EC 2113 - INTRODUCTION TO CLIMATE SCIENCE

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Important Feed back Cycles

21 Glacial - Climate Feedback, Terrestrial biomass feedback

40 Longterm feedback cycle - Carbonate - Silicate weathering
Seafloor spreading rate hypothesis

78 Bjerkenes feedback

Forces (Centrifugal, Coriolis, Frictional) - 51

Deflection of poleward moving & Zonal winds - 52, 53, 54

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Monsooon - 64, 65, 66

Western Intensification, ~~Boundary~~ Vorticity - 74, 75, 76

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INTRODUCTION TO CLIMATE SCIENCE

EC 2113 - Semester 3

2/9

Earth System

A system is a portion of universe under consideration. Boundaries of the system defines the limits.

System is characterised by whether it exchanges matter and energy with its surroundings (open/close)

Changes in one part affects other parts : coupling & feedback.

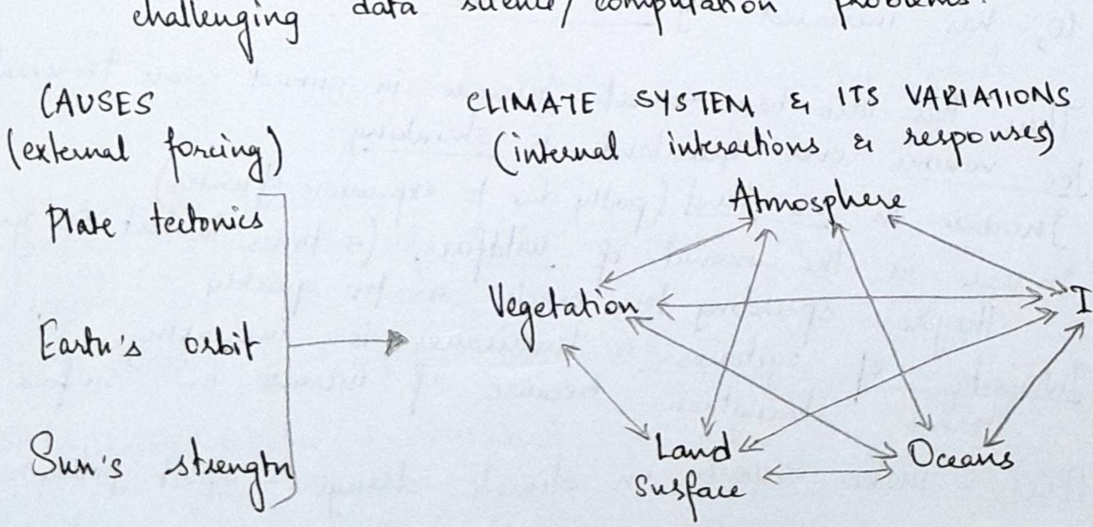
Components of Earth's Climate - Atmosphere, Hydrosphere, Geosphere and Biosphere.

Each of these spheres has its own processes and variables but they interact with other spheres across different timescales and spatial scales

How do we study Complex Systems?

- → Identify the components & their interaction
- → Study how fast components interact & how fast a change will propogate
- → Feedback loops : interactions that tend to dampen or amplify changes to the system.

Earth Science is interdisciplinary, relatively young & it has challenging data science/computation problems.



Each part of climate responds to forcing with a characteristic response time (can vary)

Eg: Atmosphere - hours to weeks
Ice sheets - 100 to 10,000 years

Fundamental Questions

- → Climate change in the past.
- → Evolution of life following changes in climate
- → Understand physical processes
- → Understand day to day variability of atmospheric conditions
- → Model & predict weather & climate
- → Climate change and its impacts.

Keeling Curve : Scripps Intitute (Since 1958)

Measures CO_2 conc. in Mauna Loa, Hawaii : proved the increase in CO_2 in atmosphere.

There's an annual cycle in CO_2 conc - decreases from April to Oct and then increases. Its due to variation in vegetation : CO_2 drawdown in summer due to growth of plants and then increase due to their decay.

Past Atmospheric composition from ice cores

Annual Layers of snow accumulation ~ 800,000 years old in Ant. ice cores. Trapped ice bubbles give amount of CO_2 in atmosphere and H & O isotopes tell us about temperature

These records show that recent increase in CO_2 is unprecedented

CO_2 has increased by 25% since 1800s.

Pioneer effect - rise in CO_2 b/w 1800 & 1850s due to deforestation of North America by westward expanding settlers

Confirmed by

- There has also been ~~annual~~ increase in annual mean temperature.
- Ice volume over Greenland is shrinking
- Increase in sea level (partly due to expansion of water)
- Increase in the amount of wildfires (5 times in last 50 years)
  They're spreading too much & too quickly → indirectly linked (flow)
- Intensity of cyclones & hurricanes is increasing because of increase in surface T.
  Storms strengthen

IPCC - makes Assessment reports on climate change - affect policymaking

03

Ch. 2
Earth System

Lecture 2 3/9/20

System Coupling and Feedback

In a system of two components, if they're related/linked in a way such that inducing a positive change in one will cause a positive change in the other, they're Positively Coupled. If the converse, they're said to be Negatively Coupled.

Self-perpetuating mechanism of change & response to that change

Feedback - special kind of system response as result of multiple couplings & produces changes in state of system.

* Positive feedback : enhances the initial ~~conditions~~ change leads to runaway effect
  +: amplify the effect of disturbance

* Negative feedback : counteracts initial change causes self-regulation in natural system & stabilizes it

If there are no negative couplings or an even number of them, the loop is positive

Earth receives only 1-billionth of energy emitted by sun

Planetary Energy Balance

What decides the equilibrium temperature of planet is net difference between incoming and reflected radiation.

Main factors -

* 1. Distance from the sun (influences amount of incoming radiation)
2. Albedo
3. Greenhouse effect due to its atmosphere.

Equilibrium state - state of system which will not change unless disturbed

Planetary Albedo

Fraction of solar radiation reflected by the planet.

Earth-Atmosphere system reflect about 30% of incoming solar radiation. (Sand : 0.2-0.3, Fresh snow : 0.80-0.85)

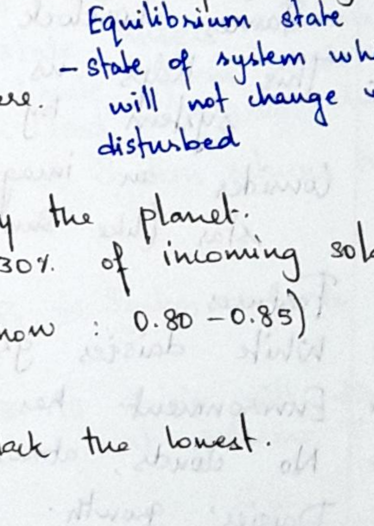
Total albedo : $\alpha = 0.3$

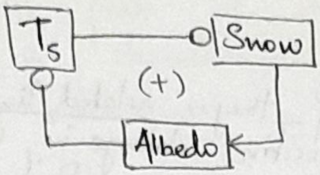
White surface has highest albedo & black the lowest.

Ice-Albedo Feedbacks

Suppose Temperature of Planet increases -↑

1. Snow covers will reduce
2. ↳ Albedo of of planet will increase
3. ↳ More radiation is absorbed
   ⇒ Temp increase



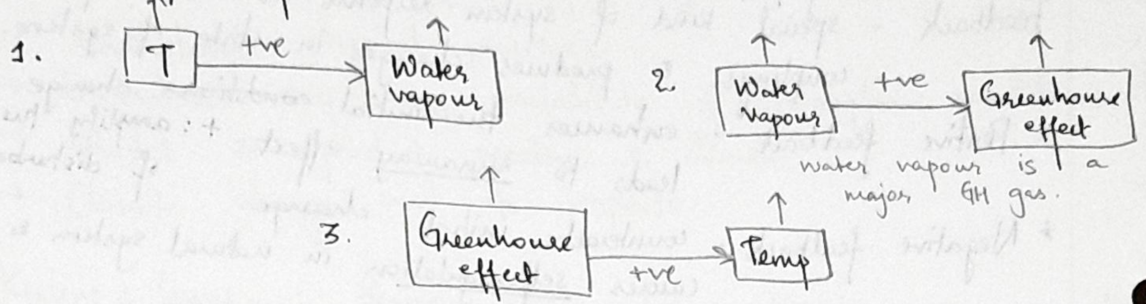


Two -ve & one ~~+ve~~ coupling gives Net positive feedback

Unchecked +ve feedback creates a runaway ("snowballing") condition.
↳ Consider the opposite case T of earth goes on decreasing

* Life itself is responsible for maintaining the stability of Earth's climate i.e biota plays an integral role in regulating climate

Water vapour feedback.



water vapour is a major GH gas.

⇒ 3 positive couplings ⟶ Net positive feedback.
This is considered a major climate change problem.

Daisy World

James Lovelock - 1983 : in response to critique over Gaia hypothesis*

This helps us understand the self-regulation of planetary system by Negative Feedback.

Consider an imaginary planet (like earth) orbiting around a star (like Sun) at same distance

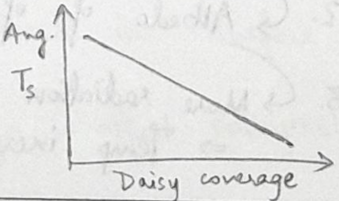
Features

- ★ White daisies growing on <u>black soil</u>
- ★ Environment has a single variable (Temp) & one species
- ★ No clouds, atmosphere, greenhouse gases.
- ★ Daisies' growth is only dependant on temp.
- ★ Planet's ~~albedo~~ Temp. is dependant on solar luminosity (fixed) and the planet's albedo. Reflectivity of a surface ↓

Daisy coverage affect planet's temp as it increases albedo.

Described by -

$$\alpha_p = A_{bare}\,\alpha_{bare} + A_{white}\,\alpha_{white}$$



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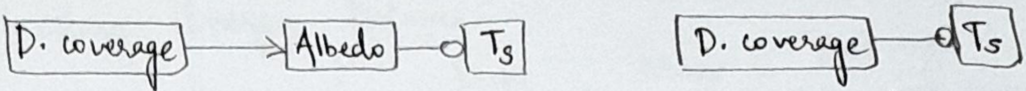
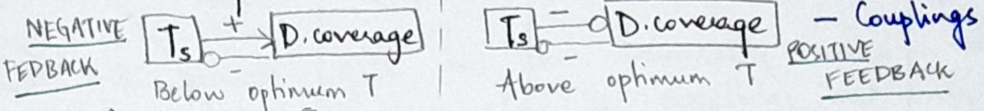
Daisy coverage - Temp Coupling

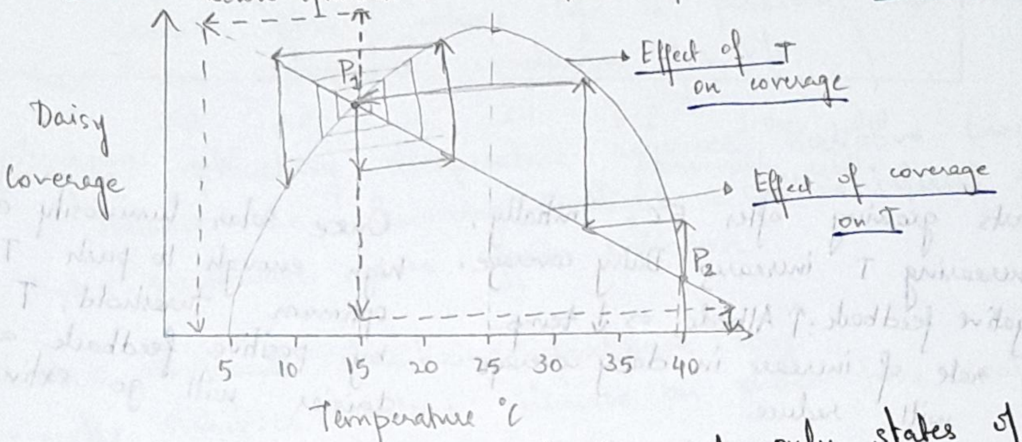


Daisies can't grow below 5°C or above 40°C.

Optimum temp = 25°C   WHY ? — upper & lower T limit, optimum T

Growth rate of daisies is <u>assumed</u> to be parabolic functn of T.





P_1 and P_2 (intersection points) represent only states of the system that shows both the effects.

At these states, the system is said to be in equilibrium i.e. system will remain in that state unless someone disturbs it.

∃ thresholds within climate system which when surpassed can lead to abdrupt changes

Perturbation - temporary disturbance of the system

Forcing - More persistent perturbation of the system

* Small perturbation in Daisy coverage at P_1 ⇒ System returns to P_1
⇒ P_1 : Stable equilibrium point

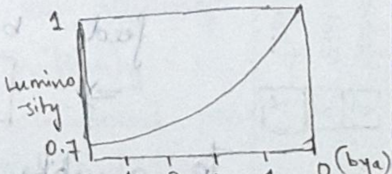
* Small perturbation in Daisy coverage at P_2 ⇒ System moves to P_1

* Large perturbation in Daisy coverage at P_1 ⇒ All daisies will die at extreme T

This is called <u>Threshold behaviour</u>

Response of Daisyworld to perturbation depends on ↑ its T

Solar Luminosity



Its the ~~avg~~ <u>major external forcing</u>.

Earth receives only one-billionth of energy emitted by photosphere.

Solar models : Since 4.6 by, Sun has become 30% more luminous.

Fusion of H → He decreases pressure in core, but its maintained by energy released :- core contracts & heats up ⇒ rate of fusion increases.

In another 5by sun will be 2-3 times brighter.

Response of Daisy world to increase in solar luminosity

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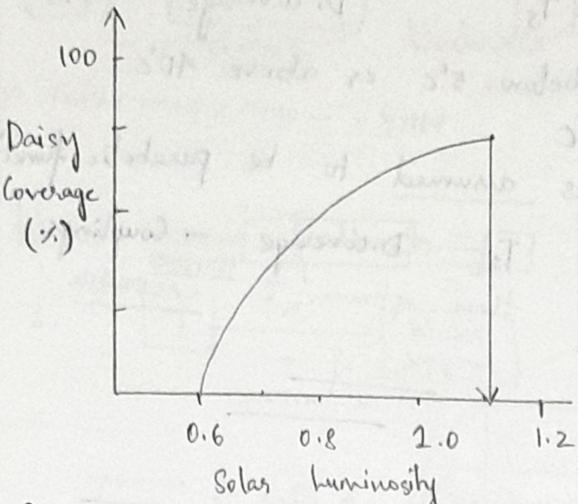
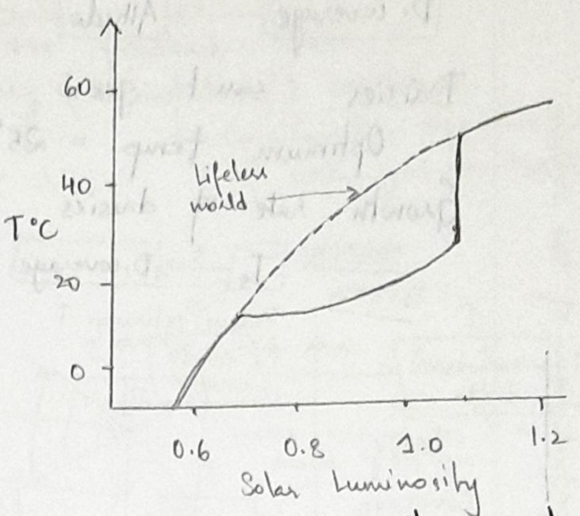
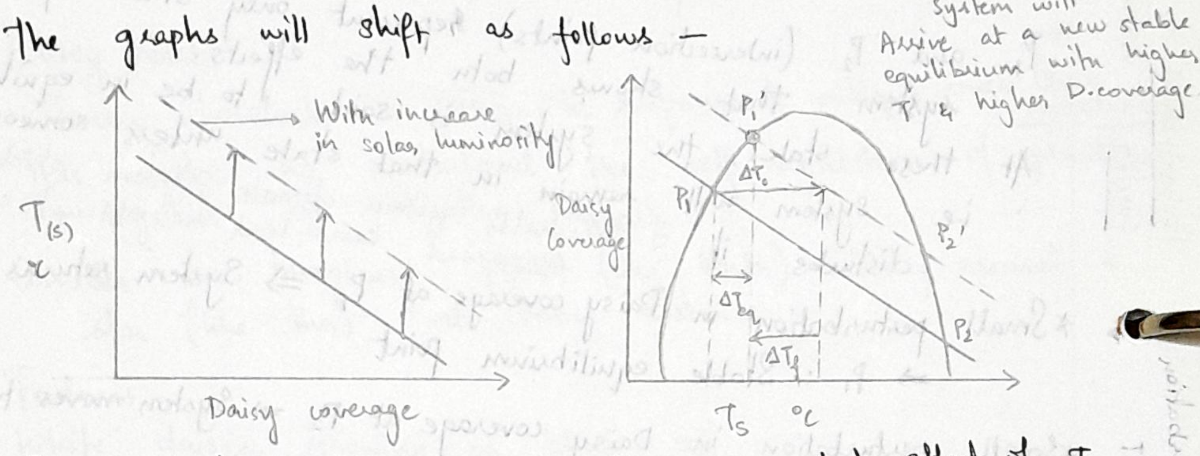




Starts growing after 5°C. Initially, increasing T increases Daisy coverage. Negative feedback: ↑ Albedo ⇒ ↓ temp So rate of increase in daisy coverage will reduce

Once solar luminosity exceed high enough to push T over optimum threshold, T increases by positive feedback and daisies will go extinct.

The graphs will shift as follows —



For all values of D. coverage, T increases but effect of T on Daisy remains unchanged.

Overall increase in equilibrium T is sum of ΔT_0 without feed back and ΔT due to feedback (-ve in this case)

$$\Rightarrow \boxed{\Delta T_{eq} = \Delta T_0 + \Delta T_f}$$

To quantify the strength of feedback, we define —

Feedback factor : $\boxed{f = \frac{\Delta T_{eq}}{\Delta T_0}}$ $f \in [0,1]$: -ve loop

$f > 1$: +ve loop

It can only be defined for systems with stable equilibrium

Lessons from Daisyworld:

1. Natural systems with feedback loops tend to self-regulate
2. Biota don't/can't optimise their environments - just regulate, that too not indefinitely
3. There exist threshold levels, beyond which, a system has to seek a new equilibrium.

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Ch.3
Earth
System

Lecture 03

Planetary Energy Balance.

Flux - amt of energy passing through given area

	Venus	Earth	Mass
Distance	0.72AU	1AU	1.5 AU
Albedo	78%	30%	17%
T_s	464°C	15°C	-63°C

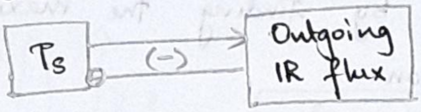
40% of suns radiation falls in IR spectrum
10% - UV

These 3 planets fall in the favorable zone - distance from star where life is possible. But only Earth has an atmosphere conducive for life.

Constant planetary temperature requires Radiative Energy Balance i.e. Incoming sunlight = emitted infrared radiation

But greenhouse gases affect radiation

Earth's dominant stabilizing feedback loop
It stabilises earth's climate on short time scales.



Major factors - Distance from sun
Planetary albedo
Greenhouse Effect

All objects above absolute 0 K emit EM waves, based on their temp.

Sun's radiation : 8% UV rays
47% Visible light
45% Infrared waves

At thermal equilibrium, emissivity of a body is equal to its absorptivity
⇒ A good absorber is a good emitter

Blackbody : Hypothetical body which absorbs and emits EM waves of all wavelengths with 100% efficiency

By Kirchoff's law - Absorptivity = 1 & Emittivity = 1

The sun and other planets can be considered as black bodies over a certain range of EM radiation wavelengths without getting a considerable error in our calculations.

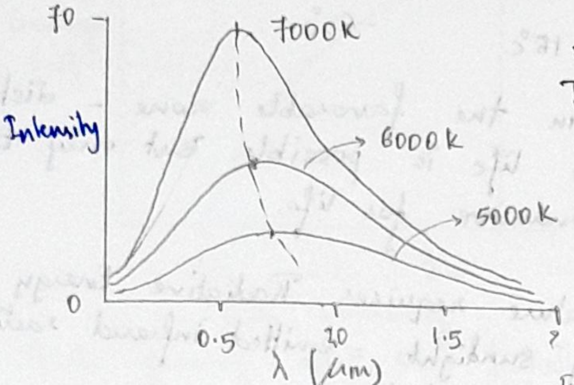
Black Body Radiation

1. Planck's Law : Intensity of radiation emitted by a black body of temp. T at wavelength λ is –

$$\boxed{B_\lambda(T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{ch/\lambda kT} - 1}} = \frac{c_1}{\lambda^5 \left(e^{c_2/\lambda T} - 1\right)}$$

$c_1 = 2hc^2$

$c_2 = \frac{ch}{k_B}$



As T increases, peak of Planck's function moves towards shorter ~~per~~ wavelengths

Distribution of intensity vs λ

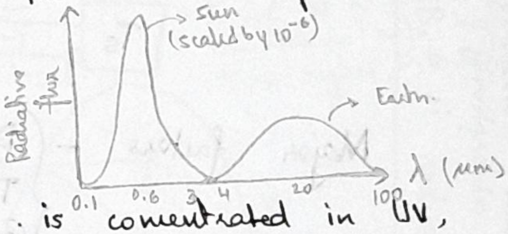
Blackbody radiation curve

2. Wein's Displacement Law

→ Explains why solar radiation is in UV, visible and near-IR region while planets emit radiation in IR spectra

The wavelength at which black body emits maximum intensity of radiation varies inversely with T.

This can be proved by finding the maxima of Planck's function.



We get: $\boxed{\lambda = \frac{2.9 \times 10^{-3}}{T} \text{ m}}$

This explains why solar radiation is concentrated in UV, visible and IR regions, while planets emit radiation mostly in IR region. Useful to predict the λ at which most of the radiant energy is emitted

3. Stefan - Boltzmann Law

Total radiant energy emitted by unit surface element of black body per unit time can be obtained by integrating Planck's function over all wavelengths.

$$\boxed{B(T)} = \int_0^\infty B_\lambda(T)\, d\lambda = \boxed{\sigma T^4}$$

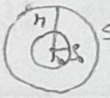
$\sigma = 5.67 \times 10^{-8} \text{ Wm}^2 \text{ K}^{-4}$

Energy flux emitted ∝ fourth power of absolute temperature

Flux – energy that passes through a perpendicular unit surface area per unit time.

Inverse Square Law : Flux decreases with increasing distance

$S = S_0 \left(\frac{r_0}{r}\right)^2$



T_s : temp at photosphere.

Flux emitted from photosphere : $\boxed{S_0 = \sigma T^4}$

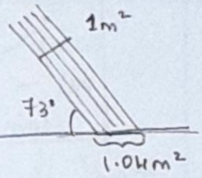
Total radiation emitted by total area of photosphere $= 4\pi R_s^2 S_0$

At a distance of earth's orbit ($R_{SE} = 1AU$) from sun, the flux is reduced.

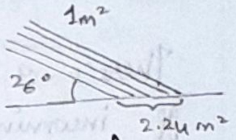
$S = S_0 \left(\frac{R_S}{R_{SE}}\right)^2$ S = 1368 W/m²

At a distance of 1.5×10^{11} m, earth intercepts less than 2-billionth of radiation emitted by the ~~sum~~. sun

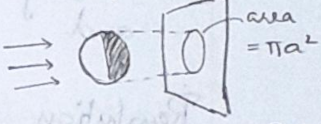
Due to spherical shape of earth, the solar flux intercepted decreases as a function of latitude



Maximum at equator, it decreases as a function of cos (?)



