Chapter 4

The waltz of the water masses in the New Caledonian lagoon

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Waves breaking on a coastal reef flat, Isle of Pines. © P.-A. Pantz

The hydrodynamic circulation in the lagoon is the result of movements of the water masses which constrained by the complex geomorphology of the lagoon. The major oceanic (CRAVATTE *et al*., 2015) and coastal (MARCHESIELLO *et al*., 2010) currents and eddies, tides (OUILLON *et al*., 2010), local winds (LEFÈVRE *et al*., 2010) and waves (AUCAN, com. pers.) are the main triggers of these movements (box. 1). Although most of us are familiar with the oscillation of tidal cycles, the properties of water masses and currents are the result of non-linear and complex interactions. Numerical models have demonstrated the critical effect of tides and wind on the lagoon rhythm. For example, they control the renewal of water masses, the properties and forms of organic matter, and larval transport.

The impact of oceanic swell combined with wind-waves (waves generated by local winds in the lagoon), whose energy propagation is in turn modulated by tides, is only starting to be studied using numerical models. The calibration and validation of our numerical models is achieved using precise and valuable observations collected over the past 20 years by scientists working at the IRD center in Nouméa. These observations are acquired using *in situ* devices (tidal or sea level gauges, current meters, drifting buoys, wave buoys, temperature and salinity sensors), automated weather stations and scientific field surveys for the measure of the water's physicochemical properties. These observations are supplemented with data collected by Météo-France and IFREMER as well as satellite data (on wind, swell, temperature, turbidity and phytoplankton surface distribution).

Box 1

New Caledonian reefs are surrounded by currents

Christophe Menkès

In the southern Pacific region, the main trigger of oceanic circulation is the South Equatorial Current (SEC), which flows westward and redistributes subtropical waters towards the Equator and the Southern Ocean. Like every archipelago, New Caledonia is an obstacle to water transport and this generates coastal currents. When it reaches the Loyalty and New Caledonia ridges, the South Equatorial Current splits into two branches (MARCHESIELLO *et al.*, 2010; CRAVATTE *et al.*, 2015). One branch flows westward around the south of New Caledonia and forms the South Caledonian Jet (SCJ). A weak and variable current, the Vauban Current, generally flows southeastward along the east coast of Grande Terre. To the east of New Caledonia, the main branch of the SEC (the East Caledonian Current - ECC) passes north, around the New Caledonia Ridge, and contributes to the North Caledonian Jet (NCJ) in the Grand Passage and to the north of the d'Entrecasteaux Reefs. This current continues westward, passes north of the Chesterfield Islands and, when it reaches the east coast of Australia, splits into a northern and a southern branch. The East Australian Current (EAC) also splits and forms the subtropical countercurrent (STCC), which flows eastward, south of New Caledonia. This countercurrent partly feeds the Alis Current (ACNC, Alis Current New Caledonia), which flows southeastward along the western margin of Grande Terre. In addition, during the warm season (November to April), trade winds, blowing from the southeast, induce an upwelling along the west coast of Grande Terre (HÉNIN and CRESSWELL, 2005; MARCHESIELLO *et al.*, 2010).

