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# Baltic Sub-basin Turnover Times Examined Using the Rossby Centre Ocean Model

Not least when judging the possible effects of climate change it proves necessary to estimate the water-renewal rates of limited marine areas subject to pronounced external influences. In connection with the SWECLIM programme this has been undertaken for two ecologically sensitive sub-basins of the Baltic, *viz*. the Gulf of Riga and Gdansk Bay. For this purpose two methodologically different approaches have been employed, based on mass-balance budgets and analysis of Lagrangian trajectories, respectively. When compared to the results obtained using the Lagrangian technique, the box-model approach proved to be adequate for the Gulf of Riga representing a morphologically highly constrained basin, whereas it demonstrated certain shortcomings when applied to the more open topographic conditions characterizing Gdansk Bay.

## INTRODUCTION

Present concerns about the effects of increasing $CO_2$ levels in the atmosphere are focused not least on the consequences global change may have for our habitat and living conditions. These questions have been dealt with extensively within the SWECLIM programme, a Swedish effort on regional climate modeling for studying the possible effects of climate change on the Nordic region (1). When attention is directed towards the regional marine environment from an oceanographic standpoint, it is to be expected that climate change will affect the seas of the Nordic region in two ways; directly *via* atmospheric forcing, but also indirectly *via* altered runoff conditions. These latter changes may be physical as well as chemical and biological, in particular as regards the trace elements and nutrients essential for a well-balanced marine ecosystem. In semienclosed basins such as the Baltic the riverborne influx of substances plays a critical role for the nutrient dynamics of the sub-basins. A highly relevant example is e.g. provided by a number of recent studies (2–4) emphasizing the altered role of riverine dissolved silica for the plankton communities of the Baltic. These investigations have focused on how the silicate flux to the Baltic Sea has changed over the last century as a result of the exploitation of Finnish and Swedish rivers for hydro-electricity. This may have led to considerable sedimentation of particulate matter already in the power-station reservoirs. Other important nutrient-balance studies have focused on well-defined sub-basins of the Baltic, such as Himmerfjärden on the east coast of Sweden (5) and the Gulf of Riga (6).

Since good insight into these matters is essential for management programs and related activities, much research has been devoted to budget studies. The standard tool when dealing with this class of problems has been mass-balance modeling based on conservative quantities, an approach originating from ideas formulated at the beginning of the last century (7). This concept has proved its worth in various contexts. However, box-model approximations represent a lowest-order approach with concomitant errors and uncertainties. This is, nevertheless, the technique favored by the International Geosphere - Biosphere Programme (IGBP) Land Ocean Interactions in the Coastal Zone (LOICZ) for establishing global-scale nutrient budgets (8), a prime reason being that it often is the only way to obtain first estimates of these ecologically important fluxes. In the present study the relevance of standard mass-balance models based on conservative quantities will be investigated for two typical sub-basins of the Baltic. The analysis of these results will be undertaken on the basis of a comparison with results obtained from a 3-dimensional numerical circulation model. The ultimate purpose of the study is to serve as an aid for the choice of adequate tools when estimating the possible biological consequences of an altered climate and, in particular, how these changes might be expected to affect such an ecologically sensitive semienclosed sea as the Baltic.

Next the two modeling concepts are introduced and discussed, whereafter the subsequent sections deal with applications to our two model areas, *viz*. the Gulf of Riga and Gdansk Bay. In addition, we compare the results obtained using the two approaches. (The horizontal delimitations of these two areas are shown in the Baltic map in Figure 1.) The study is concluded by a discussion of the advantages and drawbacks associated with each of the methodologies and suggestions for possible future work.

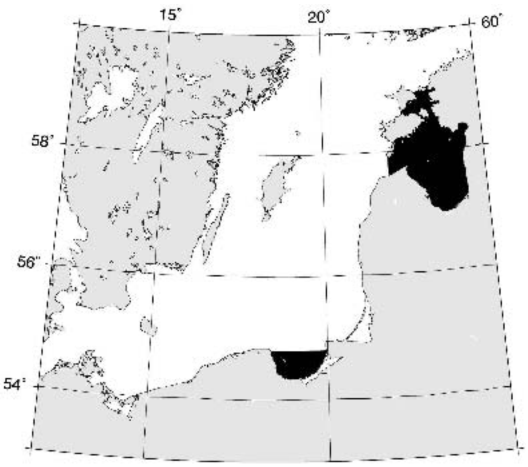


**Figure 1. Map of the Baltic proper. The Gulf of Riga and Gdansk Bay are heavily shaded.**

## METHODS

Mass-balance budgets, as further described in the Box, are based on the use of averaged quantities, *viz*. the pertinent variables have been integrated over space and time. Consequently, these models have a low spatial resolution, and indeed tend to yield better results the longer the time-scales are. In short, box models may be characterized as comparatively robust. The drawback is that they normally do not lead to a deeper understanding of the physical processes within the system.

