Exploring the relation between sea level rise and shoreline erosion using sea level reconstructions: an example in French Polynesia

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ABSTRACT

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The climate component of sea level variation displays significant spatial variability, and it is now possible to reconstruct how sea level varied globally and regionally over the past half century. The fact that sea level rose faster than the global mean since 1950 in the central Pacific stimulated a study of decadal shoreline changes in this region. Here, the study of Yates et al. (2013) was extended to two additional atolls (17 islets): Tetiaroa and Tupai in the Society islands. Both atolls remain stable on the whole from 1955 to 2001/02, however with significant differences in shoreline changes among their islets and within the period. A modeling of waves generated by historical cyclonic events in French Polynesia since 1970 reveals consistency between major shoreline changes and cyclonic and seasonal waves. As in previous studies, this suggests that waves' actions are a dominant cause of shoreline dynamics on relatively undeveloped atolls, even if affected by higher sea level rise rates. In such regions, numerous joint analyses of shoreline changes and their potential causes may help to explain the relation between erosion and sea level rise.

ADDITIONAL INDEX WORDS: *sea level rise, climate change, coastal erosion, atolls, French Polynesia, Pacific.*

INTRODUCTION

Sea level rise (SLR) is a major concern for coastal areas. However, its actual consequences on coastal erosion are still rather unknown (Nicholls and Cazenave, 2010). It is expected that SLR will favor erosion since waves will reach higher elevations in the upper beach (Bruun, 1962). However, it is also acknowledged that this will not be always the case as processes affecting shoreline mobility are complex and interact at multiple spatial and temporal scales (Pilkey and Cooper, 2004). In addition to sea level variations, potential causes of shoreline mobility at decadal scales are hydrodynamics and meteorological factors (waves, current, tides, surges, winds, including during storms), the inherited geomorphology, present sediment budgets, biosedimentary processes and human activities. Without a validated model able to represent accurately how these factors interact and cause sediment transport at decadal timescales, the actual contribution of SLR to shoreline mobility at a given site remains difficult to evaluate.

In contrast, the observation of many sites may reveal that there is an increased probability of erosion when sea level is rising. A global survey published in 1985 revealed that many beaches around the world were eroding (Bird, 1996). These changes were related to local factors affecting the beaches. However, it was acknowledged that sites in UK and USA were over represented in their study, supporting the idea that a more evenly distributed survey was required.

When exploring the relation between SLR and coastal erosion over a wide range of coastal sites, one has to consider the fact that sea level is not rising uniformly (e.g., Lombard *et al*., 2005; Cazenave and Llovel, 2010; Meyssignac and Cazenave, 2012). This is due to a number of factors (Milne *et al*., 2009; Stammer *et al*., 2013): (1) non uniform thermal expansion and salinity effects associated with ocean circulation changes and (2) static effects due to the visco-elastic and elastic response of the solid Earth to past and present mass redistributions associated with last deglaciation (called Glacial Isostatic Adjustment –GIA) and ongoing land ice melt. In addition to the large scale regional variability affecting the absolute sea level, other processes cause vertical land motions (e.g., subsidence or uplift due to tectonic and volcanic activity, subsidence due sediment loading, ground water pumping and oil & gas extraction; e.g. Wöppelmann *et al*., 2007). Such local phenomena lead to relative sea level changes (i.e., with respect to the ground) and may either amplify or reduce the climate-related components. At a given location, the variable of interest is the total relative sea level variation, i.e., the sum of the climate-related global mean rise, plus low-frequency regional variability, plus the local land motions.

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One can question if erosion is aggravated in places where the sea level is rising faster than the global mean SLR. Using the dense tide gauge network along the eastern coast of the United States, Zhang *et al*. (2004) indeed found accelerated erosion rates in the places affected by higher SLR rates. These higher relative SLR rates result from the subsidence of this area located around the former Laurentide ice-sheet. The results of Zhang *et al*. (2004) were confirmed in a probabilistic approach by Gutierrez *et al*. (2010). In Europe, Yates and Le Cozannet (2012) also showed that sea level variations are an important variable in explaining shoreline mobility: one may note that Scandinavian coasts are mostly accreting while they are also uplifting because of GIA effects in this region formerly covered by the Fennoscandian ice sheet ~20 000 years ago.