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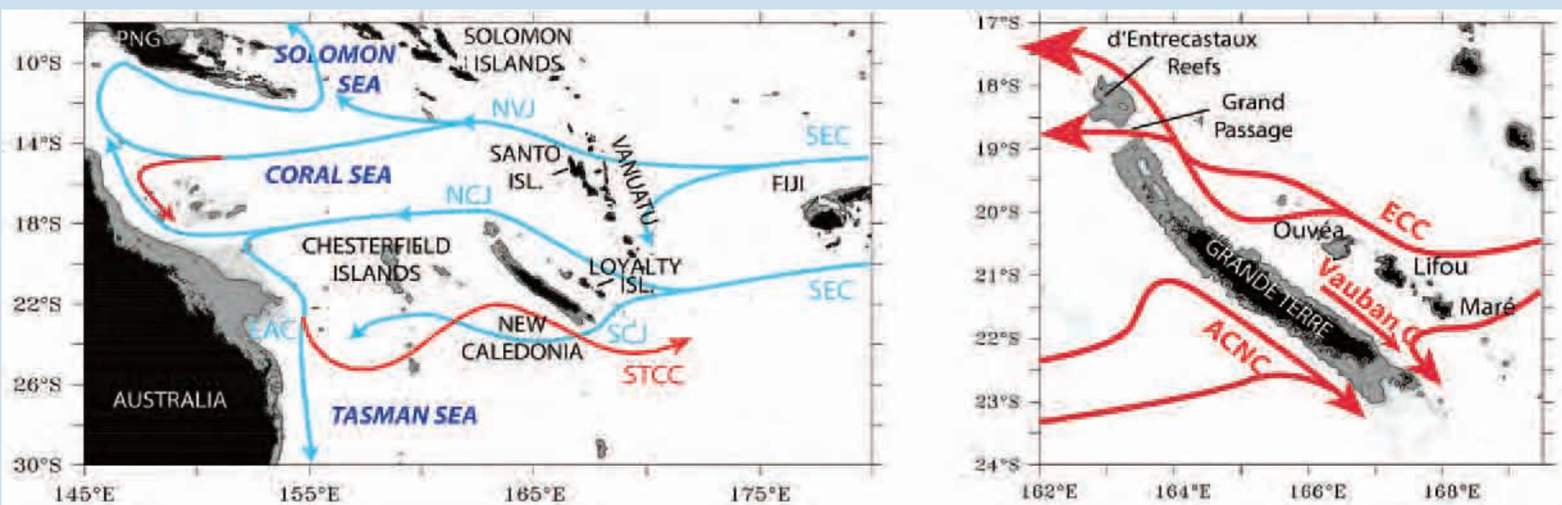


Oceanic circulation around New Caledonia. Adapted from CRAVATTE *et al.*, 2015

The influence of the planets

Tides in the lagoons are the result of a combination of tidal waves produced by the gravitational attraction of celestial bodies (moon, sun and planets) located close to Earth. Tidal currents are mainly generated by the lunar semidiurnal wave, which is the result of lunar forces (M2 waves), and, to a lesser extent, by the solar semidiurnal wave, which is the result of solar forces (S2 wave), and the solar-lunar diurnal wave, which results from the joint forces of the sun and the moon (K1 wave). Currents generated by the M2 wave (about 20 cm/s) are three-times faster than those generated by the S2 wave. Currents due to the K1 wave are ten-times slower (about 1 cm/s), except in passes where they can reach 5 cm/s (OUILLON *et al.*, 2010).

The amplitude and phase of M2 and S2, which respectively represent the sea-level and the direction of current propagation, are illustrated on Fig.2-3. The M2 wave propagates westward, perpendicularly to Grande Terre with a faster propagation in the center of the island. It propagates around the northern and the southern ends of the island and mainly enters the Southwestern Lagoon through the Havannah Channel.

The amplitude of the M2 wave increases from north to south on both sides of Grande Terre but is higher along the west coast. In the Southwestern Lagoon, the tidal amplitude decreases at the Havannah Channel, and increases inside the lagoon. The S2 wave propagation is different on the east and west coasts. Grande Terre acts as a boundary, particularly along the line "Grande Terre - Isle of Pines" and it has the same effect on the amplitude of the S2 wave as on the M2 wave. In the Southwestern Lagoon, the waves expand from the Corne Sud and the Havannah Channel into the lagoon. The currents generated by these waves flow at the same speed throughout the entire water column. An example of current fields in the Havannah Channel in the south of Grande Terre is shown for various tidal periods (box. 2).

Waves can play too

Due to its geographical position in the middle of the southwest Pacific and the intertropical zone, New Caledonia is exposed to waves of multiple origins. In both hemispheres, winter storms generate long swell that can cross the ocean and reach the archipelago. As a result, the barrier reefs to the west of Grande Terre are impacted by

