Calculations of hydrodynamic time parameters in a semi-opened coastal zone using a 3D hydrodynamic model

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Received 20 July 2005; received in revised form 9 November 2005; accepted 16 November 2005

Abstract

Hydrodynamic time parameters (HTs) in a semi-opened aquatic ecosystem are synthetic indicators offering the opportunity to bring out the links between its physical functioning and its biology. The generic term “residence time” is frequently used through literature to mention HTs resulting in various calculation methods. This article presents different computing methods relying on the use of a 3D numerical hydrodynamic model and the HTs to which they give access. Several large-scale (water exchange time, average water export time, e-flushing time) and local time parameters (export time, flushing lag, local e-flushing time) are defined. The applications presented are carried out within the south-west lagoon of New Caledonia (SLNC), on three embedded control volumes. The definition of the control volume is more important for the values of local HTs than for their comparative distribution. The comparison of the global hydrodynamic time scales applied to a control volume provides information on the mixing processes inside the control volume.

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Keywords: Residence time; Drifters; Flushing; Local e-flushing time; Tracer techniques; Mathematical model; Lagoons; New Caledonia

1. Introduction

The ecology of an aquatic ecosystem is strongly affected by hydrodynamics. The nutrient level, for example, depends on the speed at which the water is renewed, on the size of the retention areas, and generally on the circulation of the water masses. The level of turbulence is also an important factor for biological processes (e.g. the dissemination of larvae). Conversely, and in certain cases, biological activity can affect local hydrodynamics (e.g. the effect on turbulence and bed roughness inferred by the presence of benthic species). In order to obtain a better understanding of the interaction between hydrodynamics and biology, one must first identify the hydrodynamic processes likely to affect the ecology, and propose parameters or indicators for quantifying these processes.

Delesalle and Sournia (1992) adopted this approach and applied it to several coral reef lagoons. They revealed a relationship between phytoplankton biomass and a quantity characteristic of the exchanges between the lagoon and the open ocean which they called “residence time”. This quantity is...
one of the hydrodynamic parameters based on time, which are hereafter called hydrodynamic time parameters (HTs). HTs make it possible to analyse the kinetic of biological reagents or the movements of organisms with respect to the water masses. As an example, Crump et al. (2004) correlated the movement of bacterial populations along the salinity gradient in an estuary with an HT proposed by Vallino and Hopkinson (1998) which they called “residence time”; Pagès and Andréfouët (2001) showed a good correlation between an HT which they named “water renewal time” and dissolved organic matter in 10 lagoons of the Tuamotu Archipelago; Andréfouët et al. (2001) considered the possibility of using this same HT as a criterion for classifying atolls. To underline the strength of the relationship which might exist between certain HTs and biological conditions, Page` s et al. (2001) wrote: “Takapoto Lagoon fits into a gradient of water residence time that controls the overall trophic web organization”.

There is a certain amount of ambiguity in the naming of HTs. The term “residence time” relates to computation methods, which may not be the same between one study and another. The resulting parameters have a different physical significance, but are all referred to under the same name—which leads to debate (e.g. Andréfouët et al., 2003; Deleersnijder, 2003). Adding to the confusion, some studies using the same computation method refer to the same HT under different names. With this in mind, we have taken particular care in this article with the naming of the HTs we have calculated. For some of them, we do not use the names most frequently used in other publications. We are careful to point out and justify the names we do use, and mention the other names under which the reader may have encountered them elsewhere.

The aim of this article is to compare different HTs whose formulation makes use of the capabilities of a 3D hydrodynamic model. We do not discuss other computation methods, such as the resolution of an adjoint problem (Delhez et al., 2004a). Tests are carried out in a semi-opened basin, namely the south-west lagoon of New Caledonia (SLNC). Different HTs are calculated in three embedded control volumes so as to assess the sensitivity of each HT to the control volume on which it is calculated. Following a description of the study site (Section 2) and of the 3D model used (Section 3), we present our computation methods for the overall and local HTs (Section 4). Their applications to the embedded domains discussed in Sections 5 and 6 analyses their physical significance and complementarity.

2. The study site

New Caledonia is a tropical island located in the Western Pacific, about 1500 km east of Australia (Fig. 1). It is surrounded by a 23,400 km² lagoon. Noumea, the island’s main city and home to half of its population, is located on the south-west coast. The lagoon area which surrounds Noumea is known as the SLNC. Its depth averages 17.5 m. It varies in width from 5 km (northern limit) to 40 km (southern limit). It is separated from the open ocean by a barrier reef.

The ongoing integrated study of the SLNC investigates the space–time variability of its physical, chemical, biological and sedimentological parameters. It aims at assessing the impact of human activities (mines, industry, urban expansion, etc.) on marine ecosystems (e.g. Fichez et al., submitted; Fernandez et al., 2006). Concerning the physical dynamics of the lagoon, an analysis of measurements taken over a span of 5 years made it possible to distinguish between seasonal and inter-annual variability in temperature and salinity (Ouillon et al., 2005). A circulation and particle transport numerical model (MARS3D) was adapted to this particular area of the lagoon (Douillet, 1998; Douillet et al., 2001). In this article, the HT computations are performed over the whole of the SLNC as well as on two embedded sub-areas: the “Noumea lagoon” and “Dumbea Bay” (Fig. 2).

