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The Future of Giant Kelp Along the West Coast of North America Due to Rising Sea Surface Temperatures

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Abstract

Anthropogenic carbon dioxide (CO_2) emissions play a large role in heating the planet. The oceans act as a sink for atmospheric CO_2, reducing this greenhouse gas concentration within our atmosphere. Within the ocean, Giant kelp (Macrocystis pyrifera) acts as a sink for oceanic CO_2 through the process of photosynthesis. A recent estimate suggests that macroalgae, including kelp, are responsible for approximately three percent of annual CO_2 sequestration on a global scale. In addition to CO_2 sequestration, kelp also plays a vital role in providing ecosystems for marine life and is an ingredient in many of the products we use. Previous research has proven that kelp biomass and Net Primary Production (NPP) are directly related, and kelp biomass is readily retrieved using high resolution remote sensing from Landsat-8 and Sentinel-2. Additional research demonstrates that kelp biomass (and therefore NPP) is significantly correlated to availability of nitrate, and that nitrate is strongly correlated with sea surface temperature. While giant kelp appears to be somewhat resistant to short-term marine heatwaves, recent publications also identify 24°C as a key threshold beyond which kelp cannot survive in the California Current System. With SST continuing to increase due to global warming, climate models can be used to predict how the distribution of giant kelp will react to future conditions. We show that by the end of the century, suitable kelp

habitat will decrease substantially, resulting in a potentially significant reduction of natural carbon sequestration and will result in massive loss of habitat from these foundational species.

1. Introduction

There are two global trends that are, in tandem, making large impact on our planet: 1) rising carbon dioxide (CO_2) levels and 2) the loss of important ecosystems (Brondizio et al. 2019; Ruckelshaus et al. 2020; IPCC 2022; Hessen and Vandvik 2022). These trends create a “double whammy” given that a decrease in carbon sequestration (the process of absorbing CO_2 from the atmosphere) from a loss in ecosystems will result in additional CO_2 in the atmosphere in combination with the already increasing CO_2 concentrations due to anthropogenic emissions (Hessen and Vandvik 2022). Carbon cycle climate feedbacks, such as the scenario described above, vary in their contribution to global warming, making them largely unknown in comparison to the varying contribution of physical feedbacks (i.e. cloud dynamics) (Randall et al. 2007; Higgins and Harte 2012). These carbon cycle feedbacks play an extremely important role as they could strongly reinforce global warming (Higgins and Harte 2012).

Marine macroalgae, a very significant but often overlooked part of the carbon cycle, serves a crucial role with regards to carbon sequestration. Vegetated coastal habitats that include macroalgae sequester some of the highest amounts of carbon in the biosphere (Krause-Jensen and Duarte 2016). According to Krause-Jensen and Duarte (2016), an estimated 173 teragrams of carbon per year (TgC yr^-1) gets sequestered by macroalgae. This amount of carbon sequestration proves significant given that the IPCC (2022) estimates that 1300 gigatons of carbon per year (GtC yr^-1) are sequestered by the oceans. Based on standing stock estimates for macroalgae and giant kelp from Whittaker and Likens (1973) and Reed and Brzezinski (2009), approximately 2.66% of carbon sequestration from the largest natural carbon sink on the planet (i.e. the oceans) comes from marine macroalgae, annually.

Macrocystis pyrifera, commonly known as giant kelp, is a type of macroalgae that is unique to other types of macroalgae in that the biomass of giant kelp turns over approximately seven times per year (Reed et al. 2008; Cavanaugh et al. 2011). Because of this rapid turnover rate, a significant amount of annual carbon sequestration results from giant kelp. In addition, the swift turnover rate also causes the biomass dynamics of giant kelp to be sensitive to changing environmental conditions (Cavanaugh et al. 2011). The growth of giant kelp, which can be thought of as net primary production (NPP), depends on these environmental conditions, such as nutrient availability and sunlight, among other factors (Cavanaugh et al. 2011). Another factor determining the physiological condition of giant kelp depends on the turbulence of the water in which the kelp is located. Several studies have found that waves play a crucial role in determining the physical condition of the kelp. Reed et al. (2008) discovered that winter storms created more turbulence in the water in central California than in southern California, with the loss of kelp biomass in central California nearly double that of southern California.

A study conducted by Bell et al. (2017) used standing foliar biomass (SFB) measurements gathered within a kelp forest in Santa Barbara, California to estimate the NPP of the kelp. The authors also used SFB gathered from remote sensing alone to measure the biomass of the kelp forest and found a strong correlation between the in-situ measurements and the biomass measured by satellites with an r^2 value of 0.885. Therefore, an increase in NPP will yield an increase in SFB.

