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## Research papers

## Lagoon islets as indicators of recent environmental changes in the South Pacific – The New Caledonian example



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## ABSTRACT

The question of the impacts of climate change and sea level rise on small islands is currently much discussed. The many thousands of Pacific islands in their different contexts (geodynamic, climatic, etc.) and the insufficient data available explain why it is difficult to clearly discern the specific role of climate change in the recent evolution of these islands. To address this question, we investigated the recent changes affecting 21 islets in New Caledonia's lagoon. These islets are either located on small patch-reefs inside the New Caledonia Island lagoon or lie directly on the barrier reef. Based on the studies we conducted (field surveys, reconstruction of changes in the islets over the last decades, shoreline changes) we were able to define a typology of the islets that includes 6 stages and a life expectancy index. Using the life expectancy index, we found that of the 21 islets studied, 19% are in a highly critical situation, meaning they are very likely to be endangered in the short term (within the next few years), 9.5% are in a critical situation, i.e., likely to disappear in the near future and very likely to disappear in the medium term (next few decades), 19% are evolving rapidly, which could lead to their disappearance in the medium term but not in the short term, 9.5% are not endangered in the short and medium term and 43% are not endangered at all (stable or accreting, large area, relatively higher altitude). In this context, the rise in sea level induced by climate change is an adverse factor which is likely to lower the resilience of the islets to erosion processes. Other factors like the degradation of the reef ecosystem due to variations in ocean salinity, temperature and acidity, lower sediment stocks on the beaches and foreshores, human visitors, coastal development and so on are other adverse factors that could modify the capacity for resilience of these islets. Due to their variety and sensitivity, New Caledonia's islets could thus serve as integrative indicators of environmental and climatic change for New Caledonia.

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## 1. Introduction

Concern among coastal populations has been growing with the perceived increase in erosion processes and flooding affecting oceanic islands in particular. The same concern over the impact of climate change and sea level rise on the future of oceanic islands, and particularly coral islands, is shared by many Pacific Island communities.

In the last few years, various studies have attempted to understand the complex relationships between forcing factors (tectonic, climate change and sea level rise, anthropogenic factors and biological processes) and their consequences for the evolution of

oceanic islands (e.g. Webb and Kench, 2010; Romine et al., 2013; Ford, 2013; Le Cozannet et al., 2014) and for the future of the populations living there (Nicholls et al., 2007; Nicholls and Caze-nave, 2010; Nunn, 2013; Duvat et al., 2013).

Two main approaches can be identified to assess the future of low-lying islands in the context of sea level rise, based on the analogue postulate, i.e. learning from the past to predict the future (Woodroffe and Murray-Wallace, 2012; Webb and Kench, 2010; Yates et al., 2013). The first approach concerns the long-term response of atolls to the eustatic rise in the Holocene (e.g. Dickinson, 1999; Kench et al., 2005; Woodroffe et al., 1999; Yamano et al., 2014); the second focuses on shorter time scales, from multi-decadal to multi-annual (e.g. Woodroffe, 2008).

At multi-decadal time scales, coastal changes are driven by many factors (Bird, 1987; Yates et al., 2013; Garcin et al., 2013). These can be grouped into five main categories: (a) climate

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change, (b) external geodynamic processes linked to climate change, (c) internal geodynamic processes, (d) biological processes, (e) anthropogenic factors. It should be noted that these forcing factors involve numerous interactions and retroactions, so that determining the relative impact of one factor or another on an observed change is a highly complex process.

On high oceanic islands, the forcing factors (or drivers) influencing coastal processes include both marine processes and the indirect impacts of processes on land (surface erosion, landslides, solid discharge from rivers, etc.: Bird, 1987; Paskoff, 1998; Paskoff and Clus-Auby, 2007; Terry et al., 2008; Komar, 2010; Garcin et al., 2013).

On low-lying reef islands, however, the main drivers of environmental change are less numerous. Here, the main families of drivers are geodynamic (tectonic and vertical movements), meteorological (wind and wave climates), hydrodynamic (e.g. mean sea level, tidal and wave induced currents), biological (e.g. coral reef growth) and anthropogenic (embankments, dredging, sand mining, sea defences, etc.) (Stoddard, 1990; Xue, 1997; Dickinson, 1999; Ohde et al., 2002; Yates et al., 2013; Ford, 2012, Ford and Kench, 2014; Ballu et al., 2011; Ramsay, 2011; Ford, 2013; Testut et al., 2015).

Understanding how these reef islands are evolving is not easy due to the complexity of the system in itself and the multiple interactions between processes acting at different spatial scales (global, regional: southwest Pacific; local: islands) and timescales (long-term: the Holocene; medium term: climate and climate change, oceanic patterns and oscillations; short term or single events: cyclones and tropical storms) (e.g. Woodroffe, 2008; Yates et al., 2013).

The many thousands of Pacific islands in their different contexts (geodynamic, climatic, etc.) and the insufficient data available explain why it is difficult to clearly discern the specific role of climate change in the recent evolution of these islands. However, the question of the impacts of climate change and sea level rise on such islands is currently much discussed (Roy and Connell, 1991; Woodroffe, 2008; Webb and Kench, 2010; Nunn, 2013; Nurse et al., 2014). New Caledonia's islets (sand cays) are an important cultural, heritage and environmental asset (the lagoon is a UNESCO World Heritage site) and some are also of economic importance. Questions need to be answered, such as: can we isolate generic patterns of islet behaviour in their recent past changes? How relevant are such generic behaviour patterns for anticipating future changes?

To address these questions, we investigated the recent changes affecting islets in New Caledonia's lagoon. These islets are either located on small patch-reefs inside the New Caledonia Island lagoon or lie directly on the barrier reef. Thanks to their locations, human pressure is generally low and mainly due to recreational uses such as fishing or shellfish harvesting (Jimenez et al., 2011). Very few islets have any coastal development or buildings. Because of their large number and the relatively moderate human pressure, these islets are of particular scientific interest for studying the impacts of environmental and climatic factors on the evolution of low-lying islands.

Up to now, studies of New Caledonia's lagoon and islets have mainly focused on biological aspects (Pandolfi Benoit and Bretnolle, 2002; Jimenez et al., 2011; Brischoux and Bonnet, 2009; Debenay and Fernandez, 2009; Bozec et al., 2005), many of which have an important role in the lagoon ecosystem, and on the impacts of mining contamination and pollution (Bird et al. 1984; Ambatsian et al., 1997; Hédouin et al., 2008; Metian et al., 2008; Bonnet et al., 2014; Sasal et al., 2007). Some studies are based on hydrodynamics modelling (Migon et al., 2007; Faure et al., 2010; Ouillon et al., 2010, Fernandez et al., 2006); others have addressed the lagoon's evolution in the Late Quaternary (Le Roy et al., 2008) and reef changes during the Late Quaternary sea level fluctuation

(Frank et al., 2006, Lecolle and Cabioch, 1988, Cabioch et al., 1999, 2002, Yamano et al., 2014). However, none have investigated the recent evolution (last few decades) and sedimentary dynamics of the islets.

This paper describes how the islets have evolved in the last few decades and their morphodynamic characteristics, analyses the potential causes of change and presents a typology of the islets in the New Caledonian context. The paper concludes with a discussion of their plausible future and the elaboration of a Life Expectancy Index.

## 2. Contexts

### 2.1. Geography

Grande-Terre, New Caledonia's main island (South Pacific, between 18° et 23°S and 164° and 167° E, inset Fig. 1), is a long, narrow island 400 km in length and 50 km in width (about 16,000 km<sup>2</sup> in area) located on the margin of the Coral Sea, midway between Australia and Fiji. The highly dissected Central Range dominates the island, running NW-SE and culminating at circa. 1600 m. Grande-Terre island is surrounded by a barrier reef (linear extent of about 1600 km) enclosing a large lagoon covering about 24,000 km<sup>2</sup> (Bonnet et al., 2014). 15,000 km<sup>2</sup> of New Caledonia's lagoon have been listed as a UNESCO World Heritage Site since 2008 and New Caledonia's entire maritime area (1,300,000 km<sup>2</sup>) became the Coral Sea Nature Park in April 2014. The western barrier reef is sub-continuous with few passes, while the eastern barrier is irregular with numerous passes. The lagoon is relatively deep on the eastern side with depths greater than 30 m, while the western lagoon is shallow with depths of less than 15 m (Coutures, 2000, Flamand, 2006, IFRECOR.NC<sup>1</sup>; SHOM<sup>2</sup> data). The southern and northern parts of the lagoon are very wide, with distances between the barrier reef and Grande-Terre ranging from 20 to 31 km. In the middle part of the island, the lagoon narrows to just 1.7 km. There are two types of islands in the lagoon: (i) elevated islands with outcrops of the underlying rock; (ii) low-lying islets made up of bioclastic sands associated with coral reef patches. The rocky islands vary in size and generally have a relatively abrupt relief, while the low-lying islets are smaller in area and very low in altitude (generally up to 2 m except for Signal islet at 5 m; data from Province Sud).

### 2.2. Sites

Twenty-one low-lying islets were studied, sixteen in the south-western lagoon (Fig. 1), four in the eastern lagoon (Fig. 2), and one in Nohanui atoll, to the south of Ile des Pins (Fig. 3).

The islets (sand cays) are highly variable in size, ranging from only 180 m<sup>2</sup> to 360,700 m<sup>2</sup>. The islets lie on patch-reefs of various sizes and shapes (elongated, triangular, oval,...). The twenty-one islets are located at various distances from the coast and from the barrier reef. Their locations relative to the closest barrier reef passes vary, so that their levels of exposure to oceanic swells also differ (Table 1). Nineteen of the twenty-one islets are relatively well preserved from human activities and only two are fairly built-up.

<sup>1</sup> French Coral Reef Preservation Initiative.

<sup>2</sup> Service Hydrographique et Océanographique de la Marine: the French Navy's hydrographic and oceanographic service.



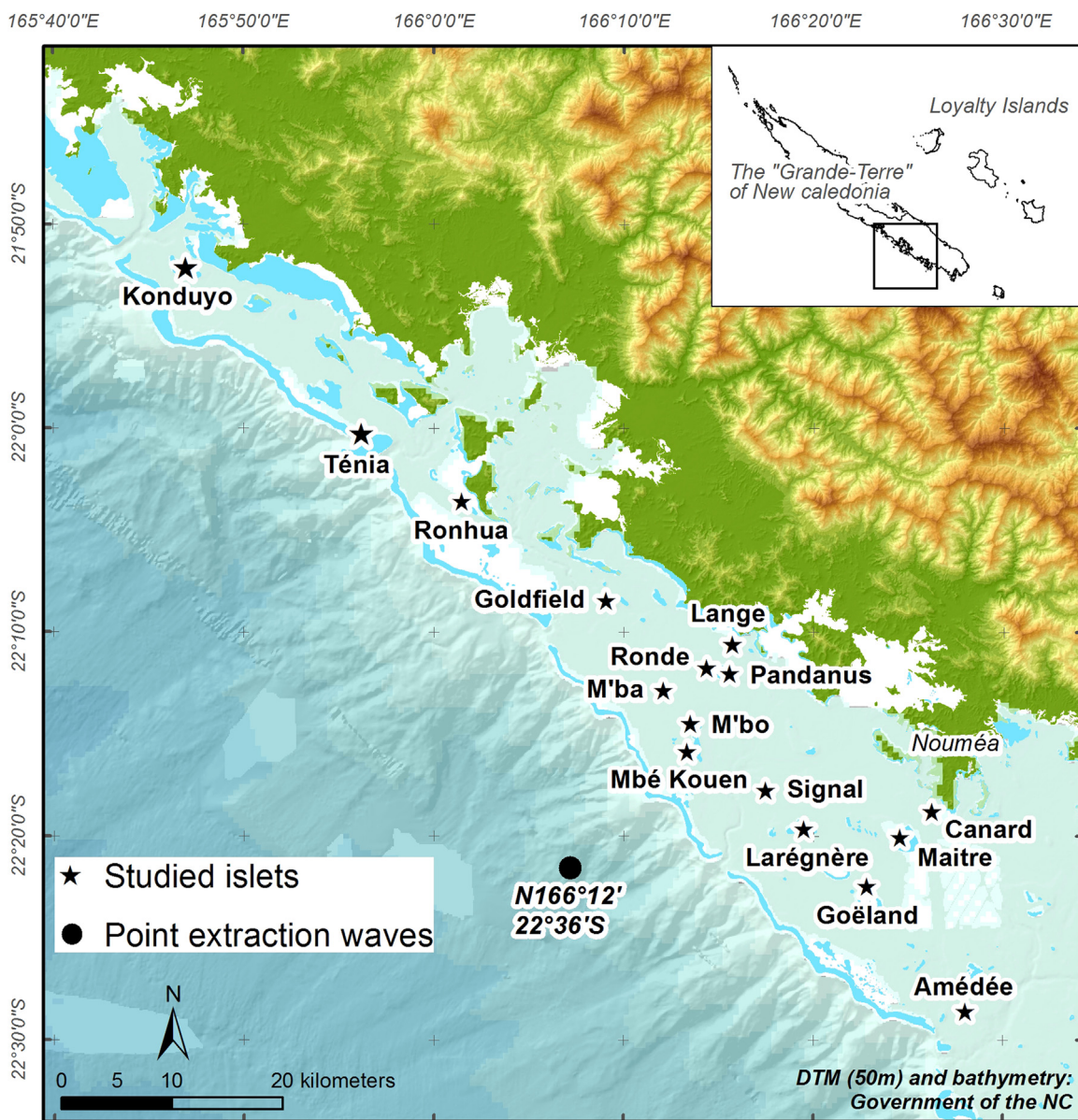


Fig. 1. Location of the islets studied in the south-western lagoon.

### 2.3. Climate and oceanography

#### 2.3.1. Tides

New Caledonia's tidal regime is semi diurnal and unequal (Dauillet, 1998). It is a microtidal regime with a maximum amplitude of 1.6 m, although it is generally lower than 0.7 m (SHOM<sup>3</sup>:<http://refmar.shom.fr>; Hayes, 1979; Jimenez et al., 2011). The tides and trade winds generate strong currents in the lagoon, which are one of the main factors acting on sediment distribution (Debenay, 1987).

#### 2.3.2. Climate and waves

New Caledonia's climate is tropical with dominant easterly trade winds. During the wet season, cyclones (Fig. 4) and tropical storms are relatively frequent (Terry et al., 2008). Average annual precipitation is unevenly distributed across Grande-Terre as a whole: the windward eastern coast is much more humid (2500 to

4000 mm y<sup>-1</sup>) than the leeward western coast (generally less than 1500 mm y<sup>-1</sup>). Although wave action in the areas studied is moderate (Jimenez et al., 2011), high winds during cyclones and tropical depressions are one of the major drivers of coastal change as they generate high-energy waves which, depending on storm trajectories and local reef characteristics, can cause reef abrasion, sediment transport and beach erosion. Therefore, the exposure of the islets to the actions of waves and swells (Table 1) is largely correlated to their distance from the passes through the barrier reef.

