EH 612 - Ocean and Global Change

Spatial and Temporal Changes of Multiple Trends in Sea Level for Indian Ocean

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Group F

Sea‑level change is not uniform around the globe: regional patterns can differ markedly from the global mean. In this project, I focus on the Indian Ocean over the past thirty years (1993–2022), using ISRO's SLA dataset and Copernicus [1] temperature and salinity records to explore how sea level, sea‑surface temperature and salinity have co‑varied both in space and time. First, I divided the thirty‑year SLA record into five roughly six‑year segments, plotted each segment's trend, and compared their slopes to reveal shifts in the rate of rise. Then, to gauge real‑world impacts, I selected four major Indian‑Ocean port cities—Colombo, Perth, Jakarta and Durban—and plotted their individual SLA time series, estimating the resulting economic damages to 2050. Throughout, I integrated insights from peer-reviewed literature to explain the drivers behind these regional variations (notably monsoon/IOD-driven temperature and salinity changes) and contrasted them with global trends.

I. Comparison of Indian Ocean SLA with Global SLA for 1993-2022

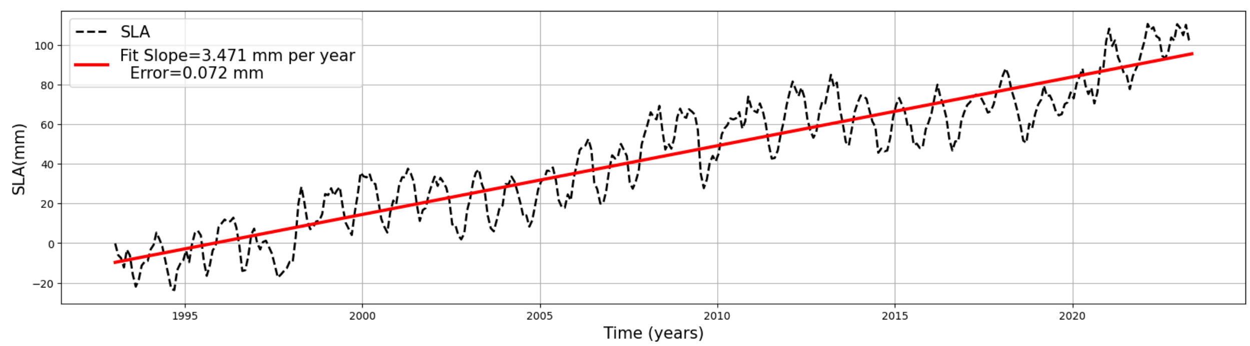


Fig. 1 Mean Indian Ocean SLA

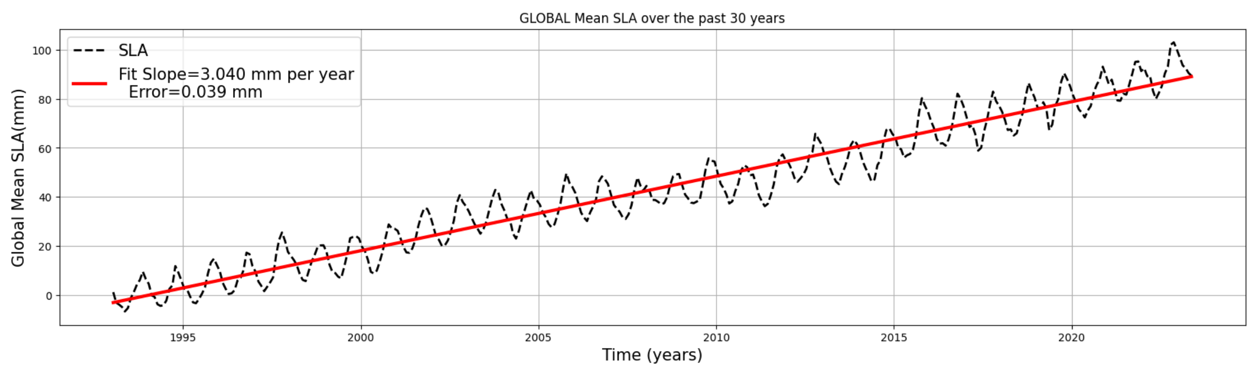


Fig. 2 Global SLA

The Indian Ocean altimeter time‑series shows several features:

- ☐ <u>Strong seasonal cycle</u>**:** There is a roughly ±20–30 mm annual oscillation, reflecting the monsoon-driven wind and thermal changes that vary with the Indian summer and winter monsoons.
- ☐ <u>~5 yearly fluctuations due to ENSO:</u> Past El Niño events occurred in 1995, 1998, 2003, 2007, 2010 and 2016 [2]. During an El Niño event, the sea levels in the Indian Ocean tend to decrease. The decrease in SLA during these years roughly reflect large‑scale climate modes (e.g. ENSO, Indian Ocean Dipole) as well as changes in wind forcing and circulation.
- ☐ <u>Upward trend:</u> From 1993 to the early 2000s, the mean SLA rises from around –10 mm to 30 mm. From 2000 onward the rise accelerates, reaching anomalies in excess of +100 mm by 2023. We obtain a fit slope of 3.471 mm/yr over the Indian Ocean.

