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REPORT

J. Pagès · S. Andréfouët

A reconnaissance approach for hydrology of atoll lagoons

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Abstract As a reconnaissance tool of the hydrology of atoll lagoons in the micro-tidal environment of the Tuamotu Archipelago, we define and compute "potential" flow rates at lagoon scale under three swell regimes (high, average, and low swell) after assessment of orientation and width of reef-flat spillways using satellite images. As a direct test, the "potential" flows were compared with field measurements of (1) measured inflows across the reef flat (for eight atolls), (2) net outgoing flow through the pass (for three atolls), and (3) lagoon-level variation rates (for four atolls). Absolute values of "potential" and field flows agreed ($r^2 = 0.94$, $n = 42$, slope ~1). Computed average water renewal times (T_{RAV}) were also tested against concentrations of dissolved organic matter (DOM). DOM and T_{RAV} were positively correlated ($r^2 = 0.54$, $n = 26$; Spearman's $r_s = 0.54$), and this relationship should enable the detection of unusual atolls. This approach would then appear to be useful for the reconnaissance of hydrodynamics processes in comparable micro-tidal environments.

Keywords Water renewal · Waves · Remote sensing · Hydrodynamics · Flow rate · Dissolved organic matter

Introduction

In aquatic environments, biological processes, especially planktonic ones, are partly controlled by physical factors. In the course of a research program devoted to atoll lagoons, TypAtoll (Dufour and Harmelin-Vivien 1997), we tried to find out whether the biological and chemical differences found in 10 different lagoons might be explained, at least in part, by their hydraulics. This hypothesis was followed up, and the data base enlarged and improved with seven other atolls, in the course of a subsequent program, the Programme Général de Recherche sur la Nacre (PGRN2), dealing with pearl-oyster culture and environment.

Material conditions during both programs precluded the usual approach of hydrodynamic modeling and in-situ validation. With similar goals, in a companion paper Andréfouët et al. (2001b) propose to classify Tuamotu Archipelago atolls by a water renewal time computed using:

1. Detailed knowledge of the structure of atoll rims (from high-resolution satellite images);
2. Statistical relationships between water flow along spillways and wave height for each type of atoll rim;
3. Wave height (H_{SAT}) estimated using satellite altimetry.

Though conceptually simple, this approach still requires a complex pre-characterization of the interface between ocean and lagoon (i.e., structure of the rims; see Andréfouët et al. 2001a) as well as a good knowledge of the variation of wave regimes with time. However, a relevant shortcut to the rim structure is provided by the total aperture of the atolls (i.e., the sum of the wet sections of the atoll rim) along sectors of different exposure. The wave regime can be simplified by considering only the principal wave-height modes and the long-term distribution of wave direction.

Therefore, we propose here an even simpler approach than that of Andréfouët et al. (2001b) to estimate what could be the "potential" flows into lagoons. We use:

1. Total aperture of atolls (from remote-sensing images);
2. Long-term distribution of wave direction;

J. Pagès (✉)
Institut de Recherche pour le Développement (IRD),
Centre de Tahiti, P.O. Box 529,
Papeete, French Polynesia
E-mail: pages@ird.pf
Tel.: +689-506200
Fax: +689-429555

S. Andréfouët
University of South Florida,
Remote Sensing Biological Oceanography Laboratory,
College of Marine Science,
140 7th Av. South, St Petersburg, Florida 33701, USA

3. Minimum and maximum specific flows measured in the field during several fieldtrips, representative of two swell regimes ("minimum" energy with $H_{SAT} < 1.5$ m, "maximum" energy for $H_{SAT} > 3.5$ m).

These "potential" fluxes, computed at the scale of the entire lagoon, can be compared to various actual ("field") measurements. Finally, the interest of this approach is tested by comparing an average renewal time with measured water characteristics for 26 atolls. Andréfouët et al. (2001b) use total chlorophyll concentration, but here we use a proxy for dissolved organic matter concentration as another bulk indicator of the state of the lagoonal waters.

