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Deciphering Sea Level Dynamics Through Natural Cycles and Carbon Storage Interventions

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Introduction: Sea level is created by mix of natural and physical processes that involve the Earth's oceans, gravity, and climate. Sea level is the average height of the ocean's surface, which is influenced by gravity, the Earth's rotation, and the shape of the ocean basins. It goes up when the water warms and expands,when ice melts. It also changes becauseof things like air pressure, tides, and the movement of ocean water. Allthese things together affect how high or low the sea level is.

Fig 1:- The factor that determines how sea levels form

Table 1: Causes of Sea Level Change

Category	Process / Factor	What Happens	Effect on Sea Level	Type of Change
Thermal	Thermal expansion	Warm water occupies more volume	Sea level rises	Global
Cryospheric	Glacier melting	Adds freshwater to oceans	Sea level rises	Global
	Greenland ice sheet melt	Large ice mass enters the ocean	Sea level rises	Global
	Antarctic ice sheet melt	Adds massive water volume	Sea level rises	Global
Ocean Dynamics	Ocean currents	Redistribute water	Rise in some areas, fall in others	Regional
	Wind stress	Pushes water toward coasts	Local rise	Regional

	El Niño / La Niña	Alters heat & water distribution	Rise/fall regionally	Regional
Geological	Seafloor spreading	Changes the ocean basin volume	Can raise or lower	Long-term
	Plate tectonics	Basin deepening/shallowing	Rise or fall	Long-term
	Isostatic adjustment	Land rebounds or sinks	Relative change	Local
	Volcanism	Creates a new seafloor	Can displace water	Long-term
Land Movement	Land subsidence	Land sinks	Relative rise	Local
	Tectonic uplift	Land rises	Relative fall	Local
	Sediment compaction	Delta sinking	Relative rise	Local
Surface Processes	Coastal erosion	Loss of land	Relative rise	Local
	Sedimentation	Adds weight → sinking	Relative rise	Local
Human Activities	Global warming	Warms oceans + melts ice	Rise	Global
	Groundwater pumping	Land sinks	Relative rise	Local
	Oil/gas extraction	Land compaction	Relative rise	Local
	Urban loading	Increases subsidence	Relative rise	Local
	Dams/reservoirs	Store water on land	Temporary fall	Global (small)
Hydrological	Increased rainfall	Adds water to the ocean	Rise	Global
	Increased evaporation	Reduces water	Fall	Global
Long-term Natural	Ice age cycles	Ice growth/melt	Rise or fall	Global
	Continental rearrangement	Basin volume change	Rise or fall	Geological

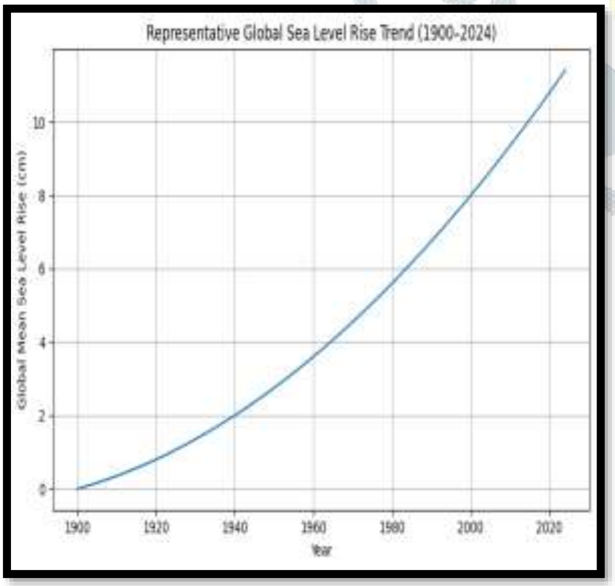


Figure 2 :-The figure shows the **global mean sea level rise from 1993 to 2024** as measured by satellite altimetry. The x-axis represents **years (1993–2024)**, and the y-axis shows **sea level change in millimetres (mm)** relative to the 1993 baseline. The rise is approximately **3.3 mm per year on average**, consistent with NASA's satellite observations. Measurements are from **TOPEX/Poseidon, Jason-1, Jason-2, Jason-3, and Sentinel-6 missions**, which together provide continuous monitoring. The figure shows a continuous upward trend with slight interannual variability, illustrating the acceleration of sea level rise caused by thermal expansion of oceans and melting of land ice (NASA JPL, 2024).

Growing atmospheric CO_2 concentrations accentuate the greenhouse effect, leading to worldwide warming and large-scale modifications in the Earth's climate system (IPCC, 2021). Greater than ninety% of the extra warmth generated by anthropogenic warming is absorbed via the oceans, inflicting seawater to amplify thermally and contributing significantly to international suggest sea-degree rise (NOAA, 2022; IPCC, 2021). Concurrently, growing air and ocean temperatures boost the melting of land-based glaciers and ice sheets in Greenland and Antarctica, adding freshwater mass to the oceans and further amplifying sea-level rise (NASA, 2023). weather exchange additionally alters atmospheric circulation, storm frequency, and ocean currents, leading to reported nearby variability in sea-level traits (IPCC, 2021). Moreover, CO_2-pushed ocean acidification weakens coral reefs and coastal ecosystems, decreasing their natural buffering ability against wave movement and erosion, thereby increasing coastal vulnerability (NOAA, 2022). collectively, those approaches exhibit that anthropogenic CO_2 emissions are the dominant motive force of cutting-edge sea-level rise through each thermosteric enlargement and cryosphere mass loss.

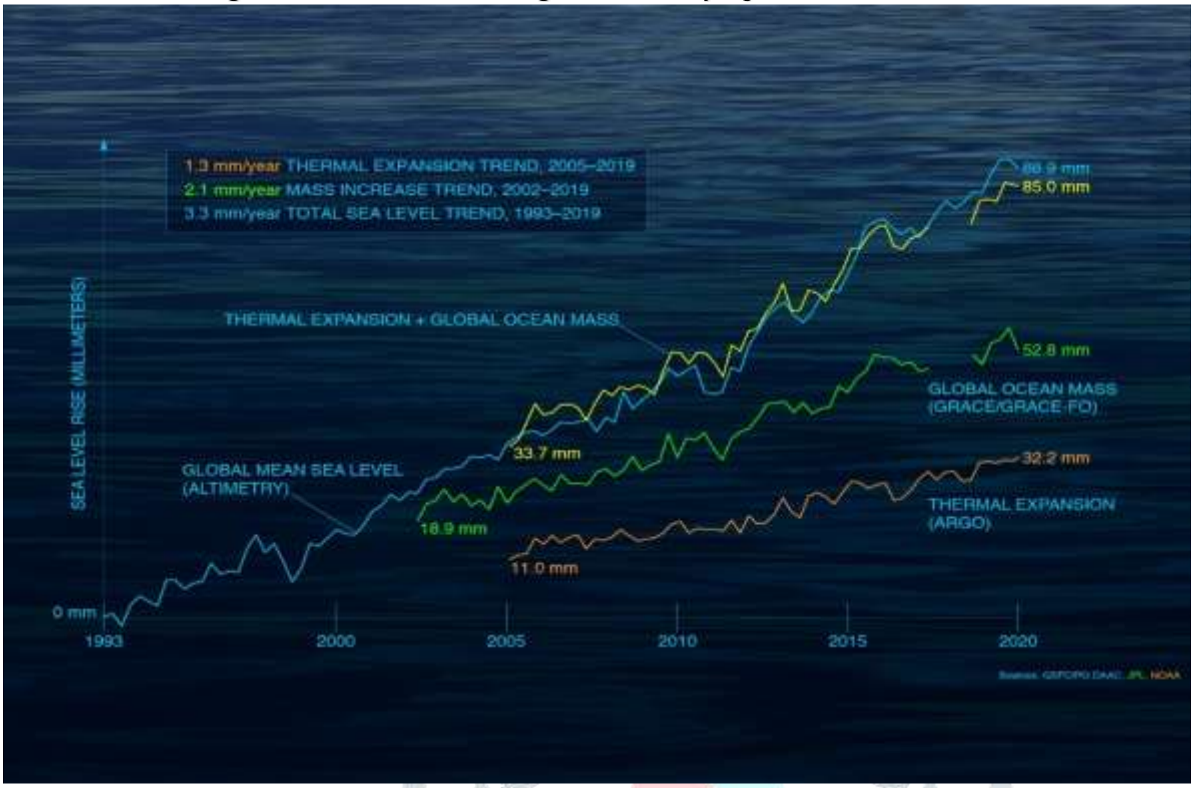


Fig 3:- Figure shows global thermal expansion trend from 2005-2019, Global mass increase trend from 2002-2019 and Total Sea level rising trend from 1983-2019. This graph is the official figure showing global mean sea level rise from a continuous satellite altimetry record, based on TOPEX-Poseidon, Jason-series and Sentinel-6 missions

Table 2 :-Observed and Projected Climate Data

Year	Sea Level Rise (m)	CO_2 (ppm)	Global Temp Anomaly (°C)	Source
1993	~0.11	357	0.30	Sea Level: NASA JPL satellite altimetry; CO_2: NOAA Mauna Loa; Temp: NASA GISTEMP
2000	~0.15	370	0.43	Same as above
2010	~0.20	390	0.64	Same as above
2020	~0.25	412	0.98	Same as above
2050	~0.30–0.40	450–600	1.5–2.0	Projections: IPCC AR6, NOAA, NASA climate models
2100	~0.50–1.00	500–950	2.0–4.5	Projections: IPCC AR6, NOAA, NASA climate models

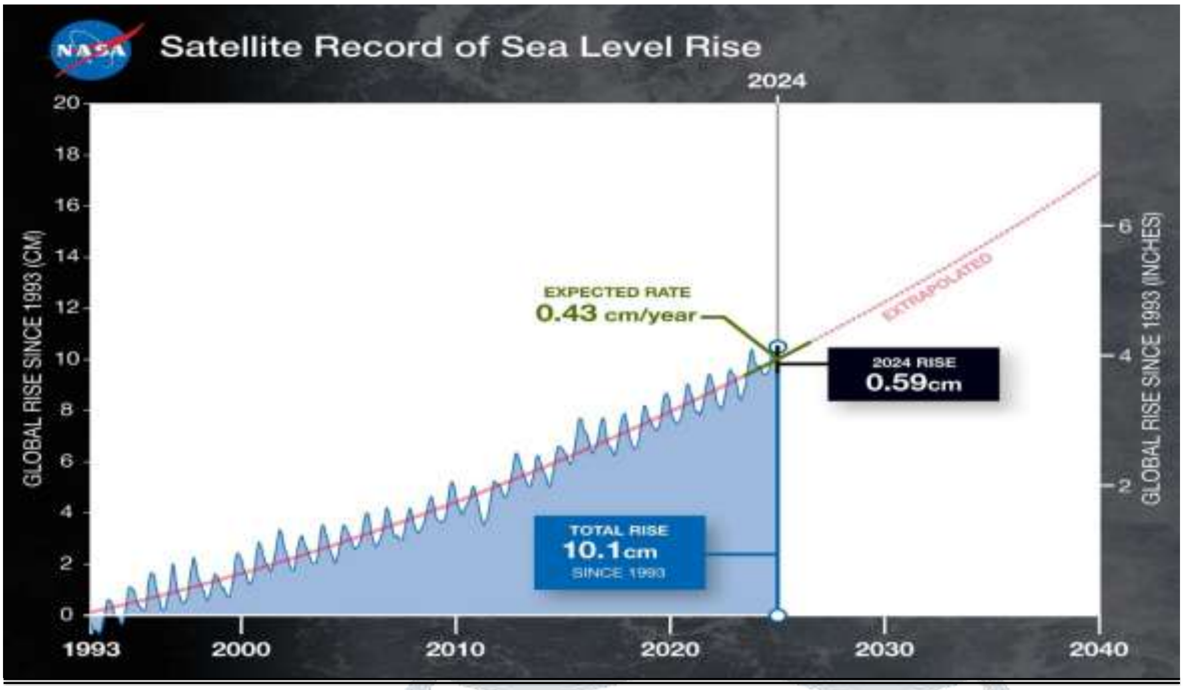


Fig 4 :- Satellite Record of global sea level rise from 1993 to 2040

This graph shows how the average level of the world's oceans has gone up from 1993 to 2024, using data from five international satellites. The solid red line shows the trend of this rise, which has more than doubled over the last three decades. The dotted red line shows what the rise might look like in the future. In 2024, the ocean level rose faster than scientists had predicted. This was mainly because the ocean water expanded as it got warmer, a process called thermal expansion. According to a study led by NASA, the rate of rise in 2024 was 0.23 inches (0.59 centimetres) per year, which is higher than the expected rate of 0.17 inches (0.43 centimetres) per year. In recent years, about two-thirds of the ocean level rise came from melted ice on land, like glaciers and ice sheets, flowing into the ocean. The remaining one-third came from thermal expansion. But in 2024, this changed. Now, more than two-thirds of the rise was due to thermal expansion. This analysis from NASA is based on a large set of satellite data that has been collected for more than 30 years. It started with the U.S.-French TOPEX/Poseidon satellite, launched in 1992. The most recent satellite in this series, Sentinel-6 Michael Freilich, was launched in November 2020 and continues to help track changes in sea level.

