy its surface receives (Milankovitch) over periods of 20 000 – 100 000 years: trigger glaciations and interglacial periods

- Couldn't changes in the Sun's activity have influenced global surface temperature?

- Observed temp. increase can only be reproduced if we factor in greenhouse gases



Impacts of warming

- At present rate of CO_2 increase in atmosphere, global surface temperatures predicted to rise by 1.1 to 6.4 °C during 21st century

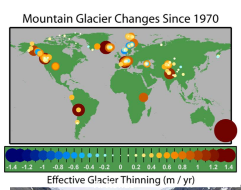
- Most climate scientists say a rise of more than 2 °C would lead to serious climate changes

(Some) global physical impacts

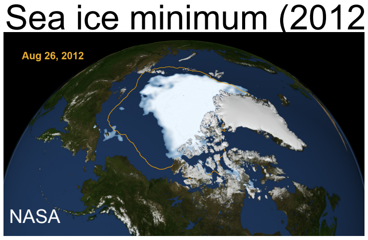
- CO_2 absorption by oceans will make them more acidic
  - Already declined by 0.1 pH units (+ increase of 0.14-0.35 by the end of the century)
  - Impact organisms that form $CaCO_3$ shells, many of which are primary producers
- Increased intensity of Atlantic hurricanes
- Glaciers, ice sheets etc. will continue to melt
- Sea levels rise
  - Rose 17 cm in past century
  - Predicted to rise by 18-59 cm by 2100

Glacier retreat

- Glacier melting and retreat observed throughout the world
  - E.g. Athabasca glacier
    - Shrinking 15 m per year
    - Lost half its volume in past 125 years



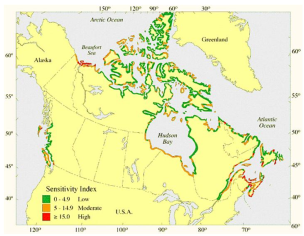
Sea ice minimum (2012)



- Arctic warming faster than elsewhere (twice the global average) (yellow line is the sea ice extent in 2007)
- Arctic predicted to be free of sea ice by 2030 – 2040
- Northwest passage...

Sea level rise in Canada

- Melting of glaciers, Ice sheets and thermal expansion (biggest effect)
- Sea levels will rise causing coastal erosion and retreat



Annual sea level rise

Annual average sea-level rise, 1993-2010

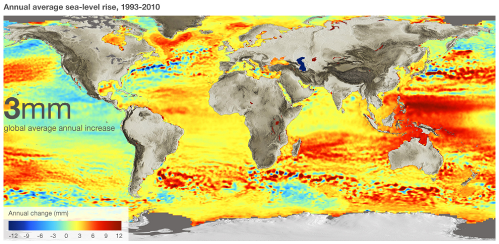


Image courtesy of Climate Change Initiative (CCI)

(Some) ecological effects

- Some 20 – 30% of species face extinction if temperature rises > 2.2°C (50% probability)
  - Species ranges shift towards poles
- A change of T° would affect the seasonal precipitation patterns (warmer climates, less precipitation)
  - Droughts in tropical parts of world
- Warmer waters can cause the bleaching of corals and the migration of fish populations (less upwelling of nutrients by cold water)
- Ocean acidification
  - Impair ability of coral and other $CaCO_3$ shell forming organisms to grow

Ecological impacts

- Polar bears
  - Hunt on pack sea ice, which is fast disappearing with climate change
- Amazon rainforest
  - Huge carbon sink (absorbs 2 billion tonnes CO_2 per year)
  - Drought in 2005 changed Amazon rainforest from a carbon sink to source
    - Released 3 billion tonnes CO_2 !
  - Sign of things to come?

(Some) societal impacts

- Crop yields in temperate zones may increase, BUT droughts in tropics will limit crop productivity → hunger/famine
- Sea level rise displace people from coasts
  - Warming Arctic disrupts aboriginal way of life
- Melting mountain glaciers reduce water supplies to millions of people
- Human health will suffer

Tackling CO_2 emissions

- Vast majority from fossil fuel combustion
- Emissions per capita are directly related to the level of industrialization
  - Canada and the U.S. are the largest producers of CO_2 per capita
- Kyoto protocol to reduce CO_2 emissions

Kyoto protocol

- Canada was one of the first countries to sign the agreement on April 1998. It expires in 2013.
- Our initial goal was to reduce greenhouse gas emissions by 6% below 1990 levels by 2008-2012
  - However, our emissions keep increasing (by 2006 they were 21% higher than emissions in 1990!)
  - The latest target was a 17% reduction by 2020 based on **2005 emissions** (607 Mt) (Environment Canada 2012)
  - Works out as about 3% reduction based on 1990 emissions
- On Dec. 12th 2011, Canada pulled out of the Kyoto protocol
- Most industrialized countries have signed the protocol but the US are not part of it
- Did it really work?

