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REPORT

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Water renewal time for classification of atoll lagoons in the Tuamotu Archipelago (French Polynesia)

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Abstract The feasibility of using hydrodynamic renewal time as the basis for a classification of atoll lagoons is tested for atolls of the Tuamotu Archipelago, French Polynesia. Renewal time depends on the inflow of oceanic water through the rim of the atoll, on a daily time scale, due to wave forcing. Renewal time is computed for a large set of morphologically diverse atolls, according to significant wave height (satellite altimetry data), morphometric indicators (high-resolution satellite images), and in-situ flow measurements. Renewal times with respect to wave height are presented for a variety of atolls. Renewal times range from less than 1 day for very open and shallow atolls, to several tens of days for semi-open moderately deep atolls, and to several years for closed or very large and deep atolls. Comparisons between phytoplanktonic biomass (in the range 0.1 to 1 $\mu g\ l^{-1}$ for total chlorophyll) and renewal time (0.1 to 130 days) leads to the identification of two groups of atolls. We obtain a significant relationship between biomass and renewal time, but only for atolls with lagoon surface areas greater than 25 km^2.

Keywords Lagoon · Atoll · Hydrodynamics · Residence time · Phytoplankton · SPOT · Landsat · TOPEX · ERS-1

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Introduction

The equilibrium and biological functioning of an aquatic system depends strongly on its hydrodynamic regime and regulation. Water renewal rate, related to the degree of closure of the system (Hatcher 1997), has been considered as one of the major forcing factors of the biological processes inside the system as well as an indicator of its trophic state. In the coral reef environment, renewal rate has been investigated by various methods in order to relate physical forcing to biological patterns at reef, or atoll, scales (Delesalle and Sournia 1992). In their study, Delesalle and Sournia (1992) quantified the relationship between residence time and phytoplanktonic biomass for 11 atolls of the Pacific Ocean. They showed a correlation only for residence times smaller than 50 days. They also observed that some atolls of the Tuamotu Archipelago (Tikehau, Takapoto) did not fit into the general trend.

The study by Delesalle and Sournia (1992) provided some justification and guidance for a further comparative investigation of atoll lagoons. Ordering aquatic systems according to one or more physical factors in order to explain biological patterns has proved to be an excellent approach for highlighting general trends at atoll scales. It can also help identify anomalies, i.e., unique individual atolls which warrant further detailed investigation. This strategy has been applied to a variety of Tuamotu Archipelago atolls in order to characterize macrobenthic communities (Adjeroud et al. 2000), particulate matter in lagoons (Charpy et al. 1997), and nutrient limitation of planktonic communities (Torréton et al. 2000; Dufour et al. 2001). For the present study, morphological morphometric indicators (atoll aperture degree, rim structure, etc.) were estimated using high-resolution remote sensing images (Andréfouët et al. 2001), and biological data were collected during short cruises (Dufour and Harmelin-Vivien 1997). Importantly, biological variables may not be significantly related to atoll morphometry alone. For this reason, we consider using a physical factor related to both atoll morphometry and atoll hydrodynamics.

According to Delesalle and Sournia (1992), residence and turnover times (see definitions in Materials and methods below) are relevant integrative factors for comparison and classification purposes. We decided to focus our study on the Tuamotu Archipelago for several reasons. First, some Tuamotu atolls exhibit an anomalous relationship between residence time and phytoplanktonic biomass (Delesalle and Sournia 1992). Second, there are 77 atolls in the archipelago, and a database of physical and biological data is available for a large subset of these atolls through two research programs: Typatoll (Dufour and Harmelin-Vivien 1997) and the Programme Général de Recherche sur la Nacre 2 (PGRN2). Moreover, these data have been acquired using consistent methodologies, whereas Delesalle and Sournia (1992) used data compiled from various sources and processed in different ways. Finally, by considering atolls located in a similar oceanic environment, we decrease the likelihood of aliasing due to different hydroclimates and forcing fields (tide, swell, and wind regimes).

We first provide an overview of water renewal mechanisms in Tuamotu atoll lagoons. Then, we define renewal time and explain how to quantify it using remotely sensed morphometric indicators, wave heights, and in-situ flow measurements. Next, we test the possibility of using a single integrative hydrodynamic variable for lagoon classification by comparing renewal time and chlorophyll concentration in 19 morphologically diverse atolls. Since this approach should be considered as a reconnaissance-level tool prior to detailed circulation studies, we detail the assumptions necessary to perform our computations as well as relevant time and space scales.

Materials and methods

Study sites

The Tuamotu Archipelago, French Polynesia, is located in the South Pacific Ocean, from 135 to 150°W, and 12 to 23°S (Fig. 1). It is comprised of 77 atolls with various morphologies. Table 1 describes the atolls considered for this study. The major characteristics of the hydroclimate of this oceanic region are described in Rougerie and Rancher (1994). To sum up, the characteristics are a low average tidal range (amplitude 0.2–0.35 m), a mean monthly evaporation of 100–200 mm, and a seasonally variable rainfall regime (50–100 mm monthly from June to October, 100–200 mm from November to May). East–southeast trade winds are dominant. More important for our purpose is the swell regime, which consists of dominant southern swell all year round and less energetic northern swell from November to March.

Mechanism of water renewal in Tuamotu atolls and working hypothesis

The oceanic waters surrounding the Tuamotu Archipelago differ in their main characteristics from those of the atoll lagoons in that the lagoons are generally more saline and warmer than the surface ocean. Furthermore, the oceanic mixed layer is oligotrophic and has a lower concentration of chlorophyll than the lagoons (Rougerie and Rancher 1994). Hence, the atoll waters are renewed by nutrient-poor surface oceanic waters (Dufour et al. 1999) flowing through passes and over reef flats. These flows are mainly driven by tide, swell, and winds (Lenhardt 1991; Tartinville et al. 1997; Tartinville and Rancher 2000).