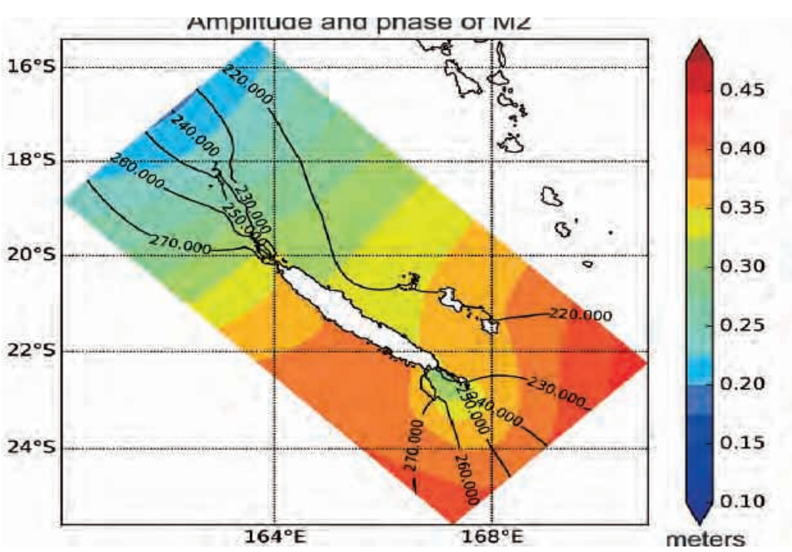


Figure 2: M2 wave phase and amplitude (in meters).

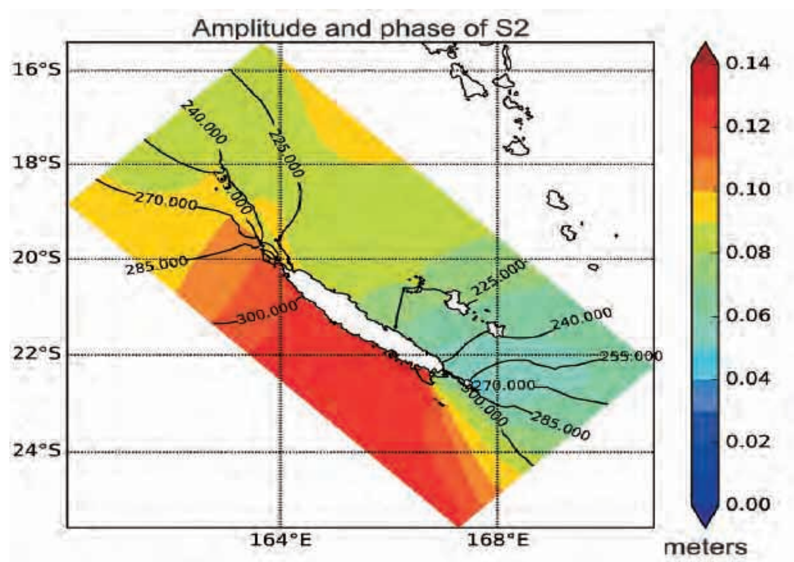
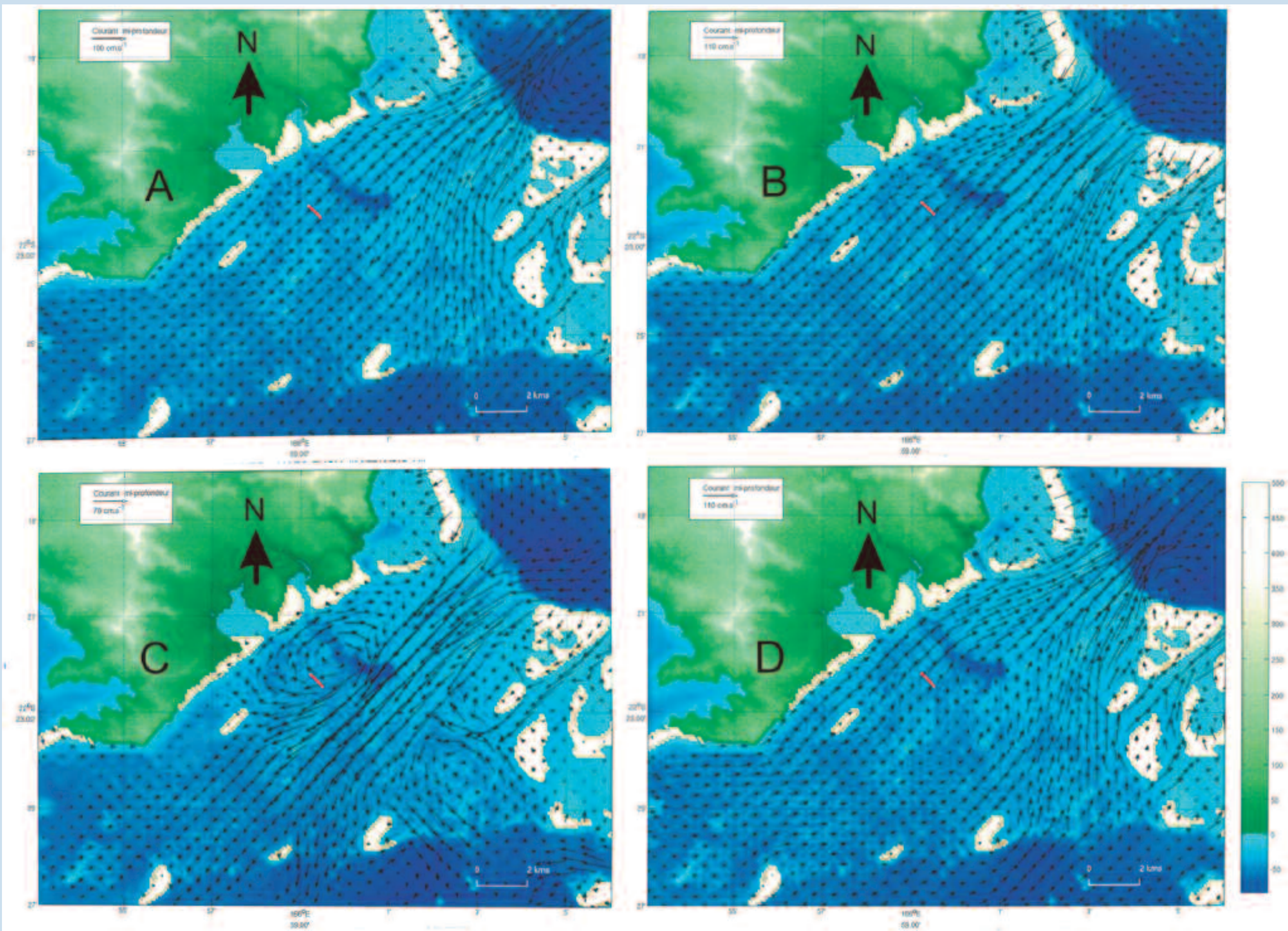


