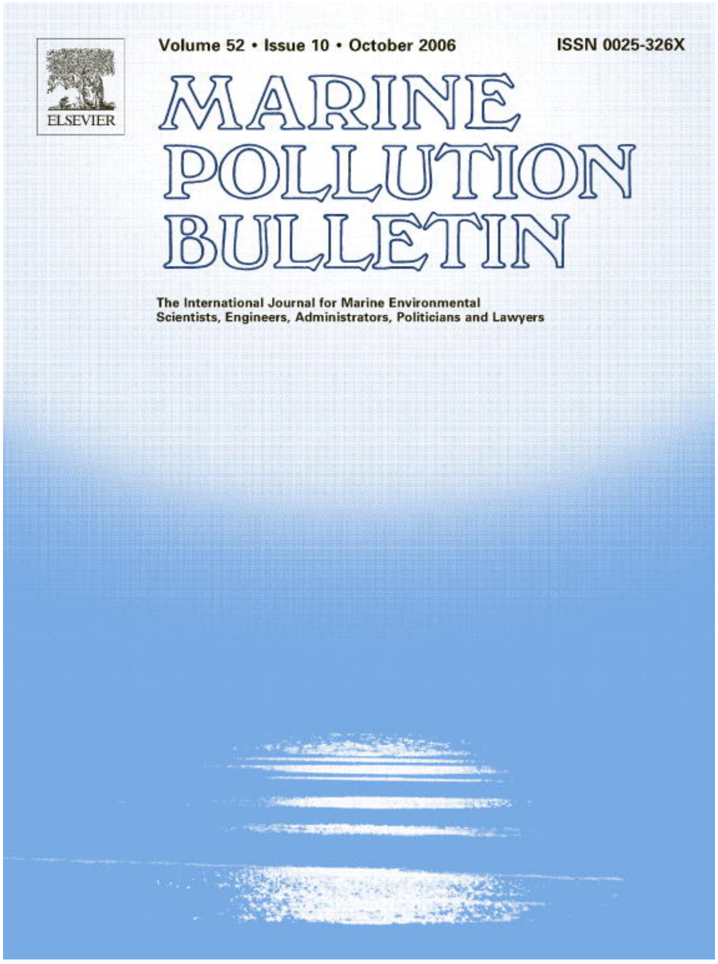
Volume 52 • Issue 10 • October 2006
ISSN 0025-326X
ELSEVIER
MARINE POLLUTION BULLETIN
The International Journal for Marine Environmental Scientists, Engineers, Administrators, Politicians and Lawyers

Available online at www.sciencedirect.com
ScienceDirect
Marine Pollution Bulletin 52 (2006) 1138–1155
MARINE POLLUTION BULLETIN
www.elsevier.com/locate/marpolbul

Review

Review of solutions for 3D hydrodynamic modeling applied to aquaculture in South Pacific atoll lagoons

S. Andréfouët [a,*], S. Ouillon [a], R. Brinkman [b], J. Falter [c], P. Douillet [a], F. Wolk [d], R. Smith [e], P. Garen [f], E. Martinez [g], V. Laurent [h], C. Lo [i], G. Remoissenet [j], B. Scourzic [k], A. Gilbert [a], E. Deleersnijder [l], C. Steinberg [b], S. Choukroun [b], D. Buestel [f]

[a] *Institut de Recherche pour le Développement, B.P. A5 98848 Noumea Cedex, New Caledonia*
[b] *AIMS@JCU, Australian Institute of Marine Science and School of Mathematical and Physical Sciences, James Cook University, Townsville, Australia*
[c] *Hawaiian Institute of Marine Biology, University of Hawaii, Kaneohe, Hawaii 96744, USA*
[d] *Institute of Astronomy and Geophysics, Universite catholique de Louvain, 2 Chemin du Cyclotron, B-1348 Louvain-la-Neuve, Belgium*
[e] *South Pacific Applied Geoscience Commission, Private Mail Bag, GPO, Suva, Fiji*
[f] *Institut Français de Recherche et Exploitation de la Mer, Centre Océanologique du Pacifique, BP 7004, 98719 Taravao, Tahiti, French Polynesia*
[g] *Observatoire Géodésique de Tahiti, Université de la Polynésie Française, BP 6570, 98702 FAAA, Tahiti, French Polynesia*
[h] *Météo France, Direction Inter-régionale de la Polynésie Française, BP 6005 98702 Faa'a Tahiti, French Polynesia*
[i] *Département Recherche et Développement, Service de la Perliculture, B.P. 9047, Motu Uta, 98715 Tahiti, French Polynesia*
[j] *Programmes Aquaculture Cellule Développement, Service de la Pêche, BP 20 Papeete Tahiti, French Polynesia*
[k] *Mission Océanographique du Pacifique, Service Hydrographique et Océanographique de la Marine, SP 9164700260 Armées-Tahiti, French Polynesia*
[l] *Institute of Astronomy and Geophysics and Centre for Systems Engineering and Applied Mechanics, Universite catholique de Louvain, 4 Avenue G. Lemaitre, B-1348 Louvain-la-Neuve, Belgium*

Abstract

A workshop organized in French Polynesia in November 2004 allowed reviewing the current methods to model the three-dimensional hydrodynamic circulation in semi-enclosed atoll lagoons for aquaculture applications. Mollusk (e.g. pearl oyster, clam) aquaculture is a major source of income for South Pacific countries such as French Polynesia or Cook Islands. This aquaculture now requires a better understanding of circulation patterns to improve the spatial use of the lagoons, especially to define the best area to set larvae collectors. The pelagic larval duration of the relevant species (<20 days) and the size of the semi-closed lagoons (few hundreds of km^2) drive the specifications of the model in terms of the spatial and temporal scale. It is considered that, in contrast with fish, mollusk larvae movements are limited and that their cycle occurs completely in the lagoon, without an oceanic stage. Atolls where aquaculture is productive are generally well-bounded, or semi-closed, without significant large and deep openings to the ocean. Nevertheless part of the lagoon circulation is driven by oceanic water inputs through the rim, ocean swells, tides and winds. Therefore, boundary conditions of the lagoon system are defined by the spatial structure of a very shallow rim (exposition and number of hoas), the deep ocean swell climate, tides and wind regimes. To obtain a realistic 3D numerical model of lagoon circulation with adequate forcing, it is thus necessary to connect in an interdisciplinary way a variety of methods (models, remote sensing and *in situ* data collection) to accurately represent the different components of the lagoon system and its specific boundary conditions. We review here the current methods and tools used to address these different components for a hypothetical atoll of the Tuamotu Archipelago (French Polynesia), representative of the semi-closed lagoons of the South Pacific Ocean. We hope this paper will serve as a guide for similar studies elsewhere and we provide guidelines in terms of costs for all the different stages involved.

Keywords: Coral reef; Hoa; Tuamotu; Pearl oyster; Remote sensing; ADCP; Multi-beam; Bathymetry; Residence time; Larval propagation

* Corresponding author.
E-mail address: andrefou@noumea.ird.nc (S. Andréfouët).

0025-326X/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.marpolbul.2006.07.014

1. Introduction

South Pacific atolls have been used for experimental small-scale aquaculture applications for decades, but a real explosion in activities came in the 1980s with the black pearl industry. In a few years, tens of lagoons were used to collect wild animals, capture spats and raise the black pearl oyster *Pinctada margaritifera*. The core of the activities lies in the Tuamotu Archipelago (French Polynesia), but it has also spread to the Society Islands (French Polynesia), Cook Islands and Fiji. In addition, Marshall Islands, Federate States of Micronesia, Tonga, Papua New Guinea, Solomon Islands and Kiribati are all in varying stages of commercialization of cultured pearls (SPC, 2005). The farming of black pearls provides the second largest source of income to French Polynesia, with ~100 millions of US$ per year. In 2004, there were ~600 farms in French Polynesia, occupying ~10,000 hectares of lagoonal surfaces. Some atolls, such as those of the Western Tuamotu (Fig. 1) are covered by farm structures between the surface and 10 m deep (Fig. 2). These lagoons are typically between 80 and 300 km^2, and registered farm structures may cover up to 10% of the area (Fig. 2). It is estimated that 7000 people were employed in pearl farm activities in 2004 (out of a total of 250,000 people living in French Polynesia). In the Cook Islands, 95% of the activity comes from Manihiki atoll which harbored 205 farms in 2003. Pearl exports represent 12 millions US$ in 2000, or in other terms, 90% of the Cook Island export revenue and 20% of the gross domestic product (GDP). Other atolls take advantage of other natural resources, such as clams or trochus, but the economic importance of these cultures/harvests is still several orders of magnitude lower than the pearl industry.

Pearl farming is a difficult activity which is no longer growing in most atolls, and even declining, due to diseases (Cook Islands) or overproduction or poor quality pearls and drop in market sales (French Polynesia). In Tuamotu, pearl farming relies entirely on the ability to collect larvae of *P. margaritifera* (spat collecting) since the natural stock is not exploited, for its preservation. Many farms actually do not grow pearls, but just collect and grow oysters that are sold to other farmers. The success of spat collection appears highly variable in space and time (Fig. 3) even in these small lagoons which are partially closed by a shallow reef rim with numerous emergent islands thus limiting their connectivity with the surrounding ocean. It is therefore a high priority for the management of the black pearl

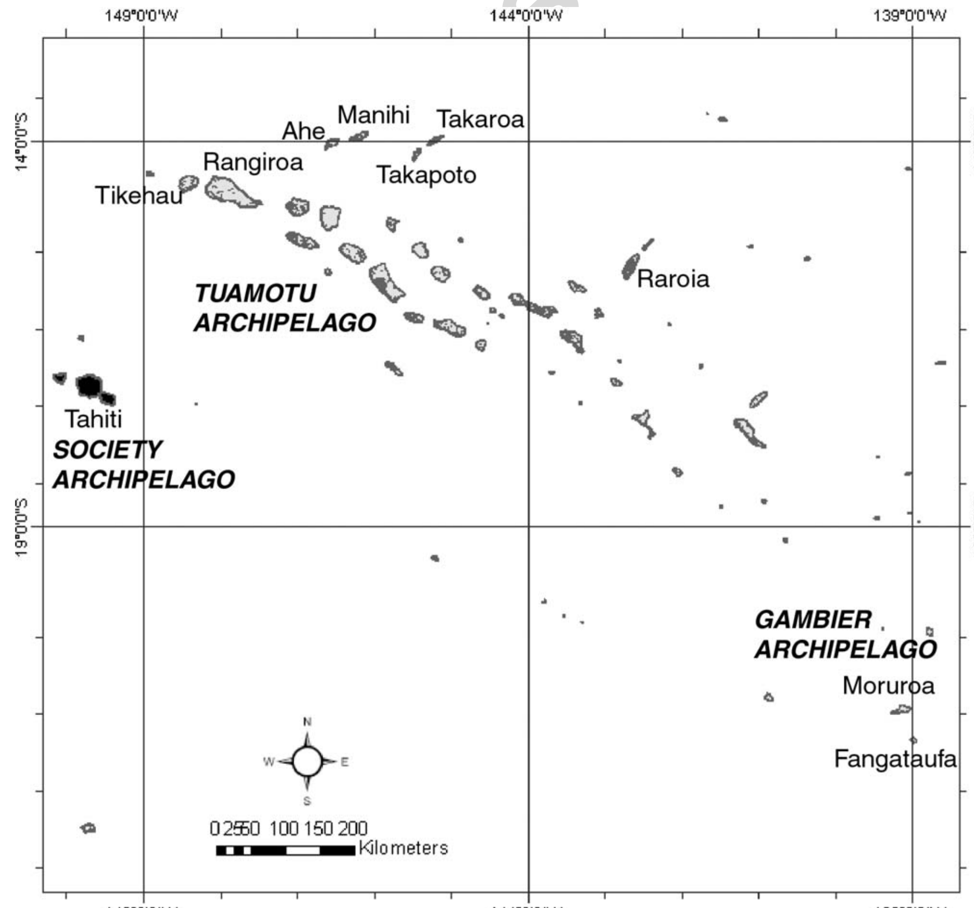

Fig. 1. The Tuamotu archipelago with location of the atolls quoted in the paper: Ahe, Fangataufa, Manihi, Moruroa, Takapoto, Tikehau, Takaroa, Rangiroa, Raroia.

