Classical vs. holistic timescales: the Mururoa atoll lagoon case study

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Abstract. A priori timescale estimates are commonly used to build dimensionless parameters allowing one to compare the order of magnitude of the terms of the governing equations of eco-hydrodynamics without having detailed information on their solutions. By contrast, over the past two decades, timescales obtained at every time and position as the solutions of partial differential problems have been developed to diagnose geophysical and environmental fluid flows and the related reactive processes. Such timescales are radically different from the previous ones. They are holistic in that they take into account all the processes under consideration. By revisiting the results of previous numerical studies of the Mururoa atoll lagoon it is seen that timescales of the previous type cannot adequately predict the rate at which the water of this semi-enclosed domain is renewed and, hence, are of little use to evaluate the flux of radionuclides toward the Pacific. On the other hand, the lagoon averaged-residence time, if evaluated in an appropriate manner (i.e. from the results of a three-dimensional model rather than by means of the tidal prism), is instrumental in building a reduced-dimension model capable of predicting the fate of radionuclides in the aforementioned domain of interest. These findings are complemented by the results of a one-dimensional transport model admitting analytical solutions, supporting the relevance of holistic timescales for understanding transport processes.

Motivation

In eco-hydrodynamics (and fluid mechanics in general), timescales are generally estimated as the ratio of either a length scale to a velocity scale (advective timescale), the square of a length scale to a typical value of the diffusivity (diffusive timescale) or the inverse of a reaction rate in the broadest sense (production or destruction timescale). Timescales may also be related to the variability of a forcing (e.g. the inverse of the angular frequency of a tidal constituent) or the rotation of the Earth, in which case the relevant timescale usually is the inverse of the Coriolis frequency. Such timescales are generally resorted to in order to build dimensionless parameters allowing one to compare the order of magnitude of the terms of the governing equations of eco-hydrodynamics without having detailed information about the solution. It must be realised that defining and using such timescales may be more complex than what is generally thought (e.g. Deleersnijder 2019a).

Over the past two decades, timescales that seem to be of a rather different nature have been developed (e.g. England 1995, Delhez et al. 1999, Holzer and Hall 2000, Delhez et al. 2004a) and used in order to diagnose geophysical and environmental flows (e.g. Du and Shen 2016, Kärnä and Baptista 2016, Shah et al. 2017, Rutherford and Fennel 2018, Cheng et al. 2019, Li et al. 2019, Shang et al. 2019), the associated reactive transport phenomena (e.g. Delhez et al. 2003, Waugh et al. 2003, Delhez et al. 2004b) as well as sediment transport (e.g. Mercier and Delhez 2007, Gong and Shen 2010, Delhez and Wolk 2013, Ralston and Geyer 2017).

In an attempt to document the differences and convergences between the two types of timescales, I will revisit hereinafter the following problem: *how to assess the rate at which pollutants leave the Mururoa atoll lagoon, a well mixed semi-enclosed domain.*

Mururoa atoll lagoon

Mururoa atoll is a cone of volcanic rocks emerging from the bottom of the tropical Pacific Ocean (at longitude 138°55' west and latitude 21°50' south), the depth of which is of order 3.5 km in this region. A layer of carbonates several hundreds of metres thick lies on top of the volcanics. The emerged part of the carbonates is a thin and almost impermeable rim that delimits, at sea level, the boundary between the Pacific and the lagoon. The latter is a shallow, semi-enclosed domain (Figure 1) that exchanges water with the ocean through a single pass, whose depth is much smaller than the mean depth of the lagoon — implying that the zone of the atoll mouth actually is a sill. Pacific water can also enter the lagoon through the so-called hoa, a Polynesian word referring to a region where the rim is so low that ocean surface waves, if they are sufficiently high, generate an overbank incoming water flux (Tartinville and Rancher, 2000).