3. The 3D hydrodynamic model

The MARS3D hydrodynamic model calculates currents, free surface elevations and concentrations of dissolved substances under the influence of tide, wind and, where appropriate, river inputs. The MARS3D model is made up of two sub-models. A depth-integrated 2D model (Douillet, 1998), which solves the shallow water equations (Blumberg and Mellor, 1987), calculates the water elevation and horizontal velocity at all points. The elevation results of combined action of wind and tidal forcing. The tide is taken into account by forcing the sea surface elevation at the boundaries (Douillet, 1998) in accordance with the results of the algorithms provided by the French Navy’s Hydrographic Department (SHOM). The boundary conditions
are imposed far away from the domain of study. The elevation is prescribed as a function of time and the normal gradient of velocity is forced to zero at each grid point of the open boundaries.

The results of the 2D model are transferred to a 3D model which uses the same horizontal grid. The vertical axis (depths) is divided in \( \sigma \)-levels (Blumberg and Mellor, 1987; Lazure and Salomon, 1991a; Deleersnijder and Beckers, 1992), which implies changing variables \((x, y, z, t)\) into \((x, y, \sigma, t)\), where \(x\) and \(y\) are the horizontal coordinates of the point, \(z\) is the depth (m), and \(\sigma\) is defined as

\[
\sigma = \frac{z + h}{\zeta + h},
\]

where \(h\) is the bottom depth and \(\zeta\) is the free surface elevation. The 3D computation module solves the Navier–Stokes equations using the Boussinesq approximation and the hydrostatic equilibrium hypothesis. The turbulence model used is of the Pacanowski and Philander (1981) type. The bottom stress is parameterized by means of a quadratic function of the velocity
that is consistent with the existence of a logarithmic layer adjacent to the bottom (Blumberg and Mellor, 1987; Deleersnijder et al., 1992; Douillet, 1998). A wind friction condition is applied at the surface (Douillet et al., 2001). Open boundary conditions are the same than those applied in the 2D model (Neumann type for velocity, Dirichlet for water height). The MARS3D model also solves transport equations of dissolved and particulate matter (Douillet et al., 2001; Ouillon et al., 2004). The heat and salt transport module available in MARS3D are not used in the present study, the simulations here shown do not reproduce the thermo-haline stratification.

Solving is based on the Alternating Direction Implicit (ADI; Leendertse, 1967) method for time discretization, and on finite differences for spatial discretization. For advection, we use a Total Variation Diminishing (TVD) method, less diffusive than the upstream scheme. We use a grid of the modified Arakawa C type (Lazure and Salomon, 1991a). Arakawa C type grid is modified for what concerns water depths which are indicated at the same grid location as velocity components. The automatic handling of emerging tidal flats is the result of the combined use of a test during the ADI procedure and the above-mentioned grid modification. The velocity component which is perpendicular to the obstacle (dried bank) is set to zero and the test conserves the linearity of the equation of motion (Lazure and Salomon, 1991a, b). It makes it possible to process automatically channels, islands, shallows, drying banks and inter-tidal areas, which represent a significant portion of the lagoon area. Lazure and Salomon (1991a), Tartinville et al. (1998) and Plus et al. (2003) have presented examples of the use of this model. In this study, we use a $\Delta x = \Delta y = 500 \text{ m}$ grid spacing (Fig. 2) and 10 $\sigma$-levels.

4. HTs: definitions and computation methods

4.1. Water exchange time

For any given domain, the simplest general HT is the ratio between its total volume $V$ and the daily
volume flux $Q$ entering or leaving it:

$$\theta = \frac{\langle V \rangle_t}{\langle Q \rangle_t}. \quad (2)$$

In the literature, the parameter $\theta$ is frequently found under a variety of names: “residence time” (Gallagher et al., 1971; Delesalle and Sournia, 1992; Kraines et al., 1998, 1999; Rasmussen and Josefson, 2001; Gómez-Gesteira et al., 2003), “average residence time” (Pagès et al., 2001), “turn over time” (Takeoka, 1984), “flushing time” (Fisher et al., 1979; Geyer et al., 1997, 2000; Monsen et al., 2002; Delhez et al., 2004a), “water exchange rate” (Kraines et al., 2001) or “water renewal time” (Andréfouët et al., 2001).

On a given site, the value of this general HT depends directly on the arbitrary choice of the control volume (Bujan, 2000; Gómez-Gesteira et al., 2003). Space and time variability of the hydrodynamics within the control volume are not considered. This HT represents the length of time required for the entire mass of water to be replaced by input water, provided that all water particles have the same transit time through the control volume (Takeoka, 1984; Vallino and Hopkinson, 1998). To name this HT “renewal time” implies that this condition is met, which is not the case for a site where the hydrodynamics are highly heterogeneous. When large variations in hydrodynamics occur, the significance of this parameter is limited. Considering that this parameter quantifies the exchanges of a given body of water (a bay, a lagoon, etc.) with the surrounding environment, we chose to give it the name “water exchange time”. This HT is widely used when studying the relation between hydrodynamics and biology in a nearly enclosed system (Delesalle and Sournia, 1992) or as a criterion for the classification of coral structures (Andréfouët et al., 2001).

