Identifying ideal locations for marine phytoplankton to enhance carbon sequestration

Ekaansh Ravuri

Introduction

The ocean plays a critical role in regulating Earth's climate by absorbing vast amounts of carbon dioxide from the atmosphere, and marine phytoplankton are central to this process. Phytoplankton, microscopic, photosynthetic organisms, form the base of the marine food web and are responsible for nearly half of global primary production. Through photosynthesis, they capture atmospheric CO_2 and convert it into organic carbon, some of which eventually sinks to deeper ocean layers, effectively removing it from the atmosphere for decades or even centuries. This biological carbon pump is a key component of Earth's carbon cycle and an essential natural mechanism for moderating global climate.

Prochlorococcus grows best in warm, clear, and nutrient-poor waters, mostly found in tropical and subtropical oceans. Since temperature has a huge impact on its ability to grow and photosynthesize, sea surface temperature (SST) is a key factor in predicting where it can survive. By combining temperature data with what we know about its needs, like light, nutrients, and carbon levels, this project helps highlight where Prochlorococcus thrives today and where it might be most useful for carbon capture in the future as ocean conditions keep changing (Figs. 2 and 3).

However, climate change poses major challenges to phytoplankton populations. Rising SST, changes in nutrient upwelling, ocean acidification, and increasing stratification all influence where and how these organisms can survive. Warmer waters can alter metabolic rates, nutrient availability, and light penetration, potentially shifting the distribution and productivity of key phytoplankton species. Because phytoplankton form the foundation of marine ecosystems and play a pivotal role in carbon cycling, even small changes in their abundance or distribution can have devastating effects on global greenhouse gas levels and ocean health.

Given these dynamics, phytoplankton like *Prochlorococcus* have drawn increasing interest for their potential in natural or enhanced carbon sequestration. Understanding where environmental conditions are most favorable for their growth, and how these conditions may change under future climate scenarios, is critical for identifying regions that could serve as "natural carbon sinks" or potential initial test sites for carbon sequestration enhancement. Identifying these areas could also help inform global climate models and guide strategies to help biological processes in climate mitigation.

In this project, I investigate the dominant environmental drivers that influence *Prochlorococcus* growth and distribution, with a particular focus on sea surface temperature. Using NOAA SST data spanning from 1854 to 2025, I aim to identify present-day and future regions where *Prochlorococcus* is most likely to thrive and contribute to carbon sequestration. Specifically, I ask: What are the optimal temperature ranges and oceanic conditions for *Prochlorococcus* growth and carbon fixation? As well as: How might changes in global sea surface temperature alter the distribution of suitable habitats for *Prochlorococcus* in the coming decades?

By combining biological data with long-term SST records, this research highlights how a single genus of cyanobacteria could play an outsized role in the ocean's ability to sequester carbon in a warming world.

Methods

In this project, I analyzed global sea surface temperature (SST) data from the National Oceanic and Atmospheric Administration (NOAA) to identify regions suitable for *Prochlorococcus* growth and carbon sequestration. The dataset was accessed through the NOAA Thredds Data Server and includes monthly global SST values from 1854 to 2025 at a 2° spatial resolution. This long-term dataset provides a detailed view of global temperature trends across both time and space, allowing for the detection of large-scale ocean warming patterns (Fig. 1).

The SST data were imported and processed using climate visualization tools and statistical software (e.g., Panoply and Python), which allowed for analysis of temporal and spatial temperature changes. Average SSTs were calculated for the modern period (1979–2025) to represent present-day conditions, while long-term trends were used to assess potential climate-driven shifts. The global SST data were then filtered to highlight regions within the optimal temperature range for *Prochlorococcus* growth (17°C–30°C), as established from published literature (Refs 1–3). These filtered data were visualized using global map projections, with green shading indicating suitable temperature ranges and red shading representing unsuitable regions (Fig. 3).

To evaluate how climate change might alter *Prochlorococcus* habitats, I compared SST changes across decades and identified areas where temperatures have shifted toward or away from the optimal range. These temporal comparisons helped reveal potential expansion or contraction of habitable zones under warming conditions (Fig. 2). Finally, regions that remained within or transitioned into the 17–30°C range were marked as potential pilot sites for *Prochlorococcus*-based carbon sequestration projects.