Since earth is a rotating sphere, it intercepts a fraction of radiation received at its orbit.



$\boxed{S_E = \pi R_E^2 S}$ where R_E = 6.371 km

The earth-atmosphere system has an albedo of 30%. ⇒ $\alpha = 0.3$

⇒ Radiation absorbed by earth per unit time $= \pi R_E^2 S(1-\alpha)$

To be at thermal equilibrium, it emits the same amount of energy per unit time

T_E : effective emission temperature of earth.

$$\Rightarrow \boxed{4\pi R_E^2 . \sigma T_E^4 = \pi R_E^2 S(1-\alpha)}$$

$$\Rightarrow T_E = \left[\frac{S(1-\alpha)}{4\sigma}\right]^{1/4} \Rightarrow \boxed{T_E = 255K = -18°C}$$

If earth were a black body

But observed mean surface temp. of earth is 288 K (15°C)

This difference is due to the greenhouse ~~gas~~ effect.

T_E : Effective radiating temp. — temp that a true blackbody would need to radiate the same amt of energy that earth radiates

In this case, greenhouse effect is not considered

Ch.1 Earth's climate past & future

1-layer Atmosphere Pg-25

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⑩

Lecture 04

Planetary Energy Balance Equation

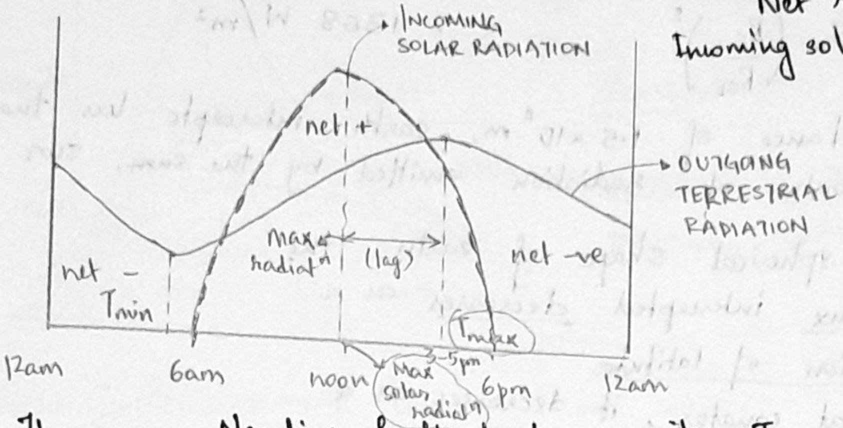
Faint ★ Leaky Greenhouse model Tutorial 01 - Pg 5

$$\pi R_E^2 S(1-\alpha) = 4\pi R_E^2 \sigma T_E^4$$

Diurnal cycle of solar and Terrestial Radiation

Because of rotation of earth, only half of it receives solar radiation.

Net radiation = Incoming solar - Outgoing terestrial



Why the lag?

There's a Negative feedback loop with T_s and Outgoing IR flux. If incoming radiation is greater than outgoing (net >0), then surface temp increases ie. from 6 am to 3-5 pm (Locally); and vice versa.

Revolution of earth around the sun causes annual variations in temperature; as the earth is tilted at ~23°c wrt the orbital plane, these variations are opposite in the two hemispheres.

Solstices - 21/6 & 22/12 — most radiation Tropic of Cancer or Capricorn

Equinox - 21/03 and 22/09 — Most radiation at equator

The hemispheres also have an annual temp cycle ie. in Northern hemisphere, T increases from Jan to June-July and then steadily decreases.

It gets maximum solar radiation in June but maximum temp. is seen about a month later, in July.

There is a planetary balance because while N. hemi has summer and S. hemisphere has winter. In a longer timescale, the planet is in a steady temp state.

⑪

Climate Forcing

Factors which can <u>change</u> <u>Earth's radiative equilibrium</u> that would cause Earth's surface temperatures to rise or fall over decadal periods are called climate forcings.

Types –

1. External forcing
   - i) Earth's <u>orbital</u> changes – occurs over 10k–100k years; it affects the amount of solar radiation received.
   - ii) Changes in <u>Solar Energy</u> – Luminosity has steadily increased; Sun-spots and sun cycles

2. Internal forcing
   - i) <u>Tectonic processes</u> – can alter basic geography & hence affect albedo, greenhouse gases etc. Occurs over millions of years
   - ii) <u>Volcanic eruptions</u> – Greenhouse gases, albedo
   - iii) <u>Ocean circulation</u> – uptake of CO_2

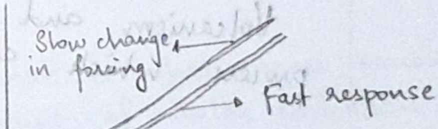
3. Internal feedback forcing

   Eg: <u>Ice-albedo</u> feedback, <u>volcanic dust-radiation effect</u>, <u>ocean-atmosphere</u> coupling etc.

Very Slow forcing compared to Response Time

Eg: Increase in Sun's luminosity, Tectonic scale changes

When it's so, the climate gets a chance to respond and change itself because it's <u>response</u> time is much faster than the forcing



Faint Young Sun Paradox

If we consider all other factors remained constant, while only solar luminosity has increased by 30%. – the earth should have been <u>frozen prior to 2 bya.</u>

But we know that it wasn't so because oldest dated sedimentary rock is 3.8 by old ⇒ earth supported running water.

Organisms which need liquid water to survive have been around for 3.5 by.

But geologic and evolutionary astr evidence indicates earth has maintained a short temperature range (~10°c) throughout its history.

Stromatolites - sedimentary rocks formed on mounds of cyanobacteria earliest fossil evidence of life (~3.5 bya)

First appearance of glacial deposits - 2.5 bya

The solution is that conc. of CO_2 in early earth was much greater than its now ⇒ greenhouse effect was seen to a great extent; but as sun's luminosity increased, CO_2 in atmosphere reduced and this has helped in maintaining earth's temp.

Gaia Hypothesis

Lovelock and Margulis in 1980s proposed that biotic factors have been responsible for regulating Earth's climate.

Extreme view: Earth is a living, self-regulating entity

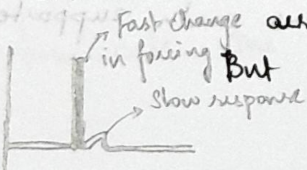
Using Daisy world, they showed that planetary self-regulation can emerge automatically from realistic feedback between life and environment.

Evolution of complex life forms kept a check on CO_2 concentrations, so T didn't rise much even with increasing luminosity

* Earth's climate has been largely coupled with amount of CO_2.
Volcanism and chemical weathering are two abiotic process which control input and removal of CO_2, respectively.

⇒ A sudden but large forcing causes a small response (slow)
Eg: ★ Solar eclipse - all radiation is cut off for a while it causes a very small response.

★ Volcanism - Eruptions can last 2-3 days and generate dust and aerosols that scatter incoming radiation.
But its affects doesn't last longer than a few years.



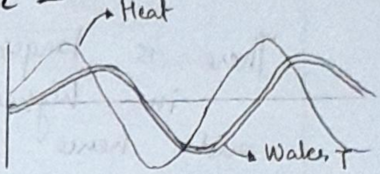
⑬ # Wilson Cycle - large period cyclic forcing - 500 million years.
Past Cycle - Refer Pg. 39

→ Cyclic Forcing

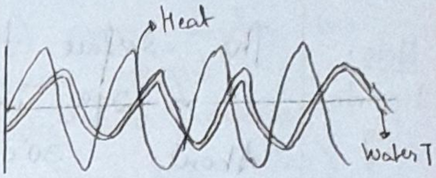
When timescales of forcing and climate response are similar

Most natural climate forcing are cyclic -

Eg: Solar cycles, orbital cycles.



Amplitude of climate response is related to the time allowed to attain equilibrium - i.e rapidly varying forcing will generate a smaller response.



1. Solar Cycles
- Approx. every 11 years, Solar magnetic feild flips
- In between flips, total solar irradiance waxes and wanes in a semi-regular cycle by upto 0.15% (1365 - 1367 W/m²)
- Substantial change in UV portion of solar spectrum
- Effect of these changes on past T is small.

2. Earth's Orbital Variations

Change in eccentricity of orbit, obliquity of ecliptic and (precession) wobble of the axis changes the solar radiation received at top of atmosphere.

This causes Milankovitch cycles in climate.

* Internal feedback forcing is what causes real impact because whatever be the initial forcing, the feedback takes over and transfers it from one component of system to the others.

15/9/20

Ch 14 Earth System

Lecture 05

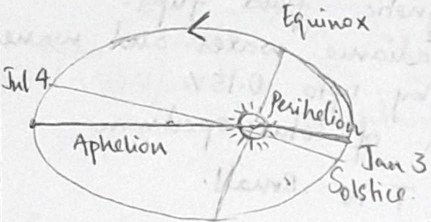
Recall: The revolution of earth around sun is what causes seasons. The tilt of earth varies the amount of solar radiation received at different latitudes.
- Equator : Receives maximum solar radiation twice a year
- Tropic of Cancer/Capricorn (23.5°) : Receive max. solar radiation once a year. They maintain a temperate climate throughout the year
- Polar regions : They receive diffused sunlight half the year and nothing the other half.

From Equator to poles, the changes in seasons due to amt. of radiation is received. ↳ intensity of

There is larger annual variation in insolation / temperature in higher latitudes – we observe distinct seasons and hence distinct vegetation.

Note: 1-month's lag

The surface temperature of Arctic circle varies from ~ -27°c in January to about ~7°c in July. About 30°c of variation.

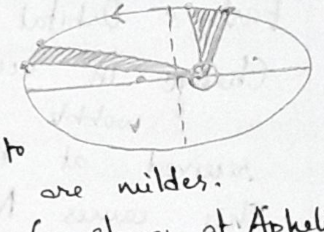


Earth's eccentric orbit.

- Perihelion (153 M km) – clossest distance
- Aphelion (158 M km) – farthest difference

There's a 3% difference in distance and this affects the amount of solar radiation received by 5-6%.

Recall Kepler's Second Law: Areal velocity remains constant



Perihelion occurs on Jan 3rd, 13 days after N. Hemisphere winter solstice (as opposed to Jul 4th ⇒ 13 days). So, NH's winters are milder.

* As the planet moves faster at Perihelion (& slower at Aphelion), we have a shorter winter (& a longer summer ⇒ 186 days).

A Breathing Earth

- This refers to the annual coverage of snow – how it declines and increases.
- In high latitude, snow deposits in winter and melts in summer. If summer insolation is less, all the snow will not melt away and more snowfall accumulates on top of it.
- Greenland and Antarctica have perennial ice cover, as temp stays subzero even in the summer.
- The Arctic and Antarctic sea ice also follow a cycle – it's maximum in March / September & vice versa.

Continental Glaciers

- They're made of accumulated snow, over many years, compresses into large, thickened ice masses.
- Ice sheet - Glacial land ice extending more than 50,000 km².
  Eg: Antartic and Greenland ice sheet.
- The Glaciers (mountaineous ones especially) moves slightly under the effect of Gravity due to their own weight.
- Historic glaciers pushed and dragged rocks and debris, ganging deep grooves and forming valleys (Leh valley) while they flowed and moved across landscapes.

⇒ Glaciers existed even in mid-latitude areas and developed landscapes.

* Greenland & Antartic Ice Cores The planet warms rapidly but take hundreds of years to become glacial.

Refer Pg. 02

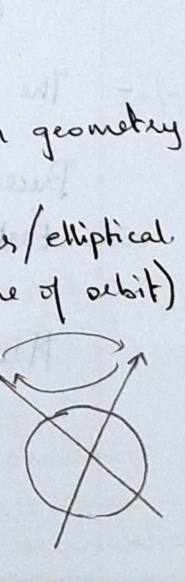
Lesser ^{18}O isotope means a colder climate and greater ^{18}O means a warmer (interglacial) period, like the current one

Last Glacial Maximum - 18,000 years ago - Most of Europe and North America was under ice sheets - whose vertical extent was of order of thousands of meters, which also spread over low altitudes.

⇒ Over the last million years, Earth's temp. has fluctuated by 4°C - 5°C as the planet has cycled in and out of glacial cycles with period of 100,000 years.

Main factor that causes glacial cycle -

1. Milankovitch Cycles
   On 10k - 100k year scale variation in earth-sun geometry is affected by -
   i) Eccentricity of orbit - shape of orbit being circular / elliptical
   ii) Change in obliquity - angle of tilt (axis with plane of orbit)
   iii) Precession - change in direction of Earth's axis of rotation i.e. axis traces a celestial circle over a period of time.
   (Wobble)

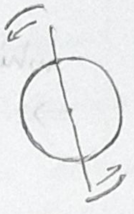


→ Variations in eccentricity

- Eccentricity of orbit is a result of gravitational pull of others planets.
- Orbit moves from circular to elliptical over a 100,000 yr cycle
- Eccentricity value : 0.005 (circle) – 0.0607 (ellispse)
  Current value – 0.0167
- Total change in total amount of solar radiation due to eccentricity is very small (0.2%). But seasonal difference is apparent only when orbit is elliptical.

→ Change in tilt of Earth's axis. (Obliquity)

- The tilt is due to planetary collissions that happened in earth's formative years.
  The change in tilt occurs due to the pull of the sun and the moon.



- Axis varies between : 24.5° and 22.1° over 41,000 yr cycle
  Current value : 23.5° and decreasing
- Change in tilt amplifies, or suppresses the strength of the seasons, especially at high latitudes
- Large tilt ⇒ increased seasonal contrast.

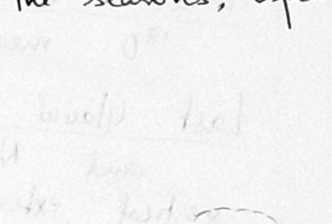
→ Precession of Axis and Orbit

- Slow wobbling of earth causes its rotational axis to point in different directions

- Today, the axis points at North Star Polaris, but 2000 years ago, North Star was Kochab & Pherkad
- The axis moves around a circular path and completes a revolution every 25,700 years

Precession of Orbit

Earth's orbit also undergoes precession due to gravitational feilds in solar system.



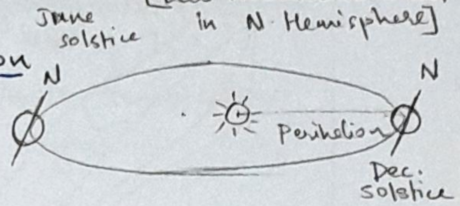
Planetary / Apsidal precession completes every 112,000 years.

(17)

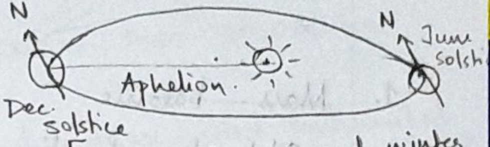
Precession of Equinoxes

Combined effect of axial & orbital precession causes solstices and equinoxes to move around the orbit, approximately every 23,000 years.

[Less seasonal contrast in N. Hemisphere]



Every half-precession cycle, the hemisphere with greatest degree of seasonal contrast switches b/w north & south



[Intense summer and winter in N. hemisphere] 4/9

Discussion

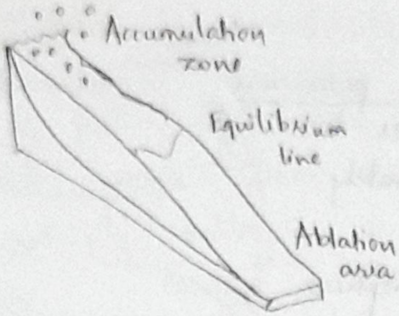
- Temp of distant planets and stars is measured/estimated by observing the radiation emitted and applying Wein's displacement law.
- If climate forcing is large, then system will take a long time to revert to equilibrium.
- The insolation is greatest for the poles during June 22nd because it receives continuous (albeit diffused) solar radiation over a small area. Hence, insolation is maximum at poles
- The lag in max. radiation and maximum temperature is due to the response time - i.e. the surface should heat up and then emit IR radiation.
- Apparent movement of the sun : In Northern Hemisphere, Sun moves from North to South from summer to winter.
- Due to Milankovitch cycle, the equinoxes and solstices also shift - so we've to make corrections to our calendar every 4,000 years to account for this

22/9/20

Introduction to Glaciers
(by Sourav Laha)

Glacier is a large mass of ice/snow on land and moves downward under the influence of its own weight.

Conditions - 1. Mean annual temp ≤ 0°C (freezing point)
2. Significant snowfall
3. Temp throughout the rest of the year shouldn't result in complete loss of winter's snow accumulation.



Velocity of glaciers is 10-100 m/year.

1. Mass balance

Plot the function (as a funtn of elevation) of accumulation of glaciers against elevation. If function > 0, the glacier is growing. If its < 0 then its melting away. If 0, its stagnant

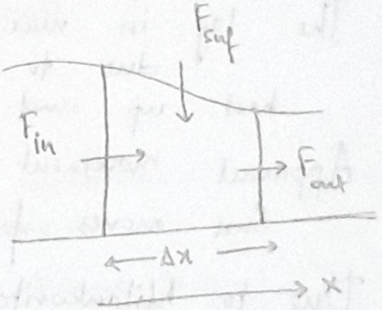
Averaging out this graph gives us the mass balance of the glaciers.

They are two kinds of glaciers – Clean & Debris covered →Himalayan
A thick layer of debris would insulate the snow and keep it from melting

Measuring mass balance – glaciological method – feild work with bamboo sticks
geodetic method – satellite images
hydrological method – using water balance

2. Flow of glaciers

H: Ice thickness
U: Velocity of ice discharge
M: rate of accumulation of ice
F: Flux



$F_{in} = HU(x)$

$F_{out} = HU(x+\Delta x)$

$F_{suf} = M\Delta x$

If $F_{in} + F_{suf} \neq F_{out}$, the ice may get thicker or thinner.

$$\frac{\partial H}{\partial t}\Delta x = F_{in} - F_{out} + F_{suf} \Rightarrow HU(x) - HU(x+\Delta x) + M\Delta x$$

Taking $\Delta x \to 0$ as continuity equation – $\frac{\partial H}{\partial t} = -\frac{\partial (HU)}{\partial x} + M$

- Glacial landscapes – they form valleys and troughs when they move
Erosional landform & depositional landform

Glaciers are an important part of water cycle – At higher altitudes, in summer, it contributes significantly to the rivers flow, while in lower altitudes rainfall sustain it.

Glaciers act as buffer and give water when ppt is less.

Glaciers change due to rising T — a glacier may retreat or thin in response to rising T.

So, Oerlemans et al 2001 extracted the past temperature using glacier 'records' i.e. their lengths.

Icesheets

Its a mass of glacial ice extending more than 50,000 km^2 and few km depth. Also called continental glacier

It contains 99% of fresh water in earth.

Two main ice sheets — Greenland & Antarctica

Major contributors to global mean sea level rise —

i) Melting polar ice-sheets
ii) Melting glaciers and ice-caps
iii) Thermal expansion of ocean
iv) Change in storage of freshwater

25/9

Ch 7.9 — Earth climate Past & Future
Ch 14 — Earth system

Lecture 07

Recall : Periodicity of Milankovitch cycle —

Eccentricity ~ 100.000 yrs
Obliquity ~ 41,000 yrs
Precession ~ 23,000 yrs

If we superimpose the three cycles, we get a wave that looks random and whose periodicity is difficult to detect with naked eye.

Northern Hemisphere June insolation (Q, climate forcing) is calculated (?) by combination of periodicity of these 3 components.

Marine oxygen isotopic composition (δ18O, climate response) is a paleoproxy for T of earth and that can also be decomposed into its 3 components

This is done by Fourier analysis i.e. the wave is moved from time domain to its frequency domain

Through this, we can detect the dominant waves that contribute —

Fourier analysis of f(t) is –

$$f(t) = a_0 + \sum^{\infty} (a_k \cos kt + b_k \sin kt)$$

$$a_k = \frac{1}{\pi}\int_{-\pi}^{\pi} f(t) \cos kt \, dt$$ a_k, b_k are fourier coefficients

$$b_k = \frac{1}{\pi}\int_{\pi}^{2\pi} f(t) \sin kt \, dt$$

Comparing the paleo-proxies, we see that glacial-interglacial cycles follow a periodicity of ~100,000 years, corresponding to eccentricity variations.

Eccentricity causes changes in total insolation (about 0.2%) but obliquity and precession donot cause any change

Milankovitch theory suggest that critical factor for glaciation is amount of summer-time insolation at high northern latitudes.

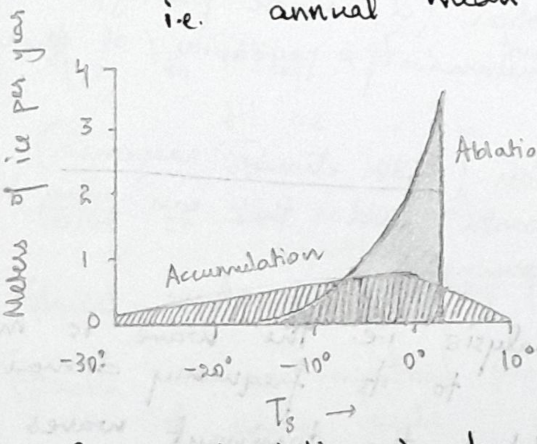
Obliquity and precession cycles can bring about 10%-12% change in seasonal insolation.

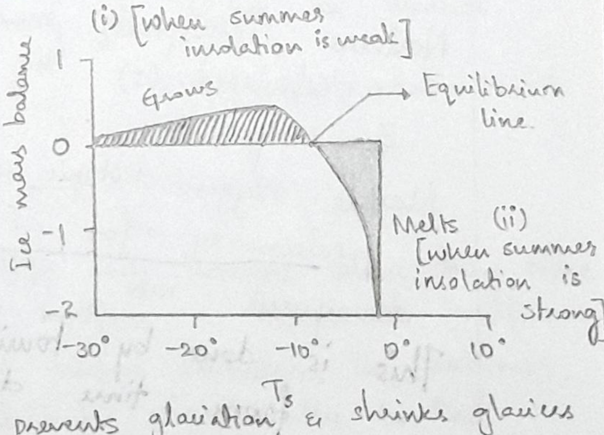
Ice Sheet mass balance

It depends on accumulation and ablation (melting) –

→ Accumulation can happen main form of precipitation is snow this happens at high altitudes and latitudes where mean annual T < -10°c.

→ Ablation : happens when summer temperature is above freezing i.e. annual mean T > -10°c.





⇒ Summer insolation is the deciding factor.

(ii) prevents glaciation, & shrinks glaciers

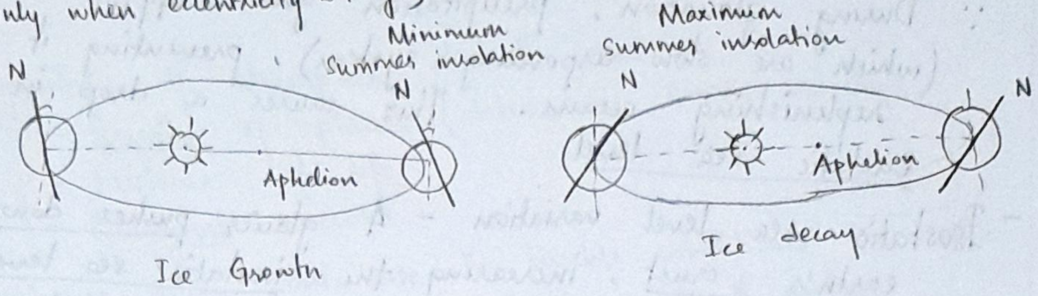
(i) Allows snow to accumulate & ice sheets grow.