Figure 3: S2 wave phase and amplitude (in meters).

Box 2

Back and forth in the Havannah channel

In the Havannah Channel, tidal currents are very strong and follow a specific rhythm linked to the height of the tide. During low tide, currents are outgoing with increasing strength towards the pass (about 1 m/s). Four hours after low tide, currents in the channel are strongly incoming, exceeding 1.5 m/s and transporting important water masses southward, into the Merlet Reserve. One hour after high tide, currents are still incoming in the center of the channel, and two eddies develop on the north and south sides of the channel. Finally, tides create a global residual current flowing southwestward into the lagoon with a strength of about a few centimeters per second.



Tidal currents in the Havannah Channel. A: Low tide. B: Low tide + 4 hrs. C: High tide + 1 hr. D: High tide + 4 hrs. © IRD/P. Douillet southwesterly swell generated by storms off the coasts of Australia and New Zealand, and which can be over 4 m high. The island of Ouvéa, in the Loyalty Archipelago, receives smaller northwesterly swell, which is generated by storms off the coast of Japan. Around New Caledonia, trade winds, which are the dominant winds, generate waves locally. In the Southwestern Lagoon, these wind-waves can reach 2 m high and, tropical cyclones can generate extreme waves, which can be higher than 10 m. The effect of waves is therefore diverse. They can impact the water circulation in the lagoons (box. 3) and shape the evolution of beaches and islets. In addition to currents induced by tides and storm winds, the action of waves breaking on reefs and beaches induces the formation of a wave setup with strong currents, particularly during tropical cyclones.

The impact of tropical cyclones

Located at the southern edge of the South Pacific convection zone, New Caledonian lagoons are exposed to tropical cyclones. Reef obstacles (barrier and fringing reefs) and mangroves provide natural protection against erosion and coastal flooding. However, the ecosystems resilience to sea-level rise is little understood.

