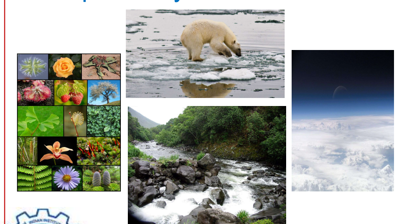
ES200/ES250
Module: Global Environmental Change

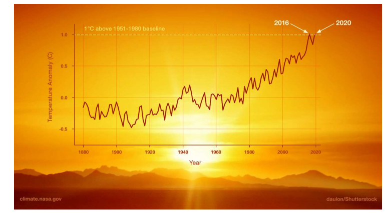
Srinidhi Balasubramanian
(srinidhi@iitb.ac.in)
Assistant Professor
Environmental Science and Engineering Department, IIT Bombay

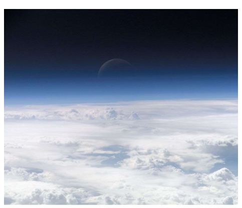
Module Objectives

1) Environmental change and planetary boundaries



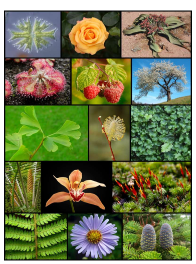
2) Global Climate Change





Environment

- Biotic and abiotic components surrounding an organism or a population, thus influencing their survival, development and evolution.
- Vary from microscopic to global scale
- Environmental science = systematic study of human interactions with the environment

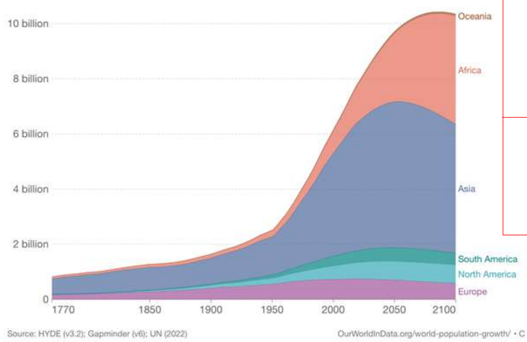


What is Environmental Change?

- Change or disturbance of the environment by either natural causes, anthropogenic factors, or even animal-environment interactions.
- Environmental degradation refers to the *"reduction of the capacity of the environment to meet social and ecological objectives, and needs"*
  - Depletion of resources
  - Reduced environmental quality
  - Habitat change

More information: http://www.unisdr.org/eng/library/lib-terminology-eng%20home.htm

Population and consumption drives environmental change



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Planetary boundaries

- Planetary boundary representative of a "safe operating space for humanity"
  - Transgressing such a boundary has a deleterious or catastrophic risk to human and ecosystem health
  - Such change likely to be irreversible, non-linear and result in regional to planetary scale impacts

More information: https://www.stockholmresilience.org/research/planetary-boundaries.html

Podcast: https://open.spotify.com/episode/69JCjeqnXpwkvKZmdI7OI6?si=9588e8645b4f4b8a

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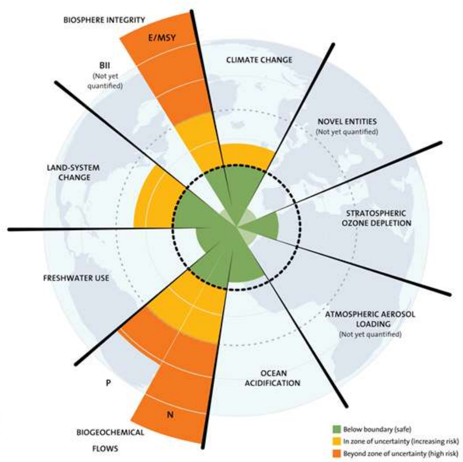


Orange sections >> "overshoot" of boundaries

Green sections >> "safe" within boundaries

The biodiversity Intactness Index (BII) assesses changes in population abundance due to human impacts.
BII = 100% >> ecosystem abundances at preindustrial levels
Lower BII >> Reflects the extent and degree of human modification of ecosystem populations

Steffen, W. et al. (2015). *Science*.

7

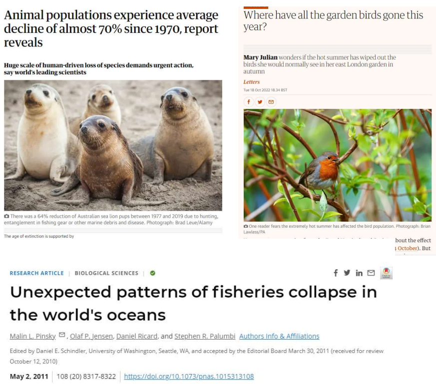
Nine boundaries: some exceeded, some at risk

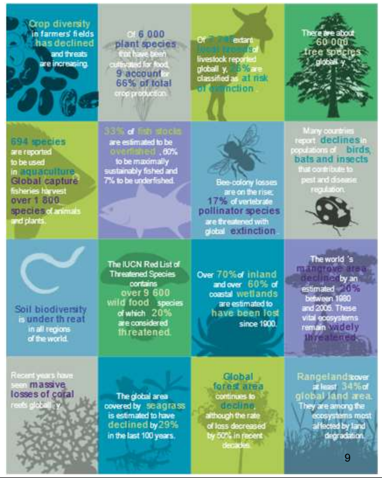
1) Climate change
2) Biodiversity loss
3) Biogeochemical flows of nitrogen and phosphorus
4) Land-system change
5) Ocean acidification
6) Stratospheric ozone depletion
7) Atmospheric aerosol pollution
8) Freshwater use
9) Release of novel chemicals

Humanity already exists outside the safe operating space for at least four of the nine boundaries

8

2) Loss of Biosphere Integrity





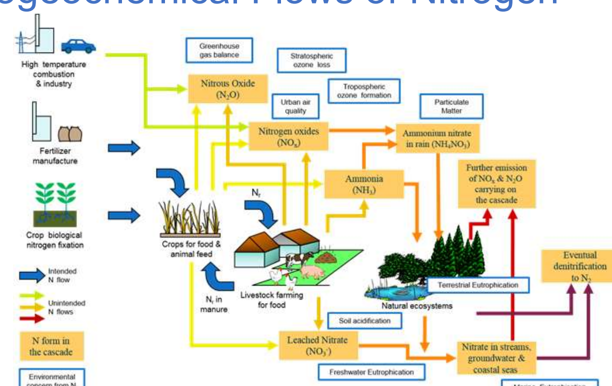
2) Loss of Biosphere Integrity

- Problem: Ecosystem changes due to human activities more rapid in the past 50 years than at any time in human history (The Millennium Ecosystem Assessment of 2005)
  - Increasing the risks of abrupt and irreversible changes in terms of biodiversity loss and extinctions.
- Main drivers: Demand for food, water, and natural resources.
- Solutions: Current high rates of ecosystem damage and extinction can be slowed by efforts to protect the integrity of living systems, enhance habitat, and improve connectivity between ecosystems while maintaining high agricultural productivity.

3) Biogeochemical Flows

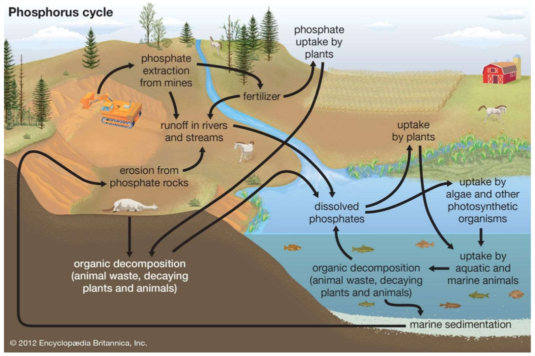
- Problem: Anthropogenic inputs of nitrogen and phosphorous for agricultural production, from mining and through smaller utilities such as detergent use.
  - Release and accumulation of reactive nitrogen (Nr includes NH_3, N_2O, NO_x, and nitrates) and phosphorous in water, air, and soil.
  - Reactive nitrogen has local, regional and global scale impacts.
- Main drivers: Demand for food, fuel, and fibre.
- Solutions: Reduced reliance on N and P inputs by shifting farming practices and consumer demands of food and fuel. End-of-life treatment to reduce Nr and P discharge to air and water.

3) Biogeochemical Flows of Nitrogen



https://www.inms.international/why-care-about-nitrogen

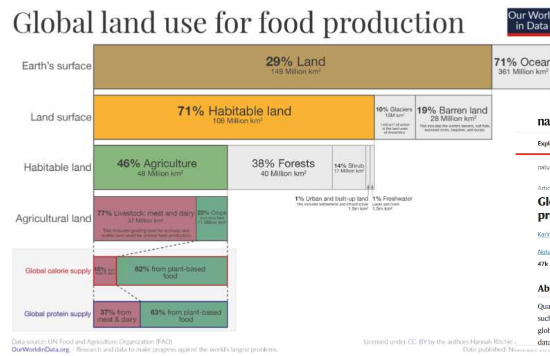
3) Biogeochemical Flows of Phosphorous

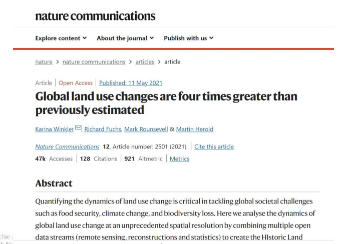


13

4) Land-system change

Land use change accelerated between 1960-2005, and has since slowed down

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Article | Open Access | Published: 11 May 2021

Global land use changes are four times greater than previously estimated

Karina Winkler, Richard Fuchs, Mark Rounsevell & Martin Herold

Nature Communications 12, Article number: 2501 (2021) | Cite this article

47k Accesses | 128 Citations | 921 Altmetric | Metrics

Abstract

Quantifying the dynamics of land use change is critical in tackling global societal challenges such as food security, climate change, and biodiversity loss. Here we analyse the dynamics of global land use change at an unprecedented spatial resolution by combining multiple open data streams (remote sensing, reconstructions and statistics) to create the HIstoric Land

14

4) Land-system change

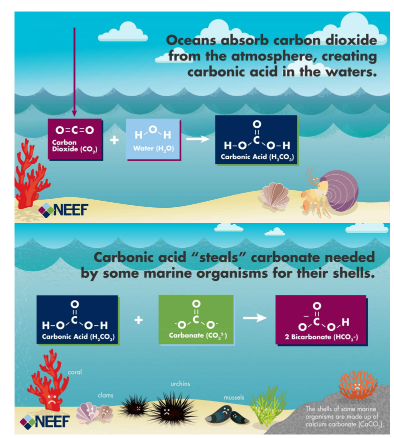
- Problem: Widespread conversion of forests, grasslands, wetlands and other vegetation types to agricultural land and for mining and logging.
- Main drivers: Demand for food (crops, grazing land, feed), biofuel, and natural resources (wood for paper products, precious metals, sand, etc.)
- Solutions: Afforestation, greener agricultural practices, reduced illegal mining and logging, and product and process improvement.

- Explore deforestation patterns and drivers: https://www.globalforestwatch.org

15

5) Ocean Acidification

- Problem: Quarter of emitted CO_2 dissolved in oceans >> reduces pH and alters biochemistry >> impacts shell and skeleton formation.
  - Ocean acidity has increased by 30% since pre-industrial times.
- Main drivers: Fossil fuel combustion
- Solutions: Climate change action, reduced dumping of illegal waste

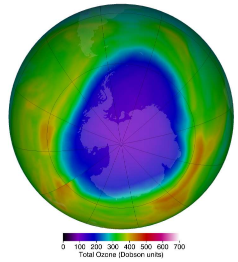


https://news-oceanacidification-icc.org/2018/08/10/marine-life-and-ocean-acidity/

16

6) Stratospheric Ozone Depletion

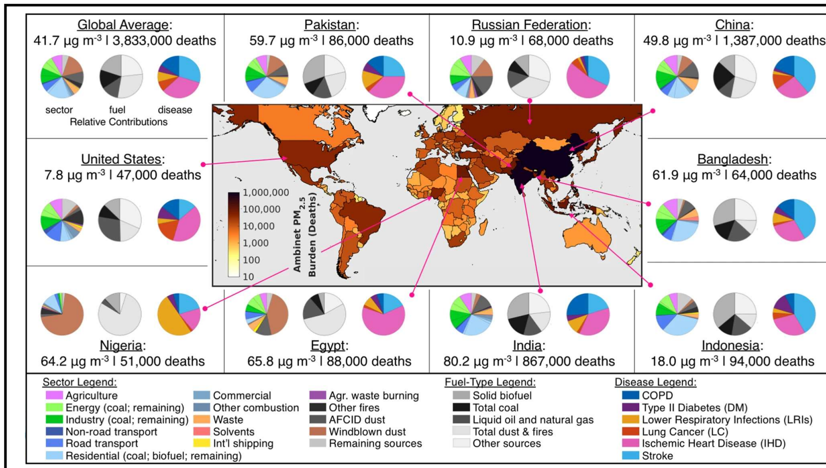
- Problem: Release of ozone-depleting substances that breakdown the protective stratospheric ozone layer >> increased cancer risk
- Main drivers: Release of ODS such as chlorofluorocarbons, halons, hydrochlorofluorocarbons that are present in solvents, refrigerants, degreasing agents, propellants, fire extinguishers and as agricultural pesticides.
- Solutions: Montreal Protocol helped reduce ODS!
- NASA ozone watch: https://ozonewatch.gsfc.nasa.gov/



Antarctic ozone hole occurs annually in September and October (Spring). Purples and deep blues indicate low ozone levels. Credit: NASA's Goddard Space Flight Center.

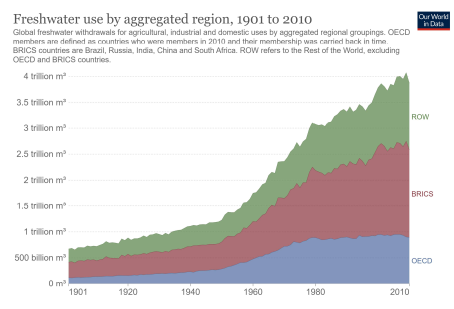
7) Atmospheric Aerosols

- Problem: Aerosols or particulate matter (PM_{10} and $PM_{2.5}$, PM with diameters ≤ 10 and 2.5 μm respectively) emitted
- Main drivers: Industry, power generation, transportation, road dust, cookstoves, mining, construction, agriculture, and waste burning.
- Solutions: Low-carbon, clean and energy-efficient technologies, and improved waste management.
- Satellite $PM_{2.5}$ data: https://sedac.ciesin.columbia.edu/data/set/sdei-global-annual-gwr-pm2-5-modis-misr-seawifs-aod-v4-gl-03



McDuffie, Erin E., et al. "Source sector and fuel contributions to ambient PM2.5 and attributable mortality across multiple spatial scales." Nature communications 12.1 (2021)

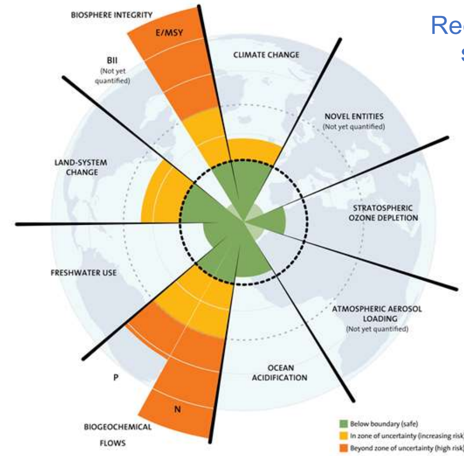
8) Freshwater Use



- Problem: Human demand for freshwater has altered the functioning and distribution of global freshwater systems impacting the hydrological system.
  - Half-billion people are subject to water stress.
  - Changes in precipitation, soil acidification, habitat degradation, and crop yield impacts.
- Main drivers: Freshwater withdrawals for agriculture, industry and municipal uses have increased nearly six-fold since 1900.
- Solutions: Water-efficient technologies, water boundaries for consumptive freshwater use.