How do Milankovitch cycles affect summer insolation?

Low insolation occurs when -

1. Small tilt - i.e. poles are pointed less directly at the sun
2. Summer at Aphelion - precession of equinoxes causes summer solstice to occur at aphelion (only when eccentricity is large)

less seasonal contrast in N.H



So, the Precession of Equinoxes (which occurs due to precession of axis and orbit) modulated by variation of eccentricity i.e. in a circular orbit, there isn't much change in amplitude of insolation.

* The combination of various orbital forcings causes earth climates to oscillate b/w glacial & interglacial states.

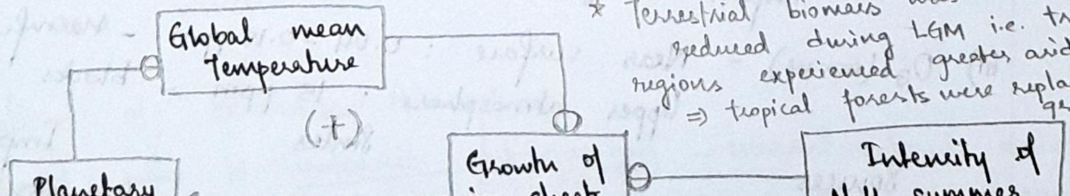
* Currently, we're at low eccentricity which will further decrease to minimum near-zero value in 30,000 years.

With such low eccentricity, unusually cold winters needed to initiate glaciation won't occur.

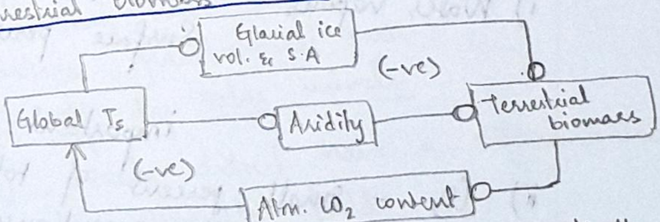
So current interglacial period will be long-lived : 1.5-2.5 precession cycles.

Feedbacks -

⟹ Glacial - Climate Feedback



* Terrestrial biomass Feedback -



* Terrestrial biomass was drastically reduced during LGM i.e. tropic regions experienced greater aridity ⟹ tropical forests were replaced by grassland

→ CO_2 and sea level variation

- The variation of CO_2 closely follows the temperature variation curve i.e. high temp — high CO_2 conc.
- Sea level also follows temp. variation

∵ During glaciation, precipitation gets trapped in glaciers (which are slow-responding system), preventing it from replenishing oceans. This causes a drop in <u>eustatic sea level</u>

- Isostatic sea level variation - A glacier <u>pushes down</u> the <u>earth's crust</u>, increasing the <u>isostatic sea level</u> w.r.t. land. Conversely, when it melts, the land rebounds, decreasing isostatic sea level.

A combination eustatic and isostatic sea levels gives total sea level.

25/9

Ch-10 Earth system (197-201, pg 217, 344-346)

Lecture 08

The atmosphere is a mixture of gases and suspended particles

- Permanant gases : N_2 (78%), O_2 (21%), Ar (0.9%), H_2, He
- Variable gases : H_2O (0-4%), CO_2 (0.036%), CH_4, NO
- Aerosols - both liquid & solid SPM.

Variable Gases -

i) Water vapours - less than 0.25% of atmosphere
Surface percentage : <1% (desert), 1-2% (mid-latitudes), 4% (tropics)

important greenhouse gas.

ii) CO_2 - small percent of total atmosphere (~400 ppm)
important greenhouse gas

iii) O_3 (ozone) - Near surface : 0.04 - 0.15 ppm - harmful
Upper atmosphere : 15 ppm - blocks UV radiation

	Sources	Sinks	Importance
CO_2	Respiration & combustion	Photosynthesis & deposition in ocean	Accounts for half of warming by human activity
CH_4	Landfills, wetlands, decomposition, domestic livestock, coal mining, pipe leaks	<u>Chemical reaction in atmosphere</u>	Its greenhouse effect is <u>20-30 times</u> that of CO_2. Could be most imp. g. gas in <u>50 yrs</u>.

NO	Burning coal & wood, soil microbes	Chemical reaction	250 times greenhouse potential than CO_2. Long-lasting & destroys O_3
O_3	Formed in atmosphere through photochemical rxn	Deposition to surface, chemical reaction	Pollutant in troposphere, blocks UV, also greenhouse g.

Composition of atmosphere depends on -

- Gravity of planet (determines escape velocity)
- Existence of life
- Geological processes

Greenhouse gases contribute to livable conditions on earth & (288K) earth's T is close to triple point of water.

Presence of liquid H_2O and biological processes helps in recycling CO_2 from atmosphere

Compared to Venus

Venus, atmosphere - 96% CO_2, 3% N_2.

It has extreme temperature due to large amount of CO_2.

⇒ No liquid water ⇒ No mechanism to remove CO_2 i.e. by dissolution (& fixing it in sediments). chemical weathering & photosynthesis.

Primordial Atmosphere

- It was a product of impact degassing - mostly comprised of H_2 & He - they have low molecular weight ⇒ in high T conditions, they have high mean velocity so they escaped earth's gravitational pull
- Or they'd have been swept off by solar winds
- In Hadean era (4.6 - 4 Bya), earth didn't have a differentiated core which creates earth's magnetic feild

Formation of Secondary Atmosphere

Produced due to volcanic out-gassing - current volcanic emission - 80-90% H_2O, 6-12% CO_2, 1-2% SO_2, traces of H_2, N_2, CO, NH_3

But in early earth environment, crust and mantle were in much less oxidised state ⇒ more of H_2, CO and CH_4 emmisions

CH_4 would have been the main greenhouse gas

In the absence of an ozone layer, photolysis of CO_2 and H_2O produced O_2 & hydroxyl radicals.

$$H_2O \xrightarrow{\nu} OH + H$$

escape to space

$$CO_2 \xrightarrow{\nu} CO + O \Longrightarrow O + OH \longrightarrow O_2 + H$$

But this O_2 would have been consumed by reduce gases or exposed minerals ($\Rightarrow$ CO & CH_4 + $OH \longrightarrow CO_2$)

N_2 is non-reactive & so its conc built up over time

As earth cooled, H_2O condensed to form oceans. CO_2 dissolved in oceans and slowly formed carbonate sedimentary reservoir.

3.8 Bya ~ earth's environment allowed for emergence of early life.

Oxygen didn't accumulate till 2.4 ~ 2.8 Bya

Anoxic State

- Banded Iron Formation (BIF) : laminated sedimentary rocks that consist of alternating layers of iron-rich minerals and silica.
- Fe^{2+} are soluble in water, but when these ions reach the ocean, due to presence of O_2 (by cyanobacteria), the precipitate as haematite and magnetite.
- The alternating layers are due to available O_2 in the ocean.
- All BIFs formed prior to 1.9 Bya

Redbeds

* Once enough O_2 was produced in oceans, it diffused to the atmosphere and oxidised earth's crust
* Redbeds are sedimentary deposits which contain haematite Fe_2O_3 i.e Fe^{3+} (oxidised ion). So they indicate oxidizing atmosphere at time of their formation.
* Earliest red beds date back to 2.2 by.

Once crust became sufficiently oxidised, it would've been possible for O_2 to accumulate in atmosphere and sunlight would act on it to form ozone - this allowed colonization of land and evolution of complex life

Natural ozone is found in stratosphere.

Production : $O_2 \xrightarrow{h\nu} O + O$

$O + O_2 \longrightarrow O_3$

Destruction : $O_3 \longrightarrow O_2 + O$ O_3 absorbse UV light (290 - 320 nm) which breaks it down to O_2 & O

$O + O_3 \longrightarrow 2O_2$

Evolution of Atmosphere

- Initial water vapour condensed to form oceans.
- Reduction in volcanic activity & increase in weathering & biological processes decreased CO_2 conc, locking it in sedimentary rocks
- H_2 & He escaped earth's gravity in Hadean era
- As life form evolved more O_2 was put into the atmosphere

N_2 accumulated

1/10/20

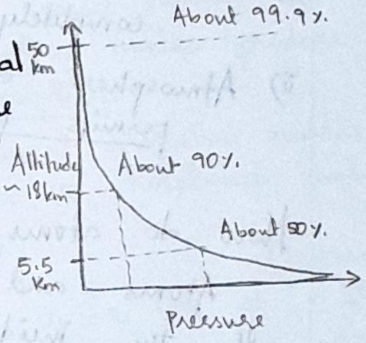
Ch3 - Earth system

Lecture 9

Atmospheric vertical structure

The gases are held due to gravitational force of earth - so most of gases are concentrated near the surface.

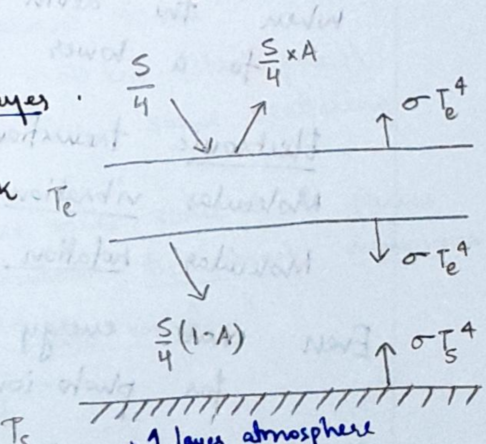
⇒ Air density & hence pressure decrease exponentially with altitude



Pressure variation can also happen due to heating difference.

If we consider the role of atmosphere while calculating planetary energy balance -

Assume the atmosphere is a single layer with albedo A & transparent to solar radiation but behaves as black body for terrestrial radiation.



T_e : Temp of atmosphere

T_s : Temp of earth surface

We don't consider the emissivity of earth's surface. Also, we consider that it (1 layer atmosphere) lets short wave radiation pass through, but absorbs all long-wave radiation emitted from earth - some of it below, some above

Energy balance for surface –

$$\sigma T_s^4 = \frac{S}{4}(1-A) + \sigma T_e^4$$

Energy balance for atmosphere –

$$\sigma T_s^4 = 2\sigma T_e^4$$ – it only absorbs energy from earth's surface

$$\Rightarrow \sigma T_e^4 = \frac{S}{4}(1-A) \quad \text{and} \quad \boxed{T_s = 2^{1/4} T_e}$$

T_E : effective emmission of planet (Refer Pg.09)

T_E = 255 K ⇒ T_S = 303 K

$\Delta T_G = T_s - T_E$ = 48K [In reality, its ~33K]

Here we've overestimated the greenhouse effect since we made assumptions. In real life –

i) About 20%- 25% incoming radiation is absorbed by the atmosphere (i.e. not completely transparent).

ii) Atmosphere doesn't absorb all IR from the earth, it permits partial transmission.

How do atoms interact with radiation?

Atoms and molecules have quantised energy states.

If the incident photon (wavelength) matches the quantized rotational, vibrational or electronic energy, the radiation will be absorbed.

When the atom comes down from higher energy level to a lower one, it emits radiation.

Electronic transition – UV & visible wavelengths

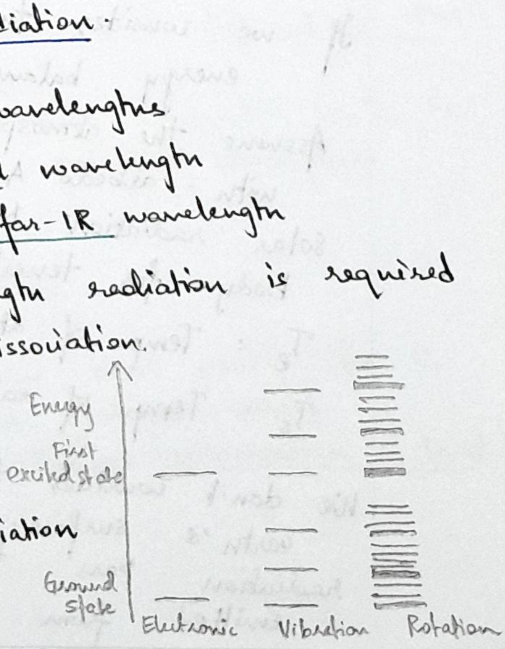
Molecular vibration – Thermal infrared wavelength

Molecular rotation – Microwave & far-IR wavelength

Even more energy i.e short wavelength radiation is required for photo-ionization & photo-dissociation.

→ Solar radiation spectra at 480 km (?)

The spectrum matches very closely to expected spectrum for black body radiation at 5800K (sun's temp)



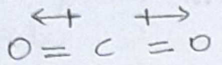
- Recall : Natural Formation & destruction of ozone (pg-25)

This absorbs (uses up) a lot of UV radiation from sun.

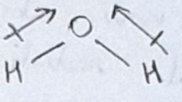
- The visible wavelength is not absorbed by atmosphere, just scattered.
- The earth emits mostly infrared radiation

For a molecule to absorb IR, vibrations or rotations within a molecule must cause a net change in dipole moment of molecule.

⇒ Homonuclear diatomic molecules (N_2, O_2) don't absorb IR radiation ∵ they don't have permanent dipole moment, which remains unchanged even if they vibrate or rotate



At rest : no net dipole moment



Net dipole moment

- CO_2 can vibrate in three ways - symmetric, asymmetric & bending. Symmetric stretching doesn't cause change in D.M, whereas asymmetric stretching and bending modes produce change in DM & causes IR absorption
- Similarly, H_2O and O_3 have 3 dominant vibration modes which cause absorption in near IR. Rotational modes also contribute to absorption of IR.

Refer to absorption spectrum of H_2O, CO_2, O_3 & CH_4 at ~ 29 min (Lecture 9)

⇒ Attenuation of different wavelengths of Solar radiation in atmosphere -

Summary

- Shorter wavelength (Gamma & X-rays) - above 90 km
- UV radiation (gets absorbed by ozone) - ~ 50 km (stratosphere)
- Visible part of spectra - no net attenuation, some scattering "Optical window"
- Most of IR - absorbed by greenhouse gases, some of it passes through atmospheric window. H_2O absorbs microwave
- Radio waves - not attenuated ⇒ "Radio window"

⇒ Solar radiation spectrum at sea level

There is reduction of energy & clear spectral gaps - Atmospheric window is very apparent.

- UV absorption by O_3 ✓
- Visible light scattered ✓
- IR absorption by H_2O & CO_2 ✓

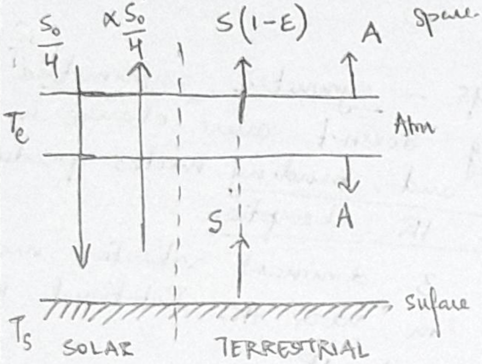
⇒ Absorption spectra of Terrestrial radiation by atmosphere (Refer to graph ~ 36 min)

- Long wave IR radiation is absorbed by greenhouse gases
- CO_2 vibrational band & H_2O rotational band are significant as they fall in the spectral range of maximum terrestrial emmission
- 8 – 12 micron range is not absorbed ⇒ atmospheric window except O_3 has an absorption channel at 9.6 μ.

⇒ Leaky Greenhouse model

Atmosphere now absorbs only a fraction, ε (emissivity) of terrestrial radiation upwelling from the ground.

Tutorial 01 Pg. 05



$\frac{S_0}{4}$: Solar insolation

S : Radiated up from ground

A : radiated to space & down to ground

S(1−ε) : Transmitted through atmosphere

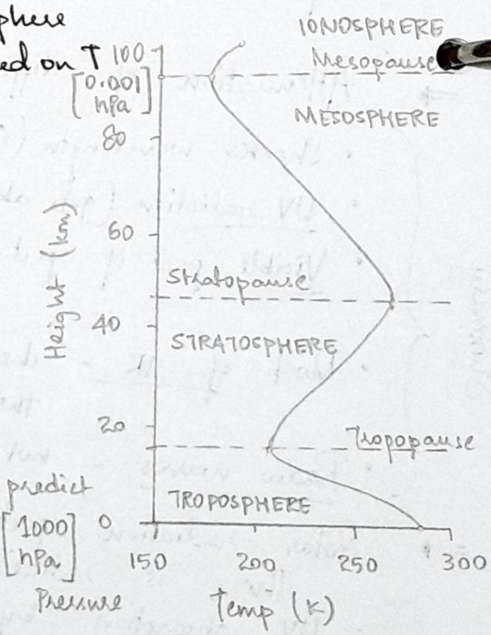
What would be T_s ?

1/10/20

Lecture 10

Vertical thermal stratification of atmosphere

- Atmosphere is broken into layers based on T
- Vertical temp profile is related to
  - absorption of radiation and
  - presence/absence of vertical motions in the layers
- Stratosphere – T increases with height & Ionosphere



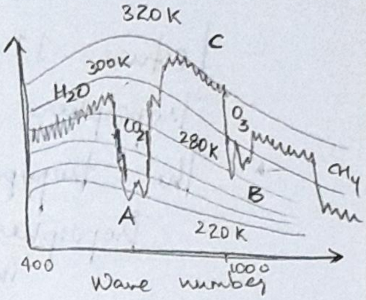
⇒ Troposphere [Upto 10-15 km] # Most studied layers – to predict & study weather

- Clouds and other weather phenomena occur here
- Most greenhouse gases are found in this region. [Recall – At 18 km, 90% of gases are below that level

Classification of Clouds

- Based on height
  High (above 7 km) - Cirrus clouds - composed of ice crystals
  Mid-level (2-7 km) - Alto clouds
  Low (< 2 km)

- Stratiform clouds have layered appearance
  Cumuloform clouds show vertical development
  Nimbo-/-nimbus : precipitating clouds.



Deduce the spectrum - Refer Lec10 - 14:12

The spectra is measured from a satellite.
At what levels A, B, C emmission would take place?

→ A : The emission is being received from a layer in atmosphere at T = 220 K - in troposphere.
⇒ Above this level, there's no significant amt. of CO_2.
But CO_2 in each layer absorbs and emits - final emmission at 220 K.

→ B , Emmission occurs at a layer with T = 280 in stratosphere

→ C : Atmospheric window ∵ emmission from 320 K i.e. surface

Greenhouse effect accounted for by O_3 and CO_2 -
If ozone & CO_2 were not there, emission would have taken place around 310 K.

$\Rightarrow \Delta T_{O_3} = \sim 30K$ $\Delta T_{CO_2} = \sim 90K$

In troposphere there's 6.5 K drop for every km

6/10

Discussion

- Why is there greater snow accumulation at -10°c than at -30°c?
  At temperatures lower than -10°c, the atmosphere loses the ability to hold water vapour, so snowfall decreases.

- Obliquity affect global T because of difference in land-ocean distribution in NH & SH.
- The oldest evidence we have of glacier debris which is in the ~~ice~~ sedimentary-cores in oceans is 2.5 Mya, not before that.

Glacial-Interglacial cycles could have happened, with different periodicity or it could not have happened.

7/10

Lecture 11

Troposphere

→ The tropopause level varies in equator and poles. Troposphere continues upto 15 km in equator & much lesser in poles because of difference in temperature

Tropopause - its a region where the decrease in T has a very small gradient & T starts increasing from this level.

Stratosphere begins from above the tropopause

→ The presence of clouds in a given region can affect the radiation emitted and hence the temperature

- If there are clouds, the emission would occur from top of the cloud, which is at lower T.
- When there are no clouds, the emission occurs right from the surface ie at higher T.

→ Effect of clouds in Earth's radiation budget.

* The clouds above 7 kms, Cirrus clouds, are composed of ice crystals and hence, they have low albedo and transfer most of insolation to the surface

Meanwhile stratus clouds have greater albedo becase they're composed of water vapour & hence they reflect most insolation

* Both cloud types contribute to greenhouse effect - they absorb the longwave radiation & re-radiate it.

But : because low clouds are at higher T, it would allow more radiation to be lost to space, than the tall clouds.

* Hence - High clouds - Net greenhouse forcing ⇒ atmospheric warming

Low clouds - Net albedo forcing ⇒ atmospheric cooling

→ Stratosphere [10 km - 50 km]

- Sun's UV light only penetrates till stratosphere, which is absorbed by ozone, heating the air.

Hence, in this layer, T increases with hight.

T decreases with height in Troposphere because radiation emitted by earth is absorbed and re-radiated by clouds and greenhouse gases in lower levels.

→ Mesosphere [Above 50 km] to 90 km

- Here, there is very little air i.e. very little ozone and hence no heating. ⇒ Temperature decreases with height.

→ Thermosphere / Ionosphere [Above 90 km]

- Here, residual atmospheric molecules absorb solar wind of nuclear particles, X-rays & gamma rays
  This absorbed energy causes increase of T with height.
- Also, the gas molecules are moving very fast & the pressure is very low (< 0.001 mb)
- Aurora Borealis - Northern Lights
  Its caused by the interaction of high energy particles (electrons & protons) of solar wind with atoms (H, He, O) of upper atmosphere
  Its observed in polar regions because magnetic feild lines are weak there ⇒ they cannot deflect charged solar particles.

Heat transfer in Earth-Atmosphere System.

- Radiative transfer : main mode of transfer of heat. Earth & atm absorb & emit radiation (in visible and IR spectra)
- Convective transfer : Atmospheric and oceanic circulation
- Conduction of heat : In lower levels i.e. land & ocean surface
- Latent heat : Heat transfer associated with change of phase of H_2O
- Advection : Horizontal transfer of heat by movement of air masses.

* Homosphere - Turbulent mixing causes atmospheric composition to be homogenous from surface to ~90 km

Variable gases are also well mixed except for H_2O which undergoes phase change above ~15 km

* Heterosphere - Above ~90 km, there is density stratification - heavies molecules settle lower (N_2, O_2) ; while lighter ones (H_2, He) float to top.

Earth's Energy Budget

Such a waste

1. Incoming Solar Radiation : 340 W/m²
   - 30% is reflected : 23% by clouds & atmosphere
     7% by earth's surface (snow)
   - 22% is absorbed by gases (O_3, H_2O, CO_2 etc) & dust, clouds
   - 48% absorbed by Earth surface.
2. Earth surface looses heat as -
   - 79% as IR : out of this 90% is absorbed by atmosphere
     10% passes through atmospheric window
   - 17% transferred to atmosphere as latent heat.
   - 4% transferred by thermals (conduction, convection).
3. The atmosphere -
   - Absorbs 22% of solar & 90% of terrestrial radiation.
     Atmospheric constituents at any level then re-emits IR radiatⁿ both upward & downward
   - There's a net downward IR flux that finally heats up Earth's surface ∴ Greenhouse effect.