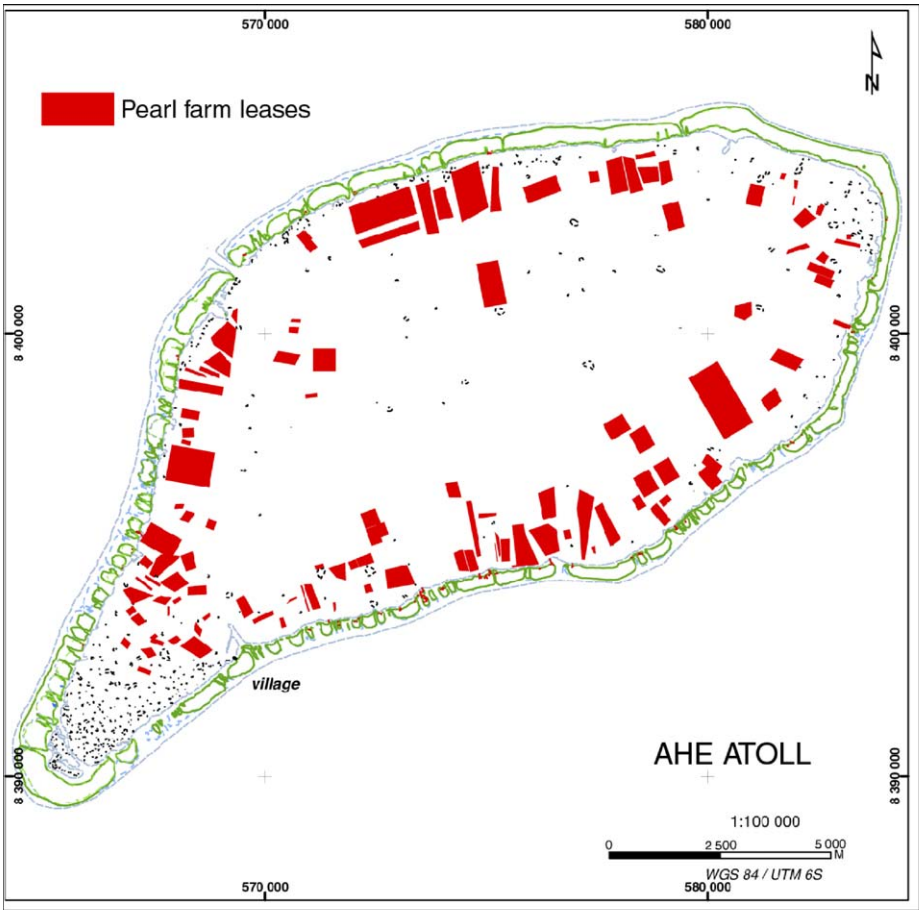

Fig. 2. Pearl farm leases in Ahe atoll (Western Tuamotu, French Polynesia) as in September 2005 showing the high density of pearl farms and larvae collectors throughout the lagoon.

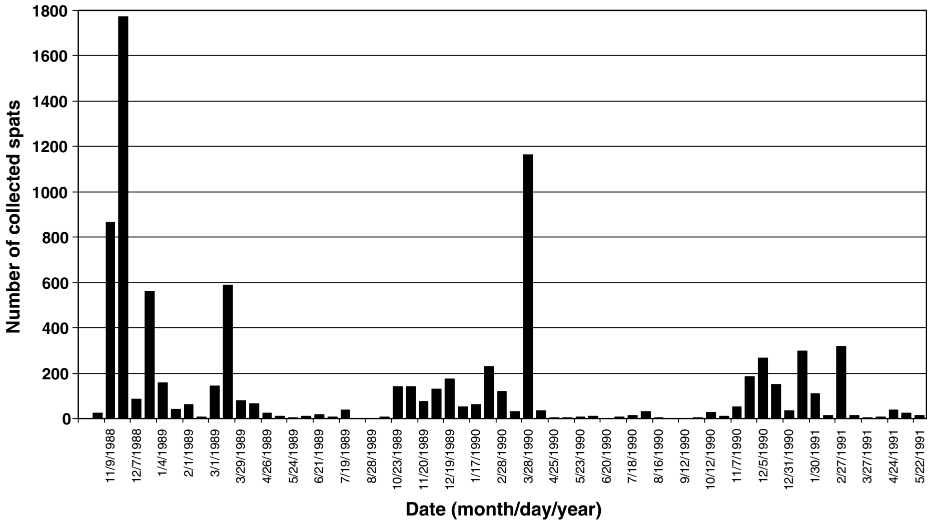

Fig. 3. Time-series of spat collecting in one location of the lagoon of Takapoto atoll (Western Tuamotu) over a three-year period (from Brié, 1999).

industry to enhance the understanding of larval propagation within a lagoon, understand the physical factors explaining the spatial and temporal variability of larval recruitment, locate the best collecting sites, and identify the best periods for spat collecting. It is timely to apply well-constrained 3D numerical circulation models, and not just rely on the past experience and empirical knowledge of farmers who often got unpredictable and sporadic success rates from one year to another. Indeed, numerical models can account for many of the important forces driving lagoonal circulation and exchange (i.e. bathymetry, wind, waves, tides, and stratification), and identify which are the most important variables governing the dynamics of a given lagoon (e.g. Nihoul, 1984; Blumberg and Mellor, 1987; Lazure and Salomon, 1991; Davies and Lynch, 2005).

This review describes the current state-of-the-art to design well constrained 3D model useful for aquaculture applications. The information comes from a workshop organized in Tahiti (French Polynesia) in November 2004 to discuss these issues. We focused on the type of atolls that are encountered in the South Pacific (specifically the Cook Islands and Tuamotu archipelago) and where black pearl farming is the most developed. We reviewed the physical processes that drive lagoonal circulation and how these processes have been modeled and measured in a variety of places. Then, we estimated the costs of implementing a 3D numerical model, calibrate and validate it for an atoll representative of the Tuamotu archipelago.

This paper digests the information provided during the workshop to raise managers' awareness of the benefits, technology involved and associated costs to conduct a 3D modeling exercise in their atoll lagoons.

2. Overview of a Tuamotu atoll

A Tuamotu archipelago atoll is made of three seascapes: the lagoon, which is bounded by a shallow rim, which is itself surrounded by the deep Pacific Ocean (Fig. 4). On top of the marine systems, we need to consider the atmospheric forcing for circulation and for air–sea energy transfer purposes.

The main object of interest are atoll lagoons, where aquaculture activities take place. They are generally saucer-shaped basins, reaching ~70 m in its maximum depth, but average depth is closer to 20–30 m (Andréfouët et al., 2001a). They are frequently dotted by coral patches that reach vertically to the surface (pinnacles), thus the fine-scale topography may be complex in places. Lagoon bottoms are generally dominated by fine carbonate sediment, but areas with significant coral and algal cover (carpets and massive patches) are frequent, especially on the shallow inner slopes. A narrow inner reef flat of coralline algae and coral may bound the lagoon. Sediments get coarser in the shallows, with rubble and boulders in the vicinity of the channels that connect the lagoon with the ocean through the rim of the atoll.

These channels (called *hoa* in Polynesian) are narrow spillways (a few tens to hundreds of meters wide) or large reef flats (up to few kilometers wide) that interrupt and cut the "land" or *motu* in Polynesian. Motus are few meters high carbonate deposits over fossile terraces of coral conglomerates that are frequently colonized by vegetation. The result is a landscape made of small islands and hoas along the atoll rim. Deeper passes through the rim may exist in Tuamotu and Cook Island atolls. They are generally narrow (few tens of meters) with a few meters depth in its shallowest part. Areas with frequent strong current (passes, functional exposed hoas) may be free of any living

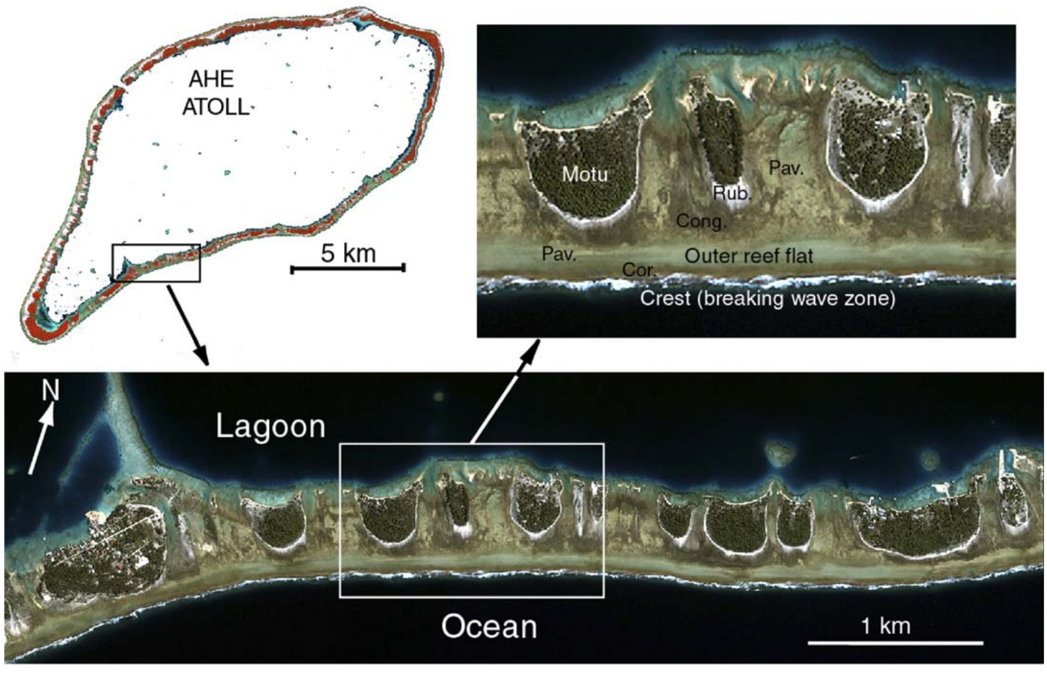

Fig. 4. Ahe, an atoll of the Western Tuamotu archipelago showing its lagoon bounded by a semi-closed rim with numerous hoas and motus. Images of the entire atoll is a Landsat 7 ETM+ image at 30 m-resolution, the image of the rim is a merged panchromatic-multispectral IKONOS image at 1 m-resolution (© Space Imaging). Details in distribution of different facies and bottoms along the rim are readily visible including erosion areas (Cong: conglomerate), deposits (Rub: rubbles), smooth pavement areas (Pav.), and coralline crests (Cor.).

cover, with only a bare carbonate pavement. In addition, some atolls of the western Tuamotu have been locally uplifted by tectonic processes (lithospheric flexure due to Tahiti island mass), from few centimeters to few meters (Pirazzoli et al., 1988). Exchanges of water through these uplifted rims are less efficient than elsewhere.

3. General circulation features of semi-closed atoll

The renewal of lagoon waters can be described generically, but what is really happening along the rim of any given atoll depends on its rim morphology, orientation, swell regimes, tides, and presence of passes or not (Tartinville et al., 1997; Kraines et al., 1999; Andréfouët et al., 2001a; Callaghan et al., 2006). The generic mechanisms are: (1) waves due to wind or swell break at the reef edge (crest) and bring water to the exposed outer rim reef flat. The basic physics is that when waves break at the crest, a radiation stress gradient (set-up on the reef flat) is created that forces water across the reef lagoon-ward (Longuet-Higgins and Stewart, 1964; Tait, 1972); (2) this water also crosses the hoas towards the lagoon; (3) lagoon water in excess gets evaporated, or may be evacuated by the passes during low tides, or may be evacuated by gravity draining water through the hoas opposite to incoming swell direction if the lagoon set-up is high enough (Callaghan et al., 2006), and if there is no pass.