Methods

Study sites and atoll morphometry

Most atolls studied here are located in the northwestern and central part of the Tuamotu Archipelago, where the semi-diurnal tide has an amplitude of about 0.3 m (spring tides), increasing eastwards to 0.8 m in Mururoa, some 1,000 km away. Most of the atolls are organized along the classical schema of a chain of low sand islets (the "motu") strung around the lagoon. These cays are separated by shallow (~0.3–0.6 m) reef-flat spillways (the "hoa"). A deeper pass, allowing entry of ocean-going ships, may also be present (see Table 1). Land runoff is practically nil on these low islands. Andréfouet et al. (2001b) review the water renewal processes for atolls of this region. To sum up, waves breaking on the reef crest create a setup on the reef flat. A portion of this water flows into the lagoon (Gourlay 1996; Hearn 1999) through the hoa, representing the main part of water exchange between the ocean and atoll lagoons. It must be stressed that the main forcing factor for water renewal over the time scale considered here (days) is the swell regime and not the tide regime.

Using SPOT images, we can assess, along any sector of a given atoll, the wetted width and orientation of hoa corresponding either to "minimum" swell energy, L'_{min}, or to "maximum" swell energy, L'_{max}. This gives the variation of the total atoll aperture with swell conditions.

Swell regime

A compilation of ship observations by NOAA (Anonymous 1979) shows dominant swells from the S-SW. These data yielded a distribution of wave energy (in percent of occurrence) among eight sectors:

N	NE	E	SE	S	SW	W	NW
4.7	9.6	17.1	22.6	16.0	17.9	5.0	3.0

To estimate the main wave-height modes, we also considered satellite (Topex/Poseidon and ERS) wave-height data (from http://www-ccar.colorado.edu/~realtime/global_data_waves/wave.html) available since June 1996. We collected these data for the period March 1997–September 1998 in a square at 207–217°E and 9–20°S. We found an average significant height, H_{SAT}, of 2.0 ± 0.5 m (median of 2.1 m), without any seasonal trend. We can separate three classes of swell height: "minimum" energy with $H_{SAT} < 1.5$ m, "maximum" energy for $H_{SAT} > 3.5$ m, and an "average" class which is in between the other two. H_{SAT} data were also collected during most of the field measurements described below.

Table 1 Overall characteristics of the lagoons studied. *Area* Lagoon surface area (km^2). *Z* Average depth (m). T_{RAV} Water renewal time under average swell conditions (days). A_{254} Absorption of light at 254 nm (m^{-1}; lagoon average and standard deviation SD). Atolls in the TypAtoll program (*underlined*) were visited in November 1994, November 1995, and March 1996. Dates for other atolls are given in Table 2

Atoll	Pass	Area (km^2)	Z (m)	T_{RAV} (days)	Av A_{254} (m^{-1})	SD A_{254} (m^{-1})
Ahe	Yes	145	50	34	0.72	0.10
Amanu	Yes	210	30	39	0.51	0.05
Anaa	No	106	4	9	0.83	0.09
Apataki	Yes	683	33	101	0.70	0.08
Arutua	Yes	516	35	60	0.73	0.14
Fakarava	Yes	1,112	45	75	0.66	0.13
Hao	Yes	497	40	90	0.62	0.08
Haraiki	No	10	14	3	0.83	0.12
Hikueru	No	82	25	37	0.76	0.10
Hiti	No	15	10	3	0.77	0.03
Kauehi	Yes	315	35	77	0.50	0.05
Makemo	Yes	603	18	15	0.72	0.08
Manihi	Yes	165	30	130	0.91	0.21
Marokau	No	217	30	55	0.63	0.04
Mataiva	Yes	25	4	21	1.34	0.29
Nihiru	No	79	20	17	0.70	0.05
Rangiroa	Yes	1,592	45	155	0.62	0.06
Rekareka	No	0.7	1	81	1.41	0.16
Tahanea	Yes	545	45	59	0.47	0.01
Taiaro	No	12	15	1,761	2.34	0.24
Takapoto	No	81	25	268	1.02	0.25
Takaroa	Yes	89	30	76	0.78	0.17
Tekokota	Yes	5	3	0.3	0.42	0.06
Tepoto S	No	2	5	0.6	0.66	0.16
Tikehau	Yes	394	28	60	0.53	0.08
Tuanake	No	26	25	17	0.57	0.02
Ocean					0.37	0.01

