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On the compressibility of the surface currents in the Gulf of Finland, the Baltic Sea

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Highlights:

- We develop a modified measure of compressibility of sea surface reflecting clustering of tracers
- Compressibility maps for the Gulf of Finland are calculated in a systematic manner
- We track areas of a marine region which are likely to form clusters of floaters
- High compressibility identified near the River Neva mouth
- Extensive seasonal-scale variability in compressibility in the Gulf of Finland

1. Introduction

Knowledge of fundamental features of pollution behaviors and impacts on marine environment is crucial for sustainable management of vulnerable sea areas. This knowledge is of key importance not only for a better understanding of the environmental responses to pollutants but even more for the development of efficient prevention measures. This knowledge is still sparse, and many factors are yet to be taken into account (Andrady, 2011; Schilling and Zessner, 2011). One of the vital questions is how and where dangerous

concentrations of adverse impacts (e.g. harmful algal blooms), frequently observed in natural conditions in the surface layer, develop from overall low readings of background fields.

The movement of different substances within the water column in the ocean is governed by the three-dimensional system of currents. Such motions generally result in spreading of initially closely located particles (Richardson, 1926; Ollitrault et al., 2005). Therefore, it is natural to expect that the concentration of different adverse impacts is the largest in the vicinity of their release site to the marine environment and that remote areas are safe. The situation is much more complicated for substances (such as oil pollution or plastic debris) that are locked in the surface layer. First of all, this layer is additionally affected by wind and waves. Both wind- and wave-induced transport are highly anisotropic and mostly mimic the behavior of the wind and wave patterns, which can be forecast and hindcast with a reasonable accuracy nowadays. As the properties of both these fields usually vary quite slowly over the open sea areas, the related transport normally does not lead to substantial changes in the concentration of different substances in the surface layer.

It is well known that large intense currents such as the Gulf Stream or Kuroshio carry large water masses from coastal areas across oceans to a distance of many 1000s of km. This feature makes the pollution or litter propagation problem a fairly general and global one. Moreover, substances in the surface layer are carried to extremely remote locations over areas that do not host such strong currents. For example, debris originating from South America is frequently found as beach litter on remote Pacific Islands (Richards, 2011).

A fascinating property of marine debris is its ability to form areas with high concentrations in the open ocean, far from jet currents. Perhaps the most well-know such area is located in the North Pacific Subtropical Convergence Zone (STCZ) and is sometimes called the Great Pacific Ocean Garbage Patch (Pichel, 2007). Therefore, even remote offshore locations are certainly not immune from problems related to high readings of pollution or litter in the surface layer.

The existence of such areas is usually associated with specific three-dimensional (3D) features of the ocean circulation (Lee, 2010). In essence, this feature can be interpreted as a particular realization of so-called patchiness of a number of different properties of the marine environment (Powell and Okubo, 1994). Many physical processes may be responsible for the presence of patches of different size and shape. For example, filament generation in quasi-two-dimensional velocity field (Held et al., 1995) naturally leads to extremely complicated spatial structure of concentrations of various properties (Kalda, 2000) and even such frequently occurring phenomena as horizontal density gradient (Burchard et al., 2008) or classical estuatione circulation (Burchard et al., 2004) may lead to accumulation of sediment particles or well-defined turbidity maxima. In the Baltic Sea patchiness has been subject to intense studies since the 1980s (Kononen et al., 1992; Granskog et al., 2005). In this area the phenomenon of patchiness is usually linked to various mesoscale hydrodynamic features such as eddies, frontal zones, or local jet currents. A similar mechanism, usually working at even smaller scales, is Langmuir circulation (Thorpe, 2009). All the listed phenomena normally have a substantial vertical component and, thus, an essentially 3D vertical structure.