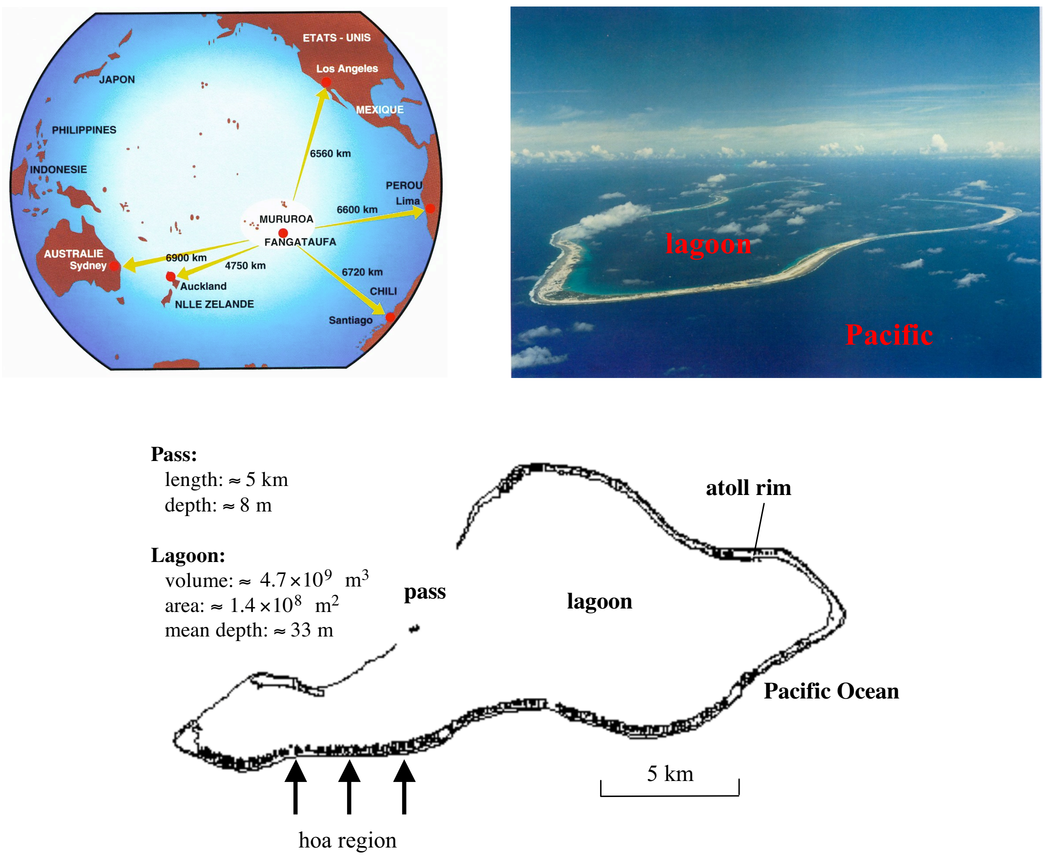

Figure 1. Geographical and bathymetric information about Mururoa atoll. The top panels are from Guille et al. (1993).

A significant amount of radioactive material is stored in the volcanics as a result of the nuclear weapon tests that the French military carried out from 1976 until 1996. Owing to geothermal endo-upwelling (e.g. Rougerie et al., 1992; Rougerie and Wauthy, 1993) and, presumably, other phenomena, water circulates upwards inside the atoll, causing a flux of radioactive elements to enter the lagoon and, ultimately, the Pacific. Determining the rate at which the lagoon water is renewed, i.e. replaced by Pacific water, helps in providing a first estimate of the time radioactive particles tend to stay in the lagoon water and, hence, the radiotracer concentration in the lagoon water (Deleersnijder et al., 1997; Anonymous, 1998).

Classical dvective and diffusive timescales

If relevant pieces of information about the flow under study (i.e. order of magnitude of the velocity components and eddy diffusivities are available), then advective and diffusive timescales may be estimated prior to the production of detailed numerical results. Such timescales may also be estimated a posteriori, i.e. from numerical results. This is what Tartinville et al. (1997) did, thereby producing the tables reproduced below. The typical values of the velocity components and diffusivities are in the left panel, whilst the corresponding advective and diffusive timescales (in days) are listed in the right panel. Four numerical simulations were performed, which are called T, TW, TWH and TWHS, depending on the forcings taken into account. They are as follows:

- T: the only forcing is the ocean tide;
- TW: the ocean tide and the wind stress are taken into account;
- TWH: the hoa overbank flow is added to the forcings of simulation TW;
- TWHS: the flow is forced by tide, wind stress and hoa overbank flow, and stratification is taken into account in a simplified manner, whilst it was disregarded in simulations T, TW and TWH.