Results

3.1 Identifying optimal conditions for Prochlorococcus growth and carbon sequestration

What we know about Prochlorococcus growth is that it depends mainly on temperature, light, nutrients, and carbon availability. Sea surface temperature (Fig. 1) is a key factor because Prochlorococcus thrives in warm waters between 17º and 30°C (Ref 1). Outside this range, its ability to photosynthesize weakens, and harmful reactive oxygen species (ROS) build up, damaging the cells (Ref 2, Ref 3). Light is just as important, with different types of Prochlorococcus suited to either high or low light levels. Some strains, like Prochlorococcus marinus (SS120), are adapted to low light, using a higher ratio of chl b/chl to absorb light more efficiently (Ref 2, Ref 4).

Nutrient levels of nitrogen, phosphorus, and iron also play a key role. Unlike many phytoplankton, Prochlorococcus does not do well in nutrient rich waters where larger organisms outcompete it. Studies suggest that its population remains steady even when nutrient levels vary, meaning it is well-suited to nutrient-poor environments (Ref 1). Another key factor is carbon availability. Prochlorococcus has a special way of concentrating CO_2 around Rubisco, the enzyme that helps it convert carbon, making it more efficient even when CO_2 levels are low (Ref 5).

The carbon sequestration ability of Prochlorococcus depends on these same factors. Light controls how efficiently it photosynthesizes, with different ecotypes thriving at different depths (Ref 6, Ref 7). It also needs nitrogen, phosphorus, and iron, which are crucial for carbon fixation, especially iron, which is vital for enzyme function (Ref 8). The best temperatures for sequestration are between 15º and 30°C, but extreme temperatures reduce efficiency (Ref 3, Ref 1). Prochlorococcus also performs well under high CO_2 conditions but struggles when CO_2 levels drop (Ref 9).

Salinity is an important factor for Prochlorococcus growth and carbon sequestration potential. It thrives in moderate salinity levels (30-40 PSU), typical of nutrient poor ocean regions. While Prochlorococcus can tolerate some salinity variation, extreme levels, either too low or too high, can stress the cells, reducing growth and carbon fixation efficiency. This makes salinity an important consideration when evaluating the species' adaptability to changing ocean conditions (Ref 10).

3.2 Identifying where Prochlorococcus thrives globally under present-day climate conditions

I found that cyanobacteria, especially Prochlorococcus, are most common in tropical and subtropical oceans, mainly between 40°N and 40°S. These areas have warm, stable, and nutrient-poor waters that create the perfect conditions for Prochlorococcus to grow and contribute to global primary production (Ref 1).

Large oceanic regions called subtropical gyres, such as the North and South Pacific Gyres, are hotspots for Prochlorococcus. These areas have very little nutrient availability, which prevents larger phytoplankton from dominating, allowing Prochlorococcus to thrive (Ref 11). Evidence suggests that early Prochlorococcus species first appeared in low-oxygen, nutrient-rich waters, but over time, they evolved to survive in today's high-oxygen, nutrient-poor conditions (Ref 7).

Some of the most important locations for Prochlorococcus include the North and South Pacific Gyres, the Red Sea, and the Indian Ocean. The North and South Pacific Gyres have low-nutrient conditions that give Prochlorococcus an advantage over other phytoplankton (Ref 1). The Red Sea, known for its warm and salty waters, provides an ideal stable environment where Prochlorococcus can flourish near the surface (Ref 12). In the Indian Ocean, Prochlorococcus is most common between 45°N and 40°S. The strong sunlight and low iron levels make it difficult for other phytoplankton to compete, allowing Prochlorococcus to dominate

(Ref 13). These patterns show how ocean conditions shape where Prochlorococcus can survive and thrive.

3.3 Identifying habitat shifts for Prochlorococcus under climate change and potential for carbon sequestration pilot project locations