In this paper, we make an attempt to link the potential of formation of patches (more generally, inhomogeneities in initially homogeneously distributed fields of passive tracers locked in the surface layer) on sea surface with so-called property of compressibility of sea surface. This property is one of important factors, which controls the behavior of the pollution spreading, and, if present, may naturally lead to the formation of high concentrations in different adverse impacts or marine garbage. We emphasize the substantial difference of this phenomenon from the more widely spread concept of compressibility of the entire medium

(sea water or air) understood as a measure of the relative volume change as a response to pressure variations. In this paper we use the notion of compressibility as the relative weight of the potential component of a velocity field. This definition relies on the motion of water particles. Three-dimensional atmospheric flows as well as the flows in the bulk of the water basins are usually almost incompressible; however, the two-dimensional velocity field at the water surface can be compressible even when water particles, initially located at the surface, are confined to stay at the surface. This happens because of the possibility of vertical motions of water masses (up- and down-welling in the marine environment) in the water column. In this sense, compressibility of sea surface can be interpreted as an indicator of the impact of 3D motions on the concentrations of different substances in a particular location of the surface. The highest values of compressibility can, thus, be naturally associated with areas prone to the development of well-defined patches.

While the effect of compressibility on different properties of the fluid motion and transport has been extensively studied both theoretically and experimentally (Falkovich et al, 2001; Cressman et al., 2004; Boffetta et al., 2004; Kalda, 2007), the evidence of its importance in marine environments is still scarce. The most prominent consequence of compressibility is the gathering of floating particles into patches. This feature is crucial in many environmental applications as it may substantially affect both the probability and propagation time of adverse impacts in different offshore areas to the vulnerable regions; for example, pollution is likely to stay for a long time in areas of high compressibility. Such areas can be interpreted as natural areas of reduced risk in terms of pollution transport from these to the coasts (Soomere et al., 2010).

In this paper, we study the effects of compressibility of a two-dimensional velocity field on the transport and mixing of substances floating on the sea surface of the Baltic Sea, in the area of the Gulf of Finland, and overlying a 3D field of motions. The key development is the introduction of a modified measure of compressibility (that is directly related to the ability of clustering of passive tracers in some regions of the sea surface) and a demonstration that its values may exceed the threshold for the formation of patches. The structure of the paper is as follows. Section 2 gives a short insight into the general problem of compressibility of 2D and 3D flows. The pool of velocity data, models used for its calculation and for tracking the surface elements on sea surface are described in Section 3. The definition of a modified measure for compressibility of 2D flows and its calculation scheme from 2D velocity fields are presented in Section 4. Section 5 depicts the resulting spatial distribution of this measure for the Gulf of Finland. The basic message from the research to the marine science is formulated in Section 6.

2. Compressibility of 2D flows overlying almost incompressible 3D motions

The fundamental theorem of vector calculus, the Helmholtz's theorem, states that any sufficiently smooth, rapidly decaying vector field in three dimensions can be expressed as the sum of an irrotational (curl-free, also called potential) vector field and a solenoidal (divergence-free) vector field. This is known as the Helmholtz decomposition. Consequently, virtually every realistic field of motions in the ocean (formally, defined everywhere in space and vanishing at infinity together with its first derivatives) can be decomposed, to a first approximation, into its solenoidal and potential components (with zero divergence and curl, respectively). In this framework, compressibility is defined as the relative weight of the potential component of the velocity field. Its particular values, therefore, are in the range from 0 (fully solenoidal flow) to 1 (fully potential flow). In what follows, however, we adopt a slightly different definition of compressibility, which will be referred to as the *finite-time*

compressibility and which coincides with the classical definition at the limit of ideal Kraichnan flows (Falkovich et al., 2001). The reasons for such an approach will be explained below.

There exists a direct link between the compressibility of a motion system (either 2D or 3D) and the possibility of formation of patches of concentration of passive tracers or particles injected into the fluid. Namely, systematic development of patches is only possible if the potential flow component dominates, that is, the values of compressibility exceed the threshold of 0.5. Compressibility of a realistic fluid motion is generally nearly 0, hence fluids are incapable of producing the patchiness of tracers (Fine and Millero, 1973). The most important exception here is the marine surface layer. Here large values of compressibility are possible due to the capability of the particles floating on it to "dive" into the third dimension (Garrison, 2011). Thus, the average compressibility of such a formally 2D velocity field on sea surface may largely exceed the analogous values for purely 2D or geostrophic flow. This property, in essence, is a generalization of several above-mentioned phenomena that lead to the development of inhomogeneities on the sea surface and can explain, at least partially, the patchiness of floaters in the marine environment.