Some atoll lagoons in the Tuamotu are connected to the ocean by passes where the flow is mainly driven by tides when the swell is low. Oceanic water enters with the flood tide but remains near the

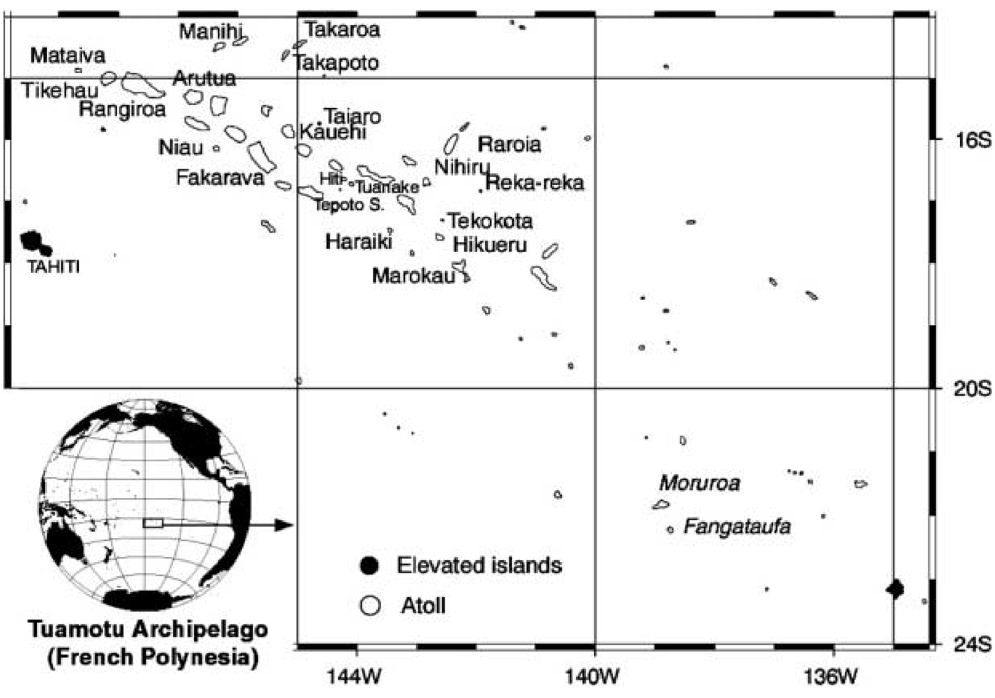


Fig. 1 Map of Tuamotu archipelago and location of atolls mentioned in the text

Table 1 Main characteristics of the atolls studied. Only the atolls with available chlorophyll concentrations (C, in μg l^{-1}) are listed. *NA* Not available

Atoll	Latitude (S)	Longitude (E)	Total area (km^2)	Lagoon area (km^2)	Volume (km^3)	C (μg l^{-1})	Total aperture	Research program
Arutua	15.31	146.74	580.67	516.20	11.91	0.21	0.32	PGRN2
Fakarava	16.30	145.60	1245.71	1112.21	50.00	0.22	0.35	PGRN2
Manihi	14.40	145.96	194.75	165.55	7.91	0.41	0.06	PGRN2
Mataiva	14.88	148.67	47.35	25.68	0.10	0.99	0.03	PGRN2
Rangiroa	15.14	147.61	1762.73	1592.02	34.17	0.29	0.22	PGRN2
Takapoto	14.63	145.21	104.14	81.14	2.28	0.34	0.02	PGRN2
Takaroa	14.45	144.97	117.35	89.47	1.44	0.5	0.04	PGRN2
Tikehau	15.01	148.17	448.85	394.31	10.00	0.29	0.20	PGRN2
Haraiki	17.47	143.45	25.46	10.43	0.14	0.46	0.19	Typatoll
Hikueru	17.59	142.61	107.05	82.47	2.00	0.19	0.18	Typatoll
Hiti	16.73	144.09	25.48	15.28	0.15	0.26	0.19	Typatoll
Kauehi	16.04	145.01	343.40	315.12	11.00	0.2	0.22	Typatoll
Marokau	18.06	142.28	256.04	217.50	6.50	0.24	0.17	Typatoll
Nihiru	16.70	142.84	100.22	79.51	1.58	0.19	0.25	Typatoll
Reka-reka	16.84	141.93	5.16	0.74	0.001	0.42	0.02	Typatoll
Tekokota	17.32	142.56	7.30	5.11	0.015	0.31	0.60	Typatoll
Tepoto Sud	16.82	144.28	6.15	1.56	0.01	0.21	0.15	Typatoll
Tuanake	16.64	144.22	38.09	25.68	0.65	0.14	0.24	Typatoll
Fangataufa	22.24	138.75	22.19	9.96	0.55	NA	0.19	
Mururoa	21.84	138.91	50.60	37.77	4.70	NA	0.33	

pass – in a 1-km radius for the 394-km^2 Tikehau lagoon (Lenhardt 1991), and a 5-km radius for the 1,592-km^2 Rangiroa lagoon (Michel et al. 1971). The widest passes are located in the Mururoa atoll (5 km wide, 8 m deep), the Fakarava atoll (1.6 km wide, 15 m deep), and Tekokota (1 km wide, 5 m deep). Since mixing of oceanic waters with lagoon waters is rather small, most of the water entering the lagoon is flushed out as soon as the tide reverses. Thus, near passes, renewal is driven by tides but is limited spatially, especially for large atolls.