Table 2. Global features of the lagoon hydrodynamics obtained in simulations T, TW, TWH, and $TWHS$. The typical scales of the depth-mean current and the deviation with respect to this depth average in the s-direction ($s = x$ or y) are denoted $\bar{U}_s$ and $\hat{U}_s$, respectively. The order of magnitude of the vertical velocity is represented by W, while A_v and K_v are characteristic values of the eddy viscosity and diffusivity, respectively. The horizontal and vertical velocity components are measured in 10^{-2} and 10^{-4} m s^{-1}, respectively, while the eddy coefficients are expressed in 10^{-2} m^2 s^{-1}.

	T	TW	TWH	$TWHS$
$\bar{U}_x = \langle \lvert \bar{u}_x{}^* \rvert \rangle$:	0.095	1.1	1.1	1.4
$\hat{U}_x = \langle \lvert \hat{u}_x{}^* \rvert \rangle$:	0.015	1.9	1.9	2.3
$\bar{U}_y = \langle \lvert \bar{u}_y{}^* \rvert \rangle$:	0.074	0.48	0.51	0.75
$\hat{U}_y = \langle \lvert \hat{u}_y{}^* \rvert \rangle$:	0.0088	0.92	0.92	3.1
$W = \langle \lvert w^* \rvert \rangle$:	0.070	1.1	1.1	2.1
$A_v = \langle a_v{}^* \rangle$:	0.023	1.1	1.1	0.18
$K_v = \langle k_v{}^* \rangle$:	0.028	1.4	1.4	0.20

Table 3. Time scales of residual transport processes diagnosed from the results of model runs T, TW, TWH, and $TWHS$. The horizontal advection along the s-axis ($s = x,\ y$) by the depth-averaged velocity and the deviation with respect to the depth-mean current exhibit characteristic times $\bar{T}_s^a$ and $\hat{T}_s^a$, respectively. The vertical advective time scale is denoted T_v^a, while T_s^d and T_v^d represent the horizontal and vertical characteristic times of diffusive processes. The quantities $L_x = 10^4$ m and $L_y = 5 \times 10^3$ m are the horizontal length scales in the x and y directions. The typical height of the water column is taken to be $H = 30$ m. All time scales are expressed in days

	T	TW	TWH	$TWHS$
$\bar{T}_x^a = L_x/\bar{U}_x$:	120	11	11	8.3
$\hat{T}_x^a = L_x/\hat{U}_x$:	770	6.1	6.1	5.3
$\bar{T}_y^a = L_y/\bar{U}_y$:	78	12	11	7.7
$\hat{T}_y^a = L_y/\hat{U}_y$:	660	6.3	6.3	1.9
$T_v^a = H/W$:	33	2.1	2.1	1.1
$T_x^d = L_x^2/(\pi^2\ k_h)$:	5900	5900	5900	5900
$T_y^d = L_y^2/(\pi^2\ k_h)$:	1500	1500	1500	1500
$T_v^d = H^2/(\pi^2\ K_v)$:	3.8	0.075	0.075	0.53

The velocity in simulation T is smaller than in the other simulations, which is the reason why the corresponding advective timescales are much greater. For simulations TW, TWH and TWHS, the advective timescale is of the order of 10 days. The timescales related to horizontal diffusion are independent of the type of simulation, for the horizontal diffusivities are fixed. The vertical diffusion timescales depend on the type of simulation, for a sophisticated turbulence closure was used. These timescale are very small.

Based on these pieces of information, it is rather difficult to identify the timescale that would help assess the rate at which pollutant would be transported from the lagoon to the Pacific. Common sense would suggest that the horizontal advection timescale in the x direction ($\bar{T}_x^a$) is a plausible candidate. As will be seen, this is suggestion wrong.