The simulation of waves generated by the tropical cyclone Cook upon its arrival on Kouaoua, shows how coral reefs absorb waves (Fig. 4, A). Coastlines with a double protection (barrier and intermediate reefs, such as at La Monéo River mouth) are relatively sheltered from waves induced by tropical cyclones (wave height is 3 m at the coast

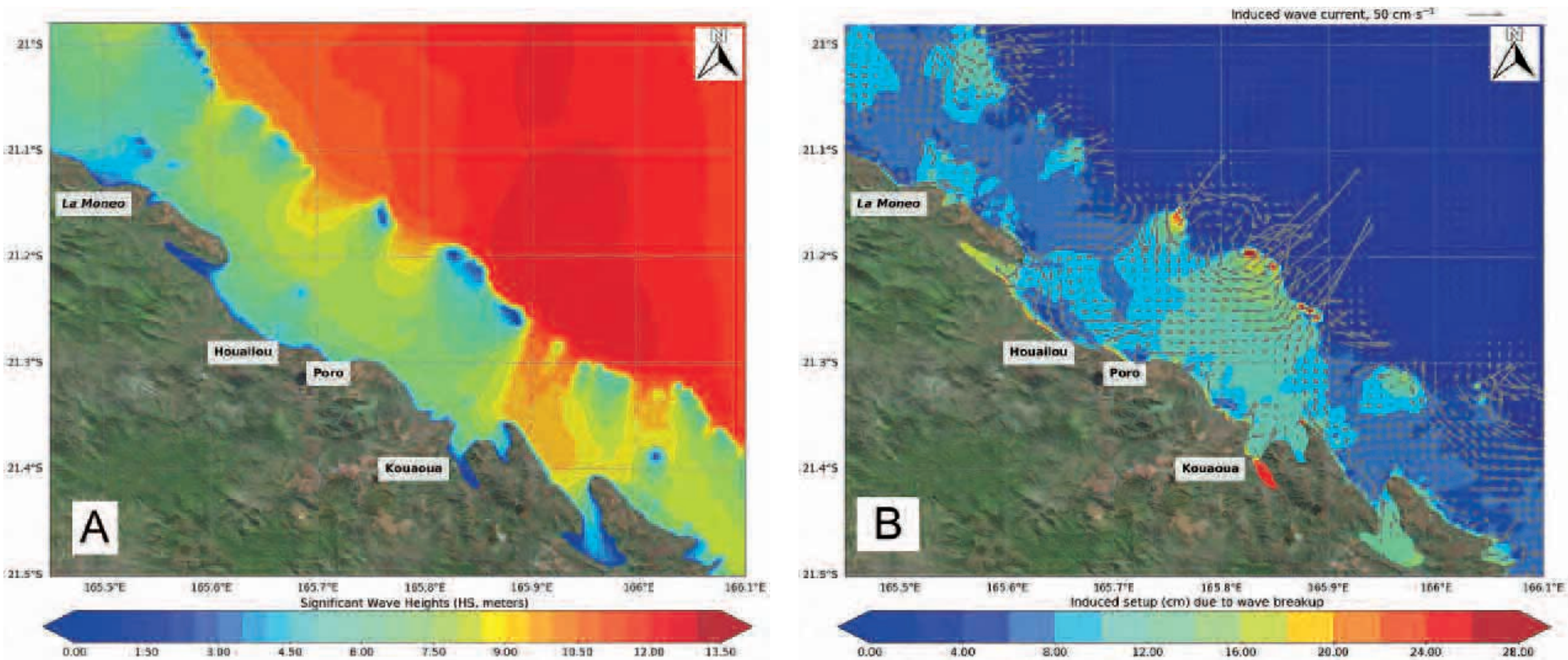


Figure 4: Cyclone Cook at its peak, upon arrival on Kouaoua, April 9th 2017.
A: Maximum significant wave heights (in meters) simulated using the SWAN wave model at 300 m resolution.
B: Wave setup (in centimeters) and current induced by wave breaking, simulated with a wave-current coupled model using SWAN and FVCOM. Wind data during tropical cyclone events are from Météo-France, bathymetry is from the New Caledonian government (DTSI). Model validation was carried out using wave observations recorded at the Fourmi pass in Poindimié. © IRD/ J. Lefèvre

vs. 13 m offshore), while shores located across the Kouaoua and Canala passes are more severely exposed (9 m at the coast vs. 13 m offshore). This example demonstrates how the diversity of reef configurations results in a diversity of exposure to flooding hazards over short distances. Water movements generated by cyclone waves also trigger a spectacular redistribution of sands and coral debris.