Nitrate concentrations in the seawater play a role in the physiological condition of giant kelp, accounting for the physical structure of the macroalgae (Bell et al. 2017; Zimmerman and Kremer 1984; Rodriguez et al. 2016; Synder et al. 2020). However, nitrate concentrations change rapidly when the temperature of the seawater changes, even slightly (Synder et al. 2020). At seawater temperatures between 10-15 degrees Celsius, nitrate concentrations prove favorable for giant kelp while temperatures above 15 degrees Celsius prove unfavorable due to nitrate concentrations dropping close to zero (Synder et al. 2020).

In order to predict the future of giant kelp across the west coast of North America, it is important to realize the sensitivity of kelp to multiple environmental factors. Giant kelp biomass is responsible for sequestering carbon in the deep ocean which helps to mitigate climate change. However, this biomass is a function of the NPP of giant kelp. This NPP is made possible by nitrate concentrations, which depend strongly on SST. The purpose of this study is to predict whether or not climate change will severely impact giant kelp across the west coast of North America. This study will use downscaled climate models to view SST predictions from the present to the year 2080. Recognizing these correlations will help to predict the future of giant kelp along the west coast of North America.

2. Data and Methodology

a. Sea surface temperature and kelp biomass

A dataset produced by Bell et al. (2022) contains a time series of giant kelp biomass collected by Landsat 5, 7, and 8 satellite imagery. The time series started gathering data from Landsat imagery in 1984 and, at the time of this writing, is continuing to collect data (Bell et al. 2022). Biomass data is measured in wet weight (kg) for 30 x 30 meter pixels (Bell et al. 2022). The area over which the data is collected spans from Ann Nuevo, California to Baja California, Mexico (Bell et al. 2022). The data is placed into multiple NetCDF files with each file containing quarterly measurements of mean canopy biomass for each pixel (Bell et al. 2022). This dataset produced by Bell et al. (2022) was used to develop an additional dataset created by Raphe Kudela (2022, unpublished data), a professor in the Ocean Sciences department at the University of California Santa Cruz. The dataset includes giant kelp biomass anomalies, gathered from the Bell et al. (2022) dataset, along with SST anomalies. Using the Kudela (2022, unpublished data) dataset, a time series was created that displays giant kelp biomass and SST anomalies from 1984 to 2022 (Fig.1).

b. Models

Earth system models (ESMs) are general circulation models (GCMs) that have been paired with biogeochemical models (Buil et al. 2021; Taylor et al. 2012). Dynamical downscaled models provide high-resolution projections but typically neglect projections due to long time periods and multiple ESMs (Buil et al. 2021). The ESMs used in this study were developed using a "…high-resolution regional ocean-biogeochemical coupled model and apply a 'time-varying' delta approach to dynamically downscale three different ESMs" (Buil et al. 2021). The area the models were downscaled over consists of western North America, a.k.a. the California Current System (CCS) (Buil et al. 2021).

Buil et al. (2021) uses the Regional Ocean Modeling System (ROMS) and a customized version of the biogeochemical model based on the North Pacific Ecosystem Model for Understanding Regional Oceanography (NEMURO), called NEMUCSC, to create high-resolution future projections in the CCS (Buil et al. 2021; Cheresh and Fiechter 2020; Fiechter et al. 2018, 2020). Coupling ROMS and NEMUCSC to create the ROMS-NEMUCSC model and paring three CMIP5 ESMs with the ROMS-NEMUCSC, Buil et al. (2021) created three new downscaled ESMs. The three CMIP5 ESMs used include the Geophysical Fluid Dynamics Laboratory (GFDL) ESM2M, Institut Pierre Simon Laplace (IPSL) CM5A-MR, and the Hadley Center HadGEM2-ES (HAD), all of which use the RCP8.5 climate change scenario. Resolution for each of the three ESMs varies from 1-2 degrees in longitude and ~0.3-2 degrees in latitude while ROMS-NEMUCSC has a resolution of 0.1 degrees (Buil et al. 2021). ROMS-GFDL, ROMS-IPSL, and ROMS-HAD refer to the new models created by Buil et al. (2021) above, respectively. Each of these downscaled models create predictions for 1980-2100 with the projections for 1980-2005 created by historical forcing and the 2006-2100 years using the RCP8.5 climate change scenario (Buil et al. 2021).