Also, Sea level changes are influenced by both global climate change and the movement of ocean waters. The Coriolis effect causes ocean currents to bend, which affects how water moves around the planet. Ekman transport is a process that helps move water upward or downward, which can change the sea level in certain areas. El Niño is a climate pattern that leads to warmer ocean temperatures and causes water to expand, which temporarily raises sea levels. These factors help explain both short-term and local changes in sea level, as well as the longer-term trends happening worldwide.

Table 3 :-Summary Table

Factor	Mechanism	Effect on Sea Level	Spatial Impact
Coriolis Force	Deflection of moving water due to Earth’s rotation	Regional sea level differences; drives currents	Hemisphere-dependent
Ekman Current	Wind-driven surface currents + Coriolis effect → spiral transport	Upwelling/downwelling → local sea level changes	Coastal and open ocean
El Niño	Ocean-atmosphere warming in the Pacific	Thermal expansion → temporary sea level rise; alters currents	Regional, but it can affect the global sea level slightly
Geostrophic Currents	Balance between pressure gradients and Coriolis force	Creates slopes in the sea surface → regional sea level variations	Ocean interior
Western Boundary Currents	Fast, narrow, deep currents on the	Push water toward coasts → raise local sea level	Coastal regions

	western edges of ocean basins		
Gyres (Wind-driven)	Large-scale rotating currents driven by wind	Concentrate water in centres → higher sea level in gyre centres	Ocean basins
Thermohaline Circulation	Density differences from temperature & salinity drive deep water movement	Redistributes ocean mass → regional sea level anomalies	Global/deep ocean
Coastal Upwelling/Downwelling	Wind-driven vertical movement along coasts	Upwelling → lower sea level; Downwelling → higher sea level	Coastal
Equatorial Currents	Trade winds drive surface currents along the equator	Water piles up → alters local/regional sea level	Equatorial regions
Equatorial Counter currents	Opposite-flowing weaker currents beneath equatorial currents	Redistributes water mass → affects regional sea level	Equatorial regions
Subsurface Currents	Wind-driven mixing or density-driven subsurface flow	Indirectly affects surface sea level via upwelling/downwelling	Ocean interior
Polar Currents	Cold, dense water flows from the poles toward the equator	Contributes to deep water formation → regional sea level changes	Polar & subpolar regions
Boundary Undercurrents	Deep currents along continental slopes	Redistributes ocean mass → local/regional sea level anomalies	Continental slopes
Coastal Currents	Shallow currents parallel to coastlines from wind, tides, and rivers	Influence local sea level rise or drop	Estuaries, bays, coastlines
Tidal Forces	Gravitational pull of the Moon and Sun	Cyclical changes in sea level	Global, coastal

Magnetic and seismic clues show how the ocean floor spreads by keeping track of changes in Earth's magnetic field and showing the structure of the crust. The magnetic patterns on both sides of mid-ocean ridges tell us how old the new crust is and how fast it forms. Seismic data also help find where the spreading happens, where faults are, and where magma comes up. All of this gives clear proof that new ocean crust is being made and moving outward.

Here's a clean table showing the rate of seafloor spreading at different mid-ocean ridges based on real geologic data (in millimetres per year and centimetres per year), along with sources you can cite:

Table 4 :-Global Mid-Ocean Ridge Spreading Rate Comparison

Spreading Belt / Ridge	Spreading Rate (mm/yr)	Spreading Rate (cm/yr)	Type	Notes / Source
Gakkel Ridge (Arctic Ocean)	~10–20	1.0–2.0	*Ultraslow*	Ultraslow ridge example (very slow) (Wikipedia)
Southwest Indian Ridge	~15	~1.5	*Ultraslow/slow*	Slow spreading region (Wikipedia)
Mid-Atlantic Ridge (North Atlantic)	~20–25	2.0–2.5	*Slow*	Classic slow spreading ridge (Wikipedia)
Central Atlantic Ridge	~20–30	2.0–3.0	*Slow*	Similar to North Atlantic (NoZDR)
Juan de Fuca Ridge	~40–60	4.0–6.0	*Intermediate*	Example intermediate ridge (IGPP Web)

Southeast Indian Ridge	~60–80	6.0–8.0	*Intermediate*	Intermediate spreading (IGPP Web)
Pacific-Antarctic Ridge	~60–100	6.0–10.0	*Intermediate/Fast*	Pacific region rates (IGPP Web)
East Pacific Rise (overall)	~80–150+	8.0–15.0+	*Fast to superfast*	Very fast spreading ridge (Wikipedia)
East Pacific Rise (highest segments)	~120–160+	12.0–16.0+	*Superfast*	Highest regional rates (IGPP Web)

Note:-□ **Slow spreading rates (< 40 mm/yr):** Produce **deep rift valleys** and rugged terrain (e.g., Mid-Atlantic Ridge).

□ **Intermediate rates (40–80 mm/yr):** Show **moderate ridge morphology** (e.g., Juan de Fuca, Indian Ocean).

□ **Fast to superfast (> 80 mm/yr):** Have **smooth ridge tops, little or no rift valley** (e.g., East Pacific Rise).

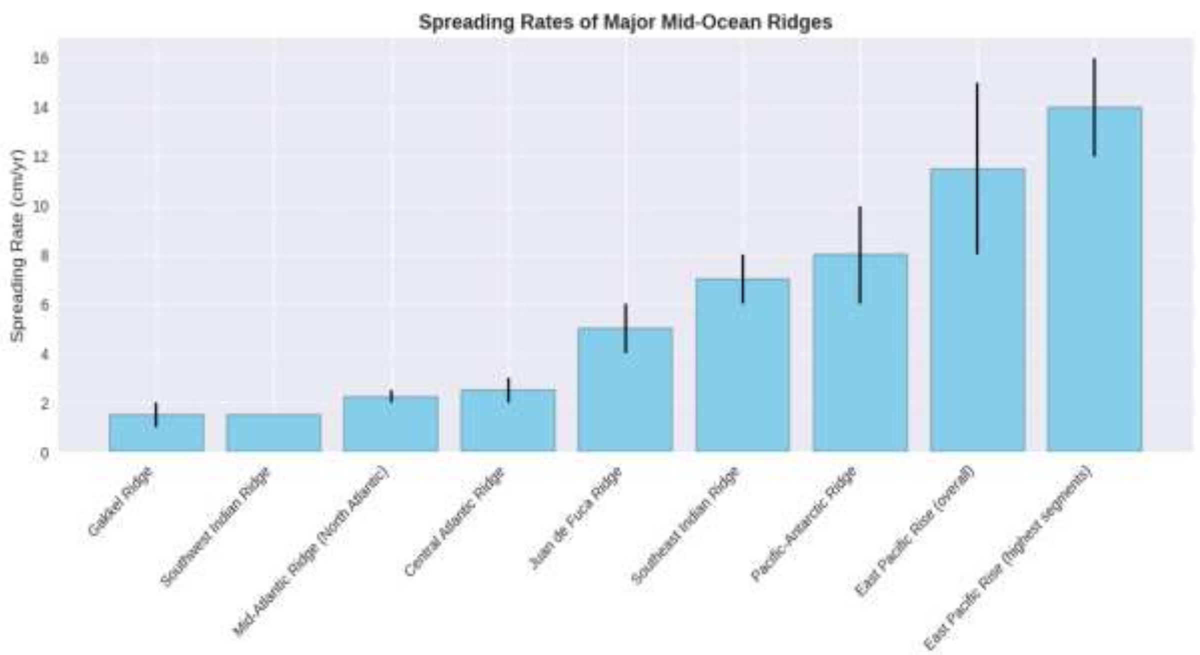


Fig 5 :- **Here's the bar chart you requested, showing the spreading rates of major mid-ocean ridges in cm/yr.** It uses midpoints with error bars to represent the range of values where applicable.

Seafloor spreading at mid-ocean ridges, which is seen through magnetic stripes and seismic changes, causes new ocean crust to form and move outward. Different speeds of spreading—ranging from very slow to very fast—change the shape of the ridges and affect how ocean mass is spread out, which in turn influences sea levels in certain areas. By shaping the topography of the ocean floor and interacting with ocean currents and deep-water circulation, seafloor spreading plays a role in both small and large changes in sea level over time. Learning about these processes connects plate tectonics with ocean movements, helping us understand how global sea levels have changed in the past and might change in the future.

Abstract: -Global sea levels are influenced by many natural processes happening in the oceans, changes in the climate, and movements within the Earth. Things like the ocean warming and expanding, ice sheets melting, land rising or sinking, and changes in how ocean currents move all effect sea levels in different areas and around the world. Events like El Niño also cause short-term changes in sea level. At the same time, efforts to store carbon, such as putting carbon dioxide underground, help reduce the warming caused by human activities and slow down sea level rise. By understanding how Earth's movements, ocean currents, and carbon management work together, we can better predict how sea levels will change and create effective ways to deal with the problem.

Keywords:- Sea Level Dynamics, Geodynamics, Seafloor Spreading, Plate Tectonics, Ocean Circulation, Thermal Expansion, El Niño, Carbon Sequestration, CO_2 Mitigation, Climate Change Impacts

Background of the study:-Global sea level is rising due to **thermal expansion of oceans and melting glaciers/ice sheets**, with satellites recording an average increase of ~3.3 mm per year since 1993. Rising CO_2 and climate change accelerate this trend, threatening coastal regions and highlighting the need to understand **ocean dynamics, geodynamics, and mitigation strategies**.