The wave-currents coupled model allows the reproduction of wave breaking impact (predicted by the wave model) on the momentum balance. Setups and currents that are associated with the wave breaking process during tropical cyclone Cook are shown on Fig. 4, B: a water bulge forms on the barrier reef and causes a wave setup of 25 cm, which is compensated by strong rip currents (1 to 2 m/s) flowing offshore.

In the wave breaking zones (surf zones) that are close to beaches, currents form streams parallel to the shore, which are able to carry eroded sediments. In bays sheltered from waves induced by cyclones (e.g., the narrow Kouaoua bay), waves breaking at the entrance of the bay act against outgoing currents. This phenomenon leads to an additional elevation of the mean water level by 20 to 30 cm.

Wind direction and dispersion of terrigenous inputs

Besides its role in wave formation, the wind also impacts the transport and dispersion of terrigenous discharge in the lagoon. Coral reef ecosystems are exposed to inputs of terrestrial nutrients, sediments and pollutants which have a negative impact on corals. Any anthropic alteration of the terrestrial biotope (fertilizers, increase in soil erodibility, pesticides, and contaminants) causes major stress to corals, including smothering by sediments. New Caledonian lagoons are no exception. The hydrological functioning of New Caledonian rivers is characteristic of high tropical islands, including quick and intense increases in flow.

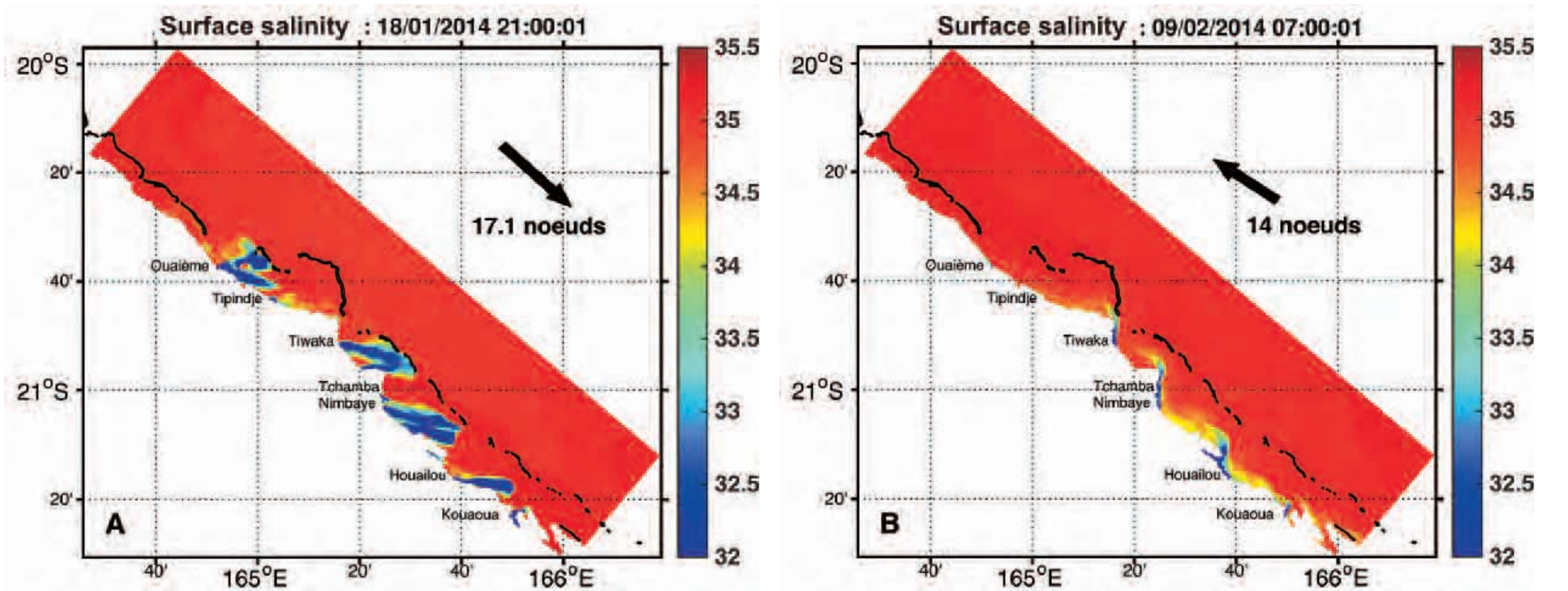
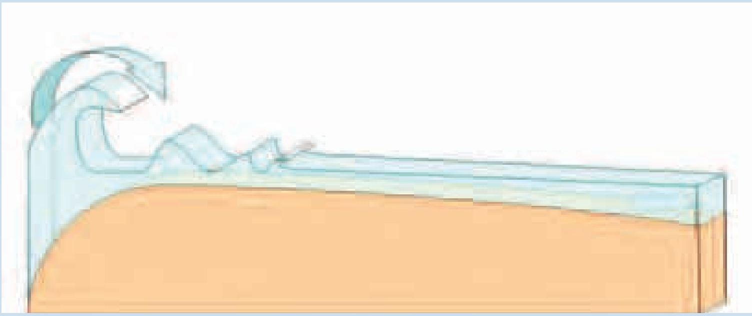