The wave climate was analysed from the wave data extracted from the Global-Multi hindcast model for the 1990–2013 period (<http://wwwz.ifremer.fr/iowaga/>). The model was run with both ECMWF operational analyses and CFSR / CFSRR winds. The wave data were extracted from a point located on the SW coast of New Caledonia (166°12'E, 22°36'S) about 30–60 km to the south-west of the sites (Fig. 1), a point that characterizes offshore conditions for the SW islets. A classification of homogeneous wave regimes based on defined resemblance criteria was made using the conventional k-means clustering algorithm (Butel et al., 2002; Thiébot et al., 2010; Le Cozannet et al., 2011; Lecacheux et al., 2012). The data

<sup>3</sup> Service Hydrographique de la Marine, the French Navy's hydrographic and oceanographic service.



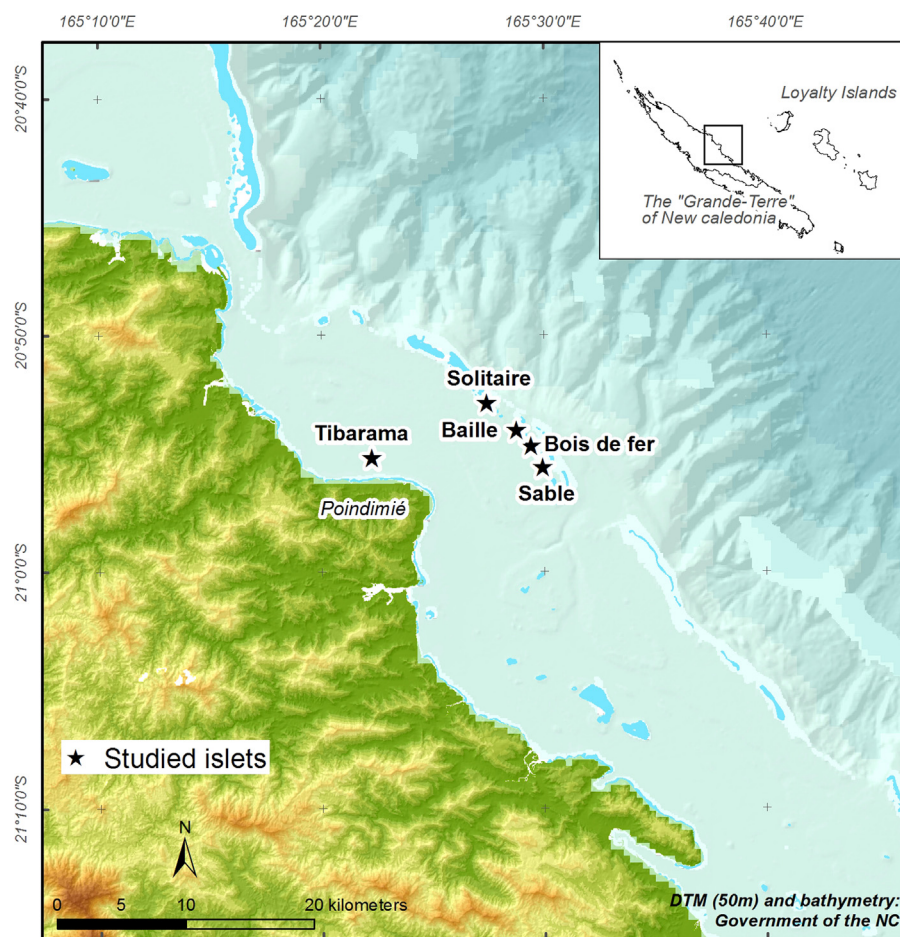


Fig. 2. Location of the islets studied in the eastern lagoon.

clustering classification is designed to partition the data so that each barycentre properly represents its class by minimizing the dispersion around it. Ten predefined classes were considered to be a satisfactory number to identify the main wave sectors and their mean wave characteristics.

The austral swell is dominant throughout the year 70–80% (Fig. 5). It is characterized by its direction (from N190° to 210°) and long wave period ( $T_p$ ) (10 s to 25 s). The mean significant wave height ( $H_s$ ) varies from 1.3 to 3.4 m and the maximum  $H_s$  is observed during the southern hemisphere winter.

Waves and swells generated by the easterly trade winds can also be observed throughout the year (around 20–25%), coming from the N130° to 160° sector (Fig. 5). This shift in direction between the wind and wave sectors is due to the refraction of the waves around the southern tip of Grande-Terre. This phenomenon causes a clockwise shift in the wave direction and lowers their heights before they reach the western reef barrier, so that  $H_s$  is 1.6 m and the period is less than 10 s. During the dry season, the waves can be significantly higher with a mean  $H_s$  of up to 2.9 m and a mean period of around 10 s.

Westerly waves are rare ( $\approx 2\%$ ) and generally observed during the wet season. They are generated by tropical storms or cyclones. Due to the diversity of their trajectories, the directional sector of the waves generated is very broad (from N240° to 300°). Similarly, the wave characteristics are highly variable with a mean  $H_s$  of 2.1 m but reaching a maximum of 7 m. Their mean  $T_p$  is 9.1 s, and may reach 12 to 14 s.

Wind and waves generated by tropical storms and cyclones can hit New Caledonia from all sectors (Data from Météo NC). However, the depressions circulating in the Coral Sea between

Australia and New Caledonia can generate waves and swells from a direction of 250–300°.

These are observed over less than 2% of the year. During the period analysed, the highest waves occurred on the 02/03/1993 at 00h00, reaching  $H_s=7$  m and  $T_p=13.3$  s. During the 1980–2013 period, only 13 cyclones hit the New Caledonian coast directly, either circulating over the Coral Sea or moving across the island.

#### 2.4. Sea level changes

Sea level has been recorded at Nouméa since 1968 with two successive tide gauges: the Nouméa Chaleix tide gauge from 1968 to 2005 and the Nouméa Numbo tide gauge from 2001 to present, with an incomplete overlap from 2001 to 2005 (<http://www.sonel.org/>, SHOM). The two tide gauges are located 6.5 km apart in two different bays of Nouméa. The period of common monitoring shows that there is only a small difference in value between the two tide gauges (the level for Numbo is 26 mm higher on average than for Chaleix, with a standard deviation of 2.5 mm), which enabled us to create a composite annual sea level curve (Fig. 6) for the 1968–2012 period.

This composite curve shows an upward trend over the whole period (Fig. 6) and also that the sea level was higher during the 2007–2012 period than during the previous decades.

The data (1968–2012) from the Brisbane and Norfolk Island tide gauges (National Tidal Centre, PSMSL: <http://www.psmsl.org/>) are remarkably consistent with those from Nouméa (Fig. 6), which indicates a regional trend for the South West Pacific.

The reconstruction by Meyssignac et al. (2012) of sea level in the Nouméa area from 1950 to 2010, validated for the Pacific by

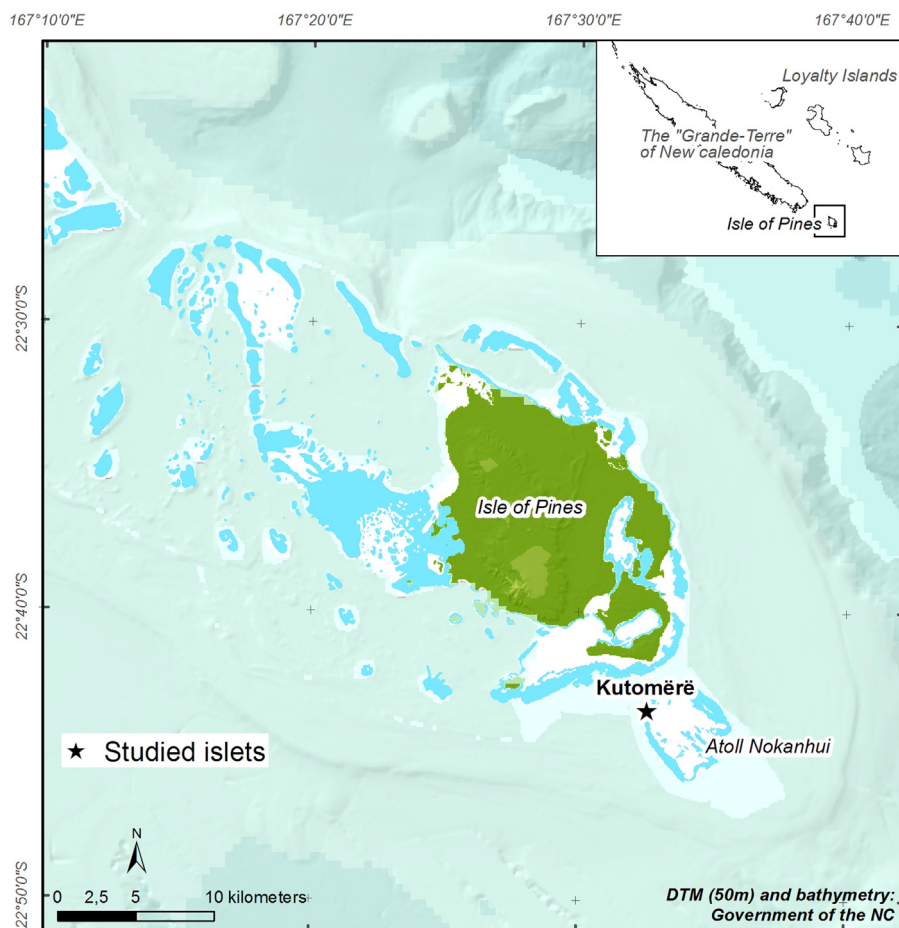


Fig. 3. Location of Kutomèrè islet in Nokanhui atoll.

Becker et al. (2012), shows that the climate component of sea level rise is about  $0.5 \text{ mm y}^{-1}$  ( $\pm 0.5 \text{ mm}$ ). This is lower than the global average and substantially lower than the recent global sea level rise recorded by tide gauges. While the climate component of sea level can be considered as constant all around New Caledonia, the relative sea level, which is the sum of the climate component of sea level and the vertical movements affecting the island, is variable. The GPS data for Nouméa show local subsidence of around  $2 \text{ mm y}^{-1}$  ( $\pm 0.2 \text{ mm y}^{-1}$ ; Becker et al., 2012), giving a relative rise in sea level of around  $2.5 \text{ mm y}^{-1}$  for Nouméa. Again, this value is substantially lower than the global value recorded for recent years.

### 3. Methods and data

#### 3.1. Field surveys

Field surveys were conducted during October–November 2013 and November–December 2014 in order to identify and characterize the morphology of the islets and the processes acting on their coastlines. The observations made concern the geomorphology and all evidence of change such as erosion (erosion scarps, uprooted trees, etc., Fig. 7), accretion, changes in the vegetation, development of pioneer vegetation, and sedimentological observations (granulometry, coral blocks eroded from the reef, presence and geometry of beach rocks, Fig. 8). Beach rocks are frequently observed around the islets, and in some places, several generations of beach rocks can be observed. The geometrical relationship between beach rocks and today beaches provide

information on their mobility and on coastline retreat. All observations and photographs were systematically georeferenced using a GPS, and incorporated into a GIS. These data were used to produce a map of coastal segments with similar behaviour, i.e. coastal segments currently affected by erosion or accretion, or remaining stable.

#### 3.2. Reconstructing the recent evolution of the islets

This study is the first substantial work investigating multi-decadal shoreline changes on New Caledonian islets. It is based on an exhaustive collection of field observations and interpretations of aerial photographs and satellite images. However, as for the majority of Pacific islands, there is little documentation and past and present data on coastline changes. Due to their distance from Grande-Terre, very few historical aerial photographs exist for the islets as a whole. Those selected are the 1935 aerial photographs of the Nouméa area (SHOM, Ifremer, Photothèque Nationale), the 1943 US army photographs (available only for Ténia islet), the IGN photographs for 1954, 1971, 1976, and 1982 and the 2011 orthophoto of the Southern Province of New Caledonia. We completed this set of data with recent available high resolution satellite images (from Digital Globe, 2004, 2006, 2007, and CNES Astrium), of which there are relatively few for some islets distant from Grande-Terre. The images were georeferenced specifically to build up a set of images that would be as accurate and complete as possible. The satellite images cover a short period from 2004 to 2012. Exceptionally and locally, some 2013 or 2014 images are available. The image resolution (pixel size) ranges from 0.6 to 2 m. Georeferencing was sometimes a tedious task due to the small

**Table 1**Characteristics of the islets studied (<sup>1</sup>on the reef barrier, <sup>2</sup> on the second rank of the barrier, <sup>3</sup>Nokanhui Atoll)

Name	Present-day perimeter (m)	Area (m <sup>2</sup> )	Reef platform area (.10 <sup>4</sup> m <sup>2</sup> )	Percentage of islet area / reef area	Nearest distance from barrier reef (km)	Distance from nearest pass (km)	Orientation of exposure to swells through pass
Faux Tabac <sup>1</sup>	51	181	63	0.03	0.0	0.4 km (Fourmi pass)	–
Bois de Fer <sup>2</sup>	116	831	31	0.27	0.0	1.7 km (Fourmi pass)	–
Goéland	201	1399	509	0.03	7.6	12.5 km (Dumbéa pass)	276–282° NW (angular aperture 6°)
MbéKuen	208	1938	37	0.52	4.2	9.6 km (Dumbéa pass)	160–161° SSE (angular aperture 1°)
Pandanus	202	2249	72	0.31	10.4	16.5 km (Uitoe pass)	279–285° NW (angular aperture 6°)
Kutomêrê <sup>3</sup>	367	2481	0	–	1.3	3 km	108–132° (angular aperture 24°)
Canard	448	8431	19	4.47	16.4	19.4 km (Dumbéa pass)	252–257° (angular aperture 5°)
Baille <sup>1</sup>	363	8832	42	2.09	0.0	0.2 km (Fourmi pass)	–
Larégnère	531	11,572	179	0.65	6.5	7 km (Dumbéa pass)	58–71° WSW (angular aperture 13°)
Tibarama	619	27,663	16	17.73	10.0	10.3 km (Fourmi pass)	64–78° ENE (angular aperture 14°)
Kondoyo	801	30,588	341	0.90	3.0	6 km (Ouarai pass)	29–33° SW/96–100° W (angular aperture 4°)
Goldfield	779	37,170	51	7.31	5.8	6 km	231–245° SW (angular aperture 14°)
Ronhua	934	49,608	40	12.35	4.5	8 km (Boulouparis pass)	297–306° NNW (angular aperture 9°)
Ange	978	49,988	117	4.28	12.0	16.7 km (Uitoe pass)	269–275° WNW (angular aperture 6°)
Ronde	990	50,785	72	7.02	8.9	14.8 km (Uitoe pass)	279–284° NW (angular aperture 5°)
Amédée	1037	61,165	65	9.36	3.2	3 km (Boulari pass)	16–60° SW (angular aperture 44°)
Maitre	1786	79,246	470	1.69	12.9	15.9 km (Dumbéa pass)	258–264° (angular aperture 6°)
Signal	1568	143,820	128	11.20	7.5	7.3 km (Dumbéa pass)	26–37° SW (angular aperture 11°)
Mbo	1579	174,116	100	17.44	5.7	11.8 km (Dumbéa pass)	166–167° SSE (angular aperture 1°)
Ténia <sup>1</sup>	2636	235,743	585	4.03	0.9–0.4	1.2 km (Boulouparis pass)	Not directly exposed
Mba	2572	360,704	86	41.92	4.5	11.3 km (Uitoe Pass)	292–299° NNW (angular aperture 7°)



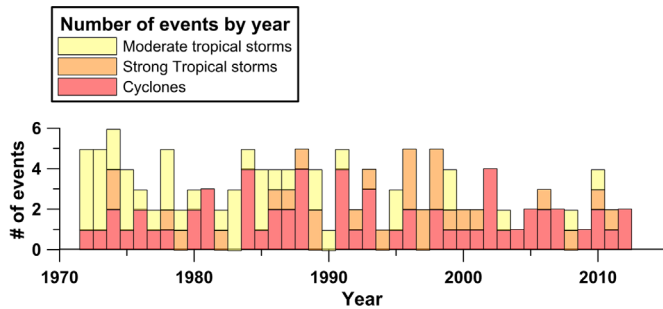


Fig. 4. Number of cyclones and tropical storms during the 1972–2013 seasons (From Météo NC data).

number of usable and stable reference points on the islets (small patch-reefs, old trees, buildings, etc.). The georeferencing accuracy of the images of the islets is therefore variable and RMS error ranges from 1.1 m to 3.8 m for the older photographs.

