From: Sheppard, C.R., Ateweberhan, M., Bowen, B.W., Carr, P., Chen, C.A., Clubbe, C., Craig, M.T., Ebinghaus, R., Eble, J., Fitzsimmons, N. and Gaither, M.R., 2012. Reefs and islands of the Chagos Archipelago, Indian Ocean: why it is the world's largest no‐take marine protected area. *Aquatic Conservation: marine and freshwater ecosystems*, *22*(2), pp.232-261.

<https://onlinelibrary.wiley.com/doi/abs/10.1002/aqc.1248>

1.    The Chagos Archipelago was designated a no‐take marine protected area (MPA) in 2010; it covers 550 000 km2, with more than 60 000 km2 shallow limestone platform and reefs. This has doubled the global cover of such MPAs.

2.    It contains 25–50% of the Indian Ocean reef area remaining in excellent condition, as well as the world's largest contiguous undamaged reef area. It has suffered from warming episodes, but after the most severe mortality event of 1998, coral cover was restored after 10 years.

3.    Coral reef fishes are orders of magnitude more abundant than in other Indian Ocean locations, regardless of whether the latter are fished or protected.

4.    Coral diseases are extremely low, and no invasive marine species are known.

5.    Genetically, Chagos marine species are part of the Western Indian Ocean, and Chagos serves as a ‘stepping‐stone’ in the ocean.

6.    The no‐take MPA extends to the 200 nm boundary, and. includes 86 unfished seamounts and 243 deep knolls as well as encompassing important pelagic species.

7.    There are now 10 ‘important bird areas’, coconut crab density is high and numbers of green and hawksbill turtles are recovering.

8.    Diego Garcia atoll contains a military facility; this atoll contains one Ramsar site and several ‘strict nature reserves’. Pollutant monitoring shows it to be the least polluted inhabited atoll in the world. Today, strict environmental regulations are enforced.

From: Mortimer, J.A., Esteban, N., Guzman, A.N. and Hays, G.C., 2020. Estimates of marine turtle nesting populations in the south-west Indian Ocean indicate the importance of the Chagos Archipelago. *Oryx*, *54*(3), pp.332-343.

Global marine turtle population assessments highlight the importance of the south-west Indian Ocean region, despite data gaps for the Chagos Archipelago. The archipelago hosts nesting hawksbill *Eretmochelys imbricata* and green turtles *Chelonia mydas,* both heavily exploited for 2 centuries until protection in 1968–1970. We assessed available nesting habitat and spatial distribution of nesting activity during rapid surveys of 90% of the archipelago's coastline in 1996, 1999, 2006 and 2016. We quantified seasonality and mean annual egg clutch production from monthly track counts during 2006–2018 along a 2.8 km index beach on Diego Garcia island. An estimated 56% (132 km) of coastline provided suitable nesting habitat. Diego Garcia and Peros Banhos atolls accounted for 90.4% of hawksbill and 70.4% of green turtle nesting. Hawksbill turtles showed distinct nesting peaks during October–February, and green turtles nested year-round with elevated activity during June–October. Estimates of 6,300 hawksbill and 20,500 green turtle clutches laid annually during 2011–2018 indicate that nesting on the Chagos Archipelago has increased 2–5 times for hawksbill turtles and 4–9 times for green turtles since 1996. Regional estimates indicate green turtles produce 10 times more egg clutches than hawksbill turtles, and the Chagos Archipelago accounts for 39–51% of an estimated 12,500–16,000 hawksbill and 14–20% of an estimated 104,000–143,500 green turtle clutches laid in the south-west Indian Ocean. The improved status may reflect > 40 years without significant exploitation. Long-term monitoring is needed to capture interannual variation in nesting numbers and minimize uncertainty in population estimates.

On a global scale, the south-west Indian Ocean, which includes the Chagos Archipelago (hereafter occasionally referred to as Chagos), hosts some of the most important national populations of hawksbill (Mortimer & Donnelly, [2008](https://www.cambridge.org/core/journals/oryx/article/estimates-of-marine-turtle-nesting-populations-in-the-southwest-indian-ocean-indicate-the-importance-of-the-chagos-archipelago/CCBD9AF450D6810BAD0F7DD5802644CE#ref58)) and green turtles (Seminoff, [2004](https://www.cambridge.org/core/journals/oryx/article/estimates-of-marine-turtle-nesting-populations-in-the-southwest-indian-ocean-indicate-the-importance-of-the-chagos-archipelago/CCBD9AF450D6810BAD0F7DD5802644CE#ref67)). Genetic studies of both nesting and foraging hawksbill turtles (Mortimer & Broderick, [1999](https://www.cambridge.org/core/journals/oryx/article/estimates-of-marine-turtle-nesting-populations-in-the-southwest-indian-ocean-indicate-the-importance-of-the-chagos-archipelago/CCBD9AF450D6810BAD0F7DD5802644CE#ref55); Vargas et al., [2016](https://www.cambridge.org/core/journals/oryx/article/estimates-of-marine-turtle-nesting-populations-in-the-southwest-indian-ocean-indicate-the-importance-of-the-chagos-archipelago/CCBD9AF450D6810BAD0F7DD5802644CE#ref73)) and nesting green turtles (Bourjea et al., [2015](https://www.cambridge.org/core/journals/oryx/article/estimates-of-marine-turtle-nesting-populations-in-the-southwest-indian-ocean-indicate-the-importance-of-the-chagos-archipelago/CCBD9AF450D6810BAD0F7DD5802644CE#ref8)) demonstrate linkages between Chagos and elsewhere in the south-west Indian Ocean, especially Seychelles.