ROMS-GFDL, ROMS-IPSL, and ROMS-HAD all display agreement with respect to rising SST over the CCS, however the magnitude in which the warming happens varies (Buil et al. 2021). ROMS-HAD projects SST and SST anomalies to be warmer than both ROMS-GFDL and ROMS-IPSL, with the latter models projecting weak to moderate increases in SST (Buil et al. 2021; Bopp et al. 2013). Furthermore, the models also disagreed with respect to spatial warming (Buil et al. 2021). ROMS-HAD projects a uniform warming pattern over the CCS, ROMS-IPSL produces increased warming offshore, and ROMS-GFDL estimates northern coastal waters to be cooler (Buil et al. 2021).

ROMS-GFDL, ROMS-IPSL, and ROMS-HAD contain SST predictions for every month ranging from 1980-2100. Taking the mean SST for each month of each model yields a mean SST for each month from 1980-2100 for ROMS-GFDL, ROMS-IPSL, and ROMS-HAD. Additionally, averaging the SST for the months of April, May, June, and July for ROMS-GFDL, ROMS-IPSL, and ROMS-HAD produces a mean SST across the three models for the four months above from 1980-2100.

3. Results

Climate change is causing SST to rise, having many negative impacts on our oceans and the ecosystems within them. Analyzing Fig.1, SST has an inverse relationship with giant kelp biomass. The 1997/1998 El Niño and La Niña event was considered to be one of the strongest on record and is evident in Fig. 1. The strong positive SST anomaly created by this event is coupled with a strong negative kelp biomass anomaly. Marine heat waves also produce strong positive SST anomalies that appear in Fig. 1, coupled with a strong negative kelp biomass anomaly.

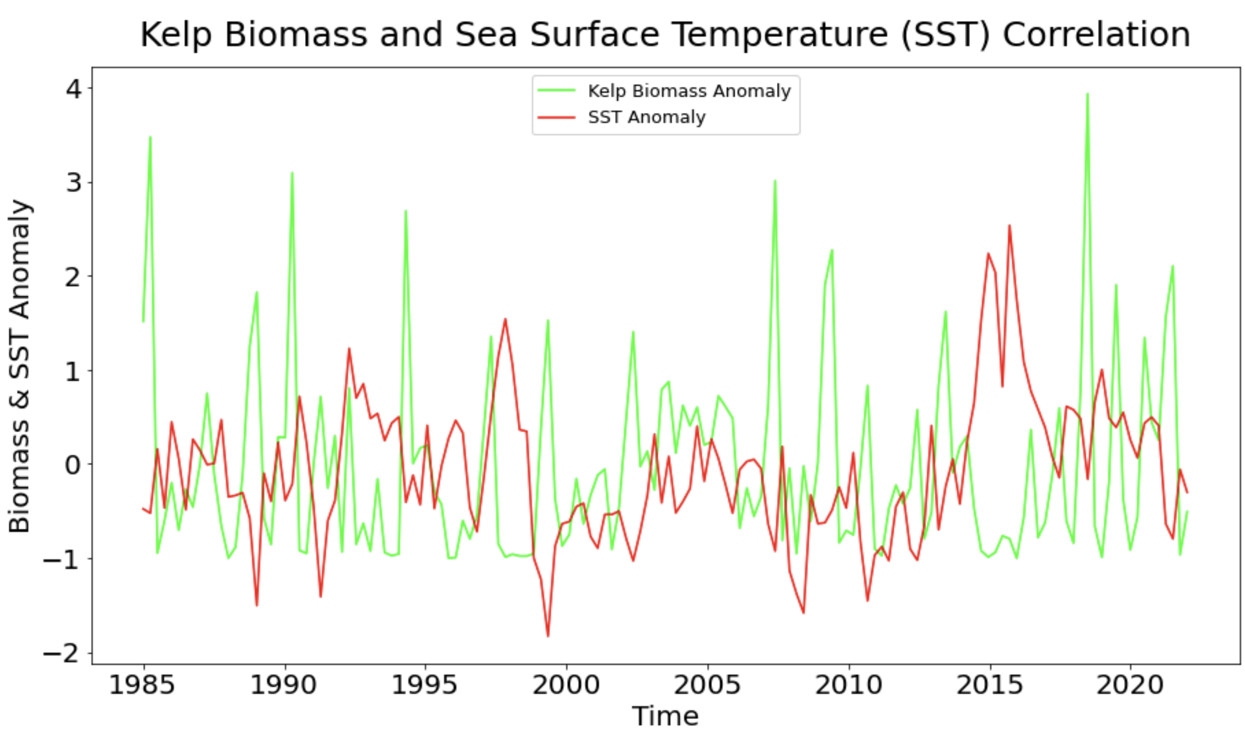

Figure 1. Time series of kelp biomass anomalies (green) and SST anomalies (red) from 1980-2100. Time is in years.