To characterise changes in the islet shorelines, we compared the positions of the permanent vegetation line (PVL) at each date (e.g. Ford, 2012; Webb and Kench, 2010; Yates et al., 2013). The PVL is considered as a good indicator of coastline changes at annual to multi-annual to multi-decadal timescales, particularly when other proxies like the mean high water line or evidence of the wet/dry or high tide line do not exist (Thieler and Danforth, 1994; Crowell

et al., 1991; Ford, 2012; Garcin et al., 2008). Comparing PVL change at various dates provides information on coastline changes (erosion, stability, accretion) and allows PVL changes and mobility to be quantified. Errors due to the interpretation of shorelines can reach the same order of magnitude as the RMS error, leading to a final shoreline positioning uncertainty of about 5 m (this is the same order of error found by Yates et al. 2013 for example). The distances between successive PVL were used to assess rates of change only when they were greater than this 5 m threshold; if the distance was equal to or smaller than the error, the coastline was considered stable. The PVL was digitized using a unique operator in order to obtain a homogeneous interpretation of the shoreline position for all dates and all islets. The coastline changes and extent of the areas affected by erosion and accretion between each date were computed using the functions incorporated in the GIS (ArcGIS ©ESRI). An illustration is given in Fig. 9. All PVL extraction results are available in Garcin and Vendé-Leclerc (2015).

## 4. Results

### 4.1. How have the islets changed?

#### 4.1.1. Erosion and accretion rates

Annual erosion and accretion rates were assessed using diachronic PVLs for two periods (Table 2). Long-term erosion and

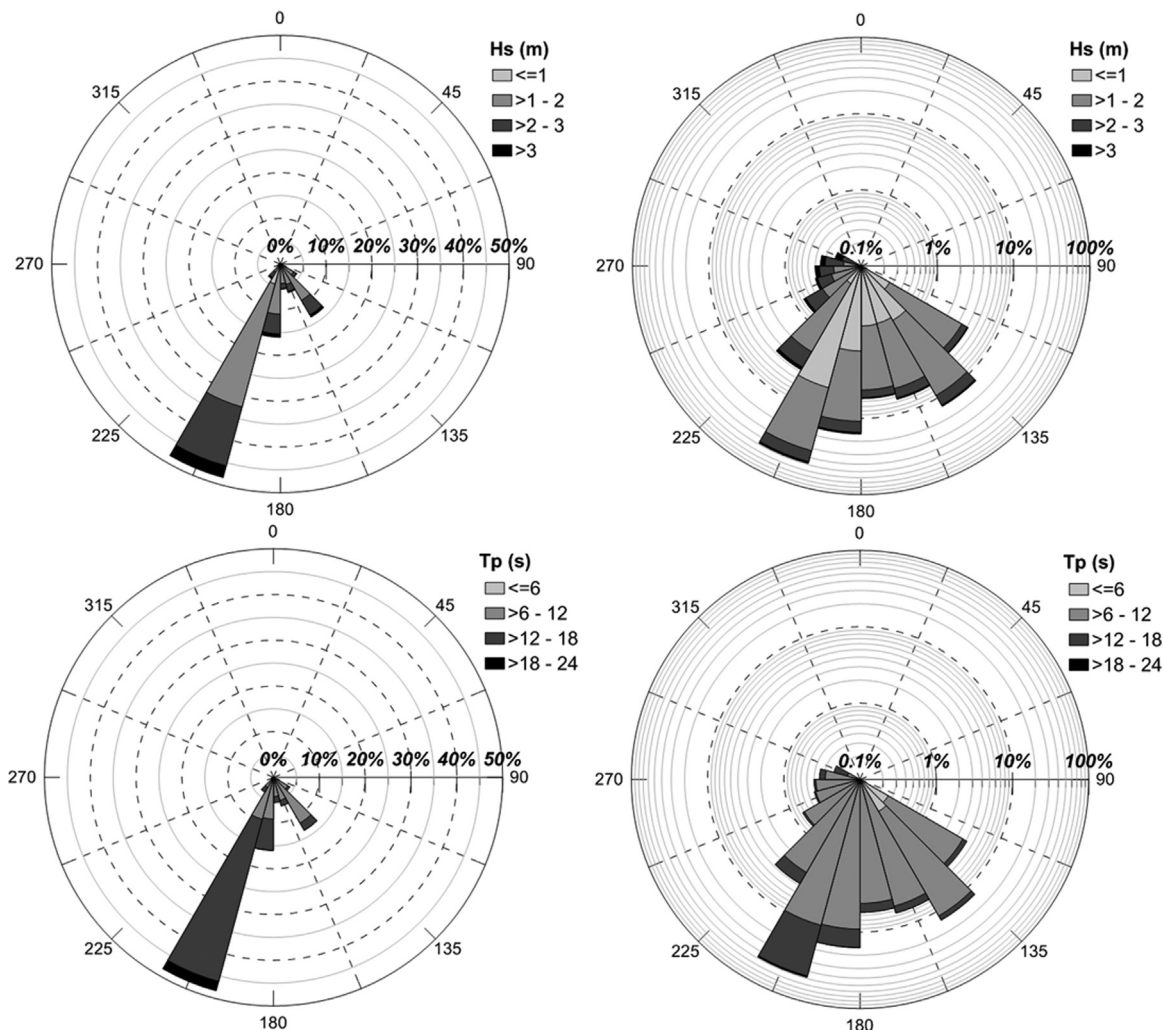
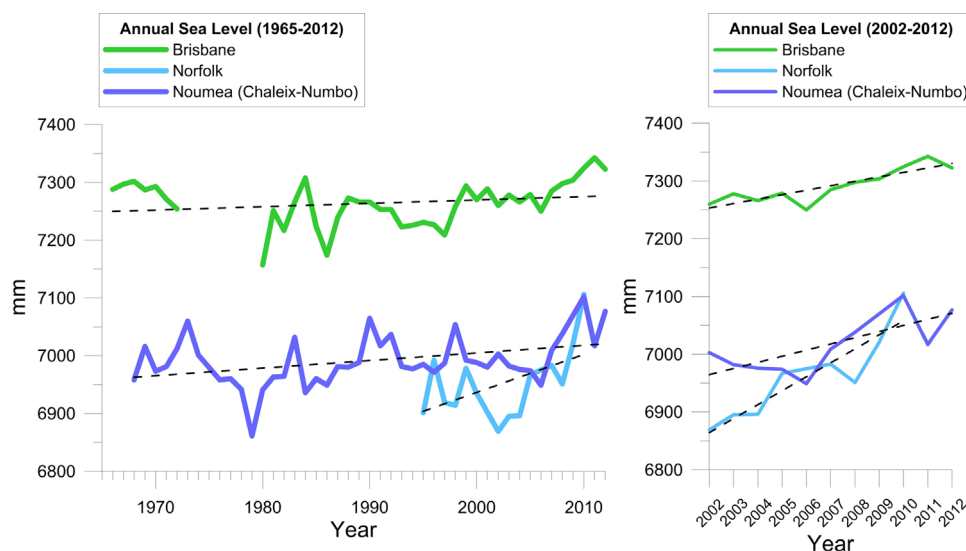


Fig. 5. Wave characteristics (top: Significant Wave Height (Hs); bottom: Period (Tp); left: linear scale; right: log scale).



**Fig. 6.** Left: annual sea level (1968–2012) from regional tide gauges. Right: detailed view of the 2002–2012 period with accelerated sea level rise. Dashed black lines show linear trends. (data from SHOM, National Tidal Centre, [www.Sonel.org](http://www.Sonel.org), [www.psmsl.org](http://www.psmsl.org)).



**Fig. 7.** Erosion scarp and uprooted trees on the southern beach of Kondoyo islet (2013).



**Fig. 8.** Concave beach with erosion scarp (rear left) and two generations of beach rocks indicating the position of palaeo-beaches (Larègnère islet, 2013).

accretion rates were computed when several decades of data (aerial photographs and satellite images) were available. Long-term rates were assessed for 7 islets over durations of 30–79 years. The long-term erosion rate ranges from  $0.39$  to  $4.9 \text{ m y}^{-1}$  while the long-term accretion rate ranges from  $0$  to  $1.7 \text{ m y}^{-1}$ . Short-term rates, over a time span of 4–9 years, were assessed for only 18 islets due to the lack of any images of the eastern reef barrier, while the rates for 3 islets (Faux-Tabac, Bois de Fer and Baye) were impossible to assess. The short-term rates obtained are logically

substantially higher than those for the long term, with a maximum of  $13.3 \text{ m y}^{-1}$  for erosion and  $7.8 \text{ m y}^{-1}$  for accretion. The high values obtained for both the short and long term indicate that the coastlines of islets can be very mobile and that the islets are very sensitive to environmental change. At the annual scale, the figure for erosion, and to a lesser extent for accretion, can be substantially higher depending on the occurrence of tropical storms, cyclones or southern swells.

#### 4.1.2. Lengths of shorelines affected by erosion and accretion or remaining stable

The dominant ongoing shoreline behaviour (erosion, accretion, stability) on the 21 islets was noted during the field surveys (2013–2014) and mapped into the GIS. These maps (Fig. 10) show that the spatial distribution of erosion, accretion or stability is highly variable from one islet to another, with no simple correlation between the orientations of the coast, the distance to the barrier reef or any single forcing factor. Table 2 gives the total length of shoreline affected by each of the processes (erosion, accretion and stability) and the percentage of these lengths compared to the total shoreline length.

The percentage of the shoreline affected by each process can be highly variable from one islet to another, with erosion ranging from 25% to 100%, stability from 0% to 62% and accretion from 0% to 45% (Fig. 11).

Among the 21 islets, three are affected by erosion along their entire shoreline (100%), 76% of the islets are eroded along at least 50% of their shoreline, while only 23% of the islets show accretion along more than 25% of their shoreline. Cumulatively, for the 21 islets, 54% of all shorelines are affected by erosion, 16% by accretion and 29% are stable (Fig. 12).

#### 4.1.3. Changes in the surface area of the islets

Diachronic mapping of the islets enabled us to assess overall changes in their surface area over time. Due to the heterogeneity of available aerial photographs and satellite images for each islet, the time spans are variable, ranging from one decade for the shortest to 70 years for the longest.

For example, due to the lack of diachronic images it was not possible to reconstruct changes in the surface areas of three islets lying far offshore from Grande-Terre (Faux-Tabac, Bois de Fer and Baille). For the others, the number of dates used to reconstruct changes in their surface areas ranges from 2 to 9 in the best



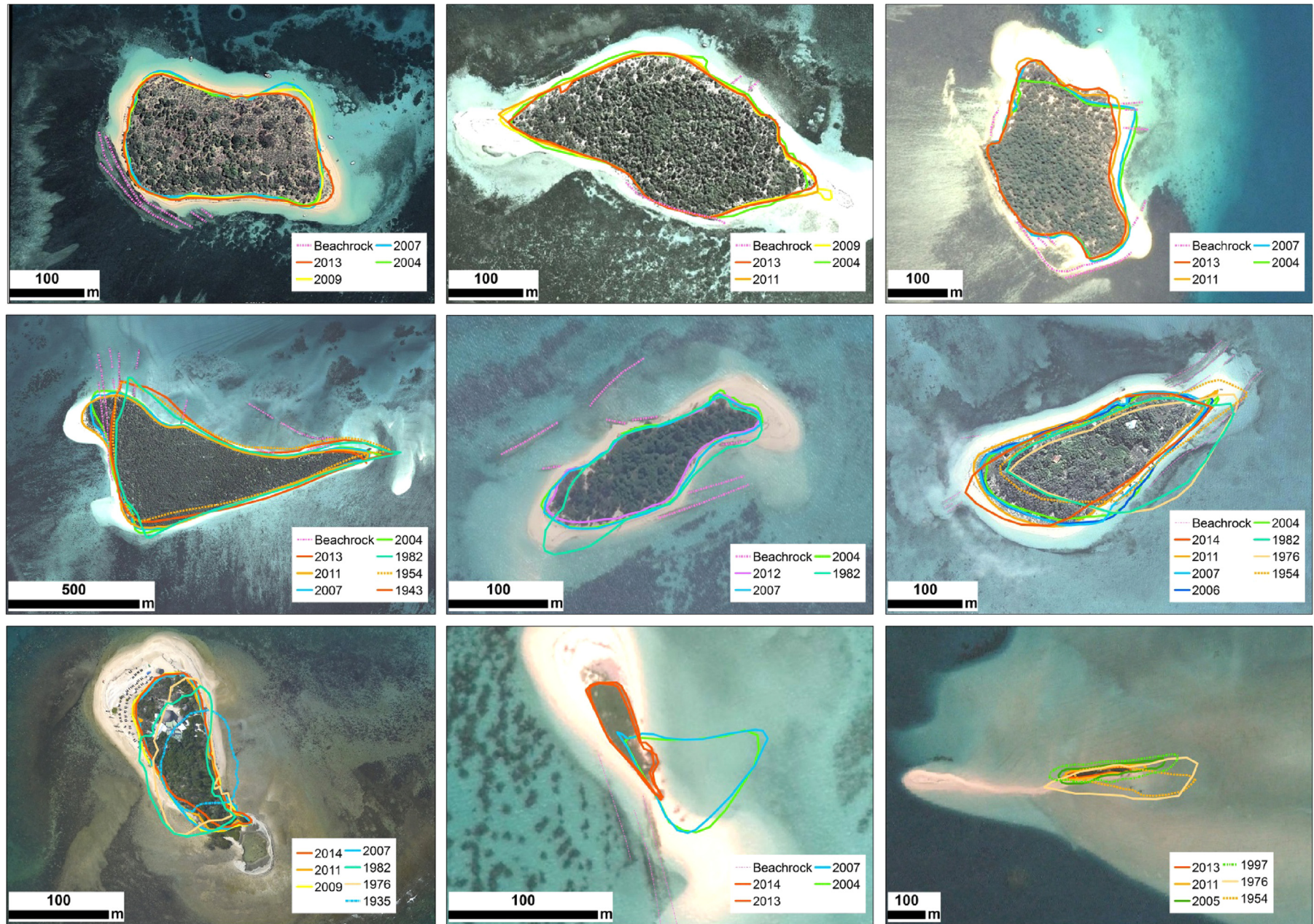


Fig. 9. Illustration of shoreline changes on some of the New Caledonian islets studied. From top to bottom and left to right: Goldfield, Ronde, Ronhua, Ténia, Larègnère, Kondoyo, Canard, Goéland and Kutomèrè.