The actual dynamics and equilibrium of all these processes depend on the magnitude (significant wave height) and direction of the swell, tide magnitude, number of hoas (degree of aperture of the rim), and size of the passes. For instance, during high swell and high lagoon set-up, the pass flows can be only directed outward even during incoming tides. Furthermore, tidal flow through small passes have little effect on circulation because the incoming water does not penetrate far on the flood before the tide changes to an ebb. Lenhardt (1991) showed that oceanic water remained only within a 1 km-radius zone around the pass of the Tikehau atoll lagoon which covers an area of 394 km^2. Mixing between ocean and lagoon waters is thus only very limited, except for atolls with very large passes (e.g. Moruroa atoll studied in Tartinville et al., 1997). Further, we will consider that our hypothetical targeted atoll has a narrow pass, but the real specificity of semi-closed atoll hydrodynamic functioning is the control exerted by the hoas (see Section 7).

Circulation within deep lagoons is usually dominated by wind stress at the surface, which generates a downwind flow at a few percent of wind speed (2–3% in Von Arx, 1948; Atkinson et al., 1981; Tartinville et al., 1997) in a 10–20 m depth layer with slower reverse flows in the deeper water that is directed to the pass if there is one. In the case of Moruroa lagoon, using an idealized simplified model and a 3D model, Mathieu et al. (2002) have studied how wind stress, pressure gradient and bathymetry combine to shape the vertical distribution of velocities, i.e. when velocities is maximum, minimum and reverse. However, in very shallow lagoons, the two-layer system may not develop, and in extreme cases circulation can be driven entirely by inflow over the reef flat from wave-overtopping and flow out through reef gaps, with little wind or tidal influence. For small and shallow lagoons, density differences due to evaporation and precipitation may induce density-driven circulation between ocean and lagoon. Within a given lagoon, similar processes may occur, however thermal and salinity differences are small on most large lagoons, with limited diurnal variation (see review in Andrews and Pickard, 1990). Vertical stratification is generally weak in atolls, with small gradients in temperature and salinity (Atkinson et al., 1981; Kraines et al., 1999), but very calm oceanic and atmospheric conditions may lead to stratification and even anoxia and mass mortalities of lagoon organisms (Adjeroud et al., 2001). Under normal forcing, differences in temperature have reached 0.5 °C for the 60 m deep Eniwetok atoll (Atkinson et al., 1981). Short term, local thermoclines can develop in the vicinity of the passes due to the entrance of cold waters during incoming tides as reported by Farrow and Brander (1971) for the shallow Aldabra atoll in the Indian Ocean. In this case, the water is brought from below the oceanic thermocline during the early flood, but the waters are then quickly mixed afterward.

According to studies published from other sites, the moderate depth and semi-closed status of Western Tuamotu atolls suggest that circulation forcing can be dominated by either winds or waves. Lagoon stratification, albeit weak, needs to be captured for an optimal model, which means that sea surface temperature (SST) needs to be known at the external boundary limit. Therefore, proper modeling of lagoon dynamics requires precise characterization of the atoll rim structure, lagoon and hoa bathymetry, wind direction and speed, swell direction and height, and oceanic and lagoon SST.

4. Aquaculture constraints on circulation modeling

In our case, the necessities of black pearl aquaculture drive the specifications of the circulation model. The model needs to be parameterized to capture the spatial–temporal variation of larval propagation and settlement. If we consider the black pearl oyster problem, current studies in Takapoto atoll (see Fig. 1) allows defining these scales. An experiment conducted on undifferentiated bivalve larvae including two species of oysters (*P. margaritifera* and *P. maculata*) in 2004 provided maps of lagoon larval densities throughout a spawning event (Fig. 5). Larvae were monitored *in situ*. These maps suggest that a spatial resolution of 100–200 m is required to capture the spatial variability in larval distributions. In addition the pelagic larval duration (PLD) for these species are typically 20–21 days. Thus, the model needs to accurately simulate the path of passive drifters released from the bottom (natural oysters) or from the water column (farmed oysters hanging on lines) at time scales no longer than one day. A

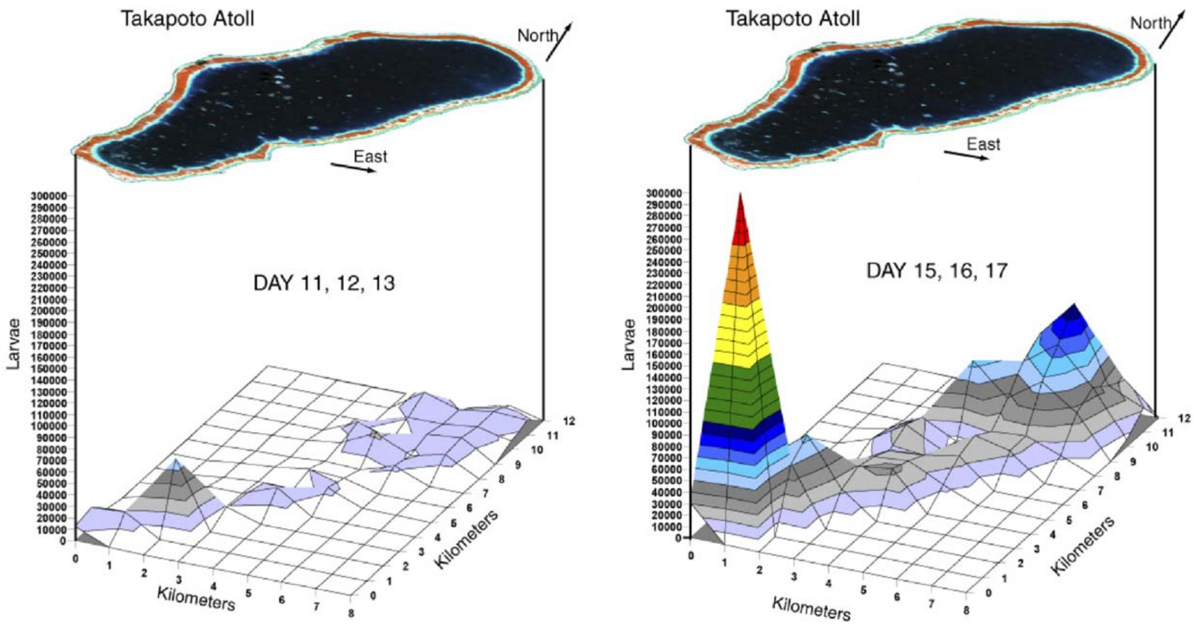

Fig. 5. First data on larval propagation of undifferentiated pool of two oyster species from *in situ* monitoring around a spawning event in the Takapoto atoll lagoon. The left panel shows census just before the spawning which occurred in the north of the lagoon. The second panel shows where the larvae have accumulated after three days. Data for D-larvae development stage (70 μm). Census were achieved along a 1 km-grid size. Patterns of accumulations are clear at the scale of the lagoon, but the 1 km resolution is too coarse to capture the fine distribution of the larvae. Workshop discussion suggested that a resolution of 100–200 m would be optimum.

parameterization of the oceanic forcing integrated over three-days or one week would be inadequate. Forcing factors (swell, SST, wind and flows through hoas and passes) need to be characterized at least daily, and preferably at higher rates. For instance, the tradewinds that are dominant in this area show diurnal/nocturnal variations, and the tides can significantly modulate the wave-driven flows across the atoll rim in case of moderate swell (Laurent et al., 2004).

P. margaritifera spawning periods are variable in Western Tuamotu. It is acknowledged that oysters spawn throughout the year in Takapoto atoll, but there are significantly more spawning events in February–March and September–October, during the change of seasons (Pouvreau et al., 2000). The black-pearl oyster is the target of choice for aquaculture, however, other benthic resources are now considered for farming, including giant clams (*Tridacna maxima* for Tuamotu) and trochus (*Trochus niloticus*). Giant clams are in high demand not only for their meat but also for the aquarium trade. On-going experiments for giant clam collecting seem to be very successful, but in atolls that are different than those that well-suited for oyster farming. Shallow (average ~10 m deep) and small (<50 km^2) atolls in the Eastern Tuamotu are the most interesting because of their impressive clam densities (Andréfouët et al., 2005; Gilbert et al., 2005). Knowledge of circulation is for the moment less of an issue for the management of clam resources in small atolls. Nevertheless, it could be more of a priority if other atolls launch aquaculture activity with a more limited natural stock to start with. The PLD for giant clams is 7–10 days while the PLD for trochus is even shorter – from 3 to 5 days. (Jameson, 1976). Spawning of giant clams also occur throughout the year, but seems to be triggered by thermal stress due to colder oceanic water inputs into the lagoon.

5. Bathymetry

Accurate bathymetry is the primary information required to build a model. However, *in situ* discrete sounding from occasional ships are generally too spatially sparse to obtain after interpolation a useful grid for a model, except near the area where detailed hydrographic surveys may exist (passes, navigation channels). To achieve high resolution bathymetry at the model scale of interest, two options are recommended. First, interpretation of optical remote sensing images may provide a first cut on the bathymetry with reasonable accuracy. However, this technique is limited to shallow clear waters. Since the late 80s, the French hydrographic survey office of the Navy (SHOM) has released atoll spacemaps where bathymetric information derived from SPOT satellite is provided in 4 classes of depth, with 5 m intervals. The theoretical limit for super clear waters over a bright bottom is ~40 m for nadir viewing satellites (Philpot, 1989). In atoll lagoon waters that have higher diffuse attenuation coefficients (Maritorena and Guillocheau, 1996), the technique still works to a depth of ~25 m, but provides only a relative bathymetry. More severe limitations occur if the bottom is dark (coral, algae) (Philpot, 1989). If ground-truth data exits, it is possible to calibrate the optical models (empirical or semi-analytical) more accurately to obtain actual depth in meters. Even if published papers have advertised excellent results in controlled situations (small area, clear waters, homogeneous bottom-types), as a rule of thumb, it is necessary to consider a RMS error of 10% of the maximum depth (Andréfouët et al., unpublished data, based on Great Barrier Reef data).

The second option of choice for measuring bathymetry is by acoustic survey. This technique can not be applied in very shallow waters, but optical data can fill the gap to obtain a complete image. Several atolls of the Cook Islands have been recently mapped with high-resolution swath mapping, using multi-beam echo sounders (Fig. 6). Those are able to map a complete underwater landscape in a fraction of the time than is currently required by a single beam echo sounder, and with much greater accuracy. Computer-processing of swath mapping data reduces complex data sets to three-dimensional visualisation images that represent, in fine detail, the morphology of the seafloor, as well as occasional wrecks and other peculiar features. Range is frequency dependant and the precision is tremendous, with for instance individual lines of pear-oysters hanging on their stations visible on the data.

6. Characterization of oceanic and atmospheric forcing at the day scale

Aquaculture applications call for high temporal resolution forcing data to track the dispersal of larvae from spawning to settlement. The forcing factors are primarily the wave regime around the island, due to local wind and oceanic swell generated in higher latitude seas. Then, the filter due to the structure of hoas and presence of passes needs to be described (next section). Oceanic SST is required to correctly solve lagoonal stratification. Finally wind is a key forcing factor for lagoon surface drift and circulation. Climatology of *in situ* or remotely sensed weather measurements is available and useful to predict an average picture of the lagoon circulation. Although there are many sources available, here we refer only to the products and software used in French Polynesia institutions. The World Ocean Atlas provides a monthly climatological coarse 1 degree resolution compilation of *in situ* data such as temperature, salinity, nutrients and geostrophic (large-scale) velocities. They can be complemented by higher resolution regional circulation model data, such as the Regional Ocean Model System (ROMS, http://marine.rutgers.edu/po/index.php?model=roms) (Fig. 7). This model allows to focus on a small area and to reach a very high spatial and temporal resolution. For instance Marchesiello et al. (2003) worked at 3.5 km resolution. Other model products used in French Polynesia include wind field products (provided at 10 m altitude, which is standard requirement in oceanography) from the European Centre for Medium-Range Weather Forecasts (ECMWF v1.5, http://www.ecmwf.int/) and the Météo-France numerical weather prediction model ARPEGE v1.5. One drawback of all these models is that they lack calibration around coastlines, including oceanic atolls.