9) Release of Novel Chemicals

- Problem: Emissions of toxic and long-lived substances such as synthetic organic pollutants, heavy metal compounds, and radioactive materials have potentially irreversible impacts on health and the environment.
  - Reduced fertility, genetic damage, and bioaccumulation through the food chain.
- Main drivers: Demand for fuel, precious metals, pharmaceuticals, and agrochemicals.
- Solutions: Reduced demand for novel chemicals, redesign of products and processes, environmental labels.



Recap: Nine planetary boundaries, some exceeded, some at risk

1) Climate change
2) Biodiversity loss
3) Biogeochemical flows of nitrogen and phosphorus
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Steffen, W. et al. (2015). *Science*.

Module Objectives

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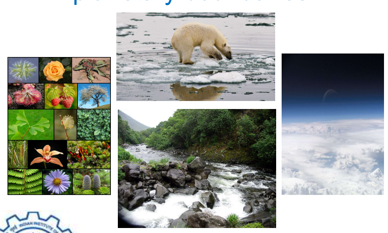
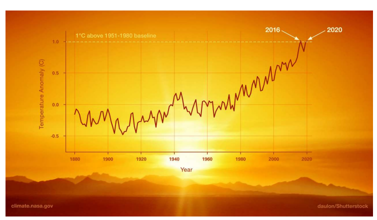


2) Global Climate Change



Is Climate changing?: Weather versus climate

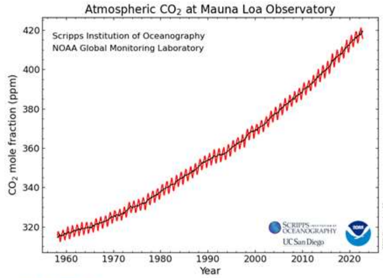
- Weather >> short-term conditions of the lower atmosphere, such as precipitation, temperature, humidity, and wind.
- Climate >> long-term atmospheric change, usually defined as 30 years or more.

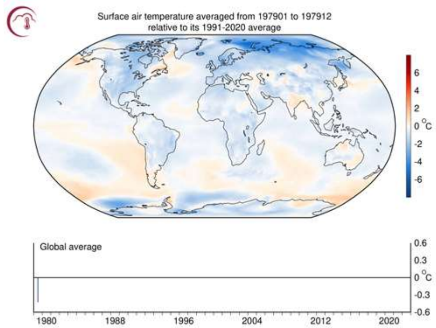
Weather-climate interlinked >> changing climate can impact short-term weather patterns

Is the climate changing? Is the change anthropogenic?

Atmospheric Trends in a Changing Climate

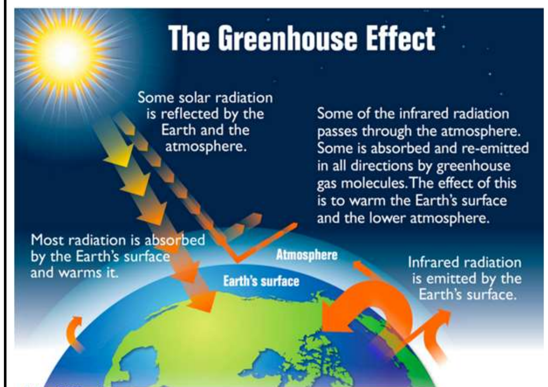
CO_2 in October 2022: 415.7 ppm





https://gml.noaa.gov/ccgg/trends/

https://climate.copernicus.eu/temperature-animations



- Global warming refers to a steady rise in global temperatures as a result of the greenhouse effect.
- Climate change is the long-term change in the weather due to greenhouse gases.
  - Net result of the interaction of GHGs and aerosols with the radiative balance >> net warming.
  - Some regions could get colder due to climate change!

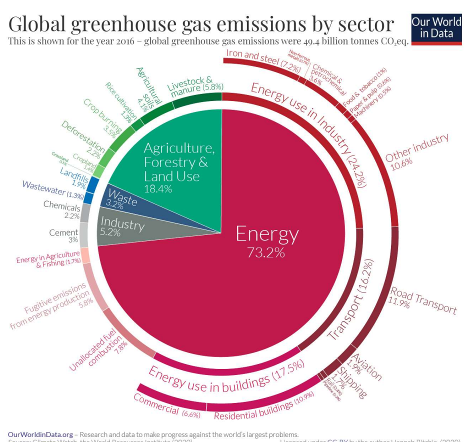
https://onetreeplanted.org/blogs/stories/difference-global-warming-climate-change

Greenhouse gas (GHG): Gas that absorbs and emits radiant energy within the thermal infrared range, causing the greenhouse effect.

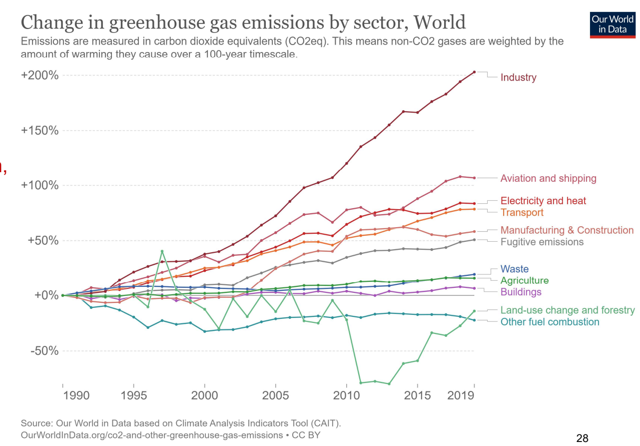
Global warming potential (GWP): measure of how much energy emissions of 1 ton of a gas will absorb over a given period of time, relative to emissions of 1 ton of carbon dioxide (CO_2).

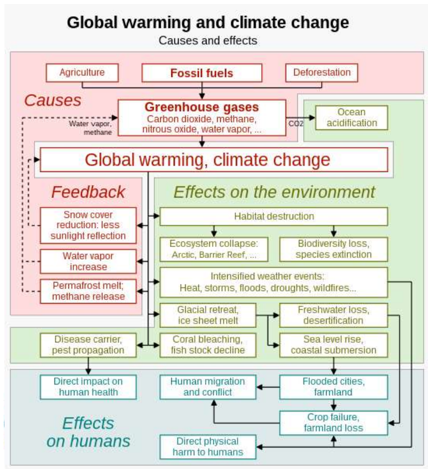
GHG	GWP for 100 years
CO_2	1
CH_4	23
N_2O	296
HFC - 23	12 000
HFC – 134a	1 300
SF_6	22 200

Source: *IPCC Third Assessment Report* (2001).



Global demand for energy, transportation, and industrial products is the key driver of GHG emissions

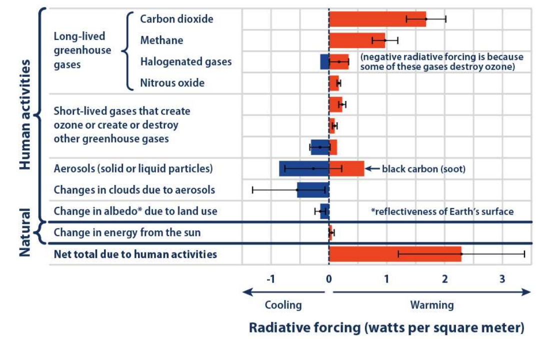




Climate System

- Five interacting components: Atmosphere, hydrosphere, cryosphere, lithosphere, biosphere.
- Forcing: measures the imbalance in the Earth's energy budget caused by a perturbation of the climate system (eg: GHG emissions).
- Feedback: processes that amplify or reduce the effects of climate forcing. Positive forcing increases temperature; negative forcing reduces the temperature.

Radiative Forcing Caused by Human Activities Since 1750

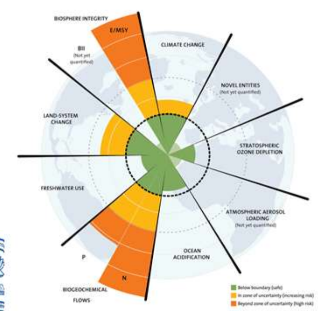


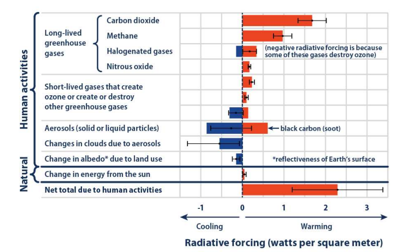
https://www.epa.gov/climate-indicators/climate-change-indicators-climate-forcing

Mitigating Climate Change is a Multi-Sector Challenge

Recap:

1) Global environmental change is largely driven by anthropogenic activities
2) Impacts are multi-fold as shown through nine interconnected planetary boundaries
3) Climate change refers to long-term changes in the weather and is largely attributed to emissions of greenhouse gases.





Recommended resources

Textbook:

- Ela, Wendell, and Masters, Gilbert M.. Introduction to Environmental Engineering and Science. United Kingdom, Prentice Hall, 2008.
- IPCC Fifth Assessment Report: https://www.ipcc.ch/assessment-report/ar5/

Publications:

- Johnson, D.L., Ambrose, S.H., Bassett, T.J., Bowen, M.L., Crummey, D.E., Isaacson, J.S., Johnson, D.N., Lamb, P., Saul, M. and Winter-Nelson, A.E., 1997. Meanings of environmental terms. *Journal of environmental quality*, *26*(3), pp.581-589.
- Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., De Vries, W., De Wit, C.A. and Folke, C., 2015. Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223), p.1259855.

Explore trends in Global Environmental Change

Global environmental change is an expansive, interdisciplinary subject. Multiple institutional repositories help provide insight into the ever-changing world around us. Select datasets are listed here. Explore these datasets and make at least three observations:

- Global Forest Watch: https://www.globalforestwatch.org/map/
- GHG from Energy Use: https://www.iea.org/data-and-statistics/data-tools/greenhouse-gas-emissions-from-energy-data-explorer
- Agriculture and Environment: https://www.fao.org/faostat/en/#data >> Select “climate”
- Climate Interactive Viewer: https://climate.nasa.gov/explore/interactives
- Food and footprints: https://www.bbc.com/news/science-environment-46459714

Thank you!

- ES200/ES250 related queries: Email the faculty in charge
- Queries related to this module: Email Professor Srinidhi Balasubramanian at srinidhi@iitb.ac.in with the subject line “Online ES200/ES250 Query”

ES 200
Environmental Studies: Science and Engineering

V. S. Vamsi Botlaguduru
Assistant Professor
Environmental Science & Engineering Dept.
IIT Bombay

Module

Natural Resources

Structure of the Lecture

- Part A: Basic Concepts in Natural Resources
- Part B: Sustainability and its Metrics

Objectives

- Create awareness on the concepts associated with natural resources management.
- Introduce the concept of sustainability and its metrics.

References

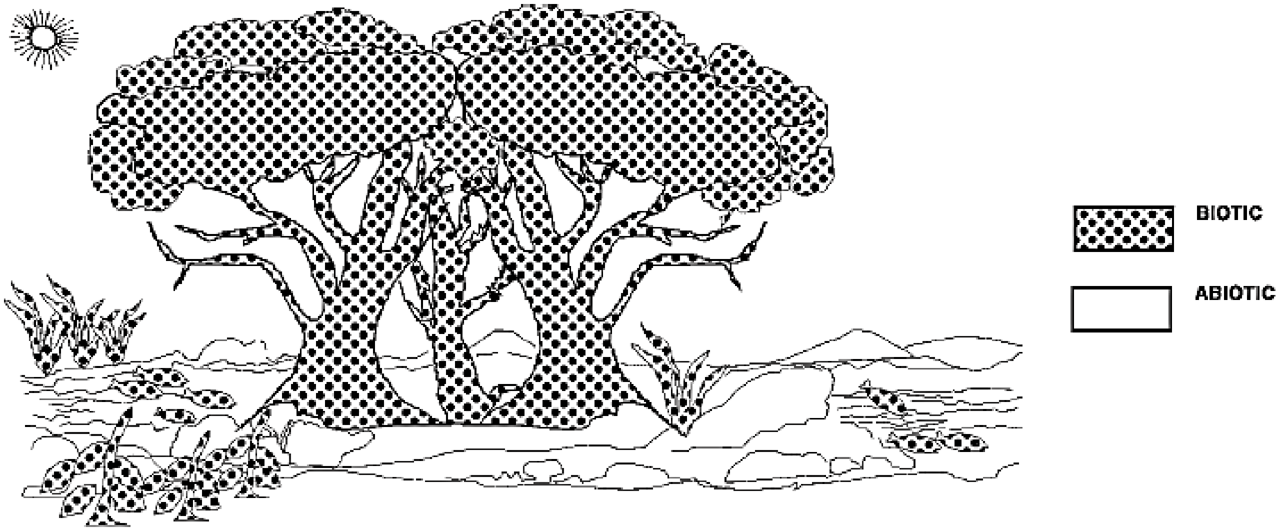
- Unit 2 of the "Textbook for Environmental Studies", Erach Bharucha, UGC, 2004.

Web References and Data Sources

- Global Footprint Network (https://www.footprintnetwork.org/)
- Water Footprint Network (https://waterfootprint.org/en/)
- International Resource Panel (https://www.resourcepanel.org/)
- Pocket Book of Agricultural Statistics, 2020, Government Of India, Ministry Of Agriculture & Farmers Welfare
- Energy Statistics India – 2023, Government of India, Ministry of Statistics and Programme Implementation National Statistical Office.

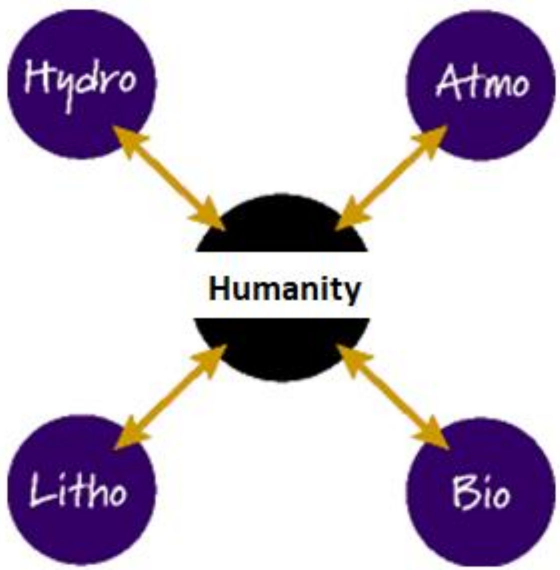
Introduction

- Our environment provides us with a variety of goods and services necessary for our day to day lives (needs and wants).
- These natural resources include, air, water, soil, minerals, along with the climate and solar energy, which form the non-living or 'abiotic' part of nature.
- The 'biotic' (living parts) of nature consists of plants and animals, including microorganisms.



Earth's Resources and Man

- The resources on which mankind is dependent are provided by various 'spheres'.