The ensemble model created from the ROMS-GFDL, ROMS-IPSL, and ROMS-HAD models displays the average SST projections for the months of April, May, June, and July for 1980-2100. The months plotted on Fig. 2 represent the months at which kelp conditions are favorable for peak growth due to SST below 15 degrees Celsius and excess sunlight for photosynthetically active radiation (PAR). In addition, April, May, June, and July represent months in which the development of large storms in the Pacific proves unfavorable. Therefore, turbulence near the ocean surface becomes negligible, proving favorable for the growth of giant kelp.

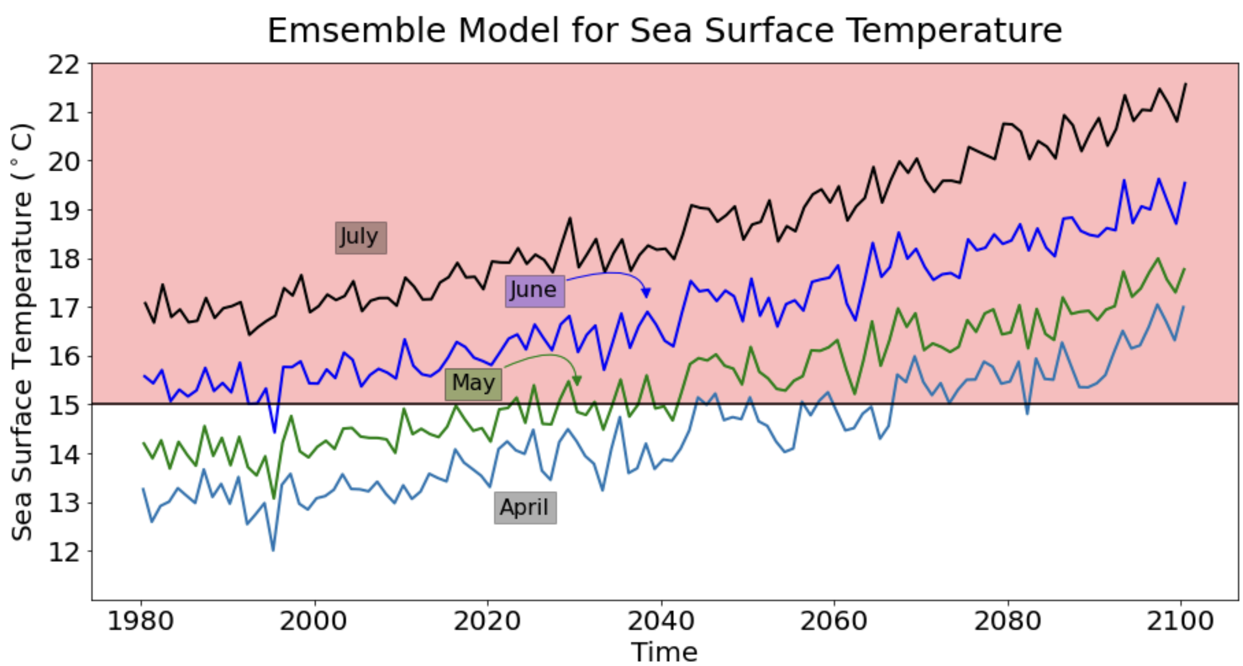

Figure 2. Mean ensemble of ROMS-GFDL, ROMS-IPSL, and ROMS-HAD downscaled model SST (degrees Celsius) projections from 1980-2100 for the months of April (light blue), May (green), June (blue), and July (black).

According to Synder et al. (2020), 15 degrees Celsius represents the SST at which kelp becomes stressed due to limited nitrate conditions. According to the ensemble, the average SST during 2022 for the months of June and July provides an environment in which giant kelp growth is stressed. By 2070, all of the months in which giant kelp tends to grow the most are stressed, with June and July becoming unlikely to promote any kelp growth.

Fig. 4 provides a spatial representation of SST projections over the CCS using the ROMS-HAD model for 2022-2080 for the months of May and June. May and June represent the peak growth of giant kelp due to environmental conditions becoming extremely favorable. However, by 2080, nitrate concentrations along the CCS will be near zero according to Synder et al. (2020), yielding a very unfavorable environment for giant kelp growth.