Swell Significant Wave Height (SWH) can be provided regionally by altimetry space missions (ERS-1, Topex, Jason), and wind speed and direction can be obtained by spaceborn scatterometers (e.g. NSCAT, Quickscat). They also provide sea surface currents and anomalies. These are primary and convenient sources of information since data are available for anywhere on the tropical belt through different web-accessible data centers. Individual altimetry satellites have poor temporal resolutions, but different sources can be combined to fill the gaps. In addition,

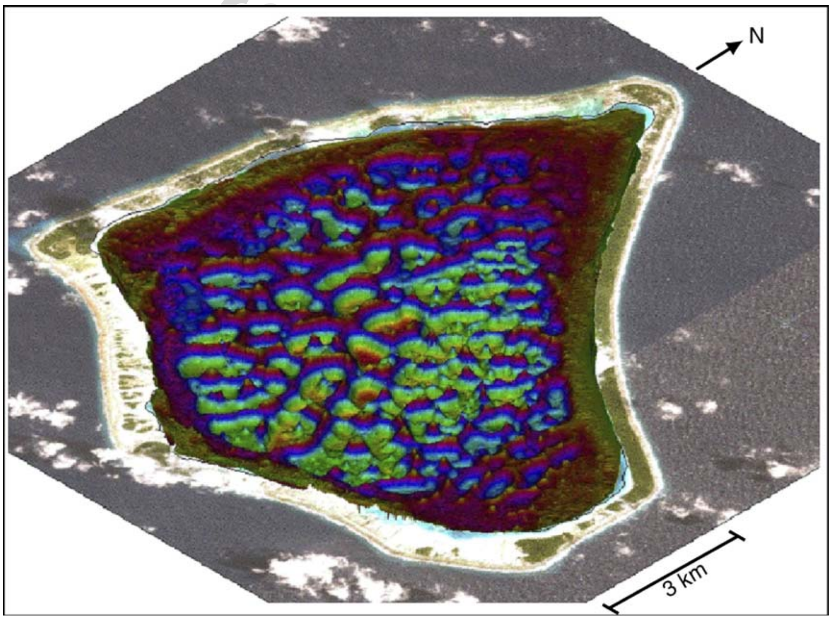

Fig. 6. 3D output of a 5 m-resolution bathymetric model from a SeaBat 8101 Multibeam Echosounder survey of Manihiki (Cook Island), overlaid on satellite image. The sounder had 101 beams operating at 240 kHz, with a swath width at 150° or 7.4× the water depth.

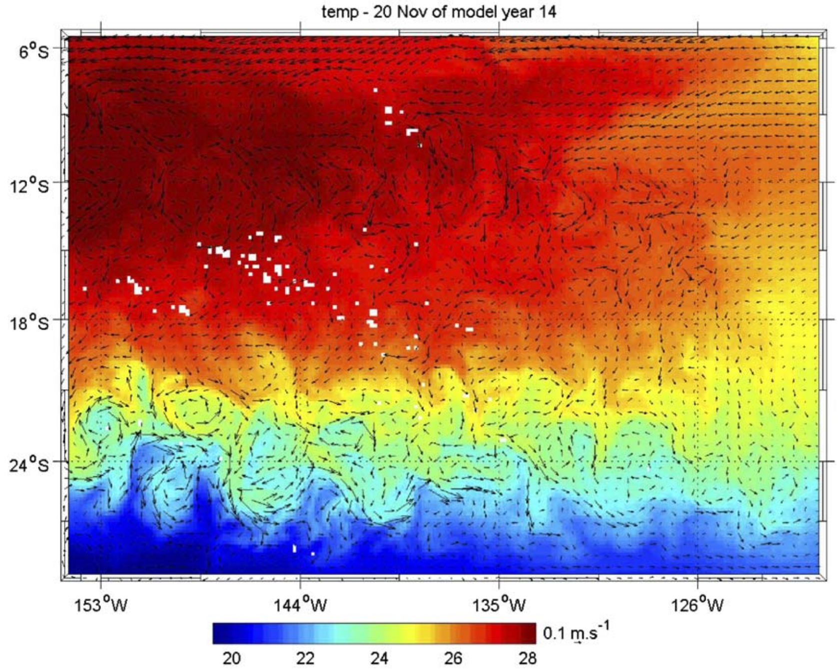

Fig. 7. Example of SST and current velocities output from ROMS model for French Polynesia.

by considering a large neighborhood (500 km radius) around one point of interest, it is possible to obtain daily remote sensing measurements. These spatially integrated measurements prove to be useful to establish relationships between SWH and water velocities and fluxes at a daily time scale in exposed hoas from a variety of Tuamotu atolls (Tartinville and Rancher, 2000; Andréfouët et al., 2001a). Altimeter data are able to capture short-term weather events (high swell or high winds, not to mention hurricanes) which can last only few days (see the abrupt passage of a southern 3 m swell in the time series of altimetry data in Andréfouët et al., 2001a). Such short-terms events are most likely to be extremely relevant to explaining the variability of spat collecting success across time.

Ocean–atmosphere interactions are investigated in different areas of the Pacific Ocean using the Weather Research and Forecasting model (WRF, http://wrf-model.org/index.php). Combined with models such as ECMWF, they allow modeling the atmospheric circulation at the kilometer-resolution. Wind and exchanges and the air–sea interface can thus be taken into account in the ocean, but also in the lagoons given the spatial resolution.

In both French Polynesia (FP) and the Cook Islands, the availability of weather data from models and remote sensing information is completed by an array of *in situ* observations, which is still the primary source of information for local weather forecasters. Shipborne observations are compiled in FP to quantify sea state and swell direction. There are a number of meteorological stations, including two in Western Tuamotu (Takaroa and Rangiroa atolls, Fig. 1) which provide a time-series of wind observations since 1951. Given the minimal impact of relief on the wind regime in atolls, these observations would be more than adequate to constrain at high temporal resolution the circulation model. *In situ* data are scarce but nonetheless help validate the model output, or point to model limitations and errors close to coastlines. For instance, models seem to overestimate the western swell when compared to ship data.

The Cook Islands opted for buoys to monitor their lagoons. In Manihiki lagoon, it measures air temperature, barometric pressure, wind direction and speed, and also sea-surface temperature, and salinity as well as dissolved oxygen, chlorophyll and pH. It is instrumented with a multichannel cosine irradiance and a profiling spectroradiometer. Data is transmitted in a daily report via satellite phone to the offices of the South Pacific Applied Geoscience Commission (SOPAC) in Fiji where a monthly report is compiled and sent back to Cook Island. These sensors are expensive (see Section 10.8) and require maintenance, but their use goes beyond just circulation modeling. They are used to monitor potential stresses and anomalies in the water column, and send warning signals to the community of pearl farmers (http://www.sopac.org/tiki/tiki-index.php?page=Cook+Islands+Manihiki+Buoy).

7. Wave-driven flows across the reef flats and hoas

The geomorphology of the rim is the most defining characteristic of atolls. A "typical" Western Tuamotu atoll rim will have an outer reef flat that follows almost the entire periphery of an atoll (Fig. 4). The hoas oriented perpendicular to the rim crest allows the exchange of waters from the exposed outer reef flat to the lagoon. Variations on this theme have been conceptualized by Chevalier (1972) who proposed a typology of hoa and hoa development. The number of hoas, their width, their depth, their degree of uplifting (relative to mean sea level) and their bottom types, are all factors that need to be quantified in order to accurately estimate flows within the hoas under varying swell and tide. One of the difficulties in modeling hoa flows is that the entire system is dynamic. Hoa's width and depth are not stable and vary constantly and quickly with the wave set-up of the exposed outer reef flat. At low tide, during low swell, and depending on the level of sediments accumulated (Kench and McLean, 2004), most of these hoas may not be functional while the rim may be almost entirely submerged during high swell events. The ratio of opened sections between low swell and high swell conditions can be as much as ten (Andréfouët unpublished data) in some Tuamotu atolls. It is possible to define an average flooding situation useful for classifying atolls in term of renewal rates regimes (Andréfouët et al., 2001a), but fine descriptions are required to accurately estimates the fluxes on a daily basis.

High resolution satellite imagery such as those provided by IKONOS (4 m resolution), and Quickbird (2.5 m) sensors would be adequate to quantify rim geomorphometrics. Those sensors, and the SPOT 5 sensor as well, also offer products that merge panchromatic and multispectral spectral bands providing visually impressive 1, 0.6 and 2.5 m resolution for IKONOS, Quickbird and SPOT respectively. Merged panchromatic-multispectral data are not recommended for mapping at depth (5–20 m), but for shallow (<3 m) hoas and rims these products are useful. Images actually provide the only feasible way to obtain rim bathymetry since most hoas would be too shallow for acoustic surveys. To our knowledge, only Yamano et al. (in press) have characterized atoll rim geomorphology with IKONOS data, but focusing on waterline extraction only. Coarser space-borne data have been used to characterize rim types (Andréfouët et al., 2001b, 2003), but we suggest that excellent characterization of the variation of water levels, bottom-types, conglomerates and sediments locations can be done using the new high resolution images (Fig. 4). The merit of image-based rim quantification and interpretation would be to identify the variety of hoas present in one atoll in order to obtain *in situ* measurements for all the different hoa configurations, and measure their efficiency in terms of water transport, or sediment transport (Kench and McLean, 2004). Then, images will help in generalizing spatially *in situ* current velocities data for each type of hoa present to up-scale local flow measurements at rim-scale. It is worth noting that if no images are available, it is also possible to apply labor-intensive and low-tech survey techniques, that local inhabitants could even learn to help out in the surveys.

To our knowledge, there are no time-series of *in situ* current measurements in Western Tuamotu hoas except in Tikehau atoll (Lenhardt, 1991). Current meter data exist for Eniwetak in Marshall Islands (Atkinson et al., 1981), Fangataufa and Moruroa (Delesalle, 1990; Tartinville and Rancher, 2000) in the south-east Tuamotu, Cocos (Keeling) Island in the Indian Ocean (Kench and McLean, 2004). However, there are more studies on barrier reef flats, which may be considered as very wide unbounded hoas between the ocean and lagoon (e.g. Hardy and Young, 1996; Lugo-Fernández et al., 1998; Lowe et al., 2005; Kench and Brander, 2006). Symonds et al. (1995) provide for a schematic reef flat a formulation of the cross-reef velocity u following:

$$\begin{aligned} u &= \beta H(h_b - H) \quad \text{if } H < h_b \\ u &= 0 \quad \text{if } H > h_b \end{aligned}$$

where H is the depth over the reef flat, h_b is the total water depth at the wave breaking point, β is a function of the geometry of the reef flat (outer slope, flat width, coefficient friction. $\beta = 0.5$ for Moruroa atoll in Tartinville et al., 1997). This definition of u is important because it provides a link with Significant Wave Height (SWH) from satellite measurements at daily scale. Indeed, H_b is proportional to wave height with $H_b = \text{SWH}/\gamma$, ($\gamma = 0.35$ in Symonds et al., 1995). Using some reef geometry-dependant tuning, it is possible to develop from altimetric SWH the flows of current on reef flat (Tartinville and Rancher, 2000; Andréfouët et al., 2001a). The Symonds et al. (1995) model was confirmed in atoll hoas by Tartinville and Rancher (2000). Other wave-driven flows models have also been proposed to include more types of reef configurations (Hearn, 1999; Massel and Brinkman, 2001), including for steep reef faces (Gourlay and Colleter, 2005). The reef flat model by Kraines et al. (1998) was able to include wave refraction behavior, and was implemented to model the boundary conditions of Majuro atoll (Kraines et al., 1999).