Field measurements and definition of "potential" flows

Field operations have been under way since 1995 (see Tables 1 and 2 for dates). We determined flow rates in numerous hoa (a minimum of 10–12, sometimes up to 50) on each atoll of the PGRN2 program. These measurements extended over at least several hours on a given day (between 3 and 6 h), hence covering various stages of the tide. Our repeated measurements of flow rate, made on a given day along a sector of a given rim type, were then extrapolated to the total length of reef with the same characteristics (including orientation relative to the swell on this particular day). The sum of these extrapolations gives a total "extrapolated" flow (mostly incoming) for the whole atoll.

From our set of measurements, we estimated the maximum and minimum specific flow rates (flow rate in m^3 s^{-1} divided by hoa wetted width in m). We also weighted the aperture distribution (L'_{max} and L'_{min}) of each atoll by the wave-energy frequency obtained from the NOAA data. The maximum and minimum specific flow rates were applied to the weighted L'_{max} and L'_{min} apertures, giving a maximum "potential" flow ΣQ_{max} (for high seas) and a minimum "potential" flow ΣQ_{min} (for very calm seas). The geometrical mean of these two extreme values, ΣQ_{AV}, corresponds to the average swell conditions. T_{RAV}, the average renewal time, can be computed as the ratio of lagoon volume (Andréfouët et al. 2001b) to ΣQ_{AV}.

To validate the "potential" flows, besides the "extrapolated" flows (see above), two types of integrated in-situ measurements can be considered:

1. Lagoon level was monitored in several lagoons, with discrete readings (about every 2nd day) on a graduated scale (arbitrary datum). The variation of level represents the net balance between inflow (across the reef) and outflow (through the pass if one exists, or through hoa on the lee side).

2. Current speed and direction have been recorded in some atoll passes by the Service Hydrographique et Océanographique de la Marine (SHOM). These recordings, kindly made available to us, generally showed a tidal signal, which is expected in atoll passes (see Andréfouët et al. 2001b for general circulation scheme in atolls). The net outflow during a tidal cycle must be equal to the inflow across the reef during the same period.

Finally, several water characteristics were assessed in the course of the various research programs. Among others, we determined light absorption at 254 nm, A_{254}, by spectrophotometry (Pagès et al. 1997), either on fresh samples or on frozen samples brought back to the laboratory in less than a week. The value of A_{254} is well correlated with the concentration of natural dissolved organic matter (Pagès et al. 1997).

Results

Measurements of flow rates through the hoa covered a total of ~250 km of reef crest (see dates in Table 2) but the coverage was variable, depending on the atoll size (4–8% of perimeter on Rangiroa or Fakarava, but 34% on Takaroa). Apart from three isolated cases, all hoa inspected during the study showed ingoing flow. The results gathered on a given day, along a given segment of reef face, have been extrapolated to the whole reef length of the same type, then summed for the whole atoll. These "extrapolated" flow rates, varying with atoll size, aperture, and swell, range between 8 $m^3 s^{-1}$ on Takapoto under very low swell conditions and ~10,000 $m^3 s^{-1}$ on Apataki under high seas.

Our measurements in the hoa, made under widely differing swell and tide conditions, gave us a "minimum" specific flow rate of 0.012 $m^2 s^{-1}$ (flow rate in $m^3 s^{-1}$ divided by hoa wetted width in m). We could not directly observe a "maximum" specific flow rate corresponding to a true maximum swell ($H_{SAT} > 3.5$–4.0 m), but our few measurements under heavy swell conditions indicated a plausible peak flow of 2 $m^2 s^{-1}$. These specific flow rates were applied to the weighted L'_{max} and L'_{min} apertures, giving a maximum "potential" flow ΣQ_{max} (for high seas) and a minimum "potential" flow ΣQ_{min} corresponding to very calm seas. The geometrical mean of these two extreme values, ΣQ_{AV}, corresponds well to "average" swells (H_{SAT} ~1.5–2.0 m). Absolute values of average "potential" flow ΣQ_{AV} range between 50 and 3,000 $m^3 s^{-1}$ (Table 1). For most atolls studied here, we find that ΣQ_{min}, ΣQ_{max}, and ΣQ_{AV} are correlated with lagoon area, in the same way that aperture (either L'_{min} or L'_{max}) is correlated with lagoon area. Since average depth also increases with atoll size, lagoon volume shows an overall correlation with potential flow rates (r^2 ranging between 0.55 and 0.62, with $n = 29$), at least with the atolls studied here (Tables 1 and 2).