* Earth absorbs 163 W/m² from solar radiation
340 W/m² from atmospheric re-radiation

* Upward directed IR radiation is finally lost as Outgoing Longwave Radiation (OLR) — 240 W/m²
composed of -
- Upward radiation re-emitted by clouds & gases (~30, 170)
- Direct IR from surface passing through atm window (~40)

Radiative Energy Balance – Summary

Picture – net absorbed by earth – 0.6
By plant (?)

1. Top of atmosphere
   + 340 (solar)
   – (77 + 23 [Reflected] + 240 [OLR]) = –340

2. Atmosphere
   + 77 (solar) + 358 (terrestrial) = + 435
   – (170 + 30 [Upward] + 340 [Downward]) = –540
   ∴ Net loss of 105 W/m^2

3. Earth surface
   + 163 (solar) + 340 (atmosphere) = 503
   – 398 (emmitted) = –398
   ∴ Net gain of 105 W/m^2

The imbalance can be accounted for by transfer of [86.4 (latent heat) + 18.4 (thermals)] energy from surface to atmosphere.

14/10

Ch. 8 Earth System

Lecture 12

Biogeachemical Cycles

Earth has a natural recycling system for all elements essential for life. Its a complete pathway through geosphere, atmosphere, biosphere, hydrosphere and back again.

- Atmosphere and Oceanic circulation and
- Plate tectonics

They're essential for biogeochemical cycles. (recycling)

Carbon Cycle.

It plays a key role in regulating Earth's climate by controlling conc. of CO_2 in atmosphere

Reservoirs of carbon –

1. Biosphere – in the form of organic matter (plants, animals, microbe)
   ~ 600 Gton

2. Atmosphere – Present as CO_2 and CH_4 (760 Gt + 5 Gt)
   Replenished about once in a decade

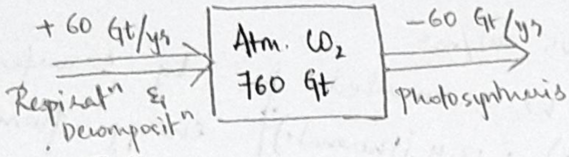
50 times more C than atm

3. Oceans - Inorganic carbon (~ 39,000 Gt) : not associated with living organisms no C-C or C-H bonds : CO_2 & HCO_3^- stored at great depth where it stays for long

4. Earth's Crust : Largest carbon reservoir (50×10^6 Gt), found in -
   * Sedimentary rocks : Eg: Carbonate rocks - limestone
   * Hydrocarbons (fossil fuel) : Eg: Coal, Petroleum
   * Soil organic carbon : temperory reservoir - microbes, decaying matter.

Carbon flux : Movement of C through reservoirs
If the influx is in balance with outflux, the size of reservoir won't change over time.

Eg:



: Only 1 component

Influx	Outflux
- Respiration	- Photosynthesis
- Burning fossil fuels	- Dissolution in rain - important for weathering
- Volcanic emmisions	- Dissolves in ocean
- Decomposition	
- Diffusion from ocean	

Time-scales

- Short-term cycling (10s of years) - biological processes
- Medium-term cycling (upto 1000s of years) - storage of organic matter in trees, forest soil & organic sediment
- Long-term cycling (upto millions of yrs) - Geologic processes - production of carbonate rocks, removal by weathering, subduction & volcanism

Exchange of Carbon with Biosphere

Photosynthesis
Respiration
Methanogenesis

Seasonal Cycle of CO_2

⇒ Linked to growth (summer) and decay (winter) of plants

Keeling Curve

Marine Organisms

- Phytoplankton – marine, photosynthetic microorganisms which take up dissolved CO_2 (even more than forests)

  They are found in photic zone – where there is sufficient light

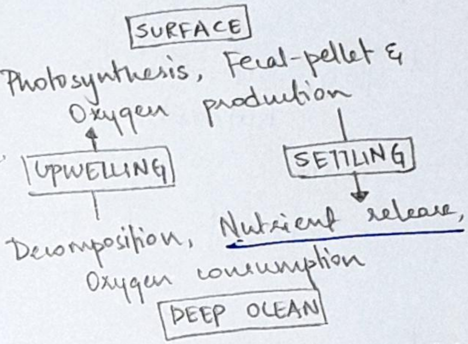
- Organic matter produced by them is consumed by Zooplankton

  Their fecal pellets & decaying organic matter (only 1%) settle through water column & on sea floor

- This decaying matter is decomposed by microbes, releasing CO_2 & nutrients to deep ocean waters.

  This is released to atmosphere by Ventilation / Upwelling of deeper ocean to surface ocean

Biological Pump



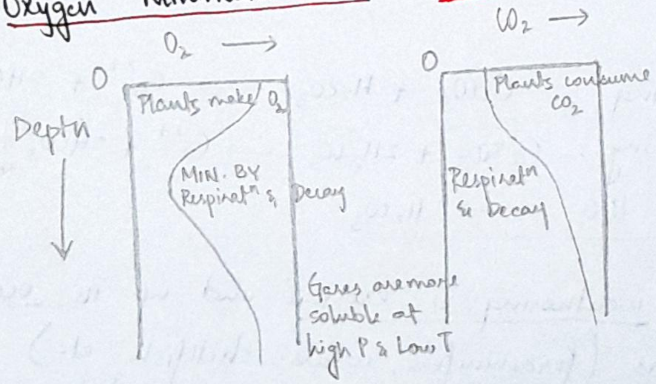
Transfer of CO_2 & other nutrients from surface water to deep ocean.

Balanced by upwelling – brings back nutrients and CO_2

- Because of this, surface waters are depleted of nutrients like phosphates & nitrates.

- Oxygen is consumed as the settling organic matter decays.

  'Oxygen Minimum Zone' : 1 km



Primary Productivity estimates from Ocean Colour.

In upper Photic zone, nutrients (not light or CO_2) are limiting factor for photosynthesis

Ocean circulation plays an important role in distribution of primary productivity.

Something to do with NO
vertical temp stratification in poles (?)

Observation is counterintuitive - Maximum Primary productive is seen at the Poles while minimum value is found in sub-tropic oceans.*

This is because mixing of ocean is more in Polar region.

Organic Carbon Cycle (including short & long-term cycles in terrestrial & ocean)

Once in a while, a C atom 'leaks' i.e. its transported by rivers to the ocean before it can decay. There it settles on sea floor - buried in a sediment or carried into a subduction zone.

In elevated Temp & Pressure conditions, it might escape as CO_2 or get converted into metamorphic rock (for 200 million years)

This 'leak' occurs once in 500 life cycles

Refer Lec 12 - Slide 22, 24

* They are net downwelling region - water sinks down, so nutrient is depleted in the surface water and hence no planktons can grow here.

"Desert of the Ocean"

15/10

Ch. 8 Earth System

Lecture 13

Inorganic Carbon Cycle

- ~~Outflux~~ : Carbonate & Silicate weathering, Sedimentation in ocean, Volcanism

Nutrient cycles are intricately linked with water cycle

Weathering

Carbonate weathering : $CaCO_3 + H_2CO_3 \longrightarrow Ca^{2+} + 2HCO_3^-$

Silicate weathering : $CaSiO_3 + 2H_2CO_3 \longrightarrow Ca^{2+} + 2HCO_3^- \downarrow + SiO_2 + H_2O$

From atmosphere $\nearrow CO_2 + H_2O \longrightarrow H_2CO_3$

The products of weathering & erosion end up in oceans.

Marine organisms (foraminifera, corals, shellfish etc.) remove Ca^{2+} & HCO_3^- from seawater and precipitate $CaCO_3$ as shell or skeleton

Carbonate Precipitation : $Ca^{2+} + 2HCO_3^- \longrightarrow CaCO_3 + H_2CO_3$

This creates a CO_2 gradient b/w ocean and atmosphere

* ⇒ Promotes diffusion of CO_2 from ocean to atmosphere in certain regions?

The oceans near the equator are CO_2 sources (i.e. CO_2 diffuses to the atmosphere) because there's net upwelling of water, which brings CO_2 from deep oceans.

The direction & rate of diffusion of CO_2 also depends on other factors –
- ocean circulation
- temperature
- biota in the region.

Oceans can store CO_2 for long because CO_2 dissolves in water to form carbonic acid, which dissociates into ions –

$$H_2O + CO_2 \rightleftharpoons H_2CO_3$$

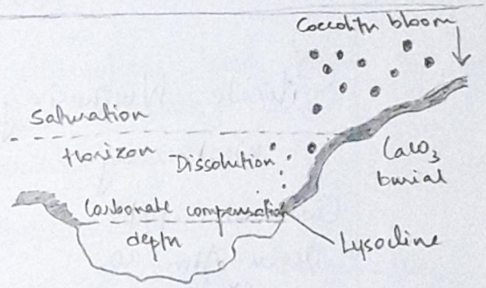
$$H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$$

$$HCO_3^- \rightleftharpoons H^+ + CO_3^{2-}$$

Rates of forward & reverse reactions depend on conc of reactants & products.

These 3 reactions mainly determine and maintain the pH of ocean. Even a small change in CO_2 influx can affect this.

Carbonate Pump



When marine animals die, their shells and skeletons sink to the bottom and become a part ocean sediment deposited in reefs & shallow depths.

⇒ They form multi-millenial Calcium & Carbon sinks until tectonic uplift brings them to Earth's surface.

At depth > 4.5 km, dissolved $[CO_2]$ is so high that it causes $CaCO_3$ to dissolve.

$$Ca^{2+} + 2HCO_3^- \underset{\leftarrow \text{Dissolution}}{\overset{\text{Precipitation} \rightarrow}{\rightleftharpoons}} CaCO_3 + H_2CO_3 \rightarrow H_2O + CO_2$$

Carbon Compensation Depth : Rate of $CaCO_3$ deposition = Rate of dissolution of $CaCO_3$

∴ Calcareous shells are not found below 5 km

When an Oceanic Plate moves under a Continental Plate, materials in subducting plate will be pushed into mantle.

This leads to –

Carbonate Metamorphism

At high Pressure & Temperature conditions, carbonate materials & silica in sedimentary rocks form silicates, releasing CO_2 —

$$CaCO_3 + SiO_2 \longrightarrow CaSiO_3 + CO_2$$

If temperatures are sufficiently high during metamorphism, it generates volcanic eruptions which release CO_2.

Inorganic carbon cycle – Lec. 13 10:40

These tectonic processes occur over millions of years

produces Ca^{2+}, CO_3^{2-} ions

Note : The net effect of carbonate weathering on land and $CaCO_3$ precipitation in ocean, on ocean chemistry and atmospheric composition is zero because they balance each other (no net removal).

Removes ions

Silicate Weathering

* Doubles for every 10°C rise in Temp

Weathering : $CaSiO_3 + 2H_2CO_3 \longrightarrow Ca^{2+} + 2HCO_3^- + SiO_2 + H_2O$

Carbonate pptn : $Ca^{2+} + 2HCO_3^- \longrightarrow CaCO_3 + H_2CO_3$

Ocean-Atm CO_2 exchange : $CO_2 + H_2O \longrightarrow H_2CO_3$

Net Eqn : $CaSiO_3 + CO_2 \longrightarrow CaCO_3 + \cancel{H} SiO_2$

R. The combined processes of weathering (on land) & precipitation (in ocean) lead to a net conversion of atm. CO_2 to $CaCO_3$ deposit in Ocean.

Carbonate – Silicate Geochemical Cycle.

Weathering → Precipitation in Ocean → Sedimentary rocks → Plate tectonics → Metamorphic rock → Volcanism releasing CO_2

* This has balanced consumption of CO_2 by weathering

* Without this, CO_2 would accumulate in rocks and stay there forever

Tectonic Processes –

* Alters the basic geography of Earth's surface – movement of continents, uplift of mountain ranges etc

* Rate of sea floor spreading (over millions of years) has controlled rate of CO_2 input into atmosphere

*Faster spreading → More subduction → More Volcanism → CO_2 emmission

⇒ Early Earth witnessed higher rates of seafloor spreading and subduction.

* Affects the rate of weathering by –
- Uplift of mountains increase availibility of fresh rocks to be weathered
- Steep slopes, orographic precipitation, mountain glaciers etc also contribute to rate of weathering

Wilson Cycles

- Continents assemble into a supercontinent, which breaks apart; these smaller continents disperse & then re-assemble.

Period of cycle : $\boxed{\text{500 Million Years}}$

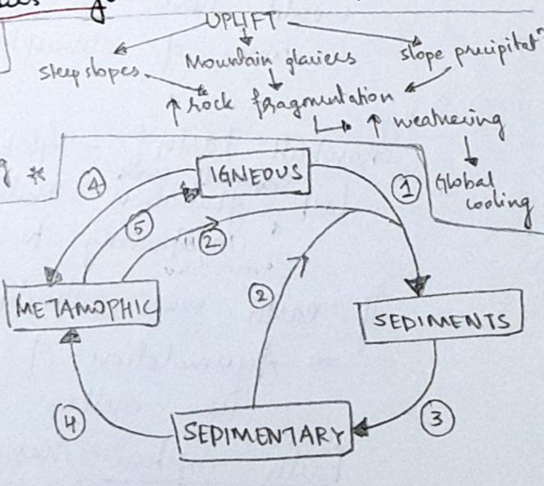
- Continents move to the colder region of cenosphere and form a supercontinent. Then due to convection currents, the heat builds up under it and it breaks up
- Subduction occurs at the edges of supercontinent.
- Opening and closing of ocean basins is associated with this.
- Pangea was formed 300 million years ago ⇒ Next supercontinent will be formed in 200 Ma

Example of Long period cyclic variation ⇒ Affects climate :: * Uplift Weathering Hypothesis *

Rock Cycle –

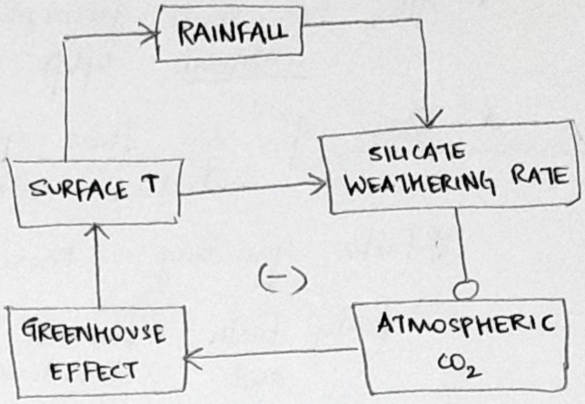
Its a consequence of plate tectonics

Period : 100 Ma.



① Weathering & Erosion
② Uplift, weathering & erosion
③ Deposition & Lithification
④ Metamorphosis
⑤ Melting in Subduction zone

Long-Term Feedback cycle in Carbonate - Silicate cycle.



- Volcanism is driven by heat in earth's interior - doesn't depend on CO_2 or climate conditions
- Silicate weathering increases with -
  - Temperature (Rate doubles for every 10°C rise in T)
  - Rainfall
  - Vegetation

This feedback loop is thought to be major factor regulating atm. CO_2 concentrations & climate on very long time ~~sclare~~ scales.

Faint Young Sun Paradox

Refer Pg. 11

This can be explained by considering an ~~early~~ CO_2 Rich Early Earth Atmosphere —

- Stronger CO_2 source : Enhanced volcanism on hot, young earth
- Weaker CO_2 sinks : - Less crustal area available for weathering
  - Low solar luminosity ⇒ Low T_s ⇒ Low rate of silicate weathering

Earth's Thermostat ?

As solar luminosity increased, CO_2 conc decreased to maintain the temperature. How?

As volcanic activity reduced & crust developed, increased luminosity would have led to increased weathering rate, bringing down conc. of atmospheric CO_2. (Most plausible explanation)

"Snowball Earth" - Global Glaciation.

Last Snowball earth glaciation ended 635 Mya (when complex life was just starting to develop).

If earth was entirely ice covered, silicate weathering would stop. ⇒ Accumulation of CO_2 in atm ⇒ Increased temperature ⇒ ice melts.

∴ Earth system has a natural way of recovering from global glaciation

Again, this is one of many feedback cycles. Major one.

$*$ Seafloor spreading rate hypothesis : Fast rate $\xrightarrow[\text{(volcanism)}]{\text{by}}$ Rapid CO_2 input ⟶ Warm greenhouse ⇒ (↑ Temp, rain, vegetation) → Increased weathering ⟶ Increased CO_2 removal ⟶ Reduced warming

↳ Affects CO_2 & climate [AND THE CONVERSE...]

Compare with Venus - Refer Pg. 23

Ch. 2
Earth's
Climate
Past and
Future

21/10/20

Lecture on Paleoproxies

Keeling Curve : Instrumental record of atmospheric CO_2 past ~62 years. Other instrumental record ~200 years

Learning about past climate can help us predict the future climate and help to tackle it.

The resolution of each of these archives is dependent on residence time of elements and response time of system

Paleoclimate Archives

They record climate data of past few thousand years in nature.

Corals & trees : Hundred - Thousand yrs
Ice cores : ~100k years
Sediments : Millions of years

01. Coral

- Marine invertebrate organisms found in shallow tropical ocean
- They secrete $CaCO_3$ from ocean to form hard exoskeleton.
- We can learn: Sea surface temp : Ca/Mg, oxygen isotopes
  Ocean acidification : Boron isotopes.

02. Speleothem

- They are cave formations - stalactites and stalagmites.
- They're created by water that contains $CaCO_3$, percolating down from surface and dripping down to the floor of cave
- Tells us about : Past rainfall pattern
  Paleo-temperature
  Paleohydrology.
- Formation: When water percolates down, in
  Soil zone : $H_2O + CO_2 \rightarrow H_2CO_3$
  Carbonate rock : $CaCO_3 + H_2CO_3 \rightarrow Ca^{2+} + 2HCO_3^-$ (Dissolution)
  Speleothem : $Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + H_2O + CO_2$ (Precipitation).
- Drawback: They only form in tropical & sub-tropical regions, so not applicable everywhere

Delta Notation.

$$\delta^{13}C = \left(\frac{\left(\frac{^{13}C}{^{12}C}\right)_{sample}}{\left(\frac{^{13}C}{^{12}C}\right)_{standard}} - 1 \right) \times 1000 ‰$$

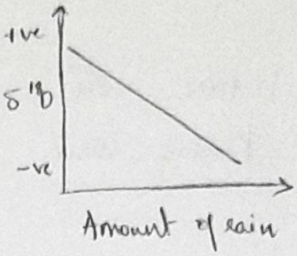
Similarly for $\delta^{18}O$

$\delta^{13}C$ standard - Pee Dee Belemnite (PDB)

$\delta^{18}O$ standard - Standard Mean Ocean Water (SMOW).

Speleothem $\delta^{18}O$

More the amount of rain ⇒ more negative -ve value of $\delta^{18}O$.



In tropical region -

$$\delta^{18}O = \begin{cases} -1.5‰ \ / 100 \text{ mm of rain} \\ -0.22‰ \ / °C \text{ of temp.} \end{cases}$$

Changes in $\delta^{18}O$ in speleothem are mainly due to variations in precipitation.

- Age of Speleothem

Age of a paleoclimate archive is determined by radiometric dating or counting annual layers.

- Radiocarbon dating.

$$\text{Carbonate sample} \xrightarrow{H_3PO_4} CO_2 \xrightarrow{\text{prepare}} \text{Benzene/Graphite}$$

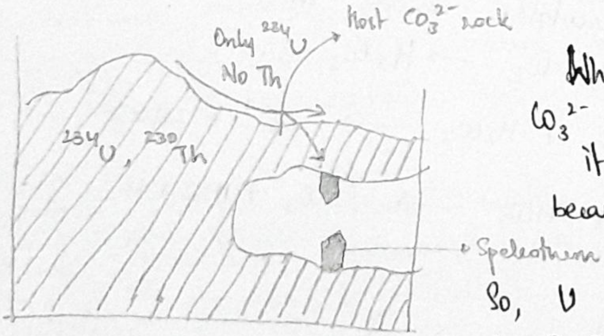
$$\text{Benzene/Graphite} \xrightarrow{\text{Analyse}} \text{Scintillation counter/ } \text{~~Atom~~ Accelerating Mass Spectroscopy} \rightarrow \text{Measure Activity}$$

We can analyse a very small sample : 7-10 μg to know the age of the sample

- U - Th decay.

$$^{238}U \xrightarrow{T_{1/2} = 4.5 Ga} {}^{234}Th \rightarrow {}^{234}U \xrightarrow{T_{1/2} = 248 ka} {}^{230}Th \xrightarrow{T_{1/2} = 75 ka} {}^{226}Ra \xrightarrow{T_{1/2} = 1.6 ka} {}^{222}Rn \text{ (gas)}$$

leaves the system



When rain erodes the CO_3^{2-} rock and percolates, it only contains U because Th prefers particulate phase to solution. So, U is deposited in the speleothem at T=0 and clock starts.

Subsquently ^{234}U starts to decay into ^{230}Th.
∴ We can determine the age by measuring & comparing the amount of U and Th.

Carbonate sample $\xrightarrow{HNO_3/HF}$ Solution phase (U, Th) $\xrightarrow{\text{column chromatography}}$ Pure U-Th fraction $\xrightarrow{\text{Mass Spectrometry}}$ Measure

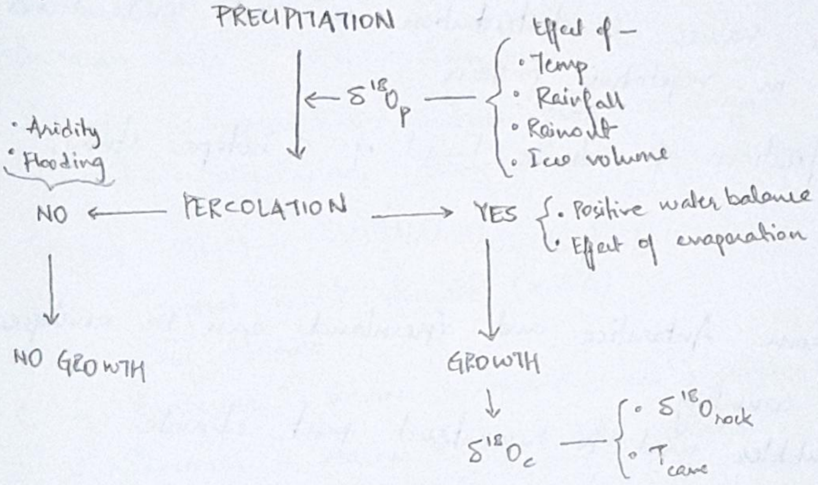
This can be measured with precision of ±0.1% (TIMS, MC-ICPMS)

This method only gives limited age ~~model~~ points.
We need to assign age for entire speleothem – we

Speleothem Age Models – COPRA – Constructing Proxy Records from Age Models
StalAge

* IRMS : Isotopic Ratio Mass Spectrometer.
CO_2 is generated by adding acid to $CaCO_3$ from speleothem, foraminifera, coral etc
This CO_2 is used to measure $\delta^{13}C$ and $\delta^{18}O$

* Speleothem $\delta^{18}O$



Climate culture link :
Comparing calcite record from North India (i.e. T & rainfall) with rise and fall of civilisations

03. Sedimentary Archive [Marine and Terrestrial]
Sediments are created by deposits carried by rivers
Gives us the record of that age

Marine sediment collection : Box coring
Piston coring

Sediment Chemistry Study – Extract, spectrometer, determine elements & isotopes

04. Foraminifera (microfossils) / Coral

They're made of $CaCO_3$ or siliceous materials.

They live on water surface (column?) and water-sediment interface

Analysing these, we can determine –

- O isotope
- Wind circulation pattern ; upwelling intensity
- Ocean acidification

03. contd ...

