CLIMATE AND OCEANOGRAPHY OF THE GALAPAGOS IN THE 21ST CENTURY: EXPECTED CHANGES AND RESEARCH NEEDS

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SUMMARY

With the likelihood that carbon dioxide and other greenhouse-gas levels in the atmosphere will continue to increase for the next decades, and that the planet as a whole will likely warm as a result, we expect the oceanography and climate of the Galapagos to change. Based on an analysis of observational studies and climate models, the main changes are likely to include higher sea-surface temperatures, continued El Niño and La Niña events, some of which will be intense, a rise in sea level of several cm, increased precipitation, lower surface ocean pH, and a reduction in upwelling. These changes will likely alter the marine and terrestrial ecosystems of the Galapagos in ways that are difficult to predict. Major uncertainties exist concerning the relationship between the expected regional changes in ocean temperatures, precipitation, upwelling and seawater pH that most climate models consider, and the local changes in the Galapagos Islands.

RESUMEN

Clima y oceanografía de Galápagos en el siglo 21: cambios esperados y necesidades investigativas. Con la probabilidad de que los niveles de dióxido de carbono y otros gases del efecto invernadero en la atmósfera continuarán incrementándose por las próximas décadas, y de que el planeta en su totalidad seguramente se calentará como resultado, suponemos que la oceanografía y el clima de Galápagos cambiarán también. Basado en un análisis de estudios observacionales y de modelos climáticos, los mayores cambios probablemente incluirán elevación de la temperatura de la superficie del mar, continuación de los eventos de El Niño y La Niña (algunos de los cuales serán más intensos), una elevación del nivel del mar en varios cm, un incremento de la precipitación, un decremento del pH de la superficie del océano, y una reducción en las corrientes ascendentes. Estos cambios probablemente alterarán los ecosistemas marinos y terrestres de Galápagos en modos difíciles de predecir. Existen mayores incertidumbres acerca de la relación entre los cambios regionales esperados en temperaturas oceánicas, precipitación, corrientes ascendentes y pH del mar que la mayoría de los modelos climáticos consideran, y los cambios locales en las Islas Galápagos.

INTRODUCTION

In April 2009, a panel of climate scientists (listed in the Acknowledgments) convened in Puerto Ayora, Galapagos to evaluate the expected changes in the climate and oceanography of the Galapagos in the coming decades. This article represents the outcome of those discussions and may be useful to scientists and policymakers interested in the impact of future climate changes on the marine and terrestrial ecosystems of the Galapagos Islands.

TEMPERATURE CHANGE

As of 2007, there had been no discernible trend in sea surface temperature (SST) in the region of the Galapagos (2° x 2°, or about 200 x 200 km, centered on 0°N, 90°W) since the start of the Industrial Revolution (Smith *et al.* 2008). Nor was there any trend in local SSTs at Santa Cruz Island in the Galapagos over the last 44 years (Wolff 2010). Yet the larger equatorial Pacific, as indicated by the Niño 3 index of SST in the region 90–150°W and 5°S–5°N, has warmed by 0.4–0.8°C over the last 40 years, and warming throughout the region is expected to continue over the course of the 21st century, with the best estimates indicating 1–3°C of additional warming (IPCC 2007a). Whether local SSTs in the Galapagos will continue to buck the warming trend observed in the greater equatorial Pacific region over the last 40 years is unknown. But it seems imprudent to extrapolate from a failure to follow the regional temperature trend when that trend is only 0.4–0.8°C, and conclude that local SSTs will not rise in the face of the expected 1–3°C of warming in the equatorial Pacific region this century.

Additionally, despite the overall trend towards warmer SST in the equatorial Pacific, decadal variability will likely continue, but this variability may well be stochastic, and there is a large consensus that its spectral character approximates a red noise process, with more power at lower frequencies (Gedalof *et al.* 2002). In other words, predicted decadal variability in equatorial Pacific SST can best be described as predominantly random with some memory. One of the most prominent decadal variations, the Pacific Decadal Oscillation, may not force temperature changes, but could simply result from the El Niño-Southern Oscillation (ENSO) (Newman *et al.* 2003).