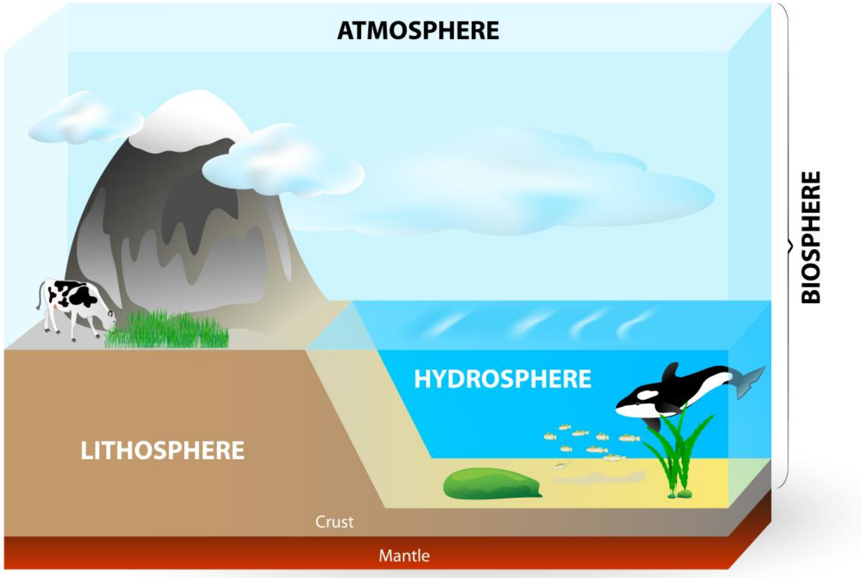
Atmosphere

- Oxygen for respiration: Humans, Wild fauna, Domestic animals
- Carbon di-oxide for photosynthesis: Plants

Earth's Resources and Man

Hydrosphere

- Clean water for drinking, washing and cooking.
- Water used in agriculture and industry.
- Food resources including fish, crustacea, sea weed, aquatic plants, etc.
- Water harnessed to generate electricity in hydroelectric projects.



Earth's Resources and Man

Lithosphere

- Soil, the basis for agriculture.
- Micronutrients in soil, essential for plant growth.
- Microscopic flora, small soil fauna and fungi in soil, which break down plant and animal wastes to provide nutrients for plants.
- Stone, sand and gravel for construction.
- Minerals on which our industries are based.
- Oil, coal and gas, extracted from underground sources.

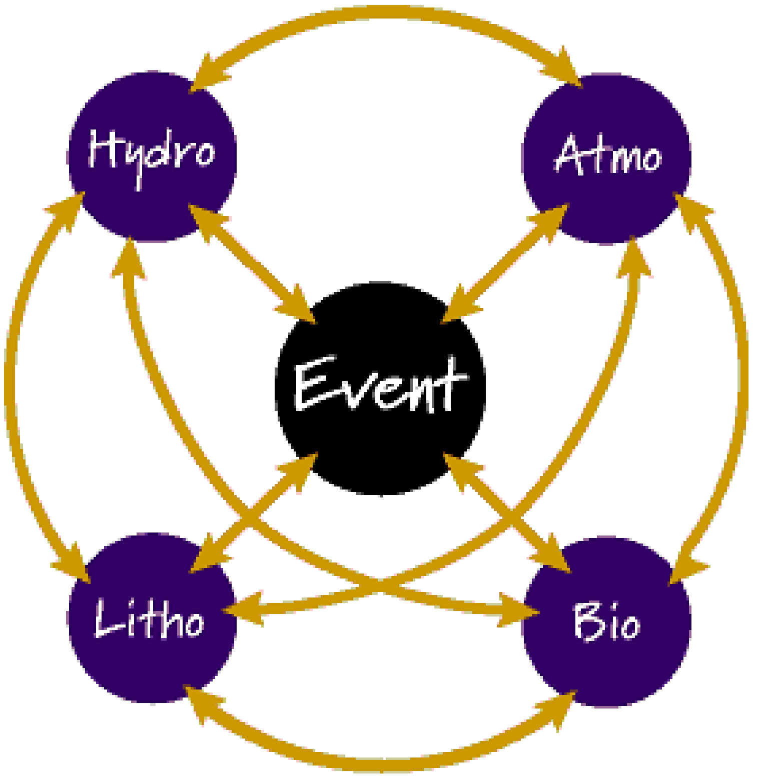
Earth's Resources and Man

Biosphere

- Food, from crops and domestic animals.
- Food, for all forms of life which live as interdependent species in a community and form food chains in nature on which man is dependent.
- Energy needs: Biomass fuel wood collected from forests and plantations, along with other forms of organic matter, used as a source of energy.
- Timber and other construction materials.

Earth’s Resources and Man

- Linkages between the spheres are mainly in the form of cycles
- Hydrologic Cycle
- Carbon, Nitrogen, Oxygen Sulfur, Phosphorous Cycles



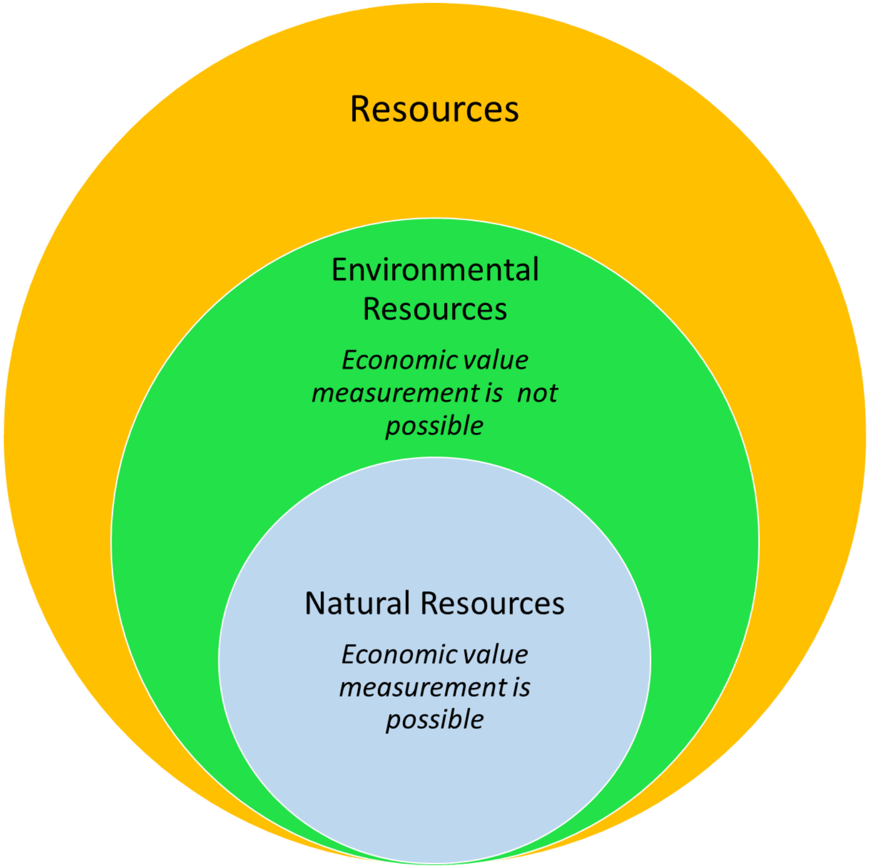
Classification of Natural Resources

Potential Resources

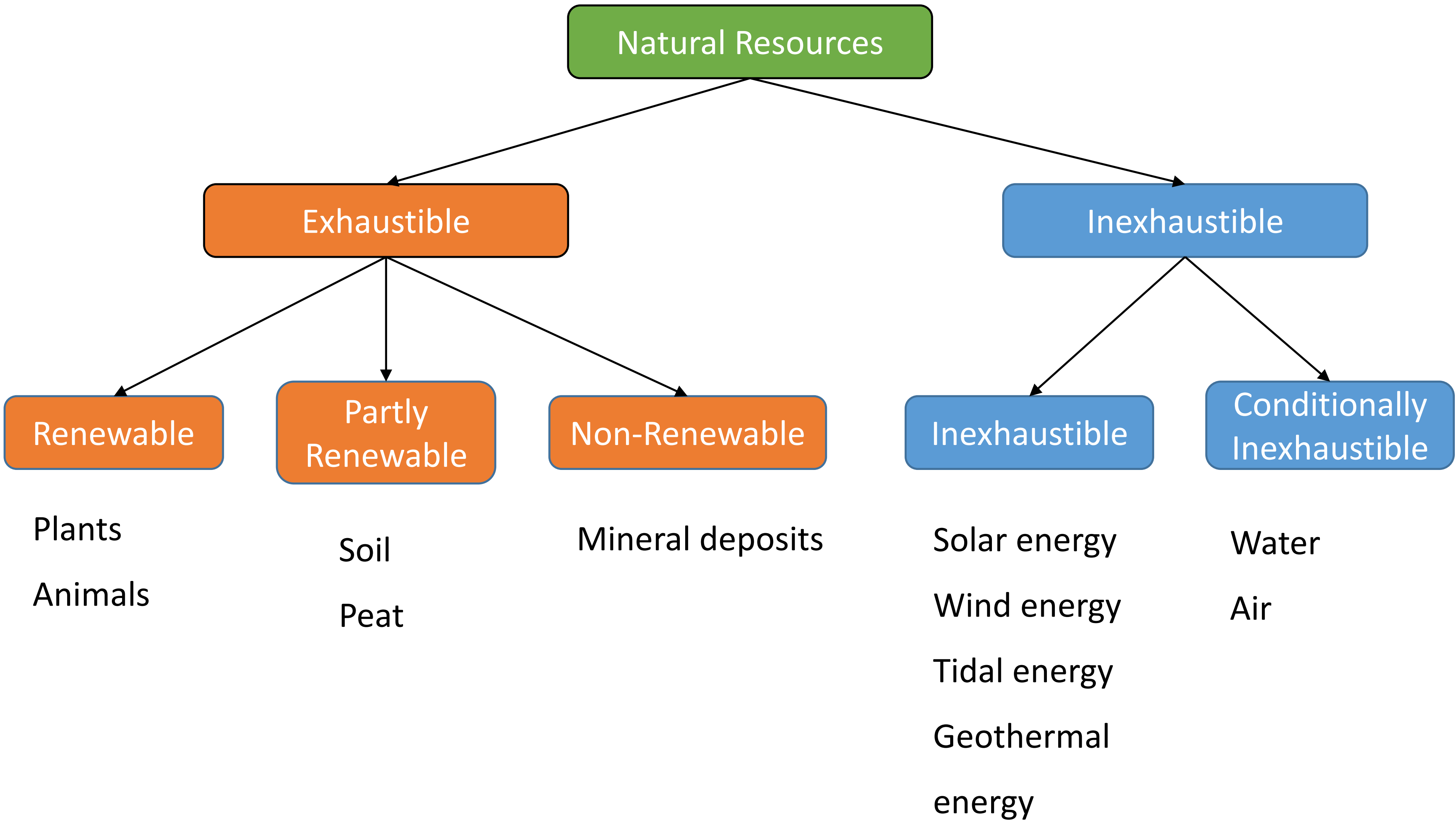
- Available in a specific region and their usage requires advanced technology
- Geothermal energy, earthquake energy, wave energy, freshwater in iceberg, etc.

Realistic Resources

- Can be accessed with existing technology
- Mineral deposits, timber, freshwater in lakes, etc.



Classification of Natural Resources



Concept of Preservation vs Conservation

Preservation	Conservation
Attempt to prevent the use of a natural resource	Attempt to use a natural resource in a away to minimize its exploitation
Aim is to keep the resources intact, 'as it is' or 'as it was'	Aim is to maintain the resource in as good condition as possible for sustained human access.
Preservationists often see nature as having an inherent value, not only when it can help us humans.	Conservationists typically support measures that reduce human use of natural resources, but only when such measures will be beneficial to humans.

Natural Resources and Associated Problems

1) **Land resources** - *Degrading soil quality, land hunger*

2) **Forest Resources** - *Over-exploitation, deforestation*

3) **Water resources** - *Over-utilization of ground water, pollution, floods, drought, conflicts over dams*

4) **Mineral Resources** - *Exploitation, environmental effects from mining*

5) **Energy resources** - *Increasing energy needs, environmental effects*

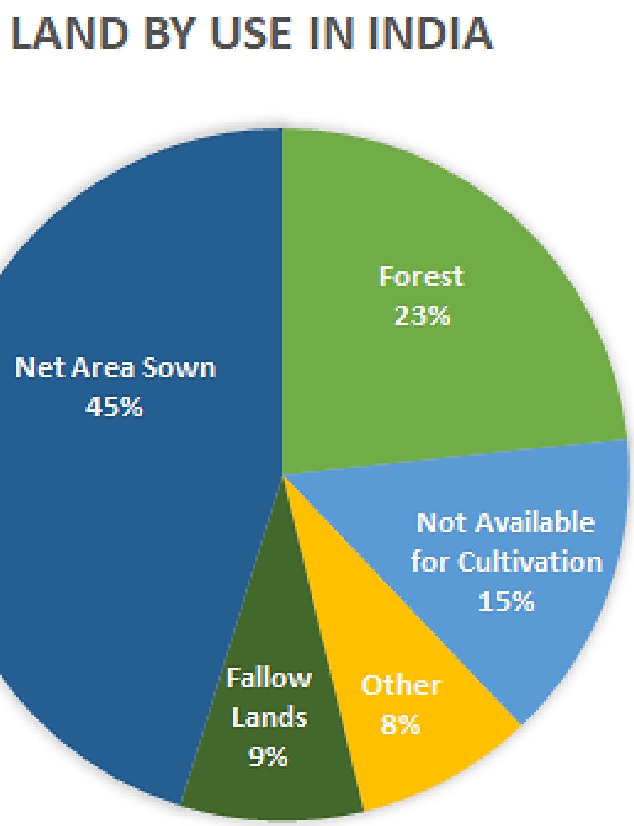
Land Resources of India

- India has 2.4% (3,287,263 km^2) of the world's land and is home to 18% of world's population. Percentage of cultivable land is ~ 60%.

- *Soil composition, groundwater availability, mineral availability, and local climatic condition* become the basis of the utilization and development of land resources.

- A decline in the net sown area is a recent phenomenon due to the increase in area under non-agriculture use.

- However, agricultural prosperity does not depend only on the total net sown area.



Forest Resources of India

- India, a tropical country should ideally have 33% of its land under forests. Currently, the land Government has identified and demarcated for forest growth is around 23%.

Types of Forests

Protected forests (53% of forest land)

- Observed by the government, but the local community is allowed to access wood/timber, grazing cattle without damaging the forests.

Reserved forests (18% of forest land)

- Under the supervision of the government and prohibited for collection of timber or grazing of cattle.

Unclassified forests

- No restrictions for tree cutting, grazing.

Forest Functions

Watershed protection

- Reduce the rate of surface run-off of water.
- Prevent flash floods and soil erosion.
- Produces prolonged gradual run-off and thus prevent effects of drought.

Atmospheric regulation

- Absorption of solar heat during evapotranspiration.
- Maintaining carbon dioxide levels for plant growth.
- Maintaining the local climatic conditions.

Land bank

- Maintenance of soil nutrients and structure.

