Consensus Report
Climate Change and Biodiversity in Melanesia: What do we know?

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CLIMATE CHANGE AND BIODIVERSITY IN MELANESIA

Series editors:
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Funding provided by:
John D. and Catherine T. MacArthur Foundation

Bishop Museum Technical Report

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1.0 Introduction

Melanesia is one of the richest biotic regions on the planet. Although consisting of slightly more than half of one percent of the earth's land area, Melanesia contains a high percentage of the Earth's terrestrial and marine biodiversity. Numerous studies have indicated that the island of New Guinea (the country of Papua New Guinea and Indonesia's Papua province) and its associated archipelagos, and the major Melanesian islands (located in the countries of Solomon Islands, Vanuatu, Fiji, and the French Pacific territory of New Caledonia) are major global priorities for conservation (Olsen and Dinerstein 2002[1]; Wikramanayake et al. 2002; Mittermeier et al. 2003; Mittermeier et al. 2005). Melanesia's conservation priorities include species and habitat protection as well as the continued provision of ecosystem services to local and global communities that depend on them. How regional climate change resulting from anthropogenic global warming will affect biodiversity in Melanesia is therefore a critical subject for examination with far-reaching implications.

Melanesia comprises the eastern half of the so-called Coral Triangle, the global epicenter of marine biodiversity. Its marine resources include sites that have been documented as among the richest and most diverse coral reefs in the world (McKenna et al. 2002; Allen et al. 2003). As an example, the Raja Ampat islands at the far western tip of Papua province are estimated to contain as much as 75% of the world's total coral species (Turak and Souhoka 2003). The reef fish fauna is characterized by high levels of both richness and endemism. Melanesia's littoral habitats are also globally significant, containing the largest unbroken stretches of mangroves found anywhere in the world (NOAA 1995).

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[1] Melanesia contains fourteen of WWF's "Global 200" priority Ecoregions: Southern New Guinea Lowland Forests (vulnerable); New Guinea Montane Forests; Solomons-Vanuatu-Bismarck Moist Forests; New Caledonia Moist Forests; New Caledonia Dry Forests; Trans-Fly Savannas (categorized with Northern Australia savanna); New Guinea Central Range Subalpine Grasslands; New Guinea Mangroves; New Guinea Rivers and Streams; New Caledonia Rivers and Streams; Lakes Kutubu and Sentani; Bismarck-Solomon Seas; New Caledonia Barrier Reef; & Fiji Barrier Reef & Marine.

On land, Melanesia is a hotspot of diversity for vascular and non-vascular plant species, and is a major center for floristic diversification. The flora within the Melanesian region has been strongly influenced by a complex geological history and historical climatic influences. Endemism and biodiversity estimates are constantly changing due to the description of new species, changes in taxonomic names and phylogenies, and range extensions of species previously thought to be restricted to other areas. However, the total number of plant species on the island of New Guinea alone is estimated to be possibly as high as 20,000 to 25,000, and species endemism between 60–90% (Supriatna et al., 1999).

Terrestrial fauna also show very high levels of diversity and endemism. Again taking New Guinea as a benchmark, the island contains at least 1,647 land and freshwater vertebrates, of which 69% are endemic, and constituting about 8% of currently recognized world vertebrates (Allison 2007). Most famously consisting of monotremes and marsupials that are affiliated with the Australian region, mammal diversity contains with high numbers of endemic and/or refugia species, and constitutes over 5% of the world total for mammals. The Melanesian avifauna is also recognized as globally significant both for richness and endemism, and numbers over 600 species in New Guinea alone – over 6% of the world total (Allison 2007).

However, knowledge of Melanesia's biotic richness comes despite relatively sparse scientific documentation of the area. Indeed, Melanesia is also among the most poorly biologically studied regions in the world. New marine and terrestrial species are still routinely identified by science on every visit to new study sites, and even less is known about local ecological interactions and processes. Basic physiographic data such as temperature, rainfall, etc. are seriously lacking and/or incomplete. Overall, there is little data, and less scientific knowledge, regarding the true extent of Melanesia's marine and terrestrial biodiversity resources or their importance to, or role in, critical ecological processes (Burnett 2007).

Given the serious knowledge gaps, how and to what degree anthropogenic global warming will affect Melanesia's biodiversity is therefore less readily amenable to easy assessment than for other more documented areas of the tropics such as the Amazon and Africa (acknowledging that assessments for those areas are challenging enough). Because of the limitations in biodiversity, climate, and oceanographic data for Melanesia, it is important to recognize that the current scientific capacity to understand and assess potential climate changes in the region has inherent limitations. Furthermore, global climate models (GCMs) are just that – they are designed to project a range of broad-scale future changes in climate patterns over very large areas. While they are increasingly good at predicting how global, or in some cases large regional, changes will take place, they are not sufficiently accurate to predict climate changes on a local (e.g. island) level. This limits their value as policy inputs to assessing and mitigating climate change impacts on biodiversity for any part of the world, and this is especially true for Melanesia. With that caveat, there is still much value in looking at GCMs in relation to a region's biodiversity, as broad-scale changes are often reasonably clear, and can provide a meaningful context to critically assess how biodiversity will fare at local levels.

The 4th Intergovernmental Panel on Climate Change (IPCC) Report concludes that:

> Sea levels are *likely* to rise on average during the century around the small islands of the Caribbean Sea, Indian Ocean and northern and southern Pacific Oceans. The rise will *likely* not be geographically uniform but large deviations among models make regional estimates across the Caribbean, Indian and Pacific Oceans uncertain. All Caribbean, Indian Ocean and North and South Pacific islands are *very likely* to warm during this century. The warming is *likely* to be somewhat smaller than the global annual mean. Annual rainfall is *likely* to increase in the equatorial Pacific, while decreases are projected by most models for just east of French Polynesia in December, January and February." (Christensen et al., 2007)

The need for more robust regional climate change assessments was highlighted in the most recent IPCC report (Christensen et al., 2007). While GCMs are constantly being improved – including progress towards finer-scale GCMs that couple atmospheric-ocean-carbon systems – there is a strong need for the development of both Regional Climate Models (RCMs) as well as GCMs that are downscaled (via statistical regression analysis) to a regional scale. And yet, as will be discussed in this report, there are many critical knowledge gaps that currently present limitations on the development of these models for the Pacific region generally and Melanesia in particular. These gaps include a dearth of data on temperature & rainfall, which are essential to "groundtruth" climate models. However, this absence of data is the current scientific context, and given the urgent need to understand the implications of climate change, it is important to use the information and methods currently available while recognizing its limitations. Scientific knowledge is never complete, but there is an obvious and critical need to assemble the best state of scientific knowledge on the subject in order to provide policy-relevant recommendations.

This overview Consensus Report draws on and summarizes eleven White Papers and/or research presentations that were commissioned for this project. These were each developed by an internationally recognized scientific expert in the respective subject (see Appendix A). We categorize these reports into two groups: Biophysical Impacts (projected large-scale physical changes to atmospheric, climate, and oceanographic processes as a result of AGW) and Biodiversity Impacts (how species and ecosystems can be expected to respond to these biophysical changes). The authors of these reports have taken care to note where data is lacking or unavailable, and what research is needed in order to fill these gaps. After reviewing these analyses, we overview the state of scientific knowledge regarding Melanesia's marine and terrestrial ecosystems and suggest best estimates for the impact that global climate change may have on the region's biodiversity, concluding with a set of recommended guidelines for conservation strategies that are implicit or explicit in the individual reports.

Finally, a critically important aspect of AGW and biodiversity is how it will affect the ecosystem services upon which Melanesian societies rely. We strongly agree with the importance of assessing these future social and economic implications, but it is outside the scope of this study. This subject is partly addressed in Component II of the project conducted by our partners at the Pacific Regional Environment Programme (SPREP) and their reports are included in as companions to this work.

Section 2.0: Projected Climate Change for Melanesia

2.1 General discussion of climate change and variability

The average temperature of the Earth's near-surface air and oceans has been increasing since the mid-twentieth century. Global surface temperature has increased about 0.74°C (1.33°F) during the last century. The IPCC has concluded that anthropogenic greenhouse gases (mainly CO_2 and methane) are responsible for most of the observed temperature increase (IPCC, 2007). Natural phenomena such as variations in solar intensity and volcanoes probably had a small warming effect from pre-industrial times to 1950, and a small cooling effect since that time (IPCC, 2007a). More than forty scientific societies and academies of science have endorsed these conclusions (Royal Society, 2005).

Sophisticated computer climate model projections indicate that global surface temperature will probably rise a further 1.1 to 6.4 °C (2.0 to 11.5 °F) before 2100. However, the global climate system is extremely complex and there is much uncertainty in these estimates, arising both from the use of models with differing assumptions on climate sensitivity, as well as differing estimates of future greenhouse gas emissions. There is some evidence that recent global temperature increases are tracking at the high end of the range projected by climate models (See Figure 1), which suggests that future warming trends may be at the high end, or even exceed, the expected range described by the IPCC's Fourth Report (Lyderson 2009). Evidence presented at a climate science conference in Copenhagen in March 2009 indicates that the worst-case IPCC projections, or worse, are being realized, because emissions are soaring faster than anticipated, sea-level rise projections are being exceeded, and climate impacts around the world are appearing with increasing frequency (Kintisch 2009).

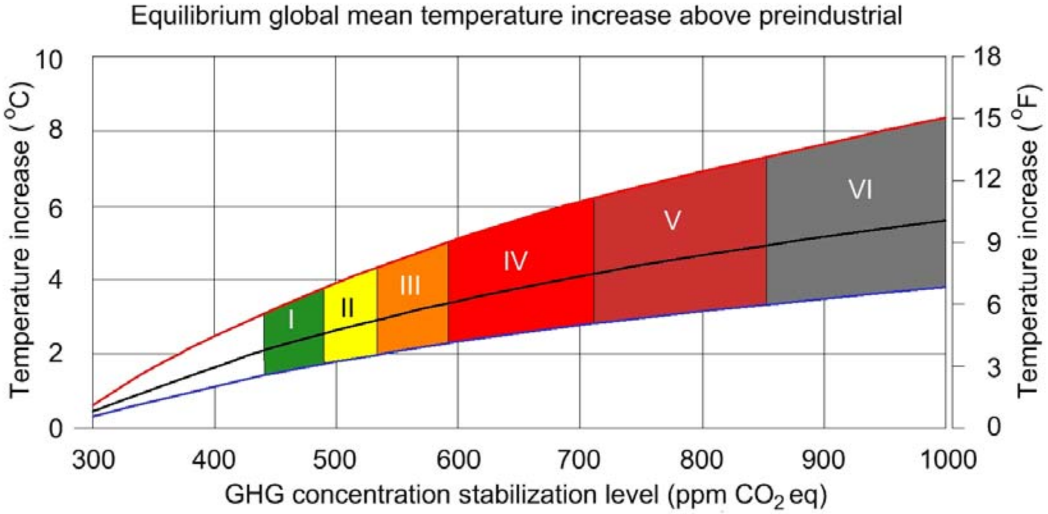

Figure 1: The projected temperature increase for a range of stabilization scenarios (the colored bands). The black line in middle of the shaded area indicates current IPCC 'best estimates'; the red and the blue lines the likely limits (IPCC 2007b).

Among the expected effects of increasing global temperature are sea level rise, regional changes in the amount, pattern, and intensity of precipitation, and possibly changes in ocean circulation patterns. Figure 2 illustrates the general implications of increased mean temperatures, increased climate variability, and the effects of these in combination.

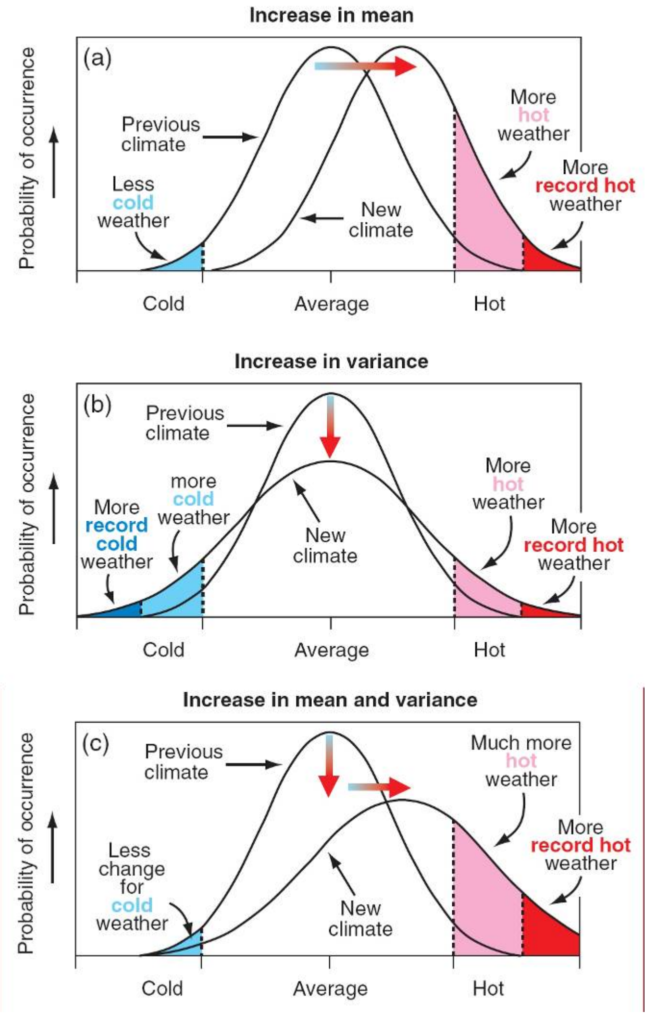

Figure 2: Illustration of climate change showing the probability of extreme temperatures when (a) the mean temperature increases, (b) the variance increases, and (c) when both the mean and variance increase for a normal distribution of temperature. Source: Folland et al. 2001.

The bell curve represents the probability of climate variations under present-day and future greenhouse warming conditions. An increase in mean (average) temperatures, which is depicted as a rightward shift in the bell curve, indicates that there is increased probability of warmer temperature events. Increased climate variability is shown as a flattening of the curve, which indicates a higher probability of temperature extremes (this may also be thought of as implying increased/decreased storm events, ENSO occurrences, etc.). The combination of increases in mean and variance, both of which are expected effects of climate change in the 21st Century, is shown as a rightward shift of a flattened bell curve.

2.2 Recent Climate Changes in Melanesia

The average global surface air temperature rise of about 0.74°C is associated with an increase in sea surface temperature (SST), upper ocean heat content (Barnett et al. 2001), and sea level height increases ("steric sea-level") due to thermal expansion and salinity variations. At the Melanesian regional level, the corresponding changes have been an increase of surface air temperature of about 0.05°C per decade during the 20th century, for a total increase of between 0.45°C and 0.50°C. In other words, the observed temperature rise in Melanesia has been somewhat less than the global average. It is important to note, however, that this warming trend has not been linear, but rather has accelerated to about 0.3°C per decade during the last 30 years. Between 1992-2009 sea-level in the region has increased at a decadal trend of up to 8-10 mm increase per year as observed on the east coast of Papua New Guinea (PNG).

2.3 Projections for Melanesia: precipitation, surface air-temperatures, sea-surface temperature

The IPCC 4th Assessment Report (AR4) from 2007 provides little information on projected climate change for the Melanesian region. The AR4 notes that “Since Atmosphere-Ocean General Circulation Models (AOGCMs) do not have sufficiently fine resolution to see the islands, the projections are given over ocean surfaces rather than over land and very little work has been done in downscaling these projections to individual islands.” (Christensen et al., 2007). The following paragraphs detail what the multi-model ensemble indicates for Melanesia.

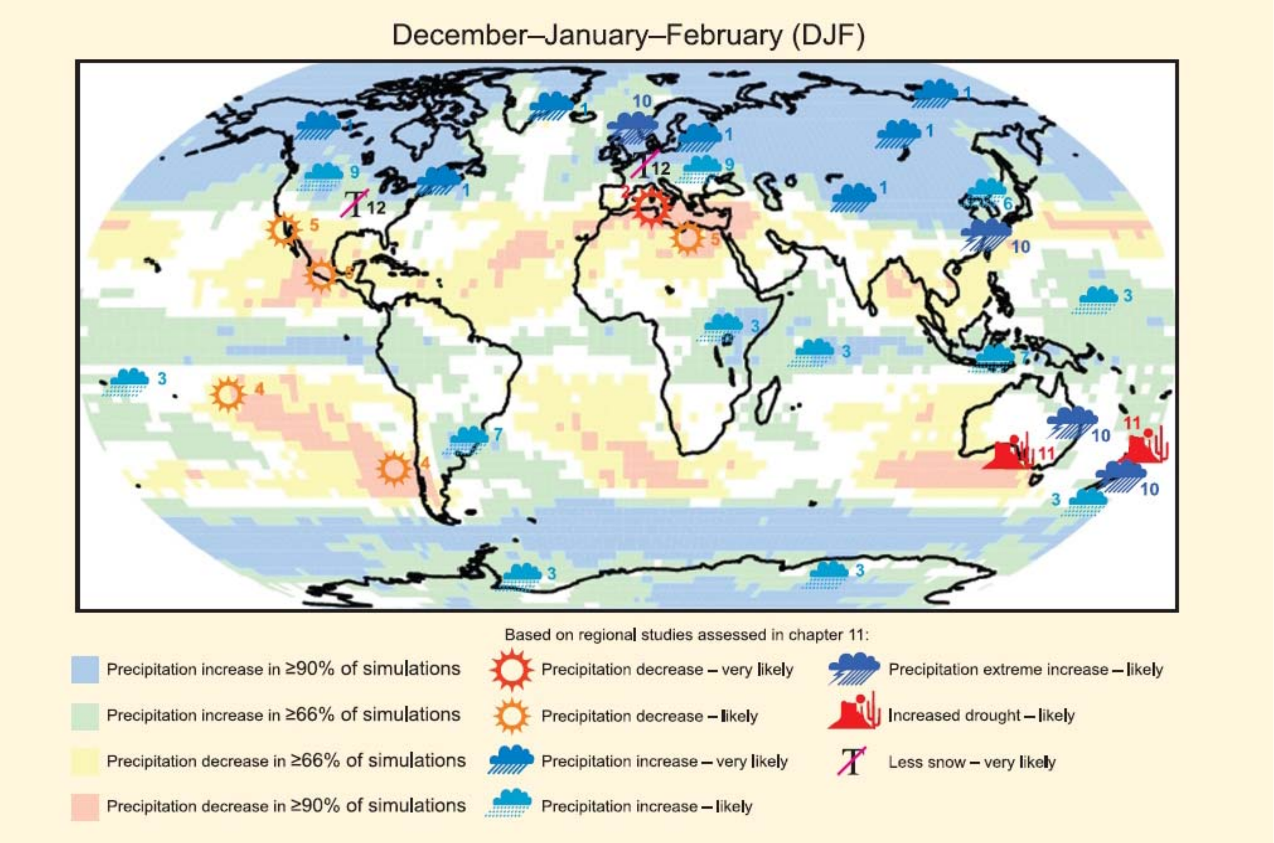

Figure 3: Robust findings on regional climate change for austral summer precipitation. This regional assessment is based upon AOGCM simulations, Regional Climate Models, statistical downscaling and process understanding (Christensen et al 2007).