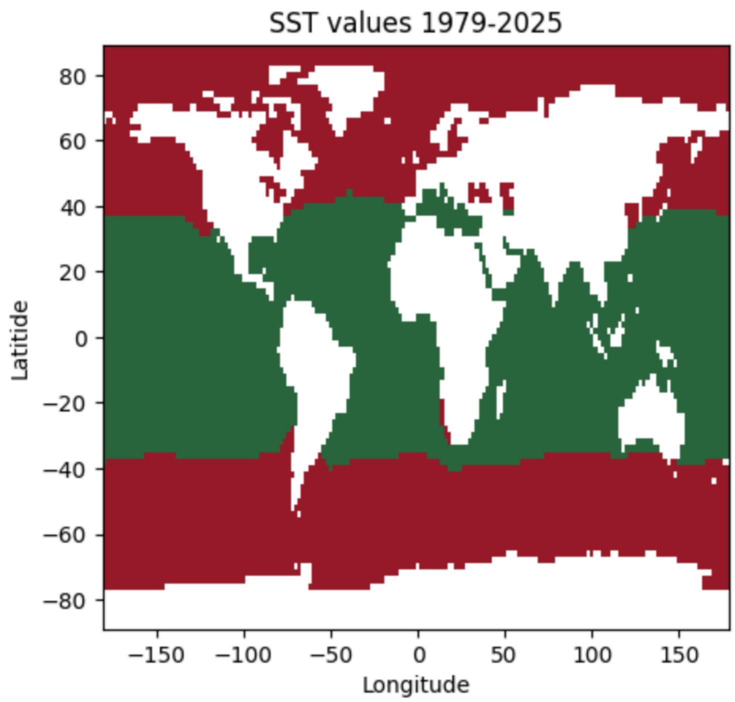

Figure 3. Suitable habitats for Prochlorococcus based on the ideal temperature range of (17º - 30ºC). Areas in this range are shaded in green and areas outside this range are in red.

Figure 3 presents a global map of Sea Surface Temperature (SST) data from 1979 to 2025, displaying regions where SSTs fall within the 17°C to 30°C range. These areas are shaded in green, representing the temperature range that supports the growth of Prochlorococcus. The map clearly illustrates that the temperature range for Prochlorococcus is widespread across tropical and subtropical oceans, especially in the Pacific, Atlantic, and Indian Oceans. The regions shaded in green largely align with known habitats of Prochlorococcus, such as the equatorial and sub equatorial zones, suggesting that these areas are optimal for the microorganism's survival and reproduction.

From this map (Fig. 3), we observe that these suitable temperature ranges cover a vast area of the oceans, spanning from the coasts of Central and South America, parts of Southeast Asia, and the coasts of Africa. This geographic distribution suggests that Prochlorococcus is well adapted to thrive in a wide range of tropical marine environments.

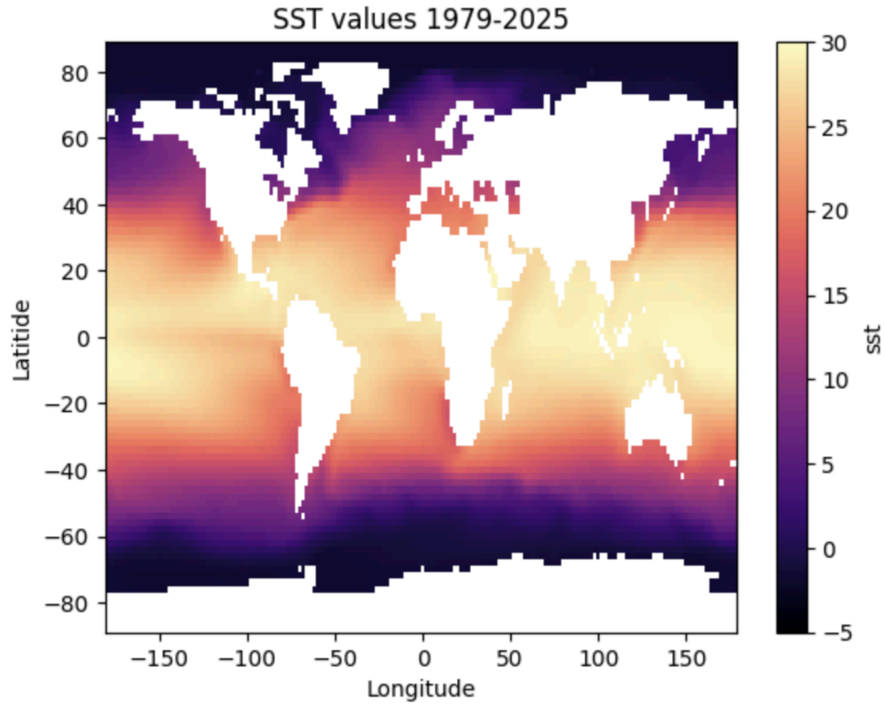

Figure 1. Average sea surface temperatures from 1979 to 2025 in ºC. Sea surface temperatures are a key driver of Prochlorococcus growth and carbon sequestration potential.