Forest Functions

Local use - Consumptive use

- Food - gathering plants, fishing, hunting from the forest.
- Fodder - for cattle.
- Fuel wood and charcoal for cooking, heating.
- Poles - building homes especially in rural and wilderness areas.
- Timber – household articles and construction.
- Fiber - weaving of baskets, ropes, nets, string, etc.
- Sericulture – for silk.
- Apiculture - bees for honey, forest bees also pollinate crops.
- Medicinal plants - traditionally used

Market use - (Productive use)

Water Resources in India

- Total 4% of world's water resources are in India.
- India uses ~ 80-90% for agriculture, 7% for industry and 3% for domestic use.
- India experiences an average precipitation of 1,170 mm per year, or about 4,000 km^3 of rains annually. However, only 6% of annual rainfall is stored.
- About 70% of surface water resources in India are polluted.
  - *The major contributing factors are wastewater from domestic sector, intensive agriculture, industrial production, infrastructure development and untreated urban runoff.*

Water Resources in India

Issues with Water Resources

- **Over-exploitation**: Groundwater provides for over two-thirds of irrigation requirements. In the last four decades, about 85% of the total addition to irrigation has come from groundwater.

- **Policy Issues**: Groundwater is used to cultivate water-intensive crops like paddy and sugarcane in rain deficit states like Punjab and Maharashtra respectively.

Water Resources in India

Issues with Water Resources

- **Poor Maintenance**: There's a large, growing gap between irrigation potential created and that actually utilized, simply due to lax maintenance.
- **Rapid Urbanization**: Reduces the ground-water replenishment.
- **Poor Water Treatment Plants and Lack of Quality Data**

Water Demands

Types of Water Demands

1) Domestic
2) Industrial
3) Institutional and Commercial
4) Demand for public uses
5) Fire Demand
6) Compensation for losses in waste and theft

Breakup of Per Capita Demand (q) for an average Indian city

Use	Demand in L/h/d
Domestic Use	200
Industrial Use	50
Commercial Use	20
Civil or Public Use	10
Waste, Thefts, etc.	55
Total	335

Mineral Resources in India

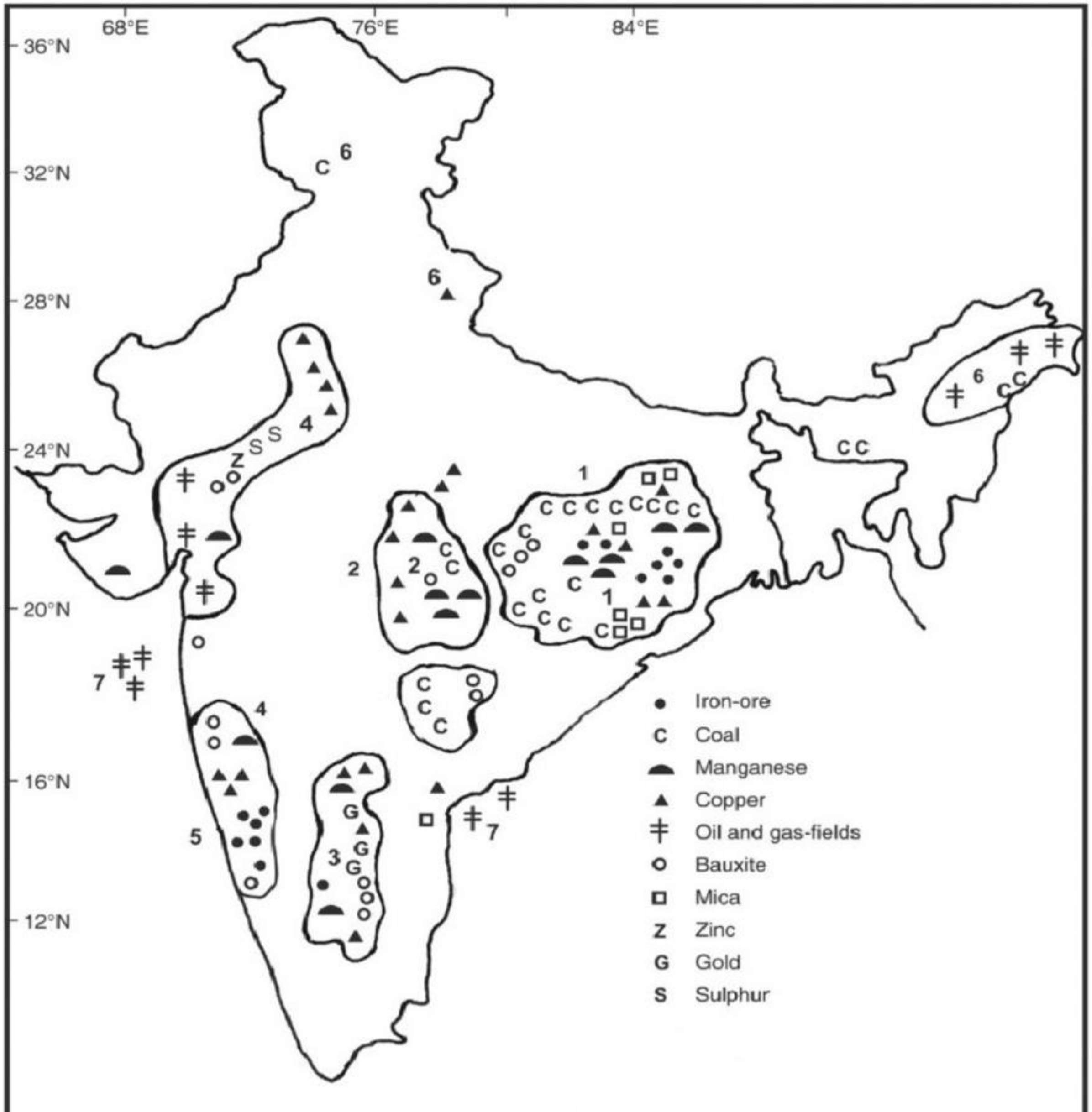
Minerals: A naturally occurring substance of definite chemical composition and identifiable physical properties.

Ore: A mineral or combination of minerals from which a useful substance, such as a metal, can be extracted and used to manufacture a useful product.

Different types of minerals

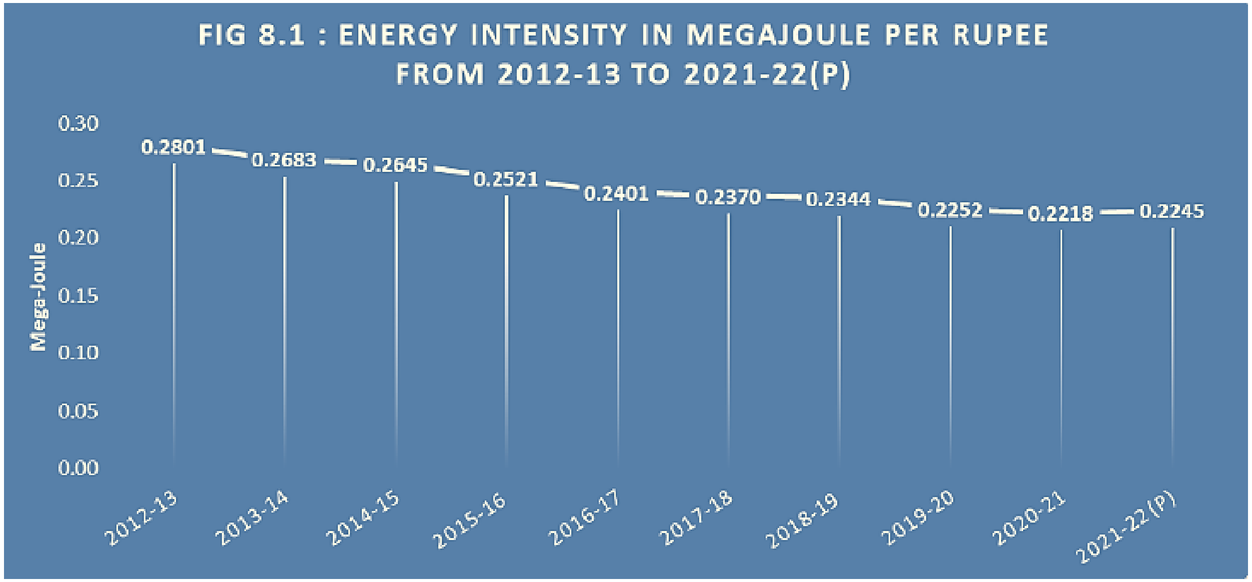
Minerals	Examples
Metallic minerals (ferrous)	Iron ore, manganese ore, chromite
Metallic minerals (non-ferrous)	Aluminum, copper, lead
Precious & semi-precious minerals	Diamond, gold, silver, ruby
Strategic minerals	Tin, nickel, cobalt, tungsten, molybdenum
Fertilizer minerals	Potassium, gypsum, phosphate
Refractory minerals	Fireclay, magnesite, graphite
Ceramic and glass minerals	Feldspar, quartz, silica sand
Others	Asbestos, fluorite, limestone, mica

Mineral Resources in India



- •North Eastern Peninsular Belt
- •Central Belt
- •The Southern Belt
- •The South-Western Belt
- •North-Western Belt

Energy Resources in India

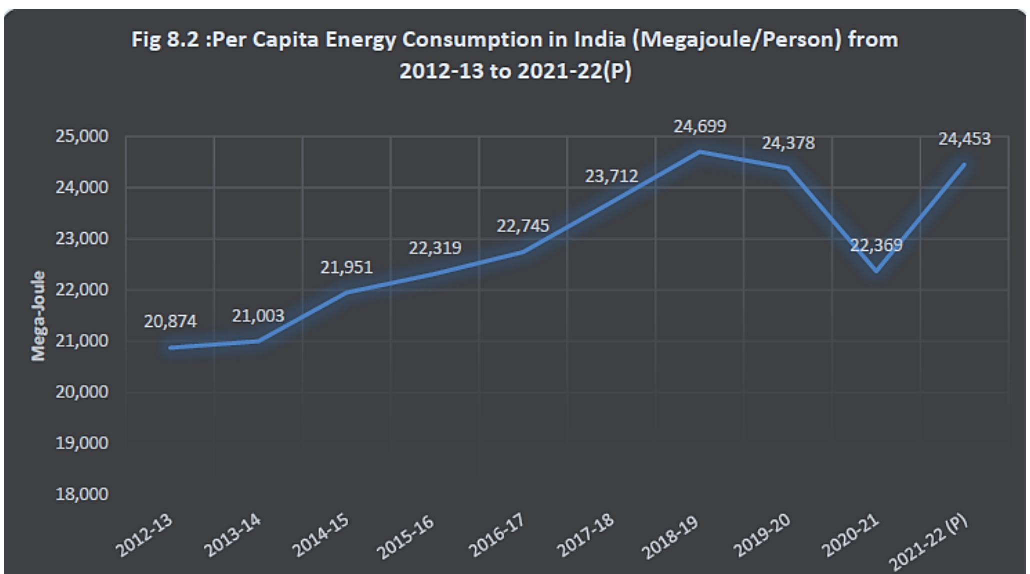


Comparative EI

China: 2.1x

USA: 1.5x

Russia: 2.3x



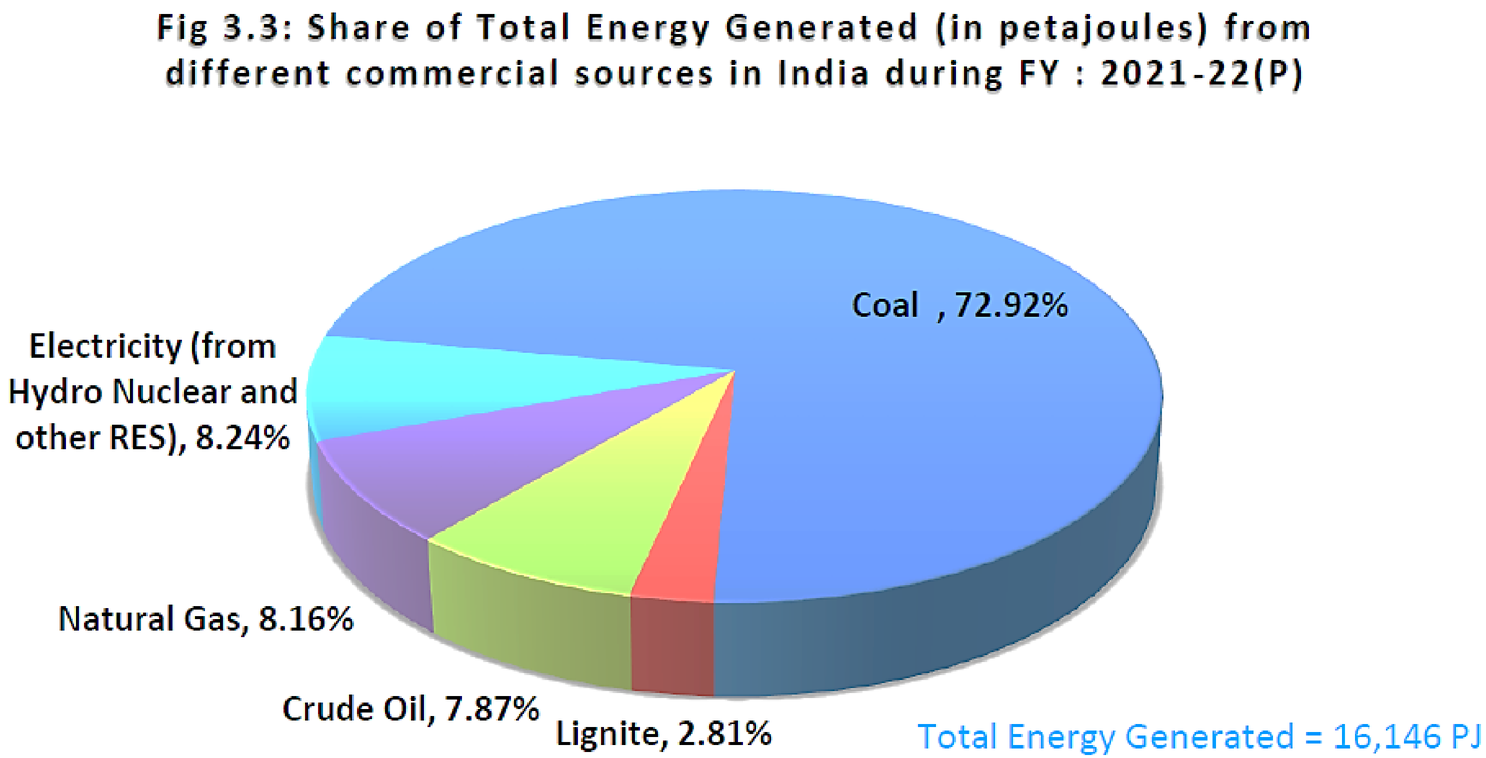
Comparative PEC

China: 1,11,784 (4.6x)

USA: 2,83,515 (11.6x)

Russia: 1,99,652 (8.2x)

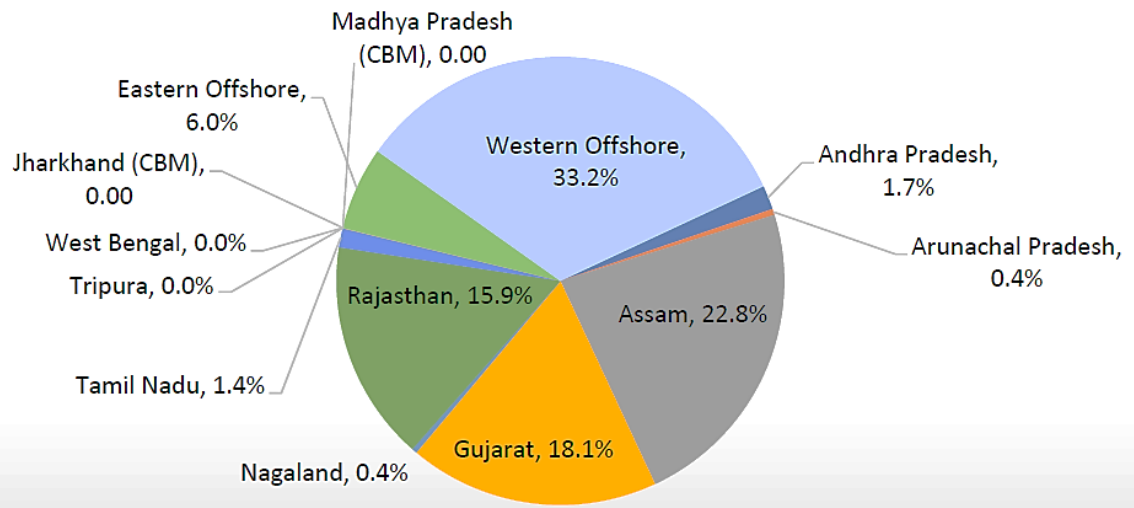
Energy Resources in India



Energy Resources in India

- Total estimated reserves of coal ~ 361 billion tonnes.
- The top three states with highest coal reserves in India are *Odisha, Jharkhand, Chhattisgarh*, ~ 70% of the total coal reserves in the country.
- The estimated reserves of crude oil in India ~ 652 million tonnes.