### 4.2. Water export time

The definition given by Takeoka (1984) for his “residence time” applies well to what we have chosen to call “water export time”: “the residence time at a given point in the lagoon is the period of time that a water parcel, initially located at the point considered, needs to leave the lagoon”. We feel that the name “water export time” is more explicit. Water export time is a local HT which means it is defined for each grid point.

The most suitable method for estimating the water export time uses a Lagrangian tracer model. Kraines et al. (2001), who introduced the term “export time”, applied it to settling particles. In this way, it was not strictly speaking an HT, but a time characteristic of particulate transport. In order to calculate the export time, we apply the same method to water particles. The method consists of following the movement of a non-buoyant particle, initially located at the centre of each grid mesh of the control volume, assuming that the trajectory of such a particle during the simulation is representative of the trajectory of the initial mesh volume. The particles are transported by advection and diffusion during the numerical simulation. Turbulent mixing is included in the particle tracking model by means of a stochastic model. The position vector $r$ of a Lagrangian particle is given in $z$-coordinate systems by the following equation (Hunter et al., 1993; Tartinville et al., 1997; Visser, 1997; Spagnol et al., 2002):

$$r(t + \Delta t) = r(t) + \Delta t \left[ u + \left( \frac{6h}{\Delta t} \right)^{1/2} d_h ight]$$

$$+ \left[ w + \left( \frac{6v}{\Delta t} \right)^{1/2} d_v + \frac{\partial k_v}{\partial z} e_z \right], \quad (3)$$

where $\Delta t$ is the time step, $u$ is the horizontal velocity vector, $w$ is the vertical component of the velocity, $k_h$ and $k_v$ are the horizontal and vertical eddy diffusivities, respectively, $d_v$ and the components of the horizontal vector $d_h$ are dimensionless numbers randomly distributed between $-1$ and $+1$, and $e_z$ is the vertical unit vector.

The time for a particle to exit the control volume from its initial position is the “export time” of this position. Its distribution expresses the hydrodynamic spatial variability. However, the water export time depends also on the choice of the control volume. The number of particles for which a trajectory is calculated depends on the site and on the grid spacing selected.

The spatial average for export time, calculated by weighting each point with the ratio of the volume of the initial grid mesh to the total volume of the system, is given the name of “turnover time” by Deleersnijder et al. (1997), Anonymous (1998), and Andréfouët et al. (2001). We prefer to use the term “average water export time”, more consistent with the terminology defined in this article.

### 4.3. e-flushing time

What we call “$e$-flushing time” is the HT variously called “flushing time” by Zimmerman.
(1976), Thomann and Mueller (1987) and Monsen et al. (2002), “residence time” by Rasmussen and Josefson (2001), Wang et al. (2004) and Shen and Haas (2004), and “e-folding time” by Dettmann (2001) and Delhez et al. (2004a). The term “e-folding time” suggests a partial replacement of the water, but is less descriptive than “flushing time”. We feel the name “e-flushing time”, which combines the two, is more appropriate. It is based on the definition by Thomann and Mueller (1987): 

If one considers that a known quantity of a substance is injected in a homogenous water mass at time $t_0$ at an initial concentration $C_0$, that no further amount of this substance is added after $t_0$, that the volume of the water mass and fluxes at its boundaries are constant, the concentration of the substance within the water mass at time $t$ is given by the equation:

$$C(t - t_0) = C_0 e^{-Q/V(t-t_0)} = C_0 e^{(-t-t_0)/\theta)}$$

where $Q$ represents the flux of substance (entering or exiting), $V$ is the volume of the control volume considered, $t$ is the time ($t > t_0$) and $\theta$ is the e-flushing time.

The e-flushing time is the time required for the tracer mass initially contained within the whole domain to be reduced by a factor of $1/e$. This is a general parameter, defined for a control volume, and therefore does not take into account the space and time variability of the hydrodynamics.

4.4. Toward a new local hydrodynamic time: flushing lag, local e-flushing time

In this article, we propose adapting the e-flushing time to the local scale in order to be able to define a hydrodynamic time for each grid element. The computation method is as follows: initially, a concentration $C_0$ of a passive, non-settling tracer is imposed on the whole of the grid within the domain, and given a non-zero value (e.g. $C_0 = 1$). On the grid meshes outside the domain, concentration is held at zero. The evolution of this concentration within the domain under the influence of the hydrodynamics is then calculated. This evolution shows the progression of a front. The moment when concentration within one grid mesh reaches a threshold value $C_1$ (arbitrarily set as 95% of $C_0$) is named $t_1$ and is considered to be the beginning of exponential decrease in concentration within this grid mesh. We call $t_1$ the “flushing lag”. The “local e-flushing time” is then defined within the grid mesh considered based on the decrease in concentration between $C_1$ and $1/e \ast C_0$, using an exponential regression of the same type as Eq. (4) that correlates best with the actual concentration decrease within the grid element.

This method generates two local parameters for each grid mesh, the “flushing lag” relating to the time required for water coming from outside the control volume to reach the mesh considered, and the “local e-flushing time” which defines the time span required after the flushing lag, for water from outside the control volume to occupy approximately 63% ($1 - 1/e \approx 0.632$) of the mesh’s volume.