In the passes, SHOM recordings show several instances of currents reaching 8 knots (4 $m s^{-1}$), flowing outwards even at low tide during times of very high swells. In the pass of Raroia, net outflows (computed for a tidal cycle) increase with H_{SAT} ($r^2 = 0.55$ for $n = 37$; Fig. 1). We note that net flow in this pass is nil for H_{SAT} of about 1.4 m, an offset also noticed and discussed in Andréfouët et al. (2001b).

Table 2 Comparison of computed "potential" flow rates with measured "field" flow rate estimations (all values in $m^3 s^{-1}$)

Atoll		Extrapolated flow	Pass flow	Lagoon-level flow	Potential flow
Ahe	Max				1,563
	Av				731
	Min	229[a]			342
Apataki	Max	10,850[b]	7,000[c]		9,070
	Av				2,573
	Min				730
Arutua	Max	4,616[d]			12,577
	Av				3,489
	Min	402[d]			968
Fakarava	Max			22,704[g]	25,573
	Av	11,352[e]			7,669
	Min	1,080[f]			2,300
Hao	Max			11,505[i]	12,940
	Av		4,986[i]		2,571
	Min	686[h]			511
Manihi	Max			267[z]	2,149
	Av	610[k]		66[z]	445
	Min	90[j]	75[k]		92
Mataiva	Max	169[l]	108[l]	116[m]	305
	Av		27[m]		72
	Min		18[m]		17
Rangiroa	Max		15,617[o]		18,169
	Av	8,152[n]	4,326[o]	4,299[z]	4,748
	Min	1,047[p]		973[z]	1,241
Raroia	Max		11,500[q]		10,666
	Av		7,200[q]		2,402
	Min		404[r]		541
Takapoto	Max			318[z]	809
	Av	64[s]		27[z]	80
	Min	7[t]			8
Takaroa	Max				2,340
	Av	556[u]			402
	Min				69
Tikehau	Max		4,600[w]	2,500[w]	8,904
	Av	3,545[v]	1,398[w]	226[w]	2,131
	Min				508
Toau	Max		47,000[x]		16,821
	Av		11,700[x]		5,040
	Min		2,400[y]		1,507

Dates of fieldwork (by J. Pagès except where indicated otherwise) and comments, [a]20–24 October 1999, [b]3–8 October 1999, [c]Probably underestimated, [d]26 August–3 September 1998, [e]5–15 June 1998, [f]4 11 July 1997, [g]8–9 June 1998, [h]27 November–4 December 2000, [i]SHOM, [j]23–30 April 1997, [k]21–26 July 1998 (J. Pagès, S. Andréfouët), [l]5–9 September 1999, [m]Delesalle (1985), [n]6–12 July 1998, [o]SHOM, 30 January–11 March 1980, [p]16–23 April 1997, [q]SHOM, 15–25 May 1994, [r]SHOM, 27 March–16 April 1997 ($1.4 < H_{SAT} < 2.1$ m), [s]22–26 August 2000, [t]15–22 March 1997, [u]15–22 July 1997, 21–28 May 1998, [v]21–29 August 1996, 2–8 April 1997, 21–28 June 1998, [w]21–29 August 1996 (Lenhardt 1991), [x]SHOM, 4–23 October 1995, [y]SHOM, 18–30 March 1995, [z]SRM, "Réseau" monitoring, 5 May 1997–18 February 1998

Apart from a dampened tidal signal when a pass exists, lagoon levels show large variations (often ~0.5 m, but up to 1.0–1.5 m in some cases) which can last several days.