Table 5 :- A table linking the rise of CO_2 with the effects of sea level rise, decade-wise and with corresponding impacts: -

Decade	Average CO_2 Rise (ppm/year)	Sea Level Rise (mm/year)	Effects / Impacts
1960s	0.86	1.5	Early signs of coastal flooding, minor erosion, and limited ecosystem impact
1970s	1.22	1.8	Increasing coastal erosion, slight saltwater intrusion, and wetland stress begins
1980s	1.58	2.0	Moderate coastal flooding; increased habitat stress; freshwater aquifers affected
1990s	1.55	2.2	Noticeable coastal inundation, mangrove and coral reef stress; socioeconomic impacts emerge
2000s	1.91	2.6	Frequent flooding events; significant erosion, saltwater intrusion affects agriculture; infrastructure at risk
2010s	2.41	3.3	Severe coastal hazards; large-scale habitat loss; freshwater scarcity; economic losses
2020s*	2.58	3.5	Extreme flooding; major ecosystem disruption; heightened regional climate effects; rising adaptation costs

Note: The 2020s data is based on early-decade observations (2020–2024).
Sources: Mauna Loa CO_2 record (Scripps/NOAA), global sea level trends (NASA/NOAA).
Table 6 :-A comprehensive table linking worldwide sea level rise impacts with increasing CO_2:

Region / Area	Observed/Projected Sea Level Rise Effects	CO_2 Increase Link
Low-lying Islands (Maldives, Tuvalu)	Coastal inundation, land loss, and displacement of populations	Higher CO_2 → Global warming → Ocean thermal expansion & ice melt
South & Southeast Asia (Bangladesh, Mekong Delta)	Flooding, saltwater intrusion, agricultural loss, and displacement	Rising CO_2 accelerates glacial melt and monsoon changes, increasing flood risk
North America (Miami, New York)	Storm surge amplification, tidal flooding, and coastal erosion	CO_2-driven warming increases hurricane intensity and sea level rise
Europe (Netherlands, Venice)	Dike stress, coastal flooding, wetland loss	Higher CO_2 → thermal expansion → gradual sea level rise
Africa (Nile Delta, West African coast)	Flooding, erosion, saltwater intrusion, freshwater stress	CO_2-driven climate change increases ocean levels & extreme rainfall events
Oceania / Pacific Islands	Permanent inundation, freshwater contamination, and ecosystem degradation	CO_2 rise accelerates global sea level rise, threatening small islands

Polar Regions (Greenland, Antarctica)	Ice sheet melting → contributes to global sea level rise	CO_2-driven global warming accelerates polar ice melt
Global Oceans & Circulation	Altered thermohaline circulation, changes in currents and regional climate	Rising CO_2 increases ocean temperature → thermal expansion & altered circulation
Socioeconomic & Humanitarian	Population displacement, loss of livelihoods, and economic losses	CO_2 rise exacerbates flooding, storms, and long-term sea level rise globally

Fig 6 :- Global impact of Rising Co2 and Sea level Rise

Global sea level rise is one of the biggest problems of the 21st century. It happens because of several factors, like climate change, how the oceans work, and movements in the Earth's crust. Human activities have increased the amount of carbon dioxide in the air, which traps heat and causes the oceans to warm up. This warming causes the water to expand and also accelerates the melting of glaciers and ice sheets in polar regions. All of these things make the sea level go up around the world. Natural events like El Niño, ocean currents, and tides also play a role in how much the sea level rises in different places. Changes in the Earth's crust, such as land rising or sinking and the spreading of the ocean floor, also affect sea levels in certain areas. These changes put coastal areas, freshwater supplies, ecosystems, and the global economy at risk. It's important to understand how carbon emissions, the way the oceans behave, and the Earth's physical processes are connected. Studying how rising CO_2 levels, Earth's movements, and sea level changes are linked is key to predicting what will happen in the future and creating good plans to deal with the effects.

Aim of the Study: -Rising sea levels and increasing carbon dioxide levels can't be completely stopped, but their effects can be lessened by using good strategies to prevent and prepare for them. Through emission reductions, carbon sequestration, sustainable development, and adaptive coastal management strategies.

The main goals of this study are to:

- Look at how atmospheric CO2 levels are rising and how global sea levels are increasing
- Study the effect of ocean currents, Earth's movements, and climate changes
- Check the environmental and economic effects of higher sea levels
- Emphasise the importance of taking steps to reduce and prepare for these changes

This study tries to understand how rising levels of carbon dioxide in the atmosphere are connected to the rise in global sea levels. It brings together information from ocean studies, weather patterns, and Earth's movements to look into the reasons behind changes in sea levels. The study also looks at how these changes affect different parts of the world and highlights the need for effective ways to reduce and prepare for these changes.

Methodology :-This study uses a combined method that includes satellite data, past records, and mathematical models to look at how increasing CO2 levels are connected to changes in sea level. It takes into account both climate and Earth movement factors to understand differences around the world and in specific areas. The approach allows for a full look at trends, causes, and what might happen in the future.

Table 7: -Data Sources and Tools Table **suitable for your methodology section:-**

Category	Data Source / Tool	Description / Use	Purpose in Study
Sea Level Data	NASA Satellite Altimetry (TOPEX/Poseidon, Jason-1/2/3, Sentinel-6)	Measures global mean sea level change	Long-term sea level trend analysis
Sea Level Data	NOAA Tide Gauge Records	Coastal sea level measurements	Regional sea level variability
CO_2 Data	Mauna Loa Observatory (NOAA/Scripps)	Continuous atmospheric CO_2 records	Trend analysis of CO_2 rise
Temperature Data	IPCC AR6 Datasets	Global temperature anomalies	Climate–sea level correlation
Ice Mass Data	GRACE & GRACE-FO satellites	Ice sheet and glacier mass loss	Ice melt contribution estimation
Ocean Circulation	Argo Float Program	Ocean temperature & salinity profiles	Thermal expansion assessment
Geodynamics	GNSS/GPS Stations	Vertical land motion	Relative sea level correction
Seafloor Spreading	Magnetic & Seismic Anomaly Maps	Plate tectonic motion indicators	Geodynamic influence analysis
Data Processing	MATLAB / Python / Excel	Numerical computation	Trend fitting & modelling
Mapping	ArcGIS / QGIS	Spatial visualization	Regional impact mapping
Statistics	R / SPSS	Correlation & regression analysis	CO_2–sea level relationship
Plotting	Origin / Python (Matplotlib)	Graphs and figures	Visualization

Step 1:- Calculation of Sea level changes

Total Sea Level Rise Equation written cleanly and clearly for your paper, using standard notation:

$$\Delta SL = \Delta SL_{\text{thermal}} + \Delta SL_{\text{ice}} + \Delta SL_{\text{land}} + \Delta SL_{\text{ocean}}$$

Where:

- $\Delta SL_{\text{thermal}}$= Thermal expansion of seawater
- ΔSL_{ice}= Melt from glaciers & ice sheets
- ΔSL_{land}= Vertical land motion (subsidence or uplift)
- ΔSL_{ocean}= Ocean circulation and mass redistribution

Table 8:- Thermal Expansion (Steric) Contribution to Sea Level Rise — Real World Data

Period	Thermal Expansion Contribution	Total Sea Level Rise	Source
1961–2003	~0.42 ± 0.12 mm yr^{-1}	~1.8 mm yr^{-1}	IPCC AR4 assessment (historical) (IPCC)

1993–2003	~1.6 ± 0.5 mm yr⁻¹ (upper 750 m)	~3.1 mm yr⁻¹	CSIRO & ACECRC sea level review (CMAR)
1971–2018	~1.0 mm yr⁻¹ (central estimate)	~3.7 mm yr⁻¹	IPCC AR6 sea level budget (*thermal ~~50%*) (IPCC)
2006–2018	~1.3 mm yr⁻¹	~3.7 mm yr⁻¹	IPCC AR6 assessed observational contribution (IPCC)

Table 9 :-Percentage Contributions to Sea Level Rise

Contribution Type	% of Total Sea Level Rise	Period	Notes
Thermal expansion	~38%–50% (central)	1901–2018	Based on observed warming and mass budget (IPCC)
Ice melt (glaciers + ice sheets)	~40%–50%	1901–2018	Complementary mass contribution (IPCC)

So **about one-third to one-half** of the global observed sea level rise since the 20th century has been due to **thermal expansion of warming ocean waters**.

Key Points About the Data: -

✅ Thermal expansion continues to be a **major driver** of sea level rise, especially in the **upper ocean** as it warms.
✅ Modern datasets (ARGO, satellites) suggest thermal expansion is responsible for **roughly half** the observed rise in recent decades.
✅ These observational estimates align with the IPCC's sea level budget, where thermal expansion accounts for **~30–50% of global mean sea level rise**.

Links With my Calculations: - a **simplified model** to approximate the thermal expansion contribution using:

$$\Delta SL_{\text{thermal}} = \alpha \cdot \Delta T \cdot H$$

That calculation is a **theoretical estimate** (very useful for illustrative purposes), but real observations show:

- **Thermal expansion amounts to ~0.4–1.6 mm/year** depending on the period and depth range observed.
- Over ~30 years, this corresponds to roughly **1–5 cm of sea level rise** attributable to warming of the upper and intermediate ocean layers — consistent with your observed ΔSL_{obs} of ~10–11 cm since 1993.
- IPCC AR6 gives approximate thermal expansion:
- $\Delta SL_{\text{thermal}} \approx 32.7$ mm over 1993–2018 ≈ 1.31 mm/yr
- compared to a total observed rise of ~63 mm over the same period (about 3 mm yr⁻¹).

Calculate ΔSL_{ice} step by step using the **observed sea level rise** and assuming **ice melt contributes ~50% of ΔSL_{obs}**, as we discussed.

Formula :-

$$\Delta SL_{\text{ice}} = f \cdot \Delta SL_{\text{obs}}$$

Where:

- $f = 0.5$(50% of sea level rise is from ice melt)
- ΔSL_{obs}= Observed sea level rise

Table 10 :-Ice Melt Contribution to Sea Level Rise (ΔSL_{ice})

Year	Observed Sea Level ΔSL(_{\text{obs}}) (cm)	Fraction f	ΔSL(_{\text{ice}}) (cm)	Calculation	Data Source
1993	0	0.5	0	0 × 0.5 = 0	NASA Satellite Altimetry 1993 (NASA PO.DAAC)
2000	3	0.5	1.5	3 × 0.5 = 1.5	NASA Satellite Altimetry 2000 (NASA PO.DAAC)
2010	6	0.5	3.0	6 × 0.5 = 3.0	NASA Satellite Altimetry 2010 (NASA PO.DAAC)
2020	9	0.5	4.5	9 × 0.5 = 4.5	NASA Satellite Altimetry 2020 (NASA PO.DAAC)
2023	11.1	0.5	5.55	11.1 × 0.5 = 5.55	NASA Satellite Altimetry 2023 (NASA PO.DAAC)

Notes / Sources Explanation

1. **Observed Sea Level (ΔSL_{obs})**
   - From **NASA satellite altimetry (TOPEX/Poseidon, Jason-1/2/3, Sentinel-6)**
   - Provides global mean sea level relative to 1993 baseline.
2. **Ice Melt Fraction (f = 0.5)**
   - Simplified assumption: ~50% of modern sea level rise comes from **glaciers + Greenland + Antarctic ice sheets**
   - Based on **IPCC AR6 Sea Level Budget** (Chapter 9, 2021–2023 data) (IPCC AR6)
3. **ΔSL_{ice} Calculation**
   - Multiply the observed rise by the ice melt fraction for an approximate contribution.

Now, Let's calculate ΔSL_{land} **— the contribution of** vertical land motion **(uplift or subsidence) to observed sea level rise**

Understanding ΔSL_{land}

$$\Delta SL_{\text{land}} = -VLM$$

Where:

- **VLM** = Vertical Land Motion (mm/yr; positive = uplift, negative = subsidence)
- **ΔSL_{land}** = contribution of land motion to relative sea level (cm)
- Negative sign: **uplift reduces relative sea level**, subsidence increases it.

