Phytoplankton Climate Regulation in Positive and Negative Feedback Systems: The CLAW and anti-CLAW hypotheses

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Abstract

The global climate crisis is bigger now than it has ever been before, pushing for much-needed research on the consequences of climate change. In 1987, Charlson, Lovelock, Andreae, and Warren proposed the CLAW hypothesis which stated that phytoplankton contribute to the production of a significant amount of cloud condensation nuclei (CCN) which in turn creates a negative feedback loop after there is an initial temperature rise. Many years later, in 2006, Lovelock proposed the anti-CLAW hypothesis, which argues that a similar process occurs except that it works as a positive feedback system. Both hypotheses have created much controversy about the effects phytoplankton has on climate and climate regulation. Research has shown that different types of phytoplankton tend to have higher growth rates within a temperature range. Coccolithophores are known for their contribution of DMSP, a compound that forms to make CCN as well as their carbon sequestration abilities. This type of phytoplankton typically function at a thermal niche where nutrient stratification is not strongly limiting, making them act like a buffer against further temperature rises in terms of the CLAW hypothesis. Based on the physiological capabilities of phytoplankton within their environment, both the CLAW and anti-CLAW mechanisms correlate strongly with coccolithophorid algae.

1. Introduction

After Charlson, Lovelock, Andreae, and Warren introduced the CLAW hypothesis in 1987 (where CLAW is an acronym for the four author’s names), much discussion has been generated around the topic. Essentially, the CLAW hypothesis describes phytoplankton growth as a mechanism that can counteract increasing global temperatures. The CLAW hypothesis assumes that phytoplankton growth will significantly increase when the surface seawater temperature rises. After a large phytoplankton bloom, the phytoplankton die, releasing the compound dimethylsulfoniopropionate (DMSP), which is then broken down by marine bacteria into dimethyl sulphide (DMS). DMS then gets transferred to the atmosphere from the ocean, which goes on to oxidize into methanesulphonate (MSA) and non-sea-salt sulphates (NSS-sulphate). The products of DMS become aerosols which act as cloud condensation nuclei (CCN) that contribute to the formation of clouds. Since clouds have a high albedo, they reflect sunlight, and consequently reduce surface temperature. Charlson et al. (1987) argue that phytoplankton growth and the following rise in CCN creates a negative feedback mechanism that offsets temperature rise and helps regulate the climate.

More recently, Lovelock (2006) proposed a similar system that acts as a positive feedback mechanism, appropriately named the anti-CLAW hypothesis. Under future global warming,
the anti-CLAW hypothesis proposes that phytoplankton growth will fall when seawater surface temperature rises. The loss of phytoplankton biomass will result in less CCN and thus clouds, allowing for even more warming to occur (Lovelock, 2006). Both hypotheses are visually presented in Figure 1.

However, there is still some uncertainty on how phytoplankton groups act in accordance to the CLAW hypothesis and anti-CLAW hypothesis since there are multiple factors that can contribute to phytoplankton health and reproduction (Cox 1997). The goal of this review is to show that both the CLAW and the anti-CLAW processes impact phytoplankton growth depending on temperature conditions. Unlike other review papers that support only one hypothesis, this review will attempt to show that both can hypothetically coexist.

It is important to study the practicality of the CLAW and anti-CLAW hypotheses so there is a better understanding on how the Earth could or could not be resilient to climate change; a lack of research would leave people with a benighted view on the Earth’s ability to recover. Therefore, this paper will look at the effects of temperature on phytoplankton growth among different taxonomic groups, and the correlations between algal blooms and cloud formation and proposes a possible relationship between the two hypotheses and phytoplankton growth.

