# Climate Change and the Bonney Upwelling System

## Introduction

The effects of the accumulation of greenhouse gases such as carbon dioxide and methane in the atmosphere continues to be the subject of research, so varied are its possible effects and so difficult they can be to predict. The use of similar variations in the global climate over both recent and distant periods of history to compare and contrast with data concerning variations to other natural phenomena continues to grow.

The effect of climate change on marine systems is no different. Recent studies indicate that the ocean, as a major carbon sink, continues to warm as carbon dioxide emissions into the atmosphere fail to abate (IPCC 2013), resulting in a range of reported and hypothesised anticipated effects on circulation currents, sea level rise and marine ecosystems.

Once such area of research of critical importance to marine ecosystems is the effect of warming on upwelling systems.

## Global warming

Carbon dioxide, a greenhouse gas, absorbs radiation of wavelengths between 7 and 14 micrometres, wavelengths commonly found in radiative reflections of light from the earth's surface (Hansen et al, 1981). This causes the chemical to temporarily store and re-radiate the energy absorbed. However, increased concentrations of carbon dioxide (amongst other chemicals) in the atmosphere is leading to increasing temperature in the troposphere. As Hansen et al (1981) put it, as the carbon dioxide concentration in the atmosphere increases, 'the temperature of the surface and atmosphere will increase until the emission of radiation from the planet equals the absorbed solar energy'.

## Upwellings and the Bonney Upwelling

Upwelling systems are an important natural phenomenon that are the basis of a valuable food source to many marine animals due the nutrients they provide to the surface waters of oceans (Rogers et al, 2013). They account for around one fifth of fish production throughout the world, thereby supporting a significant portion of the fishing industry worldwide (Nieblas et al, 2009). Although of such importance, they occur in less than 1% of area of the global oceans (McGregor and Mulitza, 2007).

The system is originally caused by winds blowing along continental shelves. The energy from the wind causes the surface waters to move in manner named 'Ekman transport', after Vago Ekman's description of the transport in 1902. Ekman transport is the phenomenon whereby the movement of the surface waters is in a direction ninety degrees anti-clockwise (in the southern atmosphere, clock-wise in the northern atmosphere) to the direction of the wind and continental shelf, forcing them away from the continental shelf. As the surface water moves away, cold, nutrient rich waters move up from the depths of the ocean to replace the surface waters (see figure 1) (PICSO, 2009)

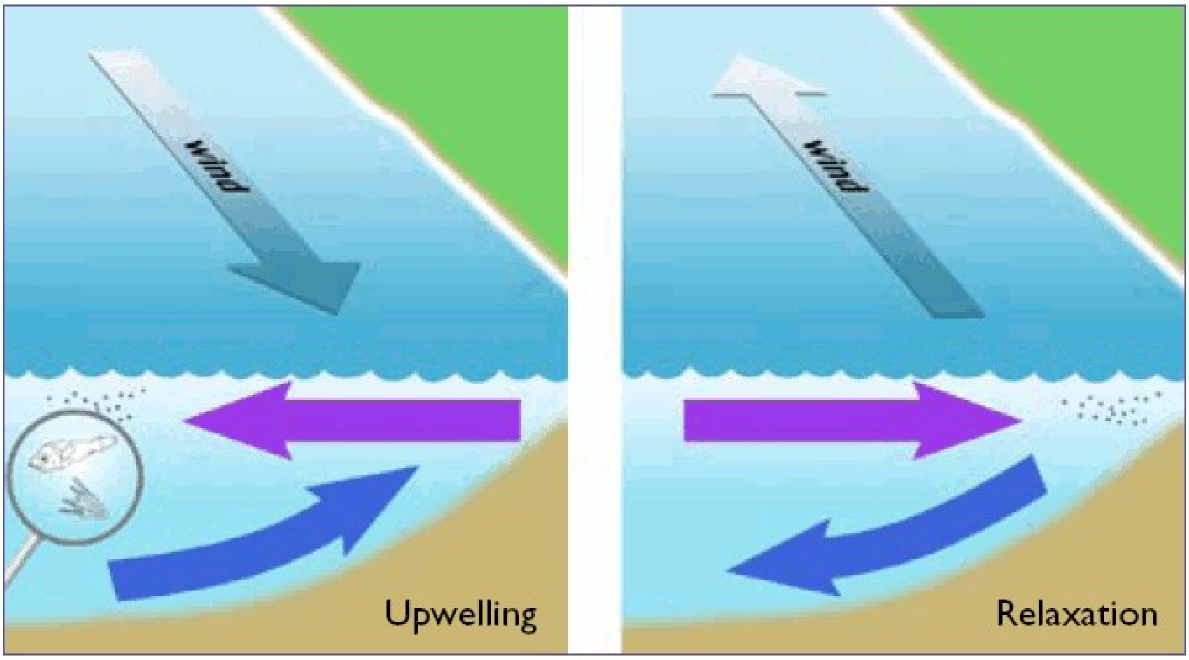


**Fig. 1.** Diagram of wind stress causing Ekman transport of surface water and upwelling of colder, nutrient rich water from the deeper ocean. (PISCO, 2009)