Symonds et al. (1995) model is satisfactory for atolls for day-scale previsions, but β is dependant on reef flat geometry (slope and width) and cover type (friction). For fine predictions in time and space, it will require local calibration around the part of the atoll exposed to waves. Reef flat width can be easily computed for any point of the rim (from high resolution satellite images), outer slope profiles could be also estimated using high resolution images and combined with the models linking outer slopes geometry and reef set-up (Gourlay, 1996). Coefficient friction C_f is a factor controlling wave energy dissipation across reef flats. Friction due to bottom roughness can be as important as the turbulent breaking wave process for energy dissipation (Lowe et al., 2005). As in Tartinville and Rancher (2000) or Kraines et al. (1999) friction can be assumed and set empirically to study wave-driven currents. Hoa-scale integrated measurements of flows would be adequate for questions regarding the net flows of water entering the lagoon, but understanding the relative role of wave breaking and friction on energy dissipation would be also relevant for biogeochemical studies on nutrients uptakes and productivity of the different living communities across the flat. Using a series of pressure sensors and current meters deployed along several cross-reef transects on Kaneohe Bay Barrier Reef flat in Hawaii, Falter et al. (2004)

obtained an average $C_f = 0.22 \pm 0.03$ over coral-algal reef flats. Similar magnitudes were previously reported by Gerritsen (1981) for Ala Moana reef flat in Hawaii ($C_f = 0.28 \pm 0.05$), and by Nelson (1996) for John Brewer Reef in Australia ($C_f = 0.15 \pm 0.04$).

Observing in Manihiki atoll, an atoll without pass, that water level gradients were generally sloping down from the lagoon into the ocean at all tidal phases during three weeks of observations, Callaghan et al. (2006) proposed for Manihiki atoll a wave-pumping analytical model (Nielsen et al., 1999) considering lagoon-scale wave-driven flushing in the case of closed lagoons (no passes). Integration of flows around the part of the atoll exposed to waves explained lagoon-levels variations for two tidal cycles and thus inflows estimated with this approach could be used at smaller time-scales than days. The main deficiency with this model is involved with defining the wave pump efficiency (or wave energy flux), but in contrast with Symonds et al. (1995) it avoids partially the nearshore geometrical complexities, the assumption of a saturated surf zone and applying linear wave theory were it breaks down. Thus far, the atoll wave-pumping model is only validated considering lagoon-scale measurements (i.e. prediction of lagoon level variance). Though not yet demonstrated, we suggest that for lagoon circulation modeling which require spatially explicit input along the rims, the wave-pumping model will provide, at day scale, a correct estimate of inflows per hoa mouth if the model is applied on the rim section drained by the hoa. In the case of closed atoll without passes, or if the passes sections are too small to efficiently drain the excess lagoon water, Callaghan et al. (2006) suggest that two different boundaries are required within the 3D model. First, a wave driven inflow boundary where water is driven into the lagoon by waves (models discussed above). Second, a gravity driven outflow boundary is required to account for flows from the lagoon towards the ocean though hoas leeward of incoming wave, when lagoon levels are higher than ocean levels.

8. Flows through the Tuamotu passes

Modeling studies have been conducted in both Majuro and Moruroa atolls (Kraines et al., 1999, 2001; Tartinville et al., 1997), both containing passes. However, Moruroa'pass is atypical of Tuamotu's due to its great width (5 km). The narrower passes of Majuro make it more representative of Western Tuamotu atolls despite its location in the Marshall Islands, although Majuro's passes are much deeper. If swell wave-driven flows are totally absent due to very calm oceanic and atmospheric conditions (an unusual situation in the Tuamotu), the tide is the main forcing factor of water exchanges through the pass. All *in situ* observations worldwide confirm this (Farrow and Brander, 1971; Michel et al., 1971; Smith and Jokiel, 1975; Atkinson et al., 1981). In Western Tuamotu region the tide amplitude is small, about 15 cm, with the M2 mode (principal lunar) being the major tidal constituent (Lenhardt, 1991).

There are several series of current measurements inside Tuamotu passes, mostly performed by SHOM. A Raroia atoll (Fig. 1) example is provided in Pagès and Andréfouët (2001). It shows well that outgoing flows are most of the time positive, and only calm seas let the tide control the process with oceanic water going lagoonward. The outgoing flux during high seas reached 4 m s^{-1} in Raroia. Lenhardt (1991) also recorded currents in the northwest oriented pass of Tikehau atoll but the mechanical device used to perform the measurements was judged unreliable above 1 m s^{-1}.

To our knowledge, atoll passes have not been specifically modeled at high spatial resolution. Instead, they have been integrated in coarse resolution 3D circulation models as in Kraines et al. (1999) or as part of the model boundary (Tartinville et al., 1997). However, similar features found along continental barrier-island coasts have been modeled using high-resolution (down to 50 m) finite-element models (Hench and Luettich Jr, 2003), in an idealized situation first, and then for an actual inlet of North Carolina, USA, with similar proportions as Tuamotu atoll passes (5 m depth, 0.5 km length, 1 km width). The high resolution model show many topography-dependant local processes (e.g. flow separation zones). Similarly as for cross-reef current along the hoas, the pass can be included in the general model and be part of the boundary of the lagoon system, or, passes and lagoon-ward vicinity of the pass can be an object of focus in itself. The sub-kilometer variability observed around inlets call for a fine modeling of atoll passes to be able to predict small-scale features that may be critical for larval propagation or retention.

9. Types of 3D models and review of past and present atoll applications

The number of available 3D models is actually quite high and numerous options are available to the practitioners. Table 1 lists some of them, with their main characteristics. More details can be found for each model on web sites and users forums, and we highlight below the 3D models previously used for reefs and atolls.

The review of existing 3D circulation models applied to true atolls is brief. Only, Moruroa and Majuro atolls have been studied with finite-difference models (Tartinville et al., 1997; Kraines et al., 1999), and one finite-element model for Rongelap atoll in Marshall Islands is currently under development (Peterson et al., 2006). Moruroa has been the target of many nuclear tests since the 60s and the primary application of the model was to predict the fate of potential dissolved radioactive pollutants (Tartinville et al., 1997). Residence times and particles trajectories were computed under different forcing conditions (Fig. 8). Another atoll targeted for nuclear testing, Fangataufa has been also investigated but the results have remained largely unpublished. In Majuro, the model was used to assess how the artificial closing of the southern part of

Table 1
Main characteristics for existing 3D models

	Vertical discretisation	Horizontal discretisation	High-order turbulence closures	Drying/flooding	Public domain
MOM-4	z	CU	N	N	Y
POM	s	CU	Y	N	Y
ROMS	s	CU	Y	N	Y
POL3DB	s	CA	Y	N	Y
GHER-M	2–σ	CA	Y	N	Y
COHERENS	σ	CA	Y	N	Y
TRIM-3D	z	CA	N	Y	N
MIKE-3	z	CA	Y	N	N
TELEMAC-3D	σ	FE	Y	Y	N
ECOM	s	CU	Y	Y	Y
MOHID	s	CA	Y	Y	Y
GETM	s	CU	Y	Y	Y
MARS3D	σ	CA, CU	Y	Y	Y
SHOC	s	OCU, CA	Y	Y	N

Extended from http://www.bolding-burchard.com/html/GETM/history_and_outlook.htm which also provides links to other oceanic models. Abbreviations used: z = z-level, s = general vertical coordinates, σ = sigma coordinates, CU = curvilinear, CA = cartesian, FE = finite elements, OCU orthogonal curvilinear.

the atoll with roads and walls have changed the renewal rates of the lagoon (Kraines et al., 1999). Abaiang atoll (Kiribati) was studied with Mike21, a 2D model, to investigate the impact of a seaweed culture project (Lelaurin, 2000). Application-wise, several platform reef (i.e. no significant lagoon completely bounded by a shallow reef flat) and continental lagoons bounded by barrier reefs have been investigated using 2D or 3D model for circulation, productivity (coupling with biological models), mapping of residence time field, sediment transport, larval transport, pollutant transport and coral bleaching (Douillet et al., 2001; Carleton et al., 2001; Pinazo et al., 2004; Fernandez et al., 2006; Jouon et al., 2006).

GETM is the 3D model currently applied on Moruroa. GETM uses a finite-volume, finite-difference approach on Arakawa's C-grid with 15 σ-levels for each of the 250 m resolution mesh (Blumberg and Mellor, 1987). The σ-levels scheme is better than the traditional z-level scheme since the later can not handle well the surface or boundary layers in case of large bathymetric variations. The (x, y, z) grid transformation into a (x, y, σ) system allows to better handle topographic variation since in a σ-coordinate system, the number of vertical levels in the water column is the same everywhere in the domain irrespective of the depth of the water column. Details on the numerical techniques used in the Moruroa hydrodynamic module and parameterization are in Tartinville et al. (1997) and references within. This study investigated the sensitivity of residence time to wind and hoa flows. Only the lagoon was modeled and the pass appeared as an open boundary. Passes and hoas were not explicitly represented. Hoa inflow was included as a boundary steady state process.

The model used in Majuro atoll is a 10 z-levels finite-difference 3D model (Guo and Yanagi, 1997; Kraines et al., 1999 and references within). Its spatial resolution is 500 m. It integrates density-driven current, tidal-stress current, wind-driven current and the radiation-stress driven cross-reef transport. It includes the Longuet-Higgins and Stewart (1964) radiation stress tensor to parameterize wave refraction along the atoll rim. The rim is explicitly included in the model (with at least two z-levels at 50 cm and 1 m depth). In contrast with the lagoon where constant eddy viscosities coefficients were used (from Bikini atoll in Munk et al., 1949), specific eddy viscosities were assigned to reef flat meshes to account for higher turbulent viscosity due to wave actions. Finally, specific drag coefficients were computed for reef flats and meshes with water depth <5 m.

Other models currently used in coral reef lagoons (not just atolls) may also provide interesting numerical techniques which have been locally validated with *in situ* data. For instance, Mars3D is a σ-coordinate finite-difference model used in New-Caledonia lagoon that have benefited from a wide array of *in situ* measurements for its calibration (Blumberg and Mellor, 1987; Douillet, 1998; Douillet et al., 2001). This model is also currently under development to integrate inflows through the barrier reef flats.

10. Options and guidelines for a case-study

The Tahiti workshop aimed at developing a model specifically for a biological/economic application so our standards for model performance are particular to the life-history of oysters and clams. During the workshop, local technical services have prioritized three of the French Polynesia main pearl-oyster industry atolls if a model could be implemented. These are Ahe, Manihi and Takaroa, all in the Western Tuamotu (Fig. 1). Thus, this narrows the scope of the options. We realize that the discussion below is fairly specific to one environment and case study, but we also believe it will provide to funding organizations (government, NGOs, managers) a general indication of what this type of work costs and the necessary items to account for.