Tidal prism

Since the above timescale estimates do not seem to be sufficiently helpful, another approach is necessary. At first glance, resorting to the concept of tidal prism seems an appealing option. In the present case, the tidal prism is approximately the product of the tidal range and the lagoon surface

For decades, it was deemed appropriate to focus on the water exchanges due to tides (Anonymous, 1998, and references therein), whose dominant constituent at Mururoa is by far the M2 tide. Accordingly, the residence time derived from the tidal prism estimate (identified by subscript TD) is the ratio of the lagoon volume to the incoming — or outgoing — water flux (Anonymous, 1998):

$$\theta_{TP} \approx \frac{\text{lagoon volume}}{\text{incoming water flux}} \approx \frac{\text{lagoon volume}}{\dfrac{\text{tidal range } \times \text{ lagoon surface}}{\text{tidal period}}} \approx \frac{4.7\times 10^{9}\,\text{m}^{3}}{\dfrac{0.6\,\text{m} \times 1.4\times 10^{8}\,\text{m}^{8}}{0.52\text{ day}}} \approx 28 \text{ days} \quad . \tag{1}$$

As will be seen, this approach, albeit very popular, is completely inappropriate at Mururoa. One aspect of it is, however, worth keeping in mind. Timescale θ_{TP} is not derived from the evaluation of the order of magnitude of a couple of terms in the governing equations. Instead, it is a holistic timescale, aimed at taking into account the impact of all the processes that contribute to the renewal of the lagoon water. In other words, no attempt is made to assess timescales related to the various advective and diffusive terms in the governing equations: it is their combined effect that is being assessed through a single water renewal timescale.

Timescales derived from realistic model results

The timescale theories developed and used over the past two decades allow calculating timescales at any time and position in the domain of interest. Figure 13 of Zimmerman (1976) turned out to be seminal, for it suggested simple definitions of position-dependent age and residence time that eventually led to partial differential problems governing the aforementioned timescales (Figure 2). The numerical solutions of these problems may be obtained in the Lagrangian framework or in the Eulerian one.

Using a thoroughly-validated three-dimensional model (Tartinville, 1998), Tartinville et al. (1997) computed the residence time in the lagoon by means of particle tracking, i.e. a Lagrangian approach, for the T, TW, TWH and TWHS hydrodynamics. At the initial time, particles were distributed homogeneously in the lagoon. Then, the trajectory of each of them was simulated until the pass was reached. Finally, the time to reach the pass was ascribed to the initial position, yielding the residence time fields displayed in Figure 3.

For the T, TW, TWH and TWHS simulations, the lagoon-averaged values of the residence time are 512, 94, 128 and 114 days, respectively. The residence time related to the flow for which the tide is the only forcing is much larger than that of the other cases. This is because the velocity directly induced by the tide is much smaller than that due to the wind, which is the most important forcing of the lagoon hydrodynamics.

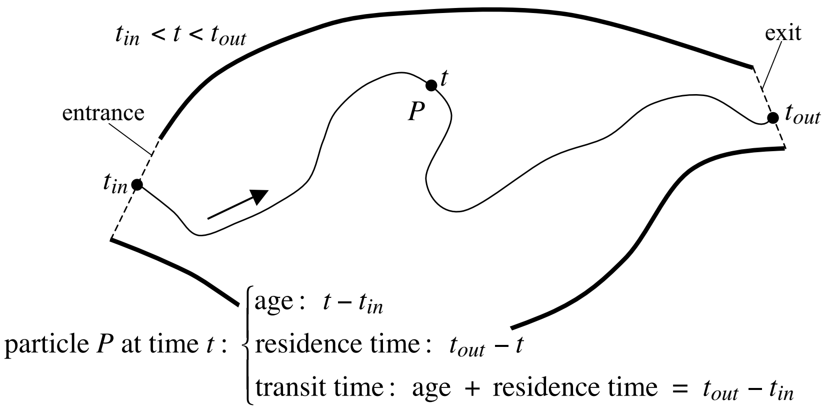

Figure 2. Illustration of the concepts of age and residence time for diagnosing the tracer exchanges of a semi-enclosed domain with its environment. At time t, the age and the residence time of particle P are the time elapsed since leaving the entrance of the domain, $t - t_{in}$, and the time needed to reach the exit, $t_{out} - t$, respectively. The auxiliary timescale representing the time spent in the domain, i.e. the sum of the age and the residence time, is termed transit time. This figure is inspired by Figure 13 of Zimmerman (1976).