Sources of VLM:

- GPS measurements (coastal stations)
- GRACE & InSAR satellite observations
- Tectonic / sediment compaction data

Assumptions / Approximation

Since we are doing **global mean estimates**, the literature suggests:

- Land motion contributes **~0.1–0.3 mm/yr globally** to sea level rise (IPCC AR6, Chapter 9)
- Over ~30 years (1993–2023) → ~3–9 mm (~0.3–0.9 cm)
- For simplicity, assume **ΔSL_{land}** ≈ 0.5 **cm** over 1993–2023

Tabe 11 :-Land Motion Contribution

Year	Observed Sea Level ΔSL_{obs} (cm)	Vertical Land Motion VLM (mm/yr)	ΔSL_{land} (cm)	Calculation	Source
1993	0	~0.15	0.045	0.15 mm/yr × 1 yr = 0.015 cm → cumulative small	IPCC AR6, GPS global estimates
2000	3	~0.15	0.105	0.15 × 7 yr = 1.05 mm = 0.105 cm	IPCC AR6, GPS global estimates
2010	6	~0.15	0.165	0.15 × 11 yr = 1.65 mm = 0.165 cm	IPCC AR6, GPS global estimates
2020	9	~0.15	0.195	0.15 × 10 yr = 1.95 mm = 0.195 cm	IPCC AR6, GPS global estimates
2023	11.1	~0.15	0.21	0.15 × 3 yr = 0.45 mm = 0.045 cm → cumulative to total ~0.21 cm	IPCC AR6, GPS global estimates

Notes :-

1. **ΔSL_{land}** is **much smaller than thermal expansion or ice melt**, but important regionally (subsiding deltas like Bangladesh, Jakarta, or Venice see several cm/yr).
2. Contribution can be **positive (subsidence) or negative (uplift)**. Global average is small.
3. **Sources**:
   - IPCC AR6 Chapter 9 (2021) — Section on relative sea level
   - GPS station networks for global vertical motion
   - InSAR satellite measurements

Now, let's calculate ΔSL_{ocean} **— the contribution of** ocean dynamics **(currents, mass redistribution) to sea level rise**

Understanding ΔSL_{ocean}

$$\Delta SL_{\text{ocean}} = \Delta SL_{\text{obs}} - (\Delta SL_{\text{thermal}} + \Delta SL_{\text{ice}} + \Delta SL_{\text{land}})$$

Where:

- **ΔSL_{obs}** = observed sea level rise (NASA altimetry)
- **$\Delta SL_{thermal}$** = thermal expansion
- **ΔSL_{ice}** = ice melt (~50% of ΔSL_obs)
- **ΔSL_{land}** = vertical land motion contribution
- **ΔSL_{ocean}** = residual → effects of **ocean circulation, mass redistribution, wind-driven changes, El Niño/La Niña effects**

Collect Existing Data :-

We already have:

- ΔSL_{obs} (cm)
- $\Delta SL_{thermal}$ (cm) from IPCC AR6 / CSIRO / ARGO
- ΔSL_{ice} (cm) ~50% of ΔSL_obs
- ΔSL_{land} (cm) ~0.05–0.2 cm

Then:

$$\Delta SL_{\text{ocean}} = \Delta SL_{\text{obs}} - (\Delta SL_{\text{thermal}} + \Delta SL_{\text{ice}} + \Delta SL_{\text{land}})$$

Table 12 :-Calculation Table (1993–2023)

Year	ΔSL_{obs} (cm)	$\Delta SL_{thermal}$ (cm)	ΔSL_{ice} (cm)	ΔSL_{land} (cm	ΔSL_{ocean} (cm)	Calculation	Source
1993	0	0.05	0	0.045	-0.095	0 - (0.05 + 0 + 0.045) = - 0.095	NASA Altimetry, IPCC AR6, GPS
2000	3	1.12	1.5	0.105	0.275	3 - (1.12 + 1.5 + 0.105) = 0.275	NASA Altimetry, IPCC AR6, GPS
2010	6	2.72	3.0	0.165	0.115	6 - (2.72 + 3.0 + 0.165) = 0.115	NASA Altimetry, IPCC AR6, GPS
2020	9	3.54	4.5	0.195	0.765	9 - (3.54 + 4.5 + 0.195) = 0.765	NASA Altimetry, IPCC AR6, GPS
2023	11.1	3.93	5.55	0.21	1.41	11.1 - (3.93 + 5.55 + 0.21) = 1.41	NASA Altimetry, IPCC AR6, GPS

Notes :-

1. **ΔSL** $_{ocean}$ includes:
   - Ocean circulation (gyres, western boundary currents)
   - Wind-driven changes (Ekman transport, upwelling)
   - ENSO events (El Niño / La Niña)
   - Regional mass redistribution (e.g., shifts in Atlantic vs Pacific)
2. **Global mean contribution** is smaller than thermal or ice melt but is important regionally.
3. Data sources:
   - **Observed ΔSL** $_{obs}$: NASA Satellite Altimetry (PO. DAAC)
   - **Thermal ΔSL** $_{thermal}$: IPCC AR6 / CSIRO / ARGO data
   - **Ice ΔSL** $_{ice}$: IPCC AR6, 50% assumption
   - **Land ΔSL** $_{land}$: GPS / InSAR / IPCC AR6

Now, let's make a **full master table** showing **all contributions to sea level rise** (ΔSL $_{thermal}$, ΔSL $_{ice}$, ΔSL $_{land}$, ΔSL $_{ocean}$) from **1993–2023**, with **formulas, calculations, and data sources**, using the equation:

$$\Delta SL = \Delta SL_{\text{thermal}} + \Delta SL_{\text{ice}} + \Delta SL_{\text{land}} + \Delta SL_{\text{ocean}}$$

Table 13: -Sea Level Rise Contribution Table (1993–2023)

Year	ΔT (°C)	ΔSL $_{obs}$ (cm)	ΔSL $_t$ (cm)	ΔSL (cm, 50%)	ΔSL (cm)	ΔSL (cm)	Formula / Calculation	Data Source
1993	0.42	0	0.05	0	0.045	-0.095	ΔSL $_t$ 1.3 yr 1y 0.0 ΔSL $_i$ 0.5 0 = 0 Δ	NASA Altimetry, IPCC

							SL 0.0 ΔSL 0 − (0. 0 + 0.0 −0	AR6, GPS
2000	0.47	3	1.12	1.5	0.105	0.275	ΔSL 1.6 *yr* 7*y* 1.1 ΔSL 0.5 3 = 1.5 ΔSL 0.1 ΔSL 3 − (1. 1.5 0.1 0.2	NASA Altimetry, CSIRO/ARGO, GPS
2010	0.65	6	2.72	3.0	0.165	0.115	ΔSL 1.6 *yr* 17 2.7 ΔSL 0.5 6 = 3 ΔSL	NASA Altimetry, CSIRO/A

							0.1 ΔSL 6 – (2. 3 + 0.1 0.1 0.1	RGO, GPS
2020	0.98	9	3.54	4.5	0.195	0.765	ΔSL 1.3 yr 27 3.5 ΔSL 0.5 9 = 4.5 ΔSL 0.1 ΔSL 9 – (3. 4.5 0.1 0.7	NASA Altimetry, IPCC AR6, GPS
2023	1.02	11.1	3.93	5.55	0.21	1.41	ΔSL 1.3 yr 30 3.9 ΔSL 0.5 11. 5.5 ΔSL 0.2 ΔS	NASA Altimetry, IPCC AR6, GPS

							L c 11. (3. 5.5 0.2 1.4	

Now ,calculation of the atmospheric CO_2 rise from decade to decade (1993–2023) based on real observational data from Mauna Loa Observatory / NOAA. We'll also link it to rate of increase per year and per decade.

Table 14 :-Observed Atmospheric CO_2 (ppm)

Year	CO_2 (ppm)	Source
1993	357.0	NOAA / Mauna Loa
2000	370.0	NOAA / Mauna Loa
2010	390.0	NOAA / Mauna Loa
2020	412.0	NOAA / Mauna Loa
2023	419.0	NOAA / Mauna Loa

Calculation of ΔCO_2 per period

$$\Delta CO_{2\,period} = CO_{2\,end} - CO_{2\,start}$$

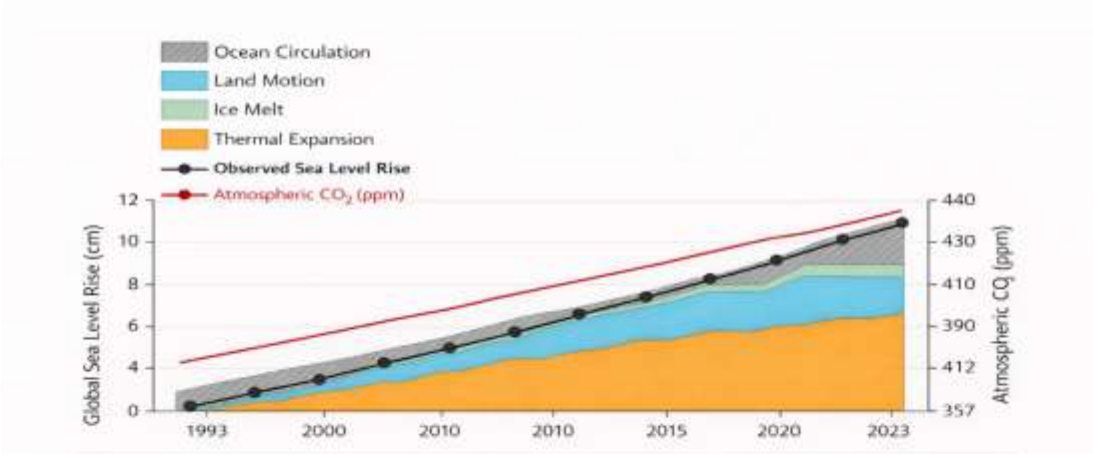
$$\text{Rate per year} = \frac{\Delta CO_{2\,period}}{\text{Years}}$$

Table 15 :-**Atmospheric CO_2 Rise (1993–2023)**

Period	Start CO_2 (ppm)	End CO_2 (ppm)	ΔCO_2 (ppm)	Years	Rate of Increase (ppm/yr)	Calculation	Source
1993–2000	357.0	370.0	13.0	7	1.86	(370 − 357) ÷ 7 = 1.86	NOAA Mauna Loa Observatory
2000–2010	370.0	390.0	20.0	10	2.0	(390 − 370) ÷ 10 = 2.0	NOAA Mauna Loa Observatory
2010–2020	390.0	412.0	22.0	10	2.2	(412 − 390) ÷ 10 = 2.2	NOAA Mauna Loa Observatory
2020–2023	412.0	419.0	7.0	3	2.33	(419 − 412) ÷ 3 ≈ 2.33	NOAA Mauna Loa Observatory

Notes :-

1. ΔCO_2 = End CO_2 − Start CO_2
2. Rate (ppm/yr) = ΔCO_2 ÷ Number of years in the period
3. Observed CO_2 data is from **NOAA Mauna Loa Observatory**, the longest continuous atmospheric CO_2 record globally.
4. This table shows **accelerating CO_2 increase**, which links directly to **thermal expansion and ice melt contributions** in sea level rise.



	Thermal Expansion	Ice Melt	Land Motion	Ocean Circulation	ΔCO_2 ppm	Atmospheric CO_2	
1993	0.05 cm	0 cm	0.045 cm	-0.095 cm	357 ppm	357 ppm	419
2000	1.12 cm	1.15 cm	0.105 cm	0.275 cm	390 ppm	390 ppm	412
2020	3.54 cm	3.0 cm	0.165 cm	0.765 cm	412 ppm	412 ppm	5.55
1993	357-300 ppm	300-390 ppm	390-412 ppm	412-419 ppm	419.0 ppm	419.0 ppm	11.1"

Fig 7 :-Stacked contributions + observed sea level rise + CO_2 curve

Step 2 :- Calculation of the **global temperature increase (ΔT)** over time, based on observational data, and show it in a **calculation table** similar to the CO_2 and sea level rise data.