Oceanic waves breaking over the reef induce an additional inflow of oceanic water to the atoll lagoon. Since it depends on the wave height, this flow is intermittent and varies with the passage of disturbances (Rougerie et al. 1984). For instance, from a long-term record, it appears that the daily, average cross-reef current over the Mururoa atoll reef is linearly related to the offshore wave height (Tartinville and Rancher 2000). This result is similar to that found by Hearn (1999) for data collected by Hearn and Parker (1988) at Ningaloo Reef. This inflow could also be modulated by the tide, but such a time scale is beyond the scope of the present study. In numerous atoll lagoons, if oceanic wave heights are high enough, the tide-driven inflow through passes becomes negligible compared to the flow induced by breaking waves (Rougerie et al. 1984; Pagès and Andréfouët 2001). This is especially true during southern swell. Due to rapid filling of the lagoon, outflow will occur through passes, if they exist, and through spillways and reef flats located leewards of the incident waves. Nonetheless, the increase in surface level (less than 0.8 m) is generally small in comparison to the lagoon mean depth (Pagès and Andréfouët 2001). Thus, lagoon volume remains almost constant. The major unknown is which part of the lagoon will be flushed first. The answer to this question requires numerous long-term in-situ observations and/or numerical modeling studies (Atkinson et al. 1981; Tartinville et al. 1997; Kench 1998; Kraines et al. 1998; Kraines et al. 1999; Hearn and Atkinson 2000), since circulation within the lagoon is mainly wind driven and depends on the rim geomorphology and lagoon hypsometry. For instance, Kench (1998) has shown by using measurements of current that the northwest passage is the major exit point for lagoonal water in the Cocos Islands (Indian Ocean).

Finally, for completely closed lagoons (e.g., Taiaro, Niau), exchanges are only driven by interstitial and atmospheric exchanges. The former exchanges have been recently addressed by Leclerc et al. (1998, 1999) using numerical modeling, but this is beyond the scope of the present study.

Residence time, turnover time and renewal time: definition and computation

Residence time, turnover time and renewal time must be clearly defined before they can be estimated. According to Tartinville et al. (1997), residence time, T_r, is the time which a water parcel, initially located at a given point, requires to leave the lagoon through the pass or the rim. Turnover time, T_t, is obtained by averaging residence time over lagoon volume. T_t is relevant at lagoon scale and is spatially independent whereas T_r is explicitly spatially dependent. Only numerical modeling or tracer tracking can provide T_r and T_t. On the other hand, a lower bound of T_t can be calculated as the ratio of the volume of the lagoon (V, in m^3) to the daily volume flux entering (V_e, in m^3 day^{-1}) or leaving the lagoon (von Arx 1948; Gallagher et al. 1971):

$$T_t \geq R_r = \frac{V}{V_e} \qquad (1)$$

R_r is defined as the renewal time and is equal to the turnover time only if the characteristic time scale of mixing inside the lagoon is much lower than the characteristic time scale for exchanges with the ocean.

The volume V can be estimated from bathymetric grid data along the entire surface of the lagoon. High-resolution remote sensing images may be suitable for this purpose (Loubersac et al. 1991). Under good conditions (relatively clear waters, no surface effect due to wind, clear atmosphere), accurate bathymetric information may be derived at 20-m resolution from SPOT High Resolution Visible (HRV) down to depths of 20–25 m. The Landsat satellites (Thematic Mapper and Enhanced Thematic Mapper Plus sensors) provide information to a depth of 35 m from their blue spectral bands (Andréfouët, unpublished data). For the deeper areas of the large lagoons which are not visible using Landsat data, we relied on some rare marine charts and reports, or statistical relationships between lagoon area and maximum depth.

Renewal time is calculated here assuming that inflow of oceanic water is mainly driven by flow over the reef flats and spillways. It is to be emphasized that the present study focuses on renewal times which are due to rim overflow. As discussed above, this flow is driven by oceanic swell over daily time scales.

Flows across atoll rims were estimated from velocity measurements made on numerous spillways and reef flats as well as by morphological identification of open rim types. Rim classification is detailed in Andréfouët et al. (2001), providing definitions and descriptions of relative aperture (percentage of open rim) and relation to swell exposure. Figure 2 provides examples of the main rim types. Rim-type 2, 5, and 7 apertures are made of spillways, whereas large reef flats are dominant for rim type 4. Velocity has been measured for rim types 2, 4, 5, and 7. Rim types 3 and 6 (the latter is actually encountered in only two atolls) have not been sampled. Velocity measurements were performed for 76 sections of rims in various morphologically diverse atolls (Manihi, Takaroa, Rangiroa, Arutua, Tikehau, Mataiva, Fakarava) between 1997 and 1998, and during various swell and tide conditions. We used a Lagrangian approach, by timing the drift of drogues over a distance of 10 m. For narrow (<300 m) spillways, the widths were estimated by triangulation and compared with estimations from 20-m resolution SPOT images. Large spillways and reef-flat widths were estimated with images. Water depth (mostly between 0.4 and 0.8 m) was assessed at each measurement point. We thus determined the total flow (in $m^3 s^{-1}$) and the specific flow per meter of aperture F_r (in $m^2 s^{-1}$).

To estimate wave height, Tartinville and Rancher (2000) described an original approach based on satellite altimetry data, considering a 500-km radius area around their study site. In theory, altimetry provides access to several parameters for swell: significant wave height, wave period, wave direction, as well as wind speed and direction. These parameters may be available commercially for several tropical regions in the form of wave atlases. However, such products were not available for French Polynesia at the time of the study. Only total (wind + swell) significant wave height was readily available. Significant wave-height data for the period concurrent to our field trips (1996 to 1998) were provided by the Colorado Center for Astrodynamics Research, University of Colorado. Wave-height data came from Topex/Poseidon and ERS-1 space missions. Applying parameters computed for the open ocean to a coastal regime is risky (Cotton and Carter 1994):

1. Data must be filtered to remove spikes of overestimated values of wave height due to heavy rains. We removed several unrealistic values between 10 and 20 m.
2. Data may be biased around islands over a radius of a few tens of kilometers, and wave height should be vicariously calibrated near coasts to correct for local variation in sea level.
3. Wave-height data are not available continuously in time and space for a given area (Fig. 3), and a relatively large area of interest (500 km for Tartinville and Rancher 2000) is necessary to capture enough data each day. An example of a time series of significant wave height as estimated by satellites (H_{sat}) is provided for the central Tuamotu archipelago during a period concurrent with several field trips (26 June 1997–22 July 1997; Fig. 3).