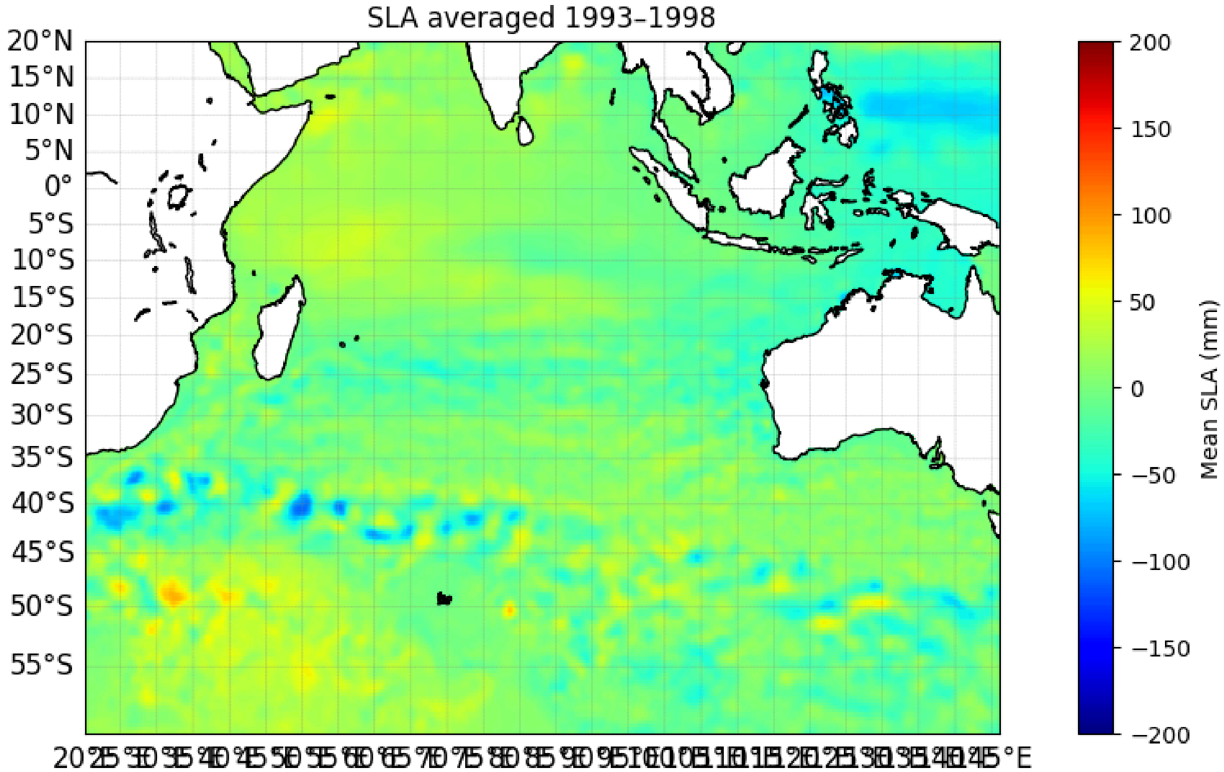
In comparison, the global SLA:

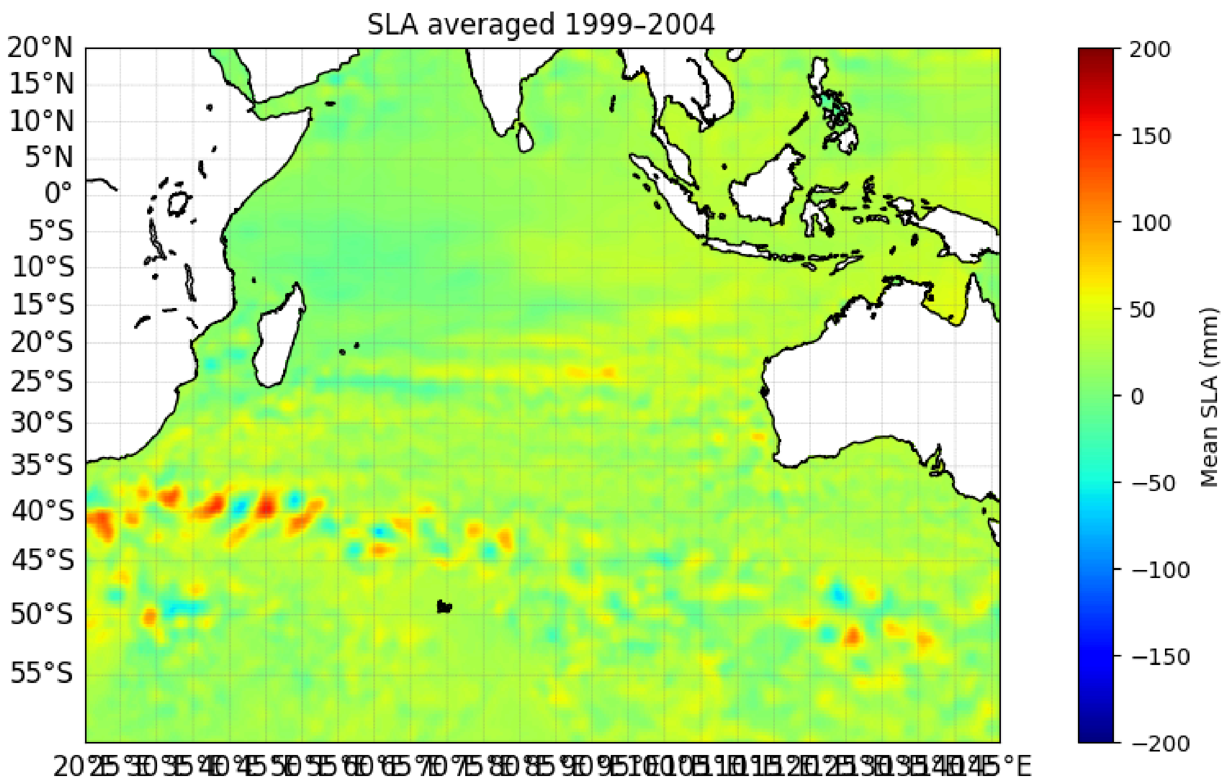
- ☐ Has not shown as much variation due to ENSO and has oscillated seasonally consistently.
- ☐ We obtain a fit slope of 3.040 mm/yr globally.