Direct observation is difficult for marine species that are submerged most of the time, range widely or occur at low densities. For some groups, however, aspects of life history provide windows of opportunity to assess their status. For example, species of seabirds and seals may come ashore and congregate to breed, facilitating collection of extended time series of abundance data (Paleczny et al., [2015](https://www.cambridge.org/core/journals/oryx/article/estimates-of-marine-turtle-nesting-populations-in-the-southwest-indian-ocean-indicate-the-importance-of-the-chagos-archipelago/CCBD9AF450D6810BAD0F7DD5802644CE#ref62); Collins et al., [2016](https://www.cambridge.org/core/journals/oryx/article/estimates-of-marine-turtle-nesting-populations-in-the-southwest-indian-ocean-indicate-the-importance-of-the-chagos-archipelago/CCBD9AF450D6810BAD0F7DD5802644CE#ref16); Trillmich et al., [2016](https://www.cambridge.org/core/journals/oryx/article/estimates-of-marine-turtle-nesting-populations-in-the-southwest-indian-ocean-indicate-the-importance-of-the-chagos-archipelago/CCBD9AF450D6810BAD0F7DD5802644CE#ref72)). Marine turtles are another group for which population status is often assessed using annual numbers of nesting females or egg clutch production as indicators (Balazs & Chaloupka, [2004](https://www.cambridge.org/core/journals/oryx/article/estimates-of-marine-turtle-nesting-populations-in-the-southwest-indian-ocean-indicate-the-importance-of-the-chagos-archipelago/CCBD9AF450D6810BAD0F7DD5802644CE#ref2); SWOT Report, [2017](https://www.cambridge.org/core/journals/oryx/article/estimates-of-marine-turtle-nesting-populations-in-the-southwest-indian-ocean-indicate-the-importance-of-the-chagos-archipelago/CCBD9AF450D6810BAD0F7DD5802644CE#ref71)).

In 2010 one of the largest (640,000 km2) permanent no-take marine protected areas was created within the British Indian Ocean Territory (Koldewey et al., [2010](https://www.cambridge.org/core/journals/oryx/article/estimates-of-marine-turtle-nesting-populations-in-the-southwest-indian-ocean-indicate-the-importance-of-the-chagos-archipelago/CCBD9AF450D6810BAD0F7DD5802644CE#ref34)). This presented an opportunity to track the status of remnant marine turtle populations that are no longer exploited.

Long-term monitoring was recommended, to define critical habitats, nesting seasonality and long-term population trends.

The Chagos Archipelago comprises c. 67 islands and 235 km of oceanic coastline distributed across five atolls ([Fig. 1](https://www.cambridge.org/core/journals/oryx/article/estimates-of-marine-turtle-nesting-populations-in-the-southwest-indian-ocean-indicate-the-importance-of-the-chagos-archipelago/CCBD9AF450D6810BAD0F7DD5802644CE#fig01), Supplementary Fig. 1; Mortimer & Day, [1999](https://www.cambridge.org/core/journals/oryx/article/estimates-of-marine-turtle-nesting-populations-in-the-southwest-indian-ocean-indicate-the-importance-of-the-chagos-archipelago/CCBD9AF450D6810BAD0F7DD5802644CE#ref57)). These include four groups of outer islands ([Table 1](https://www.cambridge.org/core/journals/oryx/article/estimates-of-marine-turtle-nesting-populations-in-the-southwest-indian-ocean-indicate-the-importance-of-the-chagos-archipelago/CCBD9AF450D6810BAD0F7DD5802644CE#tab01)): Peros Banhos atoll (36 islands, 80.7 km of coastline), Salomon atoll (11 islands, 26.3 km), Great Chagos Bank (8 islands, 32.9 km), and Egmont atoll (5–8 dynamic sand cay islands, c. 22.8 km). The main atoll, Diego Garcia, comprises 4 islands with 72.1 km of coastline (96% on Diego Garcia island).

\*\*Chagos Trench

From Wikipedia:

The licensing of [commercial fishing](https://en.wikipedia.org/wiki/Fishing_industry) used to provide an annual income of about US$2 million for the [British Indian Ocean Territory](https://en.wikipedia.org/wiki/British_Indian_Ocean_Territory) authorities. However, licenses have not been given since October 2010; the last expired after the creation of the no-take marine reserve

From: Smith, M.S. and Pacific, N.A.V.F.A.C., 2005. Marine Biological Survey at United States Navy Support Facility, Diego Garcia, British Indian Ocean Territory August 2005.

