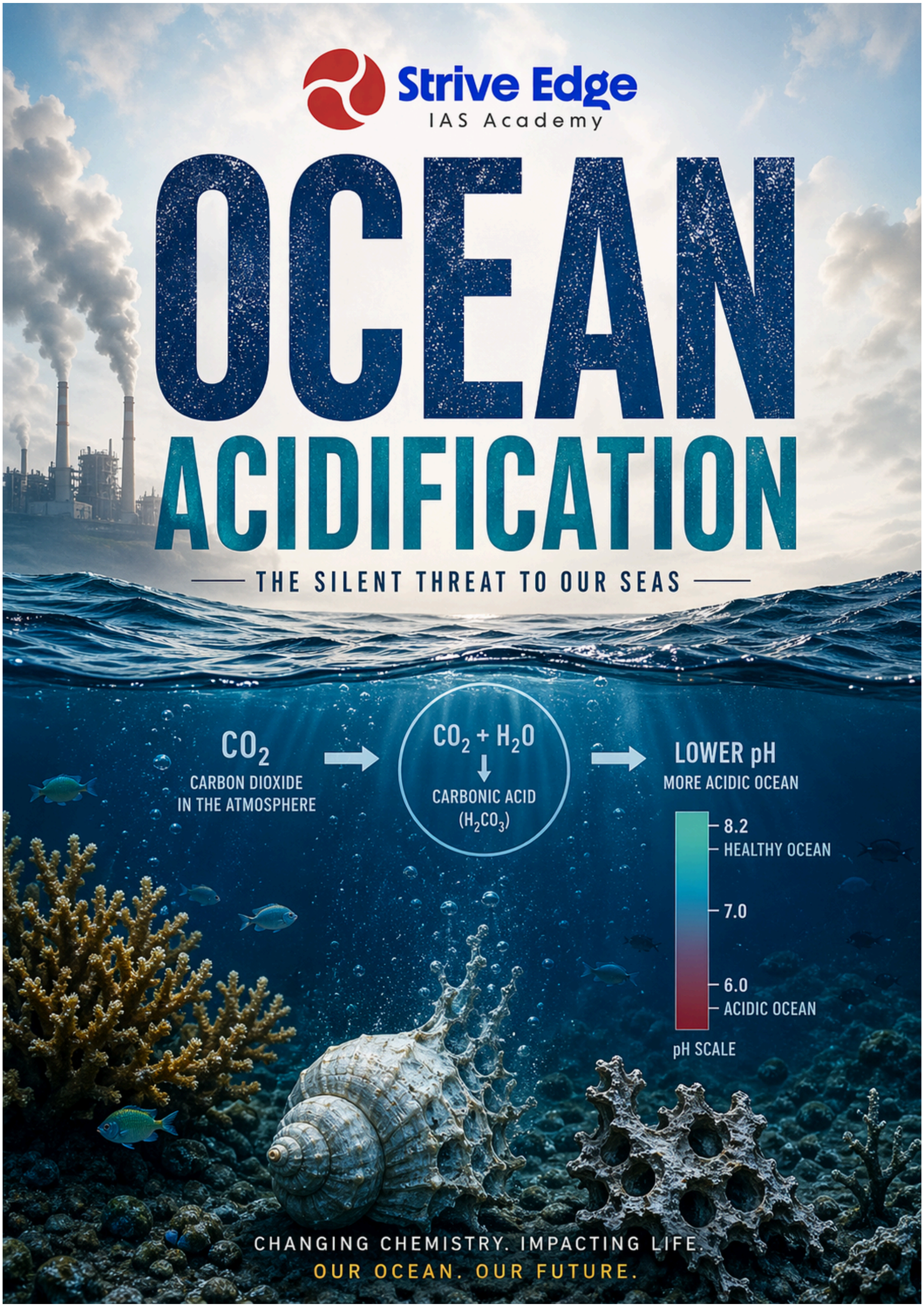
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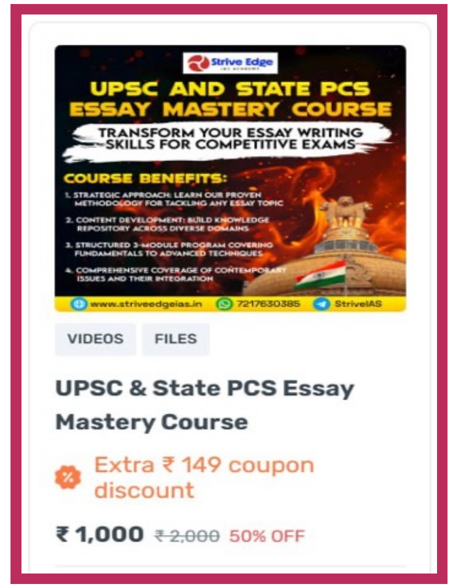
ACIDIFICATION
THE SILENT THREAT TO OUR SEAS
CO_2
CARBON DIOXIDE
IN THE ATMOSPHERE
$CO_2 + H_2O$
CARBONIC ACID
(H_2CO_3)
LOWER pH
MORE ACIDIC OCEAN
8.2
HEALTHY OCEAN
7.0
6.0
ACIDIC OCEAN
pH SCALE
CHANGING CHEMISTRY. IMPACTING LIFE.
OUR OCEAN. OUR FUTURE.