Lagoon and inner slopes cover 140, 160 and 85 km^2 for Ahe, Manihi and Takaroa respectively. Maximum reported depth on nautical charts are 60 and 40 m for Ahe and

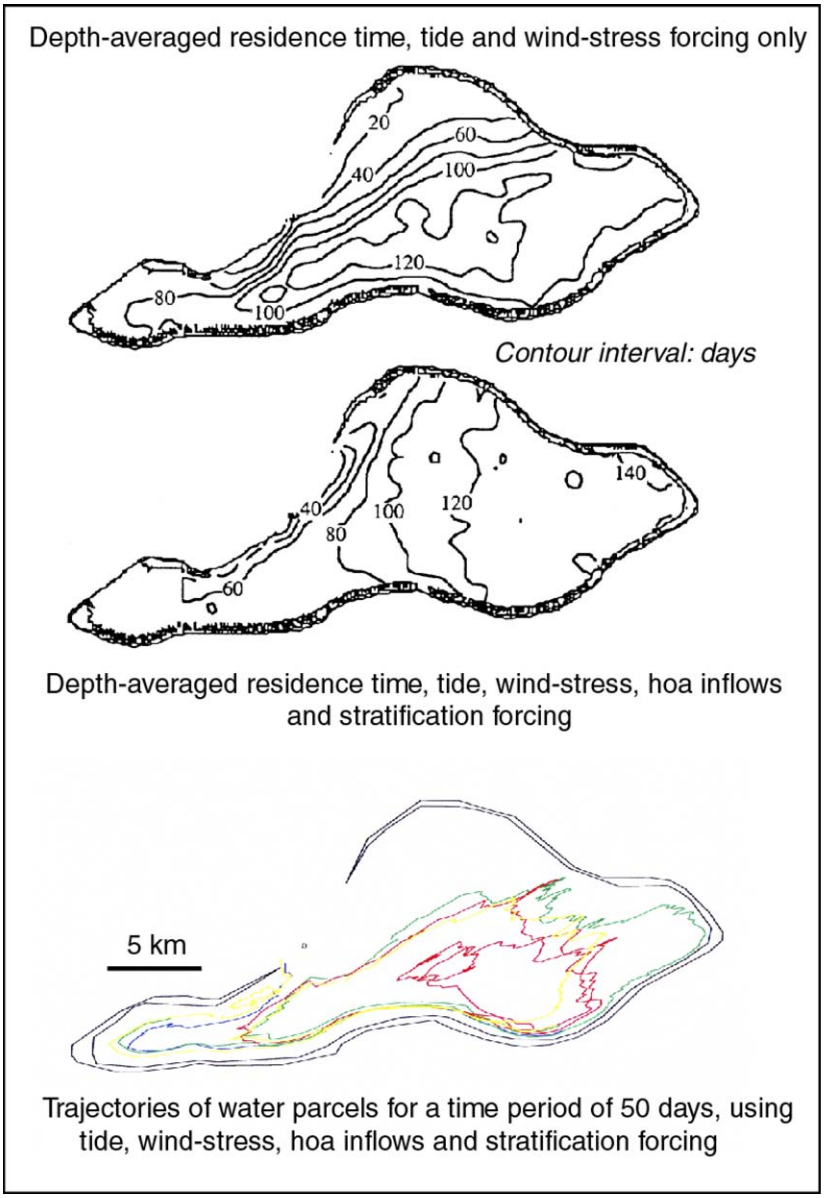

Fig. 8. Examples of 2D products from Moruroa 3D model: atoll residence time and particle tracking sensitivity study to different forcing factors such as wind, tide, hoa inflows and stratification (from Tartinville et al., 1997).

Takaroa respectively, and unknown for Manihi. They all have a unique narrow pass. These passes have a least charted depth of about 3–4 m though deeper channels occur. Each pass also differs in morphology and exposure from one atoll to another. According to the atoll rim typology from Andréfouët et al. (2001b), their rims are mostly made of rim types Rim 1 or 8 in the north (completely closed and vegetated), and Rim 2, 5 and 7 in the south (semi-closed to semi-opened with succession of hoas and motus). Thus they are asymmetrical atolls, more open in the south than the north.

Following these basic morphometrics information, it is necessary to discuss the different options if a model is implemented in one of these atolls. First, only technical criteria were considered as if an ideal sampling and modeling scheme could be achieved without cost constraints. These options set an obviously upper limit that is further put in perspective by the evaluation of the induced costs (Table 2) that are discussed in Section 10.8.

10.1. Lagoon spatial resolution, horizontal and vertical discretisations

A fine spatial resolution of 100–200 m for the lagoon would be satisfactory for larval propagation applications, however the need for better representation of rim and passes points to several options:

1. a finite-difference model throughout the entire domain, but at very high resolution (10–50 m),
2. a finite-element model with variable mesh size (Hench and Luettich Jr, 2003; Pietrzak et al., 2005),

Table 2
Itemization of the main costs for a 3D atoll modeling project

Item	Time and salary		Others	Comments
Expertise				We assumed experienced scientists (postdocs) immediately operational who do not need to learn the tools and the theory. The 3D model is assumed from-the-shelf (Table 1)
Ocean modeling	12 months	60 KUS$		
Rim modeling	12 months	60 KUS$		
3D lagoon model and integration of boundary models	24 months	120 KUS$		
		240 KUS$		
Computers	3 months	15 KUS$	>10 processors-cluster	One IT technician to install, maintain and tune the system
		15 KUS$	*20 KUS$*	
Satellite imagery	6 months	30 KUS$	High resolution (<4 m) satellite image	A 170 km^2 atoll is assumed. Cost is 18 US$/$km^2$. The image and the 6-months post-doc provide the rim structure
		30 KUS$	*3 KUS$*	
Field work				
Bathymetry (multi-beam survey)	2 × 1 months on site		Boat rental Freight (600 kg) Transport Post-processing	On site costs are estimated considering a 150US$/day per-diem rate
		10 KUS$	*20 KUS$*	For bathymetry, we assumed a 170 km^2 atoll implying a 3-weeks survey for 2 people + transfer
Circulation (incl. 3 ADCPs, pressure sensors, tide-gauge, 2 ADVs, 1 CTD, and moorings)	4 × 2 months on site		Boat rental Freight Transport	For circulation instruments, we assumed data acquired during two one-month periods by 4 technicians
		40 KUS$	*100 KUS$*	
Instruments				
Bathymetry (multi-beam sensor)			One month rental Post-processing *120 KUS$*	We assume that the multibeam sensor can be rented with DGPS, motion sensor, gyros, survey and post processing software and data logging computer
Circulation			Initial capital cost	Instruments are priced based on list prices available from the web from a variety of providers. Full options were considered (e.g. 6 sensor-CTD, transect mode for ADCP, etc.)
3 ADCPs			120 KUS$	
4 pressure sensors			5 KUS$	
2 ADVs			40 KUS$	
CTD			25 KUS$	
Moorings			5 KUS$	
			195 KUS$	

Salaries, transport boat rentals, freight and perdiems are highly variable between locations and institutions. Here, we have considered salaries with benefits corresponding to an experienced US or French overseas-based post-doc. The targeted site is a 170 km^2 atoll of Western Tuamotu which is accessible by plane or ship cargos. Total cost is ~800 KUS$ for a project that could be staged in a 3 year-period.

3. high resolution rim and passes nested models within the coarser atoll model.

The choice of option 1, and the choice of the spatial resolution, is a question of balancing computational costs and the availability of adequate bathymetry. For Ahe atoll (140 km^2), a 10-m regular mesh grid involves 1.4 million cells and would require very high computation costs. A 100 m-resolution would mean a more manageable 14,000 cells model. Current computer technology allows building and tuning a powerful cluster of personal computers for ~KUS$20 (as at 2006). The Mars3d finite-difference model at 500 m resolution running in New Caledonia lagoon is an 18,700 cells model, running on a PC or, for long-term simulations, on a 20 processor pc-cluster.

The choice of option 2 allows increasing the spatial resolution where it is needed. However, the set-up of a high resolution, unstructured mesh may not be trivial and the complexity of the network depends on the complexity of the topography (Legrand et al., 2006). This technique is currently applied to Rongelap atoll (Peterson et al., 2006).

Regarding option 3, no nesting models have been used in atolls thus far, but this technique is now frequently used elsewhere. It allows increasing grid resolution in a subregion of the whole domain, without the cost of running a high resolution everywhere. Several levels of nested models have been implemented. For instance, Tang et al. (2006) uses three levels of nesting. The two-ways interaction between the fine and coarse model can be achieved in different ways depending on the type of nesting: through a dynamic boundary if the models do not overlap or through substitution if domains overlap (Sheng et al., 2005 and references therein). Nesting is applied in New-Caledonia lagoon using Mars3d and the AGRIF library (Debreu and Blayo, 2002), in the Belize barrier reef system using the 3D CANDIE model (Sheng and Tang, 2004; Tang et al., 2006) and is currently under development for the Capricorn-Bunker group of the Great Barrier Reef in Australia using the Sparse Hydrodynamic Ocean Code (SHOC) model (Walker and Waring, 1998). SHOC is a finite difference general purpose model applicable to scales ranging from estuaries to regional ocean domains.

Topography variations in atolls due to large pinnacles call for the use of σ-coordinates. Even if σ-coordinates have been introduced to better represent complex topography, sharp depth variations pose other problems, and careful vertical discretisation is required (Deleersnijder and Beckers, 1992).

10.2. Rim modeling

The rim could be separately modeled at high resolution to define the boundary conditions of the lagoon model. The rim could be also fully included in the lagoon model like in Kraines et al. (1999), with a specific parameterization. Rims could be also processed within a nested-model. The resolution achieved by Kraines et al. (1999) at 500 m is here judged too coarse to accurately model the Western Tuamotu rim morphology since hoas widths are of the order of few tens to hundred meters at best (Fig. 4). For a finite-difference model, a spatial resolution on the rim coarser than hoas width would imply a parameterization of an aperture factor (e.g. ratio of land and hoas) for each cell of the rim. This can be easily computed with high resolution satellite images (Fig. 4). Furthermore, it should be possible to modify dynamically this aperture for different levels of wave energy and set-up. It would be possible to calculate volumetric flux as a function of dynamic sea-level for different rim zones and use these calculations to define the rim computationally as a permeable boundary.

Hoas also require a model able to handle drying/flooding conditions (Table 1), which can take into account the change in computation domain when some cells become dry following sea level variations. For such a model, hoas also require a dynamic shift from a 3D model towards a 2D model when the depth is too low to accommodate too many σ-levels. Indeed, very small vertical discretisation leads to computational instability that can be handled only using a very short time-step inducing excessive computation costs.

10.3. Oceanic boundary conditions

Nesting the atoll model within an oceanic model (e.g. ROMS) is also an attractive option to account for oceanic SST and current. There is no need to include very deep atoll slopes, in order to avoid vertical digitization problem, but it is necessary to set the depth limit of the model in the ocean to below the average thermocline to account for possible temporary drains of cold water through the pass during flood.

The oceanic boundary conditions set by Kraines et al. (1999) is a 10 km domain around the island. Here, if the wave field is estimated through altimetry data or models, the boundary domain needs to be temporarily set around ~500 km at least (Tartinville and Rancher, 2000) to include enough satellite tracks. Then, the oceanic wave field can be reduced to a 2D model near the coastline and the Kraines et al. (1999) scheme could be used to adequately account for wave-driven processes.

After the 1997/1998 El Niño transition to La Niña, mean sea level increased up to 40 cm in Samoa. Given that other regions of the Pacific Ocean would experience a similar signal it is necessary to consider the affect of this low-frequency sea-level variation on long term atoll flushing.

10.4. Bathymetry

The required precision of the topography depends on the spatial resolution of the model. Eventually, the model resolution is driven by the scale of flow or feature that needs to be captured by the model and by the computing power. The potential need of creating nested model at higher resolution than 100 m for the passes or dense pinnacles areas justifies the collection of high-range data similar in quality than those obtained for Manihiki atoll, at 5 m resolution using a multi-beam system (Fig. 6). Very shallow water bathymetry can be estimated from optical satellite images to fill the gaps.

In addition, fine-scale bathymetry offers the possibility to estimate the bathymetric variation within each mesh. This provides a way to quantify a roughness coefficient for each mesh. This requires a model domain in which the friction coefficient is spatially variable. This is not typically done in hydrodynamic models over coral reefs. In practice, there is no established scheme to define this coefficient. Bottom roughness needs to be empirically tuned by *in situ* velocities measurements, for instance on both-sides of a pinnacle-rich areas.

10.5. Tracking module

A tracking module is mandatory to study larval propagation under different forcing. Lagrangian models of advection–diffusion such as Hunter et al. (1993) are now common in most 3D models (Table 1). They may also tend to accumulate particles in region where depth or diffusivity are the smallest. However, this is a numerical artifact that can be corrected with proper numerical solutions (e.g. Spagnol et al., 2002 for a 2D model).