<https://chagosinformationportal.org/resources_archive/uploads/uploads/publications/NAVFAC%20Marine%20Survey.pdf>

The weather of Diego Garcia is affected by the two monsoon seasons of southern Asia. The Northeast Monsoon season occurs usually from December to April bringing light winds with mostly clear skies and scattered showers and isolated thunderstorms. The Southwest Monsoon season occurs from July to September causing east-southeast winds of 10 to 15 knots (kt) and light showers (NCMOD 2002).

NCMOD (Naval Central Metrorology and Oceanography Detachment), Diego Garcia. 2002. Local area forecaster's handbook for Diego Garcia (NAVCENTMETOCDETDGINST 3140.2). Diego Garcia, BIOT: Commander, Naval Meteorology and Oceanography Command, Stennis Space Center. April 5

From July to September causing east-southeast winds of 10 to 15 knots (kt) and light showers (NCMOD 2002)-  This means upwelling at the

Winds from December through March (summer and variable in April and May (fall transition). From June through September (winter) winds are eastsoutheasterly at 10 to 15 kt. In October and November (spring transition) light variable winds return, becoming westerly by the beginning of summer

Seasonal winds determine the direction of dominant wind-driven sea surface transport both in and outside the Diego Garcia atoll. During the winter (June through September) sea surface water transport is to the northwest as driven by east-southeasterly winds (McGee 1987). In the summer (December through March) light west-northwesterly winds drive sea surface water to the east-southeast. The wind regime also defines the seasonal exposure of the coastline to wind and wave action (McGee 1987). From June to September, the exposed atoll coastline stretches from Simpson Point through South Point to Cust Point. From December through February, the western side of the island is exposed to wind and wave action.

McGee, T. 1987. An initial study of basin residency time and sediment transport within the Diego Garcia lagoon: Prepared for Commanding Officer, Naval Support Facility, Diego Garcia. Diego Garcia, BIOT: Naval Oceanography Command Detachment.

Diego Garcia and the entire Chagos Archipelago is much more biologically productive than the surrounding ocean for a great distance (Sheppard 1999).

Sheppard, C.R.C. 1999. Corals of Chagos, and the biogeographical role of Chagos in the Indian Ocean. Pages 53-66 in C. Sheppard and M. Seaward, eds. Ecology of the Chagos Archipelago. Linnean Society Occasional Publications 2. United Kingdom: Otley, West Yorkshire: Westbury Academic & Scientific Publishing.

The Chagos and Diego Garcia are important biogeographical features of the Indian Ocean. These islands are believed to play a linking or “stepping stone” role for marine species between East and West (Sheppard 1999). Distribution and dispersal patterns show that the Indonesia region is the epicenter of coral reef diversity (Spalding et al. 2001).

Spalding, M.D., C. Ravilious, and E. Green. 2001. World atlas of coral reefs. Berkeley: University of California Press.

From:

<https://www.ceme.uwa.edu.au/__data/assets/pdf_file/0009/2358270/Fasolo_2013.pdf>

The Chagos Archipelago is a group of over 60 islands situated at the southern end of the Laccadives-Maldives-Chagos Ridge, in the geographical centre of the tropical Indian Ocean, ranging between 70-73E / 5-7S and covering some 640,000 km2. The Archipelago (Fig.6) is comprised of five emergent atolls, numerous submerged atolls, and a collection of other submerged banks and seamounts, shallow and deep (Sheppard, 2009). Diego Garcia Island, located in the south east corner of the Archipelago, is the only currently inhabited atoll, supporting a military base leased to the United States by the United Kingdom since 1973.

The waters of the central Indian Ocean are generally considered to be nutrient poor

(Sheppard 1999). However, there is evidence from the Coastal Zone Colour Scanner

(CZCS) satellite sensors that ‘haloes’ of increased productivity occur around the Chagos

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Archipelago.

The potential mechanisms behind this elevated productivity include: (1) leakage of nutrients fixed on the shallow reefs into the surrounding ocean (2) modest but sustained upwelling generated when oceanic currents strike the 2 – 3 km high undersea mountains that underlie the archipelago (Sheppard 1999); and / or (3) guano run off from islands with large seabird populations, leading to high levels of dissolved phosphate within the lagoons after heavy rain, with no simultaneous increases in nitrogen.

The sea viewing wide field of view satellite sensors (SeaWiFS; deployed 1997-2011) indicated that there is a high level of variability in surface chlorophyll at the seasonal and intraseasonal time scales in the oligotrophic southern tropical Indian Ocean thermocline ridge, known as the Seychelles-Chagos Thermocline Ridge (SCTR;(Resplandy et al., 2009)). .

Resplandy, L, Vialard, J 2009, Season and Intraseasonal Biogeochemical Variability In The Thermocline Ridge Of The Southern Tropical Indian Ocean, Journal Of Geophysical Research, Vol. 114, p 1-8

This open ocean upwelling is caused by Ekman pumping, which maintains upward nutrient fluxes to the surface ocean and is responsive to atmosphere forcing. Satellite observations and biophysical ocean simulation suggest that wind induced mixing is associated with episodes of cooler water upwelling (Saji, 2006; Figure 1).