Until recently, further investigation was limited by the lack of dense tide gauge measurements along the world coastlines. Fortunately, reconstructions of past SLR have been produced recently (e.g. Church *et al*., 2004; Llowel *et al*., 2009; Meyssignac *et al*., 2012). For coastal geomorphologists, these data provide a unique opportunity to know how the climate component of sea level variation has evolved since 1950, even when no tide gauge data are available, thus providing new sites for investigating the relation between SLR and coastal erosion.

The objectives of this paper are (1) to discuss the general approach that motivated this study, i.e. the exploration of the relation between SLR and shoreline changes through surveys in regions where sea level has most significantly deviated from the global mean average since 1950, taking advantage of sea level reconstructions; (2) to illustrate this approach through examples in atolls of French Polynesia, owing to increasing knowledge of decadal shoreline changes and associated causes in this region, and taking advantage of a new modeling of cyclonic waves from 1970 to 2001.

Obviously, there is a gap between the spatial scale of the problem (erosion of atoll islands in a region as large as Europe, with the hope to better understand how sea level is affecting shoreline mobility at a whole) and the number of case studies presented in this study: together with Yates *et al*. (2013), 4 atolls (64 islets) have been analyzed. We acknowledge this limitation. However, as important as the conclusion on the potential effects of SLR on shoreline mobility, is the general approach consisting in taking advantage of sea level reconstructions indicating higher rates of sea level in a region, then focusing on the analyses of shoreline mobility in this region.

The paper starts with a brief review of sea level reconstructions and their implications for Pacific and French Polynesia. Then, methods and results of the shoreline changes study are shown. Finally, the discussion attempts to find the potential causes of decadal shoreline changes in Tupai and Tetiaroa and to examine the significance of the results.

THE CASE OF THE PACIFIC

Climate related regional SL variations since 1950

To determine the decadal/multidecadal spatial trend patterns in absolute sea level prior to the altimetry era, 2-dimensional past sea level reconstructions can be used. These provide estimates of regional sea level variations, as well as time series of estimated sea level at any locality over a longer period than is often available from individual tide gauge records alone. The general approach consists in combining long, good quality tide gauge records with the dominant spatial modes of gridded sea level fields (either from satellite altimetry or numerical ocean models) through an Empirical Orthogonal Function (EOF) decomposition and computing new EOF temporal amplitudes through a least-squares optimal interpolation that minimizes the reconstructed field and the tide gauge records at the tide gauge locations. The sea level reconstruction used in this study is that of Meyssignac *et al*. (2012). It is based on 91 long (up to 60 years) but sparsely distributed tide gauge records and shorter gridded sea level fields based on satellite altimetry data and outputs of two numerical ocean models: the DRAKKAR/NEMO without data assimilation (Penduff *et al*. 2010), and the SODA reanalysis (Carton *et al*., 2008).

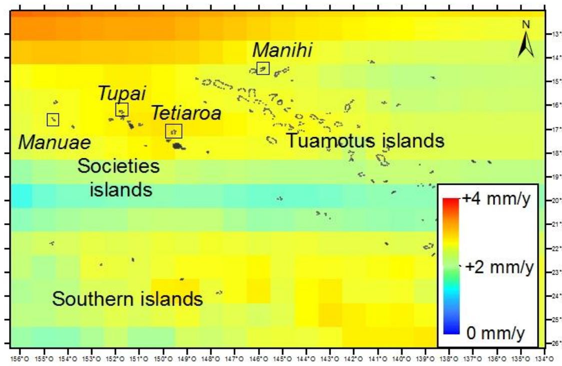

Figure 1. Linear trends of sea level variations from 1955 to 2002 according to the DRAKKAR reconstruction in French Polynesia and atolls considered in this study (Data: Meyssignac *et al*., 2012).