Copenhagen conference

- December 2009
- Meant to take over from Kyoto protocol
- No legally binding agreement made
- Stumbling blocks
  - Technological & financial assistance to developing countries to address climate change
  - Worry of China/India in limiting their economic growth
- CO_2 reduction pledges

CO_2 emission reduction pledges

Area	1990→2020
Norway	−30% to −40%
Japan	−25%
EU	−20 to −30%
Russia	−20 to −25%
South Africa	−18%
Iceland	−15%
New Zealand	−10 to −20%
Australia	−4 to −24%
	−15 to −33%
United States	−4%
Canada	−3%
Brazil	+5 to −1.8%
Area	**2005→2020**
China	−40 to −45% (per GDP)
India	−20 to −25% (per GDP)

Emissions achieved

Nation	Observed emission change (1990-2006)
Russia	-32%
Germany	-17.2%
United Kingdom	-14.3%
France	-0.8%
Italy	+12.1%
Japan	+6.5%
United States	+15.8%
Canada	+29.1%

UN climate change conference: Cancun 2010

- To commit to a maximum temperature rise of 2°C above pre-Industrial levels, and to consider lowering that maximum to 1.5 degrees in the near future.
- To make fully operational by 2012 a technology mechanism to boost the innovation, development and spread of new climate-friendly technologies
- To establish a Green Climate Fund to provide financing to projects, programs, policies and other activities in developing countries via thematic funding windows

(http://unfccc.int/meetings/cancun_nov_2010/meeting/6266.php)

UN climate change talks Durban, South Africa, 2011

- 194 nations agreed to start negotiations on a new accord that would put all participating countries under the same binding commitments to control greenhouse gases

Country	% change of CO_2 emissions (1990-2010)
Europe	-7%
Russia	-28%
Canada	+ 20%
US	+ 5%
India	+180 %
China	+ 257%

Source: Netherlands/Join Research Center of the European commission

UN climate change conference , Doha, Qatar, 2012

- They worked on the second phase of the Kyoto protocol for 2013-2020
- They set up plans to address future “loss and damage” in developing countries that may arise as a result of climate change - ranging from a rise in sea levels to severe weather events.
- Experts say that the planned emission reductions will not prevent the planet from warming up above 2 degrees

Some steps to lower CO_2 emissions

- Improve efficiency of vehicles (fuel economy) and reduce their use (better public transport)
- Replace coal power plants with nuclear and wind/solar power
  - Improve efficiency of coal power plants
- Capture CO_2 from power plants
- Stop deforestation and re-establish tree plantations

What if it doesn't work?

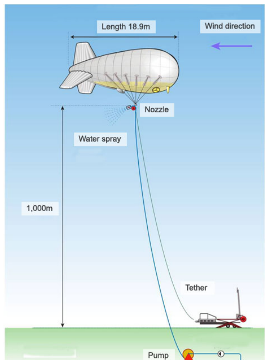
- Climate geoengineering
  - "options that would involve large-scale engineering of our environment in order to combat or counteract the effects of changes in atmospheric chemistry" Nat. Acad. Sci.
  - CO_2 sequestration
    - Carbon capture & storage
    - Ocean iron fertilization
  - Solar radiation management
    - Stratospheric sulfur aerosols
    - White roofs (enhance albedo)

Geoengineering – CO_2 sequestration

- Carbon capture & storage methods
  - See earlier lecture on energy resources
- Ocean iron fertilization
  - Iron often limiting nutrient in open ocean
  - Add iron : stimulate phytoplankton: sequester CO_2
- Spraying sulfate aerosols in the atmosphere
  - Political aspects to consider

Sulfate aerosols

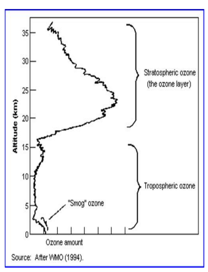
Aerosols would reflect back the solar energy into space: cooling effect



Proposed altitude of 10-20 km

Strastopheric ozone

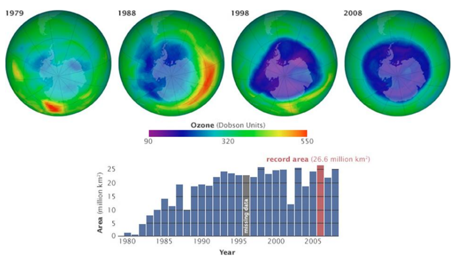
- Ozone (O_3) primarily occurs as a “layer” in the stratosphere, at 20 – 30 km altitude
  - Smaller amounts in the troposphere present as a pollutant (not naturally produced)
- Stratospheric ozone layer acts as a “shield” against potentially harmful UV radiation from sun