The modeling of larvae is not as simple as modeling a dissolved tracer. Buoyancy needs to be parameterized, and in some cases, larvae may have behaviors which require specific developments. This is obviously true for fish larvae with swimming abilities, but mollusk larvae, though passive during a good part of their PLD, have the capacity to avoid settling in unsuitable areas, and bounce from the bottom. This warrants further investigations in terms of coupling physics and biology, like this is increasingly done for fish larvae connectivity modeling. A first-order model where larvae are considered passive throughout their PLD and bottoms equally suitable would be a useful decision-support tool. However, substrate suitability could be considered as a secondary product of the model and explicitly included in it.

10.6. Tide model

A global oceanic tide model such as FES99 or FES2004 provide a useful source for forcing at the deep ocean boundary (Le Provost et al., 1994; Lefèvre et al., 2002). The FES (Finite Element Solution) model is based on the resolution of the tidal barotropic equations on a global finite element grid without any open boundary conditions and no assimilation, which leads to solutions independent of *in situ* data. The accuracy of these "free" solutions is improved by assimilating tide gauge and TOPEX/Poseidon (T/P) altimeter information through an assimilation method. For the eight main constituents of the tidal spectrum (M_2, S_2, N_2, K_2, $2N_2$, K_1, O_1, and Q_1), about 700 tide gauges and 687 T/P altimetric measurements are assimilated. FES2004 gives heights of tidal constituents on a $1/8° \times 1/8°$ grid for a global coverage. Data files in NETCDF format can be downloaded through the web portal of FES2004 (http://www.legos.obs-mip.fr/en/soa/).

10.7. In situ data collection

Climatology data clearly shows two different seasons for wave and wind regimes. From November to March, there is a north swell which is absent the rest of the year. It would be optimal to collect data during the two seasons.

Existing meteorological stations should provide wind direction and speed (at least for Western Tuamotu), in addition to irradiance, cloud cover, humidity, evaporation and rain. The buoy used in Cook Island atolls would be an ideal sensor to monitor at the lagoon level atmospheric parameters, and sea surface parameters as well.

In addition to conductivity-temperature-depth (CTD) casts to measure temperature and salinity, several types of sensors can be deployed to calibrate the model: tide gauge, pressure sensors, current meters, Acoustic Doppler Velocimeters (ADVs) and Acoustic Doppler Currentmeter Profilers (ADCPs). Current meter measures speed velocity of flowing water and can be capable of measuring directional waves. The three most common types of modern current meters are mechanical (rotor and vane), electromagnetic, and acoustic Doppler. Current profilers provide current simultaneously over a range of depths and generally have a pressure sensor as well. Acoustic sensors uses the Doppler effect (change in frequency) on backscattered echo from plankton, suspended sediment, bubbles and waves all assumed to be moving with the speed of the water. Doppler instruments are now the industry standard for current measurements. Indeed, measurements are made in a remote sampling volume free from flow distortion from the sensor itself. Doppler technology has no inherent minimum detectable velocity, giving excellent performance at low flows, however care must be taken in stratified waters as density differences can refract sound waves. In addition, ADCP can be used mounted on a boat, to provide large coverage instead of being used in one single spot.

We do not advertise or recommend any particular brand here, but readers may refer to detailed tests for evaluating new and developing coastal sensor technologies made by third-party scientists independent from manufacturers. For instance, the Alliance for Coastal Technologies is a consortium of academic groups who publish detailed instrument fact-sheets on www.actonline.ws.

The use of an ADCP on transect mode would be an ideal configuration to characterize the flows in passes and lagoons under different forcing. The lagoon and passes can be also instrumented with fixed ADCP either bottom mounted or downward looking off a buoy. Lagoon location may be difficult to select, but south lagoon and rim are likely the most interesting areas due to presence of hoas where cross-rim exchange between the lagoon and ocean is most dynamic. Finally, to characterize hoa currents, the best configuration would be to deploy two pressure sensors, one upstream the entrance the hoa, and one close to the mouth. Between them, an ADV would measure current velocities. This set-up should be used on different hoa types, during different wave regimes. Finally, one tide-gauge and wave-gauge should be deployed on the fore-reef, before the hoa sensors.

All depths, ocean and lagoon levels should be measured against the same vertical datum, such as the Mean Sea Level (Callaghan et al., 2006).

10.8. Costs

The various options described above all have pros and cons. The final factor that needs to be accounted for is obviously the costs induced. Options need to be selected depending on the funds available for the modeling exercise. Costs can be itemized based on 6 main categories:

- expertise,
- computers and software,
- high resolution satellite images,
- field work for acquisition of observations,
- instruments for acquisition of observations,
- administration.

Table 2 itemizes the costs for the ideal implementation of a Western Tuamotu atoll model if they were part of a hypothetical grant proposal. We have not included overheads administration costs which vary widely. Administration also includes all the costs related to organizing purchases, trips, meeting, provide information to locals, etc. Some variables are the same for any sites worldwide (time for expertise), but salary costs, surface area, remoteness, shipping costs and field trip costs are fairly specific to each region. Also, costs may decrease or increase with time.

The total cost of the exercise would be around 800 KUS$ based on the present cost analysis (without administration costs included). In comparison, the oceanography and modeling component of a large on-going project focused on Scott Reef (Indian Ocean) by the Australian Institute of Marine Science is estimated at 300 KUS$, but with large in-kind contributions. Here, we have priced all the different items, including instruments, and rental of a multibeam system. We have not considered for instrumentation a permanent buoy like in Manihiki but the cost would be an additional 75 KUS$ for the buoy itself, plus cost for maintenance and communications for 3 years. There are different ways to lower the costs of instrumentation through short term rentals, loans and collaborations with equipped laboratory. Prices for academic research can also be lower, and taxes on equipment are waived for research activities in some countries.

11. Conclusion and perspectives

The implementation, calibration and validation of a high resolution 3D circulation model are expensive tasks if all the best advanced options are used. The implementation of the different components required to model the atoll lagoon and its boundaries is possible with the right expertise and right tools. The cost to make an optimal, state-of-the-art, scenario a reality appears quite high. However, the benefits of a decision-support tool well tuned for the aquaculture application are also high. A cost benefit analysis was achieved in Manihiki (Cook Islands) to evaluate if on-going monitoring projects generate pearl revenue in excess of project costs and contribute to long-term sustainable development of the pearl industry. The outcome of this socio-economic analysis suggested the ratio of benefits *vs* costs would be 10:1 (Mckenzie, 2004). The Manihiki project has potential multi-million dollar net benefits, but to gain these benefits an effective resource management regime is needed. Without a management plan farmers will continue to stock oysters at high densities favoring diseases spreading and employ unsustainable farming practices (Mckenzie, 2004). A Manihiki Pearl Farming Management Plan is currently being implemented by the Island Council. Beyond increasing productivity the study can aid the sustainability of the industry by identifying causes of potential negative impacts of physical processes or periods and so allow management to take action.

For other atolls with high density of aquaculture installation, similar conclusions could likely be applied. Circulation model outputs will be technically more effective for collecting spats and cost-effective for the industry by identifying key aggregation or trapping areas. But as in Manihiki, a management plan needs to be implemented as well so that model outputs are really used and transferred to the technical services and farmers. We have not discussed here the products that the technical services in charge of aquaculture management will use. Will they use the model itself? This is unlikely given the level of expertise and computer power required. More likely, they will use a climatology provided by model runs, or an Atlas of circulation features under different forcing scenarios, and on request simulations for specific events or locations within the lagoon.

To conclude, 3D models would be useful for aquaculture, but also for a wide range of research and management applications. Specifically all programs on trophic functioning of lagoons would benefit from a circulation model, including for elucidation of dystrophy events. Research on the implications of sea level rise on atoll and islands morphologies would benefit from fine characterization of the hydrodynamics of the rims. Another application would be risk-assessment on populations and structures during high swell. Finally, even if we focused on mollusk larvae, all other drifters (coral larvae, pollutants, pathogens, etc.) and their propagation can be studied with the tools we presented here.

Acknowledgements

The November 2004 workshop was hosted by the IRD research center in Tahiti, and was funded by a grant from Ministère de l'Outre Mer (France) to SA. The IKONOS image of Ahe atoll was provided by Service de l'Urbanisme de Polynésie française. Eric Deleersnijder is a Research Associate with the Belgian National Fund for Scientific Research.

References

Adjeroud, M., Andréfouët, S., Payri, C., 2001. Mass mortality of macrobenthic communities in the lagoon of Hikueru atoll (French Polynesia). Coral Reefs 19, 287–291.

Andréfouët, S., Pagès, J., Tartinville, B., 2001a. Water renewal time for the classification of atoll lagoons in the Tuamotu Archipelago (French Polynesia). Coral Reefs 20, 399–408.

Andréfouët, S., Claereboudt, M., Matsakis, P., Pagès, J., Dufour, P., 2001b. Typology of atolls rims in Tuamotu archipelago (French Polynesia) at landscape scale using SPOT-HRV images. International Journal of Remote Sensing 22, 987–1004.

Andréfouët, S., Robinson, J.A., Hu, C., Feldman, G.C., Salvat, B., Payri, C., Muller-Karger, F., 2003. Influence of the spatial resolution of SeaWiFS, Landsat 7, SPOT and International Space Station data on landscape parameters of Pacific Ocean atolls. Canadian Journal Remote Sensing 29 (2), 210–218.

Andréfouët, S., Gilbert, A., Yan, L., Remoissenet, G., Payri, C., Chancerelle, Y., 2005. The remarkable population size of the endangered clam *Tridacna maxima* assessed in Fangatau atoll (Eastern Tuamotu, French Polynesia) using in situ and remote sensing data. ICES Journal of Marine Science 62, 1037–1048.

Andrews, J.C., Pickard, G.L., 1990. The physical oceanography of coral-reef systems. In: Dubinsky, Z. (Ed.), Ecosystems of the World, Coral Reefs, vol. 25. Elsevier, Amsterdam, pp. 11–48.

Atkinson, M., Smith, S.V., Stroup, E.D., 1981. Circulation in Enewetak Atoll lagoon. Limnology Oceanography 26, 1074–1083.

Blumberg, A.F., Mellor, G.L., 1987. A description of the three-dimensional coastal ocean circulation model. In: Heaps, N.S. (Ed.), Three-Dimensional Coastal Ocean Model. American Geophysical Union, Washington, DC, pp. 1–16.

Brié C., 1999. Étude expérimentale du collectage de naissain de *Pinctada margaritifera* (Linné, 1758) à Takapoto, atoll des Tuamotu, en Polynésie française. Thesis, Ecole Pratique des Hautes Etudes, 87p.

Callaghan, D.P., Nielsen, P., Gourlay, M.R., Ballock, T.E., 2006. Atoll lagoon flushing forced by waves. Coastal Engineering 53, 691–704.

Carleton, J.H., Brinkman, R., Doherty, P., 2001. The effects of water flow around coral reefs on the distribution of pre-settlement fish (Great Barrier Reef, Australia). In: Wolanski, E. (Ed.), Oceanographic Processes of Coral Reefs: Physical and Biological Links in the Great Barrier Reef. CRC Press, Boca Raton, pp. 209–230.

Chevalier, J.P., 1972. Observations sur les chenaux incomplets appelés hoas dans les atolls des Tuamotu. In: Proc. Symposium Corals and Coral Reefs, Mandapan Camp, India, pp. 477–488.

Davies, A.M., Lynch, D.R. (Eds.), 2005. Recent developments in physical oceanographic modelling: Part II. Continental Shelf Research (special issue) 25, 749–1001.

Debreu, L., Blayo, E., 2002. AGRIF: Adaptive Grid Refinement in Fortran. Rapport Technique RT 0262, INRIA.

Deleersnijder, E., Beckers, J.M., 1992. On the use of the σ-coordinate system in regions of large bathymetric variations. Journal of Marine Systems 3, 381–390.

Delesalle, B. 1990. Ecologie du phytoplankton des lagons de Polynésie française, PhD Thesis, Ecole Pratique des Hautes Etudes, 214p.

Douillet, P., 1998. Tidal dynamics of the south-west lagoon of New Caledonia: observations and 2D numerical modelling. Oceanologica Acta 21, 69–79.