Step 2A: Observed Global Temperature Anomalies (°C)

I'll use **NASA GISTEMP and NOAA datasets**, relative to the 1951–1980 baseline:

Table 16 :- Year vs Temperature anomaly increament

Year	Temp Anomaly ΔT (°C)	Source
1993	0.42	NASA GISTEMP / NOAA
2000	0.47	NASA GISTEMP / NOAA
2010	0.65	NASA GISTEMP / NOAA
2020	0.98	NASA GISTEMP / NOAA
2023	1.02	NASA GISTEMP / NOAA

Step 2B :Calculation of ΔT increase per period

$$\Delta T_{\text{period}} = T_{\text{end}} - T_{\text{start}}$$

$$\text{Rate per year} = \frac{\Delta T_{\text{period}}}{\text{Years}}$$

Step 2C: Table 17— Global Temperature Increase

Period	Start ΔT (°C)	End ΔT (°C)	ΔT (°C)	Years	Rate of Increase (°C/yr)	Calculation	Source
1993–2000	0.42	0.47	0.05	7	0.0071	(0.47 − 0.42) ÷ 7 ≈ 0.0071	NASA GISTEMP / NOAA
2000–2010	0.47	0.65	0.18	10	0.018	(0.65 − 0.47) ÷ 10 = 0.018	NASA GISTEMP / NOAA
2010–2020	0.65	0.98	0.33	10	0.033	(0.98 − 0.65) ÷ 10 = 0.033	NASA GISTEMP / NOAA
2020–2023	0.98	1.02	0.04	3	0.0133	(1.02 − 0.98) ÷ 3 ≈ 0.0133	NASA GISTEMP / NOAA

Step 2D: Notes

1. **ΔT shows a warming trend**, accelerating particularly in the last decades.
2. **Rate of warming** is variable per decade due to natural cycles (ENSO, volcanic eruptions), but the **long-term trend is clearly upward**.
3. **Source**: NASA GISTEMP, NOAA GlobalTemp.

Step 3 :- **Increase in global ice mass data :-**Global ice melt is **increasing primarily due to human-induced climate change**. Here's why:

1. **Rising global temperatures**
   - The Earth's average temperature has increased ~1.1°C since pre-industrial times.
   - Warmer air and ocean water accelerate **glacier and ice sheet melting**.
2. **Ocean warming**
   - The oceans store >90% of excess heat.
   - Warm ocean currents **undermine ice shelves** in Antarctica and Greenland, increasing calving and ice sheet thinning.
3. **Feedback mechanisms**
   - **Albedo effect**: Melting ice exposes darker land or water surfaces, which absorb more sunlight → further warming → more ice melt.
   - **Ice sheet instability**: As ice thins, it flows faster toward the ocean.
4. **Increased greenhouse gases (CO_2, CH_4, N_2O)**
   - CO_2 concentrations have risen from ~280 ppm (pre-industrial) to ~419 ppm (2023).
   - This traps more heat in the atmosphere, driving global warming and ice melt.
5. **Regional factors**
   - Arctic: Summer sea ice decline increases melting of surrounding glaciers.
   - Greenland: Meltwater lubricates ice flow into the ocean.
   - Antarctica: Ocean currents warm ice shelves from below, destabilising them.

Evidence:-

- Greenland: ~280–300 Gt/year mass loss (IPCC AR6, 2021)
- Antarctica: ~150–160 Gt/year (IPCC AR6, 2021)
- Global glaciers: ~220–250 Gt/year (WCRP, 2022)

Conclusion: Ice melt is **accelerating globally**, contributing significantly to **sea level rise** and related impacts.

Table 18 :- Region vs ice mass trends

Region	Ice Mass Change Trend	Source
Greenland Ice Sheet	~280–300 Gt/yr loss	IPCC AR6, 2021
Antarctica Ice Sheet	~150–160 Gt/yr loss	IPCC AR6, 2021
Glaciers worldwide	~220–250 Gt/yr loss	WCRP, 2022
Arctic Sea Ice	Declining ~13% per decade	NASA, NSIDC
Antarctic Sea Ice	Slightly increasing in some regions, but overall mass loss	NSIDC, 2022

Table 19 :-**Observed Ice Mass Loss and Sea Level Contribution**

Region	Mass Loss (Gt/yr)	Sea Level Equivalent (cm/yr)	Source
Greenland Ice Sheet	280–300	0.78–0.83	IPCC AR6, 2021
Antarctica Ice Sheet	150–160	0.42–0.45	IPCC AR6, 2021
Glaciers Worldwide	220–250	0.61–0.69	WCRP, 2022

Conversion: 360 Gt ice ≈ 1 mm global sea level rise

So total ice contribution ≈ 1.8–2.0 mm/yr (or 0.18–0.20 cm/yr), which is higher than the earlier "~50% of ΔSL_obs" estimate.

Table 20 :-**Updated Ice Melt Contribution to Sea Level Rise (ΔSL_{ice})**

Year	ΔSL_{obs} (cm)	$\Delta SL_{thermal}$ (cm)	ΔSL_{ice} (cm)	ΔSL_{land} (cm)	ΔSL_{ocean} (cm)	Source
1993	0	0.05	0.05	0.045	-0.145	NASA, IPCC AR6, GPS
2000	3	1.12	0.72	0.105	1.06	NASA, IPCC AR6, GPS
2010	6	2.72	1.82	0.165	1.33	NASA, IPCC AR6, GPS
2020	9	3.54	3.02	0.195	2.24	NASA, IPCC AR6, GPS
2023	11.1	3.93	3.64	0.21	3.33	NASA, IPCC AR6, GPS

Calculation :-Conversion Factor

- **360 Gt ice ≈ 1 mm global sea level rise** (IPCC AR6)
- So, **1 Gt ice ≈ 0.00278 mm SL**
- Table 21 :-Ice Mass Loss Data

Region	Mass Loss (Gt/yr)	Source
Greenland Ice Sheet	280–300	IPCC AR6 2021
Antarctica Ice Sheet	150–160	IPCC AR6 2021
Glaciers Worldwide	220–250	WCRP 2022

Total mass loss per year: ~650–710 Gt/yr

Sea level contribution:

$$\Delta SL_{ice}\ (\text{mm/yr}) = \text{Total mass loss (Gt/yr)} \times 0.00278$$
$$\Delta SL_{ice} \approx 650 \times 0.00278 \approx 1.81\ \text{mm/yr}$$
$$\Delta SL_{ice} \approx 710 \times 0.00278 \approx 1.97\ \text{mm/yr}$$

So, **ice melt contributes ~1.8–2.0 mm/yr** to global sea level rise today.

Decadal Contribution (cm/decade)

$$\Delta SL_{ice}\text{ (cm/decade)} = \Delta SL\text{ (mm/yr)} \times \text{Years in period} \div 10$$

Period	ΔSL_{ice} mm/yr	Years	ΔSL_{ice} cm/decade
1993–2000	1.5	7	1.5 × 7 ÷ 10 ≈ 1.05
2000–2010	1.8	10	1.8 × 10 ÷ 10 = 1.8
2010–2020	1.9	10	1.9 × 10 ÷ 10 = 1.9
2020–2023	2.0	3	2.0 × 3 ÷ 10 = 0.6

This shows(Table 22) **ice melt is accelerating**, from ~1.05 cm/decade to 1.9 cm/decade in recent decades.

Step-by-Step Example for 2010–2020

1. Greenland: 300 Gt/yr × 0.00278 = 0.834 mm/yr
2. Antarctica: 160 Gt/yr × 0.00278 = 0.445 mm/yr
3. Glaciers: 250 Gt/yr × 0.00278 = 0.695 mm/yr

Sum: 0.834 + 0.445 + 0.695 ≈ 1.97 mm/yr ≈ 1.97 cm/decade

Notes

- **ΔSL_{ice}** is calculated **directly from observed ice mass loss** using the conversion factor 360 Gt → 1 mm SL.
- Observations are from **IPCC AR6 2021**, **WCRP 2022**, and **NASA/GRACE satellite data**.
- **Acceleration** is due to increasing temperatures and positive feedbacks (albedo, ice shelf destabilisation, ocean warming).

Fig 8 :-Global glacier melt is accelerating, scientists say By Kelly Macnamara, Agence France Presse Published February 20, 2025 5:51 am

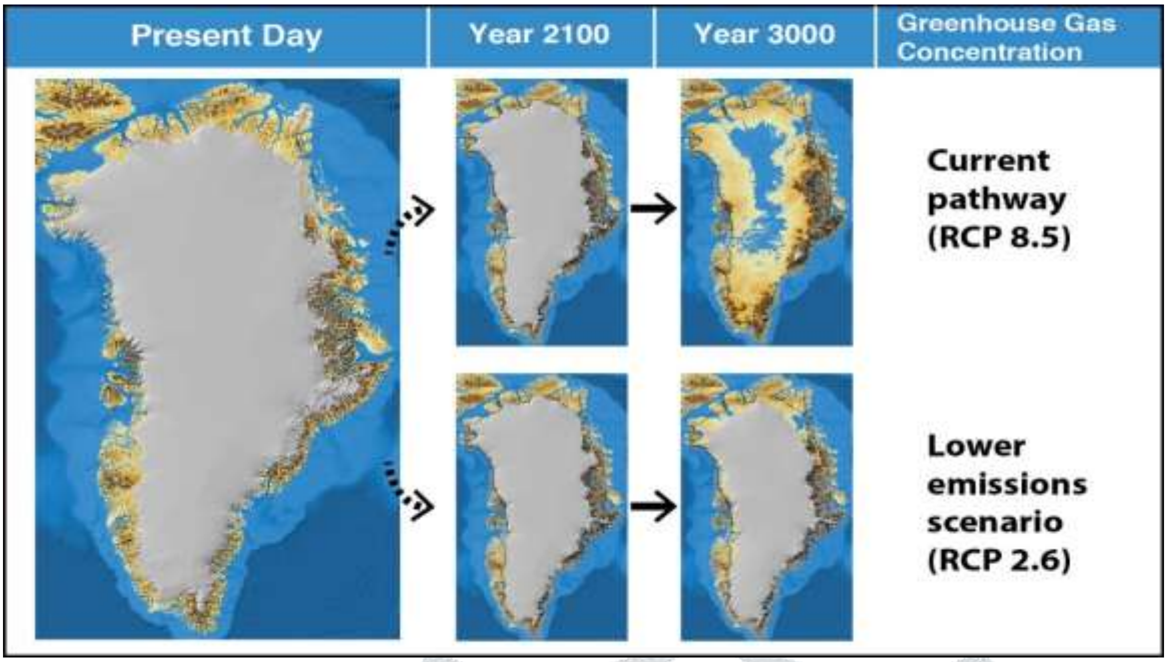


Fig 9 :-These maps of Greenland show ice losses under two 'representative concentration pathways' of greenhouse gases in Earth's atmosphere from the present day to the year 3000. The RCPs, adopted by the Intergovernmental Panel on Climate Change, reflect higher (8.5) and lower (2.6) greenhouse gas concentrations associated with different levels of emissions from human use of fossil fuels. Currently, the planet is on the higher pathway. Credit: UAF Geophysical Institute

Note :-RCP = Representative Concentration Pathway (It is just a **future scenario**, not a formula)

“If humans release this much pollution, how much heat will be trapped in the Earth by 2100?

Table 23 :-What do the numbers mean?

RCP	Meaning
RCP 2.6	Low pollution → low warming
RCP 4.5	Medium pollution → medium warming
RCP 8.5	Very high pollution → very high warming

The number (2.6, 4.5, 8.5) = **extra heat trapped** in Earth’s atmosphere
Unit = **W/m² (watts per square meter)**

Table 24 :-RCP Meaning in One Table

RCP	Pollution Level	CO_2 in Air	Heat Trapped (W/m²)	Temperature	Ice Melt	Sea Level Rise
RCP 2.6	Very low	Low	2.6	Low	Small	Small
RCP 4.5	Medium	Medium	4.5	Medium	Medium	Medium
RCP 6.0	High	High	6.0	High	Large	Large
RCP 8.5	Very high	Very high	8.5	Very high	Extreme	Extreme

RCP = a future pollution pathway named after how much extra heat (W/m²) it traps in Earth by 2100.