In a regional validation of the DRAKKAR-based sea level reconstruction, Becker *et al*. (2012) showed that, in the central Pacific, the climate-related sea level rose significantly faster than the mean global mean rate (of about 1.7 mm/yr) over the 1950-2010 time span. This statement is also true in French Polynesia. Figure 1 and Table 1 provides the sea level trends in atolls of interest for this study during 1955/2002 (earliest and latest shoreline observations in this study) for three versions of the Meyssignac et al. (2012)'s reconstruction (i.e., using successively the EOF spatial patterns from the DRAKKAR and SODA ocean models and from satellite altimetry). While the DRAKKAR reconstruction has been validated upon independent tide gauges observations and satellite altimetry, all reconstructions agree in finding sea level trends higher than the average sea level trend in this area (except for Manihi in the altimetry EOF-based reconstruction) : the average rate over 1955-2002 in this area amounts to 2.4 mm/yr, i.e., it is 40% higher than the global mean sea level rate (of 1.7 mm/yr) over this time span. It is worth reminding that Becker *et al*. (2012) estimated uncertainties in the DRAKKAR reconstruction at +/-0,5mm/yr.

Internal geodynamic component of SLR

Sea level at the coast may be amplified by subsidence or reduced by uplift. In order to estimate these vertical movements, one can use data from permanent GPS stations. Existing permanent GPS stations in Tahiti show linear trends ranging from

Table 1. Linear trend of sea level changes (mm/year) at atolls locations, according to the three reconstructions of Meyssignac *et al*. (2012) from 1955 to 2002.

Atoll	*Drakkar*	*Soda*	*Altimetry*
Tetiaroa	2.75	2.23	2.89
Tupai	2.76	2.21	2.27
Manihi	2.41	2.32	1.74
Manuae (Scilly)	2.59	2.34	2.18

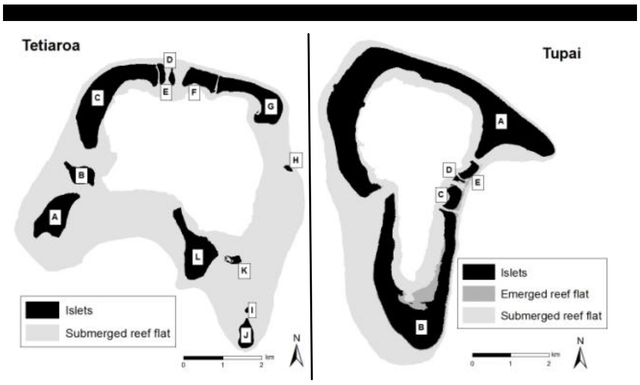

Figure 2. Tetiaroa and Tupai atolls.

-2.2 to -0.45mm/year, with associated uncertainties ranging from +/-0.4 to 0.6 mm/year (more details on www.sonel.org). Some of these GPS stations are located in an area considered as prone to landslides, according to an analysis of slopes and geology undertaken for the risk prevention plans of French Polynesia (Sedan, 2012, personal communication). Moreover, the vertical ground movements in Tahiti are not necessarily representative of those of nearby islands. The second way to estimate potential vertical land motion is to analyze geological observations of past shorelines. Pirazzoli and Montaggioni (1988) undertook an intense field campaign to collect shoreline's footmarks of the +1m high mean sea level standstill from 4.5 to 1.25ky B.P. Their analysis included 38 islands in French Polynesia and provided a regional picture of subsidence rates, revealing a subsidence anomaly around Tahiti of about 0.15mm/year, possibly affecting Tetiaroa, but not Tupai, according to their data. In any case, these rates are less important than those of recent SLR. Hence, they were not considered in this study. However, more permanent GPS data or tide gauges measurements are needed to better address this issue.

Implications for erosion and site selection

Many atoll islands located in the Pacific are commonly considered as very vulnerable to SLR. However, in previous studies, shoreline mobility of emblematic atolls is attributed to human actions and waves (Webb and Kench, 2010; Ford, 2012). Indeed, on highly anthropised coasts, it is expected that human activities will dominate natural processes in controlling shoreline mobility.

In French Polynesia, shoreline changes in major high islands and their relations with human activities have been studied (Aubanel *et al*., 1999). On the other hand, atoll shoreline changes are poorly known, although a database of ancient aerial photographs exists. Since human pressure in atolls in this region is rather low, natural processes are not expected to be dominated by human actions in many coastal sites.