More than 66% of the AR4 climate model projections for the 21st century using a conservative A1B scenario (i.e., modified “business-as-usual”: assuming rapid economic growth, a more convergent world, with more balanced energy sources than present) show increased precipitation in the northern Melanesian region, and more than 90% of the model experiments predict a drying in the southern areas of Melanesia (Figure 3). These projected precipitation trends are accompanied by an increase in mean surface air temperature of 1.8°C in the Melanesian region. A consensus of the models also shows an increase in sea-surface temperature (SST)[2] in the Melanesia region over the next century. SSTs will increase more rapidly in the north and northeastern part of Melanesia (e.g. the extreme northern part of PNG and Solomon Islands). It is projected that sometime between 2080 and 2100, SSTs will on average be 2.1°C higher than they are today. In the same time period, average SSTs in central and southern Melanesia (e.g. New Guinea, eastern Solomon Islands, New Caledonia) are projected to increase 1.7°C to 1.9°C higher than present. In eastern Melanesia (i.e. Fiji) the average SST increase is expected to be between 1.6°C and 1.7°C above present.

Essentially, any single Coupled General Circulation Model (CGCM) does not produce results with an acceptable degree of accuracy for a largely oceanic regional level such as Melanesia. However, in order to investigate SST changes in the Melanesian region at a more detailed resolution, Timmermann (Richards and Timmermann 2007) applied a statistical downscaling method to the GCM multi-model ensemble projections. His conclusions were broadly similar to the lower resolution GCM model predictions, and show that SST increases more rapidly towards the equator and less rapidly away from the equator. The results of Timmermann's downscaled models broadly confirm the results of the general trends described by the IPCC discussed above, and have clear implications for biodiversity in the region. Figure 4 is an example of downscaling SST projections and calculating projections for the number of degree heat weeks (DHW) per year during a decade. The figures and DHW are further discussed in the sections on coral reefs below.

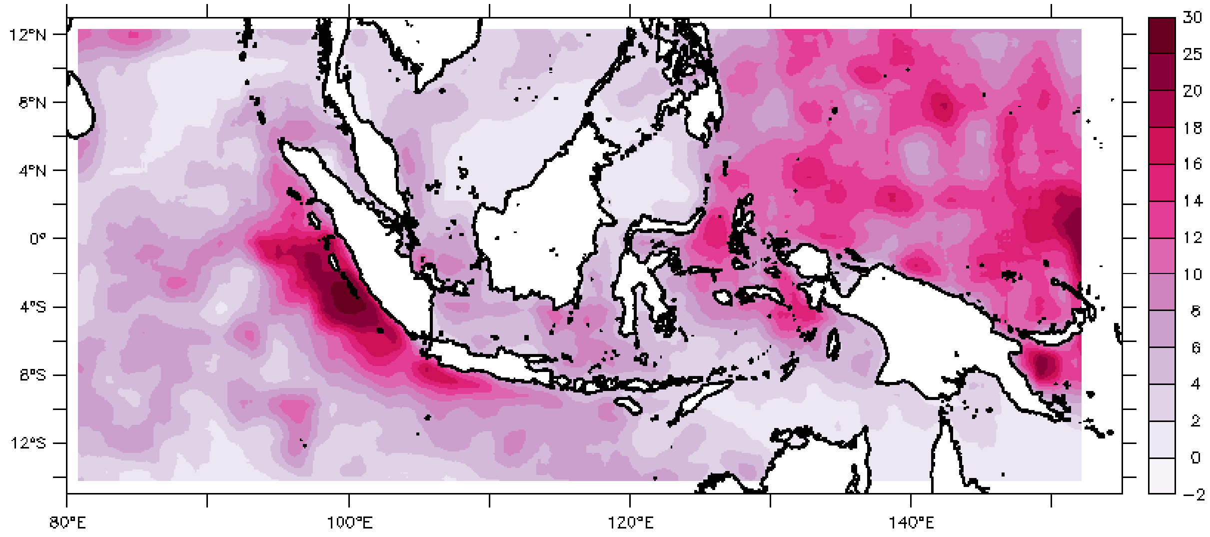

Figure 4: Results of downscaling DHW projections for western Melanesia and Indonesia for the period 2090 – 2100.

There are known uncertainties for each of the CGCM projections. Many of the present-day state-of-the-art CGCMs exhibit severe temperature biases in the Pacific. Most commonly

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[2] SST is defined as the average temperature of water to a depth of 10 meters.

the models exhibit a cold bias in the eastern to central equatorial Pacific and a warm bias in the southeastern tropical Pacific. This bias in the southeastern Pacific is due partly to an under-representation of the stratus cloud deck, and partly due to an underestimation of oceanic heat export from this region. This warm bias results in a misrepresentation of the entire southern trade wind regime and presumably also affects the simulated position of the South Pacific Convergence Zone (SPCZ). Many of the climate models used as part of the AR4 simulate a SPCZ that either is positioned too far to the east, or has a structure that is too zonally uniform. Neither of these are correct, and represent significant deficiencies in current GCMs. Furthermore, most of the state-of-the-art climate models have severe difficulties in simulating the mean present-day rainfall in the Melanesia region. This weakness in the individual models leaves some doubt on the reliability of the multi-model ensemble mean precipitation scenario shown in Figure 3. These misrepresentations have large implications for the representation of the mean climate in the Melanesian region, and resolving these modeling biases is essential for improving projections for the Melanesian region and other areas of the Pacific.

2.4 Projections for Melanesia: El Niño-Southern Oscillation (ENSO)

The El Niño-Southern Oscillation (ENSO) exerts a strong influence on the climate in Melanesia on inter-annual timescales. During El Niño events, Melanesia generally has lower than normal precipitation and relatively cool SSTs; during La Niña events, higher levels of precipitation and warmer-than-normal SSTs are typically observed in the region. However, each El Niño event has unique characteristics, and deviations from standard patterns are common.

Kug et al (2009) report that intraseasonal variability has increased over the tropical Pacific, and its interaction with ENSO has intensified in recent decades. This is consistent with evidence from climate change projections that the amplitude of this type of intraseasonal variability might increase under greenhouse warming conditions (Jin et al. 2007). Greater ENSO intensity and/or variability would have a very important impact on the occurrence of extreme weather patterns in northern Melanesia in particular since it is closer to the equator. Given ENSO's critical influence on precipitation and other weather patterns in Melanesia, it is crucial to ascertain how this phenomenon will change with global warming. Unfortunately, however, the CGCMs are not clear on this point. Oldenborgh et al. (2005) analyzed the changes in the variability of ENSO in 17 state-of-the art GCM simulations, run under business-as-usual greenhouse gas concentration scenarios. The study showed several models projecting an intensification of ENSO variability by 2100, while other models showed a weakening or little change. This current uncertainty therefore makes it very difficult to develop reliable and robust regional projections for the Melanesian region. The bottom line is that there is currently no definitive answer to the question of what will happen to the El Niño-Southern Oscillation in the future (Meehl 2006).

2.5 Projections for Melanesia: Sea-level rise and Ocean circulation

IPCC AR4 predicts that the average worldwide sea-level will rise between 0.5 and 1.0 m. above the present mean sea-level by 2100. However, regional factors (including ENSO, which affects water massing over large-scales[3]) will play major roles in how much sea-level rises in a particular area.[4]

Globally, sea level rise has occurred at a mean rate of 1.8 mm per year for the past century (Douglas 1997; Church and White 2006), but more recently is estimated to have accelerated in the latter half of the century to rates between 2.8 to 3.1 mm per year (Chambers 2003; Bindoff et al. 2007). The South Pacific Sea Level and Climate Monitoring Project (2006) recently estimated the trend of sea level rise in Papua New Guinea is +6.2 mm/year, which if accurate would be significantly higher than the global mean.[5] Satellite-based measurements from the University of Colorado at Boulder (2009) suggest these estimates are consistent with observations (see Figure 5). Based on documented sea-level rise in the 20th century, it can be expected that there will be an above-average sea-level rise for northwestern Melanesia (specifically the eastern side of the island of New Guinea), while other parts of the region may experience slightly higher than average sea-level rises.

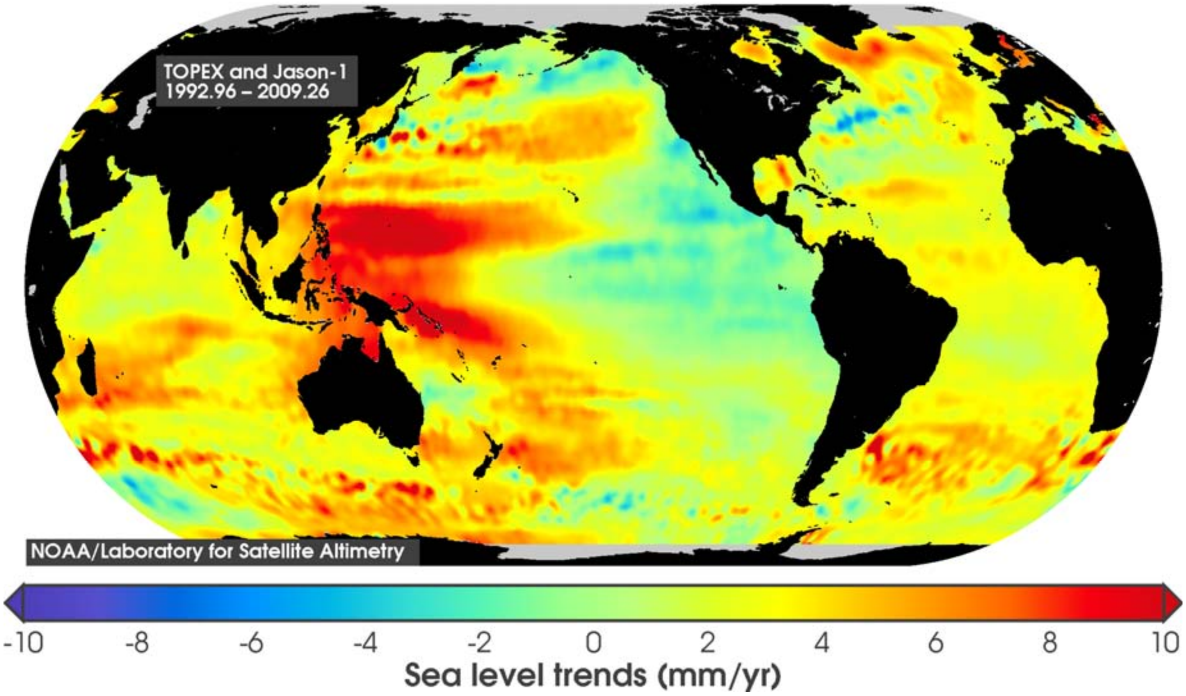

Figure 5: Global map of the rate of change sea level height as measured by satellites from 1992-2009. The rate of increase in the Melanesia region, at 8-10 mm/year is approximately three times the global average. Source: NOAA (http://ibis.grdl.noaa.gov/SAT/slr/slr/map_txj1_sst.png).

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[3] For example, La Niña events tend to “push” water westward over very large regional spatial scales, which results in higher probability of above-mean SL variations.

[4] It is important to recognize that measurement of sea level changes is not straightforward. Tide gauges measure changes in sea level relative to the tide gauge. However, the tide gauge is on land, which is subject to vertical movement unrelated to sea level (caused by island uplift, compaction of sediment or withdrawal of ground water, etc.). In terms of what matters to local people, of course, what is important is the relative sea level change (whatever the cause). From the standpoint of climate change studies, it is imperative to differentiate between possible causes of observed sea level rise in a particular area in order to establish absolute sea level change, (i.e. sea level referenced to the centre of the Earth). (South Pacific Sea Level and Climate Monitoring Project 2006a).

[5] Analogous estimates for Solomon Islands are +6.7 mm/year; for Vanuatu +2.2 mm/year; and for Fiji +1.7 mm/year. (South Pacific Sea Level and Climate Monitoring Project 2006b,c,d)

The complex topography of the Melanesian region and corresponding changes to atmospheric forcing have a large impact on the circulation and pathways of water movement, which in turn influences the local and regional properties of water, the marine ecosystem, the transport of larvae, and even short-term changes in local and regional sea-level. Small changes in the wind field can produce shifts in the relative strengths of ocean current jets and the paths water takes as it approaches the western coast of Australia. Larger changes are brought about by changes in the state of the tropical Pacific under ENSO conditions. For example during El Niño conditions the New Guinea Coastal Current, along the northern coast of New Guinea, is very strong, while during La Niña conditions it is virtually absent. Conversely, during La Niña the South Equatorial Current (close to the equator) and South Equatorial Counter Current at 5^{o} S latitude are particularly strong.

Details of the flow along the coasts of individual islands can also vary by ENSO event. For instance, using sea level and *in situ* temperature measurements, Ridgway and Godfrey (1993) infer large changes to the flow through the Vitiaz Strait and along the coasts of New Ireland and New Britain during the 1982-83 El Niño event, and similar changes are found in the results from high resolution ocean models. Associated with this change in currents are large changes in sea level height, surface temperature and precipitation (discussed above). Satellite measurements comparing El Niño and La Niña conditions show changes in sea level height on the order of +/- 20 cm, and changes in SST of 1 to 2 degrees Celsius.

Based on historical trends in the last century and particularly the past few decades, as well as likely climate warming scenarios, sea level rise in much of Melanesia (particularly the north and east coasts of New Guinea) is thought likely to be higher than the global mean sea level rise. Global sea level is projected to rise by up to 1m by 2100, although there are recent studies that indicate this may be an underestimate. The next IPCC report will address many of the current uncertainties. However, it is important to note that some recent sea level rise projections for the Melanesian region are based on faulty elevation data and are thus very misleading overestimates (see Figure 6). Until models using more accurate elevation data are developed, innundation projections should be treated with caution.

Figure 6: Estimated inundation zone that would result from a 1 m rise in sea level in the Papuan region (from http://www.geo.arizona.edu/dgesl/research/other/climate_change_and_sea_level/sea_level_rise/aus_pac/slr_aus_pac_i.htm). Such maps, which are based on course-level digital elevation models for the world, should be used with caution when assessing impacts at the local and regional levels. For example, areas along the Fly River included in the inundation zone are actually at around 80 m in elevation.

Impacts on coastal areas from a 1m sea level rise are obviously a very serious concern. Discussions at our 2007 workshop raised two possible mitigating scenarios however. First, a 1m sea level rise may redistribute sediment, causing the creation of more wetlands and tidal forest areas rather than the complete innundation of vast low-lying areas. This will also depend on maintaining adequate mangrove cover to retain sediment. Second, it is also possible that increased precipitation resulting from climate change (the prevailing IPCC projection for New Guinea) could have two effects: a. increased sediment loads from the mountains may cause sufficient land aggradation to somewhat offset sea level rise effects; and b. increased river discharges may create sufficient back pressure to somewhat mitigate stochastic tidal innudations. However, these possible effects depend on ensuring there is minimal human disturbance to the mangrove and upland watershed forests.

2.6 Local variability

Conditions at specific individual locations are influenced by numerous physical processes. Much of the variability in sea-surface temperatures and sea-level comes from so-called mesoscale eddies (the ocean equivalent of weather systems in the atmosphere) that have spatial scales on the order of 100km. These eddies influence local ocean conditions and have surface and sub-surface temperature and sea level signals that can persist for a few days to weeks at a single location. Typical values are up to +/- 10 cm in sea level height and 1 to 2° Celsius in SST. The sea level rise associated with the passage of warm core eddies can be enough to inundate coastal regions.

In addition to mesoscale eddies, there are a number of relatively small-scale processes that introduce significant spatial variability in such properties as ocean temperature, salinity and turbidity. These local processes are controlled by the local topography and coastline, the exchange of waters off-shore or at depth, and the local atmospheric forcing such as winds, heating and precipitation. Two specific examples found in Melanesia follow.

The first is tidal mixing. Tidal streams can be enhanced by flowing over submarine ridges or through narrow passages. Swifter currents increase the amount of mixing of waters which can have the effect of bringing colder water to the surface and producing significant reductions in the near surface temperature. Tides can also produce large (100m) uplifts of deeper waters (c.f. Wolanski et al 2004) which can flush coastal lagoons with cold water.

The second is the impact of the presence of steep mountains on islands. The airflow over and around these topographic features is highly distorted and can be channeled through narrow gaps producing strong wind jets. These wind jets can produce upwelling of cold water or the production of eddies in the lee of islands which in turn affect primary production in the ocean (Xie et al 2001, Calil et al 2007), as well as have an impact on SSTs.

It is clear that climate change will impact on Melanesia. The results of analyzing the multi-model ensemble indicate that it is reasonable to expect changes in precipitation patterns. Current modeling suggests that climate change may result in drier conditions in southern Melanesia (ex. New Caledonia) and wetter conditions in northern Melanesia (ex. New Guinea); increases in surface air temperatures of about 1.8°C by 2100; increases in sea-surface temperatures ranging from 1.6°C to 2.1°C by 2100; and a greater-than-global average increase in sea-levels by 2100. It needs to be emphasized that these are expected regional average changes based on composite AOGCM projections using historical data. It is also clear, as just noted, that there are local and temporal factors that can mitigate or amplify some aspects of climate change for different parts of Melanesia, but the ways in which climate change will affect the intensity or variability of these processes in Melanesia (or elsewhere) is not yet well-understood. These local and temporal factors need to be considered in any discussion of the implications of climate change for specific localities within Melanesia.

Section 3.0: Ocean Acidification and Melanesia

3.1 Overview of Ocean Acidification

Scientific data collected over many years are conclusive that oceanic absorption of atmospheric CO_2 is causing chemical changes in seawater, making them more acidic (i.e. lowering pH). Increasing levels of anthropogenic CO_2 are causing this process to accelerate. The average pH[6] of the world's oceans has dropped by about 0.1 pH units since the beginning of the industrial age. Without deep and early reductions in global carbon emissions, oceanic uptake of anthropogenic carbon will likely result in a further drop of 0.3 to 0.7 pH units by the year 2100. The degree and rapidity of these changes in ocean chemistry have not occurred in millions of years.

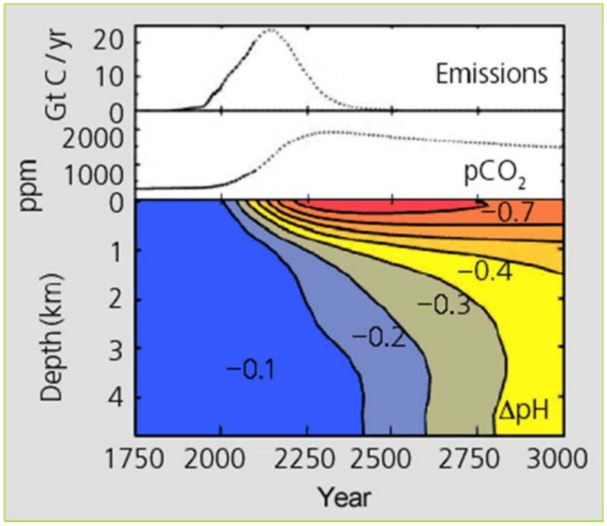

Figure 7: Atmospheric release of CO_2 from the burning of fossil fuels will result in a marked increase in ocean acidity. This figure illustrates atmospheric CO_2 emissions (upper figure), historical atmospheric CO_2 levels and predicted CO_2 concentrations from the IS92a emissions scenario (second figure; this is an older IPCC scenario depicting a middle-range scenario in which population rises to 11.3 billion by 2100, economic growth averages 2.3% year between 1990 and 2100 and a mix of conventional and renewable energy sources are used), together with changes in ocean pH based on horizontally averaged chemistry (third figure, in color). Source: Caldeira and Wickett, 2003.

Current data is highly suggestive that ocean acidification (OA) will negatively impact many important marine organisms. Lower pH interferes with the physiological processes of calcifying organisms, including corals, echinoderms, coccolithophores, mollusks, and some zooplankton, by reducing the bio-available amount of aragonite in surface waters. Aragonite is a form of calcium carbonate used by various organisms to construct cell coverings or skeletons. Fishes may also suffer adverse effects from OA, either directly as reproductive or physiological effects (e.g. CO_2-induced acidification of body fluids), or indirectly through negative impacts on food resources.

