Title: *Long-Term Temporal and Spatial Variability in the Four Major Eastern Boundary Upwelling Systems*

Background: Our world is already beginning to show the effects of climate change; records illustrate that polar ice caps are melting, ocean levels are rising, and tropical storm systems are becoming more powerful. These changes are projected to have a profound influence on society, thus understanding the details of these impacts is arguably one of the most important scientific pursuits of the modern era. Climate is the statistical average of physical atmospheric and oceanic conditions in a given area over a long period of time. It is a complex, dynamic system that we can model through two major concepts: *climate change* and *natural variability*. Although CO_2 is a naturally occurring substance in the atmosphere and retains valuable heat by trapping outgoing long-wave solar radiation, the atmospheric concentration of CO_2 has increased by 31% since preindustrial times, largely due to anthropogenic emissions, and the current level of over 400 parts per million by volume may be the highest concentration in the past 2.5 million years.[1,2]

In contrast to anthropogenic influence, natural variability is caused within the system. Variability is categorized into three components: variation from periodic sources (*e.g.* orbital variations of Earth and other objects in the Solar System); variation from feedback loops (*e.g.* colder temperatures increase ice coverage, in turn increasing surface albedo); and variation from random fluctuations (*e.g.* volcanic eruptions loading the atmosphere with aerosols).[3]

Natural variability and climate change also impact the oceans due to constant interactions between the atmosphere and sea. One possible consequence of this relationship, proposed by Dr. Andrew Bakun in 1990, is the intensification of continental low-pressure systems through surface warming, which would in turn increase the local onshore-offshore pressure gradient, thus amplifying alongshore winds.[4] Future alterations in these winds are important to consider as they drive a physical ocean mechanism known as coastal upwelling. By placing physical stress on the ocean surface, alongshore winds induce a net transport of water down the coastline, forcing deep cold nutrient-rich waters to replenish the surface. Coastal upwelling occurs along all eastern boundaries of ocean basins and supplies surface phytoplankton with inorganic nutrients that are converted into useable organic compounds, resulting in high levels of primary production and a flourishing ecosystem.[5] Thus, the prosperity of eastern boundary upwelling ecosystems (EBUEs) is strongly linked to the timing and amplitude of upwelling season.[5] We consider EBUEs to be of significant global relevancy, as upwelling regions cover only 5% of the surface ocean, but contribute more than 25% of the world's fisheries catch.[6] Due to the importance of EBUEs to commercial fisheries, understanding the potential impacts of climate change on coastal upwelling is a critical question that will impact fishermen, coastal communities, and ocean sustainability worldwide.

The Bakun Hypothesis of upwelling intensification was originally formulated using short-term upwelling indices—however, complex mathematical climate models offer opportunities to more reliably project the future behavior of oceanic-atmospheric interactions. These models take full advantage of the measurement technology available today—not only do they combine fluid dynamics with the geophysical properties of the atmosphere and oceans, but they also integrate empirical data from satellites to compensate for model error. They are useful for projecting decades to centuries into the future—since they are formed through fundamental physical equations, one can simply experiment with different initial conditions and external forcing scenarios to consider an array of possibilities for future climatic scenarios. Today, these physical simulations are known as General Circulation Models (GCMs).

In my most recent funded research project, I investigated the Bakun Hypothesis through GCM simulations. I evaluated the output of 37 models corresponding to each step of Bakun's hypothesis. After running statistical analyses to compare future surface temperature, sea-surface pressure, and alongshore wind stress with historical values from the California coast during peak upwelling season, I did not find support for the Bakun Hypothesis of upwelling intensification.[7] Although model output indicate that coastal landmasses heat more quickly relative to their neighboring oceans, they did not demonstrate overall intensification of the local onshore-offshore pressure gradient. Corresponding alongshore wind stress, used as a proxy measurement for upwelling intensity, portrayed a statistically significant trend toward *downwelling*-favorable winds (Fig. 1).