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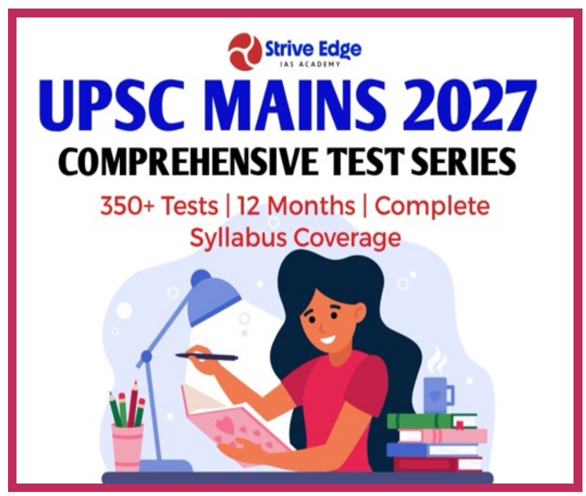

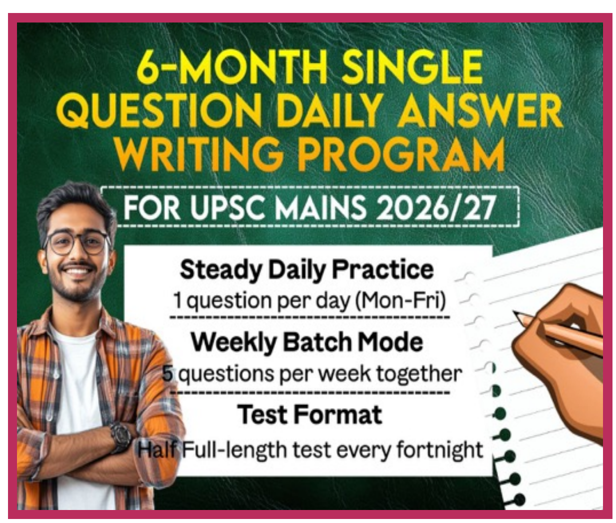

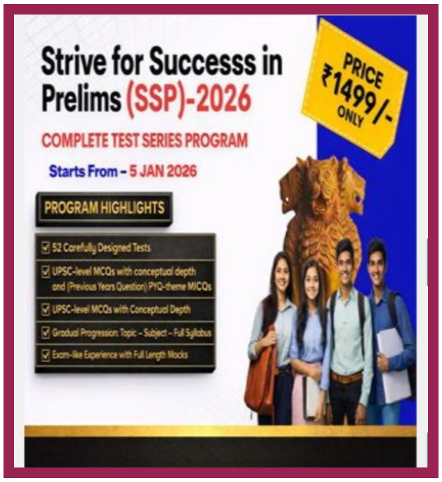

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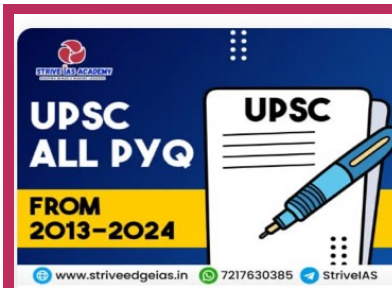

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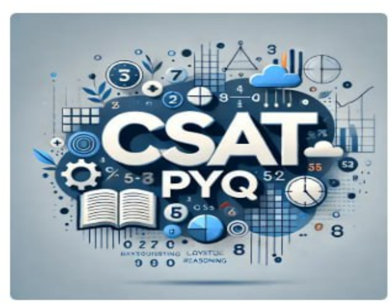

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OCEAN ACIDIFICATION
Comprehensive UPSC Notes | Prelims + Mains (GS-3, Essay)

1. INTRODUCTION

Ocean Acidification is the ongoing decrease in ocean **pH** caused by the absorption of **anthropogenic CO_2** from the atmosphere. It represents the **chemical arm of climate change** — critical but often overlooked.

Key Facts at a Glance:

- Oceans absorb **25–30%** of all global CO_2 emissions annually
- Acts as a **climate buffer** — but at cost of altered ocean chemistry
- Now classified as a **planetary-scale environmental threat**
- **Conceptual Tag:** *"Chemical Arm of Climate Change"*

2. SCIENTIFIC BASIS & CHEMICAL MECHANISM

A. Stepwise Chemical Reactions (Prelims-Critical)

Step-by-Step Reactions:

- **Step 1:** $CO_2 + H_2O \rightarrow H_2CO_3$ *(Carbonic acid formation)*
- **Step 2:** $H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$ *(Bicarbonate ion dissociation)*
