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The Trapping Index: How to integrate the Eulerian and the Lagrangian approach for the computation of the transport time scales of semi-enclosed basins

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ABSTRACT

In this work, we investigated if the Eulerian and the Lagrangian approaches for the computation of the Transport Time Scales (TTS) of semi-enclosed water bodies can be used univocally to define the spatial variability of basin flushing features. The Eulerian and Lagrangian TTS were computed for both simplified test cases and a realistic domain: the Venice Lagoon. The results confirmed the two approaches cannot be adopted univocally and that the spatial variability of the water renewal capacity can be investigated only through the computation of both the TTS. A specific analysis, based on the computation of a so-called Trapping Index, was then suggested to integrate the information provided by the two different approaches. The obtained results proved the Trapping Index to be useful to avoid any misleading interpretation due to the evaluation of the basin renewal features just from an Eulerian only or from a Lagrangian only perspective.

1. Introduction

The definition and the computation of the flushing features or water renewal capacity is a fundamental procedure to apply when evaluating the ecological status of a water body (Lucas et al., 2009; McLusky and Elliott, 2004; Andutta et al., 2014). In literature several examples demonstrated its usefulness when determining coastal marine ecosystem health, as well as its sensitivity to pollution threats (Wolanski, 2007; Wolanski et al., 2012). Within this context, the European Water Framework Directive (Directive, 2000/60/EC, henceforth WFD) established the flushing feature to be one of the main natural water descriptors to be evaluated when assessing the water quality status of water bodies.

In its simplest form, the flushing feature of a semi-enclosed basin can be estimated through the computation of the Turn Over Time (TOT hereafter) which can be defined as the time needed to drain the basin volume V through its outlet A with the current velocity v. The TOT quantifies the water renewal capacity through the definition of a basin time scale, without considering its spatial variability (Monsen et al., 2002; Valle-Levinson, 2010).

In recent years, several methods, based both on the use of simplified parametric formulation or on the use of complex numerical models, were adopted to compute the TOT of water bodies (e.g. Asselin and Spaulding, 1993; Luff and Pohlman, 1996; Edinger et al., 1998; Gillibrand, 2001; Rasmussen and Josefson, 2002; Choi and Lee, 2004; Fukumoto and Kobayashi, 2005). Despite the differences, all the approaches were based on the same basic assumptions and leaded to a similar interpretation of the results.

In domains characterized by complicated geometry and flow patterns, such as coastal lagoons, bays or gulf, it is suggested to evaluate the spatial variability of the water renewal capacity rather than the basin integral value, as the one provided by the TOT (e.g. Bowden, 1967; Dyer, 1973; Takeoka, 1984).

The spatial heterogeneities of the water renewal properties of a semi-enclosed basin can be investigated through the definition and the computation of the so-called Transport Time Scales (TTS hereafter). Different techniques, all relying on numerical modeling, can be adopted to compute the TTS of a water body (Grifoll et al., 2013).

These methods often foresee a different evaluation of the obtained results and, as a consequence, a different meaning of the computed TTS (Oliveira and Baptista, 1997). It follows that multiple concepts of the TTS have been defined in literature, e.g., residence time, age, flushing time, renewal time, transit time,

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etc., and still there is no consensus on their exact meaning and on how to apply them (Grifoll et al., 2013; Gomez et al., 2014a). Therefore, when the computation of the basin flushing feature implies the evaluation of its spatial variability, the differences in the adopted methods can lead to differences in the interpretation of the obtained results.

Considering the type of numerical approach adopted to compute them, the TTS can be grouped into Eulerian Transport Time Scales and Lagrangian Transport Time Scales (Cucco et al., 2009; Gomez et al., 2014b). The first group includes all the applications where the TTS were computed using a solute transport model to estimate the dilution time scale of a passive tracer released within the domain (Abdelrhman, 2002; Cucco and Umgiesser, 2006; Ribbe et al., 2008; Umgiesser et al., 2014; Gomez et al., 2014a,b). The second group includes all the applications based on the use of a particle trajectory model to estimate the time taken by the basin water masses to exit out of the domain (Meyers and Luther, 2008; Bilgili et al., 2005; Oliveira and Baptista, 1997; Jouon et al., 2006; Cucco et al., 2006; Grifoll et al., 2014). The choice of one method with respect to the other one is often made on arbitrary basis or without any preliminary evaluation of the meaning of the selected TTS.

In this work we investigate how the Eulerian and the Lagrangian approach to compute the TTS provides different results when applied to similar test cases and how the two TTS can be used to define the spatial variability of the basin flushing features. The two approaches will be compared to each other when applied both to simplified basins as rectilinear channels or lake-type basins and to a realistic domain representing the Venice Lagoon under different hydrodynamic regimes. Finally, to summarize the information contained in both approaches we introduce a new index, the Trapping Index that indicates areas with potential high exchange time scales independent from the TTS chosen.