Fig 1.3: Estimated Reserves of Crude Oil in India as on 01.04.2022



Total Estimated reserves 651.77 Million tonnes

Part A:
Basic Concepts in Natural Resources

Additional Information

International Resource Panel, UNEP
(https://www.resourcepanel.org/)

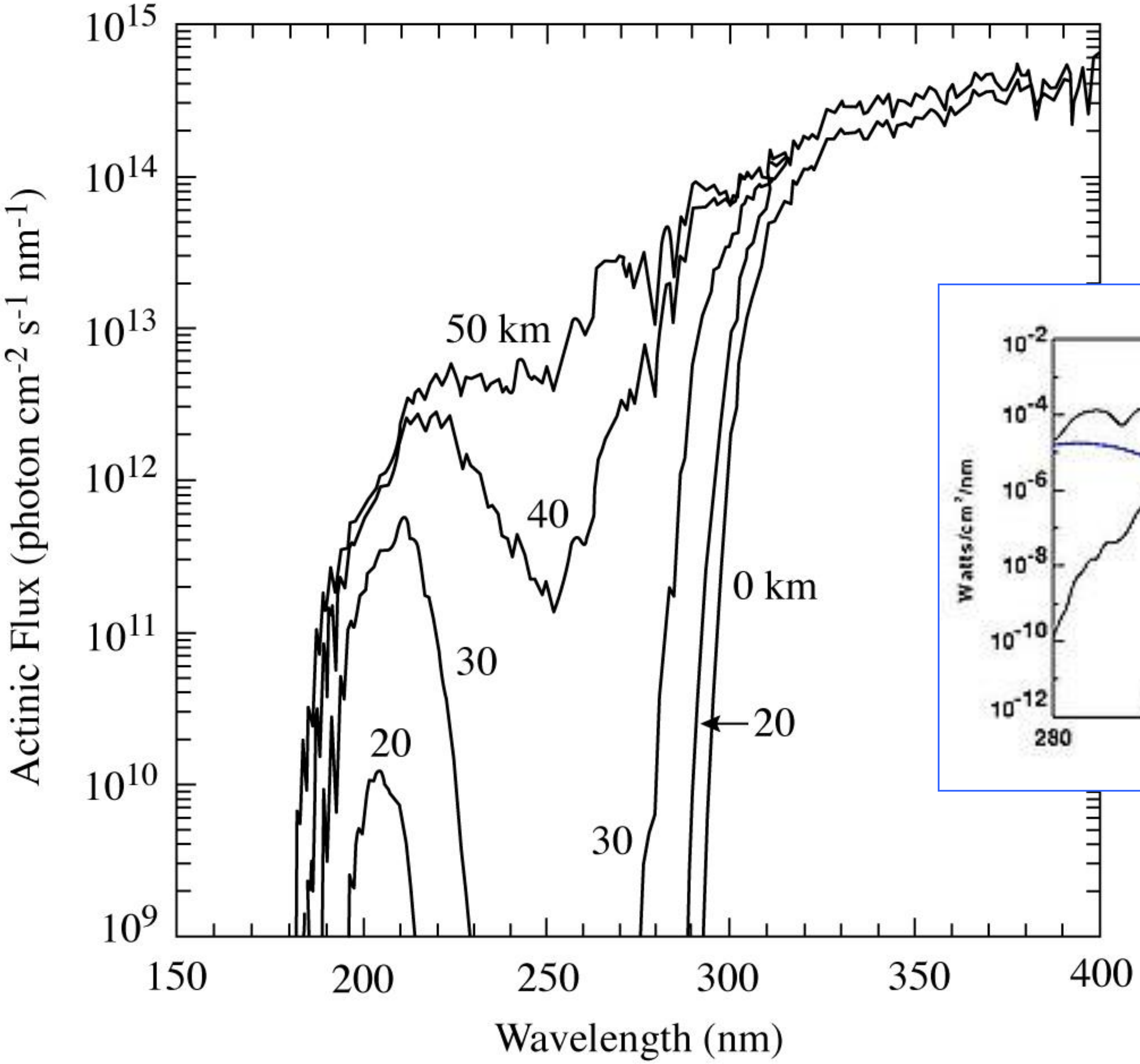
Ozone Layer Depletion

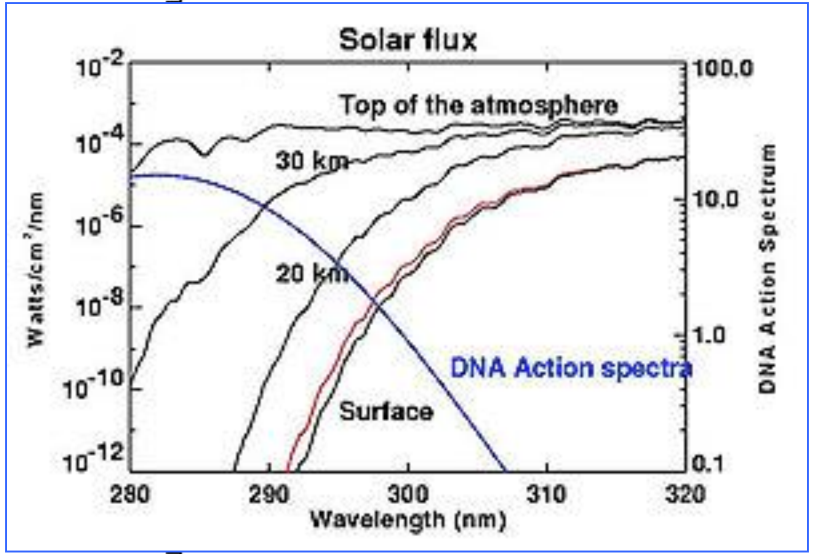
Stratospheric ozone and its importance

– *The 'hole' story*

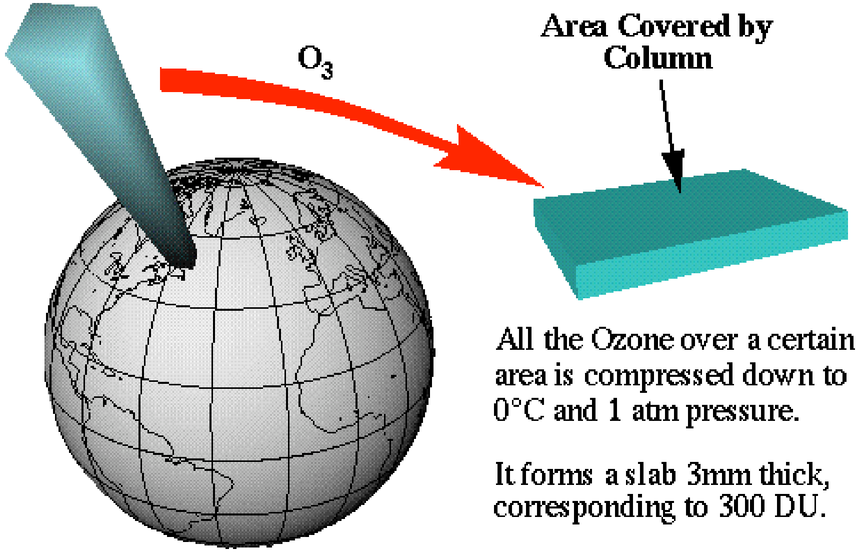
Atmospheric attenuation of SR

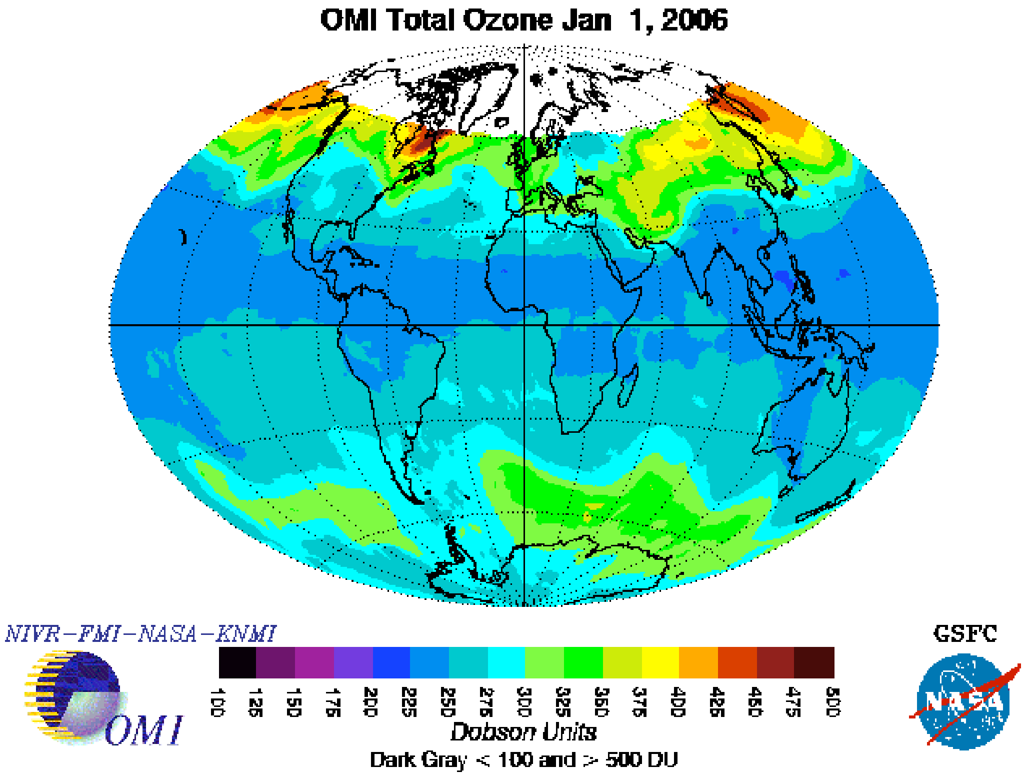
Solar UV radiation reaching the top of the atmosphere is absorbed by ozone





Dobson Unit





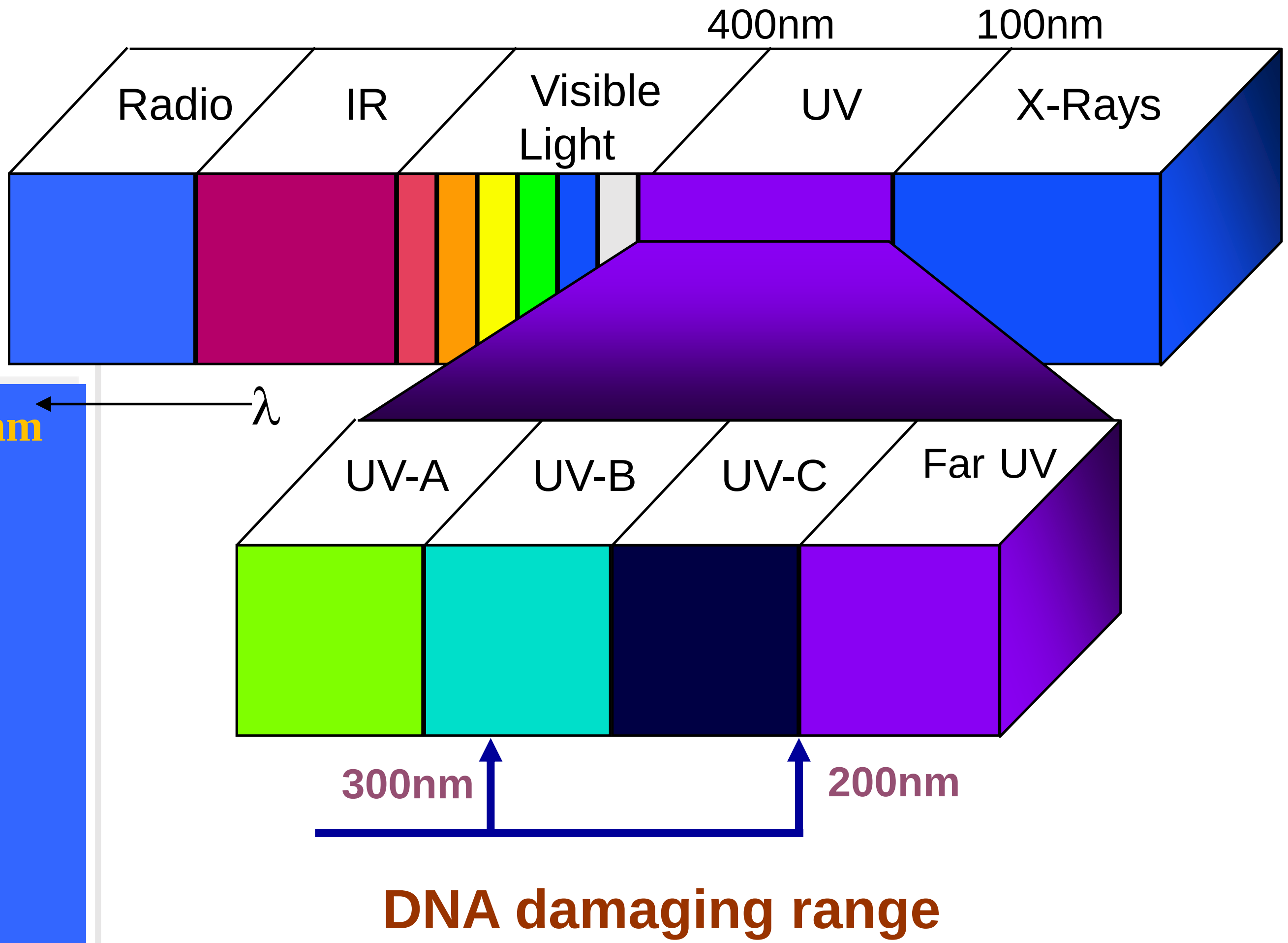
1 Dobson Unit (DU) is defined to be 0.01 mm thickness at stp; the ozone layer over Labrador is ~300 DU.

Mean ratio,
column O_3: air = 5 x 10^{-7}

Ozone in Stratosphere: Dobson Units (DU)

If 100 DU of ozone were brought to the Earth's surface, it would form a layer 1 millimeter thick. In the tropics, ozone levels are typically between 250 and 300 DU year-round. In temperate regions, seasonal variations can produce large swings in ozone levels. For instance, measurements in Leningrad have recorded ozone levels as high as 475 DU and as low as 300 DU.