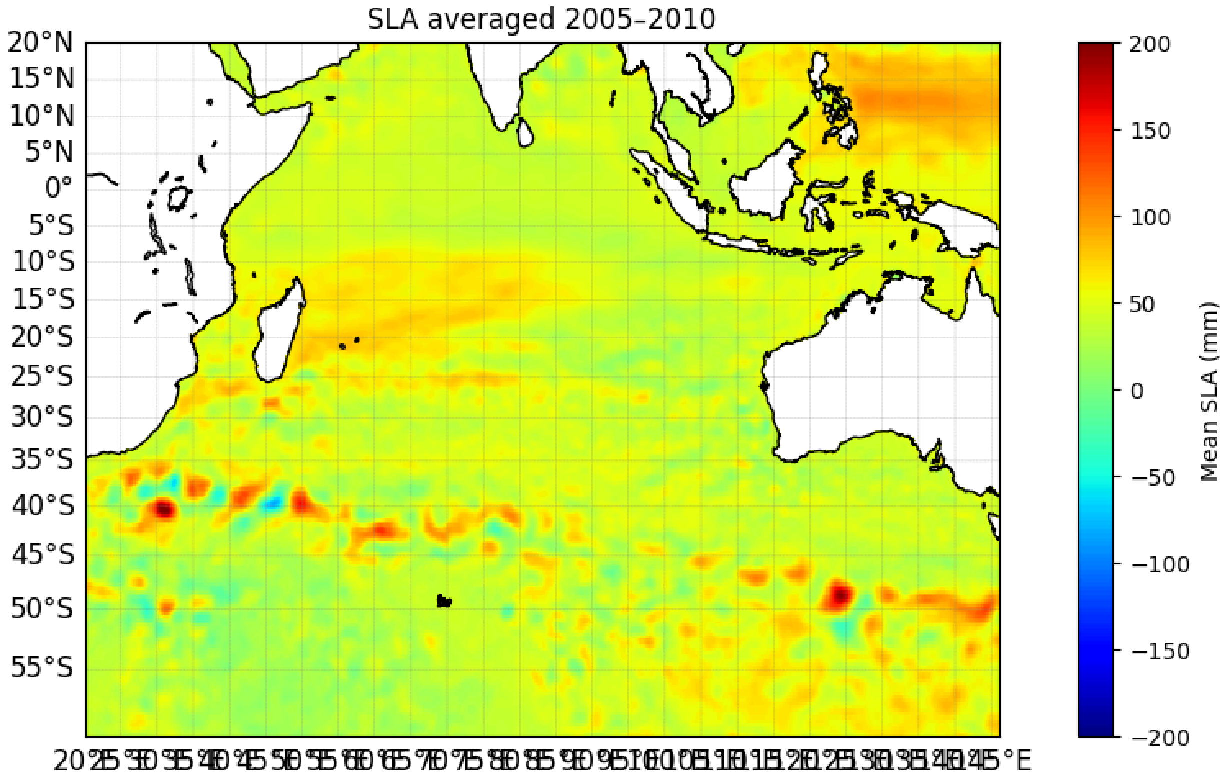
The Indian Ocean has **warmed and risen slightly faster** than the global average.

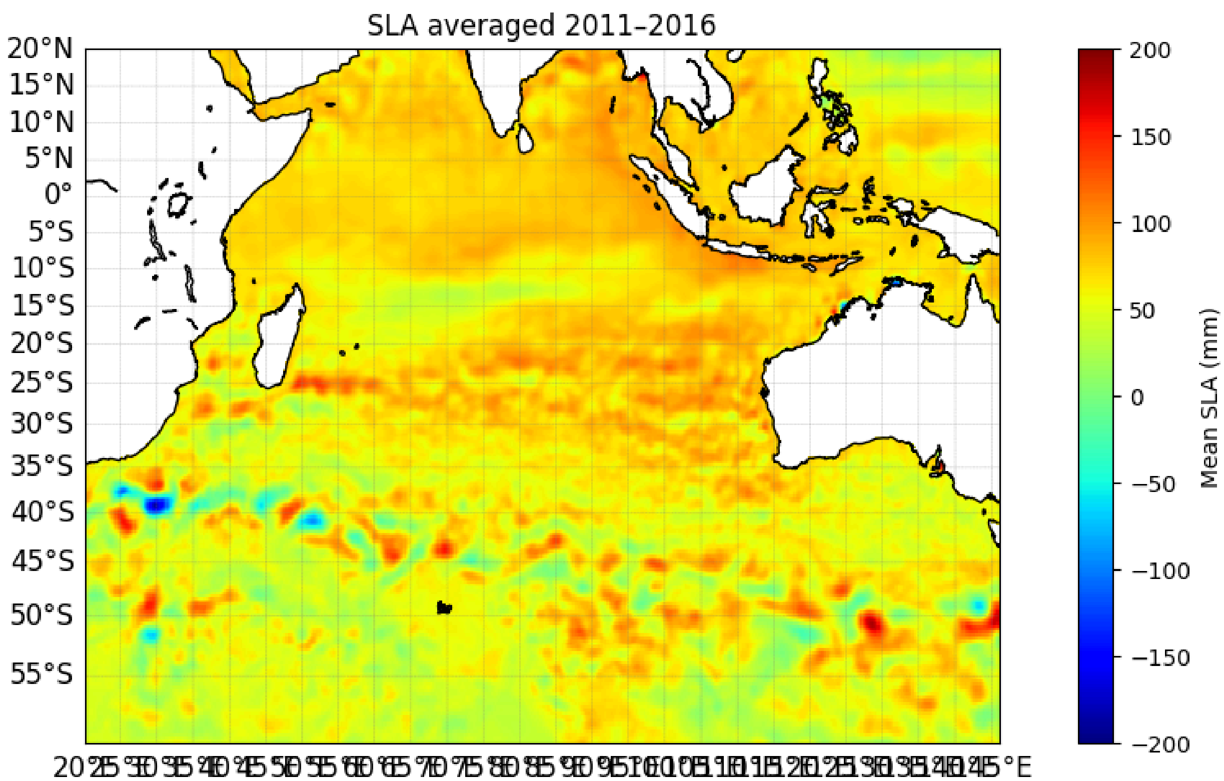
These results are confirmed by existing literature. The ~3 mm yr^{-1} altimeter trend from 1993-2022 is consistent with the sea level rise rate of ~3.4 mm/yr in 2018 (slightly lower due to inclusion of 1990s sea level). The pronounced steepening after 2000 aligns with studies showing rapid southwest Indian Ocean rise of ~40 mm per decade since 2000, which is about 41% due to barystatic (freshwater mass) increases and 30% by thermal (steric) warming.