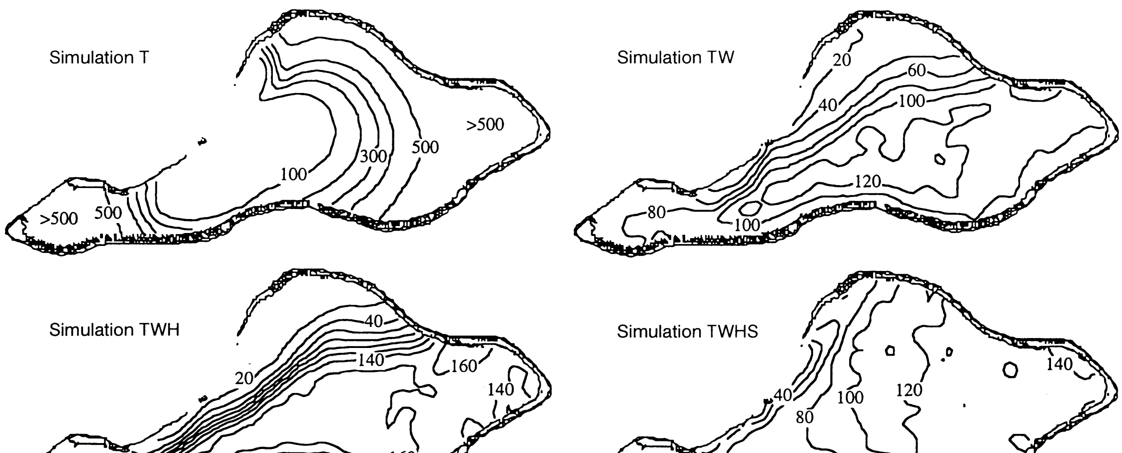

Figure 3. Depth-averaged residence time in Mururoa Lagoon from Tartinville et al. (1997). As vertical mixing is very efficient in the lagoon (the corresponding timescale is rather short), the residence time exhibits small vertical variations, implying that little information is lost by displaying only depth-averaged residence time fields.

The lagoon-averaged residence time estimated from the tidal prism is about 20 times smaller than that deduced from the T simulation. Thus, the tidal prism method is wrong at Mururoa. This is partly because a large fraction of the water that enters the lagoon when the tide rises leaves it when the tide is ebbing (Tartinville 1998). Thus, this water does not participate in the renewal of the lagoon water.

The TWH residence time is greater than the TW one. At first, this may be viewed as counterintuitive, for the hoa overbank flow increases the outgoing water flow through the pass. However, it also modifies the flow pattern in the lagoon: the rate of water exchange between the neighbourhood of the pass and the rest of the lagoon is reduced, thereby increasing the lagoon-averaged residence time (Deleersnijder 2003). This is another illustration of the fact that the volume/flux formulas must be considered with caution.

It must also be underscored that the classical advective and diffusive timescales evaluated by Tartinville et al. (1997) (see table above) have little to do with the residence time ensuing from three-dimensional particle tracking (Tartinville et al. 1997). This is because the processes contributing to the water renewal of the lagoon presumably are due to a subtle combination of complex advective (e.g. Mathieu et al. 2002) and diffusive (essentially in the vertical direction) processes that cannot be captured by a single advective or a diffusive timescale, hence the need for a holistic diagnosis approach.