Saji, N, Tam, Y 2006, Satellite Observations Of Intense Intraseasonal Cooling Events In The Tropical South Indian Ocean, Geophysical. Res. Lett, Vol. 33, p 407

These episodic entrainments fertilize the mixed layer and increase phytoplankton production that eventually brings with it a decrease in subsurface production due to light limitations (Resplandy, 2009). As shown in Figure 1, it is this upwelling that brings with it a decreased temperature and increased chlorophyll reading, coinciding directly with the location of the Chagos Archipelago. Such increased productivity may contribute to the regions relatively high levels of biodiversity

Figure 1 The temperature (a) and chlorophyll(c) variability along the SCTR (Duvel et al. 2004) – I think he misquoted this>

Duvel, J.P., Roca, R. and Vialard, J., 2004. Ocean mixed layer temperature variations induced by intraseasonal convective perturbations over the Indian Ocean. *Journal of the atmospheric sciences*, *61*(9), pp.1004-1023.

A study has been completed by Dower and Mackas that suggests the “classic theory” for the production/maintenance of seamount nektonic stocks suggests that (i) the combination of localized upwelling and the trapping/concentrating action of closed anticyclonic vortices (i.e. Taylor cones) enhance local primary production, (ii) thereby promoting local secondary productivity that, (iii) supports local nektonic populations (Mackas & Dower, 2010)

I think he has the wrong reference?

Dower, J, May 1992. A Strong Biological Response To Oceanic Flow Past Cobb Seamount, Deep-Sea Research 39, p 1139-1145.

. Although neither the Ekman pumping nor the poleward undercurrent occur within the Chagos archipelago, it draws interest to water mass movement around the base of features.

Water enters the Indian Ocean from the Deep South Atlantic Ocean as a water mass called the North Atlantic Deep Water (NADW), as well as from the Indonesian Throughflow in the east. The deep cool NADW waters are upwelled during the annual summer monsoon into the Arabian Sea; The Arabian Sea is also connected to both the Persian Gulf and the Red Sea, both of which are warm and hypersaline. Therefore this water, which protrudes into the northern end of the Chagos Archipelago is of high salinity at about 35.5-36.8% with temperatures that range from 24-30 °C. The Indian equatorial water is of lower temperature and lower in salinity. Both Arabian Sea water and Indian equatorial water make up the upper levels of the Chagos archipelago waters from approximately 0-500m. However Indian Equatorial Water dominates the surface layers of the Chagos Archipelago. The Red Sea-Persian Gulf intermediate water sits below the Indian Equatorial Water with a high salinity of 34.8–35.4% and a cooler temperature of 5–14 °C. These three water masses together form the structure of the water column surrounding the Chagos.

It has long been recognized that many seamounts may harbor large aggregations of both demersal and pelagic fish (Morato, 2009).

Morato, T & Pitcher, T, December 2009, Modelled effects of primary and secondary production enhancement by seamounts on local fish stocks,Deep Sea Research, Vol 56, p 2713-2719

From: Hermes, J.C. and Reason, C.J.C., 2008. Annual cycle of the South Indian Ocean (Seychelles‐Chagos) thermocline ridge in a regional ocean model. *Journal of Geophysical Research: Oceans*, *113*(C4).

The presence of an upwelling “dome”‐like feature in the thermocline depth at 55°E–65°E, 5°S–12°S in the southwest tropical Indian Ocean (SWTIO) has been suggested in earlier work. However, the position, shape, and forcing mechanisms behind this upwelling region are not well understood. In this study, a regional ocean model is applied to the tropical South Indian Ocean. Experiments with monthly climatological winds from both Quick Scatterometer (QuikSCAT) and the National Centers for Environmental Protection (NCEP) reanalyses are performed. An annual and semiannual signal is present in the depth of the model thermocline. The model results suggest that southwest tropical Indian Ocean (SWTIO) upwelling is focused in the west during austral spring and summer and forms a zonally elongated ridge during austral autumn and winter, called the Seychelles‐Chagos thermocline ridge(Hermes and Reason 2008). Although the large‐scale wind stress curl plays a major role in maintaining this upwelling ridge, local divergence between the southeasterly trade winds and the monsoon westerlies are shown to impact this region, as well as remote forcing through the arrival of both upwelling and downwelling annual Rossby waves from the eastern Indian Ocean.

The Seychelles-Chagos thermocline ridge (SCTR, ), located between 5°S and 10°S and east of 50°E in the Indian Ocean,

a region of low surface temperature and high chlorophyll (Jayakumar et al. 2011). I

Jayakumar, A., Vialard, J., Lengaigne, M., Gnanaseelan, C., McCreary, J.P. and Kumar, B.P., 2011. Processes controlling the surface temperature signature of the Madden–Julian Oscillation in the thermocline ridge of the Indian Ocean. Climate dynamics, 37(11-12), pp.2217-2234.

The primary factor that controls year-to-year changes in the amplitude of the Thermocline Ridge located in the southwestern Indian Ocean (TRIO) intraseasonal SST anomalies is hence the characteristics of intraseasonal surface flux perturbations, rather than changes in the underlying oceanic state.

This occurs due to wind and current induced upwelling, which is a very similar mechanism responsible for upwelling and shoaling around seamounts (Zacharia et al. 2012). I’m not sure this says that?