Bay of Bengal Geochemical Data (Temporal variation)

30% reduction of sediment supply from Himalaya during LGM

⇒ Weakening of SW monsoon

05. Vegetation Patterns / Tree ring

Growth of C_3 or C_4 plants depends on amount of rainfall and their C isotope ratio varies

Past C isotopic values & distribution can help understand change in vegetation pattern

Ponton et. al. 2012 Holocene aridification of India based of C isotope study.

07. Geological Evidences.

06. Ice cores

Ice cores from Antarctica and Greenland can be analysed –

- Annual layer counting
- Trapped gas bubbles used to reconstruct past climate
- Geochemical character of water
- Volcanic dust / wild fire carbon trapped in ice

O isotope record from Greenland ice sheet helps reconstruct past temperature

Younger Dryas –

Earth began to warm 15,000 yrs ago. This stopped temperorily and earth became cold 12,900 yrs ago for 1,300 years climatic reversal known as Younger Dryas.

⇒ Ice sheets grew over Europe and N. America

Lecture 14

1/11/20

Revision lecture - Notes made in respective sections

Basic understanding of past climate -

Time scale	Temp. range	Evidence
300 My	10°C	Tectonic
3 My	10°C	Orbital
50k years	3°C	Deglacial / Millenial
1000 yrs	1°C	Historical (tree ring).

4/11/20

Lecture 15

In Africa

Congo : 4°N - 1800 mm annual rainfall

Sahel, Niger : 16°N - 400 mm

Saharan oasis : 32°N - 75mm

Climate is persisting weather over a region. Its best described by vegetation, temperature & rainfall.

Koppen - Geiger Classification

A - Tropical moist climate (> 18°C)

B - Dry climate

C - Summers - warm & humid, mild winters

D - Summers - warm & cool, cold winters

E - Polar climate (< 10°C)

Earth's energy budget is for the whole pelanet, but it varies from region to region based on emissivity, albedo etc

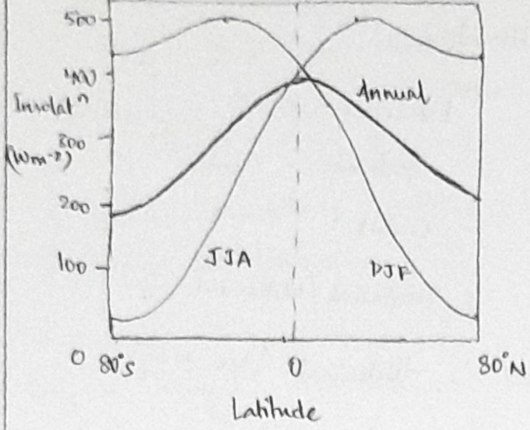
Incoming solar radiation

This is uniformly distributed based on -

- Latitude
- Season
- Time of day.

Also, earth is at perihelion during Southern Hemisphere summer, so it receives 6.9% more insolation that Northern Hemisphere

Zonal Mean Incoming radiation



- Annual mean insolation over poles is less than half its value at equator (max)
- Equator goes through semi-annual variation with maxima at equinoxes and minima at solstices

Inhomogeneity in climate mainly arises due to –

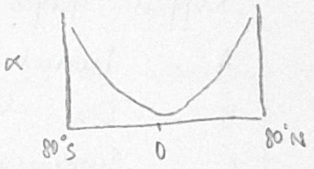
⇒ Reflectivity of region

Snow	0.9
Ocean (zenith angle)	0.95
Ocean (high angle)	0.05
Clouds : Thick	0.8
Thin	0.4
Ice	0.35
Soil	0.2

Planetary albedo

- Maxima at poles
  Due to snow, ice and large zenith angle
- Secondary maxima at tropical region
  Due to thick clouds & bright surface like Sahara desert
- Lowest albedo : Tropical ocean sparsely distributed clouds

Generally, albedo increases with latitude
∵ more snow cover & solar zenith angle



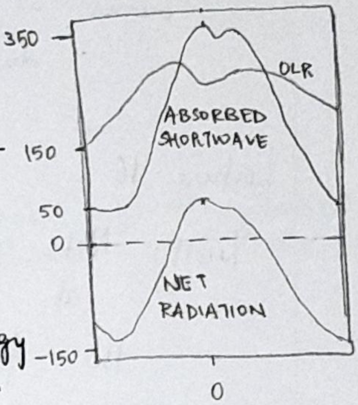
⇒ Emissivity of region
Range : 0.6 – 1.0
Deserts & semi-arid areas – $\varepsilon < 0.85$
Vegetation, water & ice – $\varepsilon \sim 0.95$

⇒ Outgoing Longwave Radiation (OLR)
It depends on temperature of the emitting surface
Lowest OLR – polar region & cold cloud tops over tropical region
Highest OLR – warm, cloudless deserts & cloud-free tropical oceans

Net radiation = Solar insolation - OLR

- Net radiation is +ve in tropics where insolation > OLR
  Highest value : $140\ Wm^{-2}$, tropical oceans (↑ insolation, ↓ albedo)

- Poleward of 40°, absorbed insolation < OLR, so climate system loses energy to space



  - Polar regions at winter experience greatest loss of energy
  - Dry desert areas also lose energy because
    - * Relatively high albedo
    - * High OLR as they're cloudless regions

- Averaged over the year, there's net +ve energy at the equator and net -ve at poles.
  This imbalance is the fundamental driver for of atmospheric & oceanic circulation.

- This transport of energy from low to high altitude maintains local equilibrium.
  Poleward flux of energy in each pole : 6×10^{15} W

(*) - If the fluid envelope didn't transfer energy, poles would be much colder and equator much warmer

Global temp. patterns are influenced by distribution of land & ocean

→ Land-sea contrast : Diurnal scale
  Land and sea breeze circulation helps moderate the temperature at coastal regions.

Oceans :
- lower albedo
- higher (3-4 times) heat capacity
- transfers heat downward by turbulent mixing

No downward transfer in land due to poor thermal conductivity.

⇒ Land heats up quickly during the day & cools quickly at night whereas oceans warm slowly and temp. drops very little at night.

→ ## Continentality

- Land areas closer to ocean have a smaller range of temperature variability than inland regions which experience extreme climates.
- Seasonal temp. variability is much larger over continents than oceans — land is warmer during summer and colder during winter.

5/11/20

Lecture 16

Recall: Net energy surplus ~~and~~ at equator and net deficit at poles causes an energy imbalance that is the fundamental driver of atm. & oceanic circulation

Refer Net radiation figure: Pg. 47 or 3:10 mins

Mean surface temperature

Geographical distribution of temperature and its seasonal variability is a result of net absorbed radiation.

This temp. gradient gives rise to a surface pressure gradient which in turn drives circulation High T: Low P & vice versa.

Scales of Motion

All scales of atmospheric motion is driven by temperature gradient & help in redistribution of heat.

SCALE	TIME	DISTANCE	EXAMPLE
Planetary	> Weeks	1,000 - 40,000 km	Westerlies, trade winds
Synoptic	Days - weeks	100 - 5,000 km	Cyclones
Mesoscale	Mins - hours	1 - 100 km	Tornado, T-storm
Microscale	Seconds - mins	< 1 km	Turbulence, wind gust

If heat wasn't distributed poleward, the climate at tropics and poles would be more extreme. This redistribution makes the climate of earth more equable.

The large scale circulation tries to equate the pressure gradient i.e by flow of wind from region of high P (low T) to region of low P (high T).

Atmospheric Circulation.

- Basic element : winds. They arise from P gradient.
- Driving forces :-
  1. Gravity
  2. Pressure gradient force -

     $\frac{dP}{dx}$: Zonal + eastward

     $\frac{dP}{dy}$: Meridional +ve northward

     $\frac{dP}{dz}$: Vertical +ve upward
  3. Coriolis force
  4. Friction
- Winds are named based on the direction from which they flow

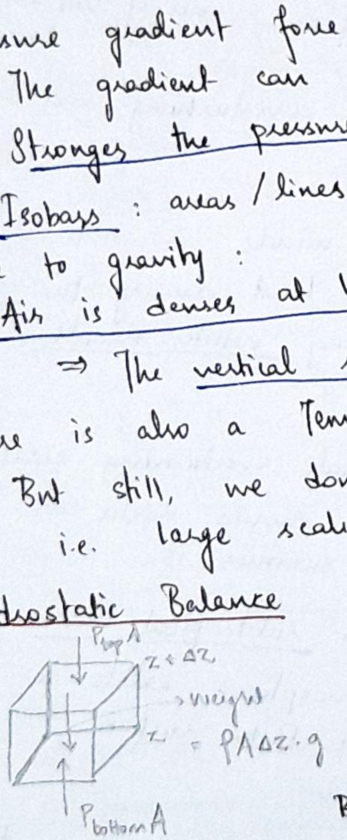
  Westerlies : blowing from west.
- Pressure gradient force
  - The gradient can exist along any/all of the three axes
  - Stronger the pressure gradient, stronger is the resulting wind
  - Isobars : areas / lines where there's no Pressure difference
- Due to gravity :

  * Air is denser at lower altitude : Height, 50 km but >90% exists at <20 km

  ⇒ The vertical scale is much shorter than horizontal scale
- There is also a Temp. gradient in atmosphere (i.e in troposphere)

  But still, we don't observe massive vertical circulation i.e. large scale convection currents are not seen due to - despite a large Temp / Pres gradient

Hydrostatic Balance



$F_{top} = -P_{top}A$ $F_{bottom} = +P_{bottom}A$.

$F_{weight} = -\rho A.\Delta z.g$

By balancing the total forces, we get -

$P_{top} - P_{bottom} = -\rho.\Delta z g$ ⇒ $\boxed{dP = -\rho.g\,dz}$

∴ The vertical pressure gradient force is cancelled out / balanced by gravity i.e. $-\rho g$. ∴ $\boxed{\frac{dP}{dz} = -\rho g}$

Convection

Vertical motion of air. The heated particles rise above lower-density air — called Convection of atmosphere

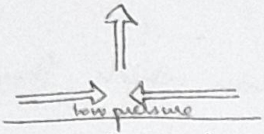
The sinking of colder air is called Subsidence.

Convection is an important aspect affecting weather pattern & climate because it affects atm. circulation in that region.

This produces Convective Uplift.

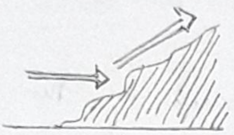
Uplift Process

01. Convergent uplift.



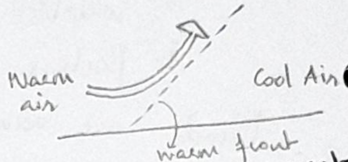
Convergent winds cause uplifts, since the only direction they can go is up.

02. Orographic Uplift



Mechanical barriers like mountains can force vertical ascent of air

03. Frontal Uplift



When warm air meets a mass of cool air, its forced to rise. Eg: Polar front.

All these processes add to convective overturning and affects local weather.

Mean sea level pressure and surface winds (Animation ~ 25 mins)

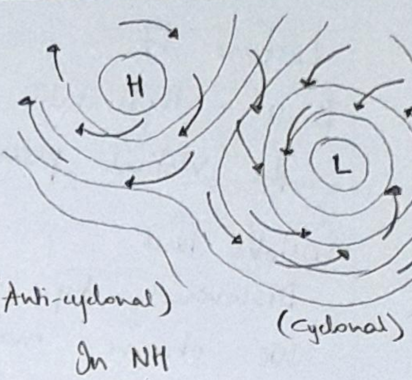
- There is low pressure over the land during the summer and higher pressure during winter months.
- High pressure near the poles.
- This pattern results from large-scale overturning circulation
- Low pressure at equator — which moves north or south, depending on where the summer is.
- High pressure is also observed in subtropical ocean.
- Averaged (globally & over time), atmosphere exists a pressure of 1013 mbar on Earth surface.

Surface Pressure pattern and winds (~28 mins)

Subtropical high pressure centres are found over the oceans in summer and land/continent in winter.

The wind pattern roughly flows and glides from high P region to low P region. Its not radial because of other forces.

The motion of winds following the pressure gradient is not radial, rather cyclonal while moving towards low pressure center and anti-cyclonal which moving away from high P in the Northern Hemisphere.



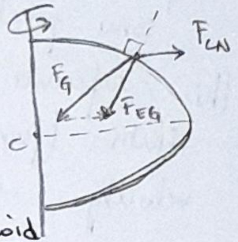
This flips in the southern hemisphere

* Closely spaced isobars on a weather map indicate a steep pressure gradient.

This is caused by the effect of other forces –

▸ Centrifugal force

- It's an apparent force, acting away from centripetal force and directed away from that axis of rotation



- Action of centrifugal force and gravity causes shape of earth to be oblate spheroid
- Effective gravity which acts along the vertical is in fact the vector sum of gravitational & centrifugal force

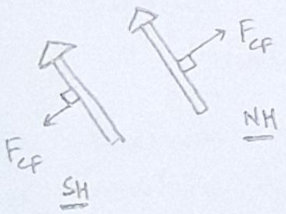
▸ Coriolis force

Its an apparent force caused by earth's rotation.

It acts perpendicular to the wind direction,

to the right in N. hemisphere

to the left in S. hemisphere



This is what causes the winds to deflect & converge / diverge in cyclonal motion, rather than radial

▸ Friction

It affects the wind speed and pattern upto altitudes around 1 km

Remember: Faster the wind, more the friction.

So the wind pattern in sort of erratic near the surface but winds are stronger and more zonal (~~eastward~~ westward) in the upper levels.

18/11/20

Lecture 17

Recall : Hydrostatic Balance

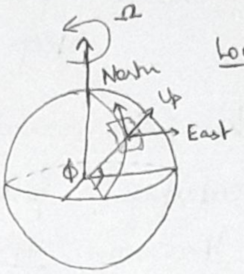
The vertical pressure gradient is balanced by gravity

Coriolis Force

Discovered by Gustave Coriolis. Its an apparent force.

We observe motions in atmosphere (from earth's surface) in a non-inertial (rotational) frame of reference

Rotating Earth as a frame of reference.



Local Cartesian

Consider a reference frame on earth's surface, whose origin is fixed wrt some point, at latitude φ.

This reference frame also rotates with Earth (from West to East) at angular velocity Ω.

East - x
North - y
Up - z

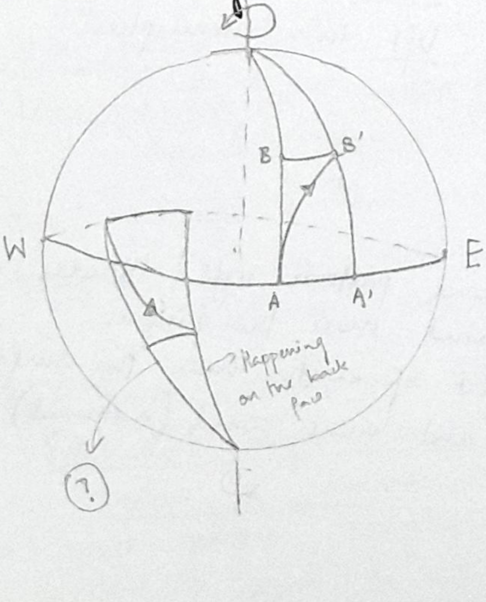
$$\Omega = \frac{2\pi}{24 hr} = 7.292 \times 10^{-5} s^{-1}$$

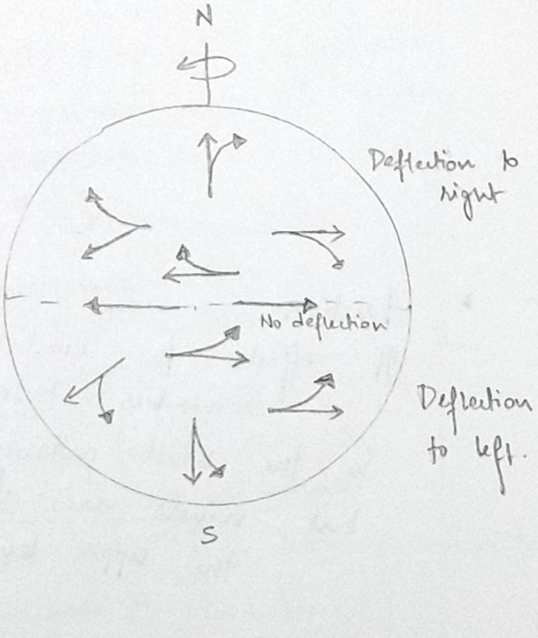
At latitude φ, linear velocity due to earth's rotation is -

$$\Rightarrow \boxed{V = \Omega . R \cos\phi}$$

$\Rightarrow V_{eq} = 464 ms^{-1}$ $\qquad V_{Pole} = 0 ms^{-1}$

⟹ Poleward moving winds.





Absolute velocity of zonal moving air parcel is given by —

$U_{abs} = U_{Rot} + u$ $\quad$ U_{ROT} : in rotation with Earth

u : Relative velocity (+ve / −ve)

Zonal? — Nah, moving north overall.

Suppose a parcel of air starts moving from latituted ϕ to ϕ', the absolute angular momentum would be conserved, provided no ext. torques act —

$U_{abs}\, r = (U_{rot} + u)\, r$ -

$\Rightarrow (\Omega . R\cos\phi + u)\, R\cos\phi = (\Omega \cos\phi' . R + u') . R\cos\phi'$

If $\phi' > \phi$, $R\cos\phi' < R\cos\phi$ $\Rightarrow$ $u' > u$ to remain constant.

$\Rightarrow$ At higher latitude, there's an increase in relative velocity (u).

∴ Air parcels moving meridionally (N-S) acquire a zonal velocity relative to the rotating earth.

They get deflected to the right in NH & to the left in SH

⟹ Why do zonal winds get deflected?

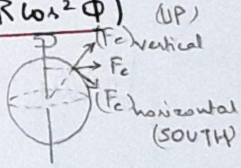
Centrifugal force

- Its an apparent force that acts normal and outward to the axis of rotation

$$F_c = -\Omega \times (\Omega \times R) = (0,\ -\Omega^2 R\sin\phi\cos\phi,\ \Omega^2 R\cos^2\phi)$$

→ Distance from axis

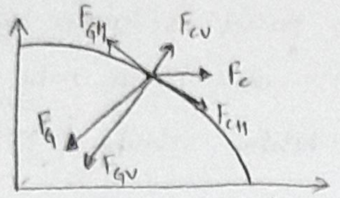
∴ Centrifugal force has a horizontal component directed towards the ellipsoid.



- It's maximum at the equator : $\sim \Omega^2 R = 0.032\ ms^{-2}$ $\quad$ $g = 9.8\ ms^{-2}$
  minimum at the poles : $\sim \Omega^2 R = 0$ $\quad$ ↓ Negligible.

$$\boxed{g' = g - \Omega \times (\Omega \times R)}$$

- Due to this, apparent gravity is max at poles & min. at equator
  ⇒ Earth has deformed into an ellipsoid over geological time scales
- And, in an ellipsoid earth (with equatorial bulge), there's a horizontal component [directed poleward] to gravitational acceleration.



For an object at rest

For an object at rest on earth's surface — $F_{GH} = F_{CH}$

Apparent F_c felt by an air parcel of unit mass moving with a relative zonal velocity 'u' would be —

$$= \boxed{\frac{U_{abs}^2}{R}} = \frac{(U_{ROT} + u)^2}{R}$$

u : Positive

- ⇒ Air is spinning faster than solid earth ↗ Along rotation of Earth

Westerly wind (west to East)

- Since its moving faster, it experiences a greater centrifugal force

⇒ Horizontal component of F_c, directed equatorward will be greater than F_{GH}

So, it'll experience a net equatorward displacement.

u: Negative

- Air parcel is spinning slower than solid earth

Easterly wind (East to West)

- Since its moving slower, it experiences a weaker centrifugal force.

⇒ $F_{CH} < F_{GH}$

So, wind moving towards west, will be deflected poleward

19/11

Lecture 18

Consider a stationary object in a rotating frame of reference.

In the inertial frame, the position vector will precess about the origin with angular velocity Ω.

Linear velocity : $\boxed{\frac{dr}{dt} = \Omega \times r} = V$

Suppose object moves with velocity v'

$$\Rightarrow \frac{dr}{dt} = v' + (\Omega \times r) = \frac{dr}{dt'} + \Omega \times r$$

Relationship b/w apparent time derivatives in non-rotating and rotating frame frame of reference is —

$$\boxed{\frac{d}{dt} = \frac{d}{dt'} + \Omega \times}$$

Apparent velocity v of an object (with velocity v' in rotating ref. frame & position vector r in inertial ref. frame) –

$$\boxed{v = v' + \Omega \times r}$$

Acceleration is given by –

$$a = \frac{dv}{dt} = \left(\frac{d}{dt'} + \Omega\times\right)(v' + \Omega \times r)$$

$$\underline{a = a' + \Omega \times (\Omega \times r) + 2.(\Omega \times v')}$$

a : apparent acceleration in non-rotating ref. frame
a' : acceleration in rotating frame of ref
r : position vector in non-rotating ref. frame 24/11

Apply Newton's II Law of Motion, in inertial/non-rotating ref. frame we get apparent eqn of motion in rotating ref. frame –

$$\underline{ma' = f - m\Omega \times (\Omega \times r) - 2m(\Omega \times v')}$$

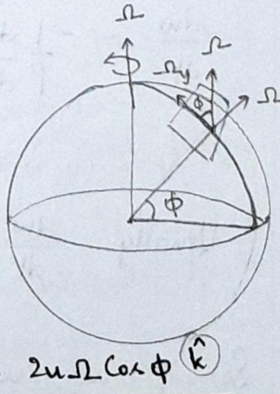
So, in rotating frame, there are 2 more apparent forces –

* $\underline{-m\Omega \times (\Omega \times r)}$: Centrifugal term – deals only with rotation of coordinate system

* $-2m(\Omega \times v')$: Coriolis term – deals with motions within rotating frame
\# If there's no relative motion, this term becomes 0.

For large scale atmospheric movement, centrifugal term is an order of magnitude larger the coriolis term.
They become comparable when $v' \simeq 200 \text{ ms}^{-1}$

Coriolis force



$$\boxed{\frac{F_{cor}}{m} = -2.(\Omega \times v')}$$

$$\Omega = (0, \Omega_y, \Omega_z) = \underline{(0, \Omega\cos\phi, \Omega\sin\phi)}$$

$$v' = (u, v, w)$$

$$\Rightarrow \frac{F_{cor}}{m} = (2v\Omega\sin\phi - 2\overset{\text{negligible}}{w}\cos\phi)\hat{i} - 2u\Omega\sin\phi\hat{j} + 2u\Omega\cos\phi\,\hat{k}$$

For horizontal movement → Coriolis parameter, f, at latitude φ is defined as $\boxed{2\Omega\sin\phi}$, such that horizontal components of F_{cor} are fu and fv

Magnitude of F_{cos} depends on —

1. Rotation of earth
2. Speed of moving object $\boxed{F_{cos} = f.\vec{v}}$ where $f = 2\Omega \sin\phi$
   ⇒ Stronger the wind speed, more the force
3. Latitudinal location
   ⇒ Higher the latitude, stronger the force. At equator $F_{cos} = 0$

General Cirulation of Atmosphere

We know, $V = v' + \Omega \times r$

From motions of equation and Navier Stokes equations.

$$a = a' + \Omega \times (\Omega \times r) + 2(\Omega \times v') = -\frac{1}{\rho} . \Delta p + g + F$$

Ω : Angular velocity of earth

v' : Relative velocity

ρ : Density of air parcel

Δp : Pressure gradient

F : Frictional / viscosity forces.

g : Acceleration due to gravity.