2. The method

The comparison between the Eulerian and the Lagrangian Transport Time Scale was carried out considering only water bodies characterized by the presence of just one single source of water renewal. This category includes semi-enclosed basins such as bays or gulfs, and lagoons where water exchange occurs mainly with the open sea. The computation of the TTS for such basins entails the definition of a reference inner area generally covering the whole domain, hereafter defined as “*source area*“, and the definition of an outer domain, generally the open sea, hereafter defined as “*well*”. In such approximation, the number of connections between the *source area* and the *well* can be manifold but, any external flux of water into the *source area* coming from a further outer domain was not taken into account. In other words, considering the case of a lagoon, the basin (*source area*) could be connected to the open sea (*the well*) through several inlets, but any river inflow (external source of water) was not taken into account when computing the TTS. This simplification cannot be applied to estuaries or chocked lagoons characterized by major river inflows and low tidal forcing, where, for each selected source area, a further external source of water, with respect to the outer domain, will always affect the TTS computation. On the other hand, in the case of a semi-enclosed coastal basin and restricted or leaky lagoons characterized by low river inflows, the previous assumptions can be considered as acceptable. In the following, the definition of the two TTS and the numerical method adopted to compute them are reported.

2.1. The transport time scales

The two TTS already defined in Cucco et al. (2009), specifically the Lagrangian Transport Time Scale (LTTS hereafter) and the Eulerian Transport Time Scale (ETTS hereafter), were taken into account.

Considering a schematic semi-enclosed basin (*source area*) connected with the open sea (*well*) through one or more inlets, the ETTS was defined as the time required by the water mass inside the source area at time t_0 and position x_0 to be replaced by new water entering from the inlet. For the same basin, the LTTS was defined as the time required by each water parcel located inside the source area at the time t_0 to exit the domain through one of the inlets.

The ETTS and LTTS can be computed for each point x_0 of the *source area* and for different hydrological regimes obtaining, as a results, the spatial distribution of an “Eulerian” property in the first case and the spatial distribution of a “Lagrangian” property in the second case.

2.2. The numerical method

A set of applications were carried out to compute the ETTS and the LTTS for both idealized basins and for the Venice Lagoon under different flow regimes. Numerical modeling is an essential tool to reproduce both the hydrodynamics and the spatial variability of the two TTS.

To this end, a state of the art finite element hydrodynamic model (SHYFEM, Umgiesser et al., 2004) was adopted and implemented for a set of different case studies. SHYFEM was already used with success in several applications with the aim of computing both ETTS and LTTS for lagoons and semi-enclosed coastal basins (Cucco and Umgiesser, 2006; Cucco et al., 2009; Ghezzo et al., 2010; Canu et al., 2012; Ferrarin et al., 2013; Umgiesser et al., 2014; Ferrarin et al., 2014).

The model resolves the 3-D shallow water equations vertically integrated over z-layers. It uses a semi-implicit algorithm for integration in time, which combines the advantages of the explicit and implicit schemes. The spatial discretization of the unknowns is carried out with the finite element method. The hydrodynamic module is coupled with both a solute transport model to compute the spreading and the fate of an Eulerian conservative tracer and a particle tracking model to calculate the transport of Lagrangian numerical particles. Details of the model equations and adopted numerical solution are reported in Umgiesser et al. (2004).

In this work, the 2D version of the model was applied with the aim of reproducing the vertically integrated water circulation for each domain and test case.

The ETTS was computed by simulating the transport and diffusion of an Eulerian conservative tracer released uniformly over each source area with a concentration corresponding to 1. The initial tracer concentration was reduced due to the exchange fluxes between the source area and the outer domain, where the concentration was set to 0. The ETTS was then obtained by integrating, for each point of the domain, the remnant function of the tracer concentration for the whole duration of the simulation obtaining the e-folding time of the tracer concentration (Takeoka, 1984; Cucco et al., 2006). A first order explicit numerical scheme based on the TVD method was adopted to integrate in time the tracer advection and diffusion equation and a Smagorinsky formula was used to compute the horizontal tracer diffusion coefficients (Smagorinsky, 1963).

The LTTS was computed by seeding the source area with a statistically relevant number of particles and simulating their transport and diffusion inside the source area and outside the model domain. The LTTS for each initial particle position was then defined as the time each water particle takes to exit the domain (Jouon et al., 2006; Cucco et al., 2009; Grifoll et al., 2014). A particle tracking numerical module based on the finite element formulation was adopted to compute the advective component of the transport,