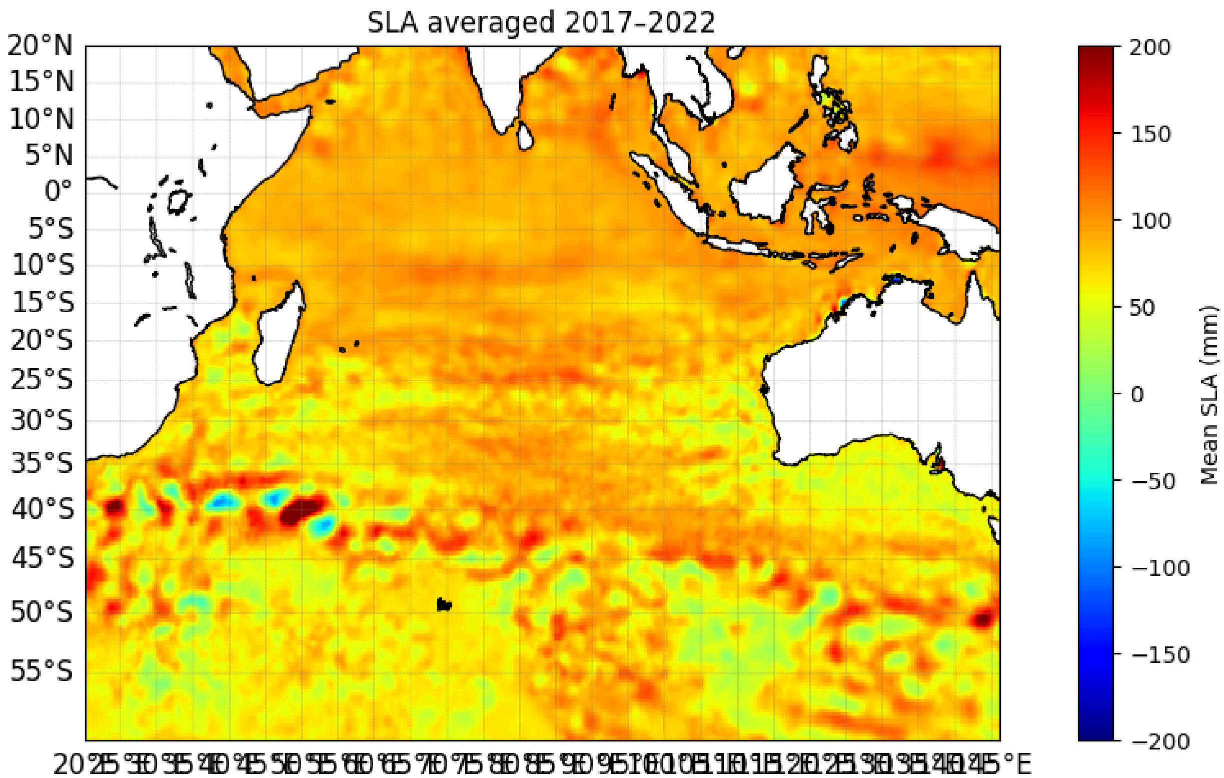
II. 6-Yearly Regional SLA Plots of Indian Ocean, from 1993-2022






SLA averaged 2005–2010
20°N
15°N
10°N
5°N
0°
5°S
10°S
15°S
20°S
25°S
30°S
35°S
40°S
45°S
50°S
55°S
Mean SLA (mm)
200
150
100
50
0
−50
−100
−150
−200


SLA averaged 2011–2016
20°N
15°N
10°N
5°N
0°
5°S
10°S
15°S
20°S
25°S
30°S
35°S
40°S
45°S
50°S
55°S
Mean SLA (mm)
200
150
100
50
0
−50
−100
−150
−200