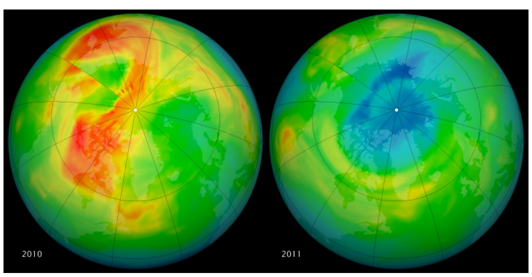
Falling stratospheric ozone levels

- Between 1980 and 1994, the concentration of stratospheric ozone declined by about 5–6% over southern Canada and by 7–8% over the north
  - Our UV shield weakening
- Part of a global phenomenon that includes the seasonal formation of "ozone holes" over Antarctica

Stratospheric ozone loss



Recent stratospheric ozone loss



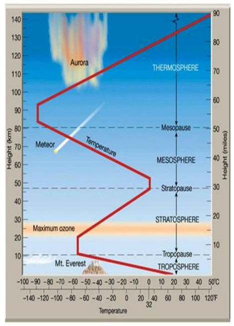
40% loss over the Arctic in one year (NASA) due to unusual long winter

Stratospheric ozone loss

- Stratospheric ozone loss linked to several widely used chlorine and bromine compounds
- Chlorofluorocarbons (CFCs) most abundant of these anthropogenic chemicals
- Other significant ozone-depleting compounds include:
  - Halons
  - Carbon tetrachloride (CCl_4)
  - Methyl chloroform (CH_3CCl_3)
  - Methyl bromide (CH_3Br)

Chlorofluorocarbons (CFCs)

- Stable, nontoxic, nonflammable, highly versatile chemicals first developed in the 1890's
  - Used over the past several decades as spray propellants, refrigerants, foam-blowing agents, solvents, and cleaning fluids
- Because of their chemical stability, CFCs can survive in the atmosphere for several decades to a few centuries
- They diffuse gradually from the troposphere into the stratosphere



CFCs vs. ozone in the stratosphere

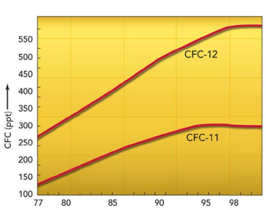
- CFC's in stratosphere subjected to intense solar radiation (UV-C)
  - Molecule breaks down (photodissociates), releasing a Cl atom
  - Cl atom breaks up ozone molecule:

    $Cl + O_3 \rightarrow ClO + O_2$
  - ClO formed reacts with oxygen atom , regenerating free Cl atom:

    $ClO + O \rightarrow O_2 + Cl$
  - In this way, a single atom of Cl can destroy hundreds of thousands of ozone molecules before finally forming a more stable combination with another substance

Other important ozone depleters – chlorine-bearing chemicals

- CFC-11 and CFC-12 together account for about half of the ozone-depleting chlorine entering the stratosphere
- Other important chlorinated ozone depleting chemicals include
- Hydrochlorofluorocarbons (HCFCs)
- Carbon tetrachloride (CCl_4)
- Methyl chloroform



Other important ozone depleters – bromine-bearing chemicals

- Halons
  - Fire extinguishers
- Methyl bromide
  - Agricultural fumigant
  - Unlike other ozone depleting chemicals, methyl bromide has a relatively short lifetime
  - Bromine is, however, highly effective in removing ozone and methyl bromide is therefore considered to be a significant contributor to ozone depletion

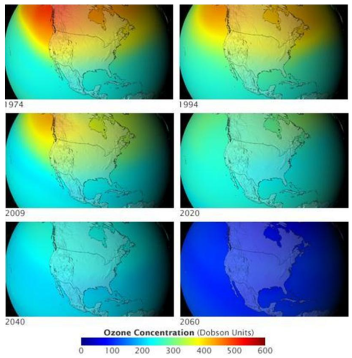
Methyl bromide

- In addition to anthropogenic input, CH_3Br also has natural sources
  - Marine bacteria can produce it
- Highly toxic
  - Gas used in fumigation
- High potential for depleting ozone
- Banned in Canada (2001) and USA (2005)

Protecting the ozone layer

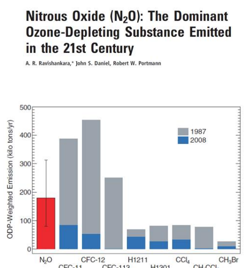
- Global production of ozone depleting substances has decreased since the signature of the Montreal Protocol in 1987
- Other agreements have been reached since, further decreasing the emission of ozone depleting chemicals
- If emissions are maintained at the present levels, stratospheric ozone should replenish itself to pre-industrial levels by 2050 (chlorine atoms can persist for decades in the stratosphere)

What if we didn't have the Montreal Protocol (and its amendments)?