Using significant wave height H_{sat} and simultaneous F_r, we can compute the regression line F_r vs H_{sat} for each type of rim. In order to remove tidal effects and to compute relations which are valid at day scale, we averaged F_r over a 1-day period. Since the distribution along the rim of the total aperture L is quantified for each atoll (Andréfouët et al. 2001), the total daily volume flux due to the rim overflow, V_e, could be derived for each atoll. Then, renewal time R_r was computed by normalizing in terms of volume lagoon V (Eq. 1).

Results and discussion

Specific flows vs wave height

The current measurements did not show any significant flows in the northern rims, providing evidence that swells were mostly from the south, an expected behavior since field trips occurred between March and November. However, since altimetry data were not processed for wave directions, we cannot separate southwestern, south, and southeastern swells. In-situ surveys showed that when observed wave heights were near zero (flat ocean), without any flows in the southern or northern sections, H_{sat} was about 1.3 m, thus evidencing a quite important offset. According to Cotton and Carter (1994), such an estimated significant wave height corresponds to the calmest global ocean conditions found. Therefore, this offset should be linked to a bias in the remote-sensing estimate for relatively calm conditions.

The significant ($p < 0.001$) linear relations found for each rim type are displayed in Fig. 4. The result could be biased by an outlier at $H_{sat} = 3.5$ m for rim 4. The similarity of the regressions was tested with an analysis of covariance (Zar 1984). The null hypothesis of equality of the slopes was not rejected (computed $F_{\alpha=0.01,\ 3.67} = 3.20$). The common slope considering all rim types is 0.293. On the other hand, the analysis rejected the hypothesis that elevations of the regressions were equal. An a-posteriori Newman-Keuls test (Zar 1984) confirmed that rims 2 and 7 were significantly different from rims 4 and 5. This reflects either a morphological

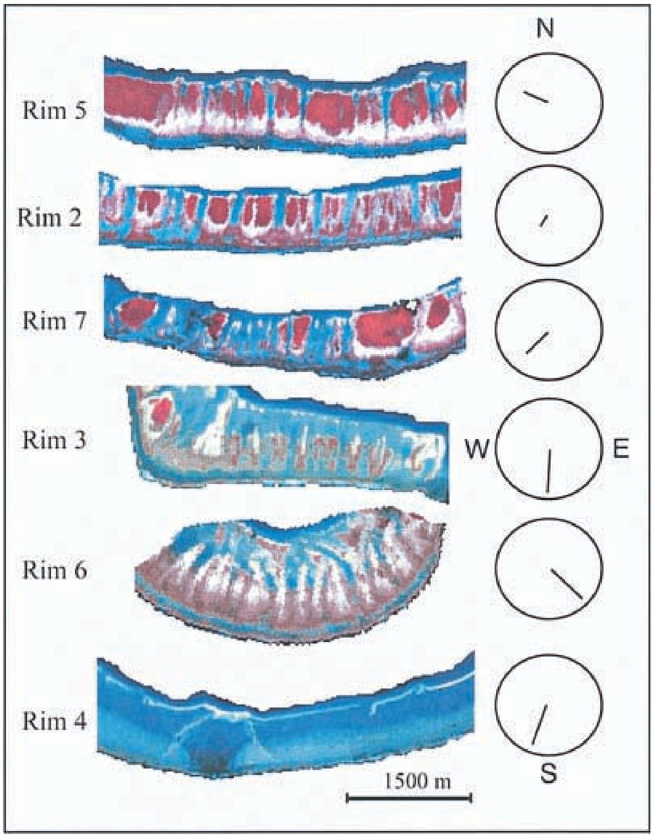


Fig. 2 Examples of open atoll rims (rims 5, 2, 7, 3, 6, and 4) sorted by increasing degree of aperture during high swell. Each rim has been rotated so that the lagoon side of the rim faces upwards. Vegetation appears *red*, submerged areas are *blue/green*, emerged areas are *white* and intertidal areas are *brown*. The *line* inside each *circle* indicates the direction of the dominant exposure. The length of the line shows the significance of this relation (e.g., sections of atolls belonging to rim 4 are statistically strongly exposed to the south; see details in Andréfouët et al. 2001)

difference at the oceanic edge of the sampled rims, a different mean depth, or a different exposure. Finally, to compute R_r, we applied the adequate equation F_r vs H_{sat} for each type of rim, and summed the different rims to obtain the total overflow for each atoll. For rim 3 (without in-situ flow measurements) present in southern sections like rim 4 (Andréfouët et al. 2001), we applied the rim-4 model.

Renewal time vs wave height

Relations between renewal time R_r and wave height H_{sat} were computed for more than 30 atolls, assuming a southern swell (dominant all year long) ranging from $H_{sat} = 1.5$ to 3.5 m. Results for representative atolls are presented in Fig. 5. Renewal times vary from typically less than one day, for very open and shallow atolls (Tekokota) which could be likened to barrier reefs, to several tens of days for semi-open, moderately deep atolls (Tikehau), increasing to several years for closed (Takapoto) or very large and deep (Rangiroa) atolls.