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[6] pH is a measurement of the acidity/alkalinity of a substance, on a scale from 0 (highly acidic) to 14 (highly basic). For example, battery acid has an approximate pH of 0, fresh distilled water is 7, and household lye is about 14. Acidity is defined as a measurement of the activity of hydrogen ions (H+). The pH scale is logarithmic, and so a reduction of 0.1 pH units indicates a 30% increase in the concentration of hydrogen ions.

There is not yet a perfect understanding of these physiological processes, their implications for marine ecosystems, or for the human societies and economies that depend on marine resources and services. However, given the critical ecological, economic, and cultural function of oceans in Melanesia and elsewhere, the ocean acidification has recently emerged as a prominent focus of scientific research.

3.2 Ocean Chemistry

The lowering of upper ocean pH that is caused by the absorption of atmospheric CO_2, which is the byproduct of the burning of fossil fuels, is an uncontested reality. CO_2 is highly soluble in seawater, forming an intermediary state of carbonic acid before disassociating to bicarbonate (HCO_3^-), carbonate (CO_3^{2-}) and hydrogen (H^+) ions. The relative concentrations of bicarbonate and carbonate are highly pH dependent; the present ocean pH of 8.1 favors a relatively high proportion of bicarbonate. Higher concentrations of CO_2 in the atmosphere and increased oceanic dissolved CO_2 result in increasing (H^+) ions that are buffered by available carbonate, with lower concentrations of that ion thus available to combine with calcium ions (Ca+) for the process of calcification. This means that increasing dissolved CO_2 results in decreasing saturation of dissolved calcium carbonate ($CaCO_3$) in seawater. This is having two results. First, calcifying organisms need to use increasingly more energy for the bio-accumulation/deposition of calcium carbonate (e.g. coral organisms have a harder time building reefs). Second, decreasing pH will increase the rate of dissolution of calcium carbonate that has already been formed, (e.g. the natural bioerosion rate of coral reefs will exceed their accretion rate).

Over 530 billion tons of fossil fuel CO_2 has already been absorbed into the ocean by gas exchange with the atmosphere, and the absorption rate is currently 24 million tons per day. This massive removal of CO_2 from the atmosphere is the main reason why large-scale climate change has not yet happened. Surface ocean waters mix with deeper waters over geological timeframes and so CO_2 will eventually be deposited in deeper waters, but since the mean ventilation age of the deep waters of the world ocean (the mean time for re-exposure to the atmosphere) is about 575 years, ocean uptake of CO_2 will continue for some centuries to come. Eventually some 85% of all atmospheric CO_2 emissions will reside in the ocean as air and sea reach equilibrium.

The transfer of quantities of CO_2 that are forecast will come at an ecological price. In pre-industrial times the pH of the surface ocean varied about 8.2; today the mean value is about 8.1, and if reasonable predictions of future CO_2 emissions are followed (such as the AR4 business as usual scenario), then by the end of this century pH will be lowered by about 0.4 units. This will result in the loss of about 55-60% of the dissolved carbonate ion that calcifying organisms (corals, sea urchins, calcareous phytoplankton, etc.) use to build their shells. One important measurement of bioavailable carbonate is the degree of aragonite saturation. Present ocean surface waters are saturated with aragonite, a prerequisite condition for skeletal formation for calcifying organisms. Decreasing pH is reducing the aragonite saturation at the ocean surface[7]. First-order chemical changes are

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[7] More specifically, the aragonite saturation horizon within the ocean water column is becoming thinner. In other words, the boundary between aragonite-rich surface waters and aragonite under-saturated water from deeper waters is rising. Because CO_2 is taken up more rapidly in colder waters, lower pH is occurring more rapidly at higher latitudes, so that aragonite undersaturation will occur first in northern/southern oceans and spread towards the equatorial regions.

known and directly predictable, as illustrated above, but the impact on marine organisms is far less certain, and the ability of animals to adapt to and cope with the stress imposed by higher CO_2 levels is to a significant degree unknown.

While the immediate focus on lowered ocean pH and reduced aragonite saturation is understandable, far more complex and widespread issues are quickly emerging. The dissolved CO_2 content will probably rise by about 12%, which will put increasing stress on the respiration and reproduction of both surface and deep-sea animals. In addition to the purely inorganic addition of CO_2 from fossil fuels, higher ocean temperatures and lowered atmospheric ventilation will result in increased stress on organisms as a result of lowered oxygen and higher respiratory CO_2 in the deep-sea. This will greatly expand the areas of the ocean that do not have enough oxygen to support life.

Far too little is known about the response of modern marine animals to the epochal-scale changes in the ocean that are occurring and their ability to cope with the combined physiological stresses of temperature, CO_2, and lowered oxygen levels now being imposed. Experimental protocols for true field CO_2 enrichment techniques are only now being developed, and the genetic resources possessed by marine animals to cope with such changes are still unknown.

Realizing these limitations to our knowledge, overall it appears that:

- The future changes in ocean CO_2 status may be underestimated given the present atmospheric trajectory, the rapidity of change, the economic challenge of changing this course, and the additional impacts of reduced ventilation and increased respiration.
- The *combined* effects of higher CO_2, higher temperature, and lower O_2 have not yet been adequately simulated in field experiments or models.
- Impacts on reproduction and embryonic and larval forms have not yet been fully investigated and there is evidence that these are the most sensitive life stages.
- The ability of ecosystems to adapt to such changes, their resilience, or the co-opting of as yet unknown survival strategies is very much unexplored.
- Almost all work has been done at the organism level – very little work on the genetic resources that may be available to marine populations has been carried out[8].

It is difficult at this point to make any specific assessment for Melanesia, but it is clear that the Melanesian ocean areas will exhibit changing pH levels similar to the rest of the world. Since the aragonite saturation state of the oceans varies with latitude and is maximal in tropical regions where organisms with calcareous structures predominate over those with siliceous structures, it is clear that the amount of saturated aragonite near the equator will continue to be greater than is found at the higher latitudes. However, the rate of decrease will be the same for all latitudes, and projections indicate that under likely CO_2 emission scenarios, aragonite undersaturation will occur at the equator before 2100.

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[8] The last “high CO_2 ocean” condition analogous to what can be expected by the end of this century is thought to have occurred 55 million years ago during the so-called Paleocene-Eocene Thermal Maximum (PETM). Some researchers speculate that adaptive genes may exist within the genomes of various organisms, and if so, it is possible these genes may be able to “switch on” as ocean pH decreases.

Section 4.0 : Climate Change and Marine and Freshwater Systems

4.1 Coral Reefs

4.1.1 Coral Bleaching

Coral bleaching has apparently been a natural process occurring on reefs for an indeterminate time. It was first described from observations made during the Australian Great Barrier Reef Expedition in the late 1920s (Coles and Brown 2003). Coral bleaching is the result of the combined and synergistic effects of elevated light and temperature that impact the coral-algal symbiotic association. It is important to note that threshold temperatures leading to coral bleaching are not fixed limits. Rather, they are closely tied to the ambient annual maximum temperature normally occurring in the local environment of the coral. Thus, if the SST of water exceeds by 1° - 2°C the historic ambient maxima temperature of the area where the coral is living for a period of time, bleaching will occur. The National Oceanic and Atmospheric Administration (NOAA) has combined this temperature threshold concept with a duration factor to develop the "degree heating weeks" (DHW)[9] alert system which uses satellite imagery of sea surface temperature to detect potential areas of coral bleaching (see http://coralreefwatch-satops.noaa.gov/SBA.html). Generally, a DHW value of >4-5 for an area is considered sufficient to result in extensive coral bleaching; a DHW of 10 corresponds to massive coral mortality.

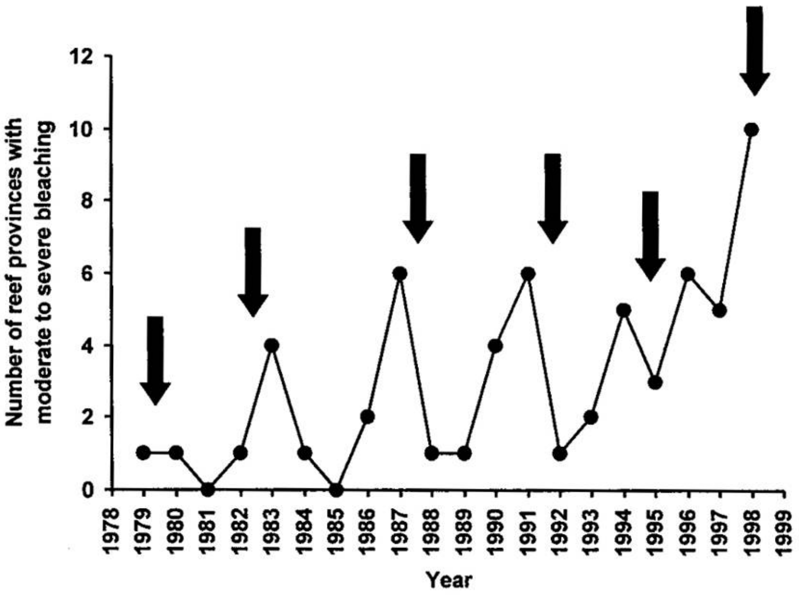

Figure 8. Major bleaching events occurring worldwide 1978-1999 (Hoegh-Guldberg 1999).

Rising seawater temperature in the last 30 years have coincided with repeated major bleaching events throughout the world, most, but not all of which have been linked with years of El Niño Southern Oscillation (ENSO) (Figure 8, Hoegh-Guldberg 1999). In Melanesia, coral bleaching-related temperature stress appears to be more closely related

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[9] DHW is defined as the number of weeks in which the sea surface temperature of an area exceeds its average thermal maximum by 1-2° C. DHW has become a key operational metric for reef monitoring and management.

to La Niña, rather than El Niño, years. Three major bleaching episodes have been reported in the Papua New Guinea (PNG) region of Melanesia since 1982 (Figure 9). The first was a minor event in 1982-83 in the waters of Kimbe Bay and Port Moresby (Srinivasan 2000). The major event for PNG occurred in 1996, when four months of elevated temperatures of 1.3°C above the normal maxima of about 30.5° resulted in bleaching and mortality of 54% of the corals surveyed down to 20 m (Davies et al. 1997, Foale 2006); bleaching was also observed in areas near Motupore and Madang and the Lihir Islands and Lak region near New Ireland (Srinivasan 2000). In 1999-2000 increasing bleaching with depth was observed to 20 m at some areas in Kimbe Bay and Milne Bay (Srinivasan 2000). The 1999-2000 La Niña also coincided with the most extensive bleaching event that has been observed in the Fiji islands (Cumming et al 2002). Moderate coral bleaching was observed in Suva Bay in 1999 but the major bleaching occurred in early 2000 when water temperatures exceeded normal summer maxima for five months (peaking in March and April). Six DHWs, with highest values of 30.5°C, produced >80% mortality on the southern and eastern Fiji reefs. Coral recovery from this event was highly variable, with rapid recovery and growth observed in Suva Harbor and Beqa Lagoon (Coles and Brown 2003, Coles pers. obs.), but long-term damage was reported for the Great Astrolabe Reef near the Kandavu Islands.

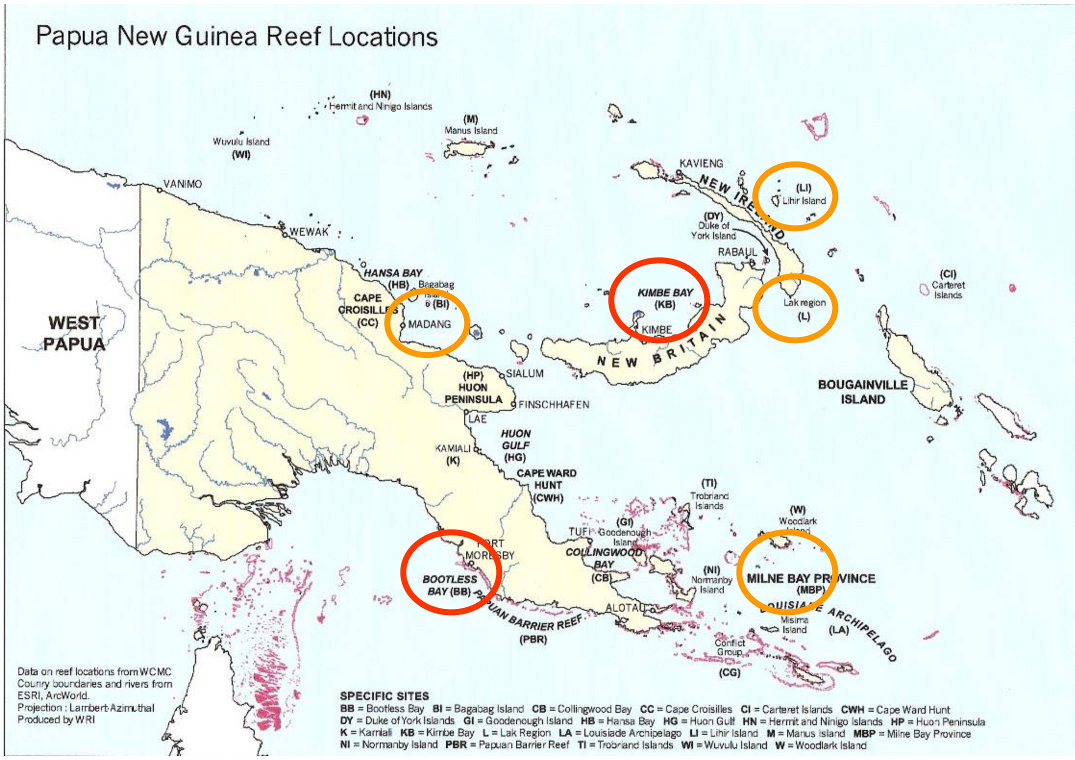


Figure 9. Areas of coral bleaching reported for Papua New Guinea in 1983 (red circles), 1996 (yellow) and 1999 (yellow) (Davies et al. 1997, Srinivasan 2000, Foale 2006)

Atmospheric and sea surface temperature models have been developed to project the probability of coral bleaching events throughout the 21st century. Models developed for various reef areas by A. Timmerman for this CCBM study and based upon assumed thermal thresholds for corals of those areas and SST temperature projections, show a consistent pattern worldwide where annual temperature maxima will exceed coral bleaching temperature tolerances by about 2030. This is consistent with Heogh-Guldberg

(1999), and would result in annual bleaching and mortality that has previously been confined to El Niño or La Niña years. Projections for the western Pacific that can be used to evaluate possible future trends for Melanesia are available in Guinotte et al. (2003). Using an annual maximum monthly temperature of 31.1°C as a threshold for coral bleaching for the region and a projected pCO_2 atmospheric rise of 517 ppmv by 2069 (an emission scenario that is more conservative than the IPCC estimates of 600 ppmv) their models suggest relative stability until mid-century, with rapid increases in temperature stress thereafter resulting in large areas of Melanesia subject to annual coral bleaching. Similar results are shown by a downscaled DHW model for New Guinea and Indonesia developed by A. Timmerman using IPCC temperature projections, where DHW of 4 begin to occur in 2040-49 and DHW of >10 in 2060-69 for PNG (personal communication). Timmermann's exact projections for this area will be described in a report by The Nature Conservancy that will be published in June 2008 (personal communication with Rod Salm, The Nature Conservancy). Figure 10 is the result of this model for eastern Melanesia that shows DHW > 10 by mid-century just northwest of Solomon Islands, DHW >10 for the middle Solomon Islands by the end of the century. Details of how the downscaling was done and how DHW were calculated are in Timmermann (forthcoming). Further extrapolation of model results suggests that DHW values of up to 20 could occur during the last decade of this century for the New Guinea and northern Solomon Islands area.

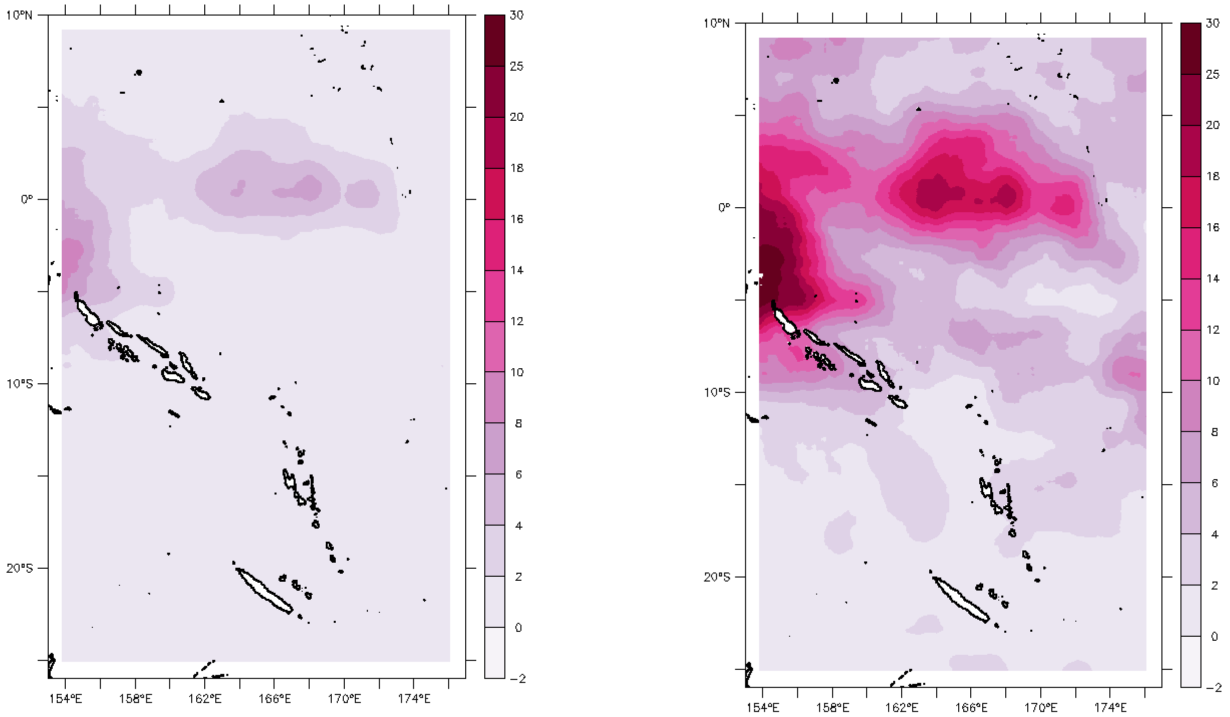


Figure 10. DHW projected for eastern Melanesia during 2040-50(left) and during 2090-2100 (right). Source: Timmermann 2007.

When a bleaching event occurs, not all corals are affected equally; there is substantial interspecific and intraspecific variation in the degree to which coral bleaching and mortality occurs for corals in the same area and subject to the same stresses. Extrinsic factors such as water turbidity, circulation, shading and pre-exposure to elevated temperatures are a major influence on susceptibility to bleaching. Intrinsic factors associated with both corals and their specific zooxanthellae are believed to play a major role in selection of corals that are resistant and resilient to stresses inducing coral bleaching (Coles and Brown 2003). However, if the DHW projections produced by Timmerman for this study do occur by the end of the century, the severe thermal stresses on corals of the region will probably exceed any adaptive mechanisms.