In vertical direction, incorporating centrifugal force and g —

$$g' = g - \Omega \times (\Omega \times r)$$

Momentum equations —

$$\frac{du}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + 2\Omega . \sin\phi . v - 2\Omega \cos\phi \, w + F_x$$

X : East / zonal

$$\frac{dv}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial Y} - 2\Omega \sin\phi \, u + F_Y$$

Y : North / Meridional

$$\frac{dw}{dt} = -\frac{1}{\rho}\frac{dp}{dz} - g' + 2\Omega \cos\phi \, u + F_z$$

z : Vertical

* $v = (u, v, w)$ — observed velocity

Usually $\frac{dw}{dt}$ i.e vertical accelerations are negligible, except in case of intense convective activity (Eg. cyclone or thunderstorm)

So, if we consider $\frac{dw}{dt} \approx 0$, we get the hydrostatic balance

i.e. $\frac{1}{\rho}\frac{dp}{dz} = g'$ Vertical pressure gradient is balanced by gravity.

When is Earth's rotation important?

- Coriolis deflection in wind system
- Cyclones and Hurricanes
- Ocean currents and gyres
- Ocean eddies - low pressure circulation system in ocean
- River plumes - when river opens into ocean, the direction it turns into is determined by coriolis deflection

Effects of planetary rotation are significant only for large spatial scales, away from equator where F_{cor} is large

Rossby number

A non-dimensional parameter that's a measure of whether the effects of planetary motion are important or negligible.

$$\boxed{R = \frac{U}{f \cdot L}}$$

U - velocity

L - length scale

f - Coriolis parameter

→ Small Rossby number ⇒ strongly affected by coriolis force

Eg: R = 0.1 to 1 for cyclones

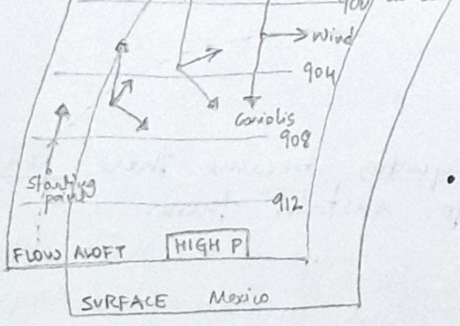
→ Large Rossby number (∵ small f at lower latitude, small length scale like motion in bathtub, or large u like tornadoes)

⇒ negligible effect of planetary motion.

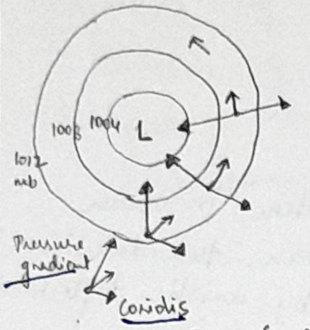
Eg: R = 103 for tornadoes.

Lecture 18.2

- The movement of the winds at a larger scale is dependent on the Pressure Gradient which in turn is determined by Temperature
- At smaller scale, movement is determined by local variations and factors.
- In the figure, the wind is moving poleward at a low altitude. As it moves, the effect of the coriolis force increases and the direction changes



until ultimately, the winds flow parallel to the isobars. They're called Geostrophic wind (High altitude, high latitude)



Cyclonic Flow (NH)

Low pressure centre with concentric isobars — this system is seen in cyclones too

This is observed in the upper levels, where there's no friction. So, air just keeps going around L, without converging

Geostrophic balance : Balance of pressure gradient force and coriolis force.

Winds above boundary layer — above 850 hPa, ~1.5 km

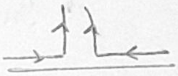
Surface movement

Frictional forces are dominant in atmospheric boundary layer upto 1.5 km

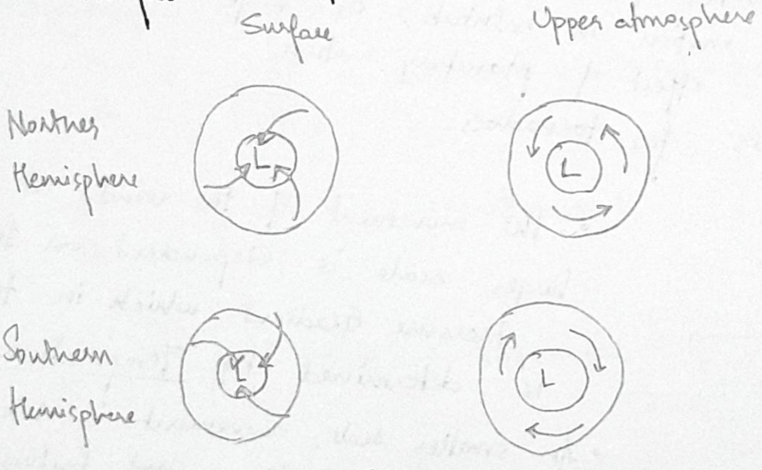
Balance of Pressure Gradient force, Coriolis force and Friction causes convergence of air in low pressure systems.

So, in the cyclone, the air near the surface converges and pushes up.

Top view



Side view



With localized high pressure, the direction of arrows are opposite

Cyclonic

Cyclones don't form near the equator because there isn't enough coriolis force to sustain them.

Scale analysis — the actual values of physical properties, like speed, are compared to the terms in atmospheric equation to see which are relevant in which scale

1/12/20

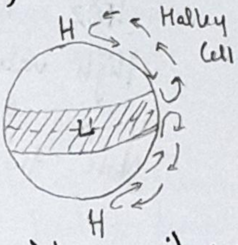
Lecture 19

Atmospheric Large Scale Circulation

The major driving factor of the circulation is the temperature gradient from tropics to poles, as a result of net radiation Refer graph in Pg. 47

The meridional gradient is less in the tropical regions (warm ocean & land surface), whereas it increases sharply in the mid-latitude region.

→ Early Idea of General Circulation – Edmond Halley (1686)



- Thermally direct circulation results from heating difference between poles (High P) and equator (Low P)
- Heated air rises up, creating surface low pressure
  - ⇒ At surface, winds blow from poles to equator
- In the upper levels, tropical air moves poleward & sinks as it cools

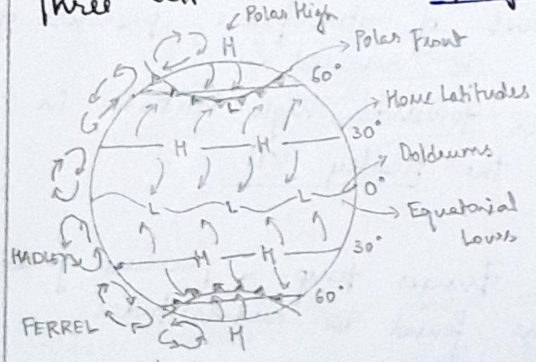
→ Columbus' ~~Theory~~ Route

Columbus' expedition succeeded because he harnessed the Trade / Easterly winds that blow east to west in the tropics

In the return journey, he caught the westerly wind in the mid-latitude regions

These observations don't support Halley's meridional winds.

→ Three Cell Structure – George Hadley, 1735



- Circulation is composed of 3 meridional overturning cells
- Polar cell and Hadley cell in tropics, are both thermally direct cells
- Ferrel' cell in the midlatitudes is a thermally indirect cell i.e. rising air in cooler region and sinking in warmer region.

Intertropical Convergence Zone (ITCZ)

- In the equatorial region. warm T facilitates convection i.e upward moving air which condenses in the upper layers to form clouds by Convective & Convergent Uplift
- So, ITCZ is characterised by extensive, planetary scale areas of cloud covers & hence, heavy precipitation
- Its also known as doldrums since this area of low pressure surface & weak winds are not conducive for sailing.

Precipitation

ITCZ is also a region of strong precipitation

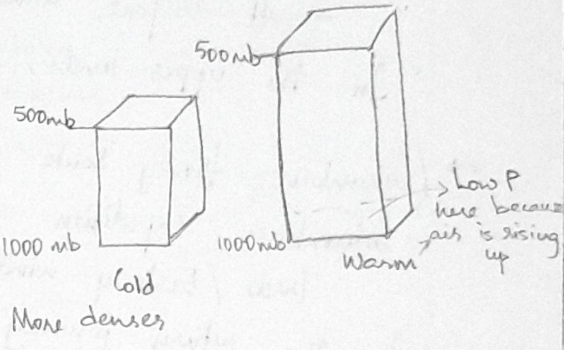
High values of precipitation are also observed over sub-polar oceanic regions.

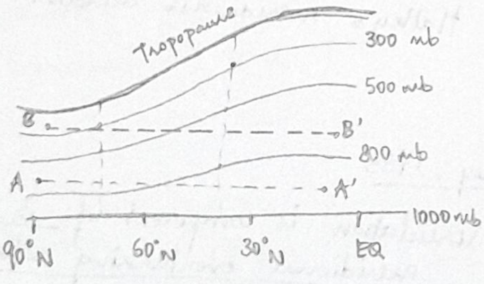
Note the seasonal variation in precipitation over the Asian monsoon domain

Upper level Circulation

Pressure decreases with height as a function of temperature

Pressure drops faster with height in a cooler air column than in a warmer one





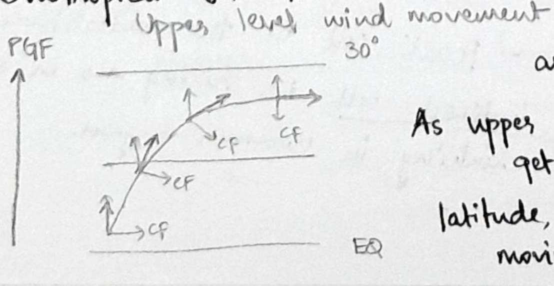
- Near Surface : (AA') A ~ 750 mb A' ~ 900 mb

  B ~ 300 mb B' ~ 700 mb

As pressure gradient decreases rapidly in colder regions, in the upper level of atmosphere, pressure gradient is reversed

⇒ Winds blow from tropics towards high latitudes in the upper level of the Hadley cell

Subtropical Jet Stream

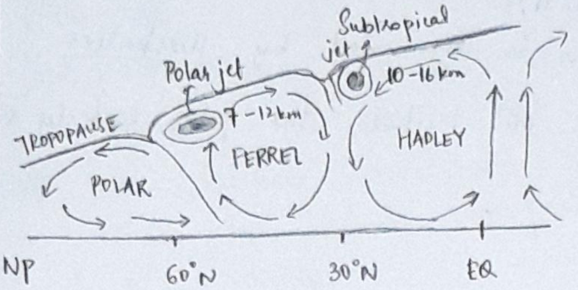


Stronger temp. & pressure gradients are found in mid-latitudes

As upper level winds blow poleward, they get deflected by CF, & at some latitude, they become Geostrophic winds, moving rapidly from west to east

Jet Streams

Narrow currents of **strong winds** (60-90 m/s) in higher latitudes generally found in upper troposphere.



Each hemisphere has 2 primary jet streams, with width of few hundred kms & vertical thickness less than 5 km

Subtropical : 20°-30°N, 10-16 km, ~60 m/s

Polar : 50°-60°N, 7-12 km, ~85 m/s

The jet streams are not uniform, rather meandering because the pressure gradient is not uniform along a latitude over land and water.

They're important for aviation because by flying in a jetstream planes get a boost from tailwind, saving fuel & time

Conversely planes flying in opposite direction lose time & fuel So, pilots adjust their altitudes to avoid them

2/12/20

Lecture 20

Recall: Hadley cell

- Low surface P zone near the equator — surface easterly winds converge lots of clouds and precipitation at ITCZ.
- Upper level pressure gradient – Equator to poles - Geostrophic winds Jet streams at 30°N and 60°N.
- As the **geostrophic winds** reach 30°, they become **cooler** and **sink down**, so that **30°N/S is a high pressure region** — easterly trade winds blow equator-ward and westerly winds blow poleward
  surface winds

30° latitude also called **Horse latitude**

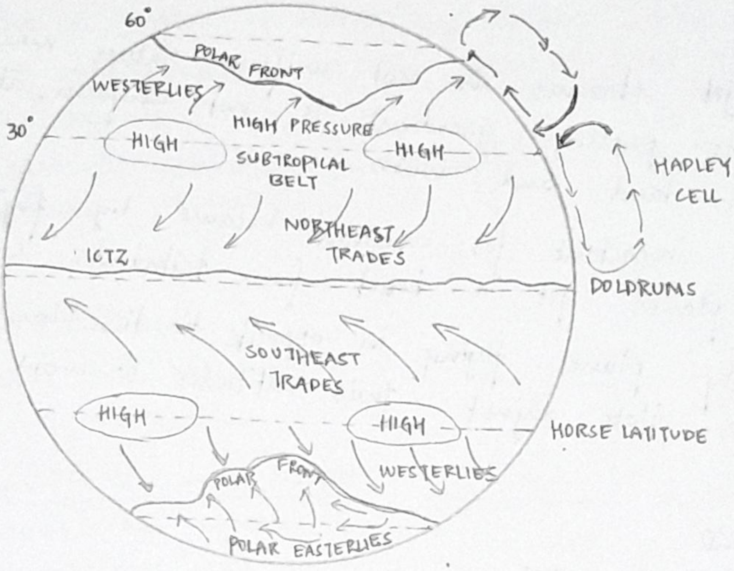
Surface winds that move towards equator from high P subtropical regions are called **Northeast and Southeast Trade winds**

So the equatorial region is dominated by **easterlies**.

* The wind also diverges poleward from the High P Subtropical region and gets deflected right in NH. This warm air meets the incoming cold air from the pole (driven by surface T & pressure gradient) at the Subpolar latitude, 60°N/S.

So, the mid-latitude region is dominated by Westerlies

* In the polar region, above 60° latitude, the polar easterly winds dominate the region.



Factors affecting meridional circulation of atmosphere —

* {
- Equator to pole temperature gradient
- Coriolis force (which is determined by ~~wind~~ speed of rotation)

For earth, the meridional extent of Hadley cell is found at 30° latitude, where Sub-tropical jet streams are formed

* Venus rotates slowly, so it has 2 cells of circulation, overall.

Faster rotating planets have several bands of alternating wind patterns.

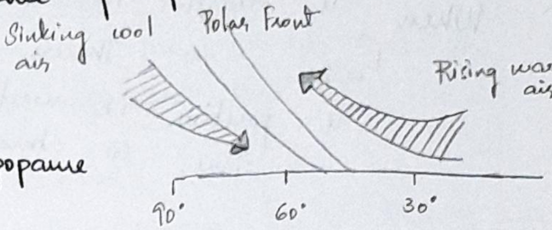
Horse Latitudes — 30°N & 30°S — Subtropical High Pressure Belt

Its characterised by weaker winds (~~descending~~ vertical descent motion dominates), sunny skies, no clouds & no precipitation (lack of convecting upward movement). All deserts in the world fall in this zone

The subtropical high pressure centers are found over the continents (land) in winter & over subtropical oceans in the summer, due to differential heating

Polar Cell

- Coldest T is near the poles ⇒ Polar high pressure. Winds moving towards the equator get deflected as Easterly winds
- At 60° latitude, this cool air meets warm air, which rises up which can produce precipitation due to frontal activity.



- Rising warm air diverges at tropopause (~ 8 km) and moves poleward, * descends over polar regions creating surface high pressure

Ferrel Cell

- Thermally indirect cell — observed in mid-latitudes with surface westerlies and upper level easterlies
- Current understanding suggests that midlatitude circulation is made up of high & low pressure systems which play a major role in transferring heat from sub-tropics to polar region.

Surface westerlies are observed but upper level 'easterlies' are just opposite circulation due to baroclinical instability

The storms observed in Europe & Northern America are created due to Frontal activity — instability and rotating vortices created when warm & cool air meet.

There are also a lot of migrating weather systems in this domain

General Circulation of Atmosphere

It helps remove net excess energy in lower latitudes to the polar regions, where there's net energy loss

In addition to that, there's an Angular Momentum Budget

In angular momentum budget, atmosphere gains $\vec{L}$ in low latitudes (easterly surface winds) and loses it in midlatitudes (westerly surface winds). So, a poleward atmospheric flux of $\vec{L}$ is thus implied

② U_{ROT} : Linear velocity of solid earth (westerly-positive)
u : Wind velocity

When u : negative i.e easterly trade wind, $\vec{L}_{atm}$ is lesser than $\vec{L}_{earth}$, so there's a net gain of angular momentum.
u : positive i.e. westerlies in mid-latitude, the converse is true, so atmosphere loses $\vec{L}$ to the earth.

⇒ If there were only easterly winds on earth, transfer of $\vec{L}$ from earth to the winds would eventually slow down earth

If only westerly winds existed, $\vec{L}$ would transfer from atm to earth, which would lead to faster spin of earth (super rotation), decreasing the length of day.

Seasonal Variation of Meridional Circulation

The ITCZ shifts upward in N.H. summer and it moves downward in S.H summer, wherever there is maximum solar radiation.

Its not a uniform line / belt. It varies according to pressure gradient, maximum heating

Important # ITCZ is over the Asian landmass (Tropic of Cancer) in the summer months.

In the summer months —

- Subtropical High P zone is over the oceans ⇒ there's a low pressure zone over ~~southeast asia~~ Indian subcontinent
- Southern Indian ocean experiences high pressure ⇒ there's a strong pressure gradient b/w ocean & land

↳ Relevant for explaining monsoons.

- Similarly, the whole system (ITCZ, Hadley circulation, subtropical high P zones) shifts northward in the N.H. summer due to the variation in heating i.e solar radiation.
- Deep convection belt (~ ITCZ) shifts northward to South Asia in the summer from Southern Indian Ocean

Monsoon

It means a seasonal reversal of winds associated with a change in precipitation patterns.

This system is observed all over the world (→ Africa, Americas), but the Asian-Australian is the most important one

→ Characteristic features of winter circulation

Surface : North-easterlies over northern Arabian Sea & Bay of Bengal

Upper level : Subtropical westerly jet stream at ~ 25°N

→ Summer circulation

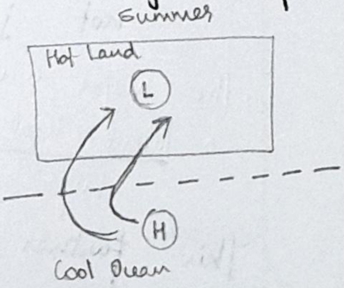
Surface : Cross-equatorial flow, south-westerlies i.e. low level jet stream. ?

Upper level : Tropical easterly jet stream (~ ITCZ)

Northern Hemisphere is associated with shift in ITCZ and Hadley Cell.

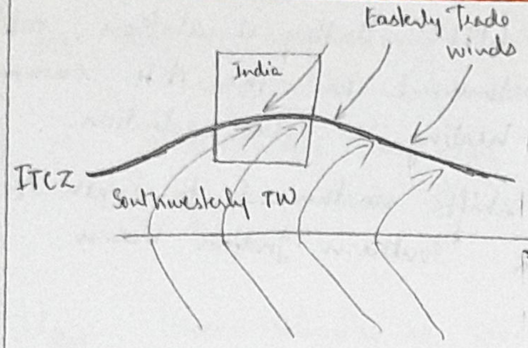
Due to the extra landmass in NH, there's a differential heating which creates a strong pressure gradient.

As there is more land in NH, the land-sea thermal contrast is also greater, the maximum heating zone gets shifted northward, even more than expected.

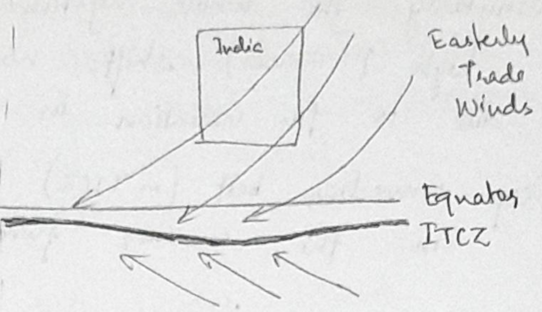


This unusual shift of ITCZ and Hadley cell creates a shift in direction of the wind.

When the South-east trade winds move across the equator (towards ITCZ which has shifted), the coriolis force causes it to deflect to the right & the pressure gradient drives it towards the Indian landmass, so that now they become South-westerlies. (surface)?



Summer

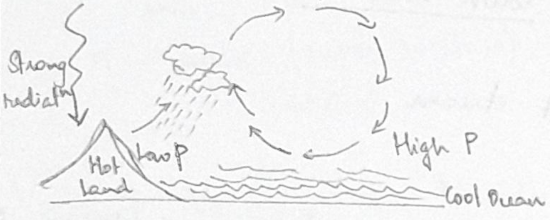


Winter

Since the ITCZ falls across the Indian landmass, the Southwesterlies and Easterly Trade Winds converge here, which favours ~~con~~ convection ⇒ monsoon rainfall.

Also, the precipitation is facilitated by clouds which form above the ocean and hence carry a lot of moisture inwards.

Classical Model of Monsoon: Large Sea Breeze Circulation



Summer

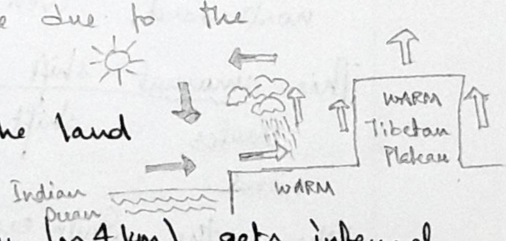
This simple model cannot explain –

- Vertical extent of monsoon circulation. The existing extent can't be explained by variation in surface heating
- After initial rainfall, land temperature is actually cooler than that of ocean.

In the summer months, the whole Troposphere gets heated up, not just the surface. This drives the monsoon

The major contributing factors are the
- topography of the region &
- latent heat released to the atmosphere due to the large scale precipitation

This further intensifies low P over the land



North of Himalayas, the Tibetan Plateau (~4 km) gets intensely heated which contributes to the temperature gradient, which in turn drives the cross-equatorial flow

It also prevents the loss of moisture to higher latitudes by being a mechanical barrier.

Research links the evolution of this climate system with the growth of Himalayas & Tibetan plateau (which facilitates the heating of upper level atmosphere)

Major uplift 8-10 Mya & a minor one 3.6 - 2.6 Mya phased in the monsoon

Other plateaus in India such as Western Ghats & Northeastern mountains act as topographic barriers, holding in moisture-laden winds & causing Orographic Precipitation

The air passing over the plateau doesn't contain as much moisture, creating a rain-shadow region

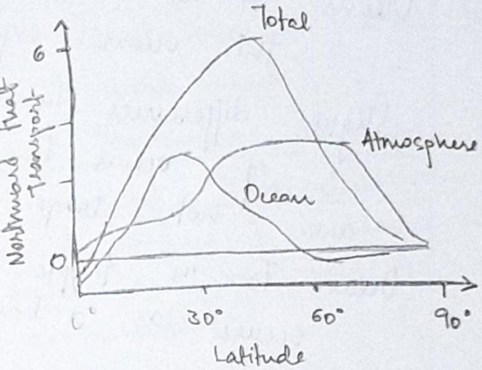
6/12/20

Lecture 21

Ocean Circulation

It helps transfer excess energy in the tropics to the poles.