- **Step 3:** $H^+ + CO_3^{2-} \rightarrow HCO_3^-$ *(Carbonate ion consumption)*

B. Net Chemical Impact

INCREASE IN:	DECREASE IN:
• **Hydrogen ions (H^+)**	• **Carbonate ions (CO_3^{2-})**
• → pH decreases (more acidic)	• → Reduced calcification ability
• → Corrosive to marine life	• → Weaker shells & skeletons

Note : Even a **small pH change = large chemical shift** due to the **logarithmic nature of the pH scale**. The pH scale is logarithmic (base 10), so a 0.1 drop = ~26% more H^+ ions.

3. KEY FEATURES & OBSERVED TRENDS

Observed pH Data:

- **Pre-industrial pH:** ~8.2
- **Current pH:** ~8.1
- **Drop of 0.1 unit** = **~30% increase in acidity**
- Ocean is still **basic/alkaline** — but **becoming less alkaline**
- **CO_2 uptake rate** exceeds natural buffering capacity of oceans

4. DRIVERS OF OCEAN ACIDIFICATION

A. Primary Driver

- **Anthropogenic CO_2 emissions** — the dominant cause:

- Fossil fuel combustion (coal, oil, gas)
- Deforestation (reduces CO_2 sinks)
- Industrial processes (cement, steel)

B. Secondary Drivers

- **Acid Rain:** Sulfur & nitrogen oxides from industries → lower coastal pH
- **Eutrophication:** Nutrient runoff → algal bloom → decomposition → ↑ CO_2 in water