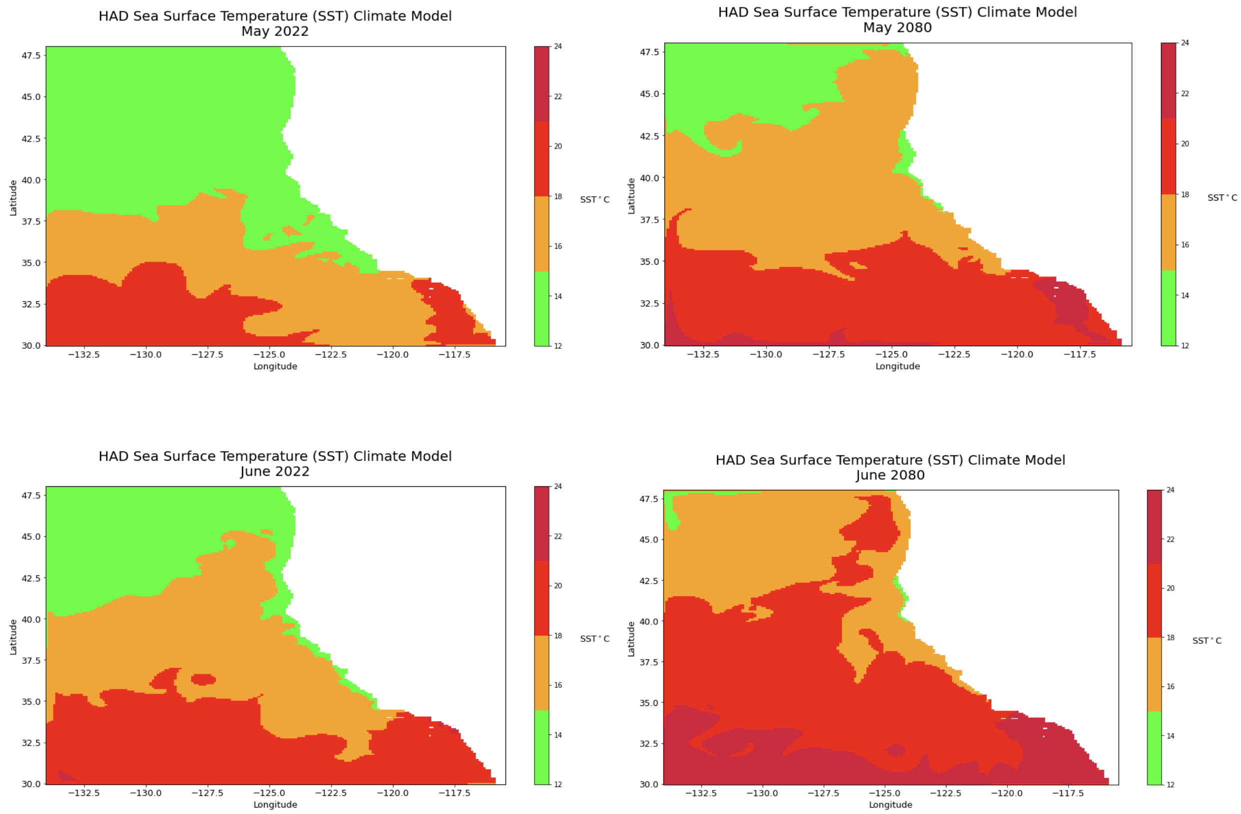

Figure 4. ROMS-HAD SST (degrees Celsius) projections across the CCS for the months of May (top) and June (bottom) from 2022 (left) to 2080 (right). Green areas represent temperatures less than or equal to 15 degrees Celsius. Orange, red, and dark red represent values at which the temperature is above 15 degrees Celsius.

4. Discussion and conclusion

The rising SST projections given by the ROMS-GFDL, ROMS-IPSL, and ROMS-HAD provide insight regarding the future of giant kelp across western North America. Although these models are predictions, by 2080, giant kelp biomass is likely to be on a steady decline. This has implications for our future climate given that giant kelp is a large sink for anthropogenic CO_2. With giant kelp biomass starting to decrease, there will only be an increase in anthropogenic CO_2 in our atmosphere by 2080. This will lead to an increase in the radiative forcing due to CO_2. With global temperatures continuing to rise and projections of other models demonstrating a continuous rise over the next century, the additional anthropogenic CO_2 not absorbed by giant kelp may cause global temperatures to exceed habitable conditions. The marine ecosystems that giant kelp provides along the west coast of North America will become likely to fail, impacting local economies.

Additional research is needed to quantify the amount of radiative forcing due to additional CO_2 not absorbed by giant kelp.

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