The Ultraviolet Spectrum



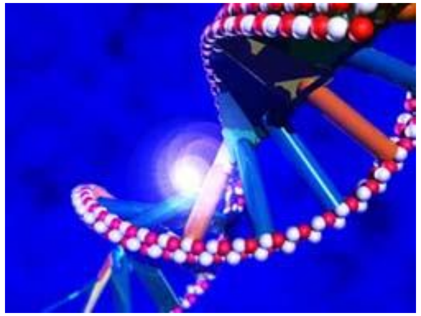
- **UV light: 100 to 400 nm**

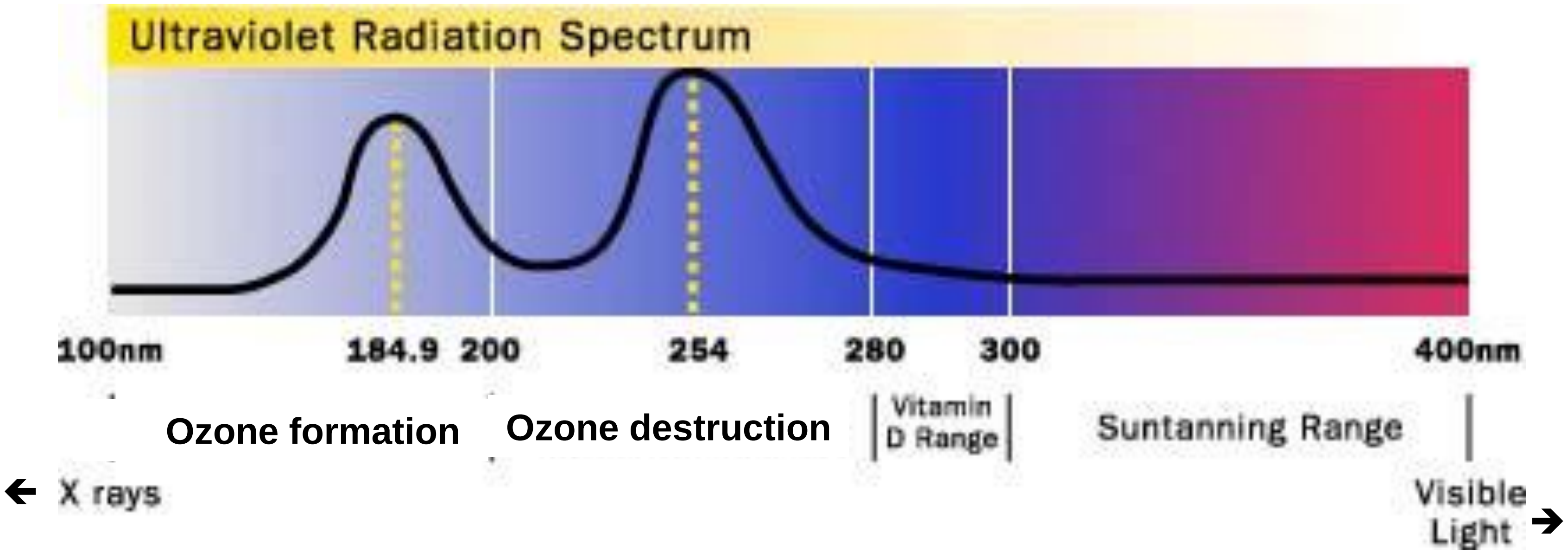
UV spectrum – 4 regions

- o Far UV: 100 – 200 nm
- o UV – C : 200 – 280 nm
- o UV – B : 280 – 315 nm
- o UV – A : 315 – 400 nm

Ultraviolet Radiation

- 230-280 nm damages nucleic acids
- Stops reproduction of cells by breaking apart the DNA bonds
- Ozone production peaks at 185nm
- Ozone absorbance and destruction at 200-320nm





UV ozone generation and destruction: equilibrium

- O_2 + $h\upsilon_{185}$ ➔ $2O^{\cdot}$
- $O^{\cdot}$ + O_2 + M ➔ O_3 + M
- O_3 + $h\upsilon_{254}$ ➔ O_2 + $O^{\cdot}$

Equilibrium between production and destruction

Chapman Mechanism

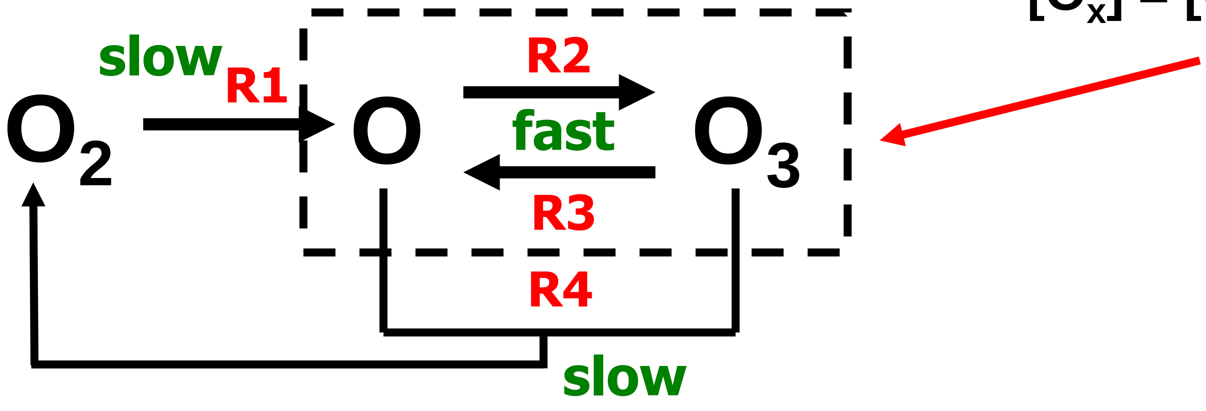
(R1) $O_2 + h\nu \rightarrow O + O \quad (\lambda < 240 \text{ nm})$

(R2) $O + O_2 + M \rightarrow O_3 + M$

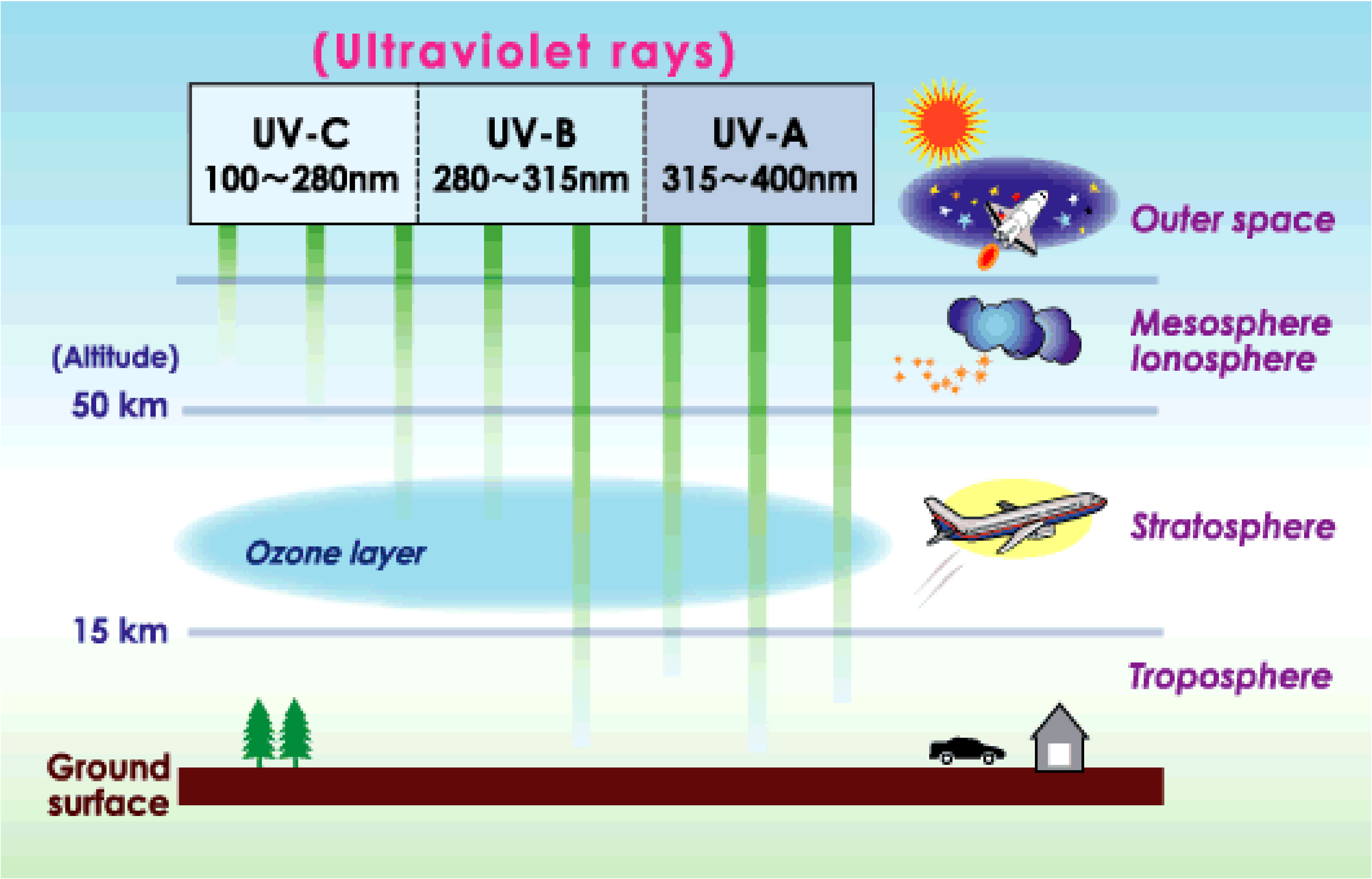
(R3) $O_3 + h\nu \rightarrow O_2 + O \quad (\lambda < 320 \text{ nm})$

(R4) $O_3 + O \rightarrow 2O_2$

Odd oxygen *family*
$[O_x] = [O_3] + [O]$



Atmospheric Layers

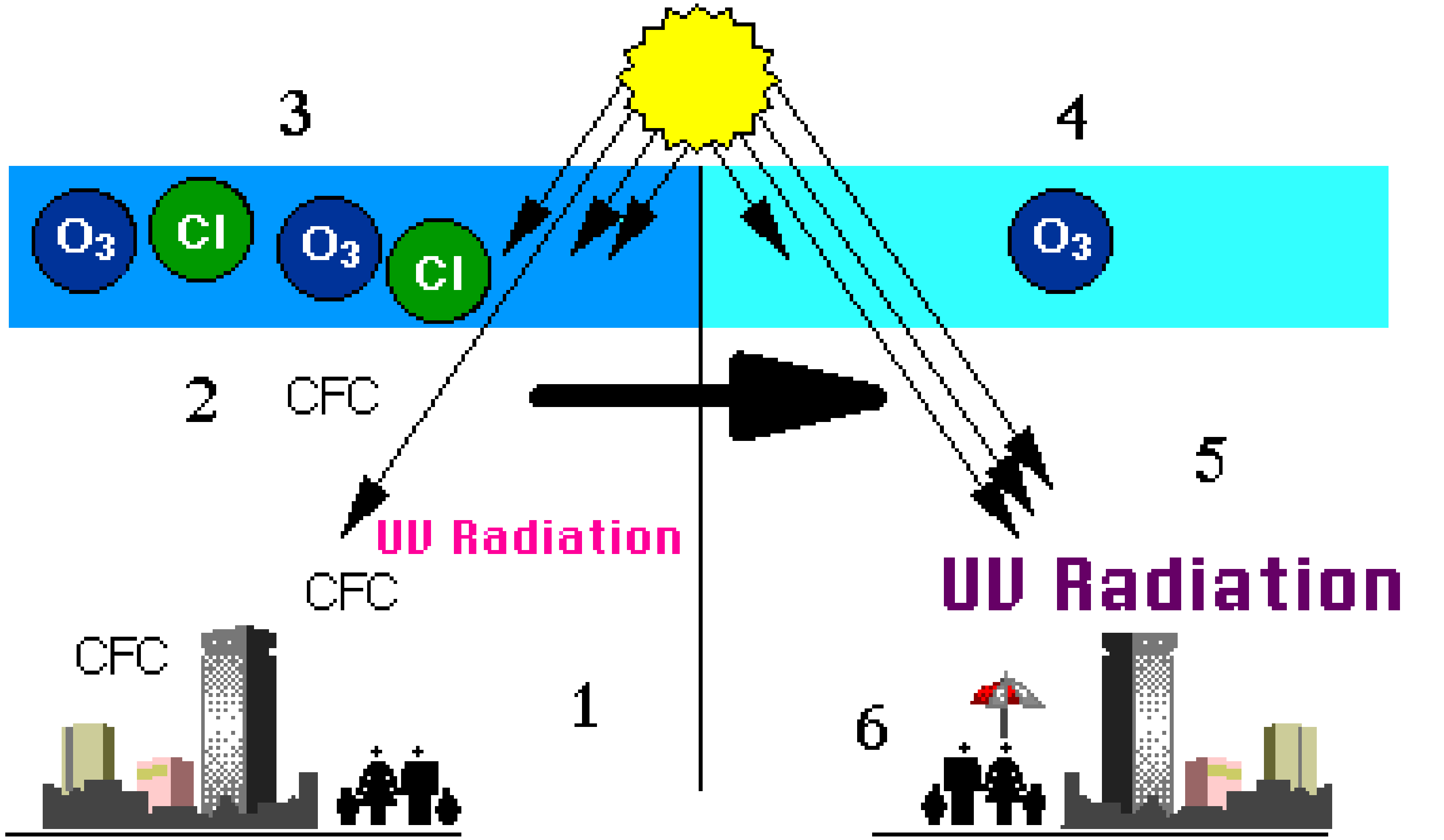


The catalyzed cycle of stratospheric ozone production and destruction

1. $h\upsilon + O_2 \rightarrow 2O\cdot$
2. $O\cdot + O_2 \rightarrow O_3$
3. $O_3 + X \rightarrow O_2 + OX$
4. $OX + O\cdot \rightarrow O_2 + X$