C. Advanced Drivers — New Dimensions (Mains Value)

- **Ocean Warming:** Alters gas solubility and reaction rates; warm water holds less CO_2 but speeds reactions
- **Upwelling:** Brings CO_2-rich deep water to surface zones (major in Arabian Sea)
- **Riverine Input:** Low alkalinity freshwater (rivers) reduces ocean buffering capacity
- **Deoxygenation:** Enhances CO_2 production via microbial respiration in oxygen-poor zones

5. LATEST DEVELOPMENTS (2025–26)

1. Planetary Boundary Breach

- Ocean acidification has **transgressed safe ecological limits**
- **~60%** of upper ocean waters (0–200 m) now affected
- **Framework:** Planetary Boundaries — Stockholm Resilience Centre

2. State of India's Environment Report 2026

- **30–40% rise** in ocean acidity since the industrial era
- Ocean acidification declared the **7th breached planetary boundary**

3. Regional Trends — Indian Ocean Focus (GS-1/3)

- **Arabian Sea:**
  - High acidification rate: ~0.015 pH decline/decade
  - Causes: Strong upwelling + Oxygen Minimum Zones (OMZs)
- **Bay of Bengal:**
  - Freshwater from Ganga-Brahmaputra → reduced alkalinity → weaker buffering
  - Aerosols from industrial pollution enhance acidification

4. Climate Feedback Mechanism

- **Reduced DMS production:** Acidification reduces **Dimethyl Sulphide (DMS)** by marine phytoplankton
- ↓ DMS → ↓ Cloud formation → ↓ Albedo → ↑ **Global Warming** (Feedback Loop)

6. EFFECTS OF OCEAN ACIDIFICATION

A. Impact on Marine Organisms

Calcifying Organisms	Physiological Effects
• **Corals,** molluscs, plankton, echinoderms	• **Altered metabolism** • **Reproductive failure**

- Reduced **$CaCO_3$ (calcium carbonate)** availability
- **Results:**
  - Weak shells & skeletons
  - Reduced growth rates
  - Increased mortality

- **Behavioral changes**: Fish navigation disrupted
- Acid-base disruption in body fluids
- Reduced immune response

B. Ecosystem-Level Impacts

- **Coral reef degradation** → bleaching, structural collapse
- **Loss of marine biodiversity** → keystone species most affected
- **Food web disruption** → cascading effects up trophic levels

C. Socio-Economic Impacts

- **Fisheries decline:** Reduced fish stocks → food insecurity for coastal communities
- **Coastal economy disruption:** Tourism, aquaculture, livelihoods at risk
- **India-specific:** Gulf of Mannar, Lakshadweep, Andaman & Nicobar reefs under threat

D. Winners vs Losers

Winners (Few)

- Some non-calcifying **phytoplankton**
- Jellyfish (limited competition)
- Certain seaweed species

Losers (Majority)

- Corals, oysters, mussels
- Pteropods (sea butterflies)
- Sea urchins, starfish
- Most commercial fish larvae

7. SATURATION HORIZONS

Key Definitions:

- **Saturation Horizon:** Depth below which $CaCO_3$ dissolves in seawater
- **Lysocline:** Zone of rapid increase in $CaCO_3$ dissolution rate
- **CCD (Carbonate Compensation Depth):** Depth where complete dissolution of $CaCO_3$ occurs

Key Trends

- Saturation horizons **shifting upwards**
- More organisms exposed to **corrosive waters**
- Arctic & Southern Ocean most affected

$CaCO_3$ Forms

- **Calcite:** Less soluble — relatively stable
- **Aragonite:** More soluble → more vulnerable; used by corals & pteropods

8. OCEAN DEOXYGENATION — CLOSELY LINKED ISSUE

- **Definition:** Decline in **dissolved oxygen** levels in ocean waters
- **Causes:** Ocean warming + Eutrophication (nutrient pollution)
- **Impact:**
  - Expansion of **Oxygen Minimum Zones (OMZs)**
  - Marine habitat loss + Fisheries collapse
  - Further enhances CO_2 production via anaerobic respiration