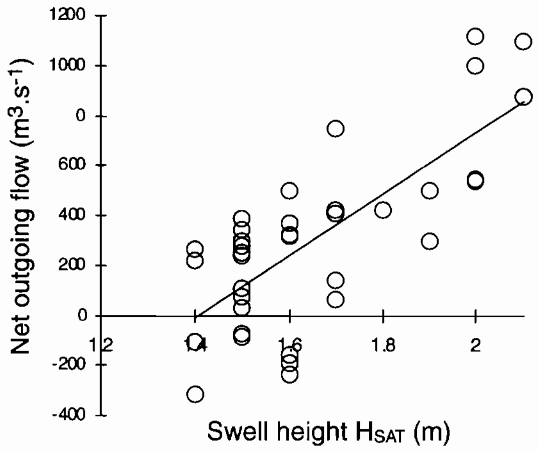

Fig. 1 Outgoing flow through the pass of Raroia in response to swell height (shift of 24 h to allow for lag)

Some of these variations may represent seiches, or wind setup, whereas the larger ones were caused by high swells. With several series of increasing swell (Fig. 2), a clear causal relationship exists between lagoon level and H_{SAT}, with coefficients of determination r^2 ranging between 0.72 for Takapoto ($n=6$; $P<0.05$) and 0.94 for Rangiroa ($n=6$; $P<0.01$). This increased level corresponds to an influx of oceanic water across the reef. Although we cannot know the simultaneous outgoing flow (through the pass, if any exists, or through leeward hoa), we can have an integrated estimation of ingoing flow rate.

Direct test of "potential" flows

Each "field" flow (D, be it "pass", "lagoon level", or "extrapolated") has been assessed under known wave conditions. We can then order each figure into one of the three broad swell categories, in order to compare it with either ΣQ_{min}, ΣQ_{max} or ΣQ_{AV}. This comparison (Table 2 and Fig. 3) indicates a relationship between computed "potential" flows, ΣQ, and "field" flows, D. The overall correlation is satisfactory ($r^2=0.94$ for $n=43$; $P<0.01$), with a regression equation indicating a good agreement in the absolute values themselves: $D=0.87\times(\Sigma Q)^{0.98}$ (slope not significantly different from 1; t test, $P<0.05$).

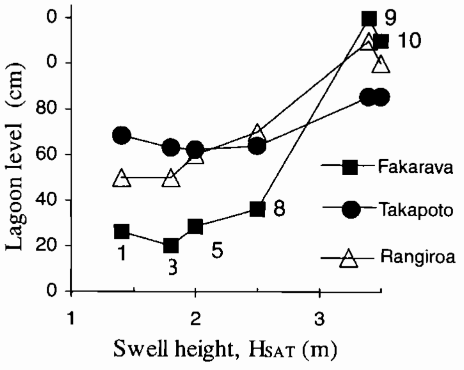

Fig. 2 Lagoon level in Rangiroa, Fakarava, and Takapoto versus swell height. *Numbers* along the Fakarava curve are the dates in June 1998

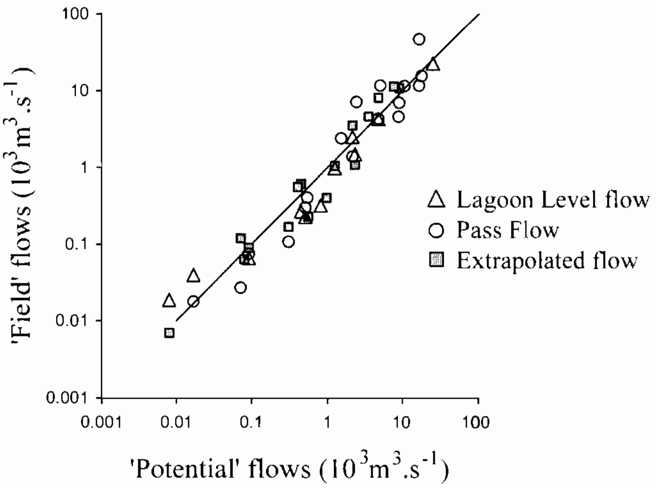

Fig. 3 Comparison between computed "potential" flows and the three classes of "field" flows: "lagoon-level flow", "pass flow", and "extrapolated flow". The *straight line* is the 1:1 ratio

In detail, this agreement persists for each category of "field" or "potential" flow rates, with coefficients of determination $r^2=0.94$–0.95 (with a power regression) for each category ($n=31$, 17, and 11 for "extrapolated", "pass", and "level", respectively), indicating that no particular set of "field" data would be a better test of "potential" values.