2. Phytoplankton and the CLAW and anti-CLAW Hypotheses

The huge contribution that the CLAW hypothesis made in 1987 to climate science has led to much research into the relationships between biology and climate. Subsequently, an extensive investigation into phytoplankton growth and climate regulation gave rise to the anti-CLAW hypothesis, the opposing positive feedback system. Although the processes work differently, both still consist of the same components, which are: phytoplankton growth, DMS production, and cloud production. For the rest of this paper, it is important to keep these main factors in mind as the paper will draw on each of these points in the context of phytoplankton growth.
3. Effects of Temperature on Phytoplankton Growth and Communities

Temperature plays a more important role than sunlight in regulating phytoplankton reproduction (Miao and Yang 2009; Steemann-Nielson 1975). Generally, phytoplankton reproduction rates and metabolic activity will increase with rises in seawater temperature (Eppley 1972). By compiling data from other experiments using cultured phytoplankton, Bingzhang (2015) shows that growth is positively correlated with temperature until they reach a maximum temperature. At this temperature, or ‘thermal limit’, growth begins to plateau and then decreases, resulting in phytoplankton mortality (Miao and Yang 2009).

The optimal growth temperature is typically higher than the mean environmental temperature, meaning that when environmental temperature rises, phytoplankton are functioning and reproducing at a higher rate (Figure 2; Bingzhang 2015; Lovelock 1995). With more phytoplankton biomass, the CLAW hypothesis presumes that these marine primary producers will start counteracting the initial rise in temperature with increased production of DMSP. The physiological capabilities in these marine phytoplankton supports the idea of a CLAW mechanism: increased temperatures lead to increased phytoplankton growth.

![Figure 2. Scatter plot of optimal growth temperature and environmental annual mean temperature. The black dots represent marine phytoplankton; the triangles represent freshwater cyanobacteria; the black line represents the regression line for marine phytoplankton while the dashed line represents the regression line for freshwater cyanobacteria. The thin dotted lines represent the 95% confidence intervals (Bingzhang 2015)](image)

When considering the actual range of temperature that a CLAW mechanism can function at, it is important to keep nutrients in mind. Phosphorus, silicon, and nitrogen all play significant roles in phytoplankton development and growth. In terms of temperature, elevated seawater surface temperature stratifies nutrients, which creates a barrier between accessible nutrients and phytoplankton, ultimately slowing the growth of algal...
communities. Both nitrogen and phosphorus deficiency can reduce the capacity to photosynthesize (Miao and Yang 2009; Yang and Zhu 1990). Temperature alone can limit the amount of nutrients made available to phytoplankton communities, so nutrient stratification must be minimal in order to support the CLAW hypothesis. In tropical regions, where the surface waters are stratified and lacking sufficient nutrients, phytoplankton are more likely to follow anti-CLAW hypothesis; thus, the CLAW mechanism could only function in relatively colder waters.

4. The Significance of Phytoplankton Groups in Biogeochemical Processes

Although difficult to measure, the production of cloud producing agents after phytoplankton blooms are key piece of evidence supporting the CLAW and anti-CLAW hypotheses. Over an 8-day period using satellite data, Meskhidze and Nenes (2007) measured chlorophyll-a concentration and cloud effective radius over a section of the Southern Ocean. They found that clouds consistently form directly after phytoplankton blooms, as shown in Figure 3. Soon after DMS forms, it is presumed that CCN becomes more abundant in the atmosphere. It is unclear if this same mechanism will occur in cooler climates, and phytoplankton in mid to high latitudes will produce algal blooms that will generate sufficient amounts of DMS to contribute to cloud production.

![Figure 3](image)

*Figure 3. The 8 day average of SeaWiFS-observed chlorophyll-a (A) and MODIS retrieved cloud effective radius (B) both observed between 49° to 54°S and 35° to 41°W. White spots indicate missing data; chl-a data is gridded at a resolution of 9 by 9 km and effective radius is gridded by 1 by 1° (Meskhidze and Nenes 2007)*