This motivated a survey of decadal shoreline changes on relatively undeveloped atolls in French Polynesia. Yates *et al*. (2013) started with shoreline mobility analysis in Manihi in the western Tuamotus and Manuae in the Leeward Islands, suggesting it is primarily due to hydrodynamic processes. Here, this analysis was extended to two other atolls in French Polynesia in the Society Islands (Figures 1 and 2): Tupai (resp. Tetiaroa) encompass 5 (resp. 12) islets, covering a surface of 950 ha (resp. 520 ha). 45% of the reef flat is occupied by islets in Tupai (22% in Tetiaroa).

METHODS

Shoreline changes and associated uncertainties

Shoreline changes have been analyzed in Tupai and Tetiaroa from 1955 to 2001/02, using remote sensing images provided by the Urban Services of the French Polynesian government (Table 2). The method for shoreline change detection follows the same steps as in Yates *et al*. (2013). First, images are georeferenced using secondary control points (Thieler and Danford, 1994). Then, the permanent vegetation line is digitalized. This limit is a valuable indicator of decadal shoreline changes and can be identified with sufficient accuracy in oldest aerial photographs. Other indicators of shoreline position could be chosen (Boak and Turner, 2005), for example the mean yearly position of high tides water limit on the beach. However, intensive field surveys and high repeatability in remote sensing observations are required for monitoring accurately this limit.

Two sources of uncertainties affect the accuracy of shoreline positioning and thus shoreline change evaluations: (1) uncertainties due to image resolution, images georectification and shoreline digitalization (errors of the operator), which can be classified as random uncertainties; (2) uncertainties due to the convention used for digitalizing shoreline: for some sections of the shoreline, delineating the permanent vegetation line is not straightforward because vegetation becomes sparse. These can be categorized in epistemic uncertainties.

Random uncertainties were estimated to 5m around digitalized shorelines, as in Yates *et al*. (2013). This defines three categories in observed shoreline changes (Figure 3, right): "confirmed shoreline change" when the distance between the old and new shoreline positions exceeds 10m; "suspected shoreline changes" when this distance is comprised between 5 and 10m; and "stability of shoreline" when it is lower than 5m. For each islet, the maximum range of random uncertainties has then been estimated calculating surface changes under the most unfavorable hypothesis (Figure 3, left): the lowest (resp. highest) surface change value is obtained by calculating confirmed surface changes only (resp. confirmed and suspected surface changes).

Table 2. Remote sensing images used in this study.

Date	***Source***	***Scale / resolution***	***Islet covered***
Tupai			
1955	Aerial photos	1:45 000	All
1984	Aerial photos	1:20 000	All
2001	Satellite	0.9 m	All
Tetiaroa			
1955	Aerial photos	1:40 000	All
1981	Aerial photos	1:25 000	BCDEF; Most of AG
2002	Satellite	0.5- 0.6 m	All

First, any area presently covered by vegetation (even sparsely distributed) was considered as inland. Then, using knowledge about the vegetation species distribution with respect to the assumed islets topographic profile, substrate, lens of freshwaters and exposure to oceanic events (Florence, 1993), the dense vegetation was delineated, as a proxy of the area the less exposed to oceanic events. The maximum range of epistemic uncertainties was estimated by considering those two opposite indicators.

Exposure to cyclonic and seasonal waves

In order to evaluate the consequences of recent cyclones, cyclonic waves affecting French Polynesia from 1977 to 2001 were modeled. The modeling approach is the same as in Lecacheux *et al*. (2012): the trajectories and maximum velocities provided by the Joint Typhon Warning Center (JTWC) database are used to generate 2-dimensional cyclonic wind fields using the Holland (1980) model. Then the waves are computed with the third generation wave model Wavewatch 3 (Tolman, 2009) and the bathymetric data from ETOPO1 (Amante *et al*., 2009), with a resolution of 0.2°x0.2°. Due to the restricted number of parameters available to reproduce de 2D wind fields in the JTWC database, the modeling of the cyclones wind and associated waves must be considered as approximations rather than close representations of the reality. However, this approach provides sufficient information for this first analysis, even if near shore wave transformation and changes are not accessible at this spatial scale of modeling.