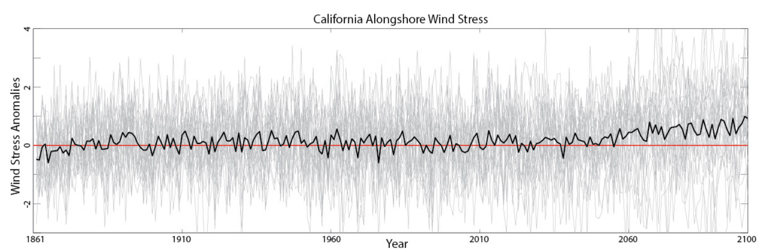

Figure 1. *Predicted alongshore wind stress on the California coast. A more positive time-series suggests a trend toward downwelling-favorable winds. Each of the individual 37 models are in gray, with the ensemble mean in black.*

Current Research Goal: Recently, I found that various models forecast the North Pacific High (NPH) to shift poleward in the next century during upwelling season (Fig. 2). The NPH is a major component of the California Current Upwelling System, thus a poleward shift could disrupt the onshore-offshore pressure gradient, supporting my past conclusions of a trend toward downwelling-favorable winds (Fig. 1).

To extend my past results, I propose to use GCM output to predict the future timing, amplitude, and position of the four major eastern boundary upwelling systems (California, Humboldt, Canary, Benguela) and to work to better understand the large-scale atmospheric changes that cause the resulting scenarios. Furthermore, I will address the consequences these changes would have on their corresponding EBUEs.

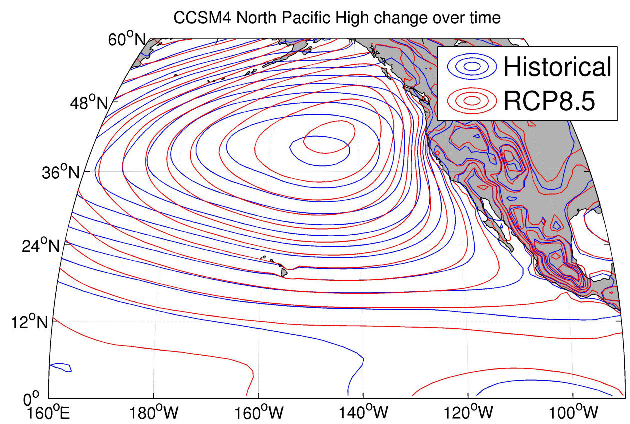

Figure 2. *Contour plot of the CCSM4 modeled sea-surface pressure indicating the mean location of the Jul-Sep oceanic high from 1861-1891 (blue) and from 2070-2100 (red).*

GCM External Forcing Scenarios: To conduct this research, I will use model output with historical external forcing, which covers years 1850-2005 with "very high confidence" that it accurately reflects the rapid warming phase due to emissions during the late 20th century, as well as the cooling phases immediately following large volcanic eruptions.[8] I will compare historical output with data forced by the Resident Concentration Pathway 8.5 (RCP 8.5), which covers years 2005-2100 and produces output that correlate with high population growth and corresponding CO_2 emissions.[9] RCP 8.5 is typically referred to as the "business as usual" scenario.

Methodology: I will work with two separate ensembles to investigate the relative impacts of natural variability and climate change on major eastern boundary current upwelling systems. The first ensemble will be used to consider future upwelling conditions influenced by *natural variability*. It will be an intramodel ensemble, the CESM-LE, which uses a *single* GCM run 30 times under historical and RCP 8.5 radiation forcing, with minor differences in each run's initial conditions.[10]

The second ensemble will be used to consider future upwelling conditions influenced by *climate change*. I will construct this ensemble using models that satisfy both historical and RCP 8.5 radiation forcings and include all necessary output variables. Using a multi-model ensemble is advantageous because it eliminates model bias by sampling various initial and boundary conditions, parameters, and structural uncertainties.[11]

These two ensembles enable me to calculate the future timing, amplitude, and location of oceanic high-pressure zones in upwelling regions to identify significant trends toward seasonal and spatial shifting in the coming century. Modeling the future behavior of Oceanic Highs will help to predict alongshore winds, as they are determined by the gradient between the Oceanic High and Continental Low.

Finally, I will consider alongshore wind stress output in each upwelling system to determine if its future behavior aligns with that of the seasonal and spatial shifts measured in the Oceanic Highs. This information will allow me to assess the future behavior of phytoplankton blooms, their impact on marine fisheries, and thus, the relative health of Eastern Boundary Upwelling Ecosystems.

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