X could be Cl from a CFC

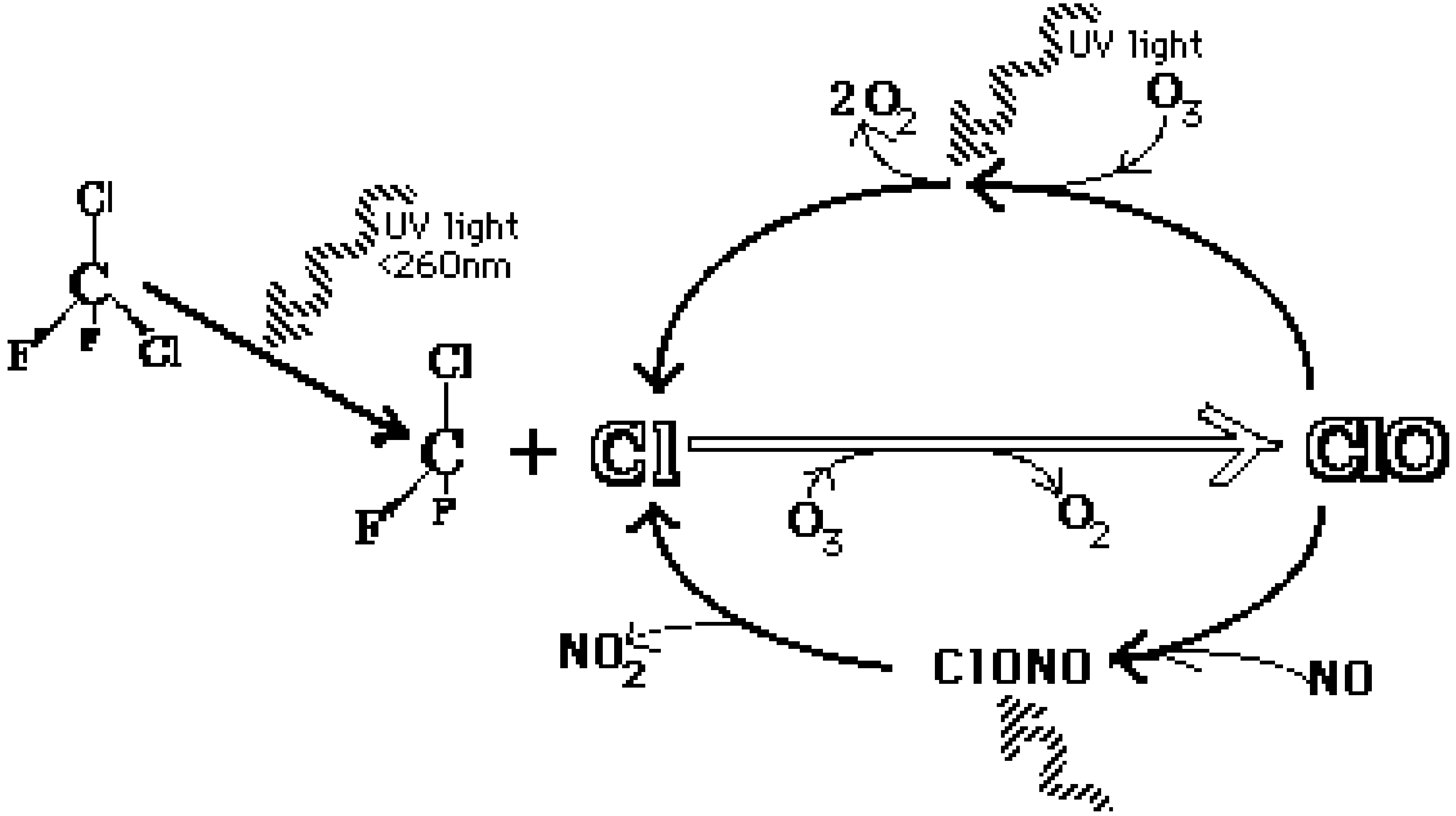
Ozone Depletion Process



1 - CFCs released
2 - CFCs rise into ozone layer
3 - UV releases Cl from CFCs
4 - Cl destroys ozone
5 - Depleted ozone -> more UV
6 - More UV -> more skin cancer

Halogen catalysis of ozone destruction

ozone:



Halogen removal from atmosphere

- $Cl + CH_4 \rightarrow HCl + CH_3\cdot$
- $ClO + NO_2 \rightarrow ClONO_2$

  Both HCl and $ClONO_2$ inactive: rain out
- $Br + O_3 \rightarrow BrO + O_2$
- $Br + CH_4 \rightarrow HBr + CH_3\cdot$

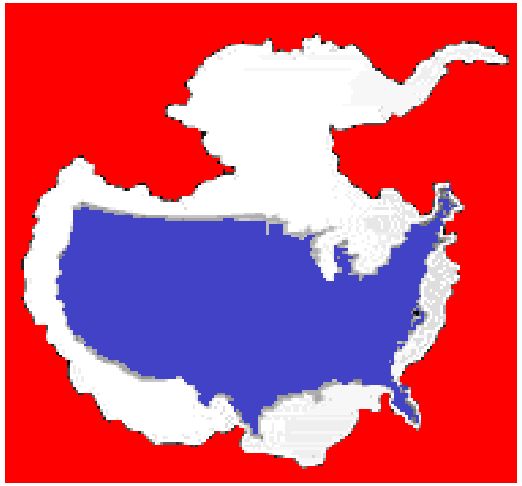
  HBr can photolytically provide Br again

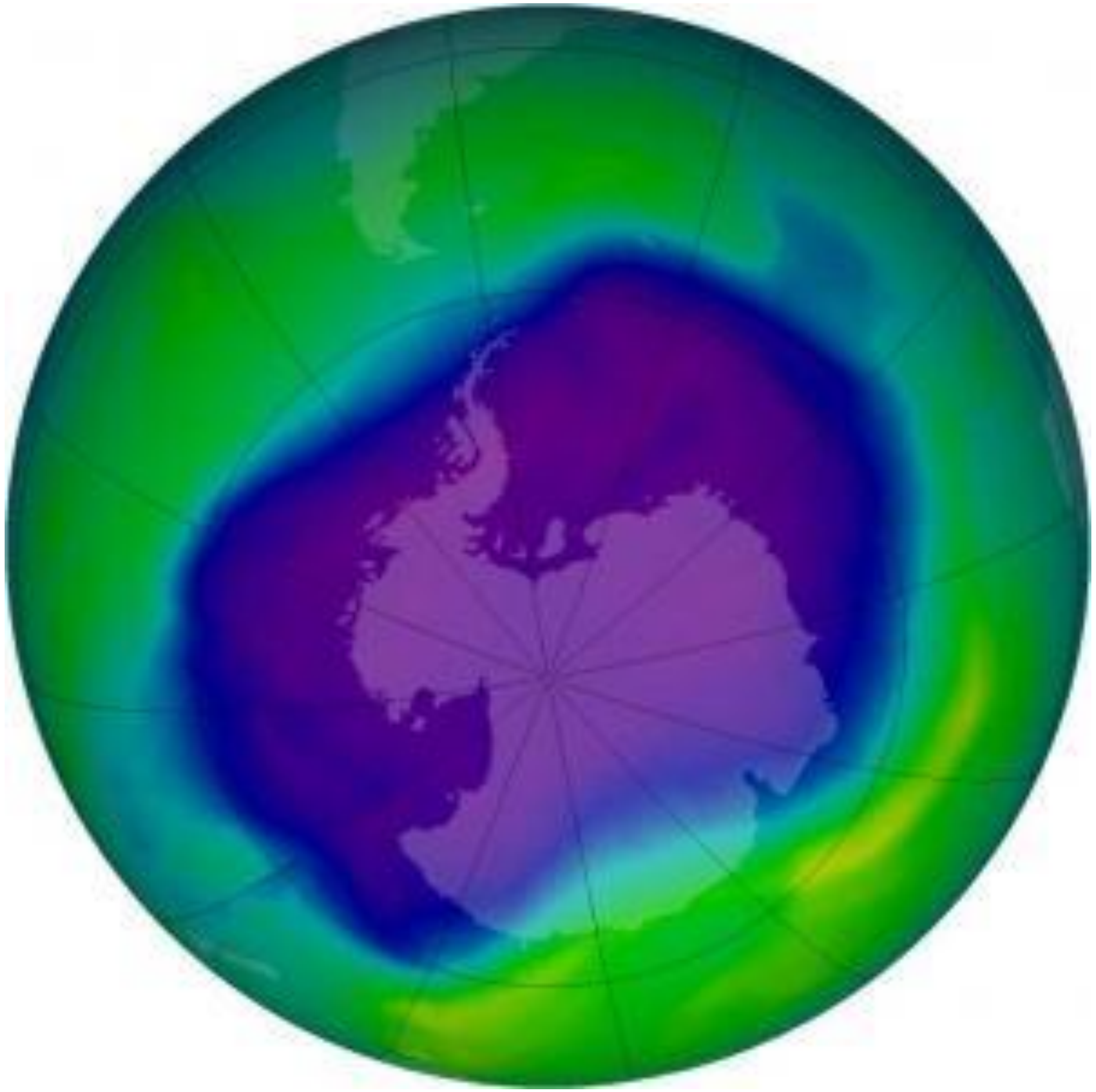
  Halons and CH_3Br provide Br

Ozone Depleting Substances

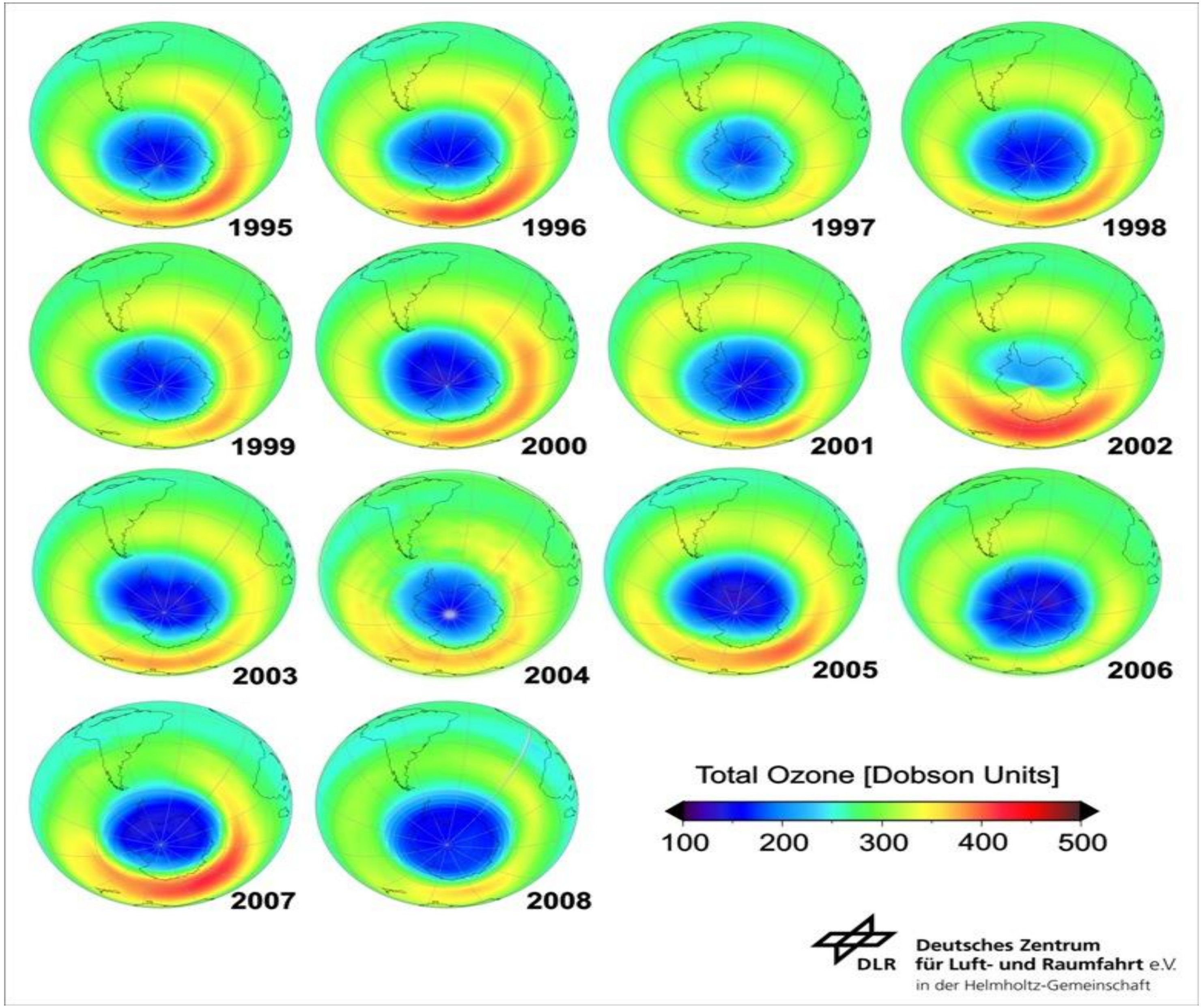
List of ozone depleting substances [**http://www.epa.gov/ozone/ods.html**](http://www.epa.gov/ozone/ods.html)