Timescales in reduced-complexity models

In the TW, TWH and TWHS simulations, the lagoon is sufficiently well mixed that the mass of the particles remaining in the lagoon, $m(t)$, decreases almost exponentially (Figure 4). Accordingly, the outgoing mass flux (i.e. the mass flux from the lagoon to the Pacific through the mouth of the lagoon) is approximately $m(t)/T$, where T is a constant timescale. Deleersnijder et al. (1997) and Deleersnijder (2019b) demonstrated that this timescale is the lagoon-averaged residence time.

The above considerations show that, at least for Mururoa lagoon, the mean residence time should not be determined from simple, ad hoc formulas. The best option presumably is to estimate it from a sophisticated, three-dimensional model, such as that of Tartinville et al. (1997) and Tartinville (1998). Denoting this timescale θ_{3D}, the following reservoir model (also termed box model) was built

$$\frac{dm}{dt} + \frac{m}{\theta_{3D}} = 0 \ , \quad m(0) = m_0 \tag{2}$$

and validated against three-dimensional tracer transport model results (Deleersnijder et al. 1997). See, for instance, error map in Figure 3 of Deleersnijder et al. (1997).

The reservoir model can be further developed in order to simulate the fate of a tracer exhibiting a first-order decay process characterised by a constant rate of decay (e.g. a radionuclide). If constant τ denotes the mean-life of such a tracer, then (2) must be modified as follows (e.g. Deleersnijder 2019b)

$$\frac{dm}{dt} + \frac{m}{\theta^{*}} = 0 \ , \quad m(0) = m_0 \tag{3}$$

with

$$\theta^* = \left(\frac{1}{\theta_{3D}} + \frac{1}{\tau} \right)^{-1} = \frac{\theta_{3D}\,\tau}{\theta_{3D} + \tau} \ , \tag{4}$$

leading to solution

$$m(t) = m(0)\, e^{-t/\theta^*} \ . \tag{5}$$

The evolution of the tracer under consideration is characterised by a single timescale, which is a function of a classical timescale (τ) and a holistic one (θ_{3D}). Though (5) is a simple mathematical expression, the method of arriving at it far from trivial.

Solution (5) is in good agreement with results from a three-dimensional model, which is hugely more complex than (3). In other words, (3) is an efficient reduced-complexity (or reduced-dimension) model, focusing on a lagoon-scale variable, $m(t)$. There are other domains for which holistic timescales, determined from realistic (three-dimensional) models, proved instrumental in helping to develop efficient, reliable reduced-complexity models. See, for instance, Deleersnijder (2009, 2015).

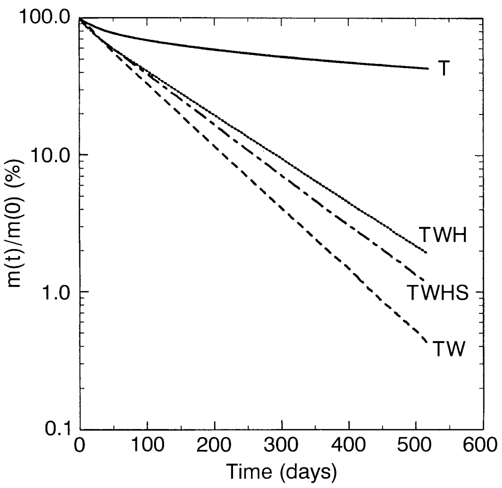

Figure 4. Ratio of the mass of particles $m(t)$ to the mass initially released $m(0)$ for the four types of simulated hydrodynamics as a function of time t. Ratio $m(t)/m(0)$ decreases almost exponentially for simulations TW, TWH and TWHS. At the initial instant ($t = 0$), the particles are homogeneously distributed in the lagoon. A three-dimensional model is used to simulate the trajectory of the particles (Tartinville 1998). This is Figure 10 of Tartinville et al. (1997).

Timescales in process models

In the words of Deleersnijder (1996), "process-oriented models focus on a few dominant or important processes. It is necessary that the key processes be well represented, at least from a qualitative point of view". One-dimensional models in which either advection or diffusion, or both types of transport are taken into account are process models that have been widely used in atmospheric research (e.g. Hall and Plumb 1994, Neu and Plumb 1999) and marine sciences (e.g. Munk 1966, Maier-Reimer 1993, Hall and Haine 2002, Mouchet and Deleersnijder 2008, Lucas et al. 2009, de Brye et al. 2012, Mouchet et al. 2012, Andutta et al. 2014).