Renewal time is the lower limit of turnover time (see definitions) and, because of the complexity of the circulation inside a lagoon, any extrapolation from renewal time to turnover time is conjectural. An example is provided by numerical experiments performed on Mururoa, a mid-sized deep atoll (Tartinville et al. 1997). Water inputs through spillways lead to higher simulated turnover times, since the incoming flow exits directly through the large pass and the central lagoon water outflow is significantly reduced (Tartinville et al. 1997). Such behavior cannot be captured by our renewal time. Using 3D numerical modeling, turnover times have been estimated for Mururoa (Tartinville et al. 1997) and, with the same method, for Fangataufa (International Atomic Energy Agency 1998). Average turnover time was 30 days for Fangataufa and 100 days for Mururoa, and these two values are very consistent with our renewal time (Fig. 5). The "residence" times published for several atolls, and derived by various other methods, are

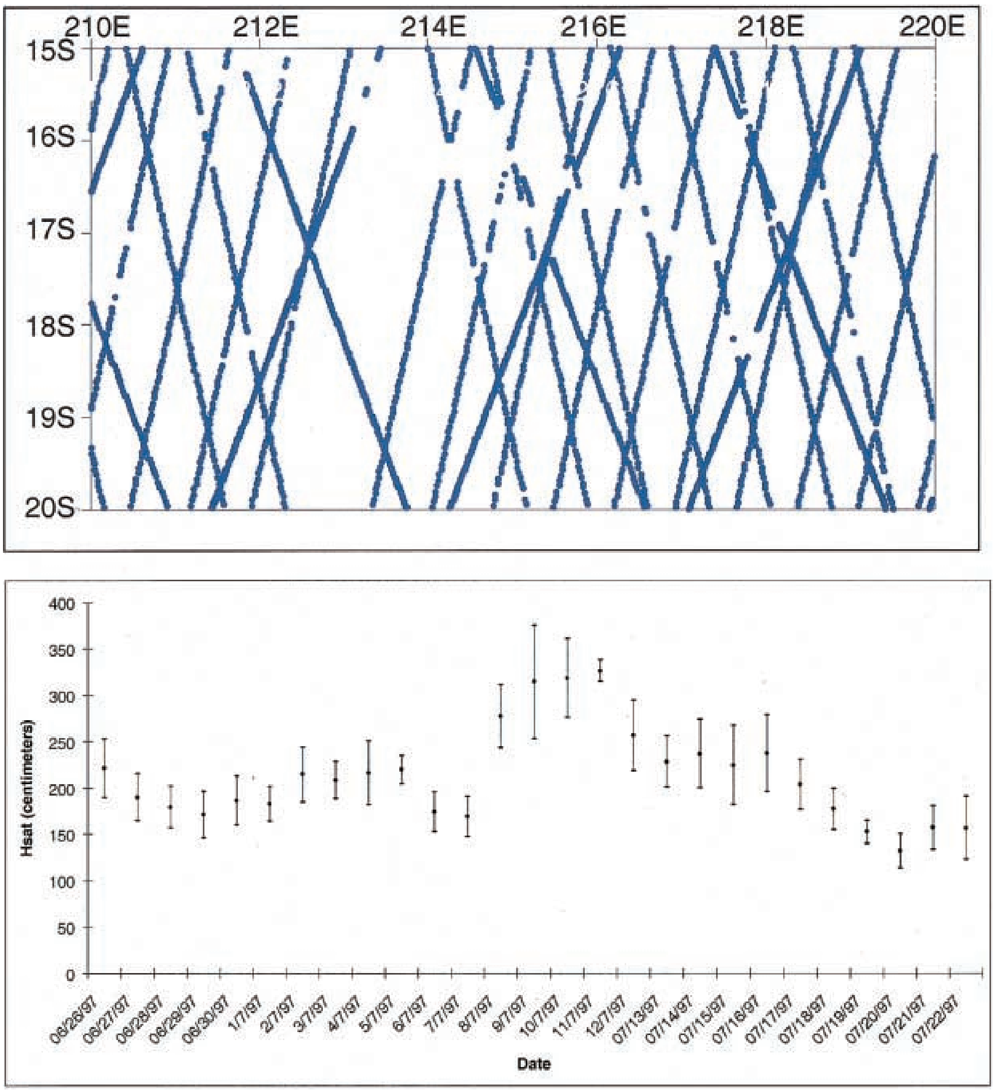


Fig. 3 *Top* Topex and ERS-1 satellite tracks at 10–15°S and 210–220°E during July 1997. *Bottom* For the same area, daily average and standard deviation of H_{sat} (m) from 26 June to 22 July 1997, a period when several surveys occurred for the PGRN2 program