The accuracy of the numerical solving of advection terms, relating to the conservation of the front, and the accuracy of the turbulence model are important for the computation. The local e-flushing time is shorter when using computation methods which correctly preserve fronts, such as monotonicity preserving schemes (TVD type, e.g. Sweby, 1984) than with a classical upstream advection scheme. Finer grid resolution also leads to a better representation of the evolution of the front, especially when near to the coastline.

Introducing such an HT brings out the spatial variability of the hydrodynamics in a domain where currents are highly irregular, which is the case for the SLNC. The HT gradients given by this method can lead to establishing a spatial differentiation of areas within the SLNC, a result which is at least as interesting as the HT values themselves.

The flushing lag relates to the minimum age of the water masses at the studied point (Bolin and Rodhe, 1973; Takeoka, 1984; Deleersnijder et al., 1998; Shen and Haas, 2004; Delhez et al., 2004b), in the sense that it indicates the time required for a water particle coming from outside the SLNC to reach this point. Unlike the flushing lag for which the end time limit is when $C_1 = 0.95 C_0$, the minimum age would be the period from initial starting time, to the time when the concentration within the grid mesh becomes less than $C_0$. The minimum age corresponds to the length of time required for water from outside the domain to begin to reach the grid mesh considered. The flushing lag is an integral part of the data which must be taken into account if our HT is to have a physical significance. It also has some similitude with the time lag as defined in Deleersnijder et al. (1998); flushing lag may
be regarded as the spatially variable version of the time lag.

5. Results

The results presented in this article were obtained for the case of a periodic tide (components M2 and S2; see tide analysis in Douillet, 1998) and a constant moderate wind, uniform over the study area, corresponding to normal SE trade wind (110°, 8 m s⁻¹). This choice has been made on the basis of a statistic analysis of meteorological data (Douillet et al., 2001; Ouillon et al., 2004) bringing out this particular wind regime as the most frequent and long-lasting scenario. Deleersnijder et al. (1998) have demonstrated the strong influence of wind intensity and direction on HTs. Wind is assumed to have a predominant effect on the HTs exposed in the lagoon of New Caledonia; however, the aim of the present study is to explore the meaning of the different HTs and not to detail the sensitivity to the wind velocity and direction. Our approach goes through the comparison of different HT’s computation under the same forcing conditions. The results presented hereafter were averaged over several simulations starting at different phases of the tide. The time step used was 100 s. Preliminary calculation tests were performed with a 1000 m grid spacing. The final 500 m grid spacing led to a better representation of the front evolution, especially near to the coastline, but the general trends obtained with both grid sizes were very much alike. A better grid resolution is scheduled with future computer upgrades.

5.1. Water exchange time

The water exchange time was calculated over the entire SLNC. We obtained the incoming flow (≥0) on each boundary grid point, then its resultant over the whole of the SLNC boundaries, and the instantaneous water volume within the domain, from simulations of the MARS3D code. These vary with the state of the tide (Fig. 3). To get around this variability, we averaged incoming volume and flow rate over several daily cycles and several cycles of spring tides/neap tides. Note that the same method can be applied as well to the outgoing flow rate which compensates incoming flow rate over a spring/neap tide.

The result yields a water exchange time of 6.8 days over the whole SLNC. This value is substantially lower than the 11 days estimated for this part of the lagoon given by Rougerie (1986) and Bujan (2000). The difference between Bujan’s calculations and ours is twofold: (a) Bujan’s study relies on a hydrodynamic model which is only forced by wind, not by tide, which reduces the flux considerably at the domain’s boundaries, and (b) there is a small difference in control volume between the two computation methods: Bujan (2000) uses the Noumea Lagoon (see Fig. 2), which is slightly smaller in extent than the SLNC as we defined it.

In order to illustrate the sensitivity of HTs to the choice of control volume, computations were performed on all three embedded domains: the SLNC, the Noumea Lagoon and Dumbea Bay (see Fig. 2). For the Noumea Lagoon, the water exchange time computed is 6.5 days. This is very

Fig. 3. Parameters used in the water exchange time calculation: (a) incoming water flux, (b) total SLNC volume.
close to the value found for the SLNC, as the difference in the volume of water is slight. For Dumbea Bay, calculations yielded a value of 4.0 days. This value, substantially shorter than for the other two domains, corresponds to the exchange time between the bay and outside the bay.

5.2. Water export time

The water export time was calculated on the basis of the release of 110,800 tracers in the SLNC, 87,990 in the Noumea Lagoon and 2390 in Dumbea Bay. Eq. (3) was applied using the vertical eddy diffusion coefficient \( k_v \) calculated from the turbulence model, and a coefficient \( k_h \) representing spreading due to velocity shear and spreading by turbulent motion. In this study, we applied a value of 0.05 m\(^2\) s\(^{-1}\), the median value of \( k_h \) measurements obtained by Riddle and Lewis (2000) in United Kingdom coastal waters. Supplementary simulations performed using a higher horizontal diffusivity (0.3 m\(^2\) s\(^{-1}\) for a 500 m grid size following Okubo, 1980) led to a diffusive contribution more important than advection for the transport of individual particles. This value was not retained for \( k_h \) in the present study.