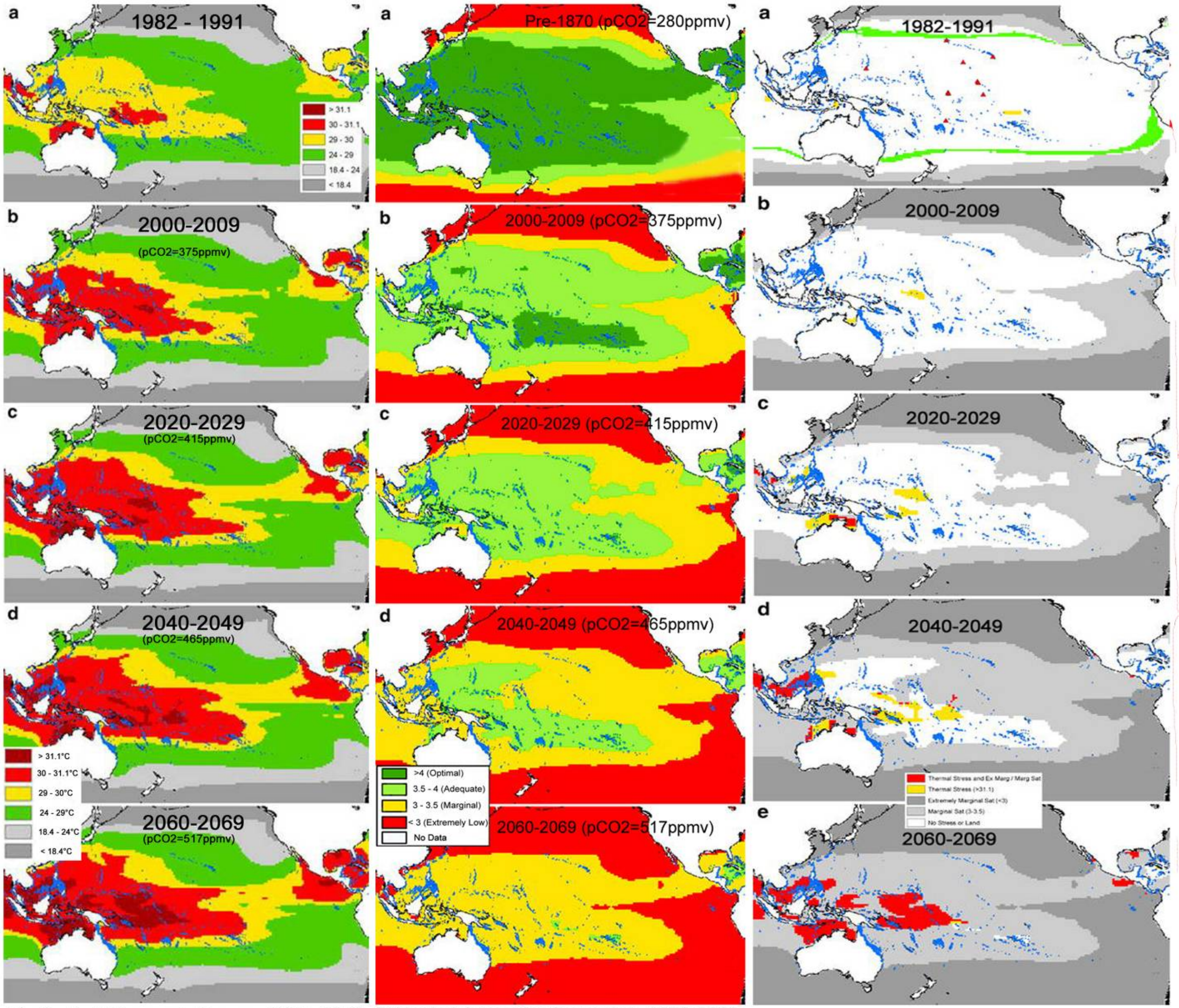
4.1.2 Coral Reefs and Ocean Acidification Effects

The anticipated result of the decreasing ocean pH and aragonite saturation state values (discussed above) in tropical water is reduced calcification rates worldwide, especially for reef-forming corals. The projections are based on results from controlled laboratory experiments, simulations of atmospheric CO_2 concentrations in mesocosms such as Biosphere 2, and mass balance calculations. Aragonite and high-calcite deposition in the tropics has been estimated to have already decreased 6-11% from pre-industrial conditions (Kleypas et al. 1999), and a further decrease of 3-60% is projected for a range of benthic organisms with a doubling of pre-industrial CO_2 by about 2065 (Kleypas et al. 2001). An average 30% decline has been shown experimentally for reef coral calcification at a $CaCO_3$ saturation state equivalent to double pre-industrial pCO_2 values (Kleypas 2008), which could result in a 14-30% overall decrease in reef calcification (Kleypas et al 2001). Reduced calcification rates will also result in weaker calcareous structures and increased susceptibility to erosion. Experimental pH reduction has been shown to result in complete loss of coral skeleton by an apparently otherwise healthy coral, which resume calcifying when pH is restored to normal levels (Fine and Tchernov 2007). The so-called "naked reef hypothesis" is that Scleractinian coral species may persist despite the coming advent of adverse pH conditions – as they did 55 mya during the last high CO_2 ocean. While this hypothesis is still being evaluated, it is important to recognize that a loss of calcareous reef structure would likely be highly undesirable from the standpoint of reef fishes and other organisms that depend on it for food and habitat, as well as the loss of reefs' ecosystem service to humans as a tidal/wave buffer.

Projected reductions in reef calcification rates pose a significant potential deficit for coral reefs world-wide, and those projected to have the greatest deficits are those in currently high saturation conditions, e.g. the Red Sea, Caribbean and the west central Pacific, including Melanesia (Kleypas et al. 1999).

Guinotte et al. (2003) developed projections that indicate the entire Indo-Pacific region had optimal aragonitic saturation ($CaCO_3$ saturation state > 4) during pre-industrial times, but by the first decade of the 21st century, optimal conditions have diminished to an area extending eastward from Melanesia; most of the Melanesian region is characterized by adequate saturation ($CaCO_3$ saturation state = 3.5–4) of aragonite. Saturation conditions are projected to continue to decrease through the second and third decade and by 2040-2049 marginal ($CaCO_3$ saturation state = 3.0–3.5) conditions are projected for most of New Guinea and adequate saturation is projected for the rest of Melanesia. By 2060-2069 a projected pCO_2 of 517 ppmv is projected to create marginal conditions for all Melanesia and all of the tropical Indo-Pacific except areas where saturation is extremely low ($CaCO_3$ saturation state = <3.0). Guinotte et al. (2003) combine the effects of SST increases and decreasing $CaCO_3$ saturation states to provide a view of possible conditions for Melanesia up through 2069 (Figure 11). It should be noted that their projections may be considered conservative since they are based on a 2060-2069 estimate of atmospheric pCO2 of 515 ppmv, which is lower than the latest IPCC estimates of 600 ppmv by the 2060-2069 time period.

As Guinotte et al. (2003) show, combining temperature and aragonite saturation state projection estimates shows patterns of even greater difficulty for Melanesian and other Pacific coral reefs than when temperature changes or ocean acidification changes are considered separately. Using a threshold monthly temperature of >31.1°C for coral bleaching, by 2020-2029 thermal stress is indicated to be a factor for reefs north of the Solomon and Vanuatu Island groups, and by 2040-2049 this area expands to include waters and reefs north of PNG. By 2060-2069 both thermal stress and marginal to sub-marginal $CaCO_3$ saturation states are indicated to affect reefs throughout most of the Melanesian region, as well as large areas throughout Indonesia and north Australia. Therefore by the second half of the 21st century, large reef areas in Melanesia and elsewhere are projected to become marginal – i.e. pushed beyond their normal environmental and possibly physiological limits (Keypas et al. 1999).



Projected Thermal Stress, 1982-2069

Source: Guinote, J. M., Buddemeier, R. W. Kleypas, J. A. 2003. Future coral reef habitat marginality: temporal and spatial effects of climate change in the Pacific basin. Coral Reefs 22: 551-558.

Projected Aragonite Saturation, 1870-2069

Source: Guinote, J. M., Buddemeier, R. W. Kleypas, J. A. 2003. Future coral reef habitat marginality: temporal and spatial effects of climate change in the Pacific basin. Coral Reefs 22: 551-558.

Combined Effects of Projected Thermal Stress and Declining Aragonite Saturation From 1870 (pCO2=280ppmv) to 2069 (pCO2=517ppmv)

Guinote, J. M., Buddemeier, R. W. Kleypas, J. A. 2003. Future coral reef habitat marginality: temporal and spatial effects of climate change in the Pacific basin. Coral Reefs 22: 551-558.

Figure 11. Projections of thermal stress, $CaCO_3$ saturation state, and combined effects of both by decade through 2069 (from Guinotte et al 2003). In regards to thermal stress, it should be noted that these projections have the underlying assumption that upper thermal threshold for coral bleaching are fixed values; this is clearly not the case however, since temperatures inducing coral bleaching range up to nearly 10°C depending on region.

4.1.3 Limitations to our knowledge regarding the interactions of coral reefs and climate change

The total effect of coral bleaching and ocean acidification by the end of the century is impossible to predict at this time and there are large areas of uncertainty that still need to be addressed. The following questions concerning organism and ecosystem response to bleaching and acidification, and their resulting impacts on coral reef systems are critical:

- Will thermal adaptation by corals occur fast enough to counter the worst effects of coral bleaching, and do mechanisms exist for adaptation by corals and other reef calcifiers to reduced aragonite saturation states?
- How will elevated temperature and the reduced aragonite saturation state affect reef bioerosion rates? Will increased dissolution of reef materials already deposited be an additional major factor in the total reef carbonate budget dynamics?
- Will marine calcifying organisms be able to adapt to elevated CO_2 if given sufficient time? What are the impacts of high CO_2 on calcification, respiration, reproduction, settlement and remineralization? How will increased bleaching, disease, and other stresses affect their ability to adapt?
- What are the effects of high CO_2 on the processes that affect ecosystem responses and global feedbacks?
- If reef structures and rugosity decrease due to climate change, will this be reflected in decreased reef biotic diversity and biomass, especially of harvestable reef fishes?
- What will be the impact of elevated temperature and reduced aragonite saturation on planktonic calcifiers, meroplanktonic larval life stages and recruitment? Will more subtle effects such as these be a major consideration in the total resulting reef ecosystem and will such effects be widespread or localized?
- What will be the impact of all this on human populations and societies in Melanesia and elsewhere?

Depending on the frequency of the stress in the case of bleaching and the magnitude of the change for both bleaching and acidification, different capacities to adapt will lead to different outcomes. These could range from short-term shifts in dominant coral species resulting from relatively mild levels of stress, to worst-case conditions of long-term “phase shifts” whereby if acidification levels proceed to where even calcite depositing calcareous algae are disfavored by decreasing carbonate concentrations, reefs are characterized by dominance of fleshy macroalgae.

In summary:

1. Ocean chemistry is changing to a state that has not existed in hundreds of thousands and possibly millions of years.
2. Shell-building in marine organisms will slow down, and reef-building will decrease or possibly stop or reverse.
3. Fundamental changes in marine community structures will occur in open-ocean and coastal marine ecosystems.
4. CO_2 projections suggest a change over from coral-dominated coral reefs to those that are mostly not dominated by coral.

4.2 Reef fishes

4.2.1 Responses of fishes and fish assemblages to projected environmental changes

The principal sources of habitat loss for reef fishes as a result of climate change are coral bleaching and ocean acidification (Sheppard, 2006; Hoegh-Guldburg et al., 2007). Second-order effects may also include local physical disturbance as a result of increased storm activity (Knowlton, 2006).

The mechanisms of coral habitat loss include the reduction of architectural complexity and integrity of reefs, habitat phase shifts towards monolithic species composition or algal-dominant rather than coral-dominant community structures, and eventual degradation to rubble and sand (Sheppard, 2006). Reef fishes are expected to make corresponding changes in assemblage structure with a reduction in species diversity, abundance, or trophic complexity (Knowlton, 2006; Sheppard, 2006). These changes are expected to proceed via two types of responses to habitat loss: direct and indirect.

Direct responses will be mainly in a decline in the species diversity and abundance of obligate and facultative coral-dwelling and coral-croucher[10] species that utilize corals for microhabitat (e.g., shelter), breeding sites, or food. Species whose larval and juvenile stages use corals for shelter – even if they do not use corals as adults – are also likely to be negatively impacted. The physical loss of coral skeletons from degradation/acidification is expected to result in declines for species that utilize corals as substrates for nesting (e.g., algal patches created on corals by the filefish and damselfishes). Obligate coral-feeding species (e.g. filefish, butterflyfish, parrotfish, and those species that farm algae in living coral patches [some species of damselfishes]), are all expected to decline either from the direct loss of food (coral polyps) or loss of structure used to “grow” food (algae). Direct responses to ocean acidification may include the interruption of ontogenetic development in larval stage of certain fishes (though which species would be most subject to this effect is not yet known).

As corals decline, so will the prey or forage associated with these corals. Indirect responses to reef degradation will include a cascade effect upon predators of species that utilize corals for shelter or opportunistically. Adult reef fishes of many species may not necessarily be affected by loss of corals, but rather will be affected negatively by loss of prey that are associated with corals. Indirect responses will also include effects upon omnivores and herbivores that feed upon specific prey or forage associated with living corals.

It is very important to recognize that climate change and/or ocean acidification effects on reefs will not operate in a vacuum. Any consideration of the effects of climate change upon reef fish diversity and abundance should also factor for proportional impacts from other intrinsic and extrinsic factors. Intrinsic factors include exploitation or over-exploitation of the resource base, cyanide fishing, etc. Extrinsic factors include pollution, poor land-use

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[10] Obligate species are those that are virtually always found in a specific habitat (ex. coral reefs). Facultative species are those that prefer, but do not require, a specific habitat.

practices leading to sedimentation, and physical destruction (i.e., coral mining, dredging, storm effects). The interaction of these factors with climate/OA effect will influence extinction susceptibility, vulnerability and risk. Localized extinctions are expected to proceed at a pace matching the loss of coral reef habitat coupled with increased pressure from exploitation and other factors.

4.2.2 Consequences of impact on reef species or ecological communities for ecosystem services

The intrinsic value of reef biodiversity includes the ecosystem services it provides to human society (e.g. subsistence and commercial fisheries, storm surge/tidal mitigation, recreation/tourism). The capacity of reef systems to maintain stability and its potential for phase shift between two dominant structural components (i.e., McManus et al., 2000) is of prime importance. Stable and diverse reef systems have been shown to be intrinsically productive within physical and chemical limits. The potential for phase shifts to stable alternate systems characterized by lower species diversity and abundance is considerable (Knowlton, 2006). One highly possible example of a phase-shift would be systems formerly driven by corals changing to ones dominated by benthic macroalgae. This would result in corresponding changes in the assemblage structure of reef fishes as a consequence of the maintenance of this alternative stability, and would be characterized by drastic declines or localized extinctions of coral-associated species and their predators, and their replacement by herbivorous fishes and their predators. Such a change would affect both human utilization of resources and also the physical structure and maintenance of reefs in Melanesia and elsewhere.

4.3 Freshwater ecosystems

Although it is clear that long term climate changes will have an effect on freshwater ecosystems in New Guinea and more generally in Melanesia, there is a dearth of data for the region by which to directly or objectively evaluate such patterns. Both precipitation and stream gauging data is inconsistent and widely scattered in terms of geographic coverage, and for the most part does not provide information across sufficiently long time intervals to accurately project trends. However, the multi-model ensemble used in the IPCC AR4 (noted above) predicts that northern Melanesia will experience increased precipitation, while southern Melanesia will experience reduced rainfall during both summer and winter months. Using available data from other areas of the Pacific (viz. Hawaii) the impacts of these scenarios are considered for Melanesia.

4.3.1 Decreasing precipitation regimes

Any decrease in precipitation regime will have an effect on freshwater ecosystems, which can be divided into two broad classes: lotic (flowing) and lentic (standing). The functional responses of each ecosystem class in regard to climate change will differ due to the underlying differences in the structure and flow dynamics of such systems.

4.3.2 Lotic ecosystems

Any long-term trend of decreasing precipitation will produce marked effects on stream discharge. Discharge in turn has two components: base flow and total flow. During periods where rainfall is low or absent, the flow in any given stream is primarily dependent on groundwater discharges, known as base flow. By contrast, the aggregate amount of flow in a stream resulting from base flow plus any direct-runoff contribution from precipitation is referred to as total flow. In general, stochastic year-to-year variations in precipitation will primarily affect total flow values by increasing/decreasing surface runoff, whereas long-term changes in a climatic regime will eventually affect underlying aquifer discharges, thereby altering base flow.

Another potential effect of prolonged precipitation decreases is a contraction of stream order hierarchies within any given drainage basin. First order streams are considered to be the smallest individual segments within any given drainage basin. Thus all headwater streamlets are first order segments. Segments of equal rank combine to create a segment of the next highest rank, thus two first order streams would join to form a second order stream. By contrast, if a first order stream joined a second order stream, the downstream segment would still be considered to be a second order stream, because the two segments that merged were not of equal rank. In a decreasing precipitation regime, former first order segments would become intermittent, and segments previously considered second order would become first order instead. Thus there would be a contraction in both the extent of perennial drainage networks, and the number of higher order segments within them.

Given the size of the New Guinea mountain chains, the extent of the aquifers lying beneath them, and the general absence of water development schemes such as tunnels and wells, it is likely that base flows will be insulated from direct climate effects for many years to come. For other Melanesian islands, base flows are largely a function of island size. These underlying aquifers could be considered near-term “drought buffers.” However, a prolonged regime of decreasing precipitation will eventually impact recharge to such systems, therefore water use and conservation strategies should be developed proactively if modeling or observations indicate a drying pattern in Melanesia. The need for such proactive steps may be particularly acute in areas of Melanesia outside of New Guinea, since given the smaller size of their aquifers, their base flows may be impacted at a faster rate.

4.3.3 Lentic ecosystems

For lentic ecosystems, a decreasing precipitation regime would likely have negative effects on both lacustrine (lakes and ponds) and palustrine (swamps, marshes, and other wetlands) ecosystems. The extent of lacustrine ecosystems in New Guinea is considerable. Chambers (1987) recorded over 5000 lakes with a surface area greater than 0.1 ha in Papua New Guinea alone. Over 80% of these lakes lie below 40 m altitude, and only 4% are found at altitudes above 2,000 m. The majority of these lakes are oxbow or tributary lakes associated with lotic ecosystems, particularly large lowland rivers, and as such may be directly affected by decreasing stream flows as described previously.

For palustrine (wetland and swamp) systems (as defined and classified by Polhemus & Allen, 2007) the effects of a decreasing precipitation regime are likely to include reduction in the extent of such systems, and possible transformation of some wetlands to grassland or savanna, particularly south of the central mountains, where patterns of wet and dry seasonality are more pronounced. Under decreasing precipitation regimes, potential consequences identified include shoreline retreat and increasing salt water intrusion. This could in turn lead to a reduction in the diversity and abundance of estuarine fish communities, and a possible decrease in nursery areas for penaeid prawns, which could impact this commercially exploited fishery.

All of the above scenarios present the prospect of adverse effects on native freshwater and estuarine organisms due to loss of habitat. Lowered water levels in major rivers may also serve to concentrate harvested species such as catfishes, rendering them more vulnerable to overexploitation by locally-based fisheries.

4.3.4 Increasing precipitation regimes

In contrast to the negative effects identified above for decreasing precipitation regimes, the consequences of an increasing precipitation regime (as climate models currently project for New Guinea and northern Melanesian islands), would in all likelihood be less ecologically traumatic. Overall, one would expect an increase in the extent of both lotic and lentic ecosystems, in particular lacustrine and palustrine systems. Stream order hierarchies within catchments would likely increase, as tributaries that currently flow intermittently become perennial instead. Bed competence of major rivers might also be expected to increase, potentially leading to increased sediment deposition in deltaic areas, which could mitigate to some extent the effects of rising sea level.

For palustrine and lacustrine ecosystems in New Guinea, there would likely be an increase in their extent in lowland basins north of the central mountains, particularly the Meervlakte (Lakes Plain) basin of Papua province, and the Sepik and Ramu basins of Papua New Guinea. Rising sea levels could interact with increased riverine discharges to create more back pressure at river mouths, promoting expansion of oxbow and tributary lakes along the lower reaches of large rivers.