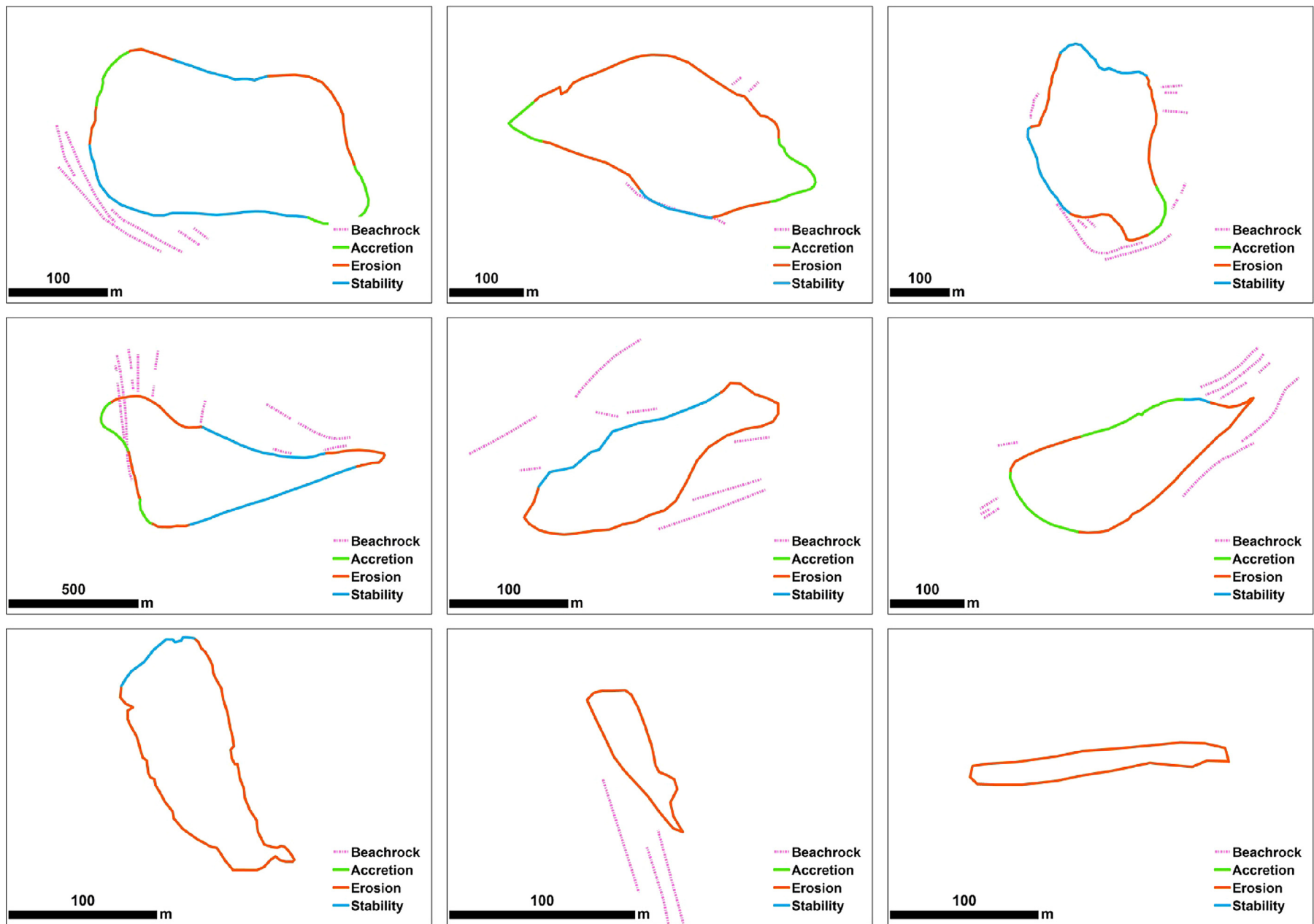


**Table 2**

Length (m) and percentage of shorelines showing erosion, accretion or stability on each islet, long and short term maximum erosion and accretion rates.

Islet	Surface (m <sup>2</sup> )	Total PVL length (m)	% of coastline length affected by...			Long term max rate (m.y <sup>-1</sup> )			Short term max rate (m.y <sup>-1</sup> )		
			Accretion	Erosion	Stability	Period, duration	Erosion	Accretion	Period	Erosion	Accretion
Faux Tabac <sup>a</sup>	181	51	0.0	100.0	0.0	–	–	–	–	–	–
Bois de Fer <sup>a</sup>	831	116	15.5	84.5	0.0	–	–	–	–	–	–
Goeland <sup>b</sup>	1 399	201	0.0	100.0	0.0	–	–	–	2007–2013 (6 y)	13.33	6.66
Mbe Kuen <sup>b</sup>	1 938	208	7.7	57.2	35.1	–	–	–	2009–2013 (4 y)	2.5	3
Pandanus <sup>b</sup>	2 249	202	25.2	74.8	0.0	–	–	–	2009–2013 (4 y)	1.75	1.5
Kutomèrè	2 481	367	0.0	100.0	0.0	1976–2013 (37 y)	4.86	0.00	2005–2013 (8 y)	11.5	0
Canard <sup>c</sup>	8 431	448	0.0	85.5	14.5	1935–2014 (79 y)	0.41	0.64	2007–2014 (7 y)	1.85	0
Baye <sup>a</sup>	8 832	363	24.5	75.5	0.0	–	–	–	–	–	–
Larègnère	11,572	531	0.0	66.7	33.3	1982–2012 (30 y)	1.20	0.66	2007–2012 (5 y)	1.52	–
Tibarama <sup>b</sup>	27,663	619	14.7	85.3	0.0	–	–	–	2004–2013 (9 y)	2.88	6.2
Kondoyo	30,588	801	35.1	60.4	4.5	1976–2014 (38 y)	1.57	1.71	2004–2011 (7 y)	2.85	2.42
Goldfield <sup>b</sup>	37,170	779	23.5	29.9	46.6	–	–	–	2004–2013 (9 y)	1.66	1.77
Ronhua <sup>b</sup>	49,608	934	10.4	52.6	37.0	–	–	–	2004–2013 (9 y)	4.33	3.77
Ange <sup>b</sup>	49,988	978	17.3	62.8	19.9	–	–	–	2004–2013 (9 y)	1.33	1.33
Ronde <sup>b</sup>	50,785	990	25.1	64.3	10.6	–	–	–	2004–2011 (7 y)	2.14	2.42
Amédée <sup>b</sup>	61,165	1037	45.2	46.0	8.8	–	–	–	2004–2012 (8 y)	1	1.37
Maitre	79,246	1786	28.9	57.4	13.7	1935–2014 (79 y)	0.39	0.54	2009–2014 (5 y)	1.8	0
Signal	143,820	1568	12.6	25.3	62.1	1982–2013 (31 y)	1.00	1.03	2004–2012 (8 y)	3.75	3.12
Mbo <sup>b</sup>	174,116	1579	20.4	55.2	24.4	–	–	–	2009–2013 (4 y)	2	0.5
Ténia	235,743	2636	13.6	41.2	45.1	1943–2011 (68 y)	1.80	1.67	2004–2011 (7 y)	7.85	7.85
Mba <sup>b</sup>	360,704	2572	0.0	49.6	50.4	–	–	–	2004–2013 (9 y)	2.22	0

<sup>a</sup> Not enough data to assess long and short term rates.<sup>b</sup> Not enough data to assess long term rates.<sup>c</sup> Human disturbance on the islet.



**Fig. 10.** Maps of current processes (2013–2014) affecting the shorelines of some of the New Caledonian islets studied. From top to bottom and left to right : Goldfield, Ronde, Ronhua, Ténia, Larégnère, Kondoyo, Canard, Goéland and Kutomère.

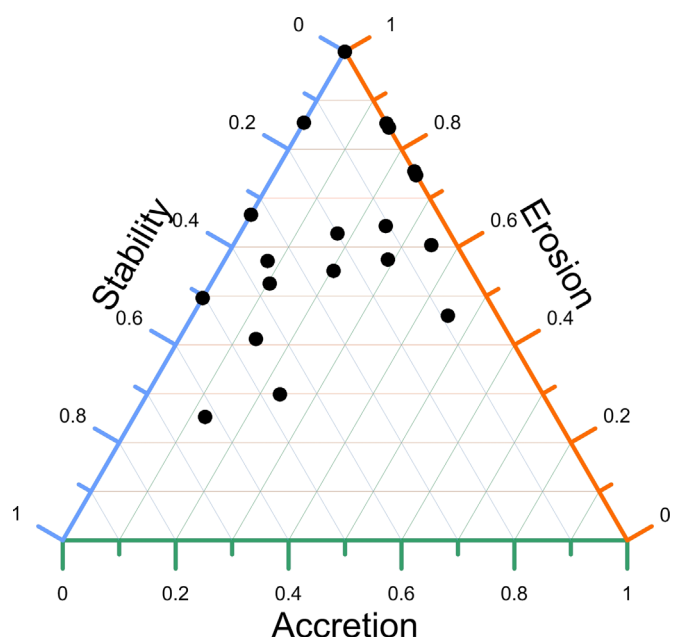


Fig. 11. Position of each islet on a ternary diagram where each axis represents the percentage of eroding, accreting or stable shoreline.

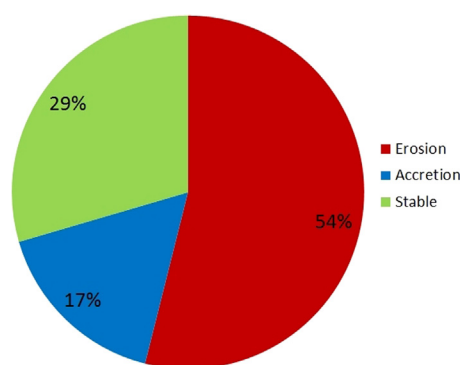


Fig. 12. Percentages of erosion, accretion or stability for the total shoreline length of the 21 islets.

documented case. Changes in surface areas in recent decades are highly variable from one islet to another (Table 3, Fig. 13), with some remaining relatively constant and others shrinking, while a few islets have increased in size.

The analysis of the longer record is instructive and shows a variety of trends and behaviour patterns among the islets:

- The surface area of Ténia islet decreased rapidly between 1943 and 1954, potentially due to the effects of a major cyclone that occurred in 1951, then continued to decrease very slowly over the next decades.
- the surface area of Kondoyo islet shows a slight tendency to increase while analysis of the PVL position shows high erosion and accretion rates on this islet and rapid migration of its shoreline. One side of the islet is severely eroded, the opposite side shows substantial accretion, and the islet's area as a whole has gradually increased.
- Maitre islet shows a continuous but very moderate reduction of its surface area from the 1930s up to the present, with a short period of stabilization from 2004 to 2009. There are not enough data for 1935–2004 to allow an in-depth analysis of surface area fluctuations linked to past extreme events. This very moderate loss of land during the past seven decades is confirmed by the

Table 3

Percentage of areas affected by erosion and accretion.

Name	Present-day perimeter	Present-day area (m <sup>2</sup> )	Period	% change in area	Dominant process
Faux Tabac	51	181	–	–	Erosion
Bois de Fer	116	831	–	–	Erosion
Goéland	201	1399	2004–2014	–68.8	Erosion
MbeKuen	208	1938	2009–2013	–3.2	Erosion
Pandanus	202	2249	2009–2013	–19.4	Erosion
Kutomèrè	367	2481	1954–2013	–167.6	Erosion
Canard	448	8431	1935–2014	+65.3	Accretion
Baille	363	8832	2012–2013	+5.7	Accretion
Larègnère	531	11,572	1982–2012	–18.4	Erosion
Tibarama	619	27,663	2004–2013	+11.1	Accretion
Kondoyo	801	30,588	1954–2011	+21.6	Accretion
Goldfield	779	37,170	2004–2013	+2.4	Accretion
Ronhua	934	49,608	2004–2013	–5.9	Erosion
Ange	978	49,988	1954–2013	–3.1	Erosion
Ronde	990	50,785	2004–2013	–4.7	Erosion
Amédé	1037	61,165	2004–2012	+8.5	Accretion
Maitre	1786	79,246	1935–2014	–10.5	Erosion
Signal	1568	143,820	1982–2013	–4.6	Erosion
Mbo	1579	174,116	2009–2013	–0.7	Erosion
Ténia	2636	235,743	1943–2011	–10.4	Erosion
Mba	2572	360,704	2004–2013	–0.3	Erosion
Min				+65.3	
Max				–167.6	

close proximity of the shoreline to the beach rocks, which protect the coast from erosion.