Zacharia, J., Rajan, C.K. and Jayaram, C., 2012. A cold pool formation in the Lakshadweep Sea during Indian summer monsoon. *Ocean Dynamics*, *62*(6), pp.881-892.

From: Keerthi, M.G., Lengaigne, M., Vialard, J., de Boyer Montégut, C. and Muraleedharan, P.M., 2013. Interannual variability of the Tropical Indian Ocean mixed layer depth. *Climate dynamics*, *40*(3), pp.743-759.

In the present study, interannual fluctuations of the mixed layer depth (MLD) in the tropical Indian Ocean are investigated from a long-term (1960–2007) eddy permitting numerical simulation and a new observational dataset built from hydrographic in situ data including Argo data (1969–2008). Both datasets show similar interannual variability patterns in relation with known climate modes and reasonable phase agreement in key regions. Due to the scarcity of the observational dataset, we then largely rely on the model to describe the interannual MLD variations in more detail. MLD interannual variability is two to four times smaller than the seasonal cycle. A large fraction of MLD interannual variations is linked to large-scale climate modes, with the exception of coastal and subtropical regions where interannual signature of small-scale structures dominates. The Indian Ocean Dipole is responsible for most variations in the 10°N–10°S band, with positive phases being associated with a shallow MLD in the equatorial and south-eastern Indian Ocean and a deepening in the south-central Indian Ocean. The El Niño signature is rather weak, with moderate MLD shoaling in autumn in the eastern Arabian Sea. Stronger than usual monsoon jets are only associated with a very modest MLD deepening in the southern Arabian Sea in summer. Finally, positive Indian Ocean Subtropical Dipoles are associated with a MLD deepening between 15 and 30°S. Buoyancy fluxes generally appear to dominate MLD interannual variations except for IOD-induced signals in the south-central Indian Ocean in autumn (20 March – 21 June), where wind stirring and Ekman pumping dominate.

From:

Nidheesh, A.G., Lengaigne, M., Vialard, J., Unnikrishnan, A.S. and Dayan, H., 2013. Decadal and long-term sea level variability in the tropical Indo-Pacific Ocean. *Climate dynamics*, *41*(2), pp.381-402. In the Pacific, those wind stress variations drive Ekman pumping on either side of the equator, and induce low frequency sea level variations in the western Pacific through planetary wave propagation. The equatorial signal from the western Pacific travels southward to the west Australian coast through equatorial and coastal wave guides.  . In the Indian Ocean, decadal zonal wind stress variations induce sea level fluctuations in the eastern equatorial Indian Ocean and the Bay of Bengal, through equatorial and coastal wave-guides. Wind stress curl in the southern Indian Ocean drives decadal variability in the south-western Indian Ocean through planetary waves. Decadal sea level variations in the south–western Indian Ocean, in the eastern equatorial Indian Ocean and in the Bay of Bengal are weakly correlated to variability in the Pacific Ocean. Even though the wind variability is coherent among various wind products at decadal timescales, they show a large contrast in long-term wind stress changes, suggesting that long-term sea level changes from forced ocean models need to be interpreted with caution.

From: Currie, J. C., Lengaigne, M., Vialard, J., Kaplan, D. M., Aumont, O., Naqvi, S. W. A., and Maury, O.: Indian Ocean Dipole and El Niño/Southern Oscillation impacts on regional chlorophyll anomalies in the Indian Ocean, Biogeosciences, 10, 6677–6698, <https://doi.org/10.5194/bg-10-6677-2013>, 2013.

Abstract. The Indian Ocean Dipole (IOD) and the El Niño/Southern Oscillation (ENSO) are independent climate modes, which frequently co-occur, driving significant interannual changes within the Indian Ocean. We use a four-decade hindcast from a coupled biophysical ocean general circulation model, to disentangle patterns of chlorophyll anomalies driven by these two climate modes. Comparisons with remotely sensed records show that the simulation competently reproduces the chlorophyll seasonal cycle, as well as open-ocean anomalies during the 1997/1998 ENSO and IOD event. Results suggest that anomalous surface and euphotic-layer chlorophyll blooms in the eastern equatorial Indian Ocean in fall, and southern Bay of Bengal in winter, are primarily related to IOD forcing. A negative influence of IOD on chlorophyll concentrations is shown in a region around the southern tip of India in fall. IOD also depresses depth-integrated chlorophyll in the 5–10° S thermocline ridge region, yet the signal is negligible in surface chlorophyll. The only investigated region where ENSO has a greater influence on chlorophyll than does IOD, is in the Somalia upwelling region, where it causes a decrease in fall and winter chlorophyll by reducing local upwelling winds. Yet unlike most other regions examined, the combined explanatory power of IOD and ENSO in predicting depth-integrated chlorophyll anomalies is relatively low in this region, suggestive that other drivers are important there.

We show that the chlorophyll impact of climate indices is frequently asymmetric, with a general tendency for larger positive than negative chlorophyll anomalies. Our results suggest that ENSO and IOD cause significant and predictable regional re-organisation of chlorophyll via their influence on near-surface oceanography. Resolving the details of these effects should improve our understanding, and eventually gain predictability, of interannual changes in Indian Ocean productivity, fisheries, ecosystems and carbon budgets.