The most significant upwelling off the Australian continent is the Bonney Upwelling which occurs off the southern coast between Portland, Victoria and Robe, South Australia, and occurs during between November and March as a result of high pressure system that sits over the Great Australian Bite, causing south easterly winds to blow along the continental shelf (Butler et al, 2002). These winds, which cause a small offshore current, draw the nutrient rich cold water from a depth of between 50 to 150 metres to the ocean surface (Narayan et al, 2010; Rogers et al, 2013).

The upwelling of nutrients and exposure to sunlight assists in the production of phytoplankton, supporting and attracting such marine species as krill, tuna and blue whales (Butler et al, 2002).

**Positive consequences of global warming on upwelling systems**

Bakun (1990) is the oft quoted seeming pioneer in researching the effects of climate change on upwelling. In his 1990 article he postulated that as global temperatures rise, the air over land surfaces will heat quicker than the air over the water, leading to a greater air pressure gradient between the two than exists in a non-warming world. This in turn would result in stronger offshore and alongshore winds, causing the upwelling  to intensify. Further, the greater the intensity of the upwelling cycle, the more cold water would be drawn to the surface, resulting in a positive feedback which would in turn magnify the air pressure gradient between land and ocean (Bakun, 1990).

As research has progressed in this area, researchers have explored greater amounts of data of increasing quality and covering greater periods of time. Models have been developed to recreate the upwelling events and model the effects different climates have on it.

Using meridional wind stress and sea surface temperature, a 2010 study of the upwelling trends off California, North West Africa and Peru provided data believed to reliably show an increase of coastal upwelling intensity over the last 50 years when other oceanic oscillations were ruled out. The increase in wind stress correlated well with lowering sea surface temperatures, generally considered a good indicator of intensified upwelling (Narayan et al, 2010), providing the basis. A similar conclusion was reached by Juillett-Leclerc & Schrader (1987).

McGregor and Mulitza (2007) reached a similar conclusion after reconstructing sea surface temperature off Cape Ghir, Morocco, from marine sediment cores which were estimated to expand 2500 years before present. They found rapid cooling of sea surface temperatures which coincided with the increases in global temperatures during the Medieval Warm Period and the Little Ice Age and that similar changes have been occurring over the last century (figure 2).