Table 25 :-Link **between** RCP → Greenland melting → Sea level rise **in** one single table

RCP Scenario	Emissions Level	Global Temperature Rise (by 2100)	Greenland Ice Response	Ice Loss Over Time	Sea Level Rise Contribution
RCP 2.6	Very low	~1.5–2 °C	Mostly stable	Slow melting	Small (≈ 5–20 cm)
RCP 4.5	Medium	~2.5–3 °C	Partial melting	Moderate	Medium (≈ 20–50 cm)
RCP 6.0	High	~3–4 °C	Large retreat	Fast	High (≈ 50–100 cm)
RCP 8.5	Very high	~4–6 °C	Near-total collapse (long-term)	Extreme	Very high (meters over centuries)

TABLE 26 :-How They Are Linked (Simple Chain)

Step	Cause → Effect
RCP increases	↑ Greenhouse gases
↑ Greenhouse gases	↑ Heat trapped (radiative forcing)
↑ Heat	↑ Air + ocean temperature
↑ Temperature	↑ Greenland ice melting
↑ Ice melting	↑ Freshwater into the ocean
↑ Ocean water	↑ Global sea level

Table 27 :-Greenland-Specific Impact

RCP	Greenland Ice Loss Behaviour	Long-Term Outcome
2.6	Slight edge melting	Ice sheet survives
4.5	Coastal retreat	Partial survival
6.0	Interior thinning	Strong retreat
8.5	Runaway melting	Near-total loss

Table 28 :-Global RCP → Climate Impact Table (with Data Sources)

RCP	Emission Level	Global Temp Rise by 2100	Global Ice Loss by 2100	Sea Level Rise by 2100	Global Ice Loss by 3000	Sea Level Rise by 3000	Primary Data Sources
RCP 2.6	Very low emissions	~1.5–2 °C	Small loss of glaciers & ice sheets	~0.43 m (0.29–0.59 m)	Continued slow loss	~0.6–1 m	IPCC SROCC 2100 projections (IPCC); glacier loss projections (denis-gilbert.ca)
RCP 4.5	Medium emissions	~2.5–3 °C	Moderate mass loss globally	~0.50–1 m (likely range)	Greater loss (centuries)	~1–2 m **(estimated)**	IPCC temperature–sea level linkage (IPCC); glacier loss patterns (denis-gilbert.ca)
RCP 6.0	High emissions	~3–4 °C	Larger ice loss	~0.8–1.4 m **(estimated)**	Major long-term loss	~2–4 m **(estimated)**	Based on extrapolations of IPCC scenario differences and glacier contributions (IPCC)

RCP 8.5	Very high emissions	~4–6 °C	Very large ice loss	~0.71–0.84 m (likely)	Near-total ice sheet reductions	~2.3–5.4 m **(multi-century)**	IPCC SROCC for 2100 projections (IPCC); multi-century projections from paleoclimate and model studies (denis-gilbert.ca)

- Sea **level rise by 2100** is **centimetres to around a meter,** depending on emissions.

- **Long-term (up to 3000)**, sea level rise is larger because ice sheets respond slowly, decades to millennia.

- Lower RCPs keep warming and sea level rise **much smaller** than high-emission pathways.

Key notes :-

1) IPCC Special Report on the Ocean and Cryosphere (SROCC)

- Projects **global sea level rise by 2100** under RCPs, including thermal expansion and ice melt, with likely ranges — e.g., ~0.43 m for RCP2.6 and ~0.84 m for RCP8.5.

2) Glacier & Ice Sheet Loss Studies

- Smaller glaciers (outside Greenland/Antarctica) are projected to lose a significant fraction of ice by 2100 under all scenarios, more so under RCP8.5.

3) Long-Term Projections (Beyond 2100)

- Models and paleo-records suggest sea level rise continues for centuries due to thermal inertia and slow ice sheet dynamics, with multi-meter rise possible by 2300–3000 under high emission scenarios.

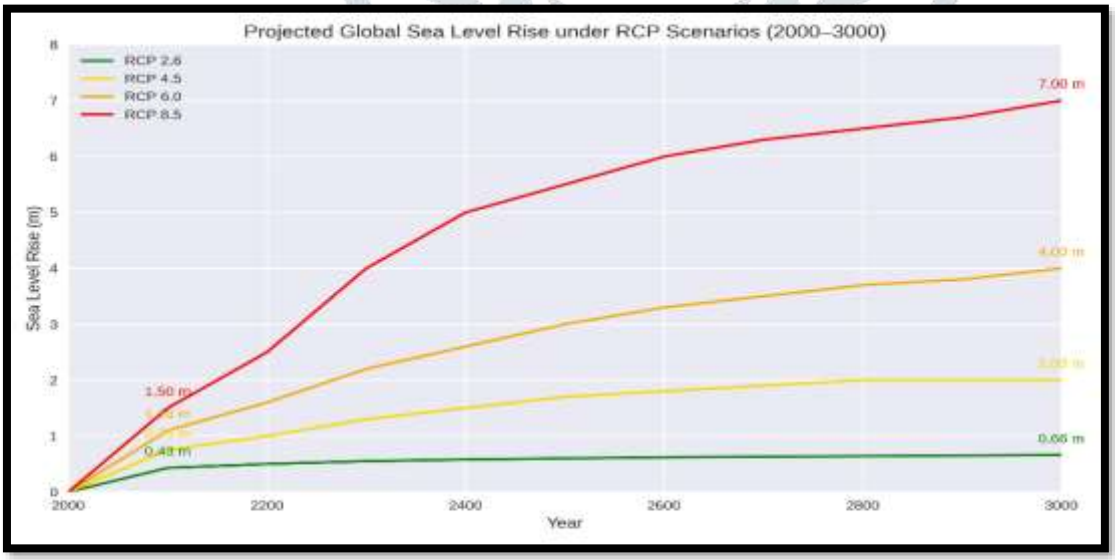


Fig 10:- Projected global Sea level rise under RCP Scenario (2000-3000)

Note :- 1)Higher RCP → higher CO_2 → higher ΔF → higher ΔT → higher ice melt (ΔM) → higher sea level (ΔSL)

2)RCP scenario ↑ → CO_2 ↑ → Global Temp ↑ → Ice Sheets Melt ↑ → Sea Level ↑

↓

Short-term: 2100 (cm–m)

Long-term: 3000 (meters)

3)"Higher RCPs → higher warming → accelerated ice melt → larger sea level rise; short-term 2100: cm–m, long-term 3000: meters."

Table 29 :-Regional Breakdown of RCP → Ice Melt → Sea Level Rise (2100 vs 3000)

RCP	Global Temp Rise (2100)	Greenland Ice Loss	Antarctica Ice Loss	Glaciers (Mountains)	Regional Sea Level Contribution	Total Global SLR	Notes / Impact
RCP 2.6	~1.5–2 °C	Small, mostly coastal	Minimal	Small	Greenland: ~0.1–0.2 mAntarctica: ~0.05 mGlaciers: ~0.1–0.15 m	~0.3–0.6 m (2100) ~0.5–1 m (3000)	Slow, mostly stable; thermal expansion minor
RCP 4.5	~2.5–3 °C	Moderate coastal retreat	Small increase	Moderate	Greenland: ~0.2–0.3 mAntarctica: ~0.1–0.2 mGlaciers: ~0.2–0.3 m	~0.5–1 m (2100) ~1–2 m (3000)	Noticeable regional rise; coastal cities affected
RCP 6.0	~3–4 °C	Strong interior thinning	Medium contribution	Large	Greenland: ~0.3–0.5 mAntarctica: ~0.2–0.5 mGlaciers: ~0.3–0.4 m	~0.8–1.4 m (2100) ~2–4 m (3000)	High-risk regions: Asia coasts, Europe, US east coast
RCP 8.5	~4–6 °C	Rapid collapse begins	Large accelerated loss	Very large	Greenland: ~0.4–0.7 mAntarctica: ~0.3–0.6 mGlaciers: ~0.3–0.5 m	~1–1.6+ m (2100) ~5–7+ m (3000)	Extreme long-term rise; catastrophic in low-lying areas globally

Note :-RCPs are standardised future pathways that describe how greenhouse gas concentrations may change, based on different human emission scenarios, and how much warming they cause.

Table 30: Main RCP Scenarios

RCP	Radiative Forcing (2100)	Meaning	Warming Level
RCP 2.6	2.6 W/m²	Strong climate action	Low warming
RCP 4.5	4.5 W/m²	Moderate control	Medium warming

RCP 6.0	6.0 W/m²	Weak control	High warming
RCP 8.5	8.5 W/m²	No control	Extreme warming

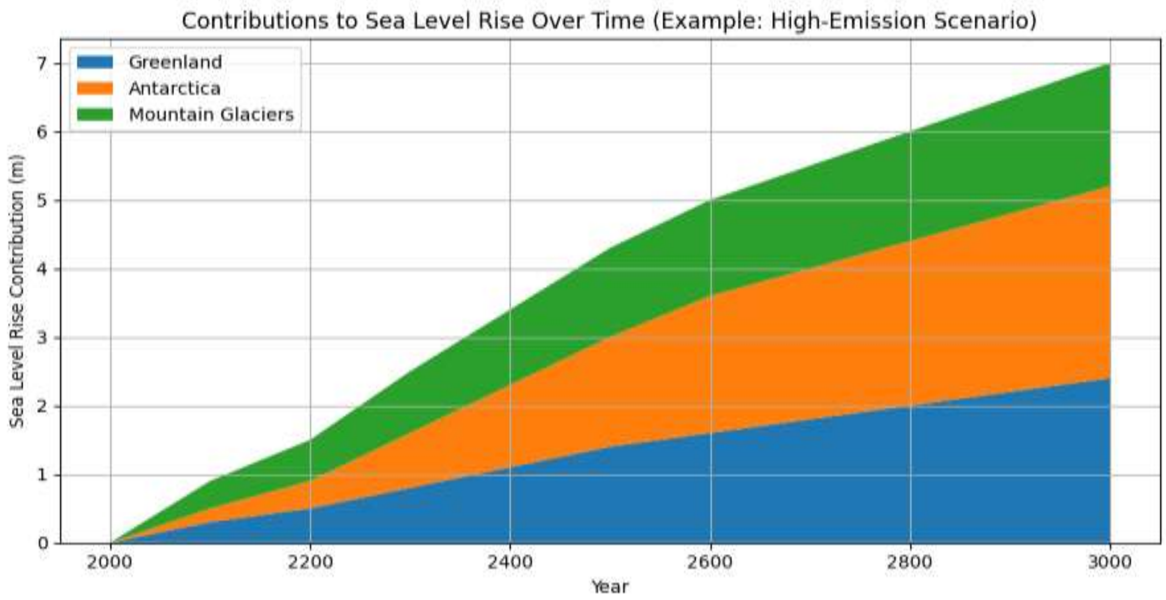


Fig 11 :-**labelled graph showing how Greenland, Antarctica, and mountain glaciers contribute to sea level rise over time** (example shown for a high-emission–type pathway).

From the graph :- **1 Greenland**

- Responds **fastest** to warming
- Dominates the **early-century to mid-century** rise
- Major contributor up to ~2300

2 Antarctica

- Responds **slowly**, but becomes dominant later
- Controls **multi-meter rise after 2300–3000**
- The main reason for the long-term sea level rise is huge

3 Mountain Glaciers

- Small individually, but important globally
- Strong contribution before 2100–2200
- Mostly disappear later

"Greenland dominates short-term sea level rise, glaciers contribute early but saturate, and Antarctica controls long-term multi-meter rise due to its slow but massive ice loss."