Consider a pipe of length L and cross-sectional area A in which water moves with constant volumetric flow rate Q. The along flow diffusivity is constant K. The related advective and diffusive timescales are $T_a = V/Q$ (i.e. volume/flux) and $T_d = V^2/(A^2K)$, where $V = AL$ is the volume of the domain of interest. These classical timescales can be easily deduced from an order of magnitude analysis of the terms of the advection-diffusion equation associated with the flow under study. As is well known, the Peclet number is the ratio of the order of magnitude of the advection term to the diffusive one or, equivalently, the ratio of the diffusive timescale to the advective one, i.e.

$$Pe = \frac{T_d}{T_a} \quad . \tag{6}$$

This dimensionless parameter is small (large) when diffusion (advection) is faster than advection (diffusion).

This classical approach does not allow answering the questions as to how long water or tracer particles stay in the domain of interest, a piece of information that is likely to be of use in pollution or eco-hydrodynamic studies. The sought-after holistic timescale must be a function of T_a and T_d since there are no other timescales associated with this problem. But, the classical method for estimating timescale provides no clue as to how to estimate such a timescale.

Let x represent the along-flow coordinate, with $x = 0$ and $x = L$ at the domain inlet and outlet, respectively. According to Delhez et al. (2004), the residence time $\theta(x)$ (i.e. the time needed to hit for the first time an open boundary) is the solution of the following differential problem

$$AK\frac{d^2\theta}{dx^2} + Q\frac{d\theta}{dx} + A = 0 \ , \quad \theta(0) = 0 = \theta(L) \quad . \tag{7}$$

The residence time is readily seen to be (e.g. Andutta et al. 2014)

$$\theta(x) = \left(\frac{L-x}{L} - \frac{e^{-Pe\,x/L} - e^{-Pe}}{1-e^{-Pe}} \right) T_a \quad . \tag{8}$$

In this formula, the classical advective and diffusive timescales are deeply interwoven. This also holds true for the domain-averaged residence time, which reads

$$\langle\theta\rangle = \frac{T_a}{e^{T_d/T_a} - 1} + \frac{(T_d - 2T_a)T_a}{2T_d} \quad . \tag{9}$$

Such an expression cannot be derived from a reasoning based only on the estimates of the classical advective and diffusive timescales, illustrating the usefulness of the holistic time- and position-dependent timescale theories such as CART (Constituent-oriented Age and Residence time Theory, www.climate.be/cart). Even the following asymptotic expressions for diffusion- and advection-dominated cases are impossible to obtain without having recourse to the relevant holistic timescale theory (viz. CART):

$$\text{diffusion dominant: } \langle\theta\rangle \sim \frac{T_d}{12} - \frac{T_d^3}{720 T_a^2} \ , \quad \frac{T_d}{T_a} << 1 \ , \tag{10}$$

$$\text{advection dominant: } \langle\theta\rangle \sim \frac{T_a}{2} - \frac{T_a^2}{T_d} \ , \quad \frac{T_a}{T_d} << 1 \ . \tag{11}$$

Conclusion

The developments above should be considered as a work in progress. This is because I have been struggling with different approaches to timescales and, unfortunately, found no entirely satisfactory way to grasp the relationships between them.

The tentative take-home messages are as follows:

1. Classical timescales help estimate the relative importance of the terms of the governing equations of eco-hydrodynamics;
2. These timescales are not well suited to grasp the complex interplay between all the processes represented in realistic models;
3. The (holistic) timescales derived from the solution of partial differential problems (e.g. www.climate.be/cart) take into account all of the processes represented in realistic models and paint a simplified picture of their impact on the larger time and space scales;
4. Holistic timescales, sometimes complemented with classical timescales, are instrumental in building reduced-dimension models that may help interpret the results of complex models.

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