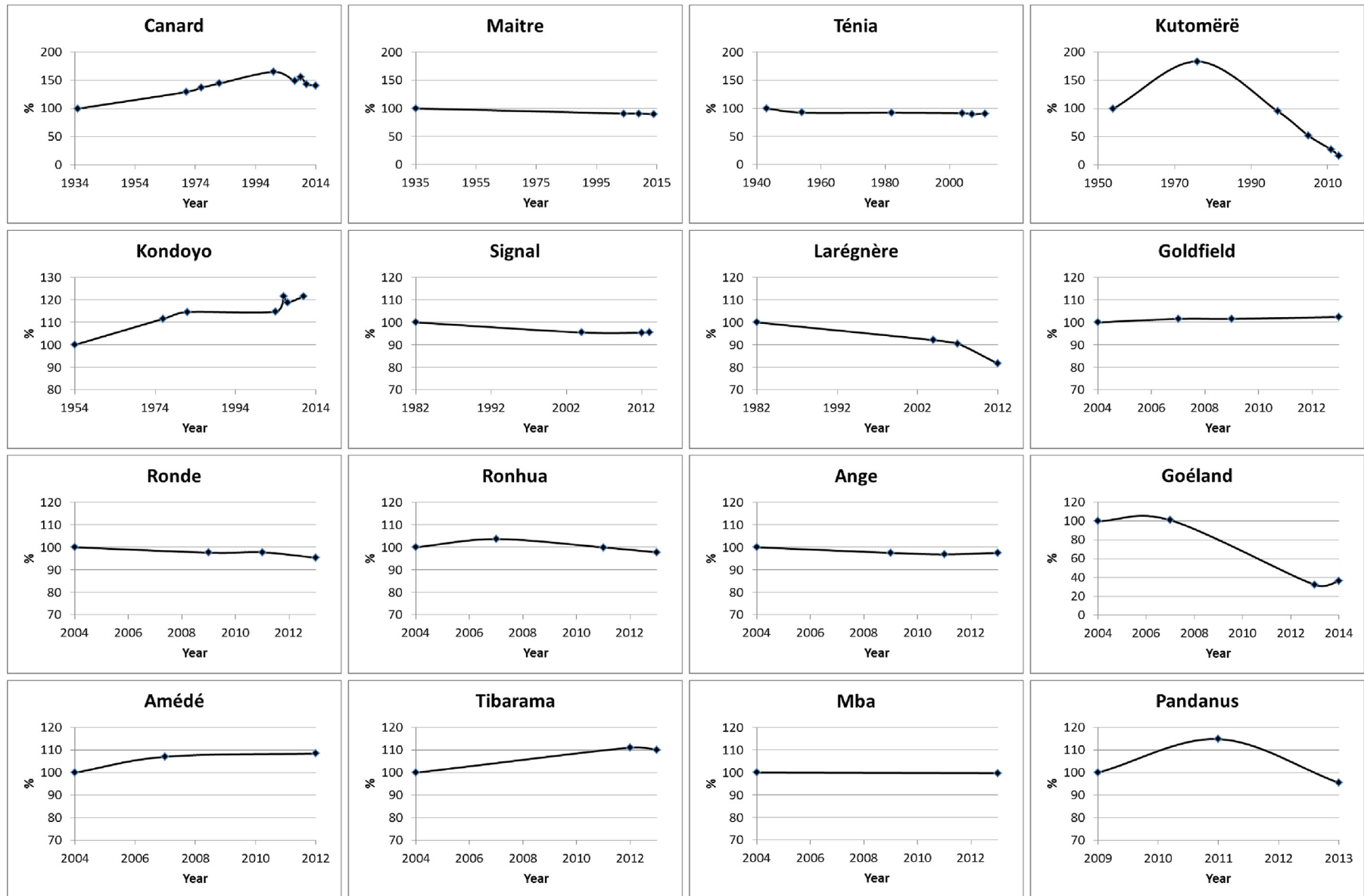
- Canard islet clearly increased in surface area from the 1930s to the 1990s, and has rapidly lost land since 2000. This has occurred despite the work carried out on the beach in the last few years to prevent erosion (sand supply, sandbag protection).
- Kutomèrè islet offers a spectacular example of a two-phase history, with a large and rapid increase in surface area from 1954 to 1976 (up to 28,245 m<sup>2</sup>) followed after 1976 by a phase of rapid and steady decay leading to the virtual disappearance of the islet today (less than 2400 m<sup>2</sup>). The cause of this spectacular evolution will be discussed further on.

In order to assess the relative impacts of erosion or accretion on each islet, we computed the percentage of their surface areas affected by these processes during the periods analysed. By convention, the islet area on the first date is considered as 100% (Table 3). We then computed the maximum difference between surface area percentages at all dates. The results given in Table 3 show that the percentage values of change are highly variable, ranging from +65% to –167%. At the longest available timescale for each islet, most of the islets are losing land, and a few are gaining new land. However, the recent behaviour of the islets may differ from the dominant trend over the longer timescale. One example is Canard islet, which was accreting land overall over the long timescale from 1936 to 2014, but has been losing land since 2000. Conversely, while Ténia islet lost land from 1943 to 1954, its area has remained constant since 1954 although its shape has been changing continually.

During the last decade, the dominant pattern of islet evolution is an overall reduction in their area (more land loss than accretion). This recent trend is not necessarily representative of their long-term evolution. The short-term analysis should be completed with an analysis of the relationship between present-day shorelines and the location and geometry of the beach rocks, which are frequent around the islets.

The beach rocks are indicators of the location of older beaches. In most cases, we observed a reduction in the area of the islets





**Fig. 13.** Percentage of surface area change for some New Caledonian islets (by convention, the area first assessed is considered as 100%; different time spans are considered depending on the availability of aerial photographs and satellite images).

between the time of cementation of the beach rocks and today. In some cases, we observed a smaller islet contained in the shape outlined by the beach rocks, which are disconnected from today's beaches and located several dozen metres out to sea, while in other cases, the beach rocks indicate that the islet has migrated over time or has changed significantly in shape. In some particular cases of migration or local accretion, the beach rocks may be partly buried by the islet. These beach rocks, although not yet dated, provide valuable additional information on possible changes in the size, shape and location of islets and on their longer term evolutionary trends.

When an islet shrinks in size, its seaward shoreline gradually moves back from the beach rocks, leaving a gap between them of a few metres to several dozen metres. This indicates the high migration potential of the islets in the long term and how far the shoreline has retreated since the time of cementation of the beach rocks.

## 4.2. Interpretation

### 4.2.1. Evolution of the islets

Our analysis of the multi-decadal changes and present-day coastal processes affecting the islets coasts shows that trends are highly variable even for islets near to each other. Some islets are growing (increasing in area), others are stable or decreasing in area. Others are remaining constant in area but continually moving or changing in shape and, finally, several islets are showing very intense coastline erosion and a drastic reduction in their area. Thus, within a given time span, the trend for New Caledonia's islets is neither identical nor uniform. However, despite the variety of islet shapes, sizes, evolutionary trends, active processes and contexts (location, exposure to waves, distance to passes etc.), some similar patterns can be identified. Having grouped the islets into families according to common past trends and present-day characteristics, we are able to propose a new typology. This differs from existing typologies (e.g. MacNeil, 1972; Richmond, 1992) because it does not aim to differentiate between different types of islands according to their origins or their morphogenetic characteristics, but between different states of the same type of island (sand cays).

In this typology, we consider that each type represents a stage in an islet's life cycle. New Caledonian islets fall into 6 distinct stages in the continuum of their life cycle: nucleation, growth, maturity, decay, relic and endangered (Fig. 14). Each of the 6 distinct stages is one subset in the set of all possible states of the islets in New Caledonia's lagoon.

**4.2.1.1. The different stages.** One difficulty with the classification proposed above arises in the case of islets in a transitional stage between two classes (e.g., decay to relic). Each stage shown in Fig. 14 is described in detail below.

**4.2.1.1.1. Stage 1: Nucleation.** The first stage is the appearance of a small sandy islet made up of bioclastic sand with no vegetation (example: Sable islet). The absence of beach rocks, uprooted trees, tree stumps etc. indicates that this is not a phantom of a pre-existing islet that had been completely destroyed (post stage 6).

**4.2.1.1.2. Stage 2: Growth.** This second stage is characterized by stabilization of the initial sandy islet by vegetation and an increase in surface area due to the supply of bioclastic sand. The sedimentary budget is positive, i.e. the supply of sediment is higher than land loss by erosion (e.g.: Tibarama islet).

**4.2.1.1.3. Stage 3: Maturity.** This stage is characterized by a lack of noticeable change in surface area and morphodynamic equilibrium. Islets in this group are characterized by their resilience and high capacity for adaptation. Extreme events can trigger severe erosion or changes but this is followed by an effective recovery

phase. Three sub-stages may be distinguished:

1. *Stage 3a (stable):* the islet is static. Rates of erosion and accretion are low (e.g.: Mba islet today),
2. *Stage 3b (with migration):* the surface area of the islet remains stable and the sedimentary budget is in equilibrium. Erosion and accretion can be very active and occur at opposite sides of the islet. In this stage, the islet is mobile, shifting on a multi-annual time scale (e.g.: Kondoyo islet),
3. *Stage 3c (with remodelling):* as in the previous stage, the sedimentary budget is in equilibrium and the surface area of the islet is stable; however, erosion and accretion can be active and occur at various locations. In this case, the islet's overall geometry gradually changes as it accommodates to evolutionary forcing (e.g.: Ténia and Ronhua islets)

**4.2.1.1.4. Stage 4: Decay.** During this stage, the sedimentary budget is negative and the islet is shrinking in size, thus increasing the distance between the shoreline and the beach rocks. The previously vegetated areas are eroded and the presence of dead trees on the foreshore, and uprooted trees and erosion scars on the shoreline, are indicators of this pattern of change (e.g.: Larégnère islet). As the sedimentary budget is negative, extreme events may have irreversible consequences on smaller islets at this stage.

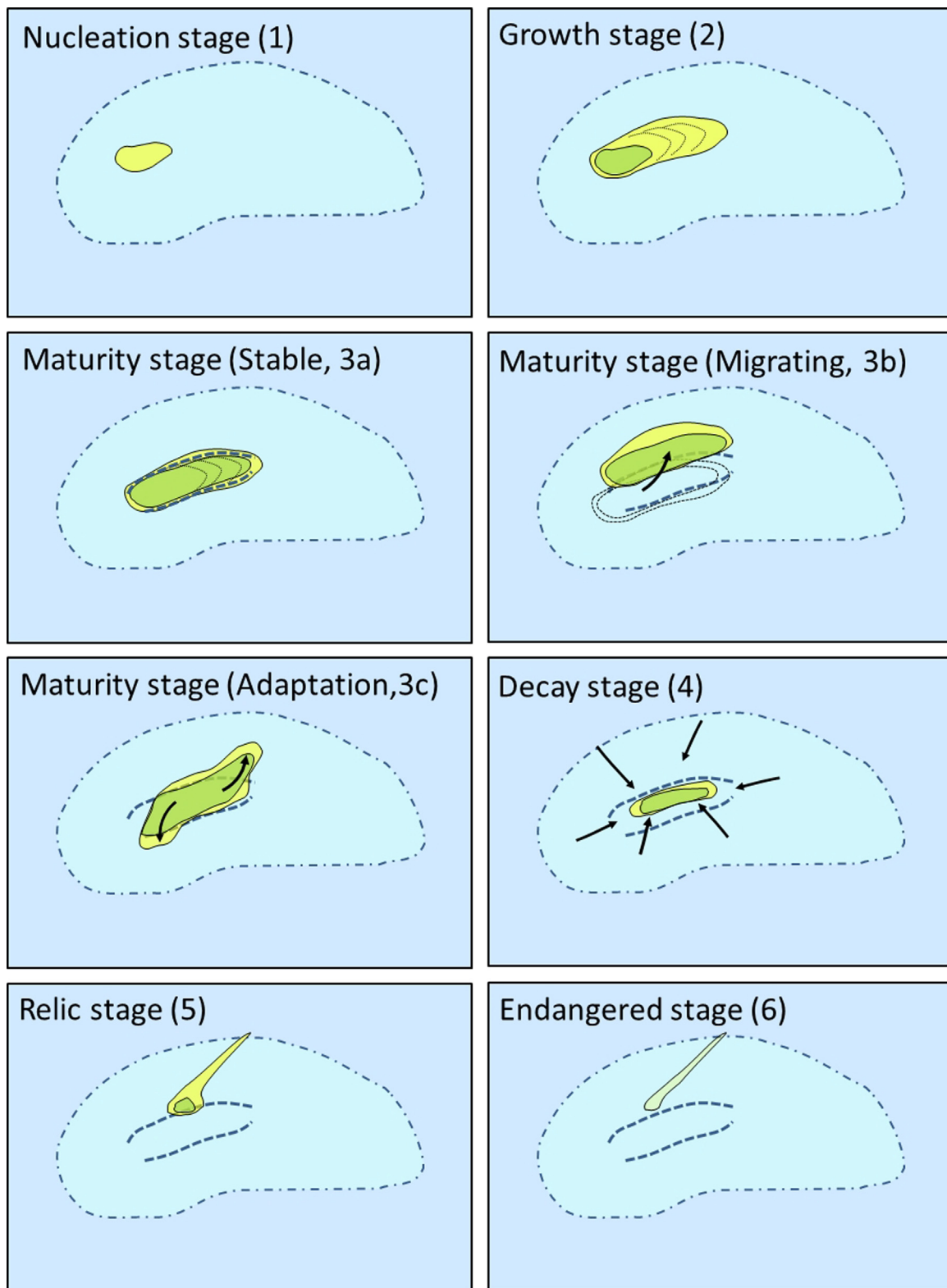
**4.2.1.1.5. Stage 5: Relic.** At this stage, the shape of the islet is very different to that in the mature stage as indicated by the beach rock geometry and/or by earlier limits. The islet shrinks dramatically and has a residual aspect. The sedimentary budget is highly negative and numerous tree stumps are present around the islet and at its previous location. The rate of land loss can be extremely high and the future of the islet is in jeopardy if the environmental conditions remain identical. A sandy plume on the patch-reef surface and connected to the islet is generally noticeable on aerial and satellite images. This plume forms as the sand, eroded by currents and waves, spreads outwards (e.g.: Goéland islet, Fig. 15).

**4.2.1.1.6. Stage 6: Endangered.** The endangered stage is the final phase before the disappearance of the islet. In this case, the life expectancy of the islet is short: if the environmental conditions remain the same, it will disappear within a few years, depending on the occurrence of high-energy events (southern swell, cyclones etc.; e.g.: Faux-Tabac (Fig. 16), Bois de Fer & Kutomërë islets).

When the islet has disappeared, its previous existence is indicated only by the presence of beach rocks (outlining the old beaches): this is known as the phantom stage. In this case, only a plume of sand shaped like a comet's tail is visible underwater. This plume is formed as currents and waves spread the eroded sediment outwards (e.g.: Baron islet off the coast of Koumac, Fig. 17).

**4.2.1.2. The islet life cycle.** Obviously, the state of a given islet at any particular time is governed by different environmental parameters such as local hydrodynamic conditions, trends in the wave climate, the shape of patch-reefs under the islet, changes in the reef itself, the local sea level etc. (e.g., Bird, 1996). The local sea level is linked in part to the evolution of the climate during the Holocene but also to natural inter-annual climatic oscillations (ENSO and IPO) and obviously to sea level rise due to anthropogenic climate change. Forcing factors also include extreme events like cyclones, storms and southern swells, which can trigger powerful erosion or accretion in a very short time, with severe impacts on the islet. The latter phenomenon and the consecutive sedimentary adjustments are illustrated in the context of atoll islets by several studies (e.g., Etienne, 2012; Etienne and Terry, 2012; Le Cozannet et al., 2013; Mann and Westphal, 2016; Ford and Kench, 2016). Finally, such extreme events are not independent and are partly linked to climate variability and climate change.

Thus, numerous parameters and forcing factors all play a role in the evolution of these islets (Garcin et al., 2011; Yates et al., 2013).