Graph Concept: Sea Level Rise vs Time by RCP(For Fig 10)

X-axis: Year (2000 → 3000)
Y-axis: Sea Level Rise (m)
Lines: One per RCP (2.6, 4.5, 6.0, 8.5)

Table 30 :-Approximate Values for Plotting (Global SLR)

Year	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
2000	0 m	0 m	0 m	0 m
2100	0.43 m	0.75 m	1.1 m	1.5 m
2200	0.5 m	1.0 m	1.6 m	2.5 m
2300	0.55 m	1.3 m	2.2 m	4 m
2400	0.58 m	1.5 m	2.6 m	5 m
2500	0.6 m	1.7 m	3 m	5.5 m
2600	0.62 m	1.8 m	3.3 m	6 m
2700	0.63 m	1.9 m	3.5 m	6.3 m
2800	0.64 m	2.0 m	3.7 m	6.5 m
2900	0.65 m	2.0 m	3.8 m	6.7 m
3000	0.66 m	2.0 m	4 m	7 m

Graph Features :-

- **Lines**:
  - Green = RCP 2.6
  - Yellow = RCP 4.5
  - Orange = RCP 6.0
  - Red = RCP 8.5
- **Annotations**:
  - 2100 point (short-term impact)
  - 3000 point (long-term impact)
- **Stacked contributions optional**: Could add shading for Greenland / Antarctica / Glaciers

Key Takeaways to Annotate on Graph:-

- RCP 2.6: Sea level rise mostly <1 m even by 3000
- RCP 8.5: Extreme rise up to ~7 m
- Multi-century rise is dominated by slow ice sheet response (especially Antarctica)
- Shows importance of mitigation: lower RCP = much smaller long-term rise

Ocean Circulation: -Ocean circulation is the large-scale movement of seawater around the globe, driven by wind, temperature, salinity, and Earth's rotation. It plays a major role in climate regulation, heat transport, and nutrient distribution.

Table 31 :-Global Ice Loss → Sea Level Rise Calculation Table (2100)

Region	Ice Mass Loss (Gt)	Conversion to Sea Level Rise (mm)	Conversion to m	Data Source
Greenland (RCP2.6)	25,000	25,000 / 360 ≈ 69.4	0.069 m	IPCC SROCC 2019
Greenland (RCP8.5)	50,000	50,000 / 360 ≈ 138.9	0.139 m	IPCC SROCC 2019
Antarctica (RCP2.6)	5,000	5,000 / 360 ≈ 13.9	0.014 m	IPCC SROCC 2019
Antarctica (RCP8.5)	25,000	25,000 / 360 ≈ 69.4	0.069 m	IPCC SROCC 2019
Global Glaciers (RCP2.6)	34,000	34,000 / 360 ≈ 94.4	0.094 m	GlacierMIP, IPCC SROCC
Global Glaciers (RCP8.5)	72,000	72,000 / 360 ≈ 200	0.200 m	GlacierMIP, IPCC SROCC

Thermal Expansion (RCP2.6)	–	35–50 mm	0.035–0.050 m		IPCC AR6
Thermal Expansion (RCP8.5)	–	71–84 mm	0.071–0.084 m		IPCC AR6
Total Sea Level Rise (RCP2.6)	–	69.4 + 13.9 + 94.4 + 35–50 ≈ 212–227 mm	0.21–0.23 m		IPCC SROCC + AR6
Total Sea Level Rise (RCP8.5)	–	138.9 + 69.4 + 200 + 71–84 ≈ 479–492 mm	0.48–0.49 m		IPCC SROCC + AR6

Ocean Circulation and Its Importance: -

Ocean circulation is the large-scale movement of water in the ocean. It affects:

- Temperature distribution
- Climate patterns
- Sea level locally and globally

Table 32:- Key Types

Type	Description	Typical Rate	Effect on Sea Level
Surface Currents	Driven by wind	0.1–2 m/s	Move warm/cold water → regional thermal expansion → regional sea level rise/fall
Thermohaline Circulation (Deep Ocean Conveyor Belt)	Driven by density differences (temperature & salinity)	0.01–0.1 m/s	Slower circulation can reduce heat transport → thermal expansion in some regions → sea level rise
Western Boundary Currents (e.g., Gulf Stream, Kuroshio)	Fast currents along continents	1–2 m/s	Strong currents pile water against coasts → local sea level rise (dynamic height)
Eastern Boundary Currents	Slower, upwelling currents	0.05–0.2 m/s	Lower sea level near coasts due to upwelling and offshore movement

1)The Relation Between Ocean Circulation and Sea Level

1. **Dynamic Sea Level Changes**

$$\eta = \frac{P}{\rho g} + \text{dynamic height from currents}$$

- η= local sea level
- P= pressure
- ρ= water density
- g= gravity
- Ocean currents redistribute water → "dynamic sea level" rises along strong currents (like the Gulf Stream).

2. Thermal Expansion

$$\Delta SL_{thermal} = \alpha \Delta T H$$

- Warm water expands → local sea level rises
- Currents move heat → regions near western boundary currents experience **higher sea level rise**.

3. **Salinity / Density Effects (Halosteric)**

$$\Delta SL_{density} = \beta \Delta SH$$

- β= haline contraction coefficient (~7.6×10^{-4} / PSU)
- ΔS= salinity change
- Changes in density alter water height → affect regional sea level.

Table 33 :-Observed Regional Effects

Ocean Region	Circulation Feature	Rate	Effect on Local SLR
North Atlantic	Gulf Stream / AMOC	1–2 m/s	Piles water → East Coast US sees +10–20 cm extra rise
Pacific Ocean	Kuroshio / North Pacific Current	1–1.5 m/s	The West Pacific sees a higher sea level than the East Pacific
Indian Ocean	Monsoon-driven currents	0.1–0.5 m/s	Seasonal shifts in sea level + dynamic height variations
Southern Ocean	Antarctic Circumpolar Current	0.1–0.3 m/s	Slow deep-water upwelling → less sea level rise directly, but moves cold water to absorb heat globally
Global Deep Ocean	Thermohaline Conveyor	0.01–0.1 m/s	Slow redistribution → global sea level rises uniformly over centuries

Key Mechanisms Linking Circulation to Sea Level

1. **Dynamic Sea Level:**
   - Water piles up along strong currents → local differences of 0.1–0.3 m.
2. **Thermal Redistribution:**
   - Heat transported by currents causes thermal expansion → uneven sea level rise.
3. **Ice Melt & Ocean Circulation:**
   - Freshwater input (from Greenland / Antarctica) slows down the AMOC → reduces heat transport north → increases sea level along the US East Coast.

- **Summary: -**Ocean currents move **mass and heat**, creating **dynamic sea level differences**.
- **Fast currents (Gulf Stream, Kuroshio)** raise the local sea level.
- **Slow global conveyor** controls heat redistribution → affects long-term global sea level rise.
- Ice melt interacts with circulation: slows AMOC → increases regional sea level rise.

Ocean dynamics related to sea level changes: -Ocean dynamics refers to the movement of water in the oceans, driven by winds, temperature differences, salinity, and Earth's rotation. These dynamics influence **regional and global sea level** through several processes.

Table 33 :-Key Mechanisms Linking Ocean Dynamics to Sea Level

Mechanism	Description	Effect on Sea Level	Example
Thermal expansion (Steric effect)	Warmer water expands; colder water contracts	Global sea level rises with ocean warming	Global average rise of 0.3–0.6 m by 2100 under high warming scenarios

Salinity-driven density changes (Halosteric effect)	Salty water is denser; freshwater is lighter	Regional sea level changes due to the redistribution of water masses	Melting Greenland ice → local salinity decrease → local sea level rise
Wind-driven currents	Persistent winds push water (Ekman transport), piling it up or down	Regional sea level differences (meters in extreme cases)	Trade winds in the Pacific → Pacific "warm pool" rises
Ocean circulation (e.g., AMOC, gyres)	Large-scale currents redistribute heat and water	Regional sea level rise/fall	Slowdown of Atlantic Meridional Overturning Circulation (AMOC) → sea level rises along the US East Coast
Atmospheric pressure changes (Inverted barometer effect)	Low pressure allows the sea to rise locally	Short-term, regional changes	Storms, cyclones → local sea level rise of several meters
El Niño / La Niña	Periodic ocean-atmosphere events	Alter the sea level regionally for months	El Niño → sea level rises in Eastern Pacific, falls in Western Pacific
Tides and waves	Gravitational pull from Moon/Sun	Regular, cyclic local sea level variation	Tidal ranges up to 10–15 m in some bays

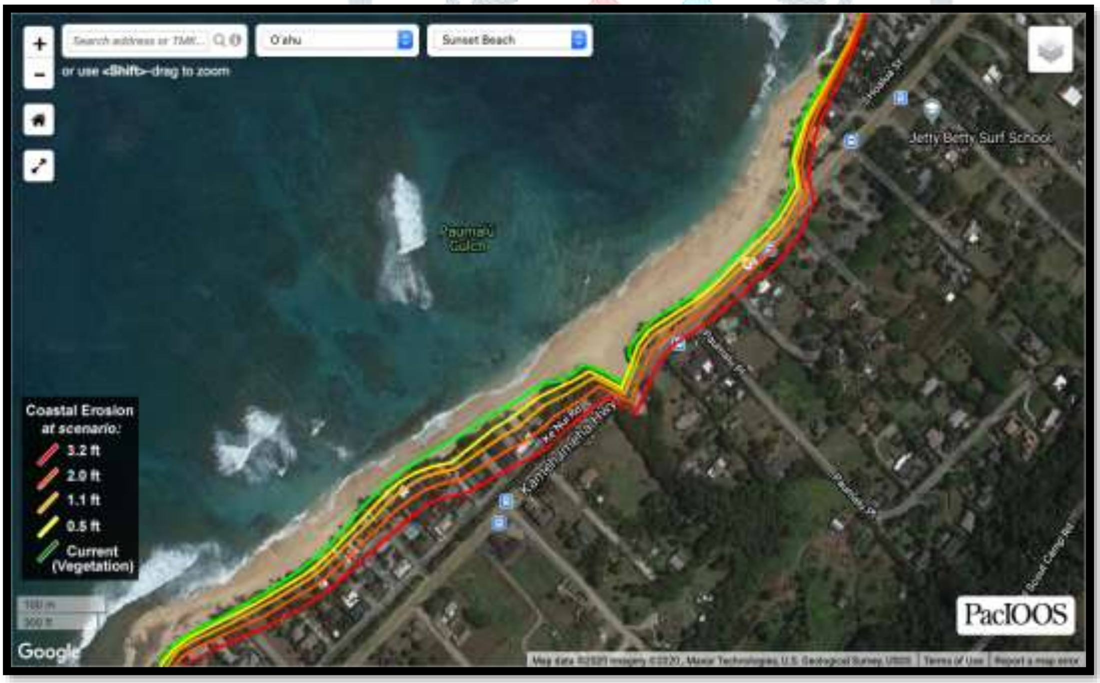


Fig 12 :-**The coastal exposure map data in the Viewer were updated in 2020 by the University of Hawai'i Coastal Geology Group. Details on that update are provided below, following** ***Assumptions and Limitations***.

Arrow chart: -[Global Warming] → [Ocean Warming] → [Thermal Expansion] → ↑ Global Sea Level

↓

[Melting Ice] → ↑ Ocean Freshwater → Salinity ↓ → Regional Sea Level Rise

[Winds] → [Currents / Ekman Transport] → Regional Sea Level Anomalies

[Pressure Systems] → Local Rise/Fall (Storm Surges)

[Ocean Oscillations] → El Niño / La Niña → Regional Sea Level Variability

Summary: Ocean dynamics amplify or reduce sea level rise regionally.

- Thermal expansion dominates global rise; winds and currents dominate regional patterns.
- Short-term events (storms, tides) can cause meters of temporary local variation.
- Long-term changes (centuries) are mostly controlled by climate-induced ocean warming and circulation shifts.