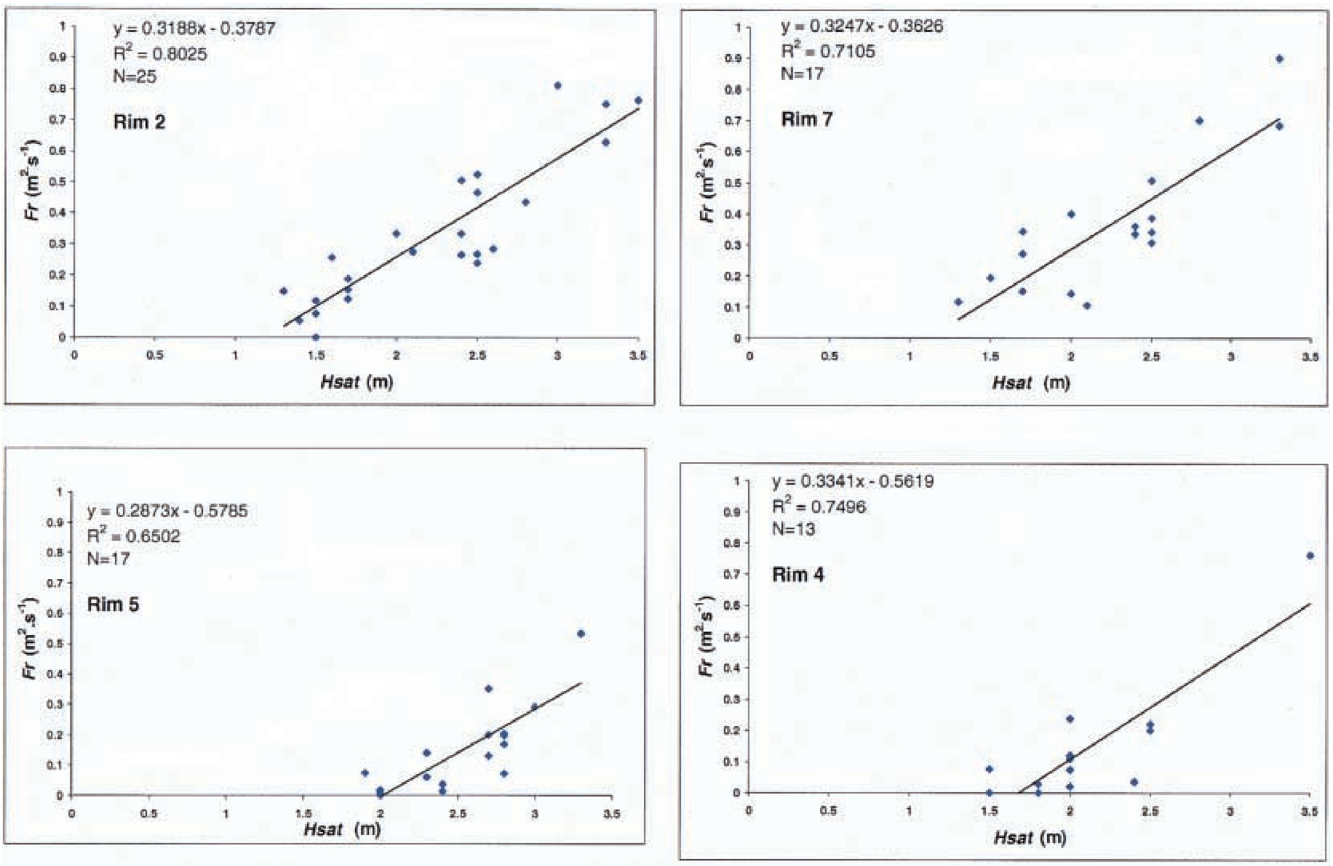
also comparable with our renewal time for wave height near the lower bound (1.5–2.0 m) of typical wave heights for this region, i.e., at Takapoto (2,190 days, Sournia and Ricard 1976), Mururoa (23–92 days, Rougerie et al. 1984), Mataiva (73 days, Wolanski et al. 1994), and Tikehau (105–230 days, Lenhardt 1991). Our method for estimating renewal time is a simple procedure and gives an estimate of exchange with the surrounding ocean which should be adequate for the classification of atoll lagoons proposed here.

Rangiroa and Hikueru, which are representative of asymmetric atolls whose southern regions are very open, display a bimodal functioning. Below or above H_{sat} values in the order of 1.7 m (south-direction swell), the renewal rates quickly rise or fall, respectively. As soon as a small swell encounters similar atolls, R_r quickly decreases to typically a few hundred, or a few tens, of days. Since very calm weather is not the norm in French Polynesia, high renewal time for open atolls should be atypical. However, it seems that there exists a threshold H_{sat} at which an atoll could shift into a drastically different functioning mode and become a different system, closed or open (Hatcher 1997). Confinement conditions adequate for the development of phytoplanktonic blooms could be favored in specific atolls when H_{sat} remains below this threshold value over a significant period. This could be related to events at Hikueru atoll in 1994, where a phytoplanktonic bloom occurring after a period of calm weather (Harris and Fichez 1995) had deleterious effects on benthic and fish communities (Adjeroud et al. 2001). The sensitivity of the atoll to such a threshold depends on the average depth and presence/absence of passes.

Relevance of renewal time for atoll lagoon classification

Long-term statistics of significant wave height could be used to infer the spectrum of renewal time for each atoll and to derive the average renewal time over various time scales. This would allow comparisons of atolls based on biological processes for various inherent time scales, such as productivity, recruitment, or maintenance of biodiversity (Hatcher et al. 1987). Here, we compare atolls according to total chlorophyll-a concentration (C), an indicator of phytoplanktonic biomass. Protocols and sampling scheme for chlorophyll estimations are detailed elsewhere (Dufour and Harmelin-Vivien 1997; Pagès et al. 2001). Data represent 19 atolls visited during the Typatoll and PGRN2 programs. Phytoplankton biomass is generally considered to be spatially homogeneous in atolls (e.g., Takapoto in

Fig. 4 Relationships between wave height H_{sat} (m) and specific flows F_r ($m^2 s^{-1}$) at daily scale for four types of open atoll rims encountered in Tuamotu Archipelago (from *top-left* to *bottom-right*: rim types 2, 7, 5, and 4



Delesalle et al. 2001). However, short-term temporal variations at atoll scale may be important depending on weather conditions (Delesalle et al. 2001), and blooms have been reported on several occasions. This temporal variation justifies an approach based on variation of renewal rate.