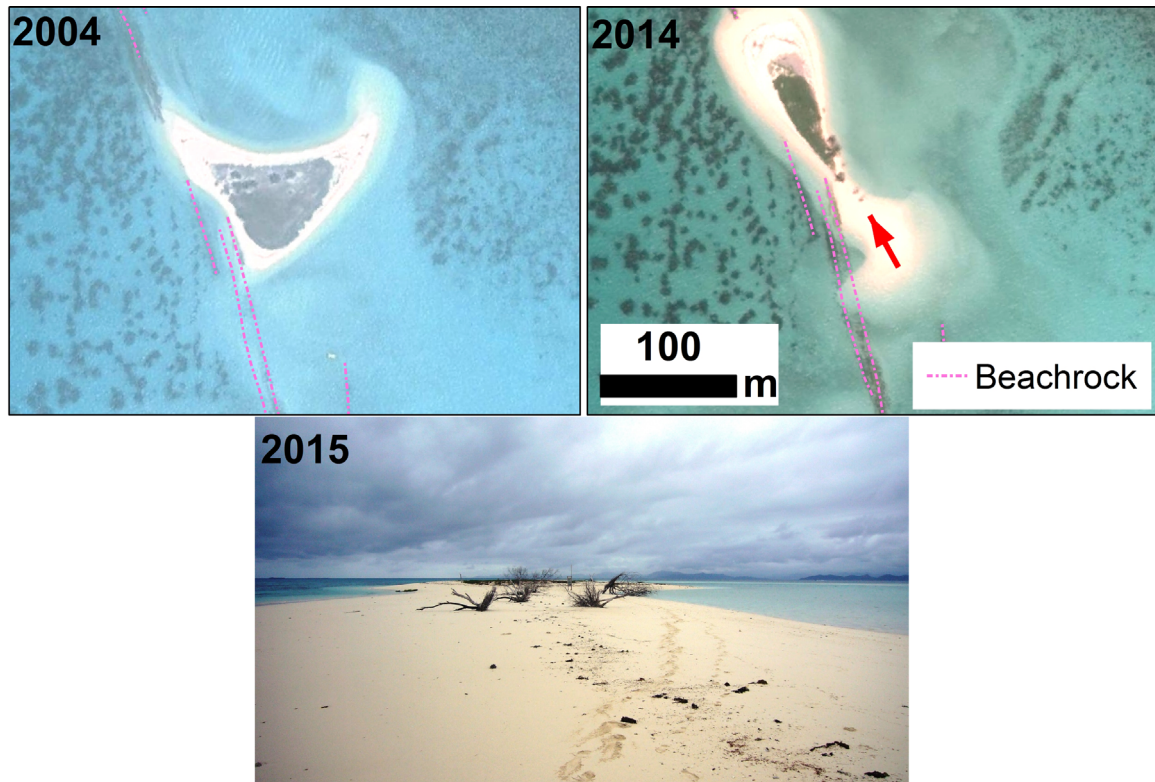
**Fig. 14.** The different stages of New Caledonia's islets – Bare sands (yellow), areas with vegetation (green), reef platform (light blue and dashed-and-dotted line), lagoon (deep blue), beach rocks (dashed line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

A change in any one of these parameters can modify the behaviour and evolution of an islet, which may then evolve from one stage to another. The six stages are therefore not necessarily sequential (Fig. 18), and if the conditions are favourable, an islet at stage 4 (decay stage), for example, could later revert to stage 2 (growth stage). Consequently, the life cycle of an islet can be as complex as

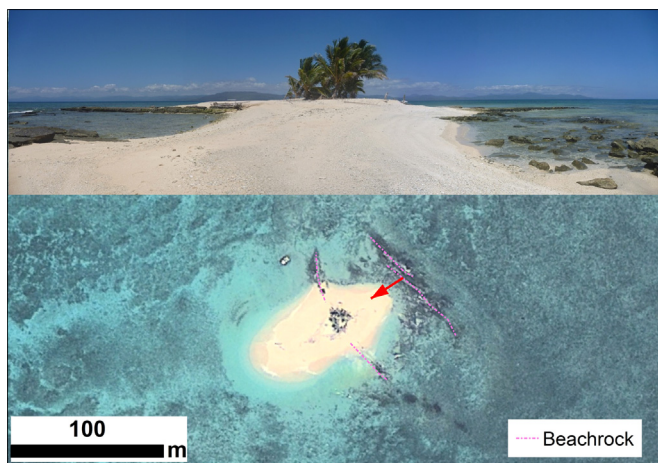
shown in Fig. 18.

The duration of each stage is highly variable. For example, Yamano et al. (2014) demonstrated that what we call stage 2 (growth stage) lasted more than 3 000 years on Mba islet. For other islets, we have evidence of rapid transitions from one stage to another within a few decades, with no occurrence of any catastrophic





**Fig. 15.** Goéland islet (stage 5 – relic) – Top: satellite images from 2004 and 2014, Bottom: field view from the South (2015) – note the drastic change in shape, the reduction in area and the presence of dead trees where the islet has been eroded.



**Fig. 16.** Faux-Tabac islet (stage 6 – Endangered) – Bottom : satellite image (Digital globe 2012), Top: field view from the centre of the north-eastern beach rock (2014). Note the two beach rock beds (foreground and background from left to right) and the residual sand at the islet's previous location.



**Fig. 17.** Illustration of a dead islet: Baron islet. Note the two beach rocks lying WSW-EN, which indicate the position of the previous islet beaches, and the sandy plume resulting from the islet's destruction.

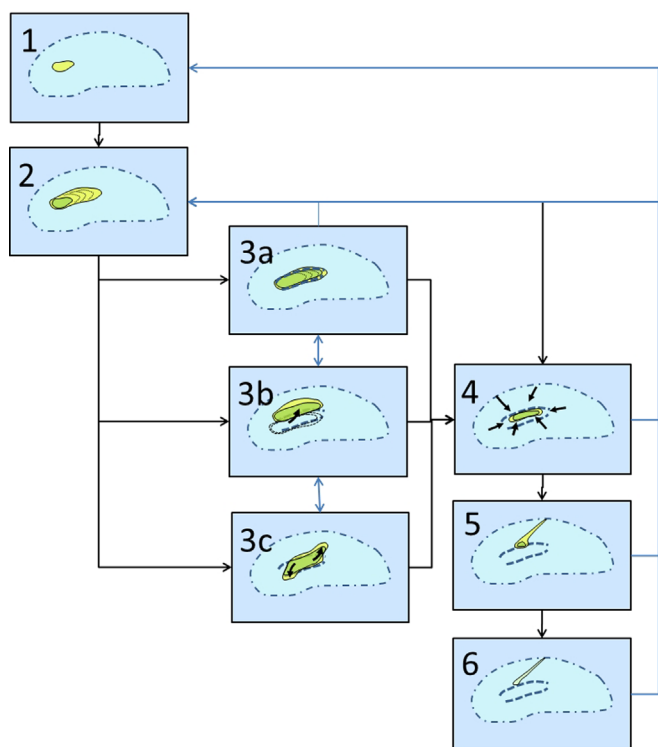
cyclonic event (Goéland and Kutomëre islets for example). Thus, Kutomëre islet shows that an observation time span of less than one century is long enough to observe a transition between several stages (growth, decay, relic stage and finally endangered). The phantom of Baron Islet is evidence that some islets have disappeared in the recent past: in this example, the only evidence of the presence of an islet are the beach rocks outlining the old beaches and a residual underwater plume of sand. In support of our observations, the speed of islet changes has been described by Ford and Kench (2014) in a different context (Marshall Islands), where what we call stages 1 and 2 (nucleation and growth) can occur in less than 6 decades. The destruction phase can occur

during a single catastrophic cyclone (e.g. Ford and Kench, 2014; Yates et al., 2013). Over longer timescales (several centuries to millennia), any particular islet can be expected to undergo different stages.

#### 4.2.2. The future of the New Caledonia's islets

Based on the above typology, 14% of the islets surveyed are presently in the endangered stage, 14% in the relic stage, 19% in the decay stage, 48% in the mature stage and 5% in the growth stage.

The question of the future of these islets may be addressed by investigating: (i) their typology (which provides information on the current stage of an islet's evolution), (ii) the specific



**Fig. 18.** Life cycle of New Caledonia's islets. Arrows indicate the possible pathways during an islet's life cycle (Beach rocks appear as indicators of past shorelines locations).

**Table 4**

Relationship between stages and life expectancy index of islets – Possible LEI are in brackets, the dominant LEI is in bold.

	Stage	Possible LEI
1	Nucleation	[undetermined]
2	Growth	[x..1]
3	Maturity	[2,1]
4	Decay	[4,3,2]
5	Relic	[5,4,3]
6	Endangered	<b>5</b>

morphological characteristics of the islets (elevation, size and shape), some of which are factors of resilience (e.g.: large area, presence of beach rocks all around the islet, relatively high

elevation) or, conversely, factors of fragility (e.g.: small area, low elevation, lack of continuous beach rock), (iii) the intensity of observed processes currently acting on the islets.

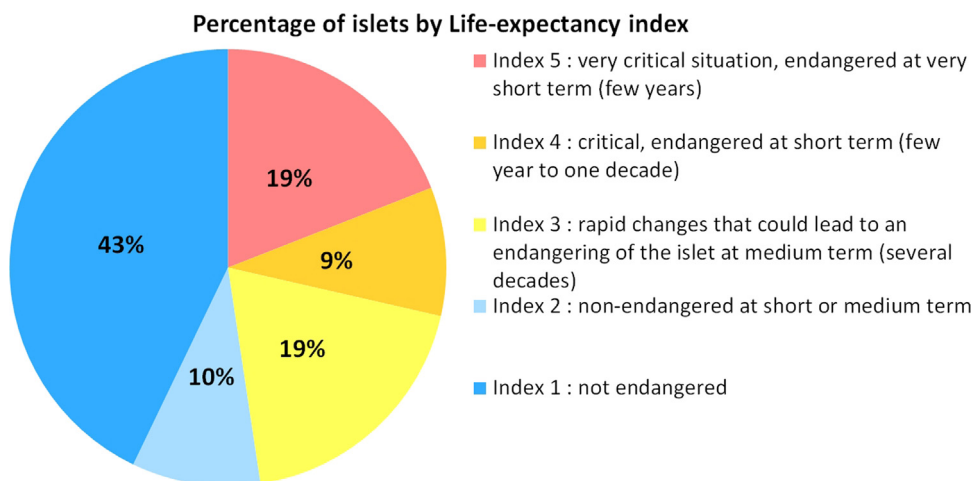
In order to assess the islets' future, a Life Expectancy Index (LEI) is assigned, qualitatively, to each islet (Table 4) on a scale of 1–5: Index 5 – very critical situation: the islet is endangered in the very short term (e.g., within a few years if, for example, a powerful storm or a cyclone occurs), erosion rates are very high all around small islets; Index 4 – critical situation: the islet is endangered in the short term (one decade); Index 3 – rapid changes that could endanger the islet in the medium term (decades); Index 2 – medium-sized islet with a low rate of accretion or large islet with a low rate of land loss: not endangered in the short or medium term; Index 1 – accreting or stable islet or large islet with very low land loss: not endangered.

The results given in Table 5 and in Fig. 19 show that of the 21 islets studied, if current conditions remains identical, 19% are in a very critical situation and very likely to be endangered in the short term (few years), 9.5% are in a critical situation, likely to disappear in the near future and very likely to disappear in the medium term (next few decades), 19% are evolving rapidly, which could lead to their disappearance in the medium term but not in the short term, 9.5% are not endangered in the short and medium term and 43% are not endangered at all (stable or accreting, large area, relatively higher altitude). The situations differ widely from one islet to another, even, in some cases, among those located in the same area of the lagoon. It should also be emphasized that there is more uncertainty regarding the medium and long term future due to uncertainties about future sea level rise and ENSO. Other sources of uncertainty concern the likelihood of reaching a threshold (values and rates of sea level rise for example), above which the resilience of each islet would be altered.

## 5. Discussion and perspectives

Our field observations of currently active processes and the work carried out on the past evolution of New Caledonia's islets at multi-decadal scales show that they are significantly affected by coastline change. In general, both erosion and accretion processes affect the islets at various levels of intensity, although the coastlines of some islets are affected by erosion along their entire length. As indicated previously, 54% of the total length of the 21 islets' shorelines are affected by erosion, 16.5% by accretion and 29.5% are stable.

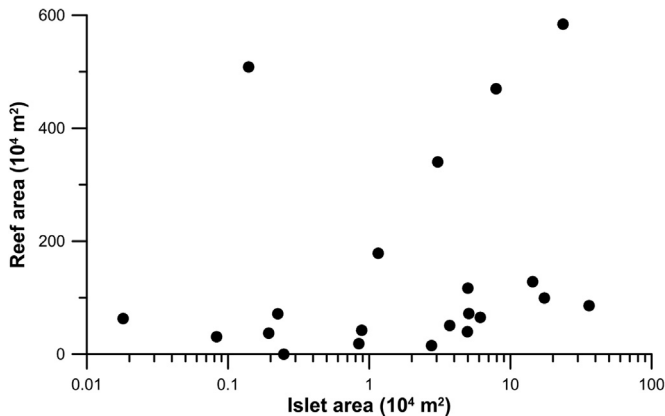
The difference between eroded land and accreted land varies



**Fig. 19.** Percentage of islets by life expectancy index.

**Table 5**  
Classification, recent changes, current area and life expectancy index of islets

Islet	Stage	Area recent changes	Area (m <sup>2</sup> )	Life expectancy index
Faux Tabac	Endangered (6)	Large reduction	181	5
Bois de Fer	Endangered (6)	Large reduction	831	5
Goéland	Relic (5)	Large reduction	1 399	5
MbeKuen	Relic (5)	Small reduction with shifting	1 938	3
Pandanus	Relic (5)	Large reduction	2 249	4
Kutomèrè	Endangered (6)	Large reduction	2 481	5
Canard	Decay (4)	Large reduction	8 431	3
Baille	Decay (4)	Small increase	8 832	2
Larègnère	Decay (4)	Reduction	11,572	4
Tibarama	Growth (2)	Large increase in area	27,663	1
Kondoyo	Mature with displacement (3b)	Small increase in area with significant shifting	30,588	3
Goldfield	Mature with remodelling (3c)	Stable with very small increase in area	37,170	1
Ronhwa	Decay (4)	Reduction	49,608	3
Ange	Mature stable (3a)	Stable	49,988	1
Ronde	Mature with remodelling (3c)	Reduction	50,785	2
Amédé	Mature stable 3a	Stable	61,165	1
Maitre	Mature with remodelling (3c)	Small reduction	79,246	1
Signal	Mature stable (3a)	Stable following a period of reduction	143,820	1
Mbo	Mature stable (3a)	Meta-stable	174,116	1
Ténia	Mature with remodelling (3c)	Meta-stable	235,743	1
Mba	Mature stable (3a)	Stable	360,704	1



**Fig. 20.** Lack of correlation between reefs and islet areas (10<sup>4</sup> m<sup>2</sup>).

from slightly positive to significantly negative depending on each islet. The pattern on change varies with each individual islet: there is no evidence of an overall pattern of erosion of all islets as would be expected if the ongoing sea level rise induced by climate change were the only (or main) trigger of coastal changes (Ramsay, 2011).

Intuitively, the relationship between the surface areas of the islets and those of the patch-reef would suggest that the islet area would be proportional to the patch-reef area. In fact, the data (Table 1) clearly show that these ratios vary considerably, from 0.03% to 41.12%, so that the surface area of an islet is completely uncorrelated with the patch-reef area (Fig. 20).