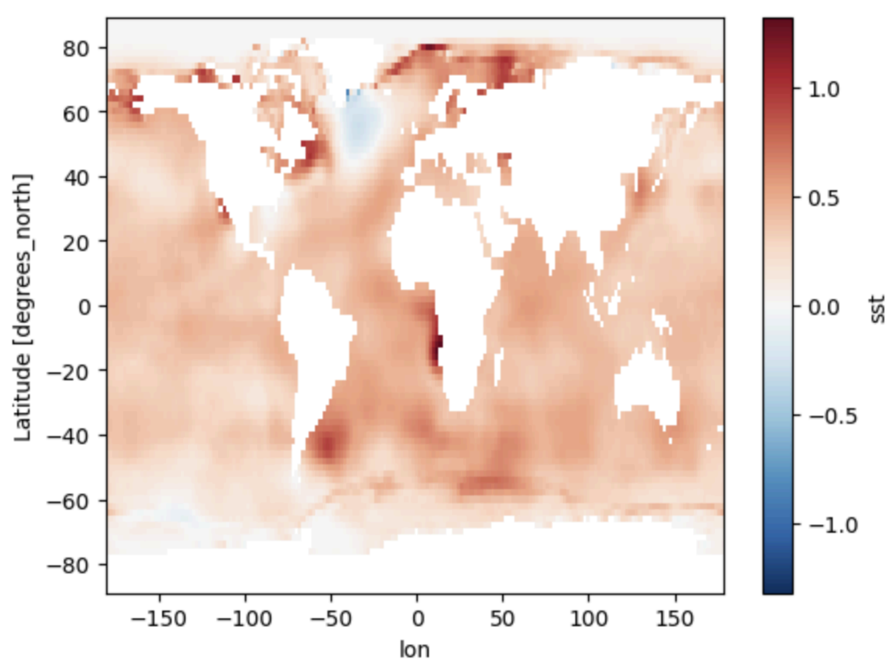

Figure 2. Change in sea surface temperatures from 1979 to 2025. Red values indicate warming waters.

Additionally, Figures 1 and 2 reveal notable SST trends over the past several decades. In particular, some regions in the tropics have experienced slight increases in SST, with a few areas that were previously on the lower end of the temperature range (17°C) now falling closer to the upper limit of the range (30°C) (Fig. 2). This shift could potentially expand the suitable habitat for Prochlorococcus, allowing it to occupy new regions as SSTs increase in response to global climate change. However, this warming could also pose a challenge for Prochlorococcus if the temperature exceeds its upper threshold of tolerance.

Furthermore, some regions that once had temperatures outside the optimal range for Prochlorococcus (either below 17°C or above 30°C) have gradually warmed, approaching the ideal conditions for growth (Figs. 1-3). This pattern is particularly notable in certain mid-latitude zones, where warming waters could open new ecological niches for the microorganism.

The time aspect of this map (Fig. 2) is also significant, as it shows how the extent of the temperature range for Prochlorococcus may change over time due to natural climate variability and other effects such as global warming. Over the decades, warming oceans have likely altered the distribution of marine species, and this map serves as a critical tool in understanding the potential shifts in the distribution and habitat of Prochlorococcus in the future. For example, there has been strong warming over the western coast of Africa (Fig. 2), and if that warming were to continue at such an accelerated rate, it may drastically shrink the habitable region for Prochlorococcus (Fig. 3).

In conclusion, the map (Fig. 3) provides a clear and compelling visualization of the global distribution of suitable temperature ranges for Prochlorococcus. The green areas (17°C – 30°C) encompass the vast majority of tropical and subtropical ocean zones, highlighting regions where Prochlorococcus is most likely to thrive. Furthermore, the trends in SST variation observed in Figure 2 underscore the potential impact of climate change on Prochlorococcus's habitat, suggesting that warming oceans could not only increase the areas where Prochlorococcus can survive but could also affect its growth and carbon sequestration dynamics.

Conclusion

This research highlights the vital role that sea surface temperature plays in shaping the distribution and function of Prochlorococcus, one of the ocean's most abundant and ecologically significant microorganisms. By analyzing long-term SST data alongside known biological requirements of Prochlorococcus, it becomes clear that tropical and subtropical oceans, particularly regions like the Pacific and Indian Ocean gyres, are optimal habitats for growth and carbon sequestration. Factors such as light availability, nutrient levels, salinity, and carbon concentration also influence how effectively Prochlorococcus can photosynthesize and contribute to the global carbon cycle. These findings reinforce the idea that this tiny cyanobacterium is well-adapted to stable, oligotrophic waters and plays an outsized role in oceanic primary production and carbon fixation.

Looking forward, warming sea surface temperatures caused by climate change could expand or shift the habitat range of Prochlorococcus, opening new opportunities for research and carbon sequestration efforts, but also posing risks if temperatures exceed the species' tolerance limits.

By identifying areas that fall within the ideal temperature range (17–30°C), especially those trending toward warmer conditions, this study offers a foundation for targeting future Prochlorococcus-based carbon capture initiatives. Continued monitoring of ocean temperatures and further investigation into nutrient and CO_2 dynamics will be critical for understanding how Prochlorococcus may adapt to our changing oceans, and how we might harness its capabilities in the fight against climate change.

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