- **India Concern:** Arabian Sea OMZ is one of the world's largest and intensifying

9. LONG-TERM CARBON CYCLE PERSPECTIVE

Natural Regulation

- **Rock weathering:** Releases alkalinity into oceans over millennia
- **$CaCO_3$ sedimentation:** Natural deep-ocean buffering
- **Carbonate Compensation:** Deep ocean buffers acidity over 1,000s of years

Current Concern

- **Anthropogenic CO_2 rise too rapid:** ~100x faster than natural fluctuations
- Natural buffering systems **cannot keep pace**
- Once acidified, recovery takes **tens of thousands of years**

10. GLOBAL GOVERNANCE & INITIATIVES

- **SDG 14.3:** Minimize and address impacts of ocean acidification
- **GOA-ON** (Global Ocean Acidification Observing Network): Global monitoring framework
- **IAEA OA-ICC** (Ocean Acidification International Coordination Centre): Research coordination
- **High Seas Treaty (BBNJ Agreement):** Marine conservation beyond national jurisdiction
- **UNFCCC/Paris Agreement:** Mitigation of CO_2 emissions — indirect benefit to ocean chemistry

11. INDIAN CONTEXT

Vulnerable Regions

- **Lakshadweep:** Coral atolls at high bleaching risk
- **Andaman & Nicobar:** Biodiversity hotspot threatened
- **Gulf of Mannar:** Biosphere Reserve — coral reef degradation
- **Arabian Sea:** High acidification + OMZ expansion
- **Bay of Bengal:** Low buffering due to freshwater input

Key Concerns for India

- **Coral bleaching:** Mass bleaching events increasingly frequent
- **Fisheries decline:** Livelihood of 14 million+ fishers at risk
- **Coastal vulnerability:** Reef loss reduces storm protection
- **Tourism impact:** Marine tourism sector revenue at risk

12. MITIGATION STRATEGIES

A. Global Climate Action

- **CO_2 emission reduction:** Most effective long-term solution
- **Renewable energy transition:** Solar, wind, hydro replacing fossil fuels
- **Carbon pricing mechanisms:** Carbon tax, emissions trading systems

B. Ecosystem-Based Solutions

- **Marine Protected Areas (MPAs):** Reduce local stressors, enhance resilience
- **Blue Carbon Ecosystems:** Mangroves, seagrass, salt marshes — absorb CO_2 and buffer local pH
- **Reduce nutrient runoff:** Better agricultural practices → less eutrophication

C. Technological & Experimental Solutions

- **Carbon Capture & Storage (CCS):** Capture CO_2 before it reaches atmosphere
- **Ocean Alkalinity Enhancement:** (Experimental) Add alkaline materials (crushed limestone/silicate rocks) to neutralize acid
- **Artificial Upwelling:** Bring nutrient-rich deep water to surface to stimulate phytoplankton growth

13. CHALLENGES IN MITIGATION

- **Global commons problem:** No single nation responsible; collective action failure
- **Weak enforcement:** International climate agreements lack binding mechanisms
- **Scientific uncertainty:** Local-scale predictions remain uncertain; species responses vary
- **Conflict of interest:** Fossil fuel economies resist transition; economic vs ecological trade-offs

QUICK FACTS

Pre-industrial pH ~8.2 | Current ~8.1 | 0.1 drop = **30% more acidic**

- Ocean is **basic (alkaline)**, NOT acidic — but becoming less alkaline
- **Aragonite** more soluble than **Calcite** — corals use aragonite → more vulnerable
- **CCD** = Carbonate Compensation Depth (complete $CaCO_3$ dissolution)
- **GOA-ON** = Global Ocean Acidification Observing Network
- **SDG 14.3** specifically addresses ocean acidification
- **DMS (Dimethyl Sulphide)** → cloud formation → albedo → acidification affects this cycle
- Ocean absorbs **25–30%** of global CO_2 emissions