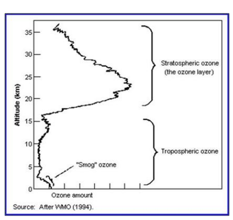
Nitrous oxide – unregulated ozone depleter

- Nitrous oxide (N_2O) is **not** regulated by the Montreal Protocol
  - Significant ozone-depleting potential
- "Limiting future N_2O emissions would enhance the recovery of the ozone layer from its depleted state and would also reduce the anthropogenic forcing of the climate system, representing a win-win for both ozone and climate"



Tropospheric ozone

- Ozone in the lower atmosphere is an important pollutant
  - Ground-level ozone
  - Respiratory irritant
- It is not naturally produced
  - It is a photochemical pollutant
  - i.e. it is synthesized in the atmosphere by photochemical reactions involving a precursor



Production of ground-level ozone

- The main precursors is NO_x
  - Originate from the combustion of fossil fuels (automobiles)

Ground-level ozone production

- NO_2 photodissociates:

$$NO_2 + h\nu \rightarrow NO + O \qquad (\lambda < 400\ nm)$$

- Oxygen atom combines with O_2 to form ozone:

$$O + O_2 + M \rightarrow O_3 + M \qquad (M = \text{third body})$$

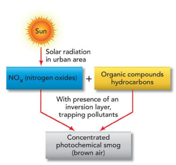
Smog

- Historically, smog was a problem from burning of coal (i.e,coal rich in sulfur), and smoke from vehicle exhausts
- Great smog of London, UK (1952)
  - Thick fog from temperature inversion (cold air trapped beneath layer of warmer air)
  - Mixed with chimney smoke, particulates and **SO_2** from coal burning
  - Respiratory problems
  - 4000 immediate deaths (8000 more following months)
  - 1956 clean air act (UK)

London

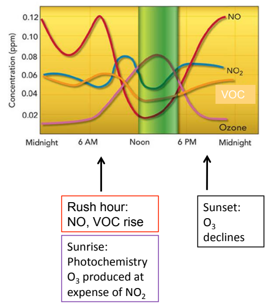
Photochemical smog

- Volatile organic compounds (VOCs)
  - Fossil fuel combustion (e.g. power plants, vehicles)
- Together, ground-level ozone and a number of other pollutants make up what is known as photochemical smog
  - It affects people with respiratory problems



Photochemical smog

- Because ozone formation depends on strong sunlight and is accelerated by heat, ozone concentrations tend to peak during the day and the summer
- In 1990, Canada decided to reduce its ozone and VOC emissions by 10% to 15 % (1985 levels)
  - Similar reductions in USA



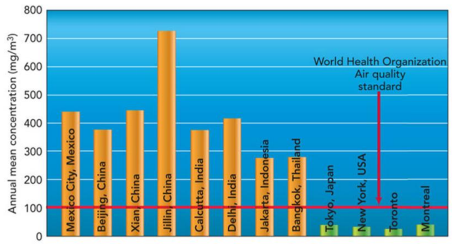
Ground-level ozone

- Ozone levels average around 100 ppb in the southern States, while they vary between 40-60 ppb in the rest of the US and Canada
  - Limits for 8 h exposure: Canada 65 ppb (later in 2010); USA 75 ppb (under revision)
- The most affected area in Canada is the Windsor-Quebec corridor, where ozone concentrations can reach 110-160 ppb, sometimes 190 ppb
- Ozone levels can reach 500 ppb in L.A. and remain above 100 ppb for weeks

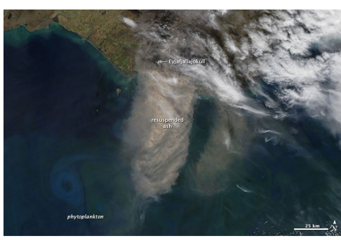
Particulate air pollution

- Anthropogenic airborne particulates that are less than 10 µm in diameter (PM 10) are primarily a consequence of industrial processes and motor vehicle use
- Human-induced particulate pollution occurs primarily in larger cities, where industries, motor vehicles, heating plants, and residential furnaces provide many emission sources.
- In BC, YT, QC & Atlantic provinces, wood smoke from the burning of logging or sawmill waste and from the use of wood for home heating is a common source of pollution

Particulate air pollution worldwide



Icelandic volcano, spring 2010 (Eyjafjallajökul)



Ocean fertilization by volcanic dust (NASA)

Automobile emissions of Pb

- Between 1923 and 1975, gasoline contained Pb. It was used to increase the mechanical efficiency
- Pb emissions (as particulates) started to decrease in 1975 due to an increased use of catalytic converters to reduce emissions by cars
- Pb emissions accumulated in terrestrial and aquatic ecosystems (in lakes, soils, plants and animals)

La fin