It has been shown that the presence of non-zero compressibility can affect dramatically the behavior of the tracers, giving rise to clusterization of the tracer particles and fractal structures (Bec et al., 2004; Perlekar et al., 2010). According to the theoretical studies of ideal Kraichnan flows (which are delta-correlated in time), the crossover to clusterization takes place at the critical value compressibility of $C = 0.5$ (Falkovich et al., 2001). However, both experimental and numerical results indicate that the time correlations (which are always present for real hydrodynamic flows) can either inhibit or catalyze the clusterization process (Boffetta et al., 2004). Regarding the compressibility of real water flows, it has been shown that the free-slip surface of fully turbulent water volumes is characterized by $C \approx 0.5$ (Schumacher and Eckhardt, 2002). However, mesoscale and large-scale marine water flows are often quasi-two-dimensional (Rhines, 1979; Kraichnan and Montgomery, 1980), which leads to the reduction of the compressibility of the surface velocity field. Theoretically, non-linear waves may contribute to the increase in the surface compressibility. This effect apparently becomes evident, if at all, in quite specific conditions. For example, it has been shown that such an effect is negligible for weakly nonlinear waves (Vucelja et al., 2007). Therefore, the major source of sea surface compressibility evidently is the specific nature of the local 3D circulation that may give rise to systematic diving (e.g. downwelling) or uplift (e.g. upwelling) of water masses in certain sea areas.

The compressibility of a velocity field coincides with that of the motion of fluid particles floating in it. This feature makes it possible to analyze the compressibility of the particle field by means of addressing the compressibility of the vector field consisting of displacement vectors of simulated floaters' trajectories.

Since the overall surface area of the sea is constant in time, the average flow divergence over the entire sea surface is strictly zero. Surface floaters (passive tracers, adverse impacts, plastic debris, oil pollution, etc.) though, tend to spend more time in contracting regions than in expanding ones: the expanding flows tend to push floaters away, while the contracting ones tend to attract and keep floaters within their areas of influence. Therefore, particles tend to gather into patches in areas that systematically reveal nonzero compressibility.

3. Circulation model and Lagrangian tracking code

In this study we concentrate on the Gulf of Finland (Alenius et al., 1998), the easternmost sub-basin of the Baltic Sea. This water body frequently hosts long-term powerful upwelling and downwelling events (Lehmann and Myrberg, 2008; Leppäranta and Myrberg, 2009) and thus is a natural candidate for sea domains with substantial nonzero levels of surface compressibility. We employ surface velocity fields calculated for 1987–1991 in the Swedish Meteorological and Hydrological Institute by the Rossby Centre Ocean Model (RCO) in the framework of BONUS+ BalticWay cooperation (Soomere et al., 2010). This time interval has been chosen in order to make our results comparable with those obtained in the framework of studies into the quantification of offshore areas in terms of their ability to serve as sources of environmental risk to the coastal areas in terms of current-induced transport of adverse impacts released at these areas to the nearshore (Soomere et al., 2011). The horizontal resolution of the model grid is 2×2 nautical miles and the model uses 41 vertical levels in z-coordinates (Meier et al., 2003; Meier, 2007). The thickness of the vertical layers varies between 3 m close to the surface and 12 m in 250 m depth. The uppermost layer corresponds to water masses at depths 0–3 m.

The RCO model has been described in a number of sources (Meier, 2001; Meier et al., 2003). As we only use velocity fields produced using this model, we present here only shortly its key features. It is a Bryan-Cox-Semtner primitive equation circulation model following (Webb *et al*., 1997) with a free surface (Killworth et al., 1991) and open boundary conditions (Stevens, 1991) in the northern Kattegat. It is coupled to a Hibler-type sea ice model (Hibler, 1979) with elastic-viscous-plastic rheology (Hunke and Dukowicz, 1997). Subgrid-scale mixing is parameterized using a turbulence closure scheme of the k-ε type with flux boundary conditions to include the effect of a turbulence-enhanced layer due to breaking surface gravity waves (Meier, 2001). A flux-corrected, monotonicity-preserving transport scheme following (Gerdes et al., 1991) is embedded. No explicit horizontal diffusion is applied. The model run, data from which is used below, is forced with 10 m wind, 2 m air temperature, 2 m specific humidity, precipitation, total cloudiness and sea level pressure fields from a regionalization of the ERA-40 re-analysis over Europe using a regional atmosphere model with a horizontal resolution of 22 km during 1961–2007 (Samuelsson et al., 2011). The atmospheric forcing fields are extended beyond the ERA-40 period with analysis data from the operational ECMWF model (Anderson et al., 2006). As the atmospheric model tends to underestimate wind speed extremes, the wind is adjusted using simulated gustiness to improve the wind statistics (Samuelsson et al. 2011). Standard bulk formulae are used to calculate the air-sea fluxes over open water and over sea ice. For further details of the model set-up and an extensive validation of model output the reader is referred (Meier, 2001; Meier et al., 2003)).