Indirect test of "potential" flows

Actual water characteristics, as measured in situ or on water samples, should provide a good test of water renewal rate, or of water residence time. Besides phytoplankton chlorophyll concentration (Andrefouët et al. 2001b), we can use dissolved organic matter, DOM, as estimated by in-vitro absorption at 254 nm, A_{254}. We should observe a positive correlation between average renewal time and A_{254}.

We found a general increase of DOM concentration with increasing renewal time (Fig. 4). A main series culminates in the lagoon of Taiaro ($r^2=0.54$ for $n=26$; $P<0.01$), and the trend remains significant ($r^2=0.50$ for $n=25$; $P<0.01$) even when ignoring this practically closed lagoon. The test of Spearman's rank correlation confirms the trend ($r_s=0.537$; $P<0.01$).

A parallel series of atoll lagoons shows a relative excess of DOM, with four lagoons (Anaa, Haraiki, Hiti, Tepoto) completed by Mataiva and Rekareka. Mataiva has been noted for its peculiar reticulated structure (Delesalle 1985), whereas Rekareka is merely very shallow. The common features of the other four atolls are their small sizes, but still more notably their shallowness (9.3 ± 3.8 m, against 28 ± 10 m for the other lagoons studied).

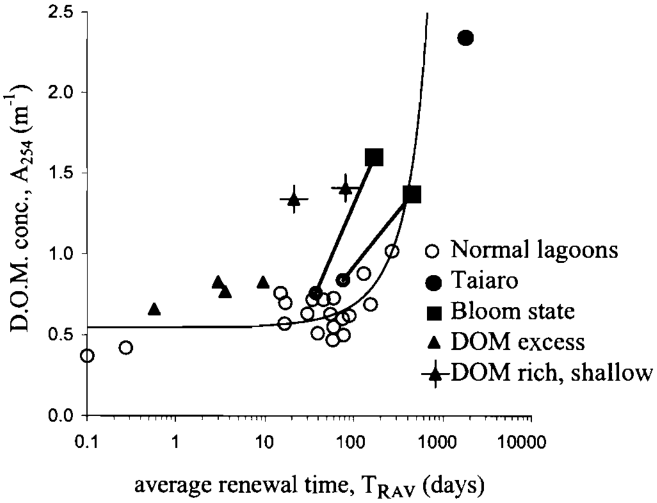

Fig. 4 Correlation between computed water renewal time and measured DOM concentration. The whole range of "normal" lagoons gives a significant regression (*thin continuous curve*) with or without the closed lagoon of Taiaro. The two *straight segments* join bloom state to "normal" state in Takaroa and Hikueru. The *crosses* mark Rekareka and Mataiva, two shallow DOM-rich lagoons which may be an extension of the DOM-excess group, all six being excluded from the overall regression

Discussion

One arguable point in our approach lies in the chain of calculations leading to "potential" flows, which is based on the distribution of relative swell energy among eight sectors. This stems from archive data, which do not account for possible climate variations (see Grevemeyer et al. 2000, in other environments). The resulting energy distribution agrees reasonably with the aperture of the atolls (most openings face south), but we nonetheless explored the possible effects of a different energy distribution. A relatively slight alteration of the percentage of energy coming from the south decreases all potential fluxes – with 45% of the energy coming from the south (instead of 60%), fluxes decrease to 70% of the present ΣQ values. This error would still be inside tolerable limits.

In our computation of "potential" flows (ΣQ_{min} and ΣQ_{max}), we have used fixed values of specific flow rates without considering possible effects of tidal amplitude or stage. This is justified since "field" flows incorporate, and smooth out, at least one tidal cycle. "Extrapolated" flows were based on measurements taken during several hours, and hence corresponding to various tidal stages. "Lagoon-level" flows were based on readings made throughout several days. "Pass" flows were explicitly net flow rates, each computed for one tidal cycle.