In order to understand the effect of latitude on phytoplankton, it is necessary to understand how different thermal ranges affect the ability to grow for different groups of phytoplankton species. Coccolithophores, a type of phytoplankton, are known for their distinctive light green algal blooms in the colder regions of the ocean. *Emiliania huxleyi*, arguably the most abundant type of calcifying coccolithophore, tends to favour temperatures around 16-21°C, with optimal reproduction rates in that range. When temperatures are above 22°C, these coccolithophores will not grow (Huertas, Rouco, Lopez-Rodas and Costas 2010). Calcifying coccolithophores generally share a similar optimal temperature range. However, dinoflagellates, another type of phytoplankton, can
tolerate higher temperatures up to 30-33°C. (Boyd et al. 2013). The optimum growth temperature is similar for diatoms (Ruth 1971; Admiraal 1976). With rising temperature, the taxonomic groups in phytoplankton communities change drastically, resulting in microthermal species being replaced by mesothermal and megathermal species, which can handle higher temperatures (Fott 1971; Miao and Yang 2009). Generally, each group of phytoplankton has a ‘thermal niche’, or a specific temperature range where optimal growth occurs. It is important to keep in mind that each species within these groups may have a different optimum growth temperature, but in general coccolithophorid algae perform better at a lower thermal level than dinoflagellates and diatoms.

Using shipboard incubation of algal communities, Lee et al. (2009) subjected phytoplankton to increased carbon dioxide conditions (690 ppm) and temperature (16 °C) that would represent future climate conditions under global warming. At the end of the experiment, coccolithophore abundances increased, while diatom and dinoflagellate abundances decreased as seen in Figure 4. Simultaneously, the relative DMSP levels were nearly 50-60% greater than under ambient controls (12°C, 390 ppm CO₂). The relative increases in both DMSP and coccolithophores show that there is a correlation between the two, which could signify a CLAW mechanism in action with these predominantly mid and high latitude phytoplankton communities.

As such, larger phytoplankton blooms that are predominantly made up of coccolithophores could help mitigate growing carbon dioxide concentrations. Calcifying coccolithophores should mitigate rises in carbon dioxide and temperature since their physiology in the polar environment is consistent with the main aspects of the CLAW hypothesis. The anti-CLAW hypothesis is only attainable in areas with heavily stratified waters, such as tropical regions that have very low phytoplankton concentrations, or extremely warm waters.

It is important to remember the findings from these studies shown here are used in a general manner, and may not reflect the abilities all of diatoms, coccolithophores, and dinoflagellates. Since most of these studies were either performed in situ or in incubation tanks over a short period of time, usually only spanning over a few weeks, the relationships described here may not reflect long term trends of temperature driven phytoplankton growth.

5. The Prevalence of the CLAW Feedback Mechanism in the Current Climate

In higher latitudes where phytoplankton are more concentrated, it is presumed that larger amounts of dimethyl sulfide are released forming higher concentrations of CCN, compared to latitudes around the equator. One study measured a strong relationship between the seasonal cycles of biologically produced DMS and the seasonal variation of the products of DMS: methanesulphonate and non-sea-salt sulphate (Ayers et al. 1991). The study showed that as DMS levels increased concentrations of MSA and NSS-sulphate increased by a factor of 12-25 and 5-10 respectively. Ayers and Gras (1991) also found a strong correlation between CCN numbers and atmospheric sulphur products.
However, this information does not mean that planetary albedo is increasing; contradictory satellite data has shown that there is an increasing amount of radiation hitting the Earth’s surface (Pinker et al. 2005). Low-lying clouds tend to be more effective at reflecting solar radiation than high-level clouds (Figure 4) and there has been a notable decline in these low-lying clouds over the past 30 years (Figure 5), helping to explain the increased radiation hitting the Earth’s surface (ISCCP 2011). It may seem that the CLAW-like mechanism is not apparent because of this, however it is also possible that this mechanism does occur. Instead the process is weakened while in an interglacial state, or warm period, and is diminished even further by heavy anthropogenic activities.

Figure 4. The relationship between low level cloud cover (%) and global surface temperature (°C). (ISCCP 2011).
Figure 5. Atmospheric water (black) is the average amount of water present in the atmosphere; cloud cover percentage of low-level clouds (blue), middle-level clouds (green), and high-level clouds (red) in the past 30 years. (ISCCP 2011)