The computation of the export time was repeated 12 times, the beginning of calculations being spaced by 1 h intervals over a full tidal cycle. These results were averaged for the export time not to be dependent on the phase of the tide at which the particles are released. As an example, eight particle trajectories are shown in Fig. 4. The distributions of water export time, for the surface layer and for the bottom layer, are shown in Fig. 5a for the SLNC and in Fig. 5b for Dumbea Bay.

In the case of the SLNC, although distribution patterns at surface and bottom generally show a sharp decrease in export time the further one gets from the shore, we noted that distribution depended notably on depth in absolute value and over the gradients. Residence times were generally longer for particles released at the bottom. Areas of short residence time were found near the barrier reef. They are fan-shaped with the apex at a pass through which nearly all particles released within the fan exit the area. We noted a cell of long residence time to the north-west of Ouen Island, located slightly differently at the surface and on the bottom. This corresponds to a gyre described by Douillet et al. (2001).
Fig. 5. Water export time calculated for two control volumes: (a) the SLNC, (b) the Dumbea Bay.
At the end of a circulation simulation spanning a 4-month period, nearly 2.5% of the tracer particles from the initial release were still within the SLNC. This is a numerical artefact of the model, which tends to immobilize particles in certain grid mesh at the bottom of the bays, rather than the expression of a physical process.

The distribution of export time in the Noumea Lagoon (not shown here), is not much different than that of the SLNC. This similarity indicates that the bulk of the water masses located within the Noumea Lagoon exits though boundaries shared by the Noumea Lagoon and the SLNC, mostly through the passes. The differences reflect those water masses which leave the Noumea Lagoon through its north-western end (see Fig. 2), thus remaining within the SLNC. For such water masses, the export time is shorter when defined with respect to the Noumea Lagoon than when defined with respect to the SLNC due to the general flow from SE to NW.

Water export times calculated using Dumbea Bay as control volume are distinctly shorter (Fig. 5b) than for the other two domains. The shortest export times are generally found at the surface near the Maa Peninsula, where the majority of currents lead outside the bay. The longest export times are found mostly at the inner end of the coves which make up Dumbea Bay, particularly Gadji Bay which was also noted as the area of maximum export time when studying the whole SLNC (see Fig. 5). The connection between length of export time and volume of the study area is more pronounced in terms of absolute rather than relative values.

The average export times, calculated using export time for each grid mesh weighted for its volume, were 10.8 days for the SLNC, 9.6 days for the Noumea Lagoon and 3.7 days for Dumbea bay, respectively.

5.3. e-flushing time

Fig. 6 shows the evolution of average concentration for the SLNC and for Dumbea Bay. For a given domain, the e-flushing time is calculated using the law of exponential decrease based on the successive moments when concentration reaches arbitrarily set thresholds. In this article, we established the regression using a range of thresholds going from 95% to 35% of \( C_0 \) in steps of 5%. The 35% threshold corresponds roughly to \( 1/e \), as the e-flushing time is associated to a decrease in concentration by a factor of \( 1/e \).

The application of the original method, seeking a relationship of exponential decrease of concentration going through \( C_0 \) in \( t = 0 \) (Eq. (4)) yields 11.4 days for the SLNC \( (R^2 = 0.978) \), 9.9 days for the Noumea Lagoon \( (R^2 = 0.969) \) and 6.6 days for Dumbea Bay \( (R^2 = 0.930) \) (Fig. 6). We also tested an adaptation of the method consisting of not forcing the exponential regression to pass through the point \( C = C_0 \) in \( t = 0 \). For each control volume, the regression relationships which resulted show a better correlation with the points yielded by the numerical model. This adapted method yields e-flushing times of 12.5 days \( (R^2 = 0.993) \), 11.1 days \( (R^2 = 0.993) \) and 7.6 days \( (R^2 = 0.974) \) for the SLNC, the Noumea Lagoon and Dumbea Bay, respectively.

5.4. Flushing lag and local e-flushing time

5.4.1. Flushing lag

The “flushing lag” describes the progression through the control volume of water coming in from outside. The adaptation of the method described by Thomann and Mueller (1987) to the computation of a local HT requires the storage of the time evolution of the concentration for each grid element which produces a vast amount of data beyond our storage capacity. We used instead the sampled times when the concentration in the grid mesh reaches arbitrarily set thresholds for the first time.

Fig. 7 shows the evolution of concentration, and the decomposition of this evolution, leading to the computation of the flushing lag and the local e-flushing time for a grid mesh located within Dumbea Bay, using first the whole SLNC then Dumbea Bay as control volume. The flushing lag is the time during which concentration within this grid mesh remains greater than 95% of \( C_0 \).