The displacement of water particles has been calculated using their Lagrangian trajectories found by the TRACMASS model (Blanke and Raynard, 1997; Döös, 1995; de Vries and Döös, 2001) from the precomputed RCO velocity fields. Theoretically, using the TRACMASS model together with the 3D velocity data, it would be possible to calculate the classical compressibility of the velocity fields. However, as mentioned above, for real time-correlated flows, the non-zero values of compressibility alone are unable to describe the development of patches on the sea surface (such as the floater clusterization). The physical reason for that is most explicitly demonstrated when we consider a hypersonic (compressible) gas flow. In such flows, at any moment of time, the velocity field is compressible, because the dynamic pressure exceeds the hydrostatic one. Meanwhile, this compressibility has long-term negative correlation. For delta-correlated flows, nonzero values of compressibility mean that the sum of Lyapunov exponents is negative, i.e. material volumes contract exponentially in time. This contraction is actually the fundamental reason of the creation of patchiness owing to the presence of non-zero compressibility. However, the material volumes of hypersonic gas

flow cannot contract exponentially: eventually the hydrodynamic pressure will play a role and stop the contraction. As a result, even though the classical compressibility of hypersonic flows can be considerable, the sum of the Lyapunov exponents remains strictly equal to zero. This property is equivalent to the absence of creation of long-term patchiness.

4. Method for compressibility calculations

Therefore, in order to reach a measure of compressibility that is more directly related to the formation of patches, the definition of compressibility needs to be revised towards accounting for the properties of real flows with finite time-correlations. Following this line of thinking, we employ the modified definition of (finite-time) compressibility. The idea is to relate the finite-time changes in the material volumes (e.g., surface areas in the case of 2D flows overlying 3D circulation) to the finite-time changes in the separation between material particles. The modification is consistent in the sense that the introduced measure coincides with the values of the classical compressibility at the limit of infinitesimally small time windows and Kraichnan flows.

The basic idea in the calculations is to look at the changes in the surface of small elements of the surface. The simplest element is formed by three points at the surface, forming a triangle with nonzero area (Fig. 1). The displacement of its vertices is tracked using the trajectory simulation code TRACMASS.

The changes to the position of the vertices were obtained by running TRACMASS for a cluster of passive tracers associated water particles placed in the center of each grid point. The initial separation of the neighboring tracers along latitudes and along longitudes is, therefore, about 2 nautical miles. Simulations are run over a data set which contains information data for the year 1991. Tracers are repositioned in the center of their belonging grid cell at the end of a 24 hours run. From these simulations, we retrieve a displacement vector field of tracers' positions, which is used to calculate a compressibility value for each grid cell. This value is calculated in terms of patches' properties.

Let us consider a grid cell, at time step 0 for a given day. As a simplest surface element representing the change in the surface area at this point, we choose a triangle consisting of this point and its immediate neighbor to the south and east (Fig. 1). This stencil is applied to the entire surface of the Gulf of Finland and its entrance area. More formally, let $\left(x_1^t, y_1^t\right)$, $\left(x_2^t, y_2^t\right)$ and $\left(x_3^t, y_3^t\right)$ be the coordinates of the vertices of an element at time step *t*. It is convenient to consider twice the surface of an element S_t, expressed at time step *t* as follows:

$$S_t = \left|\left(x_1^t - x_2^t\right)\cdot\left(x_1^t - x_3^t\right)\cdot\left(y_1^t - y_3^t\right)\cdot\left(y_1^t - y_2^t\right)\right|. \quad (1)$$

The relative change over time of its area is $dS_t = \left(S_t - S_{t-1}\right)/S_t$. Another component of our definition of compressibility is the squared length of two edges of the element:

$$A_t = \left(x_1^t - x_2^t\right)^2 + \left(y_1^t - y_2^t\right)^2;\ B_t = \left(x_1^t - x_3^t\right)^2 + \left(y_1^t - y_3^t\right)^2 \quad (2)$$