Two strategies are possible:

1. Since dates of each sampling operation are known as well as H_{sat}, we can compare R_r and C on a day-to-day basis. However, the relevant time scale for C is typically a few days (Hatcher et al. 1987);
2. As pointed out by Furnas et al. (1990), phytoplankton biomass depends not only on renewal rate but also on variations of renewal rate. Therefore, a day-

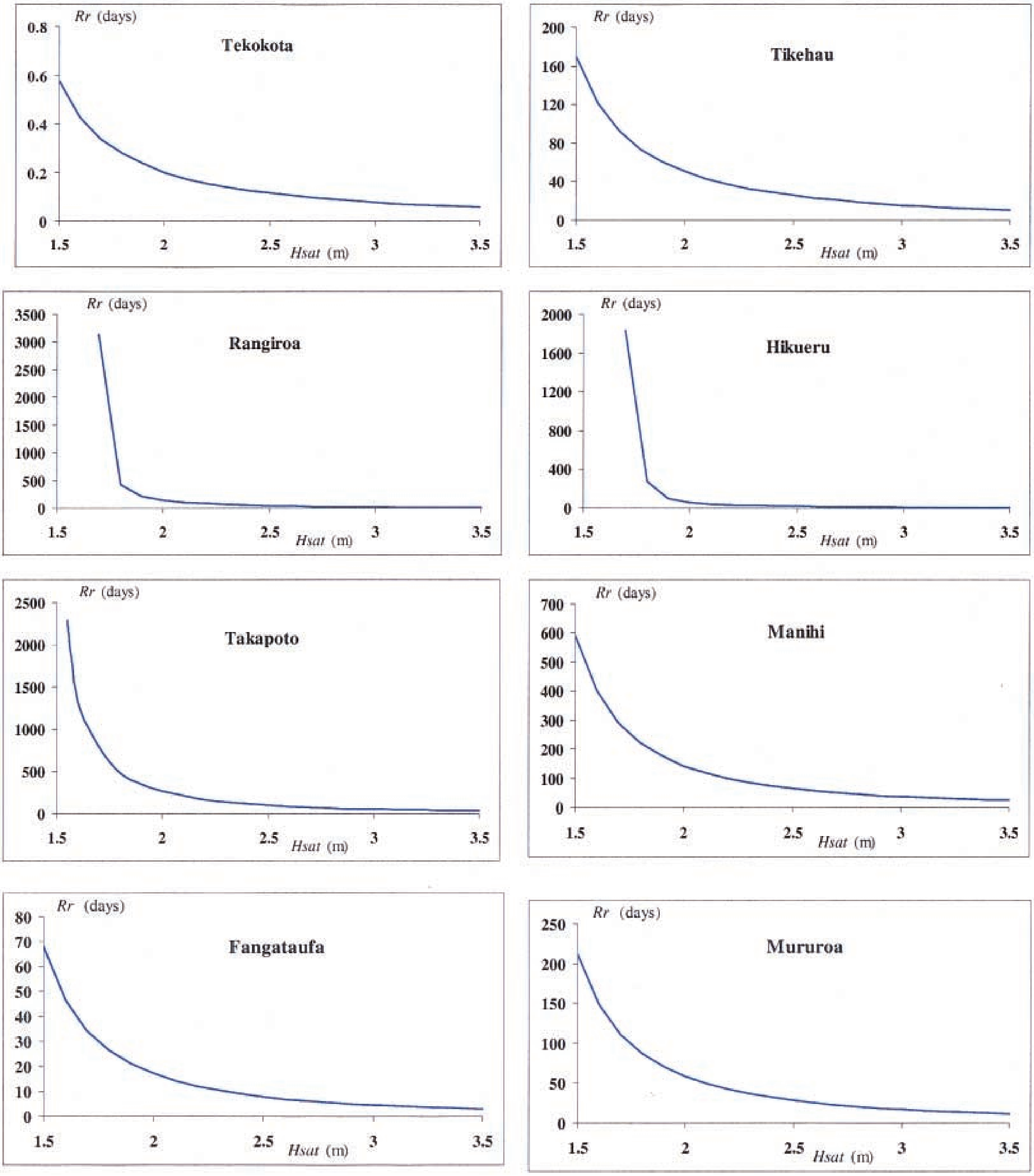


Fig. 5 Relationships between renewal time R_r (days) and significant wave height H_{sat} (m) for several representative atolls

by-day comparison is risky. Indeed, if there is a fast change (a few hours) from high- to low-swell conditions (and this happens frequently), it is possible to measure during the first day of low swell a low C resulting from previous days of high flushing rate. Such an observation would contradict the expectation of higher concentrations during calm conditions (Furnas et al. 1990; Delesalle and Sournia 1992). Therefore, for a given day of C measurement, we account for temporal variation in H_{sat} over the preceding days, with attention to high variation in H_{sat}.

Of three Typatoll cruises (Dufour and Harmelin-Vivien 1997), two occurred during periods when H_{sat} was not available (November 1994 and 1995). Thus, we used only C measurements from the last cruise in March/April 1996, for 11 atolls. PGRN2 provides data for eight atolls, some sampled twice. In most cases, there was no correction to apply, since the days of C measurements fell on a continuous smooth H_{sat} time series. In one case, for Takaroa in May 1998, we have high C (average ± SD = 0.7 ± 0.2 μg l^{-1}) in the entire atoll with relatively high renewal rate ($H_{sat} = 3$ m), but it immediately followed a period of calm weather. We used $H_{sat} = 1.7$ m for this period.