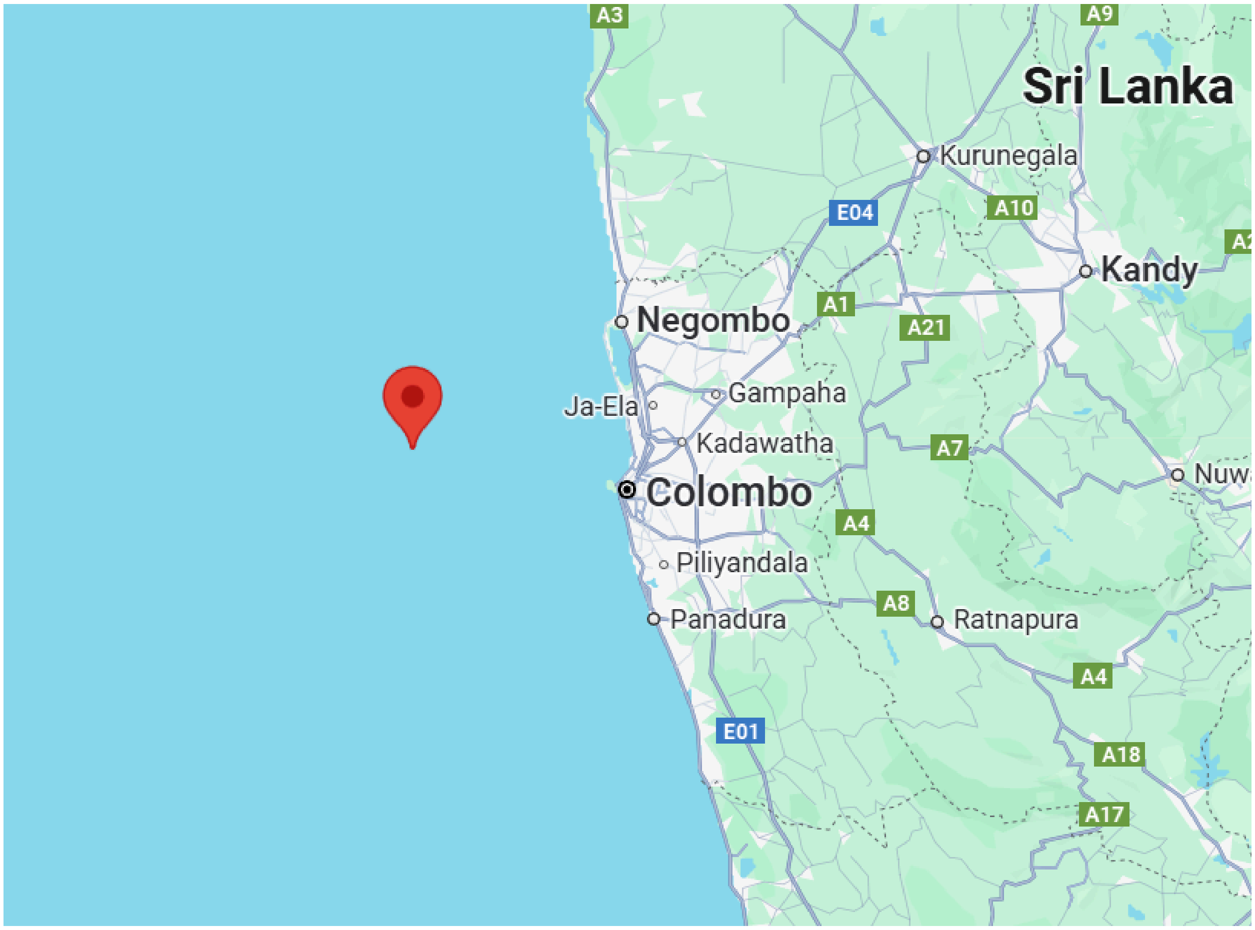
The plots show a clear **upward trend in mean sea level** over the last thirty years. For 1993–1998**,** SLA is **mostly zero** (green), with only small pockets of positive (yellow) and negative (blue) departures. From 2011–2016 onwards, there is a strong jump in SLA: much of the northern basin is orange (50–100 mm), and the southern band shows intense red-orange spots (~150 mm). The highest anomalies appear in the most recent period of 2017-2022: large areas of the tropical Indian Ocean exceed **+100 mm**, and the southern mid-latitudes are even more red (150–200 mm).

Main reasons for this trend are:

- ☐ Thermal Expansion of ocean water: As the ocean absorbs >90% of excess heat from greenhouse-gas forcing, the water column expands—raising steric sea level everywhere, but most strongly in regions of enhanced heat uptake (tropics and mid-latitudes).
- ☐ Mass Addition from melting ice: Melting of glaciers, ice caps, and the Greenland/Antarctic ice sheets adds freshwater to the ocean, increasing its total mass.
- ☐ Ocean Dynamics & Winds: Changes in wind stress (monsoon and trade-wind patterns) affect Ekman transport and basin-wide circulation, redistributing sea level laterally (sideways). For eg. stronger westerlies in the southern Indian Ocean deepen the thermocline and pile up warm water, producing the hot band around 40° S in the graphs.

III. Analysis of SLA of cities along the Indian Ocean coastline

1. **Colombo, Sri Lanka (79.5E, 7N)**



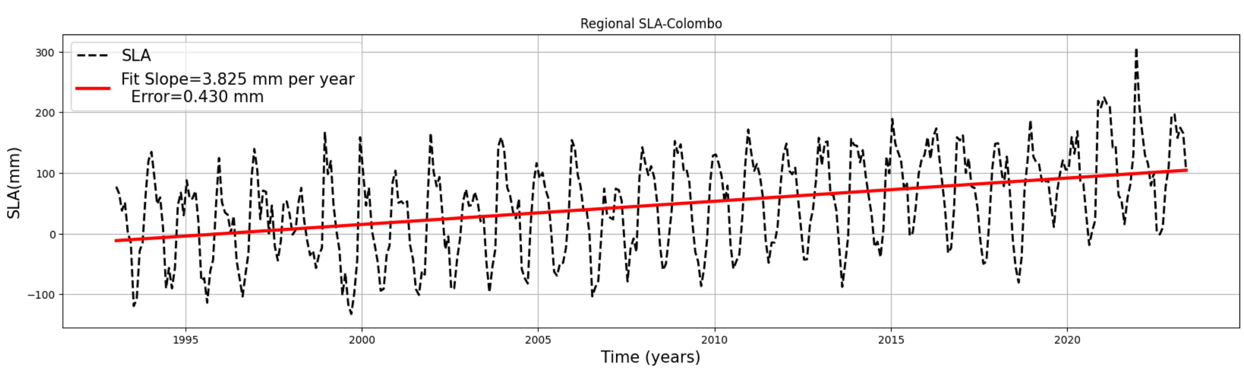


Fig. 3 SLA Colombo

- <u>Observed SLA trend:</u> 3.825 mm/yr.

- <u>Climate-driven flood risk</u>: Coastal flood risk in low-lying Sri Lankan cities is projected to climb by 2–3 orders of magnitude this century without adaptation. [3]
- <u>Impact:</u> More frequent inundation during monsoon surges, salt-water intrusion into groundwater, increased beach erosion. Tens or hundreds of thousands of vulnerables may be displaced unless seawalls and managed retreat are implemented.
- <u>Temperature</u>: Continued SST warming could exacerbate coastal storm intensity and rainfall extremes around the city.