Their respective changes over time are obviously $dA_t = \left(A_t - A_{t-1}\right)/A_t$ and $dB_t = \left(B_t - B_{t-1}\right)/B_t$. The finite-time compressibility value is calculated now from the changes to the three quantities in question at different time steps as follows:

$$C = \frac{2dS_{rms}}{dA_{rms} + dB_{rms}}, \tag{3}$$

where the components of the right-hand side of Eq. (3) have the meaning of rms (root mean square) values of the respective quantities

$$dS_{rms} = \sqrt{\frac{1}{n}\sum_i^n dS_i^2}\ ,\ dA_{rms} = \sqrt{\frac{1}{n}\sum_i^n dA_i^2}\ ,\ dB_{rms} = \sqrt{\frac{1}{n}\sum_i^n dB_i^2} \tag{4}$$

and *i* indicates a particular realization of the flow. The rms in Eqs. (4) is calculated on a number of samples that linearly depends on the size of the chosen time window. This is a direct consequence of the fact that running a simulation over a longer time window, produces a higher number of samples. It is, however, obvious that the limiting values of *C* in Eq. (3) do not depend on the number of samples provided the velocity field is statistically stationary.

From Eqs. (1)–(4) it follows that if the flow is purely incompressible, $dS_{rms} = 0$, and hence the compressibility $C = 0$ in the entire volume filled (or area covered) by such a flow. In the contrary, if the flow is purely contractive or expanding, the quantities *A* or *B* would change with the same relative rate as *S*, so that we would have $C = 1$. The values of *C* defined by Eq. (3) obviously lie in the range [0,1], with $C = 1$ implying a purely compressible flow. The importance of the presented definition of the measure of compressibility *C* is that it accounts for the finite-time correlations and its values are directly related to the ability of gathering the tracer particle into patches.

The scheme of calculations resembles a similar scheme used for the identification of semi-persistent patterns (Soomere et al. 2010). A longer time interval t_D of interest (year 1991 in the calculations in this paper) is divided into time intervals (windows) with a length of t_W =16–96 hours (Fig. 2). As mentioned above, one tracer is placed at the centre of each wet grid point of the RCO model and its displacement is traced over this window; usually over a number of time steps. The results of calculations over a particular time window form one realization of the process of changes to the area of surface elements. For a new realization, the simulations of the same pattern of tracers and surface elements are restarted with a time lag $t_S = 1$ day.

After performing simulations for such a pool of realizations, we average the value of *C* pointwise over different time spans: on daily, monthly, seasonal and yearly base. The resulting spatial maps characterize the spatial variations in the field compressibility for different time intervals over the Gulf of Finland. As discussed above, large values of compressibility in these maps show a predictive estimate of the likelihood of tracers inserted into various grid cells to gather into patches, equivalently, areas where high concentrations of floaters, garbage, adverse impacts, etc., are likely.

The above-mentioned property (that the basin-wide average 2D flow divergence is zero for a sea area of constant size) offers a way to judge to a certain degree about the correctness of the calculations. Figure 3 presents the average divergence, integrated over the entire area of the Gulf of Finland, as calculated for every day of year 1991 using the described technique with t_W =4 hours. The plot shows values which tend to be really close to zero throughout the year. The small variations reflect the surface water exchange between the area over which the divergence is calculated and the Baltic Proper. The mostly positive values apparently mirror the excess of fresh water inflow in this area (Leppäranta and Myrberg,

2009) while a few negative values evidently are connected with surface water inflow owing to specific wind events .

5. Spatial distributions of compressibility

The resulting maps vividly demonstrate that there exist areas with high compressibility values in the Gulf of Finland (Fig. 3). Most of these areas have an elongated stripe-like shape and are generally located close to the shore. Most likely the areas with a high compressibility reflect regions hosting intense vertical motions (upwelling or downwelling) in coastal areas, possibly with upwelling filaments, or divergence or convergence zones between coastal currents and offshore mesoscale circulation. For example, during the first week of November 1991, the highest compressibility is found in the vicinity of the River Kymi mouth in SE part of the Gulf of Finland. This region, with local values of C up to 0.9, is also characterized by merging of the voluminous runoff of River Neva with waters coming from River Kymi and brackish waters of the Gulf of Finland and, thus, high values of C are not unexpected.