Figure 6 presents R_r vs C. Considering all data, there is no significant relationship, but two trends are apparent. One trend (triangles) includes atolls with short renewal times ($R_r < 5$ days) and C ranging from 0.21 to 0.99 μg l^{-1}. It involves (sorted by decreasing C values) Mataiva, Haraiki, Reka-Reka Tekokota Hiti, and Tepoto Sud. These are all small atolls (lagoon surface areas less than 25 km^2). The second trend (circles) includes larger atolls with R_r ranging from 10 to 130 days, and C ranging from 0.14 to 0.71 μg l^{-1}. Considering only the second group, there is a significant linear relationship ($C = 0.004 \times R_r + 0.119$, $R^2 = 0.63$, $n = 16$, $p < 0.001$). Hiti and Tepoto Sud may be also included in

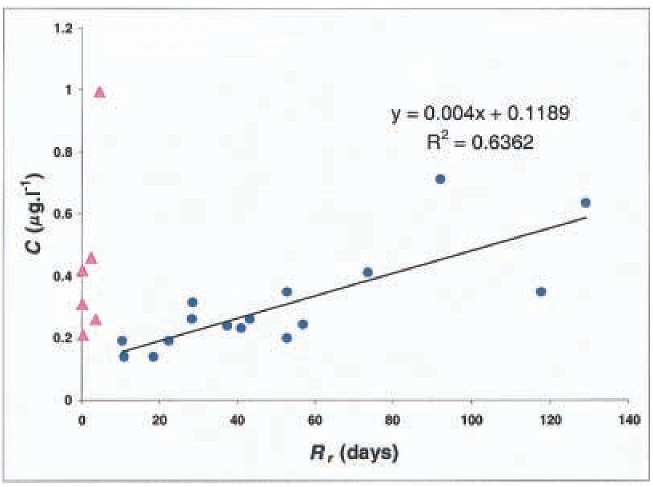


Fig. 6 Relationship between C (μg l^{-1}) and renewal time R_r (days). The regression line is for the atolls with lagoon areas larger than 25 km^2 (*closed circles*)

this group, without greatly affecting the model ($C = 0.003 \times R_r + 0.149$, $R^2 = 0.60$, $n = 18$, $p < 0.001$). These two atolls might actually be considered as transitional between the two groups.

The relation for large atolls can be compared with the one of Delesalle and Sournia (1992) who reported $C = 0.0336 + 0.0163T$ (R = 0.69, $n = 9$, T = residence time). Delesalle and Souria (1992) used both barrier reef and atoll lagoons from the Pacific, and therefore included reef systems forced by different hydroclimates. Their T was either a residence time or a turnover time. Finally, C and T were not measured simultaneously in most of the cases. Therefore, direct comparisons are difficult. However, our findings complement their relation considered as a "general trend," rather than as a "strong relation" for a specific oceanic region.

The group of small atolls clearly has a different behavior from the group of larger, deeper, and more open atolls. There are 32 atolls with lagoon surface areas less than 25 km^2 among the 72 Tuamotu atolls (for which the lagoons are not dry, filled, or uplifted). Mataiva is a reticulated atoll with numerous basins. It is the only atoll for which a spatially heterogeneous phytoplanktonic biomass has been consistently reported. The highest diversity in morphology is encountered in the group of small atolls, whereas larger atolls tend to be more similar (Andréfouët 1998). For both logistic reasons (airports or passes allowing easy access) and economic reasons (most populated and active atolls), studies of Tuamotu atolls tended to be focused on the larger atolls. An example is Takapoto, because of its pearl oyster industry, although it is not representative of the majority of atolls (Andréfouët 1998; Pagès et al. 2001). Typatoll results systematically highlight the atypical behavior of small atolls among a group of 11 atolls. This is in agreement with the present study which included 19 atolls. Therefore, we suggest that highest diversity of mechanisms linking physical factors, and biological behavior, could be found in a study focusing on the smaller atolls. Morphology is more diverse, from very open to completely closed atolls like Taiaro (Leclerc et al. 1999). The influence of the bottom could be more easily assessed, since maximum depths range from a few meters to 25 m. Land influence is also quantifiable because the ratios between lagoon and land areas vary widely for small atolls. On the other hand, time scales for water-column processes are likely to be less than a day, with rapid variations due to forcing fields not accounted for in this study (wind and tide), requiring higher sampling and monitoring rates.

Conclusions

This study sought to prove the validity of using an integrated hydrodynamic variable for a broad classification of reef systems. We used the traditional concept of residence time (Soballe and Kimmel 1987). Unfortunately, circulation patterns inside lagoons cannot be measured, or modeled, for a large set of atolls because of logistical and cost limitations. We followed a less demanding strategy, easily applicable to many sites, of studying the renewal time of lagoonal waters due to the rim overflow on a daily time scale, which is a process driven by the oceanic swell environment. The major drawback of such an approach is that it can lead only to reconnaissance-level results, and is a precursor to using more sophisticated and accurate tools and methods. However, the concept is applicable to a large set of systems, thanks to the availability of remote-sensing data and assuming some in-situ data. Renewal time was computed for a large set of atolls according to one hydroclimate forcing variable (wave height) and two morphological variables (degree of aperture of lagoons, volume).

The utility of renewal time for the classification of atolls was tested using phytoplanktonic biomass (total chlorophyll-a concentration) as an indicator, and this was known for 19 atolls. The data ranged from 0.1 to 1 $\mu g\ l^{-1}$ for biomass, and from 0.1 to 130 days for renewal time. We have shown two distinct groups of atolls: a group of small atolls where biomass and renewal time are not linked in a simple way, and a group of larger atolls (lagoon surface areas greater than 25 km^2) where biomass and renewal time are linearly related. This type of conclusion was part of our general objective of highlighting general trends, and the existence of individual atypical systems within a large set of systems. It leads to a more objective definition of which sites should be instrumented for more detailed studies (e.g., Kench 1998) and numerical modeling (Tartinville et al. 1997; Kraines et al. 1999; Hearn and Atkinson 2000).

The results presented here for South Pacific atolls are not directly applicable to Indian Ocean or Caribbean atolls, but a similar methodology could be applied accounting for specific morphologies and forcing hydroclimates.

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