RESULTS

Shoreline changes in Tupai and Tetiaroa

The results of the shoreline analysis are presented for both atolls in Figure 4. The overall surface area of both atolls remained stable from 1955 to 2001/02, with a small gain of 0.05% in Tupai and a loss of 0.01% in Tetiaroa. However, the various islets show different erosion and accretion rates. Taking into account the uncertainties, in Tetiaroa, 4 islets out of 12 are surely eroding (up to 10% and 75% of surface losses) while 5 are surely accreting (up to 18% surface gains).

In Tupai, shoreline changes are not homogeneous over the period of observations (Figure 5): the south-eastern part of Tupai was mostly eroding from 1955 to 1984, while after 1984, this coast partly recovered and the north-eastern part eroded. Together with visual observations of vegetation degradation, this suggests that a major event affected this area.

In Tetiaroa, the results show a westward translation of the smallest islets in the south eastern part of the atoll. In the north, the lagoon side of islets generally eroded, while the oceanic side generally accreted. On the western part of the atoll, some islets gained in surface on the lagoon side. This general trend was followed over the two periods 1955 to 1984 and 1984 to 2002.

Table 3. List of cyclones (C) and tropical storms (TS) whose wave affected Tupai or Tetiaroa; associated offshore significant wave heights (O-SWH) and orientation according to a modelling exercise. Events generating O-SWH<3m are shown in this table.

Cyclone and tropical storm names	*Event's date and duration*	*O-SWH*	*Side of the atoll affected by waves*
Tetiaroa			
Tahmar (C)	09-13/03/1981	~3m	South-West
Reva (C)	07-16/03/1983	~5m	North and East
Veena (C)	07-14/04/1983	~8m	East to South-West
Martin (C)	30-04/11/1997	~4m	West North-West
Osea (C)	21-27/11/1997	~3m	North-West
Tupai			
Diana (TS)	16-22/02/1978	~3m	West
Lisa (TS)	10-16/12/1982	~3m	North-West
Reva (C)	07-16/03/1983	~6m	East
Wasa (C)	05-13/12/1991	~5m	North-West
Martin (C)	30-04/11/1997	~8m	West North-West
Osea (C)	21-27/11/1997	~8m	North and West

Cyclone modeling and seasonal waves

The cyclones that are suspected to have affected the two atolls over the period 1955 to 2001 are presented in table 3. From 1955 to 1970, there is no mention of extreme waves significantly affecting these atolls (Des Garets, 2005; Larue and Chiron, 2010). After 1970, quantitative data can be provided using the modeling of cyclones presented previously. Two cyclonic wave fields affecting different shores of Tupai are presented in Figure 6 (Osea, 1997 and Reva, 1983), at the time when the waves were the highest close to Tupai. A complementary analysis of the seasonal wave climate highlighted three main wave regimes: southern waves, trade waves and northern waves using the NOAA Wavewatch 3 reanalysis from 1997-2010.