Numerical 3-D circulation models, on the other hand, can have a high resolution in time and space and hence permit process studies in the interior of the basin under consideration. The time-scales are not subject to any *a priori* limitations (except those associated with the numerical Courant-Friedrichs-Lewy criterion), but these models may require considerable computer resources and and are not always robust, partly because the results tend to be rather dependent on the parameterizations implemented in the numerical realization of the model. (Many physical processes are on a subgrid level or poorly understood and therefore not possible to model without approximations.) For the present investigation, the Rossby Center Ocean model (RCO) has been used (9). This finite-difference model, has 41 depth levels and a horizontal reso-

## Box.

**The Mass-Balance Budget**

Box models as applied to exchange processes use a conservative tracer, e.g. salt, together with the net transports in and out of the control volume, to estimate the fluxes between the system and the adjacent waterbody. The most basic type of mass-balance budget assumes a constant volume V of the system. (Even if this is not normally the case, a reasonable approximation can be achieved by averaging data over long time-scales.) The system is furthermore taken to be well mixed, implying that the conservative tracer is evenly distributed in space. The method is generally based on the salinity difference between the system and the ambient waterbody, and hence such a discrepancy is required. Frequently, the box-model formalism is applied to estuaries, *viz*. semienclosed areas of an intermediate salinity, which implies some type of physical limitations on the freshwater input as well as on the fluxes to and from the system. Such constraints can be exerted by sills, sounds, or other morphological features.

The internal and external salinities $S_i$ and $S_o$ as well as a possible riverine influx $Q_f$ are used to formulate a budget based on conservation of volume as well as salt:

$$\frac{dV}{dt} = Q_f + Q_i + Q_o ,$$

$$V\frac{dS_i}{dt} = S_f Q_f + S_o Q_i - S_i Q_o ,$$

where the salinity $S_f$ of the river discharge is equal to zero for the cases examined in the present study. Assuming stationary conditions, *viz*. $d/dt = 0$, the unknown fluxes to ($Q_i$) and from ($Q_o$) the system can be calculated from the resulting purely algebraic equations. The outflow can hereafter be used to estimate the turnover time $\tau = V/Q_o$.

lution of 2 nautical miles in the runs used here. Given standard meteorological forcing, the model yields the evolution in time of the velocity, temperature, and salinity fields.

Due to the considerable difference between the ways in which the two classes of models have been formulated, it is somewhat of a challenge to devise means whereby the results can be directly compared (note e.g. that the volume flows in box-models are usually estimated using a conservative tracer such as salt, and thus represent a combination of advective flow and diffusive fluxes, in contrast to the 3-D model results). A first approach to reducing the large quantity of data arising from a numerical model could be to integrate all fluxes across the delimitations between the basin under consideration and the ambient waterbody, and to hereafter compare with the corresponding fluxes determined using a mass-balance model. However, budgets of the latter type yield averaged mean fluxes to or from the system as a whole, whereas the numerical model provides the local fluxes at the boundaries of the modelled system. This may constitute a problem if e.g. a more-or-less permanent vortex is located at the basin boundary. A typical example hereof was found in a recent study (10) of the exchange between the Gulf of Finland and the Baltic proper, where the integrated fluxes in each direction across the Hanko-Ossmusaar transect proved to be on the order of 3000 $km^3$ $yr^{-1}$, values to be compared to a mass-balance budget estimate of around 600 $km^3$ $yr^{-1}$ for the water flux from the Gulf of Finland (10). In cases like these, a more appropriate diagnostic variable for characterizing the system is the global turnover time (11). This quantity is, by definition, integrated over time as well as space and can furthermore be calculated for both of the modeling approaches. Turnover time additionally serves as a useful indicator of the physical processes taking place in the system, and this quantity is thus frequently used in biogeochemical studies, hereby being of considerable importance in itself when evaluating the geochemical and ecological characteristics of the basin under consideration.

Calculating the turnover time of a reservoir from a mass-balance budget is easily accomplished on the basis of the estimated fluxes and the volume of the system. It is a less straightforward matter for 3-dimensional numerical models, where an indirect approach is required. In the present study, Lagrangian trajectories (12, 13) have been employed for this purpose. This methodology is most conveniently applied off-line to velocity fields originating from a numerical ocean model. It is based on following the individual tracks of numerous, initially prescribed, water parcels.