A lack of understanding of the linkage of large-scale analyses (*e.g.* IPCC-type) to local scales as in Galapagos remains, and this knowledge gap should be a focus for future research. There is a clear need for more meteorological and hydrographic observations, combined with widespread data dissemination, so existing time series of SST and meteorological conditions can be compared. One step towards achieving this aim would be to reinstate the rawisonde program in the Galapagos, which made daily weather balloon deployments to measure atmospheric temperature, pressure, humidity, wind speed and wind direction through the atmosphere above San Cristóbal Island from 1990–8. Additional research should focus on down-scaling models, especially atmospheric ones, by including more ensemble members (*i.e.* numerical predictions using slightly different initial conditions), with assistance from ocean dynamics researchers. Paleoclimate records can also be used to link large-scale analyses to local scales. Future research should focus on generating new paleoclimate records, especially from the lowlands, and linking them to more recent instrumental records. Calibration of paleoclimate proxies under modern conditions should be an integral part of this. Finally, we need a better understanding of the dynamics and interactions of the Panama and Humboldt Currents with the Galapagos (see below).

EL NIÑO SOUTHERN OSCILLATION

The ENSO is the dominant inter-annual global climate variable that strongly impacts the Galapagos (Cane 2005, Philander 1983). During El Niño events, the surface ocean around the Galapagos warms substantially and the islands receive significantly more rainfall than in normal years. The warmer water is poorer in nutrients than the cool waters that normally surround the Galapagos, which disrupts the marine ecosystem, causing mass mortality of coral, seabirds and marine mammals during the strongest events, such as those in 1982–3 and 1997–8 (Glynn 1988). Major changes to terrestrial ecosystems also occur, with heavy rain permitting the establishment of newly colonizing plants and animals, and dramatic increases in the biomass of herbaceous plants and vines at the expense of cacti (Hamann 1985, Luong & Toro 1985, Tye & Aldaz 1999, Holmgren *et al*. 2001).

Since 1880 A.D., ENSO events have occurred roughly every 2–7 years, with no clear periodicity (Cane 2005). The late 20th century was characterized by particularly strong and frequent events that led some researchers to conclude that an anomalous and unusual change had occurred in ENSO that could be attributed to increased levels of atmospheric greenhouse gases (IPCC 2001, IPCC 2007B, Trenberth & Hoar 1997). This claim has been challenged by other researchers and at best it is uncertain (Cane 2005, Rajagopalan *et al.* 1997). The duration of the instrumental record of SST and atmospheric pressure is too short to conclude that a fundamental change in ENSO variability has occurred (Wunsch 1999). Though supported by some theory and models (Timmermann *et al.* 1999), a link between greenhouse-gas-induced global warming and increased frequency or intensity of ENSO events remains inconclusive (Collins 2000), with the average of projections from coupled ocean-atmosphere general circulation models showing no change in ENSO variability over the 21st century (Collins & Groups 2005, IPCC 2007a), but rather a tendency toward a more El Niño-like state of the tropical Pacific (Cane 2005). In all likelihood, ENSO-related variability will continue in the coming decades and is likely to modulate SST, rainfall and sea level changes in the Galapagos on inter-annual timescales (IPCC 2007a).

Future research in this area should include continued efforts to understand the long-term behavior of ENSO; this is a major research thrust by IPCC-related researchers and modelers. Additionally, it is necessary to develop ENSO indicators relevant to local conditions. For example, 2008 was characterized by high rainfall in the Galapagos even though it was not an El Niño year.

SEA LEVEL RISE

Global mean sea level has risen by *c.* 20 cm since 1880 A.D. as a result of global warming and the rate of increase has accelerated since about 1930 (IPCC 2007a). However, the rate of sea level rise since the mid-20th century has not been as significant in the eastern equatorial Pacific as in other parts of the world (IPCC 2007B). There has been no discernible trend in sea level over the last 26 years on Santa Cruz Island in the Galapagos (Fig. 1). Nevertheless,

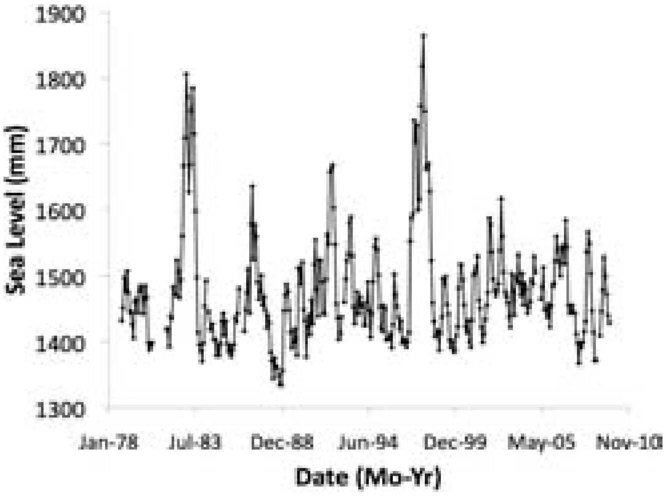

Figure 1. Sea level at Santa Cruz, 1982–2008. No significant trend exists. The two large El Niño events of 1982–3 and 1997–8 are visible as periods of higher than normal sea level. Data from the University of Hawaii Sea Level Center <http://uhslc.soest.hawaii.edu/>.