A comparison of the LEI with the characteristics of the islets (Table 1) appears to show that there is no simple and direct correlation between the mobility or life expectancy of the islets and certain simple parameters such as their distance from the barrier reef, the distance to the nearest pass or the size of the sector directly exposed to swells. This lack of direct correlation is explained by the complexity of the interactions between processes acting on an islet segment and producing a specific change. One example is the complexity of swell propagation from the passes to the islet in relation to the direction of the offshore swell, the lagoon bathymetry, the shape of the coral patches and the orientation of the shoreline.

The surface area of an islet appears to be an important factor to consider in assessing the “life expectancy” of an islet, but this

factor alone is not sufficiently explanatory, as demonstrated by Kondoyo islet. The south-eastern coast of this small islet is affected by severe erosion, which, based on field observations, we link to the strength of the waves driven by the trade winds, while the eroded sediment is transported to the north-western side of the islet, resulting in accretion. The overall budget is slightly positive (supply of sediment from the reef patch) and analysis of early photographs and satellite images shows that the islet has undoubtedly migrated westwards. This multi-decadal trend will probably continue in the coming years as long as the prevailing environmental conditions (wind and wave climates, biological context, etc.) remain similar and as long as the islet does not reach the western border of the patch-reef. In this case, a large part of the sand supply to the north-western beach would be lost as it would drop down into the deeper sectors of the lagoon.

The mobility of the islets and the Life Expectancy Index suggest that the smallest islets are not necessarily the most vulnerable and that their mobility does not imply greater vulnerability (in terms of life expectancy), but is rather an adaptation to forcing factors. Nevertheless, a large proportion of the smaller islets studied are endangered or in the relic stage, with a life expectancy index of 5 or 4.

The possibility for an islet to adapt to environmental changes is clearly dependent on the sedimentary, hydrodynamic and biological context of each one, and on how the forcing factors evolve. The resilience of an islet can be defined as its capacity to change its shape and morphology and/or to move in order to adapt to evolving environmental conditions (natural and anthropogenic forcing factors) without irreversible land loss. Thus, the fact that some islet shorelines are eroding does not necessarily imply that the islet is not resilient, if for example other sectors of the islet shoreline are in accretion or if the erosion phase is of short duration and followed by a recovery phase (accretion). Some events can cause the behaviour of a coastal segment to change, for example a phase of accretion (following an erosion phase) due to a change in the wave climate or to the appearance of a storm ridge of coarse sediment during a cyclone, which then acts as a natural levee and protects the shore.

The detailed analysis of changes in islet shorelines in the recent past shows two different patterns of change in the majority of cases: the first in the period from 2004 to 2007 and the second from 2007 to 2012–2013. During the first period, erosion rates



were generally lower than in the second, and in one case (the north-western coast of Amédé islet), we noticed a reversal of the trend, with accretion during the first period and erosion during the second. This observation is corroborated by the testimonies of a number of islet users. The question, then, is whether the causes of this reversal can be identified.

The respective roles of ordinary waves driven by trade winds and those induced by cyclones, tropical storms or austral swells must be taken into account. These waves have different impacts on erosion, transport and deposition processes. This may be illustrated by the example of Ténia islet (western lagoon), where we observed evidence of erosion on the northern, southern and eastern tips, which is confirmed by analyses of past satellite images. This erosion is easily correlated with the effects of local waves induced by trade winds and high-energy ocean swells. On the eastern part of the northern beach, we also observed geomorphological evidence of erosion, which is confirmed by the shape and position of the beach rocks but not by changes in the PVL during the 2004 to 2012 period, when it remained stable. Furthermore, unlike the western beach for example, this sector is not exposed to swells. This is because, during westerly storms (which are infrequent in this sector), the western swell, as it crosses the pass, is refracted along the reef margin to the south of the islet and shifts to an east-west direction as it curves around, i.e. the opposite direction to the ocean swell. As the swell does not break (absence of reef flats) and because the water is relatively deep, few changes affect the wave period and the waves retain enough energy to reach and erode the northern beach. The retreat of the northern beach is thus probably linked to rare westerly waves driven by storms or cyclones that did not occur during the period covered by the satellite images and photographs analysed.

The analysis of average numbers of cyclones and tropical storms affecting New Caledonia's coasts per year from 2004–2012 shows a slightly lower yearly average number of cyclones and a significantly lower number of tropical storms over this period compared to the 1972–2012 period (Fig. 4, Table 6). In detail, the first period (2004–2007) experienced more cyclones than the second period (2007–2012), while the first period experienced far fewer tropical storms than the second, when the number of storms was still significantly below the forty-year average.

These data indicate that the number (sum) of extreme events (tropical storms plus cyclones) is not the reason for the shift from accretion to erosion or for the increase in the beach erosion rate during the second period.

Table 6 suggests that a higher ratio of cyclones relative to tropical storms is less harmful in terms of erosion than a period with dominant tropical storms. It has long been demonstrated that cyclones can, depending on their characteristics (intensity, wave directions, periods and heights), cause massive erosion to the point of destroying islets entirely (Gardiner 1903 in Woodroffe, 2008; Ford and Kench, 2014) or, conversely, trigger a supply of

bioclastic debris leading to accretion (e.g. Maragos et al., 1973; Scoffin, 1993; Ford and Kench, 2014; Woodroffe, 2008).

The analysis of sea level records from the Brisbane and Norfolk tide gauges and the Nouméa tide gauge shows an overall sea level rise during the past 40 years. In detail, the 2007–2012 period shows a higher mean sea level and a faster rate of increase than the previous period (Fig. 6), which is characteristic of interannual variability. The interannual and decadal sea level variability is probably highly correlated with the Southern Oscillation Index (White et al., 2014). In this area of the south-western Pacific, this higher average sea level is generally observed during the period when "La Niña" is the dominant oscillation (Merrifield et al., 1999; Merrifield, 2011) and more particularly when the Interdecadal Pacific Oscillation (IPO) is negative, which was the case in the period studied (Messie and Chavez, 2011). The sea level rise recorded by altimetric measurements in the western Pacific was therefore strongly influenced by the ENSO and IPO (Zhang and Church, 2012). The variation in the rate of change of shoreline positions during the 2007–2012 period and the following years seems to be correlated with the higher average sea level linked to the ENSO and IPO oscillations. This suggests that the islets' evolution is at least partly governed by the ENSO and IPO oscillations and their relative influence on multi-annual mean sea level variability.

On a longer timescale, the mobility of the islets and changes in their shape are confirmed by the many beach rocks with no connection to the beach or with a different orientation relative to the present-day beach. This confirms that coastline changes, the changing shapes of the islets and their migration are not specific to recent years. The islets are constantly adapting to environmental drivers and changes.

The twenty-one islets studied represent around 10% of the total number of New Caledonian islets, and although this is a relatively low percentage, they may be considered to provide a fairly representative view of, at least, the islets of the southern and western lagoon, excluding the islets affected by uplift (e.g. some of those around Pine Island).

The rise in sea level induced by climate change and the probable increase in the rate of sea level rise in future decades predicted by the models will become more vigorous drivers and stressors for New Caledonia's islets.

## 6. Conclusion

At the multi-decadal and multi-annual timescales, the islets of New Caledonia's lagoon are evolving rapidly.

The typology of New Caledonia's islets and the analysis of field evidence and past trends over several decades have enabled us to propose a potential life expectancy index. This five-level index applied to the islets we studied indicates that 19% of islets are very likely to be endangered in the short term, 9.5% are in a critical situation and likely to disappear in the near future, 19% are evolving rapidly and could disappear in the medium term, 9.5% are not endangered in the short and medium term and 43% are not endangered at all.

At the multi-annual scale, the islets are not all shrinking and their coastlines are not affected only by erosion, as might be expected in the context of global sea level rise. Rather, we observed various patterns of change in the islets in relation to their characteristics: migration and displacement, changes in shape, slight increase in area or, conversely, huge land loss potentially leading to the islet's disappearance. On the timescale of single events (cyclones, tropical storms), powerful erosion processes can severely affect the shoreline and cause significant coastline displacement, as reported by witnesses. These extreme events, which

**Table 6**  
Average yearly numbers of cyclones and tropical storms for the 1972–2012, 2004–2012, 2004–2007 and 2007–2012 periods (from MeteoNC data).

	1972– 2012	2004– 2012	2004– 2007	2007– 2012
Average number of cyclones per year	1.53	1.44	1.6	1.2
Average number of tropical storms per year	1.73	0.67	0.4	1
Average number of extreme events per year (cyclones and storms)	3.25	2.11	2	1



are infrequent from the west, are responsible for the high rate of erosion observed on some of the western lagoon islets (eastern tip of Ténia for example). The shorelines are also very sensitive to the gradual modification of drivers such as sea level or wave climate for example, but the higher sea level of the 2007–2012 period seems to be an important factor accounting for the increase in erosion rates observed on some of the islets.

At the multi-annual scale, the regional sea level is linked to climate variability and, in the south-western Pacific, to the ENSO and IPO oscillations (see bibliography). The periods with noticeably higher erosion rates seem to be linked to the periods when La Niña events were dominant within an IPO negative. This context generates stronger trade winds and a higher sea level than during an El Niño and IPO positive period. All these parameters trigger changes in the processes that affect the shorelines and therefore the evolution of the islets.

Nevertheless, whatever the ENSO or IPO modes, the occurrence of extreme events, particularly those coming from the west (for the islets of the western lagoon), can be the most powerful driver of changes in the coastlines and shapes of the islets. These changes linked to a specific hydro-meteorological event do not necessarily follow the direction of the longer-term trends driven by climate variability.

In this context, the rise in sea level induced by climate change is an adverse factor which is likely to lower the resilience of the islets to erosion processes. Other factors like the degradation of the reef ecosystem due to variations in ocean salinity, temperature and acidity, lower sediment stocks on the beaches and foreshores, human visitors, coastal development and so on are other adverse factors that can potentially modify the capacity for resilience of these islets.

Due to their variety and sensitivity, New Caledonia's islets could serve as integrative indicators of environmental and climatic change for New Caledonia.

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## References

- Ambatsian, P., Fernex, F., Bernat, M., Parron, C., Lecolle, J., 1997. High metal inputs to closed seas: the New Caledonian lagoon. *J. Geochem. Explor.* 59, 59–74.
- Ballu, V., Bouin, M.N., Siméoni, P., Crawford, W.C., Calmant, S., Boré, J.M., Kanas, T., Pelletier, B., 2011. Comparing the role of absolute sea-level rise and vertical tectonic motions in coastal flooding, Torres Islands (Vanuatu). *Proc. Natl. Acad. Sci., USA* 108, 13019–13022. <http://dx.doi.org/10.1073/pnas.1102842108>.
- Becker, M., Meyssignac, B., Letetrel, C., Llovel, W., Cazenave, A., Delcroix, T., 2012. Sea level variations at tropical Pacific islandssince 1950. *Glob. Planet. Chang.* 8081s, 85–98, doi: 10.1016.
- Bird, E.C.F., 1987. The modern prevalence of beach erosion. *Mar. Pollut. Bull.* 18 (4), 151–157 1987.
- Bird, E.C., 1996. Coastal erosion and rising sea-level, Sea-Level Rise and Coastal Subsidence. Springer, pp. 87–103.
- Bird, E.C.F., Dubois, J.P., Itis, J.A., 1984. The impacts of Opencast mining on the Rivers and Coasts of New Caledonia. The United Nations University, Tokyo, p. 64.
- Bonnet, X., Briand, M., Brischoux, F., Letourneur, Y., Fauvel, T., Bustamante, P., 2014. Anguilliform fish reveal large scale contamination by mine trace elements in the coral reefs of New Caledonia. *Sci. Total Environ.* 2014 (470–471), 876–882.
- Bozec, Y., Dolédec, S., Kulbicki, M., 2005. An analysis of fish-habitat associations on disturbed coral reefs: chaetodontid fishes in New Caledonia. *J. Fish Biol.* 66, 966–982.
- Brischoux, F. and Bonnet, X., 2009. Life history of sea kraits in New Caledonia, in Grandcolas P. (ed.), *Zoologia neocaledonica* 7. Biodiversity studies in New Caledonia. Mémoires du Muséum national d'Histoire naturelle 198: 133–147. Paris.
- Butel, R., Dupuis, H., Bonneton, P., 2002. Spatial variability of wave conditions on the french Atlantic coast using in-situ data. *J. Coast. Res.* 36, 96–108.
- Cabioch, G., Corregge, T., Turpin, L., Castellaro, C., Recy, J., 1999. Development patterns of fringing and barrier reefs in New Caledonia (southwest Pacific). *Ocean. Acta* 22 (6), 567–578.
- Cabioch, G., Payri, C., Pichon, M., Corregge, T., Butscher, J., Dafond, N., Escoubeyrou, K., Jhilly, C., Laboute, P., Menou, J.L., Nowicki, L., 2002. Forages sur l'îlot Bayes sur le récif barrière de Poindimié côte Est de Nouvelle-Calédonie. *Rapp. De. Mission. Sci. De. La. Terre – Géologie-Géophysique IRD* 47, 27.
- Couture, E., 2000. Distribution of phyllosoma larvae of Scyllaridae and Palinuridae (Decapoda : Palinuridea) in the south-western lagoon of New Caledonia. *Mar. Freshw. Res.* 51 (4), 363–369.
- Crowell, M., Leatherman, S.P., Buckley, M.K., 1991. Historicalshoreline change: error analysis and mapping accuracy. *J. Coast. Res.* 7 (3), 839–852.
- Debenay, J.P., 1987. Sedimentology in the Southwestern lagoon of New Caledonia, SW Pacific. *J. Coast. Res.* 3 (1), 77–91.
- Debenay, J.P., Fernandez, J.M., 2009. Benthic foraminifera records of complex anthropogenic environmental changes combined with geochemical data in a tropical bay of New Caledonia (SW Pacific). *Mar. Poll. Bull.* 59, 311–322.
- Dickinson, W.R., 1999. Holocene sea-level record on funafuti and potential impact of global warming on central pacific atolls. *Q. Res.* 51, 124–132.
- Douillet, P., 1998. Tidal dynamics of the south-west lagoon of New Caledonia : observations and 2D numerical modelling. *Oceanol. Acta* 21, 69–79.
- Duvat, V., Magnan, A., Pouget, F., 2013. Exposure of atoll population to coastal erosion and flooding: a South Tarawa assessment, Kiribati. *Sustain. Sci.* 8 (3), 423–440. <http://dx.doi.org/10.1007/s11625-013-0215-7>.
- Etienne, S., Terry, J.P., 2012. Coral boulders, gravel tongues and sand sheets: Features of coastal accretion and sediment nourishment by Cyclone Tomas (March 2010) on Taveuni Island, Fiji. *Geomorphology* 175, 54–65.
- Etienne, S., 2012. Marine inundation hazards in French Polynesia: geomorphic impacts of Tropical Cyclone Oli in February 2010. 361. Geological Society, London, pp. 21–39.
- Faure, V., Pinazo, C., Torrétion, J.P., Douillet, P., 2010. Modelling the spatial and temporal variability of the SW lagoon of New Caledonia II: Realistic 3D simulations compared with in situ data. *Mar. Poll. Bull.* 61, 480–502.
- Fernandez, J.M., Ouillon, S., Chevillon, C., Douillet, P., Fichez, R., Le Gendre, R., 2006. A combined modelling and geochemical study of the fate of terrigenous inputs from mixed natural and mining sources in a coral reef lagoon (New Caledonia). *Mar. Poll. Bull.* 52, 320–331.
- Flamand, B., 2006. Les pentes externes du récif barrière de la Grande-Terre de Nouvelle-Calédonie : morphologie, lithologie, contrôle de la tectonique et de l'eustatisme. Université de Bretagne Occidentale, France, p. 221.
- Ford, M., 2012. Shoreline changes on an urban atoll in the Central Pacific Ocean: Majuro Atoll, Marshall Islands. *J. Coast. Res.* 28 (1), 11–22.
- Ford, M., 2013. Shoreline changes interpreted from multi-temporal aerial photographs and high resolution satellite images :Wotje atoll, marshall islands. *Remote Sens. Environ.* 135, 130–140. <http://dx.doi.org/10.1016/j.rse.2013.03.027>, ISSN 0034-4257 ;1879-0704.
- Ford, M., Kench, P., 2014. Formation and adjustment of typhoon-impacted reef islands interpreted from remote imagery: Nadikdik Atoll, Marshall Islands. *Geomorphology* 214, 216–222.
- Ford, M.R., Kench, P.S., 2016. Spatiotemporal variability of typhoon impacts and relaxation intervals on Jaluit Atoll, Marshall Islands. *Geology*, G37402-1.
- Frank, N., Turpin, L., Cabioch, G., Blamart, D., Tressens-Fedou, M., Colin, C., Jean-Batiste, P., 2006. Open system U-series ages of corals from a subsiding reef in New Caledonia: Implications for sea level changes, and subsidence rate. *Earth Planet. Sci. Lett.* 249, 274–289.
- Garcin, M., Vendé-Leclerc, M., 2015. Observatoire du littoral de Nouvelle-Calédonie - Bilan des activités 2014. Open file report BRGM/RP-64824-FR, 144 p., 173 fig., 4 tabl., 2 ann.
- Garcin, M., Yates, M., Le Cozannet, G., Walker, P., Donato, V., 2011. Sea level rise and coastal morphological changes on tropical islands: example from New Caledonia and French Polynesia (SW Pacific). *Geophys. Res. Abstr.* 13, 3504.
- Garcin, M., Baills, A., Le Cozannet, G., Bulteau, T., Auboin, A.L., Sauter, J., 2013. Pluri-decadal impact of mining activities on coastline mobility of estuaries of New Caledonia. *J. Coast. Res.* 65, 494–499.
- Garcin, M., Desprats, J.F., Fontaine, M., Pedreros, R., Attanayake, N., Fernando, S., Siriwardana, C.H.E.R., De Silva, U., Poisson, B., 2008. Integrated approach for coastal hazards and risks in Sri Lanka. *Nat. Hazards Earth Syst. Sci.* 8, 577–586.
- Gardiner, J.S. (Ed.), 1903. The fauna and geography of the Maldives and Laccadive Archipelagoes, being an account of the work carried on and of collections made by an expedition during years 1899 and. Cambridge University Press, Cambridge, p. 1900.
- Hayes, M.O., 1979. Barrier Island Morphology as a Function of Tidal and Wave