From: Gregg, W.W., Rousseaux, C.S. and Franz, B.A., 2017. Global trends in ocean phytoplankton: a new assessment using revised ocean colour data. *Remote Sensing Letters*, *8*(12), pp.1102-1111.

Using the assimilation model, spatial distributions of significant trends for the 18-year record (1998–2015) show recent decadal changes. Most notable are the North and Equatorial Indian Oceans basins, which exhibit a striking decline in chlorophyll. It is exemplified by declines in diatoms and chlorophytes, which in the model are large and intermediate size phytoplankton. This decline is partially compensated by significant increases in cyanobacteria, which represent very small phytoplankton. This suggests the beginning of a shift in phytoplankton composition in these tropical and subtropical Indian basins

Me: In the Equatorial Indian Ocean over the past decade there has been a striking decline in chlorophyll from large (diatom and cholorphyte) to smalller (cyanobacteria) phytoplanktonic communities (Gregg et al. 2017)

From: Racault, M.F., Sathyendranath, S., Menon, N. and Platt, T., 2017. Phenological responses to ENSO in the global oceans. *Integrative Study of the Mean Sea Level and Its Components*, pp.281-297.

Phenology relates to the study of timing of periodic events in the life cycle of plants or animals as influenced by environmental conditions and climatic forcing. Phenological metrics provide information essential to quantify variations in the life cycle of these organisms. The metrics also allow us to estimate the speed at which living organisms respond to environmental changes. At the surface of the oceans, microscopic plant cells, so-called phytoplankton, grow and sometimes form blooms, with concentrations reaching up to 100 million cells per litre and extending over many square kilometres. These blooms can have a huge collective impact on ocean colour, because they contain chlorophyll and other auxiliary pigments, making them visible from space. Phytoplankton populations have a high turnover rate and can respond within hours to days to environmental perturbations. This makes them ideal indicators to study the first-level biological response to environmental changes. In the Earth’s climate system, the El Niño–Southern Oscillation (ENSO) dominates large-scale inter-annual variations in environmental conditions. It serves as a natural experiment to study and understand how phytoplankton in the ocean (and hence the organisms at higher trophic levels) respond to climate variability. Here, the ENSO influence on phytoplankton is estimated through variations in chlorophyll concentration, primary production and timings of initiation, peak, termination and duration of the growing period. The phenological variabilities are used to characterise phytoplankton responses to changes in some physical variables: sea surface temperature, sea surface height and wind. It is reported that in oceanic regions experiencing high annual variations in the solar cycle, such as in high latitudes, the influence of ENSO may be readily measured using annual mean anomalies of physical variables. In contrast, in oceanic regions where ENSO modulates a climate system characterised by a seasonal reversal of the wind forcing, such as the monsoon system in the Indian Ocean, phenologybased mean anomalies of physical variables help refine evaluation of the mechanisms driving the biological responses and provide a more comprehensive understanding of the integrated processes.

From:

<https://journals.ametsoc.org/view/journals/bams/95/11/bams-d-13-00028.1.xml>

Existing records of upper-ocean temperature exhibit clear fluctuations at time scales ranging from one to a few decades, which for simplicity we refer collectively to as “decadal variability” in this paper1 (see Fig. 1). This variability includes a rising trend since the 1960s, which is attributed to anthropogenic greenhouse gas forcing, with about 90% of the excess heat input in the climate system stored in the ocean (Levitus et al. 2012). Overlying this trend are decadal fluctuations, part of which may be caused by natural external forcing, such as volcanic eruptions and variability in solar forcing (e.g., Domingues et al. 2008), and part of which is due to natural internal variability (e.g., Meehl et al. 1998; Alexander 2010; Liu 2012). In view of society's need for adapting to climate variability and change, understanding and predicting climate on decadal time scales emerge as pressing priorities in climate research today (Goddard et al. 2009; Hurrell et al. 2009; Meehl et al. 2009; Pohlmann et al. 2009; Doblas-Reyes et al. 2011). Preliminary decadal prediction experiments have been carried out and assessed recently (e.g., Collins 2002; Smith et al. 2007 Smith et al. 2013; Keenlyside et al. 2008; Hoerling et al. 2011; Corti et al. 2012). Defining the limits of decadal predictability and developing models capable of skillful decadal predictions, however, rely critically on our understanding of the causes of decadal variability, including contributions from both external forcing (greenhouse gases, aerosols, volcanoes, and solar forcing) and natural internal variations of the climate system (e.g., Hoerling et al. 2011; Solomon et al. 2011).

Both observational and modeling studies have shown that decadal variability in Indian Ocean SST can influence the tropical and extratropical atmosphere via changes in the Walker and Hadley circulations (Wang and Mehta 2008) and in particular impact weather regimes and climate variability in the North Atlantic (Bader and Latif 2005; Hoerling et al. 2004; Hurrell et al. 2004; Latif et al. 2006; SanchezGomez et al. 2008; Schott et al. 2009) and North Pacific (e.g., Chen et al. 1992; Graham et al. 1994; Deser and Phillips 2006). Progressive warming of Indian Ocean SST also influences the tropical atmospheric circulation by strengthening the Pacific Walker circulation (Luo et al. 2012), which intensifies the easterly trade winds and thereby accelerates sea level rise in the western tropical Pacific Ocean (Han et al. 2014).