The CLAW hypothesis is meant to be a global concept supporting Lovelock’s Gaia Theory (1995), which is the unifying theory depicting the importance of marine and terrestrial biomass in contributing to climate regulation. Putting the long-term geological timeline into perspective, Lovelock (2006) describes interglacial periods as Earth’s fever or sick state, and glacial periods as Earth’s healthy state. When the Earth is in a glacial period, there is more ice reflecting more sunlight, resulting in a lower global temperature. Once oceans recede, more land and forests are created as well as stronger ocean currents, ultimately allowing for more biomass to contribute to climate regulation. In a ‘fever state’ or interglacial period, the Earth has less ice lowering planetary albedo and consequently weakening the Earth’s biotic climate regulation. The anti-CLAW hypothesis better represents a warmer period because seawater tends to be less salty, less nutrient abundant, and warmer. Phytoplankton and other marine photosynthesizers will hypothetically have a weaker effect in climate regulation.

In addition to this, humans have essentially removed a significant amount of the natural ecosystem and replaced it with farms and urban landscape. It is possible that hundreds of years of changing the land and ocean could have unprecedented effects on the ability for a natural negative feedback mechanism like the one described by the CLAW hypothesis, to combat carbon dioxide fluxes and other severe changes in the environment.
The combined effects of strong anthropogenic activity and interglacial period dynamics probably have weakened the CLAW mechanism to a point where it may not have a significant effect on climate regulation. In other words, if a CLAW mechanism was occurring before humans started changing the composition of the atmosphere, it may not have a noticeable effect today and would not be observable in cloud coverage data (e.g. Figure 5)

6. Hypothetical Relationship Between Growth and the CLAW and anti-CLAW Hypotheses

Combined, the reviewed information reveals the relationship between both hypotheses with phytoplankton growth as a function of temperature. Essentially, the research implies that the CLAW mechanism acts up until an optimal temperature, at which point the anti-CLAW hypothesis is activated, assuming that heavy nutrient stratification is not already limiting growth at the optimal temperature. As shown in Figure 6, while the CLAW mechanism is in action, there is a downward pressure or negative feedback acting in attempt to return to regular environmental temperatures. While under the CLAW hypothesis, phytoplankton would increase reproduction with increased temperatures in their environment, excluding the effect of nutrient stratification. In the case that temperature does continue to increase past the optimal temperature, the anti-CLAW mechanism goes into effect causing a positive feedback, pushing phytoplankton growth to zero. This relationship would be most effective with coccolithophorid algae because growth peaks are at a lower temperature where stratification is not as heavily limiting as would it be with other taxonomic groups.

Figure 6. Hypothetical relationship for phytoplankton growth as a function of temperature relative to the CLAW (blue) and anti-CLAW mechanisms (red) in action. Note: the
temperature range where either mechanism is functional is subject to shift depending on the species and environment.

7. Conclusion

To understand the relationship between the CLAW and anti-CLAW hypotheses with different marine phytoplankton groups, one must review the physiological capabilities and limits of these taxonomic groups related to rising temperatures. The purpose of this paper was to show that the physiology of phytoplankton closely correlates with both the CLAW and anti-CLAW hypotheses as a function of temperature and growth (as described in Figure 6). Coccolithophores can sufficiently reproduce in colder water and, by producing high levels of DMSP, can contribute to cloud formation. When temperatures reach ranges of about 16-21°C, phytoplankton growth is at its optimum level after this optimum level is passed, phytoplankton growth begins to decline due to the inaccessibility of nutrients in stratified water; in other words, the CLAW mechanism gives way to the anti-CLAW mechanism. To conclude, coccolithophorid algae physiology shows that both hypotheses can exist as biogeochemical ocean processes, rather than only one.

Future research should be performed over a long-term period, spanning several years, looking at the correlation between chlorophyll-a concentration, cloud coverage, NSS-aerosols, and DMS levels. In addition to the study needing long term funding, it would also need to have access to a multitude of satellite data and ocean observation buoys that are able to record information such as DMS levels and NSS-aerosols in the atmosphere. Since phytoplankton-born CCN have only been studied on a relatively small scale, a long-term study such as this could greatly improve the understanding about the role that phytoplankton play in regulating the climate; furthermore, helping create better models that predict how life on Earth will react to the current climate warming crisis.

References


http://www.climate4you.com/ClimateAndClouds.htm#Cloud albedo