The Lagrangian trajectories are based on an algorithm that computes particle paths in a three-dimensional velocity field. This algorithm calculates true trajectories for a given stationary velocity field. In the numerical ocean model, the divergence is discretized and allows the exact calculation of three-dimensional streamlines within each box of the three-dimensional mesh. For a stationary field, such streamlines define exact trajectories of particles in the model. These streamlines indirectly comprise the subgrid-scale parameterizations of the numerical ocean model by using its velocity field. This method has been applied in many different studies of the world ocean circulation (12–16).

Convection has not been taken into account in the present study, but has been tested in previous investigations by assigning a water parcel a random depth whenever it enters a convectively unstable water column (12, 13). Like the velocities used to calculate the trajectories, these convection events also follow from the ocean general circulation model. These studies showed, however, that the effects of convection did not contribute significantly to the integrated transports.

## RESULTS

As already touched upon, the alternative modeling approaches will be applied to two test areas of different character, where consequently the dynamics governing the water exchange can be expected to demonstrate different properties.

The Gulf of Riga represents a morphologically almost autonomous system (only connected to the Baltic *via* the narrow and shallow Irbe and Moon straits), with a comparatively large freshwater supply from the river Daugava (17, 18). These two features acting in conjunction provide a text-book example of a situation where box-model considerations are highly appropriate, i.e. well-defined exchanges, inputs and salinity differences. Calculations of this type have previously been undertaken for the period from 1977 to 1995 (19), resulting in an estimated turnover time of 825 days.

For the Lagrangian investigation of the turnover time characterizing the Gulf of Riga the RCO model results for the years 1980–1993 were used. The off-line experiments were initiated by letting the model spin up for five years, whereafter ”release” of trajectories took place in January, April, July and October 1985, so as to examine possible seasonal variability. A total of 9000 ”particles”, each pertaining to a water volume of $10^8$ $m^3$, were evenly distributed throughout the Gulf of Riga. (As determined from a set of auxiliary experiments, this initial ”particle density” was well above that required for the results to ”converge”.) Their trajectories were hereafter followed for a time-span of approximately 6 years. Figure 2 shows the normalized temporal evolution of the number of trajectories remaining in the gulf, a quantity intimately related to the residence time of water in this volume. From the diagram it is immediately evident that the renewal process is only insignificantly affected by seasonal variations. The Figure also includes a theoretical decay curve over time ($t$), calculated on the basis of the box-model estimate of the turnover time;

$$N_t = N_0 \cdot e^{\left(-\frac{t}{\tau}\right)},$$

where $N_t$ is the current number of trajectories remaining in the control volume, $N_0$ is the number of initially marked particles and $\tau$ is the box-model turnover time. The exponential decay is seen to correspond rather well to the average of the four ”experimental” curves, which in turn do not differ markedly from one another. It has thus been concluded that the two approaches to determine the ventilation of the Gulf of Riga appear to work equally well, most likely since this aquatic system to a high degree satisfies the *a priori* requirements for successful box-modeling of nonreactive tracers such as salt.

When attention is directed towards Gdansk Bay it is recognized that this waterbody, with its open boundary towards the Baltic

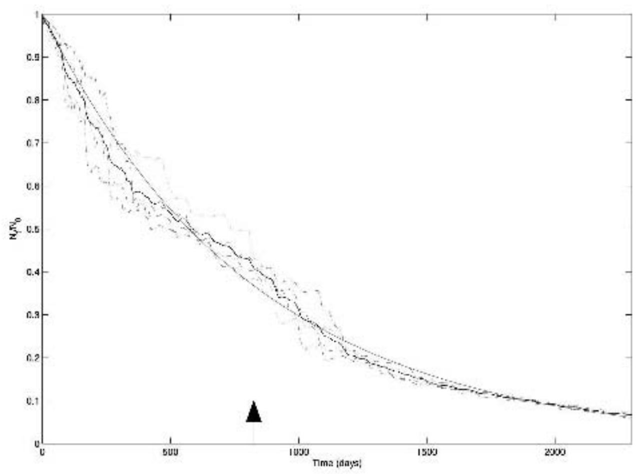

**Figure 2. Normalized temporal decay of the number of trajectories remaining in the Gulf of Riga. The 4 differently dashed lines represent the results from trajectory experiments commencing in January, April, July and October 1985 and the solid, somewhat irregular, curve shows their average. The smooth line represents a theoretical decay curve calculated on the basis of the estimate box-model turnover time 825 days (indicated by the arrow on the time axis).**