In contrast with the classical definition, our definition of compressibility makes it possible to calculate its dependence on the length of the time window used for estimates of the change to the area of surface elements. The use of very short time windows is equivalent to the calculation of pointwise compressibility. The use of longer time widows makes it possible to track the distortions of the surface elements over a certain sea area during their Lagrangian drift. This option allows identifying areas over which the compressibility increases cumulatively over some time interval. Such areas are actually the best candidates for emerging high concentrations of adverse impacts.

Calculations using different lengths of t_w show that, for shorter time windows (0 to 24 hours), the resulting values of C are relatively low and generally do not reach the critical value of 0.5 (Fig. 5). With an increase in the time window to 48–72 hours, this threshold is reached at several locations (Figs. 6, 7).

The presented results demonstrate that the locations of the high-value regions of C are qualitatively the same for all choices of the time window length. The elongated areas of high compressibility may be interpreted as regions in which the compressibility cumulatively increases in the direction of the surface current. The critical values in C are usually reached only if the time window is 12 hours or longer. Remarkably, several elongated areas of high C are oriented almost across the gulf. Such areas may reflect relatively intense cross-gulf transport pathways (Soomere et al. 2010) which also demonstrate systematic contraction or expansion. The quantitative results of the variation in the length of the time window are highlighted in Fig. 7 that shows the areas of the sea surface characterized by high (>0.5) values of C, obtained setting the time window to 48 hours, that wouldn't have been evident if the simulation was run on the same time interval using a shorter time window.

The areas characterized by high values of C seem to be affected by a strong seasonal variability (Fig. 9). For the year 1991, the maximum values of the finite-time compressibility (Table 1) are the largest in autumn (October–December) whereas the average values of C exceed the patch-generation threshold of C=0.5 at several locations. It is remarkable that the highest values of C near the mouth of the River Neva and at the entrance to the Gulf of Finland occur almost at the same locations as in simulations for one week (Fig. 3). This feature suggests that the areas favorable for the generation of patches may persist over several months.

Other seasons have clearly less maximum values of C that are close to the threshold of C=0.5 and even remain below this threshold for the spring months (April–June). The qualitative appearance of the field of C is very much the same in different seasons (Fig. 9). The life-time of high-value areas of compressibility seems to be limited to a few months: averaging over the entire year of 1991 leads to a substantial decrease in the local values of C which remained well below the threshold in question.

6. Conclusions

The property of compressibility of a 2D velocity field overlying 3D circulation is a natural generalization of the impact of various phenomena (such as upwellings, downwellings, convergence or divergence of ocean currents, Langmuir circulation, etc.) that may lead on the formation of inhomogeneities in otherwise smooth fields in the surface layer. In other words, such processes may cause contraction or extension of the sea surface, in this way affecting the behavior of different substances floating on the sea surface. Their obvious consequence is the formation of patches.

The traditional definition of compressibility basically relies on instantaneous velocity fields and does not account for the time history of motions and cumulative distortion of sea surface. The modified measure of finite-time compressibility, introduced in this paper through tracking the local changes to the area of surface elements, makes it possible to systematically quantify the impact of the listed processes, independently on their particular physical origin, on various fields on the sea surface. It allows for variable-length time window averaging for flows translating surface elements over the sea surface. This property makes it possible to calculate cumulative effects of compressibility and, thus, to highlights sea regions characterized by large values of compressibility occurring during some finite time interval and which wouldn't have become evident using the classical definition. Another key feature of this measure is its tight relation with the ability of clustering of passive tracers in some regions of the sea surface, allowing hindcast and forecast of the domains in which the patch formation is most likely.

The particular values of this measure of compressibility to some extent depend on the length of time slices over which it is calculated. The spatial variations of the compressibility are fairly strong. While its values for short time slices are fairly low, for slices of quite reasonable length (48–72 hours) its values reach and overshoot the threshold for the formation of extensive patches. Usually coastal regions are characterized by significant compressibility values (above the critical level of 0.5) but comparable values area also found in elongated offshore areas. The spatial distributions of compressibility reveal extensive seasonal-scale variations. The performed simulations for one year (1991) suggest that several regions of high compressibility (equivalently, areas prone to the generation of surface patches) persist, at least, during a few months but apparently are smoothed out when averaged over entire year. Finally, we mention that this study only focuses on mesoscale variations in the compressibility and does not cover compressibility of small-scale structures (<2 nautical miles), which can greatly enhance the effect of patchiness (Granskog et al., 2005) and will be the subject of further studies.