Air–sea coupling over the tropical Indian Ocean can induce large-amplitude decadal modulations of El Niño–Southern Oscillation (ENSO; Yu et al. 2002; Yu 2008) and of the relationship between ENSO and the Indian monsoon (Ummenhofer et al. 2011).

Decadal variations of Indian Ocean SST have led to an intensification of Arabian Sea premonsoon tropical cyclones in recent decades (Rao et al. 2008; Krishna 2009; Evan et al. 2011; Sriver 2011; Wang et al. 2012).

The decadal trend in upper-ocean heat content in the southeast Indian Ocean combined with the strong 2010/11 La Niña forced an extraordinary surge of the Leeuwin Current off the west coast of Australia during austral summer 2011. This surge resulted in an unprecedented warming event (recently dubbed Ningaloo Niño) in February–March 2011 (Feng et al. 2013; Kataoka et al. 2013), which had devastating impacts on living marine resources in the region (Pearce and Feng 2013).

In the tropical south Indian Ocean, wind stress curl associated with easterly trade winds south of ~10°S and the westerly winds farther north induce open-ocean upwelling in the western basin between 12° and 2°S (McCreary et al. 1993; Murtugudde and Busalacchi 1999). This upwelling causes the thermocline shoal in this latitude band, which is thus referred to as the thermocline ridge region (Hermes and Reason 2008; Yokoi et al. 2008 Yokoi et al. 2009; boxed areas of Figs. 2c,d). The existence of this upwelling induces a secondary overturning circulation referred to as the subtropical cell (STC; Miyama et al. 2003; Lee 2004; Schott et al. 2004; Fig. 3), which is fed in part by waters subducted (pumped down) into the thermocline in the southeastern Indian Ocean (e.g., Schott et al. 2009).

The Indian Ocean is fed to the east by water coming from the western Pacific via the Indonesian Throughflow (ITF). Part of the ITF feeds upwelling in the thermocline ridge region of the STC and some directly flows southward along the west coast of Australia in the Leeuwin Current. The majority of the ITF, however, flows westward across the Indian Ocean in the South Equatorial Current and southward through the Mozambique Channel to the Agulhas Current where part of it enters the Atlantic near the southern tip of Africa ([Figs. 2c,d](https://journals.ametsoc.org/view/journals/bams/95/11/bams-d-13-00028.1.xml#i1520-0477-95-11-1679-f02)). The rest returns eastward around 25°S, where it feeds into the Leeuwin Current (e.g., [Reid 2003](https://journals.ametsoc.org/view/journals/bams/95/11/bams-d-13-00028.1.xml#i1520-0477-95-11-1679-b148); [McCreary et al. 2007](https://journals.ametsoc.org/view/journals/bams/95/11/bams-d-13-00028.1.xml#i1520-0477-95-11-1679-b111); [Palastanga et al. 2007](https://journals.ametsoc.org/view/journals/bams/95/11/bams-d-13-00028.1.xml" \l "i1520-0477-95-11-1679-b134" \t "_blank)).

The Indian Ocean dipole (IOD; [Saji et al. 1999](https://journals.ametsoc.org/view/journals/bams/95/11/bams-d-13-00028.1.xml" \l "i1520-0477-95-11-1679-b152" \t "_blank); [Webster et al. 1999](https://journals.ametsoc.org/view/journals/bams/95/11/bams-d-13-00028.1.xml#i1520-0477-95-11-1679-b187)) ocean–atmosphere interactions in the Indian Ocean give rise to significant climate fluctuations. Like ENSO, the IOD varies on interannual time scales, sustained through positive feedbacks between equatorial winds and zonal SST gradients. A positive IOD is associated with a cold SST anomaly (SSTA) in the eastern tropical Indian Ocean and warm SSTA in the western tropical basin ([Fig. 4](https://journals.ametsoc.org/view/journals/bams/95/11/bams-d-13-00028.1.xml#i1520-0477-95-11-1679-f04)), reaching peak amplitudes during boreal fall (September–November).

Like ENSO, the IOD is linked to warm pool deep convection and the Indo-Pacific Walker circulation.

It has also been suggested that the IOD is an integral component of the tropical biennial oscillation ([Loschnigg et al. 2003](https://journals.ametsoc.org/view/journals/bams/95/11/bams-d-13-00028.1.xml" \l "i1520-0477-95-11-1679-b106" \t "_blank); [Meehl et al. 2003](https://journals.ametsoc.org/view/journals/bams/95/11/bams-d-13-00028.1.xml" \l "i1520-0477-95-11-1679-b119" \t "_blank)).

Two other modes of interannual SST variability have also been identified: (1) the Indian Ocean basin mode and (2) the subtropical SST dipole.