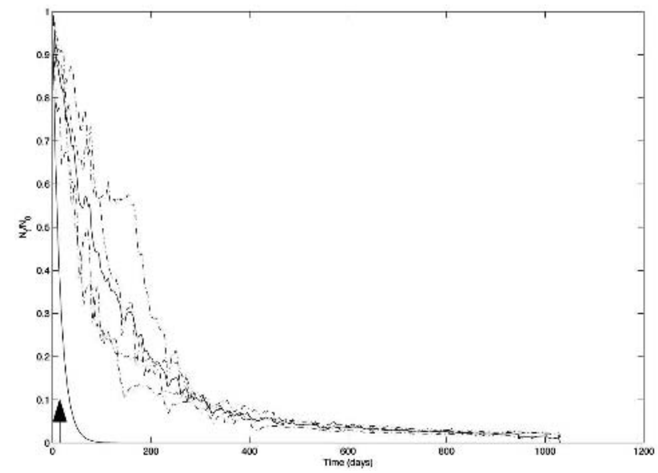

**Figure 3. Normalized temporal decay of the number of trajectories remaining in Gdansk Bay. The 4 differently dashed lines represent the results from trajectory experiments commencing in January, April, July and October 1985 and the solid, somewhat irregular, curve shows their average. The smooth line represents a theoretical decay curve calculated on the basis of the estimated box-model turnover time 15 days (indicated by the arrow on the time axis). Note the different asymptotic properties of the 2 independently established sets of results.**

proper, does not conform particularly well to the classical prerequisites for establishing mass-balance budgets. A significant salinity difference between the bay and the ambient water masses of the southern Baltic is, however, present. Since the freshwater flux from the river Vistula moreover is known from hydrological records, a box-model approach has previously been used to provide a lowest-order estimate of the exchange (20). In this study, the northerly delimitation of Gdansk Bay was taken to coincide with latitude 54°50'N, the examined period spanning between 1993 and 1998, and the resulting turnover time proved to be 15 days. A Lagrangian approach, based on the RCO-model fields from the Baltic used above, has also been implemented for the same region. This analysis included 3000 marked water parcels, i.e. the same initial particle density as in the Gulf of Riga case. The experiments were conducted along analogous lines, although for a period of 3 years, and the resulting decay patterns are shown in Figure 3, which also includes an exponential decay curve established on the basis of the 15-day box-model turnover time. This latter decay is seen to be more rapid than the average of those calculated using the Lagrangian formalism, where least-squares curve fit and use of the theoretical decay equation introduced above yields a turnover time of around 115 days. This discrepancy between the 3-D model and the mass-balance results is most likely due to the box model being highly sensitive to the prescribed salinity difference. This quantity, which is very small in the Gdansk-Bay case, may have thus been prescribed with insufficient accuracy (19). Also, the problems concerning small-scale fluxes over the basin boundary mentioned earlier probably apply here (10).

The trajectory results furthermore show considerable variance between the outcome for the four different months at which the experiments were initiated. This variability is consistent with the only weakly constricted character of Gdansk Bay, with its long open boundary towards the southern Baltic, since variations in the meteorological forcing can be expected to exert considerable influence on the exchange processes across this somewhat arbitrary delimitation of the control volume.

Seasonality thus probably has a fundamental impact on the dynamics of Gdansk Bay. (As an attempt to avoid biased results due to seasonal variations, each of the trajectory experiments was initiated at a different time of the year.) In particular Figure 3 also shows a considerable degree of variance between the different runs. Although it is beyond the scope of the present study to examine these variations in detail, a reflection that can be made is that events over short time-scales, such as storms, appear to have at least as strong an impact on the variations as do the seasonal influences.

The asymptotic properties of the Lagrangian decay curves in Figures 2 and 3 also merit comment. As evident from the Gdansk-Bay results, the number of remaining trajectories in this basin does not conform especially well to the exponential decay "predictions". Commonly a systematic discrepancy of this type (which frequently is encountered when applying the Lagrangian methodology to examine water-renewal problems) is ascribed to individual trajectories being trapped at the boundaries of the basin under consideration. The presently employed trajectory scheme (12) is, however, especially designed so as to minimize the number of such occurrences, for which reason the explanation has to be sought in another direction. To judge from a detailed analysis of the global behavior of the trajectories originating from Gdansk Bay once they have crossed the boundary of this control volume, a considerable number of these "water parcels" enter either the main Baltic circulation gyre around Gotland or a well localized bottom-water gyre encompassing the Gdansk Basin as well as Gdansk Bay. The investigation revealed that a significant number of these "fugitives" eventually reentered the control volume, a phenomenon which is clearly seen from the trajectories shown in Figure 4. This recirculation feature is completely absent from the box-model framework, which is based on assuming an infinite and thus unchanging external reservoir. Hence, the not totally compatible results obtained using the two modelling approaches.