Another effect of an increasing precipitation regime could also be a larger number of logs washed out from large rivers into surrounding ocean waters. This could in turn have an effect on regional fisheries, since such floating objects attract fish, and are often the target of purse seine sets. Although a larger density of floating logs could increase fisheries production in Melanesian waters, this would need to be weighed against the fact that several tuna stocks in the region, specifically bigeye and yellowfin, are already in declared states of overfishing. Therefore, increasing catch rates related to increasing numbers of floating logs could in fact prove counterproductive to current efforts to reduce mortality for such stocks.

In general, however, the effects of an increasing precipitation regime would probably be less severe in terms of impacts on the native New Guinea freshwater biota than a decreasing precipitation regime.

Section 5.0: Climate Change and Terrestrial Systems

5.1 Paleoecological climate changes and terrestrial ecosystems

Scientific understanding of the impacts of future climate change on the terrestrial biodiversity of Melanesia will benefit from knowledge of how past climate changes have influenced the biota of those islands. Records of climate and environmental change in Melanesia are preserved in landforms and deposits such as lake, bog and cave sediments, alluvial and colluvial mantles and glacial moraines. Information about the effects of changes on biomes comes from the reconstruction of past vegetation and fauna based on biological fossils supported by dating. Based on studies of pollen and sediments in swamps and small lakes, a considerable amount is known about the changes over the past 60,000 years or so for Melanesian environments ranging from the lowlands to the high alpine zones of New Guinea and some Melanesian island groups such as New Caledonia and Fiji. However, since most records are from the island of New Guinea, how historical climate has changed in the region can best be illustrated by focusing on New Guinea.

5.1.1 Temperature, sea-level, glacial, precipitation/forest changes

Paleoecological records illuminate how past temperatures, sea-levels, glaciers and vegetation have changed. Coring of lake beds on the islands and in off-shore areas of New Guinea indicate that from the end of the last glacial period at the end of the Pleistocene (c. 10,000 years BP) to the present, temperatures of the region have increased 3^{o} - 4^{o}C. During this period, and especially over the last 6,000 years, sea-level has risen from the lower levels associated with the last glacial periods to its present level. This sea level rise – approximately 120m from its nadir approximately 20,000 years BP (Figure 12) – may have been very rapid at times[11] (de Menocal et al 2000). Nunn (1999) reports that sea level may have been almost 1m higher than present in many parts of the Pacific about 700 years ago. The post-Pleistocene period has seen the separation of New Guinea from Australia and the creation of the basic pattern of shorelines that currently exist on each of the Melanesian islands.

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[11] Prior to the last major glacial period that ended 10,000 years BP (i.e. hundreds of thousands to millions of years ago), global sea-levels were hundreds of meters higher than they are at present.

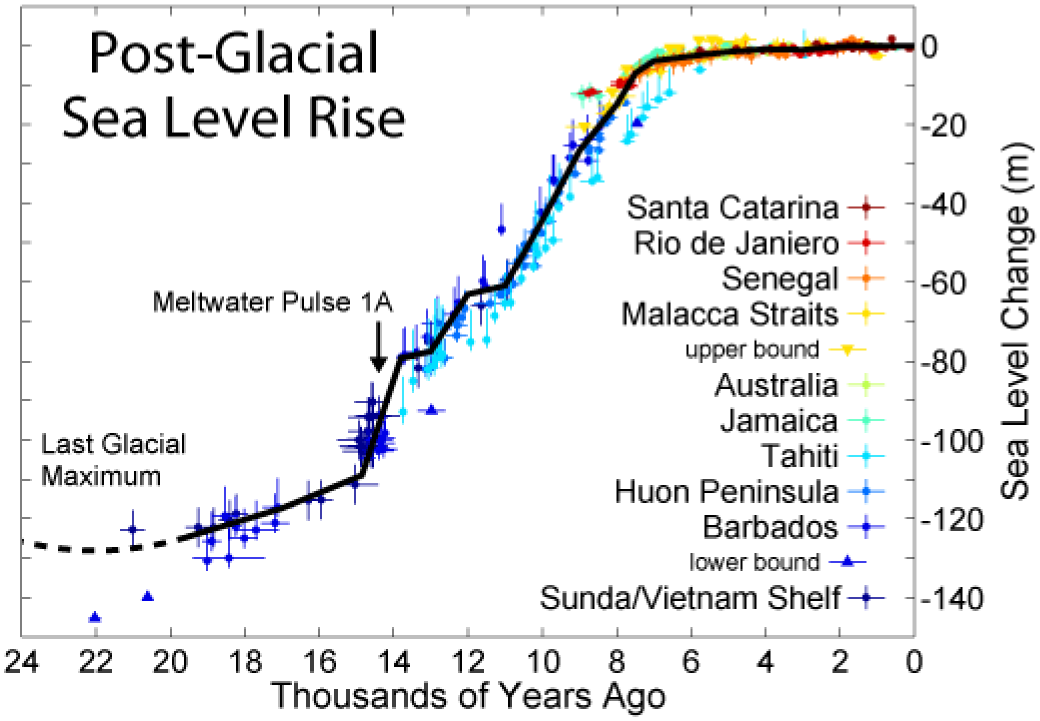

Figure 12. Sea-level rise since the end of the last glacial period

Glaciers have been found on New Guinea's mountains for long periods of time. The 3km^2 of glacial ice that today sits on Mt Jaya above 4,650 m altitude is a remnant of what were once extensive glaciers that covered about 2,200 km^2 above 3,400m on the high mountains across the island. Glacial features are found on Mt Trikora in northeastern Lorentz National Park, where a small ice cap was present on the summit until the 1960's. Paleoecological evidence indicates that the earlier retreat took place around 20,000 years ago while the latest is only 12-14,000 years old. The snowline on Mt Jaya appears to have been higher, at an estimated 3,900–4,000 m, compared to 3,450 m in the Star Mountains and further east (Peterson et al 2001, Prentice et al 2005). This apparent rise westwards in the snowline may suggest a precipitation gradient that is not as pronounced today. Prentice et al (2005) consider that at maximum the snowline was 650–850m lower than it is at present, suggesting a mean thermal change of about 5°C. It is likely that New Guinea mountain areas have experienced long periods of extensive snow cover in general sync with global glacial cycles.

From a 30,000 year record from Sirunki in central Papua New Guinea, the treeline at the height of the glaciation seems to have been at about 2,200 m above sea level (Walker and Flenley 1979). Below 2,200m *Nothofagus*-dominated forest seems to have been very common (Hope 1996a, b). From a consideration of all montane sites it seems that the boundary of mixed oak forest and beech forest rose about 700 m at the start of the Holocene, reflecting a temperature rise of 5-6°C. For non-equatorial areas of Melanesia such as New Caledonia, Nunn (2007) suggests that thermal changes and its effects were less than 2°C but still had significant environmental effects, including sea level changes.

Arid areas have also changed over time. The southern lowlands of New Guinea and the Melanesian islands currently have a much stronger seasonal rainfall pattern than the north coast and central ranges of New Guinea, but based on the modern rainforest-savanna boundary in New Guinea, southern New Guinea was likely drier during glacial periods (Hope 2007). There are as yet no Pleistocene lowland records from southern New Guinea, but the post-glacial southern migration of the rainforest boundary has been identified on the Aru islands which were then part of the New Guinea mainland (Hope and Aplin 2005). This is reinforced by evidence from faunal sequences starting about 20,000 yr BP. Around 14,000 years ago, wallabies became rarer and rainforest taxa increased, suggesting that the boundary between closed forest and savanna had reached this site. This reflected a more maritime climate for these areas as the Arafura shelf flooded (Hope 2007).

The subalpine forest-grassland alternation has produced islands of habitat that served as isolating mechanisms that encouraged speciation and the development of localized endemism in the upper mountain flora. Forest stability has also been important in encouraging biodiversity and specialization to a very variable local setting, however, in many areas the forest composition has been subject to changing climate over geologic time. *Nothofagus* became less common in the Holocene in response to drier and less cloudy conditions. At Lake Hordorli a shift to a higher proportion of secondary species occurred during warmer times. This may reflect shorter tree life spans typical of lower altitude forests that are subject to high levels of insect attack and disease.

At the height of glacial periods, the southern lowlands supported eucalypt and *Nauclea* savanna while the mountain crests above 2,000 m were more open with subalpine grasslands. On the northern coast, the Cyclops Mountains were likely humid throughout the last glacial period and have probably always been well forested, but rain shadow areas such as Sentani may have been drier and characterized by more open woodlands with grassland patches at that time (Hope 2007). While the paleoecological history of New Guinea suggests that the land has mostly remained under forest cover despite the fluctuating climates of the Quaternary, there were probably also major repeated formation shifts throughout the Quaternary that have pre-conditioned the biota to tolerate change.

5.1.2 Terrestrial refugia during past climate change and potential for future resilience

The mountain flanks of New Guinea and the windward sides of the Pacific islands are climatically relatively stable as the result of orographic (mountain-generated) rain and clouds that moderate temperature extremes. These sites are probably also less sensitive to ENSO variations. This has been demonstrated by cores from these settings such as Lake Hordorli (680m, Cyclops), Telefomin, Haeapugua, Agai Ramata, and Kosipe (southern slopes of the cordillera) and Lake Tagamaucia (Tavieuni) in Fiji). These areas may have served as refugia for species during past periods of climate change. Sites within the highland valleys have major gaps apparently associated with human disturbance, but possibly also a dry phase that allowed peatlands to burn, indicating that they may have been impacted by past changes and thus not as effective as refugia as other areas of the mountains. On the other hand, some ecosystems such as lower montane forest have not had to adapt to major climate changes as recently as higher elevations. This may have resulted in higher levels of specialization, and render those species more vulnerable to future climate change.

Past environmental change has been most dramatic at the savanna-rainforest boundary and subalpine-alpine zone. While advances by savanna can be accommodated by rainforests, the alpine zone is very restricted and habitat for specialist species and for successional communities may disappear under projected warming scenarios in the near future.

While New Guinea historically has been large enough to preserve large tracts of forest, many Melanesian islands have been stressed by human impact through burning of their seasonally dry areas. Because non-coastal lowland forest regions have for the most part not had large direct climate stresses, the ecological resilience of lowland New Guinea may be negatively impacted by significant forest modification or clearance. More specialized habitats, e.g. riparian and reef will also have lower resilience in the face of direct anthropogenic disturbance (overfishing, sedimentation, habitat destruction) as well as other environmental changes such as ocean acidification.

The Pleistocene-Holocene transition in Melanesia is quite dramatic and provides a degree of reassurance that terrestrial biota have some measure of resilience to withstand or avoid substantial impacts on biodiversity resulting from future warming, precipitation, and sea level changes. It is important to note that although ecosystem resilience has been an important element in past environmental changes, the extent to which it can continue to operate in the future depends largely on the degree to which habitats and the ecosystem services they provide remain relatively healthy and intact.

5.2 Native plant communities

Climate change is predicted to shift species geographical ranges as a result of modifications to the normal patterns of temperature and humidity that generally delimit species boundaries (Thuiller, 2007). Many studies predict that climate change impacts will consist largely of shifts in latitudinal and altitudinal distributions (Thuiller, 2007; Williams et al., 2003; Watson et al., 1997). Most plant community types in Melanesia will probably experience fine-scale shifts in species composition depending on the tolerance ranges for each species to the combination of changing climatic variables. Alterations in population size, species distribution, and the geographical extent of habitats and ecosystems, as well as an increase in the rate of species extinction and loss of biodiversity can be expected.

The ability of plant species to respond to climate change will largely depend on their ability to colonize new territory or modify their physiology and seasonal behavior. Therefore, the biggest changes in plant biodiversity would be expected near climatically-determined boundaries of species distribution. Plants with broad climatic tolerances should be able to remain in equilibrium with change, but taxa with narrow ranges may be shifted outside their climatic niche space within only one or two plant generations (Bush et al., 2004). Plant migration will be impeded by landscape fragmentation, competition from invasive species, lack of available habitat, or absence of a necessary environmental factor, such as a specific soil type, microbial community or water availability.

Because of Melanesia’s high diversity and endemism of plant species, the potential for species loss due to climate change could be large. Many publications predict that overall biodiversity in the equatorial belt is likely to suffer more immediately from deforestation and land degradation than from climate change (e.g., Thuiller 2007; Sala et al. 2000). For instance, Brooks et al. (2002) estimated that 19% of New Caledonian plant taxa are listed as threatened or extinct, and which increases to 31% with a 1000 km^2 habitat loss. However, one model used to assess extinction risks for Amazonian plant species predicted the loss of biodiversity due to habitat loss as a result of human-caused land conversion ranged from 4-8%, while extinction due to maximum expected climate change ranged from 36-79% taking into account dispersal, or 87-100% if no dispersal occurred (Thomas et al., 2004). Note that much of the disparity between these calculations is a function of small islands (ex. New Caledonia) versus continents (as the world's second largest island, New Guinea is considered "nearly a continent" in biological terms). Part of the uncertainty in predicting changes to biodiversity for Melanesia is that our knowledge of the Melanesian flora is limited and many more species may already be threatened than are currently recorded on the IUCN Red List. Currently, less than 1% of the flora is listed as vulnerable or threatened for New Guinea, Vanuatu, and the Solomon Islands. By contrast, for the well documented floras of Fiji and New Caledonia, 6% of native species are listed as vulnerable or threatened.

5.2.1 Montane ecosystems

Plant endemism in New Guinea is highest in the montane zone as a result of environmental change induced by rapid rates of geological uplift and the increasing richness of epiphytes, hepatics, and shrubs. In general, an increase in air temperature as a result of climate change in island ecosystems will result in the disappearance of the coldest climatic zones. Habitat for plant species unable to survive and reproduce in warmer climate regimes will shift upslope and shrink in area. Higher mountains and isolated mountain ranges may thus be the most at risk for species extinction.

All of the high peaks on Melanesian islands are regularly enveloped by tradewind-derived orographic clouds, resulting in the presence of unique and diverse floral assemblages of variable and patchy structure (see Prentice and Hope 2007 for a comprehensive overview of prevailing weather patterns in New Guinea). These cloud forests are adapted to high precipitation due to the deposition of cloud droplets and convective rainfall, low radiation, cooler temperatures, and often high winds. The lower limits of cloud forests are determined by moisture availability, with clouds contributing 37% of moisture budgets for these habitats (Bush et al., 2004). Simulations of climate change suggest an upslope shift of the cloud layer, which may exacerbate the effects of longer and more variable dry seasons in these areas. Increases in air temperature associated with climate change implies increased evapotranspiration by vegetation which, in combination with reduced cloud contact, could have serious implications for biodiversity (Still et al., 1999).

5.2.2 Mangroves and coastal forest

Mangrove communities are documented for all island groups in Melanesia, with diversity declining eastward of New Guinea. Climatic factors, such as temperature and moisture, affect the distribution of mangroves. While mangroves are not expected to be adversely affected by projected increases in sea temperature, increases in air temperature have been shown to impact development, with temperatures above 35°C leading to thermal stress which affect root structure and the establishment of seedlings. Decreased precipitation, resulting in increased salinity, reduces the growth and survival of mangroves, and may change the species composition and diversity.

Projected increases in the frequency and level of extreme high water events with climate change could affect the position and health of coastal ecosystems. Mangroves and coastal vegetation provide protection from coastal erosion and damage by tidal surges, currents, rising sea levels, storm energy in the form of waves, and cyclones. Roots bind and stabilize the substrate and form habitat for other biota, namely as nurseries for fishes and crustacea. The projected losses for Melanesian archipelagos are highly variable due to the uncertainty in predicting sea level rise. Mangroves will migrate landward as a natural response to rising sea level. Where this is not possible as a result of natural or artificial barriers to migration (e.g. seawalls), mangrove area may be reduced over time. Slow rates of mangrove sedimentation and the possibility of subsurface sediment subsidence due to organic matter breakdown, sediment compaction, and changes in water fluxes may result in inundation, reducing the survival of mangrove. Mangroves with low sediment supply may not be able to keep up with future rates of sea-level rise. By contrast, in some protected coastal settings, inundation of low-lying coastal land may actually promote progressive expansion of mangrove forest with rising sea level. Global warming may facilitate mangrove expansion into saltmarsh communities, in turn reducing the diversity and compromising those communities. Ultimately, the survival, composition, and diversity of mangrove communities will depend on regional factors, such as groundwater availability, salinity, substrate type, sediment input, and physical infrastructure (viz. seawalls) rather than overall global changes (Gilman et al., 2006; McLeod & Salm, 2006).

Coastal erosion, partly the result of anthropogenic factors such as sand mining, is already a problem on many islands and may be exacerbated by sea-level rise. Carbonate beaches are maintained by sand produced from productive reefs whose degradation may result in accelerated beach erosion. Because carbonate beaches are composed of the dead skeletons of calcifying organisms (ex. corals, foraminifera), it is quite possible that ocean acidification will also negatively affect coastal sand production (Andersson et al, 2007). In summary, climate change has the potential to severely impact beach development and coastal strand habitat.

5.2.3 Seagrass communities & aquatic communities

Seagrasses serve as feeding grounds and nursery habitat for many fish and marine species that are important for subsistence and commercial uses. Seagrass roots and rhizomes bind and stabilize sediments, improving near-shore water quality. Increases in global temperature and CO_2 have been shown to alter growth rates and other physiological functions of seagrasses under controlled conditions (Short and Neckles 1999). However, because different species show different responses, species distribution will most likely shift as a result of increased temperature stress, changes in the patterns of sexual reproduction, and as a result of eutrophication and changes in frequency and intensity of extreme weather events. Sea level rise increases mean water column depth, and resulting potential changes in tidal variation & altered water movement may affect salinity, turbidity and light availability, resulting in a redistribution of existing habitats. Changes in the deposition of sandy substrate will also shift community structure.

5.2.4 Vegetation responses to climate change

Elevated CO_2 concentrations: Plants differ in their direct physiological response to elevated CO_2, as well as in the less obvious responses such as changes in tissue composition, stress resistance, or rhizosphere interactions (Korner, 1998). While rising CO_2 concentrations are projected to increase productivity of some communities and alter competition among others by eliminating species and introducing new species to take their place, the actual realized effects of increased concentrations of CO_2 are unclear. For example, studies that doubled the concentration of CO_2 over temperate short-grass steppe had little impact on plant species diversity, but resulted in increased biomass of woody shrub species (Morgan et al., 2007). It is notable that studies published to date are based on relatively short-duration field studies; long-term effects of climate change on community structure and composition are unknown but possibly very significant.

Precipitation changes: All of the Melanesian island groups have distinct windward and leeward vegetation types due to orographic differences in rainfall. As previously noted, long-term rainfall projections under climate change scenarios are difficult to ascertain, and are unlikely to be spatially or temporally uniform. Reduced precipitation due to climate change, particularly in leeward habitats, may result in greater susceptibility of the vegetation to fires, and the replacement of forests with shrublands, grasslands, or savanna ecosystems. Even in non-ENSO years, global warming may increase the risk to tropical forest regions of more frequent and severe droughts.

Thermal and/or rainfall changes may result in changes in plant or forest phenology[12], which may in turn affect the availability of resources for other animal species. The most consistent pattern for species distribution in tropical forests worldwide is the distribution of rainfall and soil water availability. Seasonality and physiognomy (leaf flush and flower production) of tropical forests are mainly determined by the amount of annual rainfall and its seasonal distribution. Changes in soil moisture availability caused by global climatic change and forest fragmentation are likely to alter tropical species distributions, community composition, and diversity. Conversely, if one factors out forest loss or fragmentation, if AOGCM models are largely accurate then expected climate change may be unlikely to affect the physiognomy of rainforests with high annual rainfall and low seasonality such as New Guinea. However, there is an important caveat: because drought tolerance limits of Melanesian rainforest species are unknown, the rate and extent of future changes cannot be predicted at this time.