global mean sea level is projected to rise by 20–50 cm (IPCC 2007a) or more (Rahmstorf *et al.* 2007, Solomon *et al.* 2009) over the 21st century. In the Galapagos, subsidence of some of the islands, or portions of them, has the potential to exacerbate local sea level rise in the coming decades.

Adaptation to sea level changes may be viewed through the lens of strong El Niño events, which cause sea level in the Galapagos to increase by up to 45 cm, as occurred during the 1997–8 event (Fig. 1). Recent land use changes (*e.g.* coastal development) have made the Galapagos much more vulnerable to even modest rises in sea level, including those associated with El Niño (Clarke & Van Gorder 1994, Clarke & Lebedev 1999). It is important to determine why local sea level in the Galapagos has not been observed to rise in concert with the modest rise in sea level in the eastern equatorial Pacific, and to monitor local rates of subsidence, which may exacerbate the rise in global sea level. It would therefore be advantageous to augment the tide gauge on Santa Cruz with additional gauges throughout the archipelago.

PRECIPITATION

Mean annual precipitation in Puerto Ayora, Santa Cruz Island, has varied significantly over the last 45 years, with El Niño years being characterized by high rainfall and La Niña years characterized by low rainfall (Trueman & d'Ozouville 2010). But this relationship can break down, as observed in 2008, a non-El Niño year, when rainfall amounts were greater than in several El Niño years of the last half century. On longer time scales, rainfall reconstruction from the sediments of El Junco crater lake on San Cristóbal Island indicate that the Galapagos have been trending toward a wetter mean climate in the past 130 years (Sachs *et al.* 2009). The driest period of the last 1200 years in the Galapagos was apparently the end of the 19th century, which we attribute to the end of the northern hemisphere climate anomaly known as the "Little Ice Age" (Grove 1988). Since that time there has been a trend toward wetter conditions, though even modern rainfall amounts are lower than any other time in the last 1200 years prior to about 1880 AD. Reconciling our sediment data, which indicate increasing precipitation over the last several decades, with the observations for the last 45 years which indicate no significant trend in precipitation (Wolff 2010), is possible considering that the El Junco sediment samples average over *c.* 30 years of deposition, and there could also be differences in rainfall recorded at sea level on Santa Cruz Island and at 750 m on San Cristobal Island. Nevertheless, if the century-long trend toward a wetter climate in the Galapagos that is implied by the El Junco data continues, we would expect the Galapagos to receive increasing rainfall in the coming decades.

Whether the trend toward increased precipitation since the start of the Industrial Revolution is connected to anthropogenic alteration of the climate is unknown, but the IPCC indicates a > 90 % chance of increased precipitation over the 21st century in the region of the Galapagos (IPCC 2007a). As discussed for temperature, local changes will not necessarily follow regional changes, and a critical downscaling question concerns the trend of local Galapagos rainfall in the future. Much more extensive measurement of Galapagos weather (in both the highlands and the lowlands) needs to occur in order to address this question.

In addition to overall precipitation trends, it is necessary to assess the impact of a warming global climate on *garúa*, the mist that forms from low stratus clouds, typically during the cool, dry season lasting from June to December. This water source is critical to highland plants and ecosystems. Future trends in *garúa* formation, duration and elevation are uncertain because its formation depends on a complex interaction of SST, wind and humidity. We surmise, however, that a weakening of the Walker circulation, as predicted by theory and many global circulation models (GCMs) (DiNezio *et al.* 2009, Vecchi & Soden 2007, Vecchi *et al.* 2006), would likely result in a reduction of *garúa* in the Galapagos. In addition, if local SSTs increase, especially in the cool, dry season, the optical depth (the proportion of light absorbed or scattered by fog) and/or the seasonal duration of *garúa* would be expected to decrease. On the other hand, if the frequency and/or intensity of La Niña events were to increase, or there were an increase in local upwelling, the reverse might ensue.