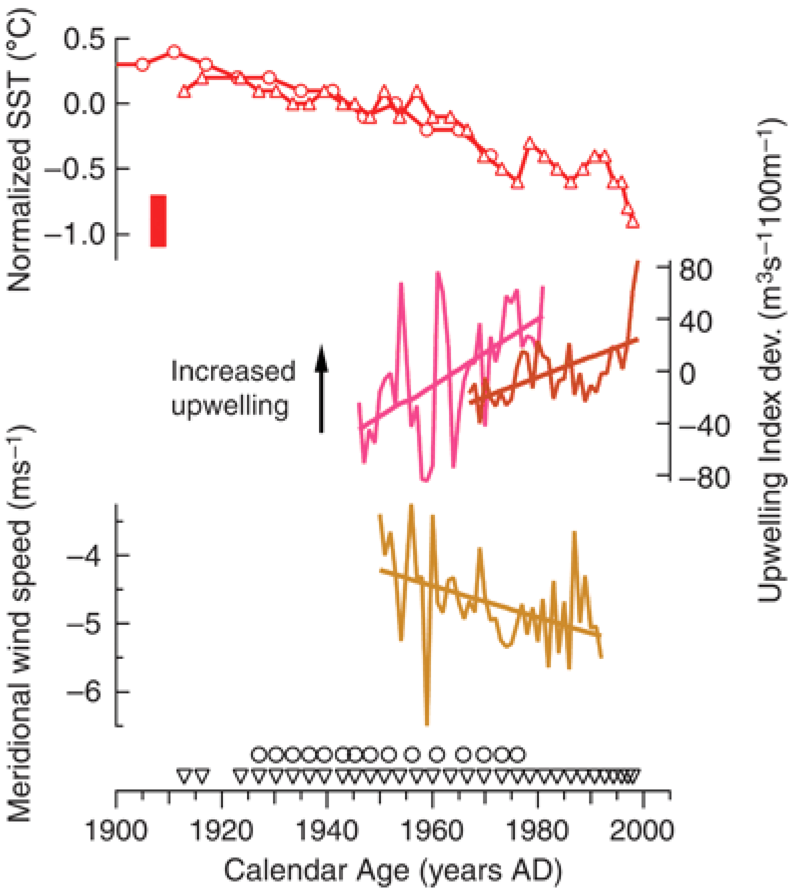


**Fig. 2.** Graphs of decreasing sea surface termperature (SST), increasing upwelling and decreasing meridional wind speed over time (McGregor & Mulitza, 2007).

The Benguela Upwelling System was studied using a similar method and a similar increase in upwelling intensity found, this time over a three thousand year period. Sea surface temperature records showed a cooling of about 2 degrees Celsius over the last 30 years due to a correlation with an increase in the concentrations of Alkenone, an organic compound which is produced by phytoplankton, among similar perturbations throughout the time tested (Leduc et al, 2010).

Greater Alkenone levels indicate greater phytoplankton which in turn indicate greater nutrient levels reaching the surface layers of the ocean waters. Leduc et al correlated the upwelling intensity changes with temperature records from ice cores for the same period and concluded that increased global warming will also increase upwelling intensity.

Similar again, Sifeddine et al (2008) used laminated sediment studies of cores taken from the Peruvian continental slope to examine mineral, organic and inorganic markers for different time periods. Increasing organic materials found were attributed to an increase in upwelling activity, and found an increase in upwelling by this method since the late nineteenth century.

Modelling of regional circulation currents to simulate the upwelling process over a period of 30 years using different global temperature variables on the Iberian upwelling found upwelling to be 'very sensitive to slight changes in the wind', in particular in regions where upwelling is episodic and not permanent, resulting in changes in the frequency, intensity or time frames of the upwelling (Miranda et al, 2012).

**Negative consequences of global warming on upwelling systems**

Despite the above research displaying a general correlation between observational data and Bakun's theory, not all studies area.

The Environment Australia 'Assessment of the Conservation Values of the Bonney Upwelling Area' (2002) was non-committal in its assessment of the effect a warming climate would have, citing Griffin et al (1997) that not all strong upwelling-favourable winds necessarily lead to stronger upwelling. The authors of that report also note the contrasting possibilities that global warming could result in lowered carrying capacity of the upwelling, or alternatively to the increases in productivity noted similar to that predicted and reported above (Butler et al, 2002).

More recent research into the Bonney Upwelling support the argument that increased strength in upwelling-favourable winds do not necessarily result in more prominent upwelling events (Figure 3). Instead, a parabolic relationship is asserted to exist between wind intensity and upwelling, whereby wind that is too strong leads to excess turbulence in the surface waters or that the cold, nutrient rich water reaching the surface moving too quickly away from the upwelling region, reducing the concentration of nutrients which give upwelling events their importance (Nieblas et al, 2009).

In the same study, Nieblas et al used modelling of wind speed, upwelling intensity and nutrient concentration to find that the Bonney Upwelling is powered by low-speed winds, with a windspeed of only 2.7 m/s required, significantly less than that required by other upwelling systems. In such low-wind powered upwelling systems, an increase in wind speed up to a certain maximum level results in a linear increase in the concentration of nutrients at the sea surface (Nieblas et al, 2009).

An earlier paper detailing the various effects of climate change on ocean life expressed similar concerns about the effect increased upwelling and advection of nutrients would affect marine fauna reliant on them, citing that this was already being observed in the North East Pacific upwelling systems (Walther et al, 2002).

The 'optimal environmental window' discussed by Nieblas et al above (2009) was previously studied by Botsford et al (2006) in a paper. The authors argue that the Bakun hypothesis that greater wind equals greater upwelling and nutrients fails to consider the rapid advection of those nutrients, preventing their concentration and reaching the point where advection losses of nutrients could outweigh the gain of nutrients in the upwelled waters reaching the sea surface.