Catastrophic disturbances: Melanesia's forests are subject to frequent damage and disturbance by cyclones, landslides, earthquakes, and changing river courses. However, because these forests have co-evolved with these natural disturbance factors over long periods of time, they are part of the overall ecosystem dynamic, and indeed give rise to renewal and thus foster biodiversity. For example a study of the recruitment and survival of tree species in Solomon Islands over a 30 year period after the impact of four cyclones in a nine year period showed no evidence of spatial variation in tree species composition (Burslem et al. 2000), indicating the potential resilience of these systems to such disturbances.

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[12] Annual or cyclical events, such as seasonal flowering or fruiting.

Drought and associated fires resulting from the periodic ENSO climatic cycles are a significant ecosystem disturbance in Melanesia. Dryland vegetation has a high level of endemism, but fire reduces the vegetation from forest-type to shrub-type communities, with frequent fires reducing the flora to fern or grasslands. This factor may be of particular significance in rare or vegetation-sensitive habitat, such as ultrabasic forest (Whitmore, 1969).

Genetic implications: The natural adaptive capacity of Melanesian species to changing climate is unclear. However, it is known that genetic diversity plays a critical role in the survival of populations in rapidly changing environments. Tropical forest plants may respond to climate change through phenotypic plasticity, adaptive evolution, migration to a suitable site, or localized or outright extinction. Forest fragmentation and deforestation may reduce genetic variation by causing extinction of genetically unique populations, promoting inbreeding, and disrupting gene flow. This implies that the response of vegetation to climate change will also depend on the extent of logging, forest conversion, and other anthropogenic disturbance. The response of forest trees to climate change will also depend upon the responses of, and interactions with, a wide variety of other organisms (e.g. pollinators and seed dispersers). Acute changes in climate during critical phases of a plant's life cycle such as flowering, seed development, and seedling establishment, may have much greater effects than the mean direct effects of climate change. The rate at which species can respond or genetically adapt to climate change will be dictated by their life span and generation cycle. Even more critical for spatially and environmentally variable Melanesian systems is that different plant species and even genetically distinct populations of the same species may have unique ecological niches and may respond differently to changes in climate.

5.3 Insects

Although not addressed by experts in our study, some discussion of the possible impacts of climate change on insect populations is merited based on the significance of many insects for pollination and other ecosystem services. One recent study by Deutsch et al. (2008) concludes that warming in the tropics is likely to have a more serious impact on tropical insects because they are relatively sensitive to temperature change and are currently living very close to their physiologically optimum temperature. Insects in temperate zones have broader thermal tolerance and are in climates that are currently cooler than their physiological optimum. This analysis implies that in the absence of mitigating factors such as migration, adaptation, and behavioral changes, the greatest extinction risk to insects from global warming may be in the tropics (Deutsch et al. 2008).

5.4 Birds

There are approximately 831 bird species on the island of New Guinea alone, representing about 8.6% of the world's avian diversity (Mack and Dumbacher 2007). New Guinea's approximately 350 endemic birds include myriad species of Birds of paradise, cockatoos, parrots, and cassowaries. Other Melanesian islands possess a number of endemics, including New Caledonia's Kagu (*Rhynochetos jubatus*), which is the only surviving member of the family Rhynochetidae. New Caledonia has 189 bird species (23 endemic);

Fiji has 149 species (27 endemic); Solomon Islands has 289 species (71 endemic); and Vanuatu has 136 species (9 endemic).

Ornithology in Melanesia is still at the stage of defining alpha taxonomy, and little is known about the ecological habits or requirements of most species. New species are still being found, and although knowledge of avian alpha taxonomy is probably well ahead of most other major taxa in Melanesia, it is still highly deficient compared to many parts of the world. This dearth of knowledge makes it even harder to discuss the threats that climate change pose for birds in Melanesia and to define how to conserve species in the face of expected climate change. With this caveat, our knowledge on the distribution and characteristics of Melanesian birds make it possible to delineate some basic parameters that will govern avian response to climate change.

5.4.1 Characteristics of birds in Melanesia

Many bird species found in the Melanesian region have very restricted ranges. These are found either on small islands or in small areas of the larger islands, such as at a specific elevation in the mountains, only in one mountain range, or even only on a specific side of one mountain range or on one mountain.

Many bird species have fairly specific habitat requirements. For example, a particular species may rely on a specific palm as the necessary food plant it requires to get through the lean season; another species my require certain kinds of large trees for nesting; another might feed on insects that need a minimum number of sunny days to grow and reproduce. To complicate matters further, a species might require a number of such factors in order to live and reproduce during a year.

There are also migrating birds which pass through Melanesia or rely on a specific location in Melanesia as a seasonal destination. The arrival of many of these migratory species coincides with an phenological or climatic event (fruiting, seasonal lakes, etc.) that provides food, habit, weather, or other factors required for their rest, sustenance, and/or reproduction during their stay.

5.4.2 Specific Threats to birds from projected climate changes

Restricted-Range Species: Specific threats to restricted-range species are: (1) Diminishment or disappearance of the areal extent of specialized habitats. In addition to habitats that may simply get “pushed off” the top of mountains, simple geometry dictates that small areas – even those of irregular shape – will have smaller perimeters. These perimeters are the ecotones where habitats could potentially shift along a gradient given enough time. As an illustration of this is the ecotone between lowland forest and hill forest and the ecotone between high elfin forest and alpine meadow. If both are found on the same mountain, the former will cover a larger area than the latter. Ecotones will most likely move as climate changes occur, further diminishing the size of the range of these species. (2) Limited-distribution species generally have overall smaller population sizes concentrated in smaller geographic areas. This makes them more vulnerable to change than species with large population size and large distributions.

Species at high elevations: These species will have less area in real terms than those at lower elevations. The less area that a species has, the greater its vulnerability to any changes in its environment. The reason for this is the same as described above for mountain ecotones: areas of habitat decrease as you rise in elevation for the simple reason that mountains are wider at their base than their peaks.

Species on isolated ranges or peaks: New Guinea has a large number of isolated ranges, many of which have endemic birds[13]. Birds on isolated ranges may be more vulnerable to climate change than ones having limited distribution. It is possible that elevational zones on isolated ranges and massifs may become somewhat lower due to the so-called Massenerhebung Effect[14], which may provide some climate mitigation. However, isolated ranges are by definition not contiguous with other montane environments. Thus as climate change causes changes in environments, taxa on isolated ranges will be less able to move (i.e. to make spatial changes in their distribution) to new suitable habitat. This effect will be even more pronounced on the mountains of smaller islands such like Normanby, Vitu Levi, etc.

Food resources are less mobile than birds: Bird species are sufficiently mobile to disperse at a pace that could keep them within their required climatic bounds (temperature and humidity) as climate changes. However, keystone food resources for many birds are not as mobile and it is unknown whether or not preferred food plants will be able to move and/or adapt quickly enough in response to climate change. This will place many birds at risk.

5.4.3 General Threats to birds from projected climate changes

Besides these threats to specific types of birds, there are also more generalized threats from climate change. These include:

- Current AOGCM climate models projections are that certain parts of Melanesia will become drier, air temperature and SST will change, sea-levels will rise, and ocean current patterns may shift. These changes can be expected to change habitat for many different bird species. Drier conditions can be expected to lead to increased fire risk and the subsequent expansion of grasslands; this will negatively impact forest birds. Changes in temperature that require extra energy input (either for heating or cooling) can push terrestrial animals past their metabolic limits. This may be a special concern for birds, which have the highest thermo-metabolism (and limited thermoregulation capacity) of all the warm-blooded animals. Sea-level rise will impact low-lying areas and mangrove habitat and the species that rely on them. Changes in ocean currents may change the transport of food required by some shore and sea birds, which could have a particular impact on nesting sea-birds who rely on specific marine food resources at specific times of the year.

- Some birds move over large areas as seasons change, tracking the availability of fruit, seed or nectar resources. For these populations to persist, their food resources over large spatial scales must be maintained, particularly through any bottlenecks of low food availability or "lean seasons." Thus even if some areas within a

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[13] "Endemic" refers to species that are found in a particular place and nowhere else.

[14] This refers to the phenomenon in which forest zones are often compressed on shorter mountain ranges. Temperature and rainfall patterns may also be compressed. For example, a mountain range with lower elevation may have the same basic structure and variety of habitat types as a higher mountain range, but each one is compressed into a shorter elevational gradient. See Figure 14.

population's range remain intact and viable in the face of climate change, if alterations occur elsewhere that either depress food availability or affect the timing of its availability, such populations could experience significant reductions.

- Changes in geographical distributions resulting from tracking food supplies will bring new species into contact. As noted above, it is likely that species of birds will be able to shift their distributions as climate and habitats change. Not all species will shift concurrently and in equal directions, however, and so avian community structures will change. New competitors will move into areas, perhaps displacing or replacing taxa they historically did not compete with. Species that are more adaptable will expand their distributions and some species will be outcompeted.

- Climate change also poses potential cascading threats for birds. One threat is the climate-related changes outside of the region that impact birds that spend part of their life in Melanesia. Another is that increased storm frequency and/or intensity could lead to situations where species do not have sufficient recovery time between extreme weather events, causing their populations to suffer accordingly. Finally, there are potential secondary impacts, one of the most important being that human adaptation to climate change may require substitution of lost resources (e.g. decline in fisheries leads to increased hunting), or human migration to new areas as climate change impact their current settlement locations.

5.5 Herpetofauna

The threats from climate change to Melanesia's amphibians and reptiles are similar to those for other vertebrate taxa groups (eg. isolated and restricted range species are at higher risk). Based on our current understanding of climate change, however, it is virtually impossible to predict its effects on specific populations and species of Melanesia's amphibians and reptiles. This is particularly difficult in New Guinea where upwards of half the species remain unknown to science. However, some general predictions are possible. It is likely that those species that have broad ecological tolerances and large geographic ranges are less susceptible to the effects of climate change than are those species that have narrow ecological tolerances and small geographic ranges. Similarly, it is likely that those species that occupy broad altitudinal ranges will be less susceptible to the effects of climate change than those species confined to narrow altitudinal bands. Similarly, species endemic to small islands are more likely to be impacted than are species occurring on large islands or mainland New Guinea.

Although our understanding of patterns of distribution and diversity of the New Guinea herpetofauna are in their infancy, it is clear that the highly dissected, mountainous terrain of that island has produced relatively high beta diversity (otherwise known as species turnover) compared to other tropical areas dominated by lowlands (e.g., Borneo, Amazonia). It is clear that the central mountains, north-coast mountains, and satellite islands, which comprise more than 60% of the land area of New Guinea and its satellite islands, are the areas with the highest overall species richness for amphibians and reptiles, and these areas also have the highest concentrations of restricted-range species.

5.5.1 Frogs, Lizards, Snakes and Crocodiles

Based on current understanding of scientifically named species, there are 133 species of frogs with geographic ranges of 500 km^2 or less; at least 105 of these have ranges of <200 km^2 and eight of those have a range of <50 km^2. Sixty-four species with a range of <500 km^2 are generally found at approximately 1000 m or higher and 21 of those are generally found at elevations of 2000 m or higher. It is this latter group that may be most vulnerable to the effects of climate change. At least half of these species inhabit mountain summits and could be driven to extinction by disappearance of their habitat attendant upon increasing temperature. It is possible that the Massenerhebung effect could play an important mitigating role, although this depends on cloud cover/precipitations changes that cannot be predicted. In fact, it is also possible that climate change could lead to reductions of rainfall and the disappearance of wet forest currently dependent on the Massenerhebung Effect (Mueller-Dombois and Fosberg, 1988). This would almost certainly lead to the extinction of species inhabiting cloud forest, including species at relatively low elevations. Although offshore islands were once thought to have low-to-modest levels of endemism, recent studies have demonstrated that many of these islands and island groups in fact support a high number of endemic species. Some of these have been named and many more are in the process of being named. As an example, a recent survey has demonstrated that the number of frogs endemic to the Louisiades has doubled from four to eight and is likely to again increase to at least 15-20 species.

Lizard species tend to occupy larger geographic ranges than do frogs, probably because they can more readily cross oceanic barriers and are less restricted to relatively wet areas. For example, the average range size of Papuan frogs is 39,079 km^2 while that for lizards is 71,258 km^2. The incidence of restricted range endemism is also lower. Only about 5% of 233 lizard species have ranges of 500 km^2 or less. There are only eight species of currently recognized species of lizards found at elevations of 2000 m or higher. Four of these (*Lobulia alpina*, *L. glacialis*, *L.stellaris* and L. *subalpina*) and at least one as yet unnamed species are confined to high elevation grasslands and would be vulnerable to extinction if this habitat disappears due to increasing temperatures and other climate-related changes (Greer, Allison and Cogger, 2005).

There are 95 species of terrestrial snakes known from the Papuan region. Five of these (~5%) are known from areas of 500 km^2 or less. While there are at least three elapids (*Toxicocalamus holopelturus*, *T. longissimus* and *T. misimae*) and a blindsnake (*Typhlops hades*) that are endemic to the Louisiade Archipelago, snakes are largely confined to low elevations. Only two species are found above 2000 m, and both are widespread.

There are only two species of crocodiles and 21 species of freshwater turtles in New Guinea. All inhabit lowland waterways, mostly on the south coast of New Guinea, and do not appear to be in any immediate peril as a result of loss of habitat due to climate change. However, elevated temperatures are known to limit hatching success in sea turtles (Western and Sinclair 2001) and to bias the sex ratio toward females. This could adversely impact freshwater and marine turtle populations in New Guinea.

5.5.2 Other considerations for amphibians and reptiles

Approximately 35 species of frogs, several species of lizards and several species of snakes are represented by small populations on islands or mountain summits and may be particularly vulnerable to extinction as a result of climate-change related habitat loss. Further biological survey work in New Guinea is likely to increase the estimated number of vulnerable lizards and snakes, and at least a doubling and perhaps as much as a tripling in the number of vulnerable frog species.

A recent global assessment of frog populations (Stuart et al. 2004) has demonstrated that upwards of a third of frog species are threatened with extinction. The factors involved vary, but primarily include habitat loss and mortality caused by a pathogenic fungus, *Batrachochytrium dendrobatidis*. This fungus, generally known as the chytrid fungus, has been documented to occur in most parts of the world, including isolated areas such as Australia but is currently unknown from New Guinea. While its potential impact in New Guinea is only speculative at this point, it could prove devastating because its virulence is known to increase with temperature. Hence the (presumed) presence or arrival of the fungus in Melanesia, combined with regional warming, could cause even more devastating loss of amphibian populations.

It is quite possible that some species that are currently confined to small, upland areas may expand their range if climate-related change produces an increase in critical habitat. However, most of the restricted-range species occur in upland areas or on small islands where additional habitat is unlikely to become available. In the case of montane species, increasing temperature could drive populations to higher elevations. Because total land area decreases with elevation, this would force such species into smaller areas and most likely lead to population declines and extinctions. Moreover, high elevation grassland and elfin forest are highly susceptible to loss due to fire, which has been increasing in frequency and severity during the past several decades (Shearman et al., 2009) and is expected to continue to increase with increasing temperatures.

The high beta diversity of the New Guinea herpetofauna and uncertainty over the impacts of climate change on the local biota make it impossible to assess site-specific effects from climate change or to identify specific areas of low risk to climate change that should be incorporated into a protected-area management network.

5.6 Mammals

Sharing close affinities with Australia, Melanesia’s mammals include the monotremes, marsupials, rodents, and bats, all of which are highest in diversity in New Guinea. Of these four, rodents and bats are found common throughout the world, but many species are unique to New Guinea. Monotremes and marsupials are restricted to the Australasian region, and a very large number are endemic to particular islands, especially New Guinea.

Mammal distribution does not naturally extend far into Melanesia, or into the Pacfic. Monotremes are limited to New Guinea, while marsupials also extend into the offshore islands of PNG. Native rodents naturally spread farther into the whole Solomon island chain. The distribution of bats extends the furthest, and extends past Melanesia to parts of Polynesia. Figure 13 shows the natural distribution of each of these groups in the Pacific.

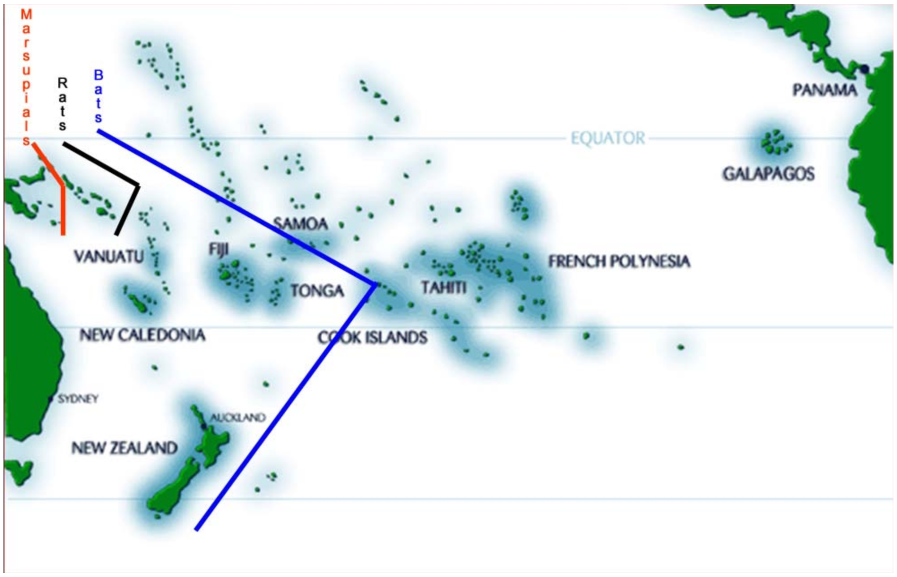

Figure 13: Natural geographic limits of mammal distribution in Melanesia

5.6.1 Threats to mammals

The biggest threats from climate change with respect to mammals include:

- Alterations in the timing of animals' seasonal activities, either directly due to changes in the thermal/precipitation regime, or indirectly through changes in the phenology of plants upon which the animals rely for food;
- Changes in their geographic range due to changes in vegetation and local climates (e.g. latitudinal and elevational shifts of vegetation);
- Changes in complex ecological interactions of ecosystems;
- Increased hunting pressure from displaced human populations; and
- Possible increased competition from invasive species or increased mortality from new pathogens, either of which may benefit from climate change.

Many of the possible climate change-related dynamics discussed earlier for birds similarly apply to mammals. It is thought that climate change may present enhanced opportunities for non-native species to become invasive (Middleton 2006), which would increase competition for food resources and/or introduce new predation pressures on native species. Similarly, new viral or other pathogens may exploit opportunities arising from thermal or precipitation changes, or existing diseases such as malaria may move into new areas. When combined with climate-stresses on animal physiology, this could increase the disease risks for Melanesia's mammals.

5.6.2 Mammal species most at risk

There are a number Melanesian mammal species that will be at risk from projected climate change. These species fall into four main categories.

<u>Mammals found at or above the treeline:</u> Most climate change projections suggest that biodiversity changes will occur along elevational gradients. In short, ecological communities on mountainsides will be pushed up the elevational gradiant as temperatures and precipitation patterns change. The species in this group will be forced upslope along with their associated ecological communities; since they are already adapted for very high

elevation, this poses a serious risk that they may almost literally be ‘pushed off’ the mountain.