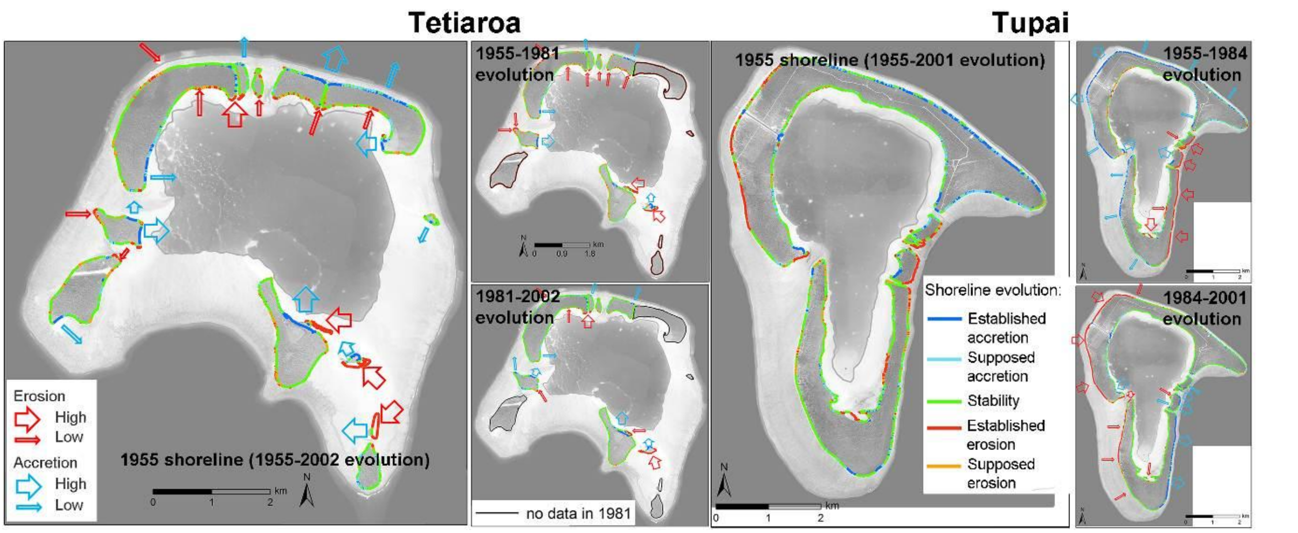

Figure 4. Above: results of shoreline change analysis in Tupai and Tetiaroa.

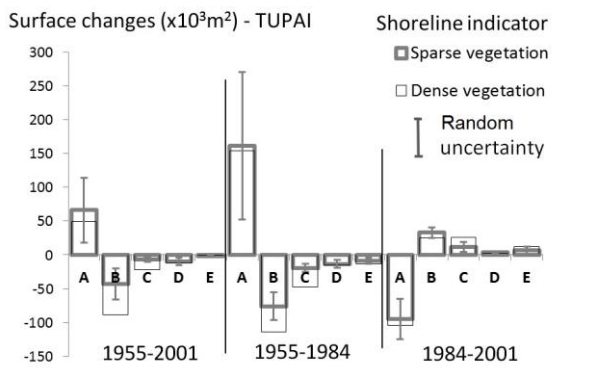

Figure 5. Surface change for each islet and associated maximum range of random and epistemic uncertainties.

DISCUSSION

Plausible reasons for shoreline change

Potential causes of these various evolutions of the shoreline were investigated. Human activities have very low impacts on shoreline changes of both atolls. The large variability of shoreline changes throughout the 17 islets of Tupai and Tetiaroa and the overall relative stability of atoll's surfaces suggest that relative sea level rise was not the dominant cause of the observed shoreline change. The results suggest a major control of shoreline position by cyclones in Tupai: observed shoreline changes are consistent with the modeled cyclonic sequence, suggesting that cyclonic waves and/or winds damaged vegetation and caused the major retreats of shoreline. Some shoreline changes around the pass between A and B islets in Tupai could be related to currents and southern waves. In Tetiaroa, the links between observed changes and potential causes is less obvious, but the eastward translation of islets and the erosion of northern lagoon-ward shoreline suggest that sediment transport was driven by combined effects of cyclone Veena and trade waves.

Summarizing the results obtained within this project (Yates *et al*., 2013 and this study), 64 islets in 4 atolls were investigated. Most of their shoreline was not affected by human activities. When investigating potential causes of shoreline change, the following processes were suggested as plausible causes: (1) cyclones causing shoreline retreat just after an event (e.g. in Tupai and possibly Manuae), but also likely supplying sediments that accumulate and cause accretion in Northern Manihi; (2) sediment transport by seasonal waves, e.g. in southern Manihi and possibly in Tetiaroa; (3) sediment transport by currents in passes (e.g. between islets A and B in Tetiaroa) and some evidences of sediment transport due to lagoon flushing in Manihi; (4) major human influence in anthropised islets in Manihi.

This major control of shoreline changes by coastal hydrodynamics (waves and currents, including during extreme events) and sediments budgets with general observations in coastal geomorphology (e.g. Etienne, 2012 in French Polynesia), but also with previous field surveys in atolls of French Polynesia (Tetiaroa, Rangiroa, Tikehau) undertaken from 2010 to 2012.