Fig. 8 shows flushing lag distributions in the SLNC and in Dumbea Bay for the surface \( \sigma \)-level. The distribution pattern varies little between levels, through the whole water column. Areas of short flushing lag indicate closeness with a point of water entry into the volume. For the SLNC, the majority of such water entry points are located in its south-eastern end, between U Reef (an extension of Ouen Island) and the barrier reef. The second largest inflow is through Woodin Channel, between Ouen Island and the mainland. Substantial amounts of
water enter also through the passes in the barrier reef. The distribution pattern of short flushing lags in the vicinity of the passes continues, in decreasing sharpness, toward the north-west along the barrier reef. Such cells of short flushing lag have a limited extent in the Noumea Lagoon, whereas they occupy more than half of the area of the lagoon between St. Vincent Pass and the north-west end of the SLNC.

The flushing lag gradient generally trends SSE–NNW. It is the result of the combined effect of the tide-induced and wind-induced circulation (SE–NW) and of water entry through the passes (from the reef toward the mainland). We observed a circular area of long flushing lag (15–20 days) west of Ouen Island. This matches the location of a gyre, described by Douillet (1998) and Douillet et al. (2001), fed by Woodin Channel.

Flushing lags are longer when calculated on the basis of the whole SLNC than when only Dumbea Bay is considered. The time required for a front to arrive at a given point increases with the distance from the open boundary of the control volume (see Fig. 7). Calculation of the flushing lag in Dumbea
Bay shows that the progress of water masses from outside of the bay is rapid along the axis of the bay, slower for the coves to leeward (Maison-neuve Cove, Gadji Bay) and even slower for the coves to windward (Grande Rade, Koutio Bay). The flushing lag gradients are very similar whether they are calculated using Dumbea Bay, the Noumea Lagoon or the whole SLNC as a control volume. The sensitivity of the flushing lag to the choice of control volume is more pronounced on the actual values than on the general patterns of spatial distribution.

5.4.2. Local e-flushing time

Local e-flushing time fields calculated for the SLNC (Fig. 9a) and for the Noumea Lagoon (not shown here) are similar over their shared areas. The major gradient is oriented from the barrier reef toward the coast. The longest local e-flushing times were observed at the inner ends of bays, with maxima in Noumea Harbour (>2 months), at the centre of the gyre west of Ouen Island (>1 month) and in the north-western part of the SLNC (>1 month). Local e-flushing times were very short within the passes (<1 day), forming structures surrounded and extended along the reef toward the north-west by zones of longer local e-flushing time (>4 days). The spatial extent and e-flushing time variation amplitude of such structures were greater in the north-western part of the SLNC than within the Noumea Lagoon.

Values computed for Dumbea Bay were much shorter when using Dumbea Bay as a control volume than when using the whole SLNC (Fig. 9). Values increase toward the inner ends of the coves which make up the bay. The highest values were found in Noumea’s Grande Rade and in the windward part of Koutio Bay. Qualitatively, this distribution is the same whether the control volume is the SLNC or the Dumbea Bay. The sensitivity of the local e-flushing time to the choice of control volume is more pronounced on the actual values than on the general patterns of spatial distribution.

6. Discussion

6.1. Water exchange time

The determination of the flux entering the domain is crucial for calculating the water exchange time. We chose to consider the whole of these fluxes. This choice amounts to considering that any water particle entering the control volume participates in
Fig. 8. Flushing lag distribution for two control volumes: (a) the SLNC, (b) the Dumbea Bay.
Fig. 9. Local e-flushing time distribution for two control volumes: (a) the SLNC, (b) the Dumbea Bay.
the overall exchange process, yielding a basic parameter for exchange time. Rasmussen and Josefson (2001) and Wang et al. (2004) proceeded differently. In calculating the volume of the water masses entering the control volume, they chose not to take into account the water which enters the domain and exits with the following turn of the tide. Often, this type of approach comes along with simplifying hypothesis on hydrodynamics, and aims at extending the significance of the water exchange time. In the case of a site subject only to tidal forcing, the residual tidal flux makes it possible, for instance, to take into account the repeated entries and exits of water particles within the control volume. The computation of the water exchange time applied to the residual tidal flux yields a water exchange time much longer than using the incoming (or outgoing) flux.

6.2. Water export time

To complement the definition of the water export time given by Eq. (3), it should be possible to take into account the water masses which return into the domain with the tide. Monsen et al. (2002) calls the cumulated duration of the times a water particle spends within the domain “exposure time”. As was done for the exchange time, we did not take this effect of the tidal oscillation into account in our computation, for the sake of consistency with the tests for the different HTs, and to adhere more closely to the definition of the water export time proposed by Takeoka (1984). This choice is equivalent to assuming that, on our site, the combined effect of wind and tide during the flow phase of the tide limits the re-entry of water particles which had been carried out during the preceding ebb.

An HT integrated over space does not provide any information of hydrodynamic spatial variability, which is high in our study area. The broad range of export time values calculated for the SLNC (0.2–60 days) gives a good indication of the wide differences in hydrodynamic processes, which would not be apparent using an averaged water export time (here 10.7 days). The water export time is also useful in establishing the direction of dominant fluxes. In simple structures, such as areas where water exits through passes, the dominant flux is orientated along an axis of decreasing values of export time.