Mammals found on isolated or outlying ranges: The island of New Guinea has many isolated mountain ranges that host a diverse mixture of endemic fauna found on no other mountain ranges. Many of these outlying ranges are extremely remote and have not yet been fully documented by science. The vegetation and fauna found in these mountain habitats are affected by the Massenerhebung Effect (compression of vegetation zones relative to those found in the central ranges; Figure 14). This results in isolated ranges being able to support a fuller range of species diversity than would otherwise be the case. However, because species are living in a more compressed area, there is increasingly less available habitat as climate pressure force communities upslope. In addition, while there may be some capacity for Massenerhebung compression to increase in large mountains, smaller or isolated ranges may have less capacity simply because they are already compressed to a large degree.

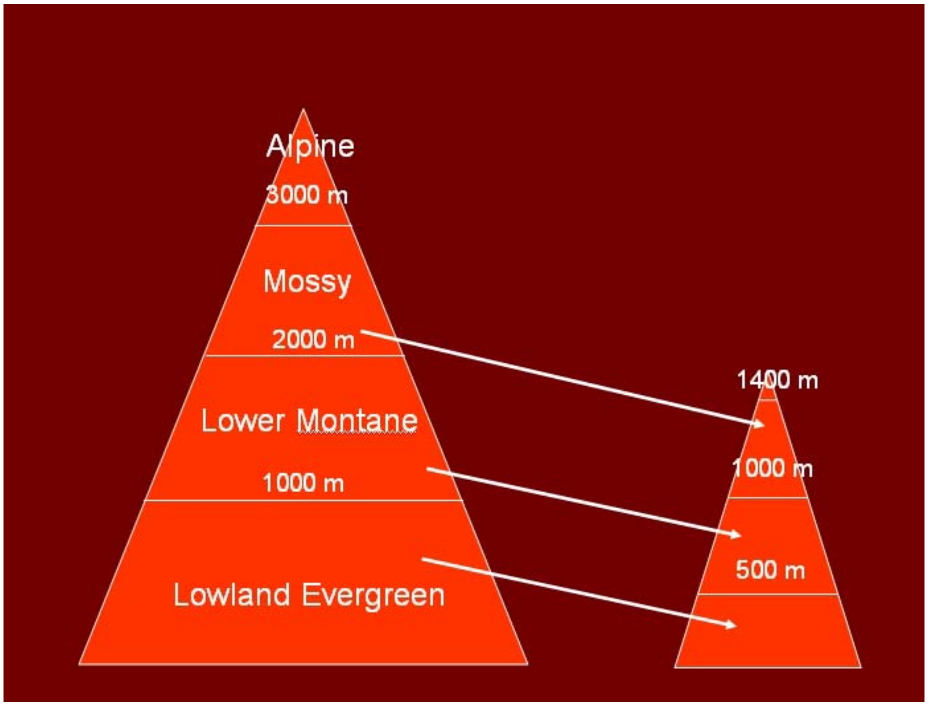

Figure 14: The Massenerhebung effect illustrating how forest zonation is compressed on isolated or shorter mountain ranges relative to larger mountains on the same island.

Mammal species on islands: Island mammal species will be particularly impacted by climate change for similar reasons as for species found on outlying mountain ranges, namely that they have a limited ability to relocate to new habitat with more suitable climate conditions. In addition, smaller islands are particularly vulnerable to the effects of sea-level rise and extreme weather events. A variety of bat species, which have evolved to be specially adapted for a specific island location will be especially at risk within this category.

Larger mammals: The largest mammals of New Guinea consist of large tree kangaroos and monotremes. These are already heavily hunted and most are today classified as threatened or endangered. Because of human pressure, many Melanesian mammals are increasingly rare and generally located far from areas of human habitation. Fossil records confirm that at one point in time their range was wider than it is today, and many species that are currently considered montane species once inhabited lowland areas in the past. Their ranges and populations, having already suffered from anthropogenic pressures, are likely to be further reduced through second order cascade effects: climate change will affect the choices of where humans settle, practice agriculture and hunting, which will in turn probably increase impacts on large mammals currently living in areas more remote to humans.

In general there is a long history of human impacts on mammals in New Guinea. Until the arrival of humans during the Pleistocene about 45,000 yrs BP, New Guinea was home to a number of very large herbivores (especially in the central cordillera). These included the rhinoceros-sized Diprotodon, and Thylacoleo, the so-called “marsupial lion”. These large marsupials became extinct at about the same time as humans arrived on the island. About 3,000 yr BP, which is thought to coincide with the arrival of hunting dogs to New Guinea, another extinction event again centered on the central cordillera took place. This involved the extinction of a number of kangaroo species, especially small kangaroos. Finally, in recent decades there is evidence for extinctions, especially in outlying ranges, of kangaroos and echidnas (medium sized mammals). In summary, there is a high probability that climate change will have significant second-order impacts on mammals in addition to other current extinction pressures.

5.6.3 Mammals: general discussion

It is important to recognize that basic biological information for most Melanesian mammals is extremely limited. In many cases almost nothing is known except their basic taxonomic status, and so conclusions about their geographic ranges, habitat preferences, behaviors, reproductive requirements, food preferences, and ecological interactions are based on general principles rather than documented field studies. However, because Melanesia’s mammals are a fairly manageable taxonomic group (i.e. they are not hyper-diverse), this makes them in principle more amenable to tracking their general status. Certainly they are an extremely important flagship group for conservation. The availability of elevation gradients is likely to be key to the ability of Melanesia’s mammals to adapt to future first- and second-order climate change.

6.0 Conclusions

6.1 Marine biodiversity

Even with the significant level of uncertainty that remains for regional climate projections, if the temperature and acidification conditions projected by the Guinotte et al. (2003) and Timmerman models are only close to accurate[15], it is difficult to avoid the conclusion that corals and coral reefs will be severely stressed by the end of the century, and that phase shifts to algal-dominated reefs are likely throughout Melanesia and elsewhere. Over the long-term, it is likely that erosion of reefs from the combined impacts of coral beaching and acidification will exceed accretion rates. This loss of coral reef structure would decrease availability of fish habitat and shelter. Coral-dependent species would likely decline in abundance and diversity, followed by species that are only dependent in part upon coral-dependent species, and further cascade effects would follow.

These physical factors, which are driven by global-scale processes, are likely to be significantly exacerbated by other extrinsic (pollution, poor land-use practices leading to sedimentation, and physical destruction such as coral mining, dredging) and intrinsic factors (exploitation or over-exploitation of the resource base, cyanide fishing, etc.). The interaction of these factors with climate change and acidification will increase extinction susceptibility, vulnerability and risk.

Ocean acidification may also negatively affect fishes in their larval stages, leading to greater impact upon fish assemblage structure and abundances on reefs and related systems. Fishers and fishing-based human communities in Melanesia are often heavily dependent upon reef resources associated directly or indirectly with corals. Thus, it is likely that significant aspects of reef ecosystem function and services will decline or even in some cases be lost to communities and other human users. Though there may be strategies to mitigate climate change and acidification impacts on reef ecosystems, it appears that the only ways to avoid such an outcome are very early and deep reductions in global anthropogenic carbon emissions and/or major technological advances in carbon capture and storage that would allow rapid, low-cost, and widespread adoption of those technologies.

To help avert serious impacts on marine ecosystems, we believe that addressing the problem will require early and deep reductions in global anthropogenic carbon emissions. We recommend increased attention to reduction of logging and forest disturbance in critical watersheds that increases sediment discharge. Reduction of land-based sources of pollution that stress coral reefs or contribute to lower pH is similarly critical. We also recommend marine conservation strategies that protect large areas of high diversity with maximal habitat heterogeneity and connectivity, and the implementation of the management recommendations of the Honolulu Declaration (TNC 2008).

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[15] Even more recent analyses (Feeley et al, in press) suggest that aragonite saturation levels will decline even more rapidly than projected by Guilotte or Timmermann, dropping to below-marginal conditions for almost all areas of Melanesia by 2060. This analysis is described more fully in our Vulnerability Report.

6.2 Terrestrial biodiversity

The current lack of climate, ecosystem process, and species information is a major impediment to the assessment of likely effects of climate change on Melanesia's terrestrial biodiversity. Habitats that are expected to be most impacted by climate change (including sea level rise) are mangrove and coastal systems, montane systems, and dryland vegetation communities. Species that are naturally located in high elevation areas, in isolated or outlying mountain ranges, on smaller islands, or that are also exploited for human use are at greatest risk. However, a salient point of unanimous consensus is that anthropogenic activities that are unrelated to climate change – such as forest conversion for agriculture, over-logging, and fire – may not only have greater impacts on biodiversity in the short-term, but will also exacerbate the impacts of climate change.

Many of Melanesia's birds, mammals, reptiles, and amphibians are potentially vulnerable to climate change in the region, especially those that are endemic and have limited ranges or distributions, are specifically adapted to distinct elevational gradients, or have specialized needs. Birds are a unique category since some are endemic to the region, but there are others which spend part of the year or part of their life outside the region. Thus these populations will also be affected by aspects of climate changes outside of the region and climate changes that are region- or area-specific. It seems clear that the full spectrum of faunal biodiversity will be impacted by climate change, but our understanding of which species may be at particular risk, and which may actually benefit is inherently impeded by a serious dearth of scientific understanding about fundamental ecological processes, species requirements, and physiologies.

6.2.1 Possible mitigating factors for terrestrial systems

Leaving aside the issue of climate variability, a key unresolved question is whether or not climate change in Melanesia will result in increased or decreased cloud cover and precipitation. Current modeling suggests that northern parts of Melanesia will experience increased precipitation, while southern parts (e.g., New Caledonia) will receive less rainfall, but deficiencies in the climate models suggest that there is still considerable uncertainty on this point.

Assuming an increased precipitation regime for parts of Melanesia, this may play some role in mitigating other climate impacts. Clouds and rainfall tend to suppress temperature; synergistically they are believed to allow the possible compression of vegetation zones (i.e. Massenerhebung effect). To the extent that mountain habitat zones can or will be compressed, this will somewhat mitigate biodiversity impacts of climate change, although the suitable range of dependent species will still be somewhat more spatially restricted. It is also important to note that isolated mountain ranges already have a significant degree of compressed habitat zonation, and so the capacity of these areas to experience further compression may be more limited than for larger mountains.

6.2.2 Exacerbating factors for terrestrial systems

The possibility of habitat zonal compression is at this stage only speculative. However, assuming that such compression is possible, absent other factors such as increased climate variability (e.g., increased drought/frost) the end result could be reductions in dependent species populations, rather than outright extinction. Increased climate variability could substantially complicate the picture, however. Drought conditions such as those associated with El Niño events substantially increase the risk of forest fires, especially in disturbed forest (viz. open canopy secondary forest with dead wood supply). Increased climate variability, in tandem with anthropogenic forest disturbance (logging or forest conversion for agriculture) may therefore create conditions favorable for a serious increase in forest fires that would result in permanent alteration of forest habitat. Specifically, a northward shift of the savanna/rainforest boundary could occur in New Guinea, and/or the expansion of *Imperata* grassland in other areas could occur.

It is currently unclear whether or not ENSO events will increase in frequency or intensity, but even current high levels of anthropogenic forest disturbance combined with "normal" ENSO cycles and expected warming may be sufficient in themselves to result in long-term habitat alteration or loss. Logging and/or forest conversion alters or disrupts hydrological cycles. Terrestrial forests control air humidity, soil moisture, stream flows, and water evaporation by regulating the hydrology through evapotranspiration, photosynthesis and regulation of rainfall runoff. Forests have a direct influence not only on the microclimate (i.e. within or immediately adjacent to the forest itself) but also at island-wide scales by sustaining higher precipitation levels compared to regions without a forest canopy (Fischlin 2009; Laurance and Williamson 2001; Betts et al. 2004; Bruijnzeel 2004; Negri et al. 2004; Werth and Avissar 2004; Avissar and Werth 2005; Field et al. 2007a). The persistence of relatively high proportions of intact (closed canopy) forest is therefore a fundamentally critical element in maintaining a degree of natural resilience to climate change impacts. Presumably there are thresholds in terms of how much closed forest cover is required to maintain basic hydrological functions, but what these may be in Melanesia is unknown and in serious need of immediate research.[16] An essential corollary of this understanding is that maintaining forest resilience in protected areas will very likely require maintaining hydrological processes outside of those protected areas as well. Enhancing biodiversity resilience will require not only conservation, but successfully applied ecosystem sustainability efforts over large expanses of terrestrial and marine areas in Melanesia.

6.3 Resilience

Because climate change has happened in Melanesia over past millennia, it is clear that intact natural ecosystems possess some significant degree of inherent resilience to these changes. Resilience is defined here as the inherent capacity of a healthy ecosystem to resist and/or recover from climate perturbations. The main current and future threat to Melanesia's terrestrial biodiversity from climate change is largely a factor of (1) the very rapid pace and degree of warming, which seems to be much faster and more intense than previous changes; and (2) the extent to which natural landscapes have been, or will be modified or degraded by human activity. Human pressure on species and ecosystems reduces their resilience to environmental changes and makes extinction risks much more likely. A very possible result of this reduced natural resilience will be a corresponding decline in the ecosystem services (food resources, provision of rainfall and water supplies, pollination, storm protection, etc.) upon which Melanesia's communities depend.

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[16] Most research on this topic has been focused on Amazonian forest ecosystems, which may have different threshold properties because they operate on a continental rather than island scale.

6.4 Second-order / indirect impacts

The scope of this study did not include in-depth examination of second-order or indirect climate-related impacts on biodiversity, but these are likely to be large. For example, coral bleaching-induced declines in near-shore reef fisheries may force human coastal communities to seek food resources in upland areas that were previously lightly impacted. Alternatively, non-climate modifications to landscapes (such as deforestation or forest conversion to agriculture) may exacerbate the capacity of species populations to adapt to climate change. Extrinsic factors are a very important part of the equation in terms of climate change impacts. These include population increases and/or population displacement (possibly itself as a result of climate change impacts), opportunistic diseases impacting species already weakened by other stresses, and land-use changes.

It may be useful to think of the range of problems in terms of global environmental change – which includes climate change impacts – rather than climate change or deforestation or ocean acidification in isolation. Each of these causes of environmental change is also in some important sense an effect; destruction or degradation of ecosystems is not likely to be caused by only one factor but by the cumulative effect of multiple stresses and perturbations acting in synergy.

6.5 Conservation implications

Given the inherent uncertainties in the global climate models as well as the current regional downscaled models, it is very important to be cautious in assessing regional climate change projections. Some areas that may look “doomed” may in fact not be. Indeed, it is important to avoid the tragic irony of a premature or facile assessment that could essentially doom such areas through lack of conservation attention or funding rather than climate change *per se*. Conversely, some areas that currently appear on paper to be relatively low-impact areas may not necessarily be. Such is the current state of climate uncertainty, and unfortunately this is likely to remain the case for the near future.

Melanesia’s high beta diversity, combined with our lack of understanding of basic ecological processes, species requirements, ecosystem interactions and behavioral/phenological responses render it difficult to precisely assess the impact of climate change to the biota. Current climate projections for any particular area in Melanesia are insufficiently robust to assess possible site-specific revisions to protected areas, or to identify specific areas of low risk to climate change that should be prioritized. For the present, use of bioclimatic models for Melanesia are likely to fail because of uncertain climate projections at scales relevant to conservation, and the lack of rudimentary knowledge of the climatic thresholds of species or the evolutionary plasticity of populations (Araújo and Rahbek 2006). We find no reason to recommend additional conservation priority-setting exercises (e.g. gap analyses) until such time as our understanding of all these elements is more advanced.

There was very strong consensus among project participants that the overall conservation priority for climate change impacts on biodiversity in Melanesia should be to maximize ecosystem resilience to climate change. Operationalizing this principle at a variety of different scales in complex social and political contexts will require elements of pragmatism, experimentation and adaptive management.

Climate stresses on both marine and terrestrial habitat are likely to vary spatially. For marine conservation in particular, refugia are likely to be very important, but what areas are the most promising candidates in this respect is not clear. For both marine and terrestrial conservation, it is critical to maximize habitat connectivity to allow species populations to move in response to their requirements and/or to allow dispersal/recruitment. Population movements are also likely to result in new ecological interactions among species, the properties of which are currently unknowable.

For marine conservation, the interactive effects of coral bleaching, ocean acidification and other intrinsic/extrinsic factors are unclear. It seems very likely that the cumulative impacts of these stressors will be large, but that certain areas are likely to have greater resilience than others, and dissimilar habitats may be connected in significant ways. While areas subject to cooler, deep water upwelling may seem, *prima facie*, to have greater capacity to resist thermal stress compared to shallow water areas, this is not necessarily the case. Some shallow water areas appear to have a wider natural temperature band than areas with more depth-diversity, and so some shallow water reef systems may be pre-adapted to thermal stress. Patterns of recovery following bleaching events are mixed both spatially, as well between and even among species in a given area. On the other hand, oceanic seawater may have higher total alkalinity relative to lagoonal waters, and thus may confer some buffer against acidification effects (TNC 2008). Protection of algal turf and seagrass habitat may help mitigate acidification effects on reefs because photosynthetic activity in those habitats reduces CO_2 levels and thus raises the calcium/aragonite saturation state (TNC 2008). These factors imply that resilience-maximizing approaches to marine conservation in Melanesia should emphasize the selection of large areas with a high degree of environmental heterogeneity (i.e. habitat diversity).

In terms of terrestrial conservation, we recommend a priority on maximizing ecosystem resilience to climate change through the successful preservation of as much intact natural habitat and their accompanying ecological processes as possible. It seems reasonably clear that large areas with high ecological diversity, particularly areas with a wide range of elevations, probably have the greatest capacity to buffer the impacts of climate change. The presence of elevational gradients will be critical to facilitate the opportunities for habitat-sensitive species to relocate to new habitat as ecosystems shift over time. Larger protected areas are less susceptible to intrinsic and extrinsic perturbations relative to smaller protected areas. This strategy will not protect island endemics, which may require other types of conservation interventions. However, given the scarcity of conservation funding resources and the need to prioritize, we recommend that current conservation efforts focus on the preservation of large areas with maximal elevational gradients (ex. “ridge to reef”). In Papua New Guinea, Papua/West Papua provinces, Solomon Islands, Vanuatu, Fiji, and New Caledonia there are a range of conservation area projects that are excellent project candidates in this regard.[17]

It is important to emphasize that the natural resilience of a specific area or ecosystem to climate change may largely depend on maximizing the amount of functionally intact habitat

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[17] Even a partial listing of viable candidate sites is a hazardous endeavor that we wish to avoid. Simply as an illustration, however, PNG currently has two major demonstration projects to test the viability of the kind of large-area, elevation-based approach we recommend. The first is based on watershed protection and located in the Kokoda/Owen Stanley Ranges; the second in the Whiteman Ranges through Kimbe Bay in West New Britain is a “ridge to reef” project.

outside that area. Climate mitigating factors such as cloud cover/precipitation reflect fundamental hydrological processes that depend on the continued persistence of adequate forest cover over large areas. This implies that conservation should not be restricted only to protected areas per se, and that extensive deforestation outside protected areas may compromise the resilience of the protected areas. Unfortunately, what ecosystem thresholds may exist is currently unknown. Given this uncertainty, sustainability principles and effective enforcement (in whatever forms are locally appropriate) should be prioritized at the community, island, and regional levels.

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Appendix A

Research Needs

1. Regional level climate change

Because of the Melanesia region's biogeophysical complexity, climate projections currently available from IPCC AR4 studies are of limited value in assessing the impact of climate change on the specific ecosystems of Melanesia. In order to derive more robust regional climate change projections that are of greater use to end users and stakeholders, a series of downscaling experiments must be conducted using both statistical and dynamical downscaling techniques.