2. **Perth, Australia (-32N, 115E)**

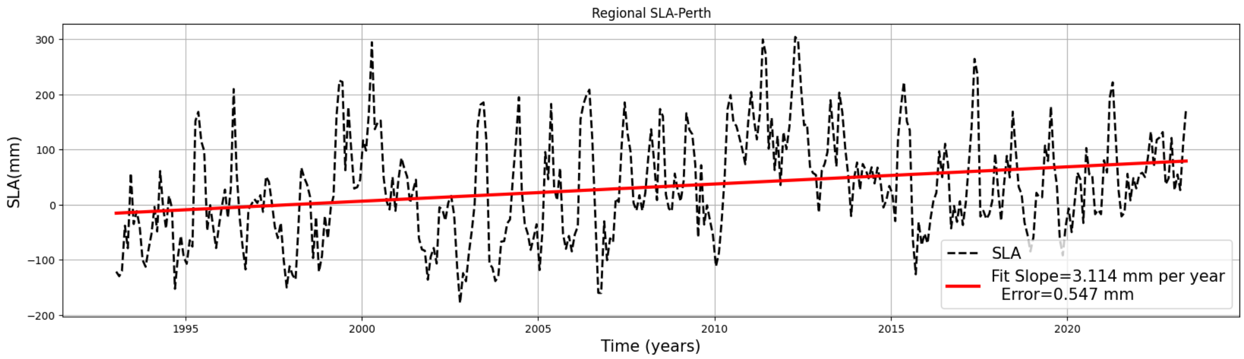


Fig. 4 SLA Perth

- Observed SLA trend: ≈ 3.114 mm/yr.
- Coastal erosion: While Western Australia has high resources for coastal defenses, continued sea-level rise will nonetheless accelerate beach erosion, undermine dunes, and increase the frequency of low-lying road and suburb inundation [3].
- Economic loss: With planned seawalls, managed retreat and dune restoration, drowning is unlikely. However, the cost of maintaining beachfront property and public amenity will rise sharply.

3. Jakarta, Indonesia (-6N, 107E)

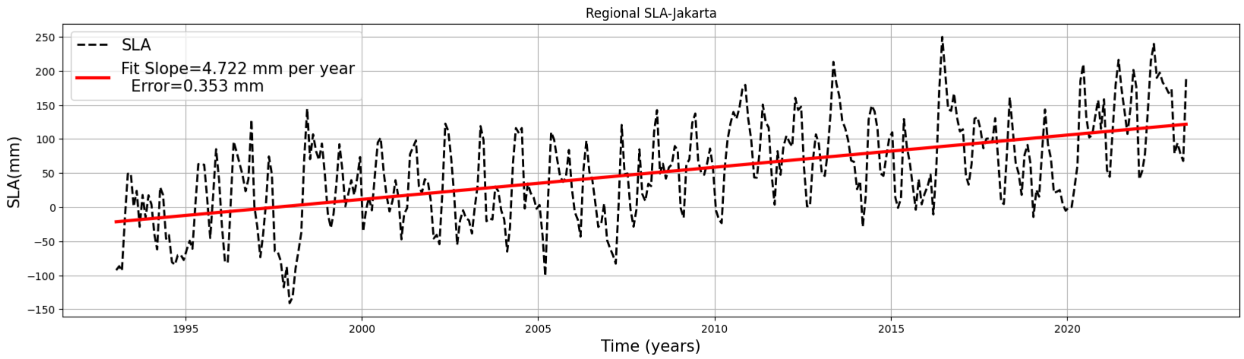


Fig. 5 SLA - Jakarta

- <u>Observed SLA trend:</u> 4.722 mm/yr, land subsidence of 5-10 cm/yr in northern districts.
- <u>Flooding</u>**:** Parts of Jakarta could sit **1 m below sea level** by 2050, leading to permanent inundation unless massive engineering works succeed [3].
- <u>Population impact:</u> Large‑scale displacement and relocation of millions are underway because of this risk of inundation.
- <u>Water quality:</u> Saltwater will contaminate aquifers, undermining freshwater supply across the metro area.

4. **Durban (-30N, 31E)**

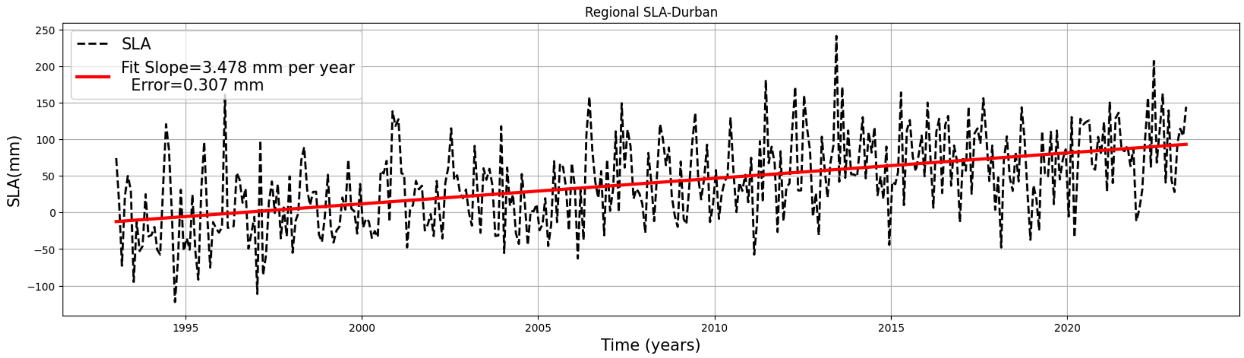
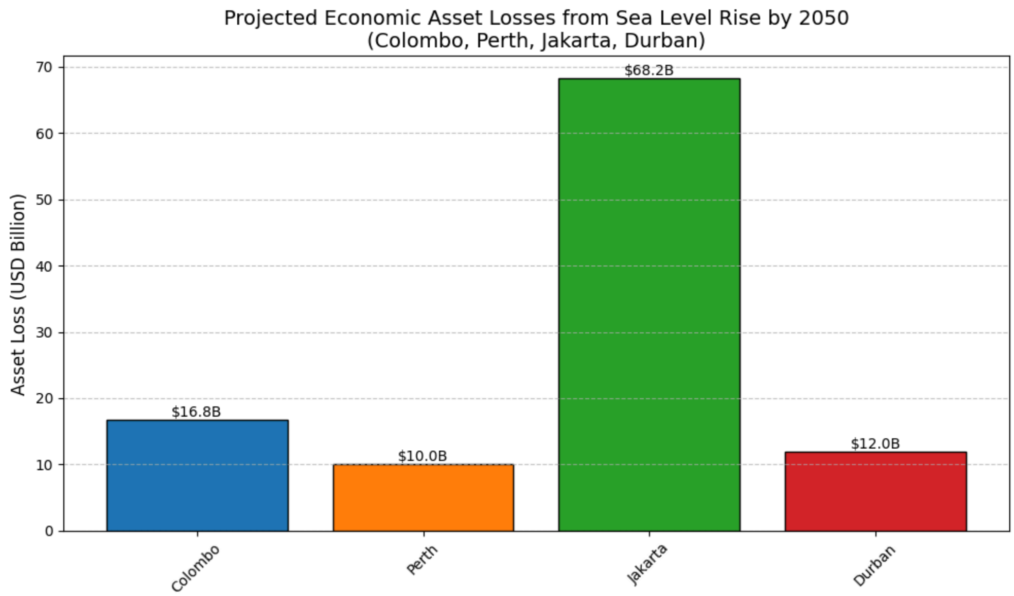