6.3. e-flushing time

There are some difficulties in computing the e-flushing time. The existence of a regression coefficient between numerical results and the regression relationship of exponential decrease raises the question of the limits of applicability of this parameter to any domain. In a constantly mixed volume, the concentration decrease is perfectly exponential. It is not, however, in the case of a system where different particles have the same transit time. More generally, when the decrease in average concentration in a given domain is not exponential one can deduce that mixing does not tend toward homogeneity of the water masses. In certain cases, exponential regression may be poorly adapted, and the results lack significance. This is a serious limitation of this method, and of this HT when compared with others which may be calculated without restriction. This consideration leads to the important question when calculating e-flushing time: up to what regression coefficient can one assume that the decrease follows an exponential law?

6.4. Local e-flushing time

Fig. 10 shows the distribution of the regression coefficient obtained between the simulated evolution of concentration in a given grid mesh and an exponential decrease regression relationship (see Eq. (4)). The values for the regression coefficient indicate that this evolution does indeed behave generally in an exponential manner. The regression coefficients calculated for Dumbea Bay are lower when the Bay itself is the control volume (Fig. 10a) than when the whole SLNC is the control volume (Fig. 10b). In this bay, the results vary significantly depending on the control volume chosen (see also Fig. 7).

In the SLNC, the areas which receive water input from the passes show low regression coefficients (e.g. station A in Fig. 10a). The evolution of concentration at station A (Fig. 11a) shows a significant lowering of concentration when water enters the pass, followed by a period during which concentration changes within a narrow range under the influence of the semi-diurnal tide, then followed by a further sharp lowering of concentration linked to water input from south-east. The existence of two plateaux, corresponding to flooding by two different water masses, makes the evolution of the concentration inconsistent.
Fig. 10. Regression coefficient between calculated concentration decrease and theoretical exponential concentration decrease for two control volumes: (a) the SLNC, (b) the Dumbea Bay.
with an exponential type of behaviour, thus the relatively low regression coefficient. The other areas with a low regression coefficient also have a concentration-vs.-time curve showing plateaux, where decrease no longer behaves in an exponential manner. At station B (Fig. 10a), the poor regression is linked to the entry of two distinct water masses, one from the south-east boundary of the domain, the other from Woodin Channel, arriving at slightly different times. The boundary between these two water masses of different concentration oscillates according to the spring-tide/neap-tide cycle (Fig. 11b). At station C we observe the arrival of a low-concentration tidal front, followed by a rise in concentration as this front recedes with the ebb, until the turn of the tide when concentration begins to drop again (Fig. 11c). The tidal cycle is responsible for these oscillations in concentration. This would not be apparent if one performed the computation using the average of a large number of simulations starting each at a different stage of the tide cycle. At station D the oscillation of the concentration (Fig. 11d) is related to the dynamics of the gyre, and concentration at the centre remains higher than outside for a long time (see Fig. 9a). The plateaux or oscillations in concentration values, which prevent concentration from following a truly exponential decrease, are in all cases linked to the input of two water masses, either originating from two different entries (by the south-east entry and through a passage at station A, by the south-east entry and by the Woodin Channel at station B, or by alternatively waters from inside and outside the gyre at station D), or from the same entry but with different ages (e.g. two entries from the south-east during two consecutive flood tides at station C).
The record of concentration decrease which we use for computing the local e-flushing time consists of the times when concentration drops below pre-set thresholds. Note that using a different method of recording the evolution of concentration within the grid elements would be likely to alter the results slightly. Note also that the regression coefficient of an exponential rule is generally better when one considers all thresholds between 0.95\(C_0\) and 0.05\(C_0\), rather than only those between 0.95\(C_0\) and 0.35\(C_0\) (i.e. close to \(1/e \times C_0\)).

As we indicated previously, in this article we applied the e-flushing time parameter frequently encountered in other publications (Thomann and Mueller, 1987; Rasmussen and Josefson, 2001; Dettmann, 2001; Monsen et al., 2002; Wang et al., 2004; Shen and Haas, 2004; Delhez et al., 2004a), which we adapted to a local HT. A parameter close to local e-flushing time can be defined in any situation, without postulating a particular mode of concentration decrease, based only on times \(t_1\) and \(t_2\) when concentration reaches arbitrary pre-determined thresholds (for instance 95% and 35% of the initial concentration). \(t_1\) corresponds to the flushing lag, and the difference \((t_2 - t_1)\) is close to the local e-flushing time. The “local residence time” proposed by Abdelrhman (2005) corresponds to the time when concentration at one point reaches a set percentage of the initial concentration. When using 95% of the initial concentration as the threshold, Abdelrhman’s “local residence time” is equal to the flushing lag.

6.5. Comparing the general HTs

Each one of the general HTs tested in our study has been called “residence time” in published articles. The differences between them and between the three control volumes used, as illustrated in Fig. 12, make it clear that there is a need to refine the terminology. There does not appear to be any simple relationship between them if one avoids making simplifying assumptions on the hydrodynamics. The average export time of a system can be longer or shorter than its water exchange time. As explained in Section 4, the two HTs do not have the same significance. Considering an idealized system where all particles have the same transit time, the water exchange time corresponds to the time required for all particles to have been replaced. In this configuration, if the incoming flux remains constant, the average export time corresponds to half the water exchange time. Outside of this ideal case, there is no simple relationship between the two parameters. Export time gets further away from half of the water exchange time when the domain includes a short transit area and large retention areas. The increase of the export time compared with half the exchange time reflects a domain with highly heterogeneous hydrodynamics. In contrast with the SLNC and the Noumea Lagoon, the average export time in Dumbea Bay is shorter than the water exchange time. Based on our results, we observe that the difference between the average export time and half of the exchange time increases with the size of the domain considered. Comparing average export time vs. exchange time over two different domains also provides information on the relative effectiveness of the processes of export and exchange.