Significance and limitations of this study

This study is too limited to draw any definitive conclusions on the actual consequences of SLR on shoreline erosion. First, only 4 of the 78 atolls in French Polynesia were analyzed. Moreover, the temporal density of image acquisition is low (one acquisition each 20 years). This is insufficient to detect a potential "second order" signal in shoreline movements, (potentially due to SLR or any other cause) beyond a "first order" signal, here likely related to sediment transport by waves and currents in islets little affected by human actions. However, it was noticed that the lagoon-ward low lying shoreline of Manuae and Tetiaroa were generally eroding. This highlights the importance of offshore wave-driven lagoon waves and thus of sea level over the opposite submerged reef. Future investigation could focus on comparative studies of atolls with similar geomorphologic characteristics. Finally, the conclusion of this study joins those of Bird (1996): understanding the consequences of SLR requires a broad survey to collect well distributed coastal data around the world coasts.

The fact that some areas of the tropical Pacific experienced increased rates of sea level during the second half of the 20th century is mainly due to variations in ocean temperature and salinity and associated circulation changes in response to wind forcing (e.g., Timmermann *et al*., 2010; Stammer *et al*., 2013). However, there is no reason to believe that sea level will continue on the long term rising faster in this area (e.g., Stammer *et al*., 2013). Coupled climate models that compute the future regional sea level at century-scale in response to future global warming show different trend patterns by 2100 (e.g. Slangen *et al*., 2011) but they cannot account for the decadal and multidecadal patterns due to internal variability of the climate system that superimposes to the long term warming trends.

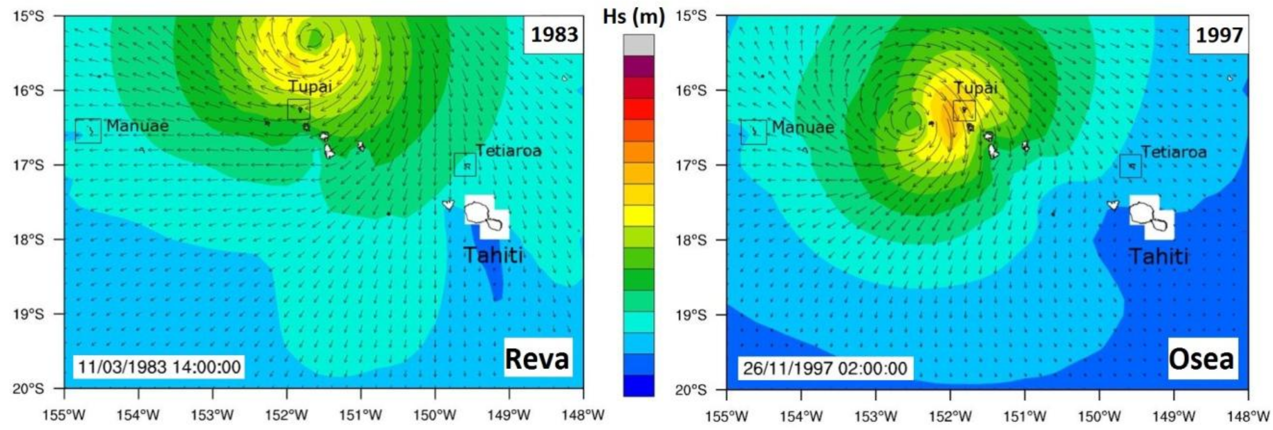

Figure 6. Examples of wave modeling for two cyclones affecting the Society islands. Colors show significant wave heights during the event while arrows show waves' directions. This modeling shows Reva (left) affecting the eastern side of Tupai while Osea hit the western side. For each cyclone in the JTWC database, the complete sequence of cyclonic waves was computed.

CONCLUSION

This paper proposes an approach to investigate how sea level change may affect shoreline erosion. When no tide gauges are available and when subsidence and uplifts can be appraised, sea level reconstructions can be used to evaluate where sea level has most deviated from the global average. Studies of shoreline mobility could then focus on these regions. Causes for shoreline mobility can then be assessed in as many sites as possible, using geomorphological evidences together with modeling of waves and storms that affected the area.

This approach has been illustrated here in the case of two atoll islands with few human activities: Tupai and Tetiaroa. While sea level rose ~40% faster than the global average in this area, shoreline movements are suspected to be mainly caused by waves, cyclones and currents at decadal timescales. Together with previous results, this suggests that SLR has not been a dominant factor of atoll's shoreline mobility.

Beyond the modest significance of our results, we believe that the approach proposed here can be usefully extended to more systematic investigations in order to further study the relationship between erosion and sea level rise.

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