Fig. 6 SLA - Durban

- <u>Observed SLA trend:</u> 3.478 mm/yr.
- <u>Storm surge & infrastructure:</u> Durban's port is not as lowly elevated as Jakarta (Jakarta elevation is 8m compared to Durban's 22m) but increased sea levels will amplify flood heights and damage the harbor, rail lines, and low-income settlements along lagoons and estuaries [3].
- <u>Ecosystem & health:</u> Rising SSTs will promote more intense marine heatwaves, stressing coral reefs offshore (already under pressure), and may shift vector-borne disease zones inland.

Hundreds of millions live in the Low Elevation Coastal Zone. Many Indian-Ocean cities (Colombo, Jakarta, Durban) are flagged as **"very high risk"** in IPCC's Cross-Chapter Paper on Cities by the Sea [3]. As of now, around 3.3-3.6 billion people live in countries highly vulnerable to climate impacts, with global hotspots concentrated in Small Island Developing States, the Arctic, South Asia, Central and South America, and much of sub-Saharan Africa [4].



Location	SLR Scenario by 2050	Asset Loss (USD B)	GDP Impact (%)
Colombo	+0.5m	16.8	1.2
Perth	+0.3m	10.0	8.0
Jakarta	+2.5m	68.2	18.0
Durban	+0.28m	12.0	14.0

The above shows the estimated economic loss of these 4 cities by 2050 according to various sources [5], [6]. Unless effective adaptation is implemented (seawalls, managed retreat, nature-based solutions), these cities will pay a steep price for holding the line.

IV. Comparison of SLA with SST and salinity over 1993-2022

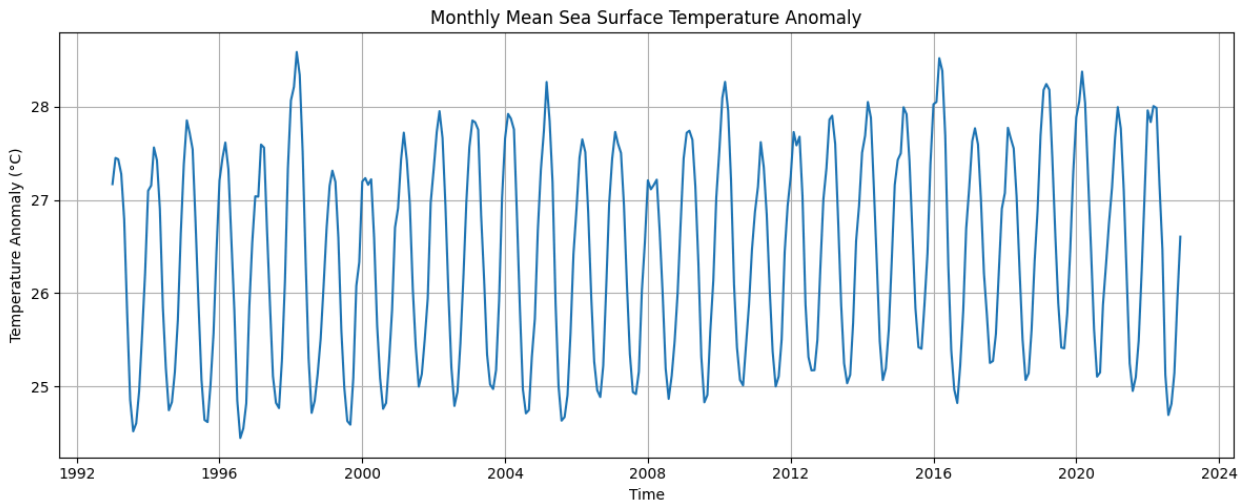


Fig. 7 Monthly SST of Indian Ocean

The plot shows the following:

- ☐ Strong annual cycle: The dominant oscillation is the seasonal monsoon cycle, which drives SSTs up and down by roughly 2 °C each year, with peaks in summer and valleys in winter.
- ☐ Spikes of ~28.5° C every 4–7 years: These correspond almost exactly to positive IOD (Indian Ocean Dipole) events, during which the western and central Indian-Ocean waters become warmer than eastern Indian Ocean [7]. Positive IOD events (1997-98, 2006, 2019) make the western basin warm. El Niño events (1998, 2003, 2016) change atmospheric circulation so that the Indian Ocean retains more heat. These phenomena are naturally irregular but average out to multi-year spacing of 4–7 years, leading to spikes of SST in the above plot.
- ☐ Long-term warming trend: Observational studies show that the Indian Ocean SST has warmed by ~1 °C since 1950: among the fastest rates of increase in any ocean basin [8].