Another complication is that although it is tempting to use past ENSO events as a model for the influence of a warmer ocean on precipitation in the Galapagos, ENSO may not be a good model for long-term climate change. The existence of a spatial pattern of SST in the tropical Pacific which is similar to that during an El Niño event does not necessarily imply that the underlying dynamics are the same (DiNezio *et al.* 2009, Vecchi & Wittenberg 2010).

Future studies should focus on understanding the dynamics of *garúa* formation, including establishing whether there is a threshold SST above which *garúa* will not form, and what the influence of the large-scale ocean-atmosphere circulation is on *garúa* formation. Better understanding of *garúa* formation might be achieved by analyzing existing precipitation, SST, humidity (both highland and lowland), pressure and wind data to determine the conditions under which *garúa* forms and persists.

OCEAN ACIDIFICATION

An increase in atmospheric carbon dioxide levels from 290 to 385 ppm since the start of the Industrial Revolution has caused the global ocean pH to decline by 0.1 since 1880 A.D. and an additional 0.4 pH unit decline is expected by the end of this century (Caldeira & Wickett 2003). The increased acidity of seawater will make the production of calcium carbonate shells by marine plants and animals increasingly difficult (Orr *et al.* 2005). Making matters worse, regions where upwelling produces surface water already rich in CO_2, such as the Galapagos, are more sensitive to increases in CO_2 (Doney *et al.* 2009, Manzello *et al.* 2008). This is demonstrated by the high buffer (Revelle) factor in the region of the Galapagos relative to most of the tropical and subtropical ocean, which indicates a decreased ability to counteract pH changes when atmospheric CO_2 concentration increases (Sabine *et al.* 2004).

The upshot is that calcifying organisms and the marine ecosystem in the Galapagos are likely to be more sensitive to an acidifying ocean than the rest of the globe, as atmospheric CO_2 levels rise. When atmospheric CO_2 levels reach 450 ppm, which will likely occur by mid-century, coral growth is predicted to be at *c.* 50 % of its pre-industrial rate (Silverman *et al.* 2009), due to a combination of higher SSTs and lower aragonite saturation levels (Fabry *et al.* 2008, Feely *et al.* 2008, Hoegh-Guldberg *et al.* 2007, Silverman *et al.* 2009). Coral reefs in the Galapagos will likely become incapable of surviving if atmospheric CO_2 levels reach 750 ppm (Silverman *et al.* 2009), the level expected by the end of the 21st century (IPCC 2007a).

Future study should address the relative vulnerability of Galapagos coral to ocean acidification, given that these corals already experience large swings in pH associated with ENSO.

UPWELLING

Many of the most sophisticated coupled ocean-atmosphere GCMs predict a reduction in trade wind strength, the Walker Circulation, surface currents, and vertical ocean velocity in the equatorial Pacific as a whole, but to a lesser extent in the eastern equatorial Pacific, as atmospheric CO_2 levels rise (DiNezio *et al.* 2009, Vecchi & Soden 2007). Weaker trade winds and equatorial surface currents are expected to reduce upwelling, Ekman divergence (the movement of water to the north and south of the equator caused by easterly winds at the ocean surface), and the east-west thermocline tilt (DiNezio *et al.* 2009).

Unfortunately, it is difficult to discern what the changes in upwelling in the Galapagos will be. This local upwelling results from a complex interplay between the bathymetry, the South Equatorial Current that flows west at the surface, and the Equatorial Undercurrent that flows east in the subsurface (Eden & Timmermann 2004). The Archipelago presents a topographic barrier that disrupts the flow of these major currents and tropical instability waves, such as the Kelvin waves that are generated during El Niño and La Niña events (Eden & Timmermann 2004). The Galapagos are small when compared to the scale of most general circulation models, and the processes that cause upwelling to occur there are influenced by basin-wide features as well as small scale bathymetry, so it is not yet possible to predict how changes in the ocean-atmosphere circulation will affect Galapagos upwelling. The same downscaling issues exist as discussed for temperature and precipitation.

The Panama and Humboldt Currents also affect the Galapagos, but there are too few model studies to predict how these currents are likely to change during the present century. Such studies should be included in future research.

CONCLUSIONS

Over the next several decades, the Galapagos will experience changes related to global warming. Although varying degrees of uncertainty exist for each factor, the future of the Galapagos will most likely include continued ENSO events, some of which may be intense, increases in sea level, precipitation and surface ocean temperatures and acidity. However, many uncertainties and areas for research remain, particularly concerning the relationship between local and regional SSTs, precipitation, upwelling and acidification.

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