It transfers more energy in lower latitudes than the atmosphere



Scales of Motion in the Oceans (1:40)

Timescale	Spatial scale	
0.01 s	1 mm	Bubbles
12-24 hrs	500-5,000 km	Tides
100 yrs	10,000 km	Thermohaline circulation
1-7 yrs	5,000 km	El Nino.

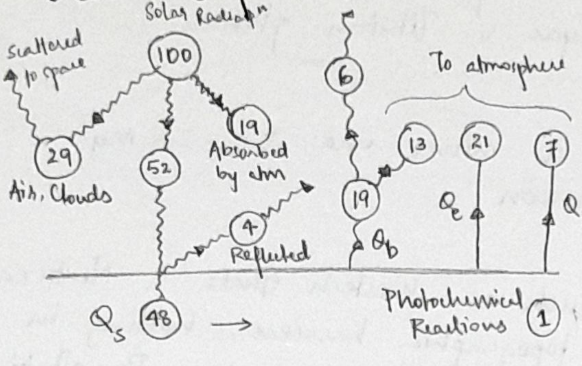
Oceans are mainly heated by solar radiation. About ~50% of incoming radiation is absorbed by Earth, 70% of which is covered by oceans.

Pg. 27 IR & other long-wave radiation is absorbed in the top micrometers of ocean surface

Visible light penetrates ~200 m - Euphotic Zone, supports marine life

Depends on amt. of SPM, turbulence and state of the ocean.

Ocean Surface Heat Balance



Q_s : shortwave radiation (absorbed)

Q_b : longwave radiation (emitted ∵ of T_{ocean})

Q_e : Latent heat

Q_h : Sensible heat (convection)

Total surface heat flux —

$$Q_{sfc} = Q_s + Q_b + Q_e + Q_h$$

- Shortwave & longwave radiation (incoming) heat the ocean surface.
- It loses heat in form of emitted longwave radiation, latent heat associated with evaporating water & sensible heat transfer to the air above ocean surface

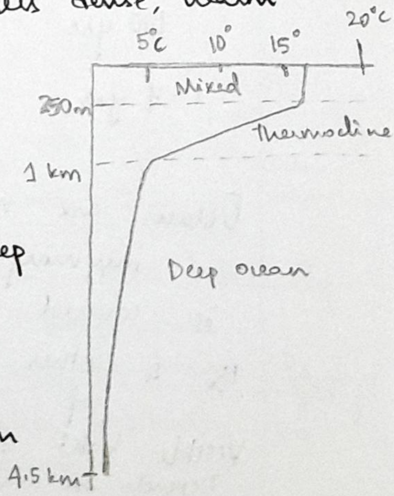
Oceans act as vast reservoirs of heat — so the places near the ocean experience a moderating effect.

Slight differences in incoming solar radiation has little impact of ocean T_s, so lateral differences in T & density are not large. — unlike atmosphere

Ocean T_s in tropic, subtropic, polar & subpolar regions occurs as bands

Vertical layers

1. Mixed layer (~200 m) under the action of turbulent wind stress
Upper layer of ocean interacts with the atmosphere. Buoyancy fluxes & This layer other properties are well mixed ⇒ less dense, warm water at the top.



2. Thermocline (between ~300m & 1km)
In this middle layer, temperature decreases rapidly with depth. This region of steep temperature gradient represents Thermocline

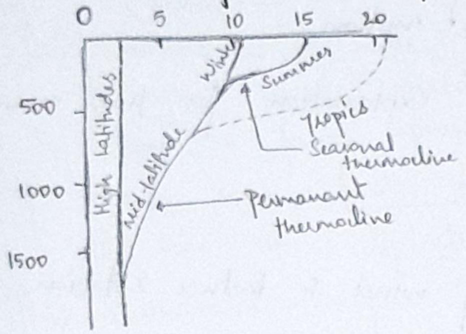
3. Deep Ocean (> 1 km depth)
T is b/w 0° & 3°c. No temporal variation in ocean's physical properties.

(09) Surface turbulence v/s Thermal Stratification

Surface waters are warmer and lighter, compared to deeper, colder ocean. The thermal stratification of ocean is impeded by turbulent processes at the surface, which is under the influence of atmospheric motion, exchanging heat and momentum.

Incoming radiation establiches thermal stratification while turbulence hampers it.

Oceanic Temperature Profile.



- ★ We can expect stronger winds and greater seasonal variation at higher latitudes and not at tropics
- ★ In mid latitudes, the mixed layer deepens in winter (stronger winds) and in summer, mixed layer is just at the surface (due to weak winds) & a seasonal thermocline develops

→ No permanent thermocline

- ★ In high latitude, there's not permanent thermocline or ~~t~~ surface T is same as mixed layer because the surface waters are very cold & deep ocean T i.e. covered by sea ice (acts as insulator)
- ★ ∴ Tropical oceans are much more stratified i.e. Temperature & density vary significantly. Not much mixing happens.

In the winter in midlatitudes —

Strong temp gradient → Strong winds → More turbulence → Deepened mixed layer

due to winds & surface heat loss (∵ ocean is warmer than atmosphere).

Types of Ocean Circulation

01. Wind driven Circulation (Faster)

Primarily horizontal motion — surface currents

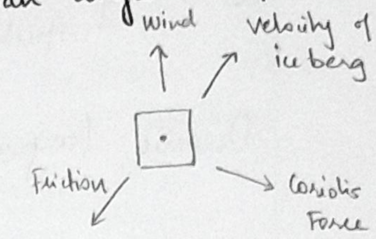
Surface T — Atmospheric circulation — Surface friction — Wind drag — Surface currents — Coriolis effects.

02. Thermo-haline circulation (slow)

Deep currents - horizontal & vertical motion of water masses, driven by density variations (influenced by Temperature and Salinity).

Theory of Wind driven Ocean Circulation.

Originated from Norwegian explorer **Nansen** who observed that that Arctic ice moves at an angle 20°-40° to the right of wind direction



This is due to coriolis effect influences ocean currents & affects ice motion

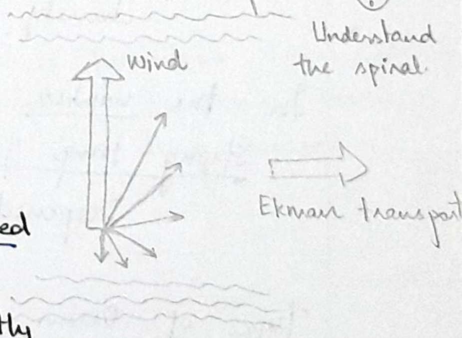
Nansen produced a quantitative explanation for this movement

Ekman's Theory (1905) (22:10 mins)

Describes quantitative effect of wind & Earth's rotation on the upper ocean.

- In this theory, water in an ocean column is considered as made up of many thin, coupled layers
- When strong & persistent wind acts on surface ocean waters, it gives rise to surface currents which under the effect of Coriolis force, flows at an angle 45° to the surface wind direction

Looking down on ocean surface



? Understand the spiral.

- Each water layer will force motion in the layer below and K.E gets transferred down the water column.
- Coriolis effect means each layer gets deflected by 20°-40° & frictional drag causes the speed of motion to decrease subsequently
- This produces a spiral until the lowest layer at which direction of the current is opposite to that of wind.

  This is Ekman Spiral
- Ekman layer - the depth of the Ekman spiral - about 100 m

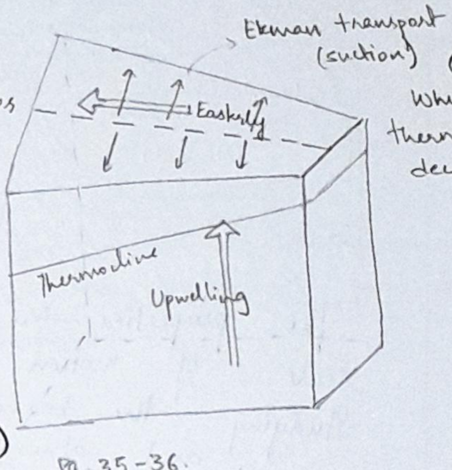
Ekman transport

When the movement of individual layers of water are integrated, the net direction of transport is perpendicular to the wind direction.

Net movement of water is known as Ekman Transport

Effects : Equatorial upwelling

- Surface winds are easterlies near the equator. So the Ekman transport is directed away from equator poleward

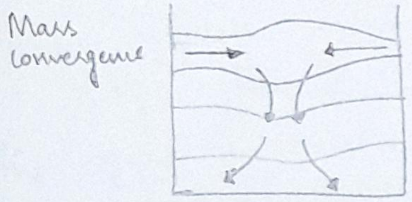


? Why is thermocline decreasing?

Pg. 35-36.

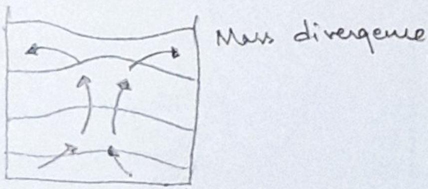
- This divergence of water by Ekman transport causes mixed layer to thin & forces upward motion of deeper waters (cooler, nutrient-rich) to rise up : Upwelling
- This increases surface biological productivity.
- Ekman transport can also cause convergence of water, increasing the thickness of mixed layer, pushing water downward causing Downwelling.

Downwelling



Surface layer thickens

Upwelling



Surface layer thins

Coastal Upwelling & Downwelling

If prevailing winds blow along the shore, the Ekman transport can be towards or away from shoreline

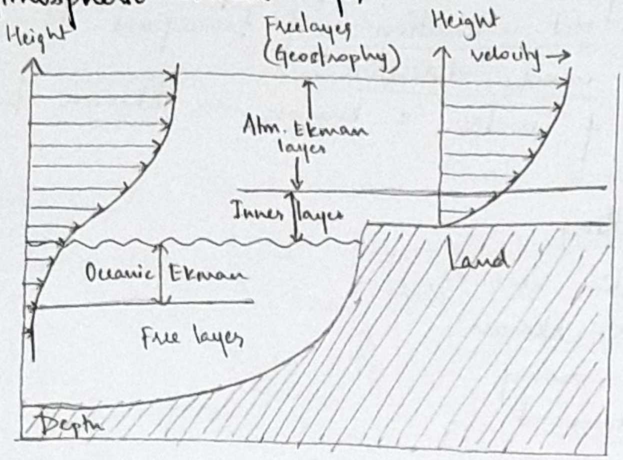
Away (Ekman transport) ⇒ Upwelling ⇒ More nutrients brought to the shore, increased biological productivity.

Towards the shore ⇒ Downwelling ⇒ Coast is not nutrient rich

Lecture 22

9/12/20

Atmospheric Ekman layer



Boundary layer

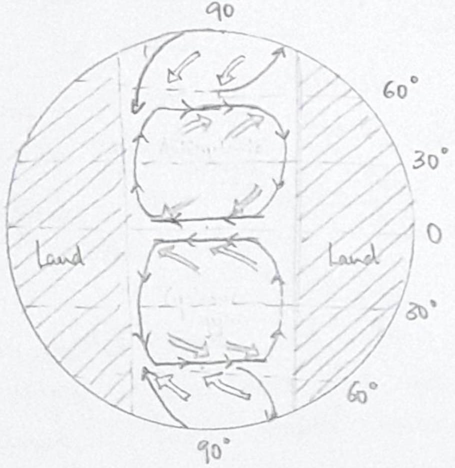
The layer of atmosphere where there's a significant increase in wind velocity due to the reduce in frictional force (that's strong near the land).

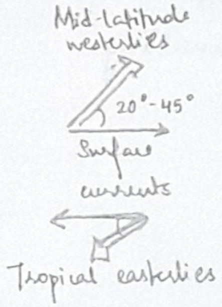
Similar to Oceanic Ekman layer.

The properties are well mixed in this layer and the scale of motion is fine.

Studying the boundary layer is critical for both ocean and atmosphere because both energy and momentum transport occur through this.

Ocean Surface Circulation





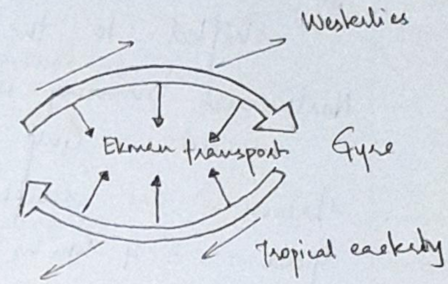
For a large ocean bounded by continents on east & west, continental boundaries would block the easterly/westerly currents, which move northward/southward forming a closed loop of circulation, called a gyre.

The pattern in the real world is more complicated because of uneven land distribution

There are 5-6 major gyres.

The ocean currents help in transfer of heat — warm surface currents move poleward, carrying energy towards the poles.

Convergence and Downwelling



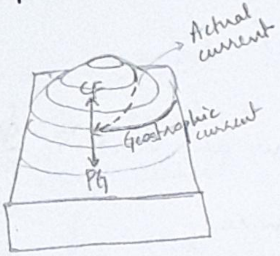
Ekman transport causes convergence in the centre of the gyre

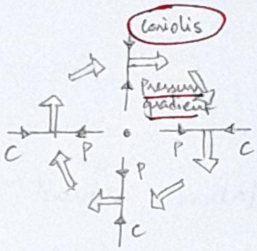
Surface layer thickens — by ~50 cm at the centre of the sea

⇒ Forced vertical downward motion i.e. downwelling

This downwelling occurs in the middle of subtropical ocean — which coincides with low biological productivity due to limited nutrient availability.

Geostrophic balance





Increased sea surface elevation at centre of gyre gives rise to an outward pressure gradient force

Water spirals outward. When the coriolis force is balanced by PGF, a geostrophic current is formed

The gyre is maintained by combined effects of —

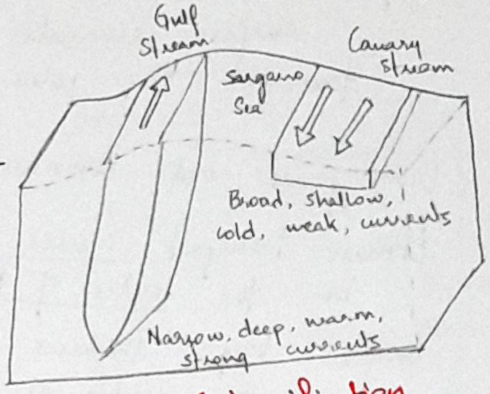
- Ekman convergence due to surface winds
- Oceanic PGF due to elevation
- Associated geostrophic currents

Note: Subtropical gyres are not symmetric — centre of gyre is shifted to the west in NH because northward moving western boundary currents are narrow while southward moving eastern currents are wide

11/12

Lecture 23

Asymmetry of subtropical gyre



Western Intensification

In the NH, the gyres are shifted to the west, so that -

- Northward moving western boundary currents - Gulf & Kuroshio stream - are swift surface currents.

  Speed : 3-4 km hr^{-1}

  Depth : Upto 1000 m

  Width : 50 - 75 km

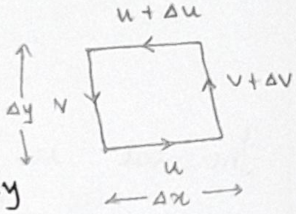
- Southward moving eastern boundary currents - Canary and California currents are wide. shallow and slow.

  Speed: 1 km hr^{-1} Width : Hundreds of kms.

  Depth: 500 m

Vorticity.

We define circulation around the contour as : $C = \oint u . dl$



In a rectangular path in a fluid whose velocity varies spatially, circulation is -

$$C = u\,\Delta x + (v + \Delta v).\Delta y - (u + \Delta u)\,\Delta x - v.\Delta y$$

$$C = \Delta v . \Delta y - \Delta u . \Delta x$$

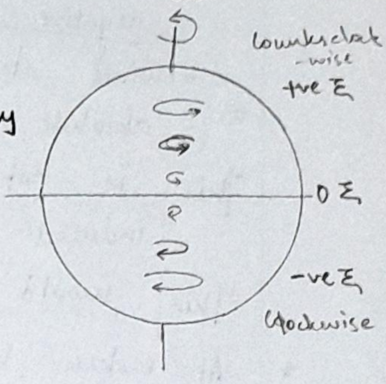
C is dependent on path length, so its useful to define Vorticity (ξ) as circulation per unit area. It describes the tendency of a fluid to rotate

$$\xi = \frac{C}{A} = \frac{\Delta v . \Delta y - \Delta x . \Delta u}{\Delta x . \Delta y} = \frac{\Delta v}{\Delta x} - \frac{\Delta u}{\Delta y}$$

$$\boxed{\xi = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}}$$

Vorticity is a vector feild which gives a microscopic measure of the rotation at any point in the fluid.

Absolute vorticity (ξ_a) is the sum of Planetary and Relative vorticities. The absolute vorticity is conserved for fluid motions in earth system



1. Planetary vorticity

Vorticity brought about because of planetary rotation is called Planetary vorticity.

$$f = 2\Omega \sin\phi$$

Mathematically, this is identical to Coriolis effect - acts in opposite direction in SH

2. Relative Vorticity : $\xi = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$

a) Due to wind stress

$\nabla \times V$

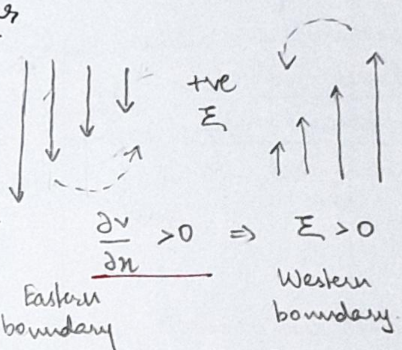
Negative ξ for anticyclonic/~~clockwise~~ subtropical gyres } NH

Positive ξ for cyclonic/~~anti-clockwise~~ polar gyres } NH

b) Due to current shear/horizontal shear

Change in speed of current across the current also produces ξ.

Friction for flow of current is maximum close to the coast - speed of current increases away from coast



$\frac{\partial v}{\partial x} > 0 \Rightarrow \xi > 0$

Clockwise — -ve ξ

Counterclockwise — +ξ

Conservation of absolute vorticity

$$\boxed{\xi_a = f + \xi}$$

As the water in NH sub-tropical gyre rotates, it must gain +ve ξ while moving south ($\because f$ decreases) in order to conserve total ξ.

There is generation of positive or negative vorticity in the arms of the gyre due to -

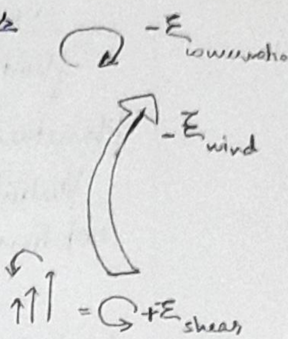
* Conservation of ξ_a
* Horizontal shear due to friction at the coast.

In a symmetric gyre —

- * The northward moving arm (western boundary) gains negative vorticity due to —
  - wind stress (anticyclonic motion)
  - * absolute vorticity conservation (f increases)

This is not balanced by the positive vorticity induced by frictional shear.

This would lead to acceleration of the gyre.

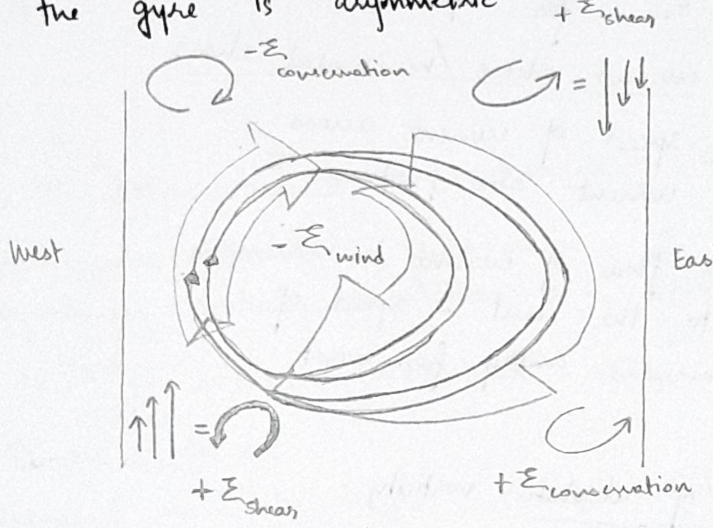


$\xi_{wind} + \xi_{cons} > \xi_{shear}$

- * At eastern boundary current $-\xi_{wind}$ is balanced by $+\xi_{shear}$ (relatively small term) and $+\xi_{conservation}$.

The only way balance can be achieved at the western boundary is by increasing friction along the boundary, by creating a narrower, deeper and faster-flowing current.

Hence, the gyre is asymmetric



IN BOTH HEMISPHERES Vorticities balanced!!

↓

Western boundary intensification: Same volume of water gets transferred in western boundary through faster, deeper currents when compared eastern boundary currents.

Importance:

Strong boundary currents are important components of climate system as they transfer large quantities of warm water poleward very rapidly. Gulf stream: $10^8 \ m^3 s^{-1}$

If Gulf stream were 2°C warmer than average, it would represent energy flow of $10^{15} \ J s^{-1}$ approx. 20% of total northward heat flow in atm & ocean combined ⇒ huge impact on climate system

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Lecture 24

El Nino Southern Oscillation (ENSO)

It is a coupled atmospheric-oceanic activity that occurs at the scale of ~10^3-10^4 km across timescale of about an year

WKT. - surface oceanic motion is caused by motion in the atmosphere

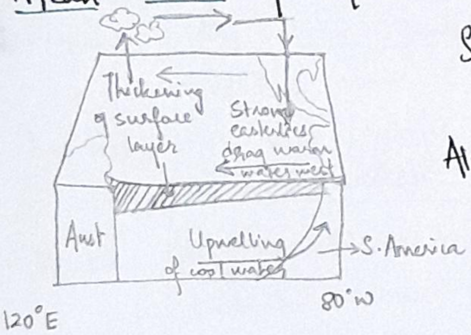
- Equatorial and coastal upwelling / downwelling
- Meridional temperature gradient decreases sharply from equator to pole. There's no zonal gradient

But, the western part of the ocean basin (pacific & atlantic) is hotter than the eastern part ⇒ ∃ asymmetry

The lower sea surface patches near the equator due to upwelling. The coastal upwelling also reduces sea surface temperature

The easterly trade winds push the surface water continuously to the west, so that it piles up and sea level is slightly higher. The accumulated water gets heated continuously resulting in the western part of the basin being at higher temperature.

Mean state of equatorial pacific coupled Ocean Atmosphere system



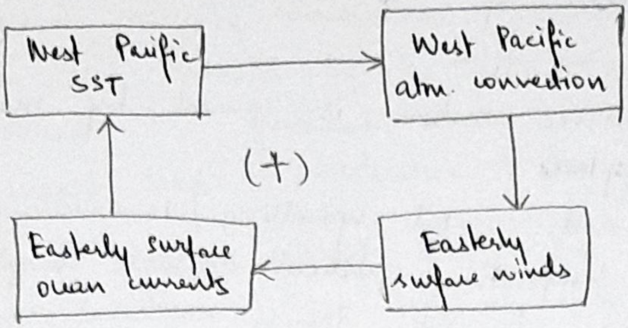
Sea level approx ~50 cm higher over West Pacific than over East

Also, warmer sea surface temperature (SST) over the west.