Douillet, P., Ouillon, S., Cordier, E., 2001. A numerical model for fine suspended sediment transport in the south-west lagoon of New-Caledonia. Coral Reefs 20 (4), 361–372.

Falter, J.L., Atkinson, M.J., Merrifield, M.A., 2004. Mass transfer limitation of nutrient uptake by a wave-dominated reef flat community. Limnology Oceanography 49, 1820–1831.

Farrow, G.E., Brander, K.M., 1971. Tidal studies on Aldabra. Philosophical Transactions of the Royal Society of London, Series B 260, 93–121.

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). Marine Pollution Bulletin 52, 320–331.

Gerritsen, F., 1981. Wave attenuation and wave set-up on a coastal reef, PhD Thesis, University of Trondheim.

Gilbert, A., Yan, L., Remoissenet, G., Andréfouët, S., Payri, C., Chancerelle, Y., 2005. Extraordinarily high giant clam density under protection in Tatakoto atoll (Eastern Tuamotu archipelago, French Polynesia). Coral Reefs 24, 495.

Gourlay, M.R., 1996. Wave induced set-up on coral reefs. 2: Set-up on reefs with various profiles. Coastal Engineering 28, 17–55.

Gourlay, M.R., Colleter, G., 2005. Wave-generated flow on coral reefs – An analysis for two-dimensional horizontal reef-tops with steep faces. Coastal Engineering 52, 353–387.

Guo, X., Yanagi, T., 1997. Variation in residual current in Tokyo Bay due to increase in fresh water discharge. Continental Shelf Research 18, 677–693.

Hardy, T.A., Young, I.R., 1996. Field study of wave attenuation on an offshore coral reef. Journal Geophysical Research 101, 14311–14326.

Hearn, C.J., 1999. Wave-breaking hydrodynamics within coral reef systems and the effects of changing relative sea level. Journal of Geophysical Research 104 (C12), 30007–30019.

Hench, J.L., Luettich Jr., R.A., 2003. Transient tidal circulation and momentum balances at a shallow inlet. Journal of Physical Oceanography 33, 913–932.

Hunter, J.R., Craig, P.D., Phillips, H.E., 1993. On the use of random walk models with spatially variable diffusivity. Journal of Computational Physics 106, 366–376.

Jameson, S.C., 1976. Early life history of the giant clams *Tridacna crocea*, *Tridacna maxima*, *Hippopus hippopus*. Pacific Science 30, 219–233.

Jouon, A., Douillet, P., Ouillon, S., Fraunié, P., 2006. Calculations of hydrodynamic time parameters in a semi-opened coastal zone using a 3D hydrodynamic model. Continental Shelf Research 26, 1395–1415.

Kench, P.S., Brander, R.W., 2006. Wave processes on coral reef flats: implications for reef geomorphology using Australian case studies. Journal of Coastal Research 22 (1), 209–223.

Kench, P.S., McLean, R.F., 2004. Hydrodynamics and sediment flux of hoa in an Indian Ocean Atoll. Earth Surface Processes and Landforms 29, 933–953.

Kraines, S.B., Yanagi, T., Isobe, M., Komiyama, H., 1998. Wind-wave driven circulation on the coral reef at Bora Bay, Miyako Island. Coral Reefs 17, 133–143.

Kraines, S.B., Suzuki, A., Yanagi, T., Isobe, M., Guo, X.Y., Komiyama, H., 1999. Rapid water exchange between the lagoon and the open ocean at Majuro atoll due to wind, waves, and tide. Journal of Geophysical Research-Oceans 104, 15635–15653.

Kraines, S., Isobe, M., Komiyama, H., 2001. Seasonal variations in the exchange of water and water-borne particles at Majuro Atoll, the Republic of the Marshall Islands. Coral Reefs 20, 330–340.

Laurent, V., Maamaatuaiahutapu, K., Maiau, J., Varney, P., 2004. Atlas climatologique de la Polynésie francaise. Direction Inter-regionale de Polynésie Francaise, Papeete, 204 pp.

Lazure, P., Salomon, J.C., 1991. Coupled 2-D and 3-D modelling of coastal hydrodynamics. Oceanologica Acta 14, 173–180.

Lefèvre, F., Lyard, F.H., Le Provost, C., Schrama, E.J.O., 2002. FES99: A global tide finite element solution assimilating tide gauge and altimetric information. Journal of Atmospheric and Oceanic Technology 19 (9), 1345–1356.

Legrand, S., Deleersnijder, E., Hanert, E., Legat, V., Wolanski, E., 2006. High resolution, unstructured meshes for hydrodynamic models of the Great Barrier Reef, Australia. Estuarine Coastal Shelf Science 68, 36–46.

Lelaurin, J., 2000. Hydrodynamic simulation with Mike 21 of Abaiang Atoll, Kiribati. SOPAC Report TR0313, 35p.

Lenhardt, X., 1991. Hydrodynamique des lagons d'atolls et d'île haute en Polynésie française, PhD Thesis, Muséum National d'Histoire Naturelle, Paris, 132p.

Le Provost, C., Genco, M.L., Lyard, F., Vincent, P., Canceil, P., 1994. Spectroscopy of the world ocean tides from a finite element hydrodynamic model. Journal of Geophysical Research 99 (C12), 24777–24798.

Longuet-Higgins, M.S., Stewart, R.W., 1964. Radiation stress in water waves: a physical discussion with applications. Deep-Sea Research 11, 529–562.

Lowe, R.J., Falter, J.L., Bandet, M.D., Pawlak, G., Atkinson, M.J., Monismith, S.G., Koseff, J.R., 2005. Spectral wave dissipation over a barrier reef. Journal Geophysical Research 100, C04001.

Lugo-Fernández, A., Roberts, H.H., Suhayda, J., 1998. Wave transformation across a Caribbean fringing-barrier Coral reef. Continental Shelf Research 18, 1099–1124.

Marchesiello, P., McWilliams, J.C., Shchepetkin, A., 2003. Equilibrium structure and dynamics of the California Current System. Journal of Physical Oceanography 33, 753–783.

Maritorena, S., Guillocheau, N., 1996. Optical properties of water and spectral light absorption by living and non-living particles and by yellow substances in coral reef waters of French Polynesia. Marine Ecology Progress Series 131, 245–255.

Massel, S.R., Brinkman, R., 2001. Wave-induced set-up and flow over shoals and coral reefs: Part 1 A simplified bottom geometry case. Oceanologia 43 (4), 373–388.

Mathieu, P.M., Deleersnijder, E., Cushman-Roisin, B., Beckers, J.M., Bolding, K., 2002. The role of topography in small well-mixed bays, with application to the lagoon of Mururoa. Continental Shelf Research 22, 1379–1395.

Mckenzie E., 2004. A cost-benefit analysis of projects implemented to assist the black pearl industry in Manihiki, Cook Islands. SOPAC Technical Report 371. Available from: <http://www.sopac.org/tiki/tiki-download_file.php?fileId=52>.

Michel, A., Colin, C., Desrosiers, R., Oudot, C., 1971. Observations sur l'hydrologie et le plancton des abords et de la zone des passes de

l'atoll de Rangiroa (Archipel des Tuamotu, Océan Pacifique Central). Cahiers O.R.S.T.O.M., Série Océanographie 9, 375–402.
Munk, W.M., Ewing, G.C., Revefle, R.R., 1949. Diffusion in Bikini lagoon. Transactions-American Geophysical Union 30, 159–166.
Nelson, R.C., 1996. Hydraulic roughness of coral reef platforms. Applied Ocean Research 18, 265–274.
Nielsen, P., Hughes, M., Brander, R.W., 1999. A wave pump model for rip currents. In: Proc. Symposium on River, Coastal and Estuarine Morphodynamics, Genova, pp. 415–423.
Nihoul, J.C.J., 1984. A three-dimensional general marine circulation model in a remote sensing perspective. Annales Geophysicae 2, 433–442.
Pagès, J., Andréfouët, S., 2001. A reconnaissance approach for hydrology of atoll lagoons. Coral Reefs 20, 409–414.
Peterson, E.M., Beger, M., Pinca, S., 2006. Three dimensional model of atoll hydrodynamics. In: Proc. 10th Int. Coral Reef Symposium, Okinawa, Japan, CD-Rom.
Philpot, W.D., 1989. Bathymetric mapping with passive multispectral imagery. Applied Optics 28 (8), 1569–1578.
Pietrzak, J., Deleersnijder, E., Schroeter, J. (Eds.), 2005. The Second International Workshop on Unstructured Mesh Numerical Modelling of Coastal, Shelf and Ocean Flows. Ocean Modelling, vol. 10, pp. 1–252.
Pinazo, C., Bujan, S., Douillet, P., Fichez, R., Grenz, C., Maurin, A., 2004. Impact of wind and freshwater inputs on phytoplankton biomass in the coral reef lagoon of New Caledonia during the summer cyclonic period: a coupled 3D biogeochemical modelling approach. Coral Reefs 23, 281–296.
Pirazzoli, P.A., Koba, M., Montaggioni, L.F., Person, A., 1988. Anaa (Tuamotu islands, central Pacific): an incipient rising atoll? Marine Geology 82, 261–269.
Pouvreau, S., Bacher, C., Heral, M., 2000. Gametogenic cycle and reproductive effort of the tropical blacklip pearl oyster, *Pinctada margaritifera* (Bivalvia: Pteriidae), cultivated in Takapoto atoll (French Polynesia). Aquaculture 186, 117–144.
Sheng, J., Tang, L., 2004. A two-way nested-grid ocean circulation model for the Meso-American Barrier Reef System. Ocean Dynamics 54, 232–242.
Sheng, J., Greatbach, J., Zhai, X., Tang, L., 2005. A new two-way nesting technique based on the smoothed semi-prognostic method. Ocean Dynamics 55, 162–177.
Smith, S.V., Jokiel, P.L., 1975. Water composition and biogeochemical gradients in the Canton Atoll lagoon. 1. Lagoon description; design of system analysis; salt and water budget. Marine Science Communications 1, 75–100.
Spagnol, S., Wolanski, E., Deleersnijder, E., Brinkman, R., McAllister, F., Cushman-Roisin, B., Hanert, E., 2002. An error frequently made in the evaluation of advective transport in two-dimensional Lagrangian models of advection–diffusion in coral reef waters. Marine Ecology Progress Series 235, 299–302.
SPC (Secretariat of the Pacific Community), 2005. SPC Regional pearl meeting. Fisheries Newsletter, vol. 115, pp. 22–25.
Symonds, G., Black, K.P., Young, I.R., 1995. Wave-driven flow over shallow reefs. Journal Geophysical Research 100 (C2), 2639–2648.
Tait, R.J., 1972. Wave set-up on coral reefs. Journal of Geophysical Research 77 (12), 2207–2211.
Tang, L., Sheng, J., Hatcher, B., Sale, P., 2006. Numerical study of circulation, dispersion, and hydrodynamic connectivity of surface waters on the Belize shelf. Journal of Geophysical Research 111 (C1), C01003.
Tartinville, B., Rancher, J., 2000. Wave-induced flow over Moruroa atoll reef. Journal of Coastal Research 16, 776–781.
Tartinville, B., Deleersnijder, E., Rancher, J., 1997. The water residence time in the Mururoa atoll lagoon: sensitivity analysis of a three-dimensional model. Coral Reefs 16, 193–203.
Von Arx, W.S., 1948. The circulation systems of Bikini and Rongelap lagoons. Transactions-American Geophysical Union 29, 861–870.
Walker, S.J., Waring, J.R., 1998. A multiple grid, 3-dimensional, non-linear, variable-density hydrodynamic model with curvilinear horizontal coordinates and level (z) vertical coordinates. CSIRO Marine Research, Report OMR-118/120.
Yamano, H., Shimazakia, H., Matsunagaa, T., Ishodac, A., McClennend, C., Yokokie, H., Fujitaf, K., Osawag, Y., Kayanne, H., in press. Evaluation of various satellite sensors for waterline extraction in a coral reef environment: Majuro Atoll, Marshall Islands. Geomorphology.