Let us consider now the similarities between the e-flushing time and the average export time. The e-flushing time is the time required for the average concentration to decrease to \(1/e\) times the initial concentration, provided the concentration decrease follows an exponential rule. As we showed previously, concentration decrease in Dumbea Bay does not always follow such a rule (Figs. 7 and 10b), making this parameter poorly adapted to the particular domain. The e-flushing time is the time required to dispose of approximately 63.2% [more precisely \((1 - 1/e) \times 100\%)] of the initial concentration in the domain. The average export time is the time required for half the water initially present to exit the domain. Both these HTs quantify the
time required for a similar percentage of the water present to exit the domain. In the case where concentration decrease is truly exponential, the average export time is the moment \( t' \) such that

\[
C(t') = C_0 e^{(-t' / \theta)} = \frac{1}{2} C_0
\]

(5)

or

\[
\theta' = \ln 2 \theta \approx 0.693 \theta,
\]

(6)

where \( \theta \) is the e-flushing time. For calculating the e-flushing time for the SLNC and for the Noumea Lagoon, concentration decrease is nearly exponential. The average export time and the e-flushing time follow the same trends (\( \theta' = 0.596 \theta \) for the SLNC; \( \theta' = 0.667 \theta \) for the Noumea Lagoon).

6.6. Comparing local HTs

Local HTs can be used to identify areas of particular hydrodynamic regime. Relating the flushing lag and local e-flushing time, while comparing the distribution of the concentration decrease regression coefficient with an exponential decrease, yields further information. The most obvious example of this can be seen in the areas near the passes. The water input through the pass is sufficiently large to affect the flushing lag (decreasing the concentration within grid elements to 95%) and start the count for the local e-flushing time, but is not enough to induce a theoretical exponential decrease for these grid elements. The other concentration thresholds are crossed when water from a more abundant source, in this case from the south-east end of the lagoon, reaches the mesh. More generally, areas where concentration decrease departs substantially from an exponential regression are areas receiving water inputs from more than one source (see Section 6.4). Fig. 10 gives a static illustration of the dynamic, particularly oscillatory, behaviour of the water masses.

Apart from this aspect, the higher the flushing lag, the more diffuse the concentration front. Regression coefficients improve, and local e-flushing times become longer.

Since the flushing lag relates to the minimum age of the water masses within the grid element, and since the export time corresponds to the length of time required for the water present locally to exit the domain, adding these two HTs gives a good estimate of the low value for the transit time.

The results obtained by this study on the three chosen domains show that the relative distribution of local HTs (export time, flushing lag and local e-flushing time) remains the same over all three domains for a given method.

7. Conclusion

Numerical modelling makes it possible to calculate at the same time general and local HTs. The interest of local HTs is most evident in domains where the hydrodynamics are highly heterogeneous, such as the SLNC. The capacity of a 3D hydrodynamic model for yielding data for the entire lagoon makes it possible to do away with simplifications of the hydrodynamic regime such as are often used to estimate HTs. The removal of the need for such simplifications (e.g. perfectly mixed waters within a system, uniform transit time for all particles, uniform velocity) can at times invalidate the theoretical relationships between the HTs found in publications. There is therefore a need for renaming the HTs derived from different calculation methods in order to arrive at a more accurate description than the generic term of “residence time”, often applied to distinct different parameters.

It is important to point out that the HT values mentioned in this article are directly dependent on the control volume chosen. This choice was easy to make in the case of the SLNC, in spite of its large internal variability, since it represents an entity quite distinct from the surrounding ocean, being naturally bounded by its barrier reef. We also wish to point out that the importance of the choice of domain is less crucial when one is more concerned with relative spatially defined HT values than with the absolute values.

The investigations carried out for this study were more focused on the nature and physical significance of the HTs than on their potential for analysing the biological dynamics of an aquatic ecosystem. Based on the definitions proposed and tested in this article in the case of a periodic forcing standing for mean conditions, it will be possible to perform calculations bearing on real climatological studies. Notably, the solution of the equation for heat transport, not included in the present study, should describe the seasonal stratification of water masses observed in the SLNC during the southern summer (Ouillon et al., 2005), a phenomenon which limits vertical exchanges at the interfaces. Such realistic simulations will yield better differentiated HT distributions between the bottom and the surface than is possible using academic types of
simulations. They may lead to a statistical analysis of HTs through the various areas of the study site. It will then be possible to undertake a comparative analysis of the relationships between HTs and biological parameters or observational data.

Acknowledgements

This work was supported by the New Caledonian “ZoNéCo” program, by the French “Programme National Environnement Côtier” and by NASA Grant NNG04GO90G from “Interdisciplinary Program”. The authors thank Eric Deleersnijder and an anonymous reviewer for their valuable comments on this paper.

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