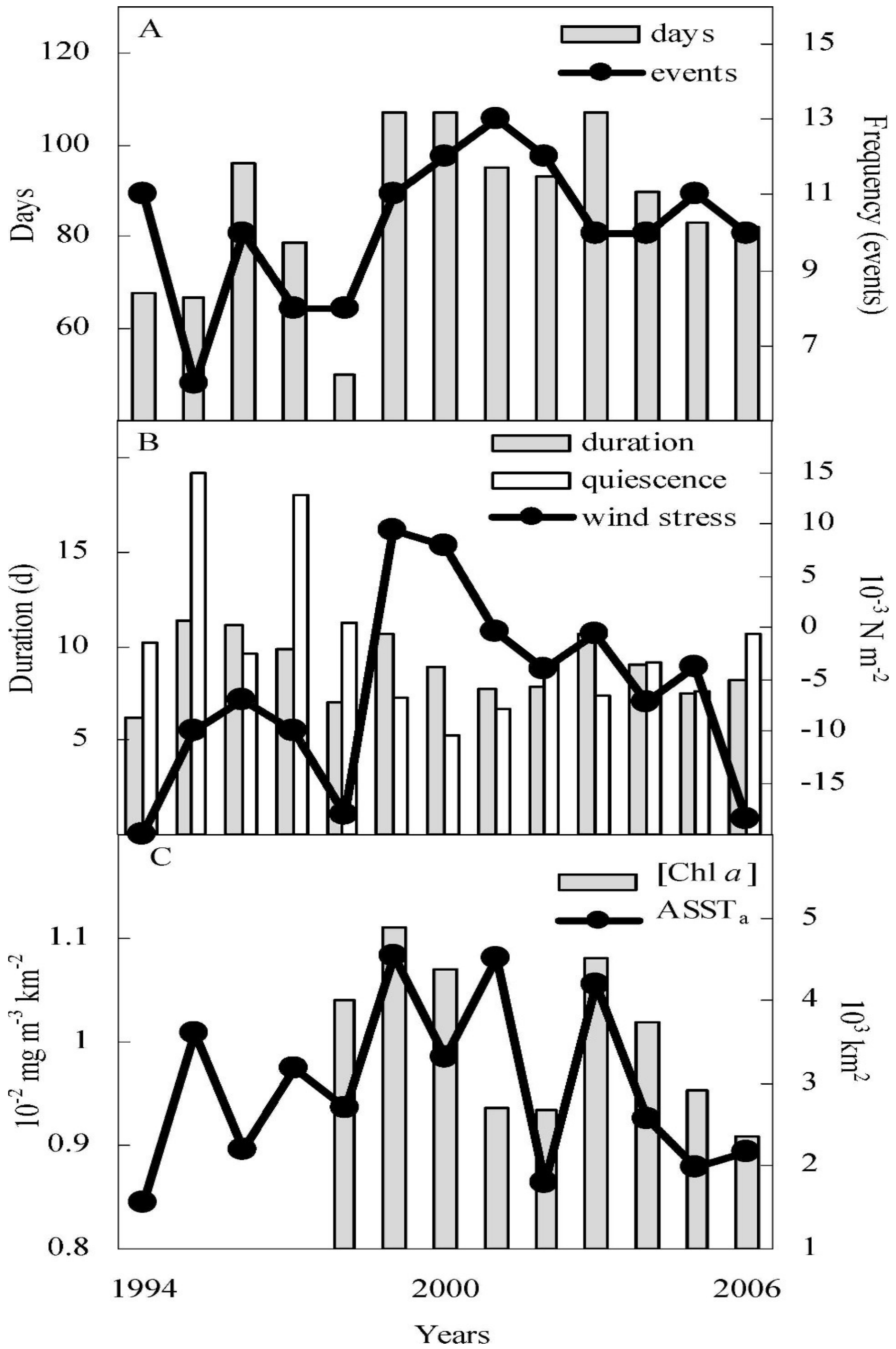


**Fig. 3.** Modelled findings on effect increased wind has on upwelling intensity and duration. (Nieblas et al, 2009)

Further illustrating the difficulty of using a 'one size fits all' approach to predicting future upwelling productivity, the same authors point to various data modelling of the California current, noting that sometimes the Bakun hypothesis is correct, and sometimes it is not.

A further effect of warming climates is the warming of the waters themselves. The Intergovernmental Panel on Climate Change recently found it likely that the ocean warmed between the depths of 700 metres and 2 kilometres from 1957 to 2009, that the upper 75 metres of the ocean have warmed by around 0.11 degrees Celsius per decade between 1971 and 2010,(IPCC, 2013).

Warm water has a lower density than colder water. The difference in temperature and density of water in a water column results in stratification of the water.