Record ozone hole, 2006

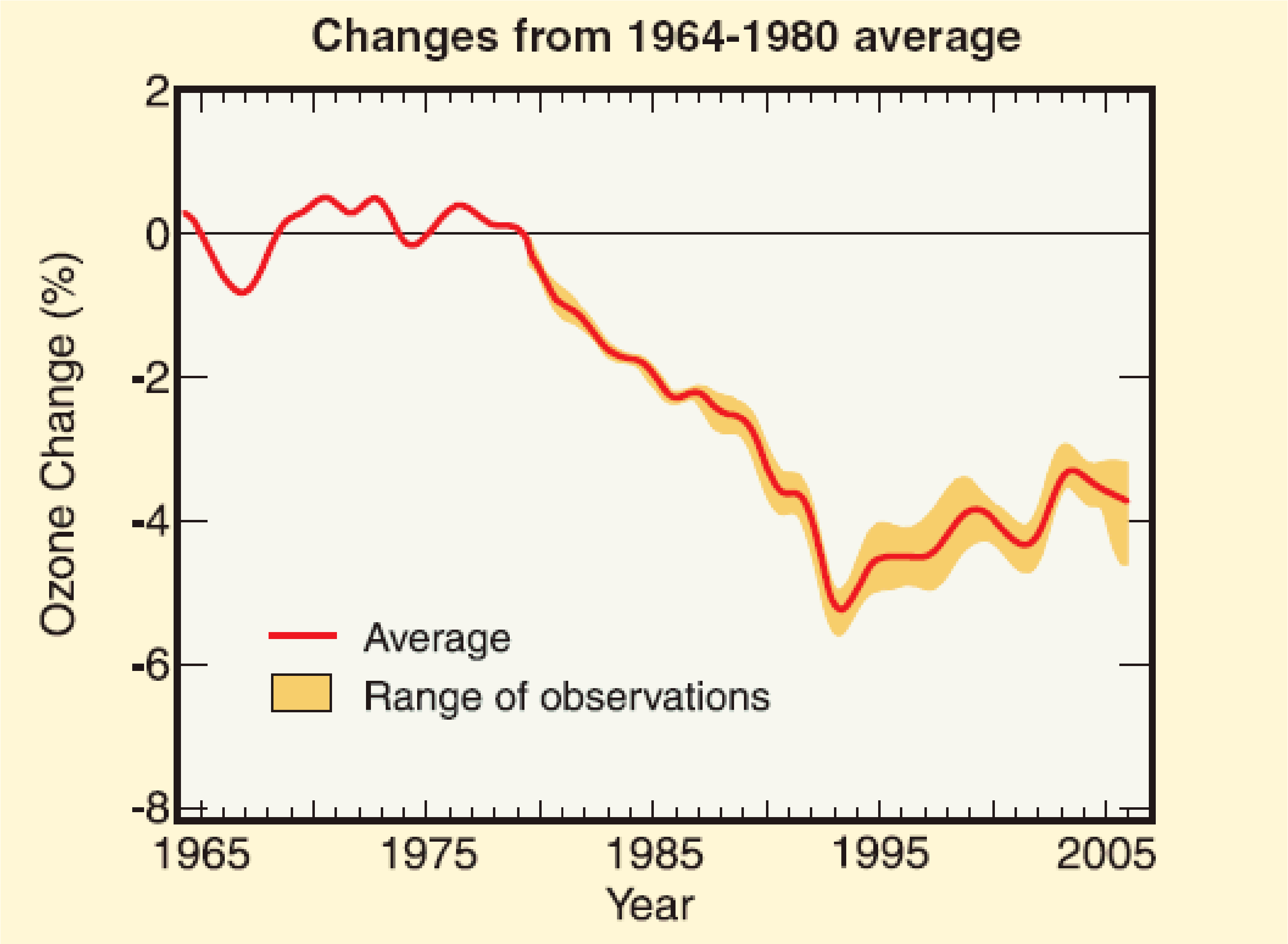




Evolution of ozone hole



Global total ozone change



Noble for Ozone hole explanation

The Nobel Prize in Chemistry 1995

Paul J. Crutzen

The Netherlands

Max-Planck-Institute
for Chemistry Mainz, Germany

1933 -

Mario J. Molina

USA

MIT, USA
Cambridge, MA

1943 -

F. Sherwood Rowland

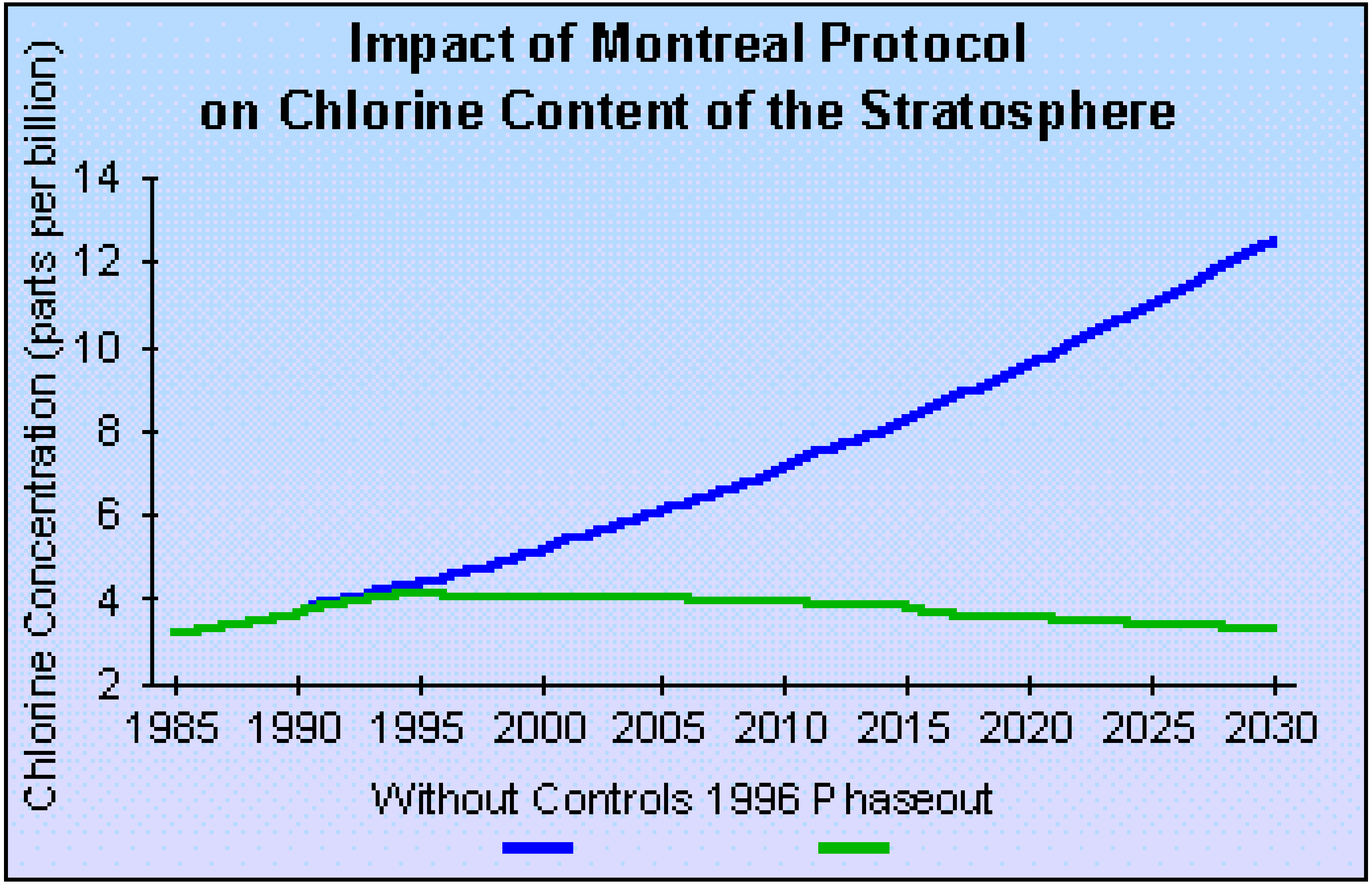
USA

Department of Chemistry,
University of California
Irvine, CA, USA

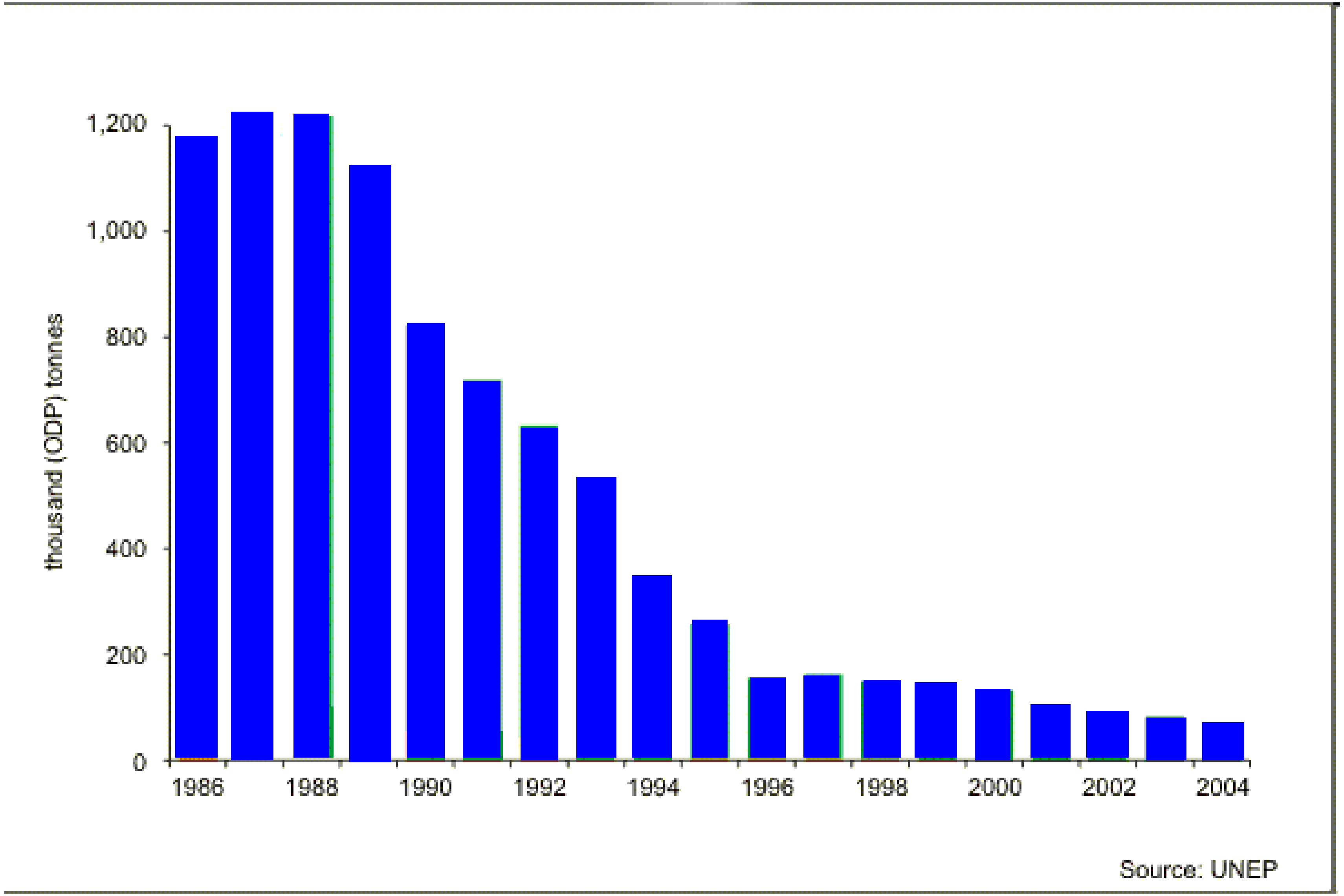
1927 -

"for their work in atmospheric chemistry, particularly concerning the formation and decomposition of ozone"

Impact of Montreal Protocol

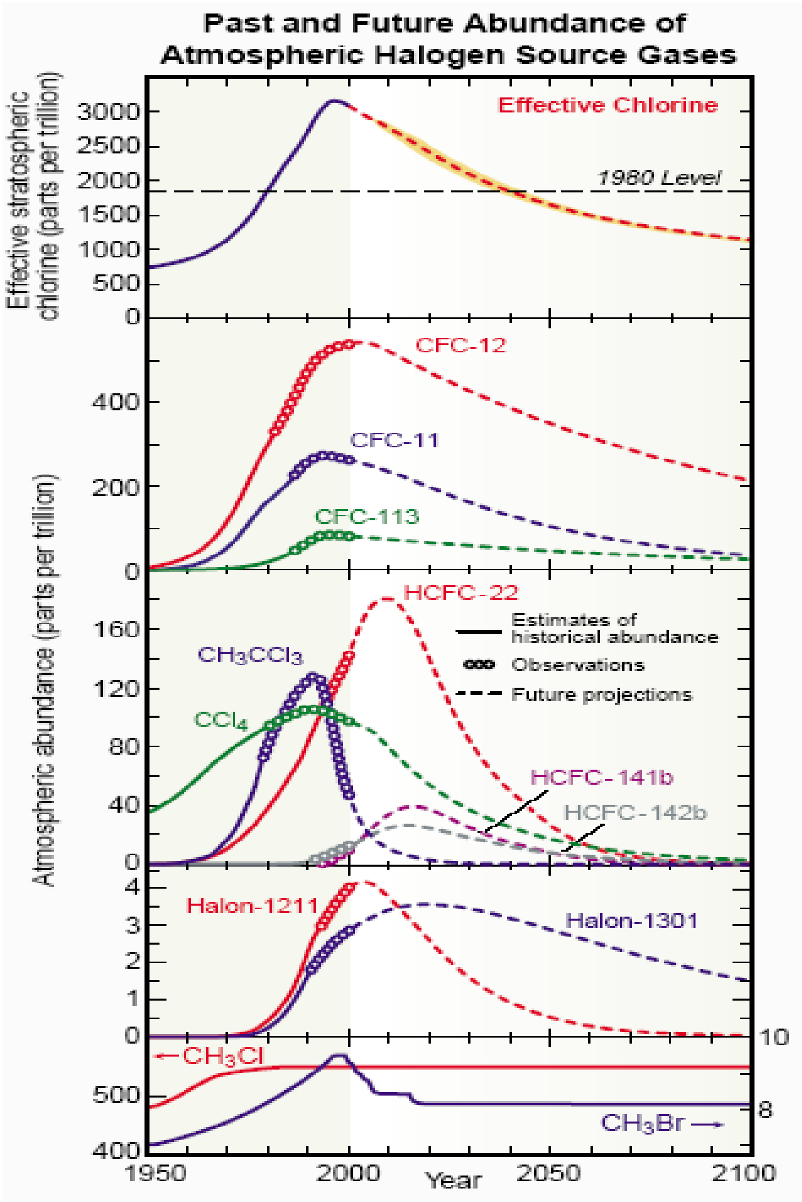


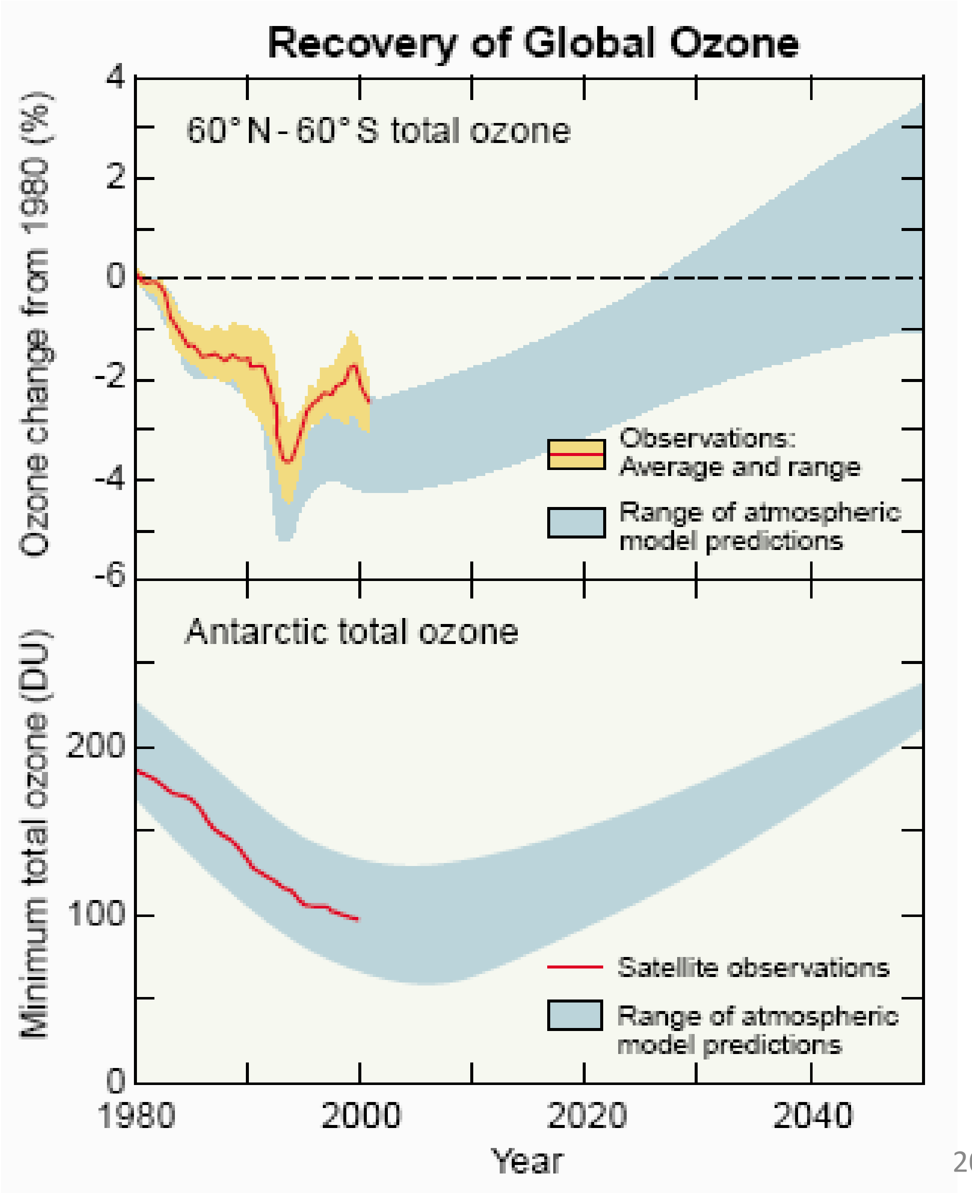
Impact of Montreal Protocol



World Production of CFCs

Impact of Montreal Protocol





Ozone layer recovery