Figure 5: Snapshot of the surface salinity distribution simulated by the MARS3D model (http://wwz.ifremer.fr/mars3d/), in PSU.
A: during the moderate tropical storm, June (January 2014), with northwesterly winds.
B: following a river flood in early February 2014 with trade winds. Only the major rivers have been considered in the model. © IFREMER/R. Legendre

Waves on Grand Récif, Bourail. © P.-A. Pantz

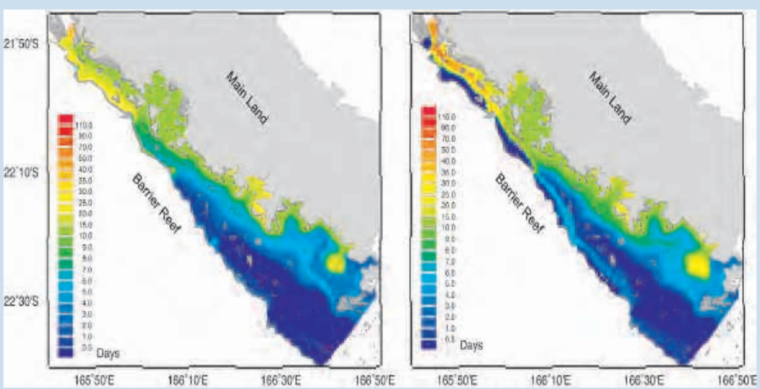
Box 3

Lagoon flushing is forced by waves



Schematic view of waves breaking over the barrier reef.

The barrier reef is higher on the west coast than on the east coast. On the west coast, the reef emerges at low tide and offshore waves breaking on the reef act as a physical barrier, preventing lagoon waters from flowing out, over the barrier reef and instead, offshore waters enter the lagoon. For average waves, this flux is about 0.25 m/s per linear meter of barrier reef (BONNETON *et al.*, 2007). It influences the residence time of lagoon waters, and this is particularly visible in the northern section of the Southwestern Lagoon. With waves, residence time decreases from 25 days to less than a day along the barrier reef, while it increases by the same amount of days at the coast.



Residence time in the Southwest Lagoon. A: Without wave breaking. B: With wave breaking.

The interactions of atmospheric conditions with local topography lead to a significant disparity between the east (wetter) and the west (drier) coast of Grande Terre (LEFÈVRE *et al.*, 2010). According to OUILLON *et al.* (2010), the low-frequency variability of salinity inside the lagoons is mainly driven by the seasons (dry and wet) and, to a lesser extent, by the consequences of ENSO (El Nino-Southern Oscillation). The major processes that more frequently structure the salinity distribution within the lagoons, are winds and river discharges. Hydrodynamic models help in understanding the spatio-temporal distribution of plumes coming out of Grande Terre's many rivers.

Figure 5 shows the spatial extent of those plumes on the east coast, as simulated after two major rainfall episodes. On the east coast, with southeasterly trade winds, the plumes are pushed northward along the coast, whereas, with a northwesterly wind, the plumes propagate eastward and southward towards the ocean.

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