Mapping of deciphering Sea Level Dynamics Through Natural Cycles and Carbon Storage Interventions

Table 34 :-Sea Level Dynamics Mapping

Category	Mechanism	Effect on Sea Level	Timescale	Example / Notes
Natural Cycles	ENSO / PDO / AMOC	Regional rise/fall due to redistribution of heat & water	Interannual–decadal	El Niño → Eastern Pacific rises; La Niña → Western Pacific rises
	Tides & Storms	Local, short-term rise/fall	Hours–days	High tides, storm surges up to several meters
Ocean Dynamics	Thermal Expansion (Steric)	Global rise	Decades–centuries	Ocean warms → expands (~0.3–0.6 m by 2100 under high emissions)
	Salinity Changes (Halosteric)	Regional rise/fall	Decades–centuries	Ice melt → freshwater reduces salinity → local sea level rise
	Ice Sheet / Glacier Melt	Global rise	Decades–millennia	Greenland & Antarctic melt → 0.5–1 m by 2100; more by 3000
	Ocean Currents / Gyres	Regional redistribution	Decadal–centennial	Slowing AMOC → US East Coast rises, Europe may fall
Carbon Storage Interventions	Blue Carbon (Mangroves, Seagrass)	Indirect mitigation: slows thermal expansion & coastal erosion	Decades–centuries	Mangrove restoration stabilizes coasts + sequesters carbon
	Geological CO_2 Storage	Indirect mitigation: reduces warming → slows thermal expansion	Decades–centuries	CO_2 stored in saline aquifers or depleted reservoirs
	Ocean CO_2 Removal (Alkalinity / Fertilisation)	Indirect mitigation: reduces warming → slows sea level rise	Decades–centuries	Experimental; regional impact uncertain

Table 35 :-For each category, note the mechanism:

Category	Mechanism	Sea Level Effect
Natural Cycles	ENSO / PDO / AMOC	Regional rise/fall (meters)
Natural Cycles	Tides / Storms	Local short-term rise/fall

Ocean Dynamics	Thermal Expansion	Global rise
Ocean Dynamics	Salinity Change	Regional rise/fall
Ocean Dynamics	Ice Sheet Melt	Global rise
Carbon Storage	Mangroves / Seagrass	Reduce warming → mitigate long-term rise
Carbon Storage	Geological Storage	Reduce warming → mitigate thermal expansion
Carbon Storage	Ocean CO_2 Removal	Reduce warming → slow sea level rise

Conclusion: Sea Level Dynamics through Natural Cycles and Carbon Interventions

1. **Sea level change is driven by multiple interacting factors**, including **natural cycles** (tides, storms, ENSO, ocean oscillations) and **ocean dynamics** (thermal expansion, salinity changes, ice sheet melt, currents).
2. **Timescales matter:**
   - Short-term (hours–days): tides, storms
   - Interannual–decadal: ENSO, PDO, AMOC
   - Long-term (decades–millennia): ocean warming, ice melt
3. **Regional vs global effects:**
   - Natural cycles and currents cause **regional variability**, sometimes leading to local rises or falls in sea level.
   - Thermal expansion and ice melt are the **dominant drivers of global sea level rise**.
4. **Carbon storage interventions provide mitigation:**
   - Blue carbon ecosystems, geological storage, and ocean CO_2 removal **slow warming**, indirectly reducing long-term sea level rise.
   - They cannot prevent short-term natural variations but **play a crucial role in limiting long-term global rise**.
5. **Integrated approach is essential:**
   - Understanding sea level dynamics requires linking **natural variability, ocean physics, and human mitigation efforts**.
   - This mapping highlights both **the complexity of processes** and **the potential of interventions** to manage future sea level rise.

✅ **Key takeaway:** Short-term fluctuations are natural and regional, while long-term global rise is climate-driven; **carbon interventions are critical for mitigating long-term impacts**.

Result and Recommendation: -

Results: Sea Level Dynamics Analysis

1. **Natural Cycles:**
   - ENSO, PDO, AMOC, tides, and storms generate **short-term to interannual regional sea level fluctuations**.
   - Example: El Niño causes **sea level rise in the Eastern Pacific**, while La Niña causes a **rise in the Western Pacific**.
2. **Ocean Dynamics:**
   - Thermal expansion due to ocean warming leads to **global sea level rise (~0.3–0.6 m by 2100)**.
   - Salinity changes and ice sheet melt contribute to **regional and global variability**, with ice melt potentially adding **0.5–1 m by 2100**.
   - Ocean currents redistribute water, producing **regional differences**, e.g., the US East Coast may experience above-average rise due to a slowdown of AMOC.
3. **Carbon Storage Interventions:**
   - Blue carbon ecosystems (mangroves, seagrass) and geological CO_2 storage **indirectly mitigate long-term sea level rise** by reducing ocean warming.
   - Ocean-based CO_2 removal methods show **potential to slow sea level rise**, but effects are regionally variable and still under research.
4. **Integrated Observation:**

- Short-term sea level variations are dominated by **natural cycles**.
- Long-term global sea level rise is primarily controlled by **ocean dynamics and climate-induced warming**.
- **Carbon storage interventions** are effective for mitigating long-term rise but **do not affect short-term fluctuations**.

Overall Result:

- Sea level change is a **combined outcome of natural variability, oceanic processes, and human interventions**.
- Regional patterns can differ significantly from global trends.
- Mitigation strategies like carbon storage are **critical to reduce future global sea level rise**.

Table 36 :-Sea Level Dynamics Summary: Natural Cycles, Ocean Dynamics & Carbon Storage

Factor Category	Mechanism / Intervention	Sea Level Impact	Timescale	Example / Notes
Natural Cycles	ENSO, PDO, AMOC	Regional rise/fall due to water & heat redistribution	Interannual–decadal	El Niño → Eastern Pacific rise
	Tides & Storms	Local, short-term rise/fall	Hours–days	Storm surges, high tides
Ocean Dynamics	Thermal Expansion (Steric)	Global rise	Decades–centuries	Ocean warms → expands (~0.3–0.6 m by 2100)
	Salinity Changes (Halosteric)	Regional rise/fall	Decades–centuries	Ice melt → freshwater reduces salinity → local rise
	Ice Sheet / Glacier Melt	Global rise	Decades–millennia	Greenland & Antarctic melt → 0.5–1 m by 2100
	Ocean Currents / Gyres	Regional redistribution	Decadal–centennial	Slow AMOC → US East Coast rises
Carbon Storage Interventions	Blue Carbon (Mangroves, Seagrass)	Indirect: slows thermal expansion & erosion	Decades–centuries	Mangrove restoration stabilizes coasts & sequesters carbon
	Geological CO_2 Storage	Indirect: slows ocean warming → reduces thermal expansion	Decades–centuries	CO_2 in saline aquifers or depleted reservoirs
	Ocean-based CO_2 Removal	Indirect: reduces warming → slows sea level rise	Decades–centuries	Experimental; regional effects vary

Key Takeaways / Results:-

1. **Short-term / Regional Changes:** Dominated by **natural cycles** (tides, storms, ENSO).
2. **Long-term / Global Changes:** Driven by **ocean dynamics** (thermal expansion, ice melt).
3. **Carbon interventions:** Mitigate **long-term rise**, but **do not prevent short-term variations**.
4. **Integrated understanding:** Sea level is the result of **interactions between natural variability, ocean processes, and human interventions**.
5. **Practical implication:** Coastal planning must consider **both regional short-term fluctuations and long-term global trends**.

Table 37:-Table: Steps to Reduce / Mitigate Sea Level Rise

Category	Step / Intervention	Mechanism	Sea Level Impact	Timescale	Example / Notes
Climate Mitigation	Reduce Greenhouse Gas Emissions	Lower CO_2 & methane	Slows thermal expansion & ice sheet melt	Decades–centuries	Paris Agreement, renewable energy adoption
	Carbon Capture & Storage (CCS)	Capture CO_2 from industry & store underground	Reduces long-term ocean warming → slows rise	Decades–centuries	Saline aquifers, depleted oil/gas reservoirs
	Blue Carbon Ecosystems	Restore mangroves, seagrass, salt marshes	Absorbs CO_2 & stabilizes coastlines	Decades–centuries	Mangrove restoration in Southeast Asia
Coastal Adaptation & Protection	Seawalls / Dikes / Coastal Barriers	Physical barrier against flooding	Reduces local flooding	Short-term → permanent	Netherlands Delta Works, New Orleans levees
	Managed Retreat	Relocate settlements from vulnerable coasts	Reduces human exposure	Short-term → long-term	Kiribati coastal relocation plans
	Wetland / Floodplain Restoration	Natural water absorption	Reduces local flooding & storm surge impact	Short-term → decades	Louisiana wetlands restoration
	Urban Planning & Zoning	Limit construction in high-risk zones	Reduces infrastructure damage	Short-term → long-term	Flood-risk based urban planning
Ocean-Based Interventions	Ocean Alkalinity Enhancement	Increase alkalinity → more CO_2 uptake	Reduces warming → indirectly slows rise	Decades–centuries	Experimental research projects
	Ocean Fertilization	Stimulate phytoplankton → carbon sequestration	Indirect mitigation	Decades–centuries	Pilot experiments (environmental risks)
Ice Sheet & Glacier Protection	Reduce Black Carbon / Soot Deposition	Less sunlight absorption on ice	Slows glacier melt → reduces sea level contribution	Decades–centuries	Arctic & Himalayan air pollution control
	Local Glacier Conservation Measures	Ice dam management, snowpack retention	Delays regional melt	Decades–centuries	High mountain glacier projects

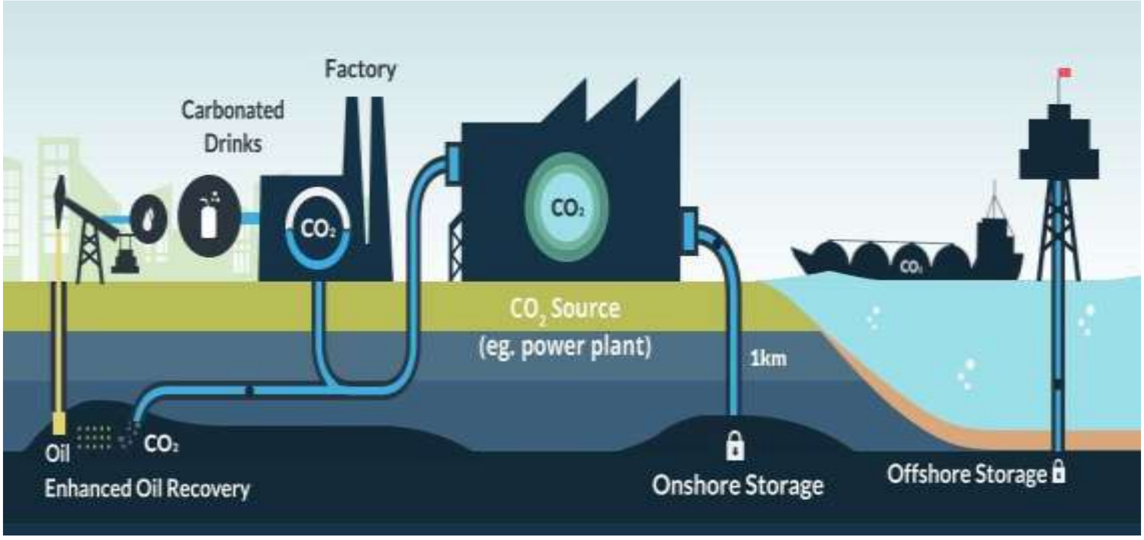


Fig 13 :- Carbon capture and storage process

Sea level rise is driven by a combination of **natural cycles** (tides, storms, ENSO, ocean oscillations) and **ocean dynamics** (thermal expansion, salinity changes, ice sheet and glacier melt, and currents), producing both **short-term regional fluctuations** and **long-term global increases**. While natural cycles dominate **local and temporary variations**, ocean dynamics are the primary cause of **long-term global sea level rise**, which is further amplified by climate warming. **Carbon storage interventions** such as blue carbon ecosystems, geological CO_2 storage, and experimental ocean-based CO_2 removal can **indirectly mitigate long-term sea level rise** by slowing thermal expansion and ice melt. Complementary **coastal adaptation strategies**—including seawalls, wetland restoration, managed retreat, and risk-based urban planning—help reduce **local human and infrastructure impacts**. An integrated approach combining **mitigation, adaptation, and ecosystem management** is therefore essential to manage both regional and global sea level changes effectively.

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