- Higher T favors atmospheric convection & ascending air motion over West Pacific which subsidence occurs over east pacific.
- There's a closed circulation with eastward winds in upper troposphere and westward flow in lower layers
- This zonal overturning is called ~~Zonal~~ Walker Circulation and it reinforces the surface easterlies

Due to this zonal asymmetry, there's almost no convection in atmosphere over East Pacific

Bjerknes Feedback

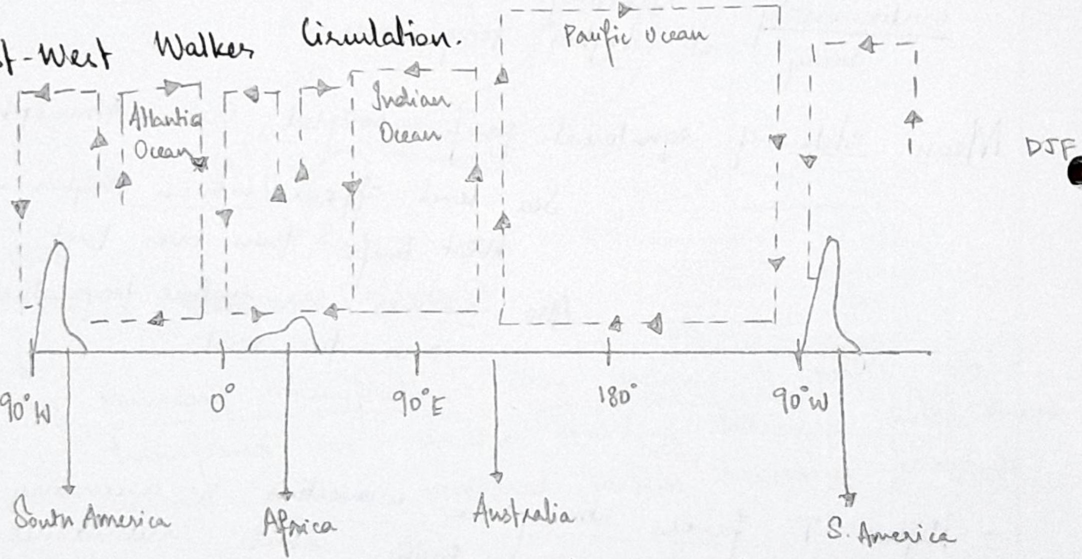


Warm SST over west Pacific drives

- drives more atm. convection
- latent heat release - heats the atmospheric column
- further decreases in surface pressure
- strengthens the surface easterlies converging over low pressure region
- reinforces the initial SST gradient

This positive feedback maintains the SST distribution, cloudiness gradient, and wind distribution over the Pacific

East-West Walker Circulation.



Walker circulation is more evident in the Pacific.

Normal State over the pacific –

WEST	EAST
• Warm SST • Low pressure	• Cooler SST • High pressure
• High convection, clouds & rain	• Subsidence, no clouds or rain
• Surface water converges • Downwelling	• Surface water diverges • Upwelling
• Sea surface hight increases	• Surface hight is reduced
• Deep mixed layer ⇒ thermocline is found at larger depth	• Shallow mixed layer ⇒ thermocline is found at shallow depth.

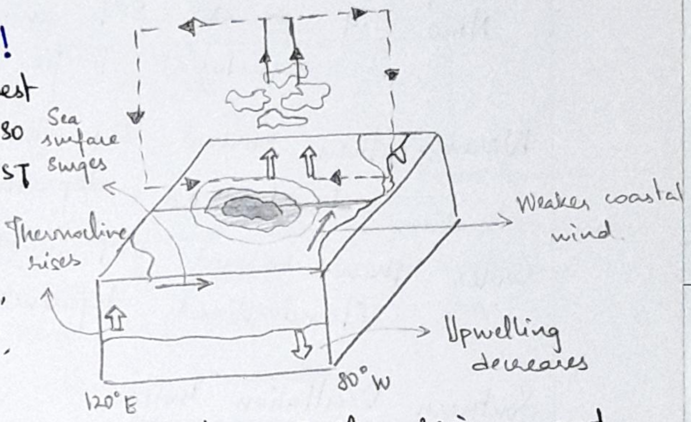
Different categories of reflected waves

There's a periodicity to this

Occassionally, Walker circulation gets disturbed –

El Nino events are departures from mean state in the Pacific which result from weakening easterlies. → # Causes will be studied later

- When the easterlies weaken, !!! the mass of water in the west pacific shifts eastward & so does the region of warm SST



- This also decreases the upwelling in the east pacific, ~~&~~ creating a warmer SST, & decreasing the gradient
- Increased convection over central & eastern Pacific regions and more subsidence over east pacific.
- Regions over west pacific which used to receive more rainfall, now get decreased subsidence, and regions in east pacific which was dry now receive more rainfall
- When the upwelling decreases, the region of high biological productivity now goes down in East pacific.

El Nino Conditions

WEST	EAST
• Cooler SST anomalies (cooler than usual)	• Warmer SST anomalies
• High P anomalies	• Low pressure anomalies
• Subsidence, no clouds or rain	• More convection, clouds & rain

The Bjerkene conditions / feedback help maintain El Nino conditions also

La Niña

Opposite of El Nino — an extreme of the normal conditions — Very strong westerlies, hot temperatures over West Pacific and cold conditions over East

1982-83 — strong El Nino effect

What is an anomaly?

It is a departure from the mean state i.e its recognised by ~~ideat~~ subtracting current state (SST) from mean state

Identifying El Nino : El Nino Index

Nino 3.4 — ~~SS~~ SST anomalies averaged in eastern equatorial Pacific box

Warmer than normal SST in Eastern pacific by >+1.0 of standardised departures — El Nino

Cooler than normal SST in Eastern pacific by <-1.0 of standardised departures - La Niña

Southern Oscillation Index

Sea level pressure is measured at Darwin (Australia) and Tahiti (mid-pacific island)

When P at Tahiti was high, the pressure at Darwin would drop on an inter-annual scale

Southern Osillation Index (SOI) measures the difference in pressure between Tahiti and Darwin. SOI is a measure of the Pacific Walker circulation and strongly correlates (anti) with El Nino

This is because they are manifestations of the same phenomena that results from unstable interactions b/w ocean and atmosphere. Hence its called El Nino Southern Oscillation

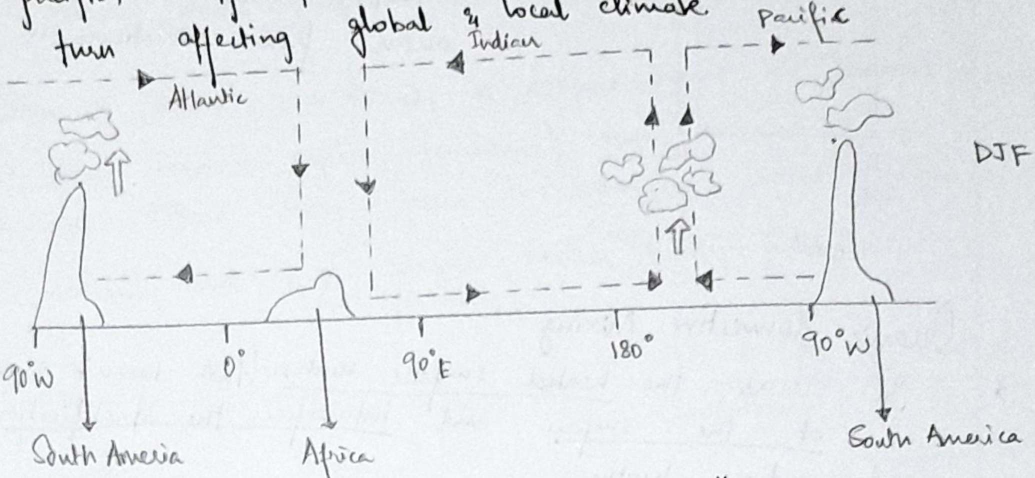
El Nino Index & SOI are strongly correlated.

The El-Nino-La Nina doesn't have a fixed period but generally ~ 3-7 years.

ENSO is the most well-studied weather phenomena because it affects global weather

Its observed by measuring P and Temp at the equator through Moored Buoy Array

These observations are used to predict El Nino, which is very important because it shifts the heat source to mid-pacific, affecting the entire Walker Circulation and in turn affecting global & local climate



El Nino (in DJF) is strongly associated with a weaker monsoon in the next year because it creates warm conditions in DJF and dry conditions in JJA over India

Conversely, La Niña produces stronger monsoon

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Lecture 25

Thermohaline Circulation

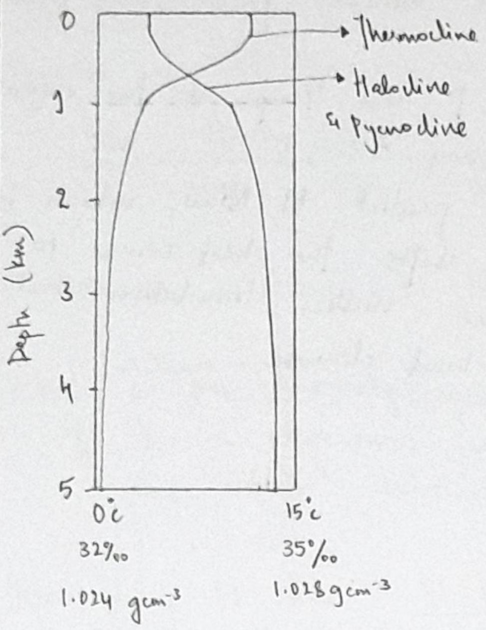
Stable thermal stratification

As the ocean is heated from above, unlike atmosphere, ocean waters are stably stratified so that warm surface waters are less dense than cold, deep waters

→ no chance for convective overturning

Wind and temp (solar radiation) play a role in mixing of ocean surface layers but not deeper than that.

Temp. difference alone cannot cause strong density driven vertical mixing observed.



Temperature, salinity and density show stable & similar stratification of the ocean.

Sea water density is a function of temp and salinity
↓ not equal

In most regions, stability limits vertical motion and ~~waters~~ insulates deeper ocean from variations in mixed layer.

Oceanic Convective Mixing

★ In oceans, the heated surface water (that doesn't evaporate) stays at the surface and intensifies the stratification during day time heating.

★ At night, when surface waters cool, they become more dense and sinks down. Similar to this diurnal cycle, there's also a seasonal cycle of oceanic convection

★ In the winter, the convection is strong. Maximum mixed layer depth is found at the end of winter. (~100 m)
In August mixed layer ~ 20-30 m. Also stronger winds.

★ This convection driven by surface cooling can extend down to ~1000 m in some regions whereas wind-driven mixing (Ekman) only goes down till ~150 m

Increase in salinity (through evaporation) can also create convection

Salt in the ocean

- Its brought in by rivers which weather crustal rocks
- Millions of years of salt accumulation & evaporation has led to current salinity at ~ 33 - 38 g/kg
- Chloride - 55% , Sodium - 30%

Variations in Salinity

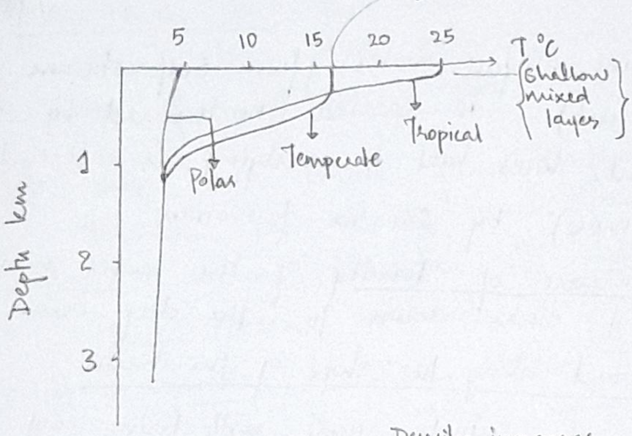
Evaporation, Precipitation, Rivers runoff, Melting & Freezing of sea ice

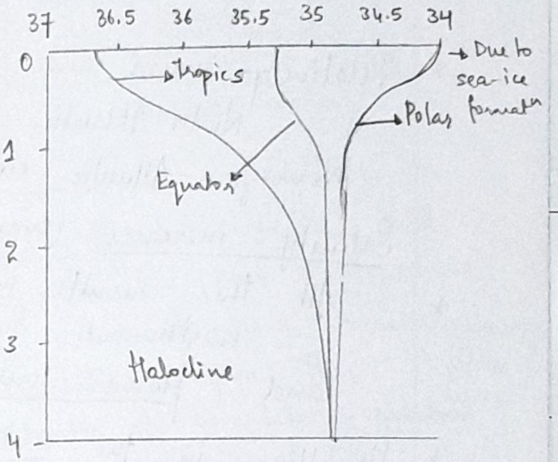
- Low salinity in equatorial region — P > E
- High Salinity in subtropical ocean — E > P → Centre of gyres
- Low salinity in subpolar region — P > E
- Regions of influx of fresh water like Bay of Bengal, Gulf of Alaska (North Pacific) have low salinity

Distribution of salinity → Density of surface ocean → Thermal stratification → How weather systems (cyclones) move around

Depth of Mixed layer fuels the intensity & speed of cyclones.

The salinity and E-P curves match pretty well
{Varies seasonally}





Density increases with depth & becomes constant

Pycnocline is present (Pg. 82) at low latitude but it's absent in high latitude (ie. high density throughout)

Absence of pycnocline is very important for deep ocean circulation because, if a water parcel of higher density comes there, it will sink to a greater depth.

* Deep ocean circulation begins with production of dense water masses near the high latitudes

Water mass — body of water with a common formation history, identified by its Temperature - Salinity (T-S) combination

Below the surface, T and S are quasi-conservative properties as there are no sources of heat or salinity in deep ocean — except mixing.

So, water masses have their origin at the surface

Dense water masses form in high latitude because -
- Low winter polar temperatures
- When cold winds (from land) blow over warm waters, water loses both sensible & latent heat
- Increase in salinity by "brine rejection" associated with formation of sea ice.

Near freezing temperatures, density is a function of salinity and pycnocline follows the ~~ha~~ halocline

Two locations which produce the densest waters -
- North Atlantic Deep Water (NADW) Mass, off the coast of Greenland
- Antarctic Bottom Water (AADW) Mass, over Weddell Sea off Antarctica

* Relatively warm and saline surface water (from Gulf stream and North Atlantic current) is carried northward by Norwegian-Atlantic current, loses heat to overlying air → loses temp.
→ loses water

Salinity increases (even more) by sea ice formation

plumes of water parcel

* All this results in increase of density of the water moving northward. So it sinks down to the deep ocean and flows southward along the slope of the basin

* Upwelling in the centre of subpolar gyre will bring cool waters to the ocean surface.

* ABW mass forms close to shallow shelves near Weddell Sea, Ross sea and Adelié coast.

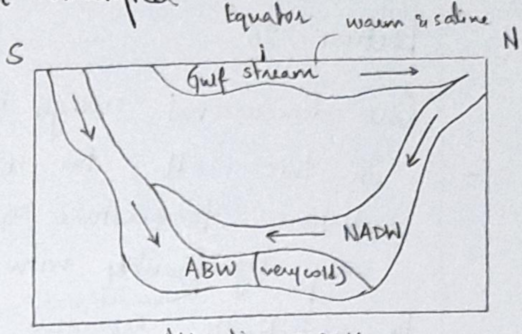
* Antarctica is a centre of high pressure, so winds blow outward from south pole, sweeping away large amounts of sea ice, which favors more ice formation

This and similar processes as above (evaporation & cooling) cause the water to increase in density and sink down and become part of Antarctic Circumpolar Current (ACC)

ACC extends from sea surface to depth of 2-4 km and can be upto 2000 m wide. Since it lies between 70°S and 45°S (maximally), it is influenced by the subpolar westerlies and hence, it flows clockwise around Antarctica, keeping warm water away and allowing Antarctica to maintain its ice - landmass.

It flows northward as the coldest and deepest layer in all 3 major basins

Water of different densities remain stratified



Atlantic ocean

- ★ ABW is very cold and saline ⇒ most dense, so it forms the bottom layer & other layers follow
- ★ More than half the world's ocean volume is filled with cold water from NADW & ABW
- ★ As seen here, NADW flows southward through the atlantic ocean and joins the ACC, which flows around Antarctica. It branches off into Indian and Pacific oceans and travels north. At the end of its route, it upwells to the surface (not sure how) and becomes a part of surface water circulation again. This eventually returns to North Atlantic to complete circulation
- ★ Thermohaline circulation brings deepwater into contact with the atmosphere every 600 yrs or so.

Regions of upwelling are very important because deep ocean waters carry a lot of dissolved CO_2, O_2 which is stored there for a long time. They come to the surface when the deepwater upwells

Importance -

- THC supplies heat to polar regions. Affects ~~equa~~ the meridional temperature gradient and hence atmospheric circulation
  It influences T in polar regions → formation of ice → ~~eath~~ earth's albedo → radiation budget.

- Helps store CO_2 in deep ocean for long time ⇒ contributes to the time lag b/w climate forcing & response

- Shutdown / slowdown of North Atlantic THC is thought to be a key feature of past NH glaciation

Slight changes in surface salinity at high latitudes caused by ice melt, precipitation or river runoff can have large effect on the strength of THC

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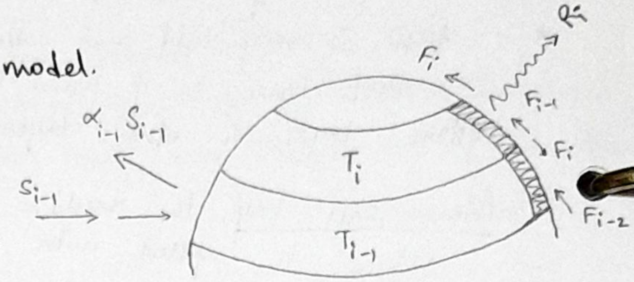
Lecture 26

One dimensional energy balance model.

- In this model, the incoming radiation, temperature & albedo vary significantly with latitude to realistically represent processes that have a strong latitudinal dependence



F: Heat transport coefficient.

- Energy balance model doesn't attempt to resolve the dynamics of climate system. It simply focuses on the energetics and thermodynamics

Weather: Current state of atmosphere defined in terms of its state variables –

Pressure	Temperature	Wind
Humidity	Clouds	Rainfall

Weather prediction

- Atmosphere is a physical system governed by laws of physics
- These laws are expressed quantitatively in form of mathematical equations
- Using observations, we can specify atmospheric state at a given initial time
- Using the equations, we can calculate how this state will change over time

History of Numerical Weather Prediction

⇒ Vilhelm Bjerknes – Norwegian mathematician

- Proposed that atmosphere is a deterministic system – given initial conditions, its possible to compute the future state using mathematical formulae
- Before this, weather prediction just had a statistical approach
- He listed 7 variables – P, T, humidity, density & 3 components of velocity to define initial conditions.
- Identified 7 independent equations which can, together explain atmospheric evolution –

Basic skeleton

1. Conservation of momentum
   3 eq^n for accelerations of wind feilds
2. Conservation of mass
   1 eq^n : cons. of air (mass continuity)
   1 eq^n ; cons. of water
3. Conservation of energy
   1 eq^n : First Law of Thermodynamics
4. Relationship b/w P, V and T
   1 eq^n : Ideal gas ~~eq^n~~ Law

$\frac{\partial u}{\partial t}$ ... $\frac{\partial \theta}{\partial t}$ etc give tendencies of each variable

Finding analytical solution to solve these equations was out of question. Initially, graphical method was used

⇒ Lewis F. Richardson

- Used finite differencing method to numerically solve primitive eq^ns
- Showed how differential eq^n could be approx written as a set of algebraic difference equations for values of tendencies of various field variables at a finite no. of points in space
- Given observed values at these grid points, tendencies could be calculated numerically by solving algebraic difference equations.

Partial differential eqⁿ need to be solved numerically in 3D grids across earth's surface extending vertically from surface.
The state variables would need to be observed and calculated in each of the grids.

Simplest form of Numerical Weather Prediction (NWP) model –

$$\frac{\Delta A}{\Delta t} = F(A)$$

- Change in forecast variable A during time t is equal to cumulative effects of all processes that force A to change

$$A^{\text{forecast}} = A^{\text{initial}} + F(A).\Delta t$$

- Future values of variables are solved for by finding initial values and adding the physical forcing that acts on the variables over time period of the forecast. → F(

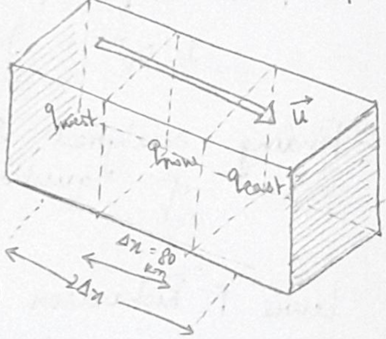
- Process is repeated for duration of simulation
This stepwise process represents the configuration of prediction equations used in NWP

Example – Moisture Equation (simplified)

tendency of moisture → advection of moisture

Derivative : $$\frac{dq}{dt} = -\vec{u}\,\frac{dq}{dx}$$

$\vec{u}$: zonal wind speed



Finite difference form –

$$\frac{\left(q^{t+1} - q^{t}\right)_{x,y}}{\Delta t} = -\vec{u}.\,\frac{q^{t}_{x+1,y} - q^{t}_{x-1,y}}{2.\,\Delta x}$$

Conceptually : $$q^{\text{forecast}} = q^{\text{now}} - \vec{u}\,\frac{\Delta t}{2\Delta x}\left(q^{\text{east}} - q^{\text{west}}\right)_{\text{now}}$$

⟹ NWP project at Princeton in 1950 – very computationally intensive
First operational numerical weather forecast : Swedish military weather service in 1954

Von Nuemann recognised the requirement of computing in solving fluid dynamic problems.

Today -

Supercomputers solve system of non-linear differential equations at ~ 1/2 billion points per time step accounting for dynamic, thermodynamic, radiative & chemical processes working on scale of ~ 100s m to ~1000s of km

- * 1,00,000 points × 100 levels × 10 variables ≃ 100 million eq^{n}s
- * Time step ~ 10 mins

Because of increased computational capaity, we can now predict weather at a greater resolution -

Gride size : 240 km → 16 km Height : 19 levels → 38 levels.

- NWP is an initial-value problem - to integrate equations, we must speify values of dependent variables at an initial time
- Observations come from instruments on board, air, water, ocean and space based platforms.
- Data assimilation : NWP models need algorithms for determining initial conditions from available large volume of inhomogenous observational data.

Coupled Atmosphere - Land - Ocean Model

Many processes in atmosphere is coupled with the ocean - cyclones, El Nino etc They have to be taken into account & studied together to make good predictions.

→ Climate Prediction

- Its an extension of weather forecasting - same set of variables and equations - just that climate models predict change over decades, not days.
- Climate models are probabilistic - indicating areas with higher chances to be warmer or cooler and wetter or drier than usual

thus, we've to consider processes that have slow responses — glaciers, deep ocean, ice sheet — hundreds to thousands of years. Taking them into account complicates the model even more

Climate models need to include more processes & each of the component has equations calculated on global grid for set of climate variables. In addition, many parts act as coupled systems

Main components —

1. Atmospheric — simulates clouds & aerosols; plays a large role in transport of heat & energy.
2. Land surface — simulates vegetation, snow cover, soil water, rivers, carbon storing
3. Ocean — current movement & mixing, biogeochemistry since ocean is dominant reservoir of heat and carbon
4. Sea ice — modulates solar radiation absorption and air-sea heat & water exchanges.

But here, at least the time steps can be much larger than the 10 mins in weather model