Of most immediate benefit would be a downscaling of present global models to scales that matter to ecosystems. The utility of such an approach has already been demonstrated for other regions and is technically straightforward. We therefore recommend a climate projection downscaling project focusing on Melanesia. The product would conduct a finer-scale assessment of projected climate change at specific locations in Melanesia that are considered high conservation priorities and/or ecologically sensitive, such as Raja Ampat, Milne Bay, Lorentz NP, Foja Mnts., Bird's Head, Huon, Kimbe Bay, and other sites. Targeting a few areas for enhanced downscaling would also have relevance for the region, since the development of the first prototype is the most time-intensive, and each successive iteration becomes easier (eventually reaching the point that they could be run on laptops). The robustness of results and an assessment of the uncertainties will be determined by comparison of the results using a number of AR4 model scenarios and statistical downscaling methods.

The task would be to setup a regional ocean model at high horizontal resolution (on the order of ~1/64 degree) which is forced (a) by climate model forecasts and reanalysis data corresponding to upcoming El Niño and La Niña events; and (b) by the climate states of different scenarios (A1, B2, etc.) from a range of models used in the IPCC AR4. The results of the first task will be compared with existing satellite data and *in situ* data that is being collected during El Niño and La Niña events. The results of the second task will be compared with existing statistical downscaling results in order to obtain robust estimates of projected climate changes. The robustness of these models will continue to improve over time with greater understanding of physical processes such as ENSO variability and oceanic warm pools.[18]

2. Ocean acidification

In order to carry out field experiments that could reliably predict the future of high CO_2 levels on the ocean, it is important to look at the FACE (Free Air CO_2 Enrichment)

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[18] Current GCMs are relatively weak in matching up present-day conditions in Melanesia for two main reasons. First, there is a serious lack of data on rainfall and temperature that are required to test the validity of the models (viz. the models run from past to present to future, and one important way to test their accuracy is how well they match current conditions). The second priority area is to achieve better understanding of the effects of clouds and albedo, as well as the basic dynamics of the Western Pacific Warm Pool and the South Pacific Convergence Zone, all of which play very large roles in climate conditions in the western Pacific. In addition there is a need for new GCMs that couple carbon models; these will help clarify future oceanic pH changes. The 5th IPCC report due in 2014 is looking to include models that incorporate additional variables such as these, which will greatly enhance the accuracy and functionality of future climate projections.

experiments carried out for terrestrial forests as a potential model. However, there are clearly fundamental differences between land and ocean CO_2 enrichment techniques. FACE experiments, which are very large scale CO_2 enrichment experiments to examine ecosystem responses, have been carried out on land, but experiments of such scale are not possible in the ocean and very different constraints apply.

Because CO_2 has no atmospheric chemistry, simple mixing of CO_2 with air is all that is required for a land enrichment experiment. But CO_2 has a complex chemistry in sea water with multiple equilibria which are established at different rates; these rates are themselves a function of temperature and pH. For a warm water site such as a tropical coral reef these restrictions do not appear to be impossible. The required sensing, feedback, and flow control systems for executing such experiments, known as Free Ocean CO_2 Enrichment (FOCE) have been explored by the Monterey Bay Aquarium Research Institute (MBARI), and prototype field testing is now well underway[19]. We recommend the deployment of FOCE in a variety of locations in the Pacific in order to test the ecosystem and organism-level responses to high CO_2 conditions.

3. Coral reef bleaching

Any model used for projecting future conditions can only be as valid as the empirical data available to formulate and test it. SST data available from satellites has been utilized in developing the NOAA Coral Reef Watch Satellite Bleaching Alert System. First made available in 1997, this service provides a variety of products as well as list server messages sent when SST models indicate that conditions are approaching or exceeding coral bleaching thermal thresholds for a given area. The NOAA system focuses on specific temperature records and alerts for 24 locations around the world, and the only site included from Melanesia is Beqa Lagoon off northern Vitu Levu, Fiji. Given the central location and importance of New Guinea for both Melanesia and the Indo-Pacific, and the inclusion of the Raja Ampat Islands of west New Guinea in the “coral triangle” of maximum species diversity for the world, the addition of a New Guinea site to the NOAA bleaching alert system should be requested at their website[20]. The deployment of such a system in New Guinea would provide specific warning information when a bleaching event was imminent, enabling the possibility of evaluating the acute effects of the stress and tracking SST conditions following the event that could be related to any recovery that might occur.

4. Terrestrial and marine research

4.1 Baseline data

The IPCC’s AR5 aims to include coupled carbon models, which includes vegetation as well as oceanic carbon cycles, but this is constrained by lack of robust data from the Melanesia region. Climate, marine and terrestrial research focused on Melanesia share a critical lack of baseline data upon which to assess trends or to provide ground truthing. Better monitoring data is a precondition both for better modeling and for evaluating impacts. Essential baseline data include those for terrestrial climate (rainfall, temperature, changes in forest and cloud cover); and site-specific marine conditions (temperature, turbidity, current direction and intensity, pH, salinity, etc.). These data are relatively easy to gather,

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[19] See http://www.mbari.org/highCO2/foce/home.htm.

[20] Visit http://www.osdpd.noaa.gov/PSB/EPS/CB_indices/indices_form.html.

and we recommend that donor organizations require gathering such monitoring data a required part of all future grantee field project activities. These data should also be required to be openly shared on a timely basis with the global scientific research community. A centralized database for all scientists and managers working in the region, containing all data ever collected, would significantly advance climate science and conservation biology in the Pacific.

There are large gaps in knowledge of the biotic diversity within Melanesia at both the taxonomic and community levels. For example, the true size and diversity of the New Guinea flora is unknown, and at least half its insects, a quarter of the mammals and more than 40% of the herpetofauna have yet to be scientifically named. There is no comprehensive description for the vegetation of Vanuatu. Even biotas that are relatively well known such as Fiji, understanding of the distributions of many species remains limited. Molecular systematics and population genetics studies for Melanesia are limited. A more complete set of baseline data on the diversity and distributions of plant and animal species in Melanesia is important to facilitate an understanding of the effects of climate change at the most fundamental level.

4.2 Research on ecological processes

There is a very serious lack of understanding about fundamental ecological processes in Melanesia, and this area of research should be of the highest priority. Critically important is expanded and enhanced research on hydrological processes such as rainfall formation, and how differences in vegetation type and/or cover affect evapotranspiration rates that influence cloud formation and inversion layer response. Current understanding of these processes in Melanesia is very poor. However, how and to what extent these hydrological processes change will fundamentally determine precipitation patterns and cloud cover, which has particularly large implications for biodiversity, especially at higher elevations.

4.3 Research on species physiologies and ecology

There is also a dearth of understanding about species behaviors/phenology, ecological requirements of species, or likely physiological thresholds of Melanesia’s flora and fauna. These areas of research should also be prioritized. There is similarly poor understanding of the behavioral or genetic plasticity of species, but these factors will be key to species’ ability to adapt to climate change.

There are few publications of the physiology of Melanesian species, especially in relation to expected climatic changes. For example, studies of plant responses to climactic variables are considered only singly as assessments of physiological response, and it is difficult to scale experimental results up to landscape and regional levels or to make useful generalizations across ecosystem types and processes. Careful selection of target research species on which climate change is likely to have the greatest impact and which are most likely to facilitate broader landscape-level conclusions are a critical first focus for physiological studies.

There have been few if any biological studies regarding how climate change will specifically impact Melanesia’s animal biota, and better understanding of the physiology of animal species is similarly critical. Many animals can have very finely tuned physiology; for example, Ring-tailed possum have thermal limits that cannot be exceeded. In order to assess potential effects of climate change on Melanesia's birds, herpetofauna, and mammals, a much greater research focus on species physiologies is essential.

Phenological events, such as flowering and fruiting, are often highly tuned to climatic conditions. Because there are often strong co-evolutionary interactions between plants and their pollinators and seed dispersers, small changes in climate may decouple these highly specialized associations and lead to reproductive failure and reduction of biological diversity. However, very little is known about the phenology and ecology of Melanesian plant species, and this is a critical area of needed research. Research on forest regeneration and forest succession is also essential to understand of the ability of plant species to migrate or disperse under the expected climate change conditions.

For animal populations, there needs to be a greater emphasis on ecological research to understand how communities interact, how different species of animals interact, sleep, eat, and breed, and what are their elevational and habitat associations. For the vast majority of Melanesia's animals, little is known about such critical topics as reproductive habits or food requirements.

4.4 Studies on invasive species

Invasive species have a very serious negative impact on island biodiversity. Climate change is likely to increase opportunities for non-native species to become invasive in Melanesia and elsewhere. Knowledge regarding the mechanisms underlying invasive biology, however, remains poor; there is not a good understanding of how the invasive species interact with the local biota and how their ranges can change with climate change. Research in other areas such as reproduction, physiology, etc. will also be important for understanding the potential increased impacts of invasive species, as well as the related subject of climate change-induced arrival of new diseases or disease-spreading organisms. It is important to recognize that there is a potential human health dimension to the problem of invasive species as well.

4.5 Need for long-term research

A combination of direct climate change impacts, reduced areas of natural habitat (ex. anthropogenic disturbance), and species invasions are likely to promote new and unpredictable interactions between plants, animals and microorganisms. Ecological studies such as those just described are best facilitated by long-term field observations. Such long-term observations and surveys have been recorded for temperate areas in the Northern Hemisphere, but baseline data on plants that are useful for climate change assessments have only recently become established through the PABITRA (Pacific-Asia Biodiversity Transect)[21] network with sites in Solomon Islands, Papua New Guinea, and Fiji. This project is gathering very important information and such projects are worthy of enhanced support. Because cloud forests have high levels of endemism and are particularly sensitive to climate change, it would logical to establish monitoring protocols in fragmented or disjunct montane areas. Coastal areas, while not the most biologically diverse, have the greatest economic implications if lost through climate change effects, and should also be actively monitored for changes to plant community composition and

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[21] PABITRA's sites also include many others throughout Micronesia and Polynesia. More information is available on their website: http://www.botany.hawaii.edu/pabitra/.

distribution. Given the low level of biological knowledge for Melanesia and the likely mechanisms of climate change, a focus on elevational gradients should guide many research efforts.

The nature of the priority research areas described above implies a relatively greater need for long-term ecological research (e.g. field station-based longitudinal studies) compared with short-term rapid biological inventories. Without these data it will be extremely difficult to understand or assess climate change impacts and what are the best mitigation / conservation strategies to address them.

In summation, biological research in Melanesia should focus on:

- Taxonomic and biogeographic characterization of plant and animal species: how many species there are, what distinguishes them, and what are their geographic distributions and habitat;
- Documentation and assessment of areas with high levels of restricted-range endemism for designation as protected areas;
- Basic biology: phenology, diet, nesting sites, sleeping areas, population dynamics, reproduction, etc.; and
- Basic ecology: elevational and habitat associations; inter-species interactions, etc.

There are also broad themes in the study of the terrestrial effects of climate change that should be pursued. These include range shifts along gradients, complex ecological interactions, and invasive species dynamics.

4.4 Cross-fertilization between marine and terrestrial research

Participants at our workshop suggested there are important opportunities for terrestrial science to learn lessons from marine science, and vice versa. In particular, participants noted the utility of the “degree heating weeks” concept for coral reef ecosystems, and voiced support for exploring whether a similar resilience metric for the terrestrial ecosystems may be possible. There is a need to achieve greater understanding of the comparative physiology of organisms, especially for terrestrial species. There exists significant information on the physiology of corals, their thresholds, temperature-dependent aspects of their biology, etc. but there is a huge lack of corresponding information on terrestrial animals and plants. This may be of greatest utility in higher elevation ecosystems, i.e. species at the tree line. Other areas of possible marine-terrestrial methodological cross-fertilization are in studies of connectivity and refugia as well as other commonalities (e.g. altitude v. depth).

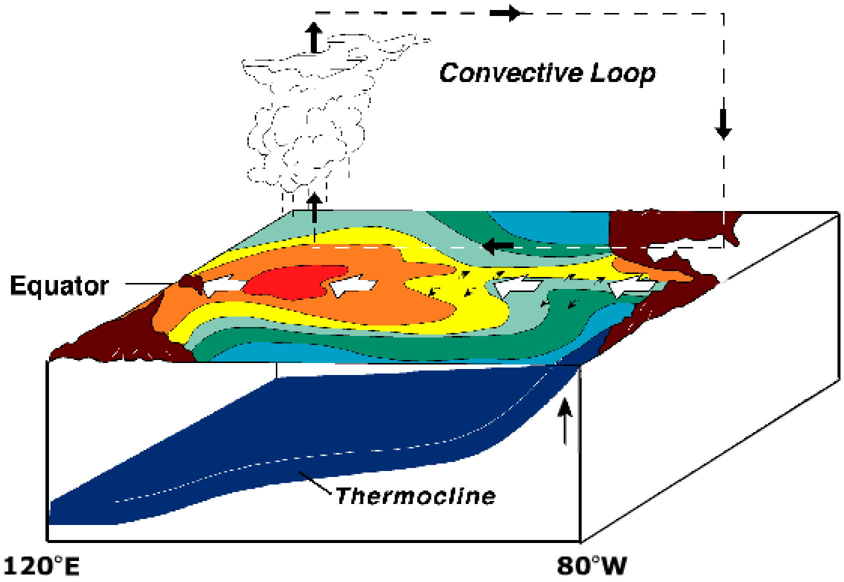
4.6 Stakeholder Dialogue

Much of the documentation of climate variability has come from the Northern Hemisphere, and as described above there is very limited long-term ecological analysis for Melanesia. The tropical forests of Melanesia are large stores of biological diversity that require study in the face of climate change, but such research will require collaboration between scientists with a broad range of backgrounds, including taxonomists, biologists, climate modelers, atmospheric scientists, economists, sociologists, as well as communities and conservation practitioners.

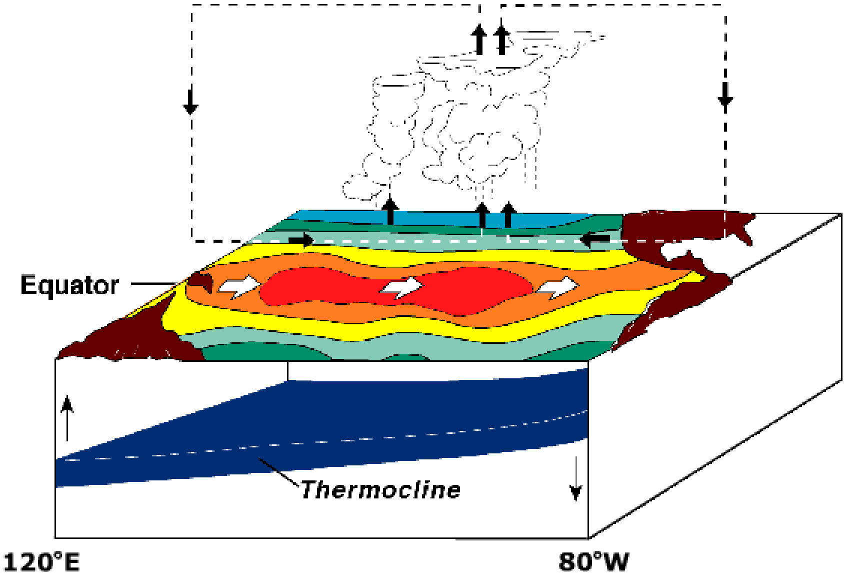
A workshop series to facilitate better stakeholder understanding about research, monitoring, and (human) community priorities would be very valuable. These should also aim to identify two to three priority threats to allow greater focus and to make mitigation efforts for manageable and effective. These workshops should openly address uncertainties and discuss the strengths and weaknesses of different intervention/mitigation options, and encourage adaptive management approaches.

Appendix B

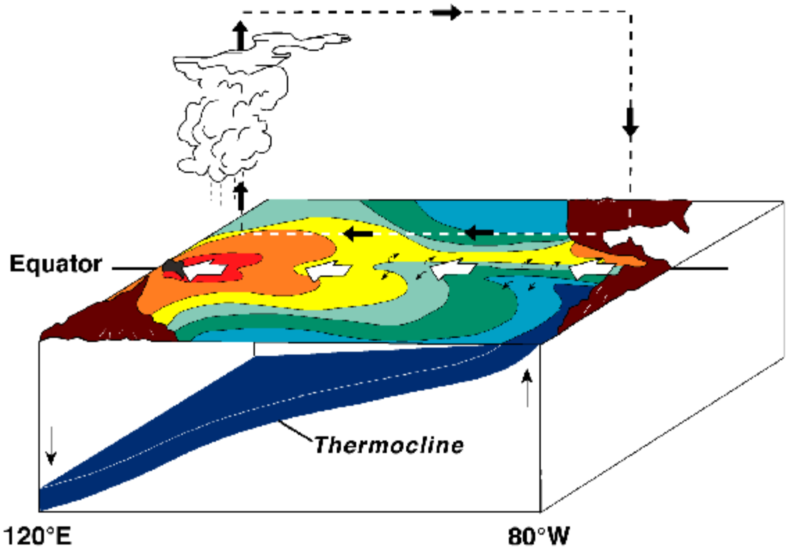
Illustrations of Typical El Niño-Southern Oscillation Patterns



Normal Pacific Circulation Pattern: Prevailing westerly wind flows at the equator draw cold water upwelling in the eastern Pacific near Peru and warm water is circulated to the western Pacific. Warm water creates normal precipitation patterns in the western Pacific.



El Niño Circulation Pattern: Prevailing westerly wind flows at the equator stop or reverse; warm water accumulates in the eastern Pacific near Peru and the central Pacific, which causes increase in convective storms and precipitation in those areas and corresponding drought conditions in the western Pacific.



La Niña Circulation pattern: Prevailing westerly wind flows at the equator accelerate; warm water accumulates in the western Pacific, which causes increase in convective storms and precipitation in Melanesia/Indonesia. Coral bleaching episodes in Melanesia/Indonesia are more likely. Corresponding drought conditions in the eastern Pacific along with increased deep water upwelling off the coast of Peru.

Appendix C

CCBM Paper Series

Paper No.	Author	Title
1	Kelvin Richards and Axel Timmermann, International Pacific Research Center (IPRC), School of Ocean and Earth Science and Technology (SOEST), University of Hawaii-Manoa	Climate change projections for the Southwestern Pacific with a focus on Melanesia
2	Peter G. Brewer, Monterey Bay Aquarium Research Institute (MBARI)	Climate Change and Biodiversity in Melanesia: Biophysical science – ocean acidification
3	Dan A. Polhemus, Department of Natural Sciences, Bishop Museum	Climate change in New Guinea and its potential effects on freshwater ecosystems
4	Geoffrey Hope, The Australian National University	Palaeoecology and resilience in Melanesia: How can palaeoecology contribute to climate change response planning?
5	Steve Coles, Department of Natural Sciences, Bishop Museum	Potential Climate Change Impacts on Corals and Coral Reefs in Melanesia from Bleaching Events and Ocean Acidification
6	Terry J. Donaldson, University of Guam Marine Laboratory	Climate Change and Biodiversity in Melanesia: Implications for and impacts upon reef fishes
7	Rodney V. Salm and Elizabeth Mcleod, The Nature Conservancy	Climate Change Impacts on Ecosystem Resilience and MPA Management in Melanesia
8	Shelley A. James, Department of Natural Sciences, Bishop Museum	Climate Change Impacts on Native Plant Communities in Melanesia
9	Andy Mack, Carnegie Museum of Natural History	Predicting the effects of climate change on Melanesian bird populations: probing the darkness with a broken flashlight
CCBM Report		
10	Allen Allison, Department of Natural Sciences, Bishop Museum, and Stephen Leisz, Colorado State University	Analysis of the Impacts of Climate Change on the Herpetofauna of the Papuan Region (New Guinea to the Solomon Islands)
Research Presentation		
11	Kris Helgen, Smithsonian Institution	Climate Change Impacts on Mammals in Melanesia: What do we know?