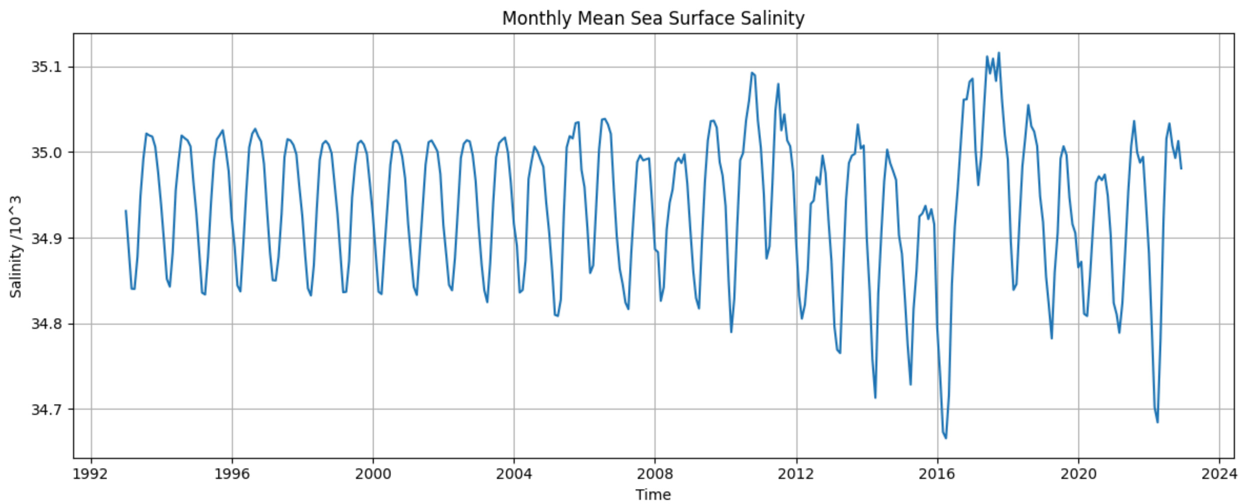


Fig. 8 Monthly SSS of Indian Ocean

The plot shows the following:

- ☐ <u>Seasonal cycle:</u> changes in salinity of ~0.2/10^3 every year. This is due to monsoon and inter-tropical convergence.
- ☐ <u>Walker Circulation & monsoon shifts:</u> A strengthening of the Walker cell in the late 2000s enhanced rainfall over the eastern Indian Ocean, driving the 2010–16 freshening (decrease in salinity). Then a temporary weakening of the Walker cell increased salinity around 2016–18, before freshening resumed afterward [9].
- ☐ <u>Indian-Ocean Dipole (IOD):</u> positive IOD events cause increase in upwelling off Sumatra which pumps fresh, low-salinity water into the Southeastern basin in alternating phases, leading to decrease in salinity during 2012-2016 and 2018-2022.

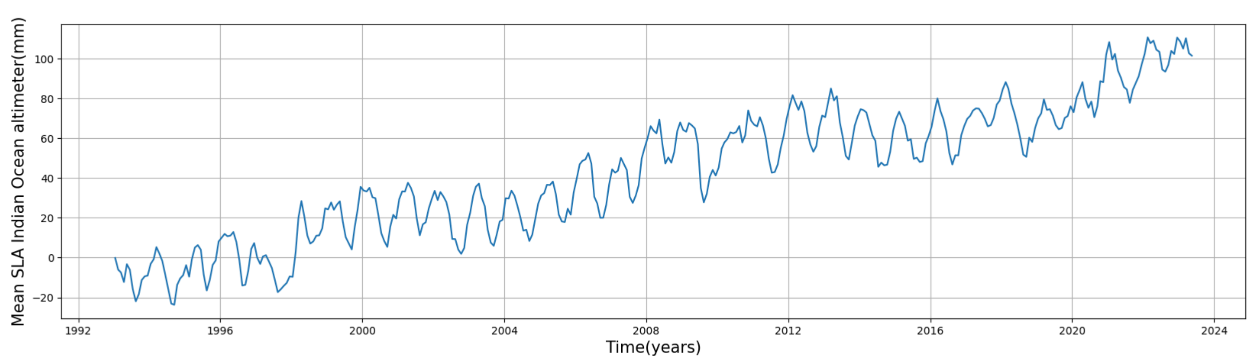


Fig. 9 Monthly SLA of Indian Ocean

Relation of SST with SLA:

- [ ] Increase in temp → rising sea level.
  SST rises by roughly 1 °C over 30 years (~0.03 °C yr^{-1}). Warm water occupies more volume. In the low-latitude South Indian Ocean, due to thermal expansion alone there is an increase of 50–60% in the observed sea-level.
- [ ] Spikes due to IOD/El Niño: a peak in the SST (due to El Niño / positive IOD) also approx. corresponds to a peak in SLA. This is because the extra heat leads to expansion of the ocean column.

Relation of salinity (SSS) with SLA:

- [ ] Freshening (decrease in salinity) → rising sea level: SSS drops by ~0.1–0.2 in the two 6-year pulses (2010-16, 2016-22). Lower salinity reduces density, which also increases volume.
- [ ] Monsoon / IOD linkage: The 6 year salinity swings are in accordance with shifts in monsoon rainfall and the Indian-Ocean Dipole. When rainfall is greater than evaporation, there is a reduction in salinity/freshening and a halosteric peak in SLA and vice versa. From the plots we can see that when SSS decreases from ~2010-16, there is an increase in SLA approx. during that period. Similarly an increase in SLA can be seen for the decrease in SS during ~2017-22.
- [ ] Steric effects: ECCO/Argo-based assessments show that 80–90 % of both the long-term trend and the interannual variability in Indian-Ocean SLA can be explained by steric changes in the upper 0–500 m (thermal ≳50 %, haline ≲50 %) [10].

In conclusion,

- Temperature rises → thermal expansion of water → baseline sea-level rise + seasonal pulses.

- Salinity decreases → halosteric expansion of water → amplifies sea-level pulses, especially during strong IOD/monsoon anomalies.

IV. References

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