Upwelling events disturb the stratification by bringing colder water to the layers where warmer water sat before being moved away in the Ekman transport. However, it is predicted by some researchers that the warming of the upper layers of the ocean waters faster than the lower levels of the column, resulting in increased stratification of the column, will result in reduced displacement of the warmer waters to allow the cold waters to reach the water surface (Roemmich and McGowan, 1995; Harley et al, 2006; Danovaro et al, 2001; Otterson et al, 2010; Brander, 2010).

Roemmich and McGowan (1995) used observational data taken over 43 years off the California coast to find warming of the ocean surface and reductions in zooplankton numbers and suggest the warming waters and increase in stratification has caused the reduced abundance. Using the data they assert that the level from which the water is upwelled from is shallower, resulting in warmer, less nutrient rich water being upwelled to the surface.

Similar findings based on the effects of El Nino conditions on stratification of water at the upwelling location off the coast of Peru have been made (Danovaro, 2001; Otterson et al, 2010), giving a reasonable comparison between the El Nino effect and climate change effects on stratification and upwelling.

The most recent article reviewed sought to again address the 'paradox' between global warming and intensified cooling by intensified upwelling. The article reviews the analysis of Alkenone levels to justify the finding of increased warming resulting in increased upwelling, such as those reported above, and asserts that the data used don’t necessarily correlate with other sources of data relevant to upwelling intensity, such as directly observed sea surface temperatures. The authors cautioned against the reliance on secondary datasets viewed in isolation, and ultimately found that:

1. Sea  surface temperatures are rising at a rate greater than 1 degree Celsius per year;
2. There was no evidence to suggest increased wind force in upwelling areas or increased upwelling generally.

In doing so, they also question the positive feedback loop of increasing temperatures over land and decreasing sea surface temperatures pushing the enhanced upwelling given the evidence of ocean warming, whilst also noting the increasing stratification as being a probably cause of the observed reductions in nutrient levels and warmer sea surface temperatures (Barton et al, 2013).

## Discussion and Conclusion

It is generally agreed that the warming effects of increasing carbon dioxide and other greenhouse gases on the atmosphere will have some effect on upwelling intensity. The most persistent idea that has influenced the literature is Bakun's hypothesis (Bakun, 1990), but the addition of more variables than just wind speed caused by increasing pressure gradients, such as the increasing stratification caused by warming of the oceans, provide a dampener on the positive effects of Bakun's hypothesis on the potential benefit of the warming we expect to continue.

The differing data analysed in the papers don't give any unequivocal indication of whether wind speeds are increasing as the climate warms, that continuing to increase wind speeds will continue to increase upwelling or that sea surface temperatures are decreasing as a result of increasing upwelling intensity. Further, reports on modelling the phenomenon tend to not involve all possible variables covered in the literature, some not factoring in increased advection of nutrients, others not modelling the effect on increased stratification, casting some doubt over their predictions given.

Finally, it is apparent that upwelling systems in different areas have the potential to react differently to warming effects, and that merely extrapolating one model of the system will provide an accurate prediction of the changes in other systems.

As a result, it is difficult to reach a final conclusion as to what effect climate change will have on the Bonney Upwelling system. Specific study into this one upwelling is very limited, especially compared to research into other upwelling systems worldwide presented in the literature and the varying data analysis portrayed in them.

Given the uncertainty in the data analysed about whether increased wind speeds have been observed in other regions, a number of conclusions could be reached about climate warming effects:

1. Global warming is and will continue to increase the land-sea pressure gradient, increasing along-shore wind speeds and in turn increasing upwelling and nutrient supply to the sea surface;

2. Wind speed increases and results in increased upwelling but also gains in advection of the nutrients, reducing nutrient concentration in the system;

3. There is no or little increase in wind speed due to increases in sea temperature occurring at roughly the same rate as increases in land air temperatures, resulting in minimal disturbance to the intensity of the upwelling systems; or

4. Whether or not wind speed increases, stratification results in less cold, nutrient rich waters reaching the sea surface.

Further reliable data about sea surface temperature both at surface and at lower levels, the degree of reduction in the temperature of waters upwelled, wind intensity and nutrient levels are needed for proper modelling to be generated. Only then can a prediction of greater reliability be made for the future.

As can be seen, the anthropogenic increases in greenhouse gas emissions into the atmosphere has remoter consequences than warming of the planet. The warming of the atmosphere seems likely to result in changes to upwelling systems, the consequence of which continues to be the subject of research and debate.

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