- Regime., In: Leatherman, S.P. (Ed.), *Barrier Islands from the Gulf of St. Lawrence to the Gulf of Mexico*. Academic Press, New York, NY, pp. 1–29.
- Hédouin, L., Bustamante, P., Fichez, R., Warnau, M., 2008. The tropical brown alga *Lobophoravariegata* as a bioindicator of mining contamination in the New Caledonia lagoon : a field transplantation study. *Mar. Environ. Res.* 66, 438–444. IFRECOR NC 2012 (<http://www.ifrecor.nc/>).
- Jimenez, H., Dumas, P., Léopold, M., Ferraris, J., 2011. Invertebrate harvesting on tropical urban areas: Trends and impact on natural populations (New Caledonia, South Pacific). *Fish. Res.* 108, 195–204.
- Kench, P.S., McLean, R.F., Nichol, S.L., 2005. New model of reef-island evolution: Maldives, Indian Ocean. *Geology*, 145–148.
- Komar, P.D., 2010. Shoreline evolution and management of hawke's Bay, New Zealand: Tectonics, coastal processes, and human impacts. *J. Coast. Res.* 26 (1), 143–156.
- Le Cozannet, G., Garcin, M., Petitjean, L., Cazenave, A., Becker, M., Meyssignac, B., Walker, P., Devilliers, C., Le Brun, O., Lecacheux, S., Baills, A., Bulteau, T., Yates et, M., Wöppelmann, G., 2013. Exploring the relation between sea level rise and shoreline erosion using sea level reconstructions : an example in French Polynesia. *J. Coast. Res.* 21372142s, 1551–5036. <http://dx.doi.org/10.2112/s165-3611>.
- Le Cozannet, G., Garcin, M., Yates, M., Meyssignac, B., 2014. Approaches to evaluate the recent impacts of sea-level rise onshoreline changes. *Earth-Sci. Rev.* 138, 47–60.
- Le Cozannet, G., Lecacheux, S., Delvallee, E., Desramaut, N., Oliveros, C., Pedreros, R., 2011. Teleconnection pattern influence on sea-wave climate in the bay of Biscay. *J. Clim.* 24, 641–652.
- Le Roy, P., Cabioch, G., Monod, B., Lagabrielle, Y., Pelletier, B., Flamand, B., 2008. Late Quaternary history of the Nouméa lagoon (New Caledonia, SouthWest Pacific) as depicted by seismic stratigraphy and multibeam bathymetry. A modern model of tropical rimmed shelf. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 270, 29–45.
- Lecacheux, S., Pedreros, R., Le Cozannet, G., Thiébot, J., De La Torre, Y., Bulteau, T., 2012. A method to characterize the different extreme waves for islands exposed to various wave regimes: a case study devoted to reunion island. *Nat. Hazards Earth Syst. Sci.* 12, 2425–2437.
- Lecolle, J.F., Cabioch, G., 1988. La limite Holocène-Pleistocène dans le récif frangeant Ricaudy (Nouvelle-Calédonie). *Géochronologie, faciès et diagénèse. Implications eustatiques et néotectoniques*. *Mar. Geol.* 81, 241–260.
- MacNeil F.S., 1972. Physical and biological aspects of atoll in the northern Marshall. In *Proceedings of the 1st international Symposium on Corals and Coral Reefs*, 1, 507–567.
- Mann, T., Westphal, H., 2016. Multi-decadal shoreline changes on Takú Atoll, Papua New Guinea: Observational evidence of early reef island recovery after the impact of storm waves. *Geomorphology*.
- Maragos, J.E., Baines, G.B.K., Beveridge, P.J., 1973. Tropical cyclone creates a new land formation on Funafuti atoll. *Science* 181, 1161–1164.
- Merrifield, M., 2011. A shift in western tropical pacific sea level trends during the 1990s. *J. Clim.* 26, 4126–4138.
- Merrifield, M., Kilonsky, B., Nakahara, S., 1999. Interannual sea level changes in the tropical pacific associated with ENSO. *Geophys. Res. Lett.* 26, 3317–3320.
- Messie, M., Chavez, F., 2011. Global modes of sea surface temperature variability in relation to regional climate indices. *J. Clim.* 24, 4314–4331.
- Metian, M., Bustamante, P., Hédouin, L., Warnau, M., 2008. Accumulation of nine metals and one metalloid in the tropical scallop *Comptopallium radula* from coral reefs in New Caledonia. *Environ. Pollut.* 152, 543–552.
- Meyssignac, B., Becker, M., Llovel, W., Cazenave, A., 2012. An assessment of two-dimensional past sea level reconstructions over 1950–2009 based on tide gauge data and different input sea level grids. *Surv. Geophys.* 33, 945–972.
- Migon, C., Ouillon, S., Mari, X., Nicolas, E., 2007. Geochemical and hydrodynamic constraints on the distribution of trace metal concentrations in the lagoon of Noumea, New Caledonia. *Estuar. Coast. Shelf Sci.* 74, 756–765.
- Nicholls, R.J., Cazenave, A., 2010. Sea-level rise and its impact on coastal zones. *Science* 328 (1517). <http://dx.doi.org/10.1126/science.1185782>.
- Nunn, P.D., 2013. The end of the pacific? Effects of sea level rise on pacific island livelihoods. *Singap. J. Trop. Geogr.* 34 (2), 143–171. <http://dx.doi.org/10.1111/sjtg.12021>, ISSN 1467–9493.
- Nurse, L., McLean, R., Agard, J., Briguglio, L., Duvat-Magnan, V., Pelesikoti, N., Tompkins, E., Webb, A., 2014. Small islands, Climate Change 2014 : Impacts, Adaptation, and Vulnerability. Part B : Regional Aspects, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 1613–1654.
- Nicholls, R.J., Wong, P.P., Burkett, V.R., Codignotto, J., Hay, J.; McLean, R., Ragoonaden, S., Woodroffe, C.D., 2007. Coastal systems and low-lying areas. In: *Climate change 2007: impacts, adaptation and vulnerability*. Contribution of Working Group II to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge, UK, 315–356.
- Ohde, S., Greaves, M., Masuzawa, T., Buckley, H.A., Van Woessik, R., Wilson, P.A., Pirazzoli, P.A., Elderfield, H., 2002. The chronology of Funafuti Atoll: Revisiting an old friend. *Proceedings: Mathematical, Physical and Engineering Sciences*, 458(2025), 2289–2306.
- Ouillon, S., Douillet, P., Lefebvre, J.P., Le Gendre, R., Jouon, A., Bonneton, P., Fernandez, J.M., Chevillon, C., Magand, O., Lefèvre, J., Le Hir, P., Dumas, F., Marchesiello, P., Bel Madani, A., Andréfouet, S., Panché, J.Y., Fichez, R., 2010. Circulation and suspended sediment transport in a coral reef lagoon: The south-west lagoon of New Caledonia. *Mar. Poll. Bull.* 61, 269–296.
- Pandolfi Benoit, M., Bretagnolle, V., 2002. Seabirds of the southern lagoon of New Caledonia; Distribution. *Abund. Threat. Waterbirds* 25 (2), 202–213.
- Paskoff, R., 1998. Les littoraux. Impact des aménagements sur leur évolution. Armand Colin Ed., Paris, 264 p., 121 fig., 41 photos.
- Paskoff, R., Clus-Auby, C., 2007. L'érosion des plages : les causes, les remèdes, Paris/Monaco, Institut Océanographique, coll. " Propos ", 184 p.
- Ramsay, D., 2011. Coastal erosion and inundation due to climate change in the Pacific and East Timor. NIWA report 76p. ISBN 978-925006-03-2.
- Richmond, B.M., 1992. Development of atoll islets in the central Pacific. *Proceedings of the 7th International Coral Reef Congress*, 2, 1185–1194.
- Romine, B., Fletcher, C., Barbee, M., Anderson, T., Frazer, N.L., 2013. Are beach erosion rates and sea-level rise related in Hawaii? *Glob. Planet. Chang.* 108, 149–157.
- Roy, P.E.T., Connell, J., 1991. Climatic-change and the future of Atoll states. *J. Coast. Res.* 7 (4), 1057–1075, ISSN 0749-0208.
- Sasal, P., Mouillot, D., Fichez, R., Chifflet, S., Kulbicki, M., 2007. The use of fish parasites as biological indicators of anthropogenic influences in coral-reef lagoons: A case study of Apogonidae parasites in New-Caledonia. *Mar. Poll. Bull.* 54, 1697–1706.
- Scoffin, T.P., 1993. The geological effects of hurricanes on coral reefs and the interpretation of storm deposits. *Coral Reefs* 12, 203–221.
- SHOM—Service Hydrographique de la Marine.
- Stoddard, D.R., 1990. Coral reefs and islands and predicted sea-level rise. *Prog. Phys. Geogr.* 14 (4), 521–536.
- Terry, J.P., Kostaschuk, R.A., Wotling, G., 2008. Features of tropical cyclone-induced flood peaks on Grande-Terre, New Caledonia. *Water Environ. J.* 22, 177–183.
- J. Thiébot, G. Le Cozannet, M. Garcin, R. Pedreros, N. Desramaut, E. Delvalée, Y. De La Torre, A. Blangy, C. Oliveros, 2010. Caractérisation des états de mer extrêmes dans les environnements soumis à plusieurs régimes de vagues. *Actes—Xième Journées Nationales Génie Côtier – Génie Civil*, 137–146, 6 figs., 2 Tabl., Les Sables-d'Olonne, France.
- Thieler, E.R., Danforth, W.W., 1994. Historical shoreline mapping(I): improving techniques and reducing positioning errors. *J. Coast. Res.* 10 (3), 549–563.
- Testut, L., Duvat, V., Ballu, V., Fernandes, R.M.S., Pouget, F., Salmon, C., Dymont, J., 2015. Shoreline changes in a rising sea-level context: the example of Grande Glorieuse, Scattered Islands, Western Indian Ocean. *Acta Oecol.*, 1–10. <http://dx.doi.org/10.1016/j.actao.2015.10.002>.
- Webb, A.P., Kench, P.S., 2010. The dynamic response of reef islands to sea-level rise: evidence from multi-decadal analysis of island change in the Central Pacific. *Glob. Planet. Chang.* 72, 234–246.
- White, N., Haigh, I., Church, J., Koen, T., Watson, C., Pritchard, T., Watson, P., Burgette, R., McInnes, K., You, Z.-Y., Zhang, X., Tregoning, P., 2014. Australian sea levels—Trends, regional variability and influencing factors. *Earth-Sci. Rev.* 136, 155–174.
- Woodroffe, C.D., Murray-Wallace, C.V., 2012. Sea-level rise and coastal change: the past as a guide to the future. *Q. Sci. Rev.* 54. <http://dx.doi.org/10.1016/j>.
- Woodroffe, C.C., McLean, R.F., Smithers, S.G., Lawson, E.M., 1999. Atoll reef-island formation and response to sea-level change: West Island, Cocos (Keeling) Islands. *Mar. Geol.* 160, 85–104.
- Woodroffe, C.D., 2008. Reef-island topography and the vulnerability of atolls to sea-level rise. *Glob. Planet. Chang.* 62, 77–96.
- Xue, C., 1997. Coastal erosion and management of Vaitupu Island, Tuvalu. Technical report 243, SOPAC.
- Yamano, H., Cabioch, G., Chevillon Ch., Join, J.-L., 2014. Late Holocene sea-level change and reef-island evolution in New Calédonia. *Geomorphology*.
- Yates, M., Le Cozannet, G., Garcin, M., Salai, E., Walker, P., 2013. Multi-decadal atoll shoreline change on Manihi and Manuae, French Polynesia. *J. Coast. Res.* 29 (4), 870–882.
- Zhang, X., Church, J.A., 2012. Sea level trends, interannual and decadal variability in the pacific ocean. *Geophys. Res. Lett.* 39, L21701. <http://dx.doi.org/10.1029/2012GL053240>.