On the basis of these results it has been concluded that Gdansk Bay is less suited for the application of box modeling than is the Gulf of Riga. The causes and consequences of this state of affairs will next be examined.

## DISCUSSION AND CONCLUSIONS

In the present study, the water-renewal problem has primarily been dealt with in order to elucidate possible consequences of climatic change as, within the SWECLIM programme, envisaged over a regional Nordic scale comprising the Baltic Sea. Since, however, the box-model concept is also widely used for more direct purposes such as environmental management, the present attempt at validation based on a direct comparison with the results from a numerical ocean model is also of a more general interest.

It was found that the mass-balance budget approach worked well for systems fulfilling the classical prerequisites, i.e. that the control volume is subject to pronounced topographical constraints and that the fluxes to and from the system are well defined (cf. the results pertaining to the Gulf of Riga). Gdansk Bay, on the other hand, proved to be less well adapted to this approach, since it is a

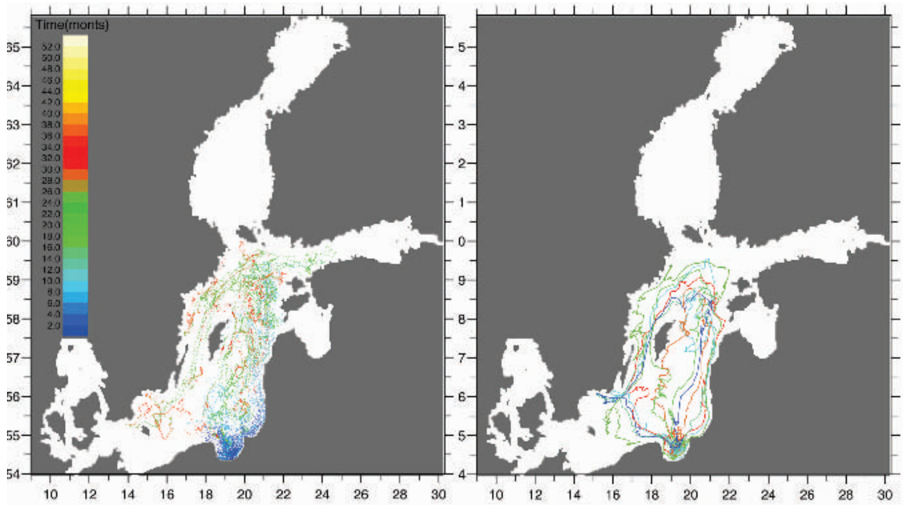

**Figure 4. The left-hand panel shows every 100th of the *in toto* 3000 trajectories used for the Gdansk Bay investigation, where the coloring indicates trajectory age (blue young; red old).The right-hand panel shows a selection of trajectories recirculating to Gdansk Bay, where color is used to characterize the individual trajectories.**

comparatively open system where the salinity difference between the bay and the open Baltic is small.

The estimates of turnover-times based on Lagrangian trajectories were not associated with this manifest drawback, but it must be kept in mind that the application of this technique is rather cumbersome and requires access to highly resolved velocity fields from a numerical ocean model.

An important point is to which extent the respective results are generalizible to reactive species such as nutrients, not least since the LOICZ guidelines (8) emphasize that budget considerations of this type have an important role to play for estimates of the global biogeochemical cycle. Even if the question is not explicitly addressed in the present study, any modelling of active tracers relies heavily on a correct estimation of waterfluxes to and from the studied system, and hence benefit from a proper choice of method. The two different model approaches, however, use completely different methodologies to incorporate active tracers, making the comparison too extensive for this study. The box-model approach outlined by LOICZ needs a correct hydrodynamical budget for estimating sources and sinks in the system. The 3-D numerical models, on the other hand, use a separate process model to describe the dynamics of reactive species. Here the accuracy of the process model is more critical for the outcome than the exact behavior of the hydrodynamical 3-D model. One could therefore expect the box-model approach to be more susceptible to errors in the water flux estimation than the 3-D numerical model approach.

Both methodologies have drawbacks as well as advantages. However, when applying an ensemble of box models to describe a larger aquatic system, such as the Baltic proper, care should be taken to avoid demarcating the various sub-basins in too arbitrary a fashion.

The versatility of Lagrangian methodology in the field of ocean circulation is important. As an example of a possible application, a modification of the trajectory analysis used in the present study will be employed to determine whether it is the River Neva discharge or inflow from the Baltic proper that plays the dominant role for the renewal of the Gulf of Finland water masses. The nature of this task makes it highly unlikely that the problem could be resolved solely on the basis of standard box-models.

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