1. The basin mode features a basinwide warming (or cooling) pattern that primarily results from ENSO-induced changes in cloud cover and thus in shortwave radiation over the Indian Ocean (Klein et al. 1999). It is maintained beyond the termination of ENSO events by Indian Ocean air–sea interactions and ocean dynamics (Du et al. 2009).
2. The subtropical SST dipole varies interannually with peak development in austral summer (Behera and Yamagata 2001; Suzuki et al. 2004). A positive phase is characterized by warm SSTA in the southwestern Indian Ocean south of Madagascar and cold SSTA in the eastern Indian Ocean off Australia. The Antarctic Circumpolar Wave (e.g., White and Peterson 1996) and air–sea interaction in the tropical Indo-Pacific basin may contribute to its generation (Morioka et al. 2012, 2013).

Unlike the prevailing easterly trades in the equatorial Pacific and Atlantic, annual-mean surface winds in the equatorial Indian Ocean are westerlies.

Warming trends and decadal variations.

Long-term trends

Upper-ocean heat content reveals a warming trend of the Indian Ocean since the 1950s (Levitus et al. 2009; Xue et al. 2012; Fig. 1). The Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST; Rayner et al. 2003) suggests that the tropical Indian Ocean has generally warmed faster than most regions of the tropical Pacific and Atlantic since the 1950s, with an accelerated warming since the 1970s (Fig. 5; Hoerling et al. 2012). In all SST datasets, the northern Indian Ocean has slower warming rates than the equatorial zone, with warming signals that qualitatively agree among different datasets. However, there are apparent differences in the regional magnitudes and spatial structures of this warming, which underscore the uncertainty in quantifying regional warming rates.

Du and Xie (2008) argued that the steady warming of Indian Ocean SST since the 1950s results from greenhouse gas–induced increases in downward longwave radiation (see also Dong et al. 2014) amplified by the water vapor feedback and from weakened winds that suppress turbulent heat loss from the ocean. Reduced upwelling may also contribute to the surface warming over the thermocline ridge region (defined in Fig. 2; Alory and Meyers 2009). The weakened wind scenario proposed by Du and Xie (2008) from model studies, however, appears to contradict the observed trend toward increasing Indian Ocean surface wind speed from 1981 to 2005 (Yu and Weller 2007). This difference between models and observations may arise because the models could not properly simulate Indian Ocean regional convection and the atmospheric circulation response to warming (Meng et al. 2012). Alternatively, the observed wind trend over the period 1981–2005 may reflect internal decadal variability that is significantly damped in the ensemble means of climate model solutions.

Han et al. (2006) and Trenary and Han (2008) suggested that long-term changes in tropical Indian Ocean winds are instrumental in causing the thermocline cooling. The increasing southeasterly trades strengthen the STC and the reduced wind stress curl on the equator weakens the CEC (see also Schoenefeldt and Schott 2006). These two effects combine to induce heat divergence and thus cool the upper thermocline over the thermocline ridge region (Trenary and Han 2008). In contrast, Alory et al. (2007) and Cai et al. (2008) suggested that in the third phase of the Coupled Model Intercomparison Project (CMIP3) climate models, the observed south Indian Ocean thermocline cooling results mainly from the shoaling thermocline in the western equatorial Pacific and wave transmission via the Indonesian archipelago, driven by the relaxation of the easterly trades in the Pacific (McPhaden and Zhang 2002).

Sea surface salinity (SSS) has increased over the past few decades in regions where evaporation exceeds precipitation and decreased in regions of excess precipitation (e.g., Roemmich and Gilson 2009; von Schuckmann et al. 2009; Hosoda et al. 2009; Durack and Wijffels 2010; Helm et al. 2010) due to the greenhouse gas–induced warming and the resultant amplification of the global hydrological cycle ([Held and Soden 2006](https://journals.ametsoc.org/view/journals/bams/95/11/bams-d-13-00028.1.xml#i1520-0477-95-11-1679-b68)). but has a decreasing trend in the equatorial Indian Ocean.

The upward trend of the IOD index (see [Fig. 4b](https://journals.ametsoc.org/view/journals/bams/95/11/bams-d-13-00028.1.xml#i1520-0477-95-11-1679-f04)) in recent decades, however, appears in some SST datasets but not in others, highlighting the uncertainties in these trends ([Cai et al. 2013](https://journals.ametsoc.org/view/journals/bams/95/11/bams-d-13-00028.1.xml#i1520-0477-95-11-1679-b22)). [Zheng et al. (2010)](https://journals.ametsoc.org/view/journals/bams/95/11/bams-d-13-00028.1.xml#i1520-0477-95-11-1679-b205) examined the impact of greenhouse warming on IOD behavior [see [Cai et al. (2013)](https://journals.ametsoc.org/view/journals/bams/95/11/bams-d-13-00028.1.xml#i1520-0477-95-11-1679-b22) for a review] and concluded that the increasing occurrence of positive IOD events in the past few decades results from a gradual increase in the mean west-minus-east SST gradient in the tropical Indian Ocean. As a result, the IOD index crosses the defined threshold more frequently near the end of the twentieth century. Climate model projections suggest that under greenhouse gas warming, the frequency of positive IOD events will increase by a factor of three near the end of the 21st century ([Cai et al. 2014](https://journals.ametsoc.org/view/journals/bams/95/11/bams-d-13-00028.1.xml#i1520-0477-95-11-1679-b23)).