Among the various classes of "field" flow rates ("extrapolated", "pass", "lagoon level"), we did not find that any gave consistently better results when compared with "potential" estimations. The "pass" data would require a long deployment of somewhat heavy field equipment. The "extrapolated" data can be collected using rudimentary equipment, but the time required in the field might be a drawback. The "lagoon-level" data also need very simple equipment, but numerous local assistants (between one and three people on each atoll) and a long period of observation. The three sets of data, each with its advantages and drawbacks, are thus mutually complementary. Testing our "potential" flows against published results would seem elementary, but the few existing studies seldom mention which wave climate had prevailed during the measurements. In the particular case of Takapoto atoll, most of the numerous measurements done by various teams obviously corresponded to very low swell conditions (Pagès et al. 2001).

Among water characteristics, salinity is the most immediate tracer of the past history of a water body which exchanges H_2O with the atmosphere. The determination of residence time from salinity has been carried out in some atoll lagoons (e.g., Smith and Jokiel 1978). In the present set of lagoons, this method would not be very effective, not least because of the very narrow range of salinities (36.0–36.3 p.s.u. for the ocean, 36.3 ± 0.4 p.s.u. in most TypAtoll lagoons, 38.6 ± 0.3 p.s.u. for Takapoto, 43–44 p.s.u. in Taiaro). The main difficulty, though, lies in cross-reef flows. Even in Takapoto, with its low exchange rates, salinity variations could be explained by rainfall and evaporation only when taking into account a sizable exchange of oceanic water (Pagès et al. 2001). Therefore, we had to estimate lagoonal renewal rate by another method (Andréfouët et al. 2001b).

Similarly to what Andréfouët et al. (2001b) observed for phytoplanktonic biomass, we note outlier atolls in the general trend DOM vs T_{RAV}. Six lagoons have "excess" DOM relative to their renewal times (Fig. 4). The two extreme members hint at supplementary DOM sources from the bottom. Microphytobenthos is a definite possibility in Mataiva (Delesalle 1985), and release from bottom sediments is probable in Rekareka, with its depth of 1.5 m. A similar bottom effect can be supposed for the other four atolls. Their small sizes, and especially their shallowness, result in a relatively more important solid/liquid interface and a stronger influence of the bottom (including increased photosynthesis under higher incident light). The reef edge can also acquire a relatively stronger influence on the lagoon, as shown in the lagoon of New Caledonia (Clavier et al. 1995). However, these side effects, although not negligible, do not undermine the general trend of increasing DOM with increasing renewal time. They only show that some circumspection is required. Conversely, both transitions between "normal" situation and bloom situation (Hikueru and Takaroa atolls) follow the general trend. In this vein, minimum potential flow ΣQ_{min} may be viewed as an estimator of risks. For a given lagoon, water renewal time under low swell conditions could be predicted, and hence the probable size of a bloom leading to dystrophy.

Chromophoric dissolved organic matter has been the subject of numerous studies often focusing upon its geochemical role, also as substrate for heterotrophy. Here, along with the study of Williamson et al. (1999), we consider DOM as an integrating descriptor of a water body. Its accumulation results from diverse biological activities, as seen in other environments by Fasham et al. (1999). In atoll lagoons, DOM mostly reflects planktonic processes (but see below) and is well correlated with phytoplanktonic chlorophyll concentration ($r^2 = 0.46$ for 28 lagoon averages; Pagès, unpublished data). This correlation is plausible in view of exudation by phytoplankton, and of sloppy feeding and excretion by various heterotrophs preying on phytoplankton. It has been shown that heterotrophic activity, and especially bacterial activity, is relatively less important in "rich" waters, compared with autotrophic production. This concept of the "inverted trophic pyramid" proposed by Dortch and Packard (1989) has been confirmed by recent studies (Conan et al. 1999; Lovejoy et al. 2000). We may then accept that DOM accumulates as a function of residence time, each lagoon representing a steady state in the gradient of residence time and trophic state. The ranking of lagoons in a gradient of water renewal time derived from "potential" flow rates is thus mirrored by their place inside a trophic gradient. The good agreement between computed flows and actual characteristics shows that our relatively rough approach, although remaining a reconnaissance tool, allows the rapid processing of a large number of atolls, provided the environmental conditions (especially those of tide and swell) are comparable.

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