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Figure captions

Figure 1. Scheme of the selection of surface elements and their distortions in time

Figure 2. Definition sketch of splitting the simulation period into time windows.

Figure 3. Divergence of the 2D flow on the sea surface, integrated over the entire Gulf of Finland, the Baltic Sea, throughout year 1991.

Figure 4. Average compressibility of water surface in the Gulf of Finland for one week in November 1991 calculated using t_W =48 hours.

Figure 5. Average compressibility of water surface in the Gulf of Finland for one week in April 1991, calculated with the time window of 24 hours.

Figure 6. Average compressibility of water surface in the Gulf of Finland for one week in April 1991, calculated with the time window of 48 hours.

Figure 7. Average compressibility of water surface in the Gulf of Finland for one week in April 1991, calculated with the time window of 72 hours.

Figure 8. Areas (green) in which the finite-time compressibility exceeds 0.5 in a simulation with t_W =72 hours compared to a simulation with t_W =48 hours during the first week of November 1991.

Figure 9. Average compressibility of water surface in the Gulf of Finland in winter and autumn 1991.

Table captions

525 Table 1. Maximum values of finite-time compressibility C calculated using t_W for different
526 seasons in the Gulf of Finland.

Figure(s)
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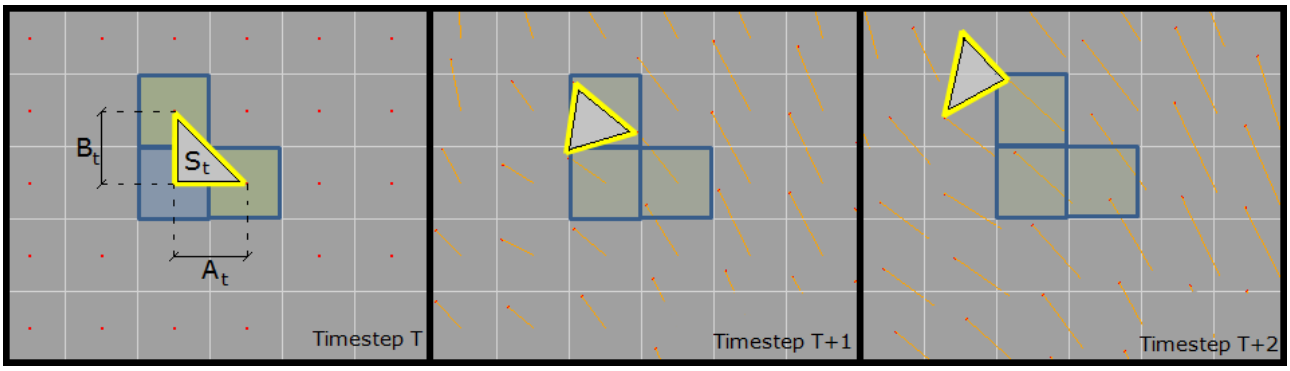
On the compressibility of the surface currents in the Gulf of Finland, the Baltic Sea

Jaan Kalda, Tarmo Soomere, Andrea Giudici

Figures



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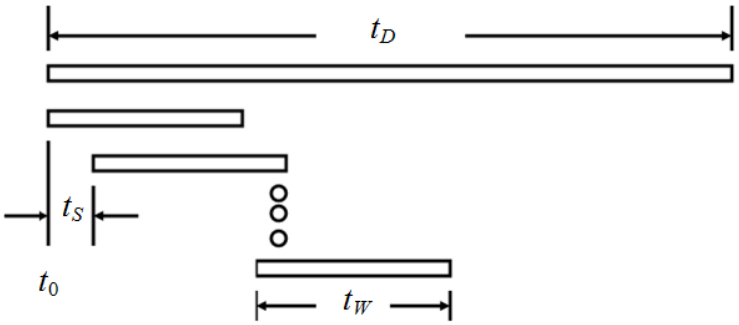

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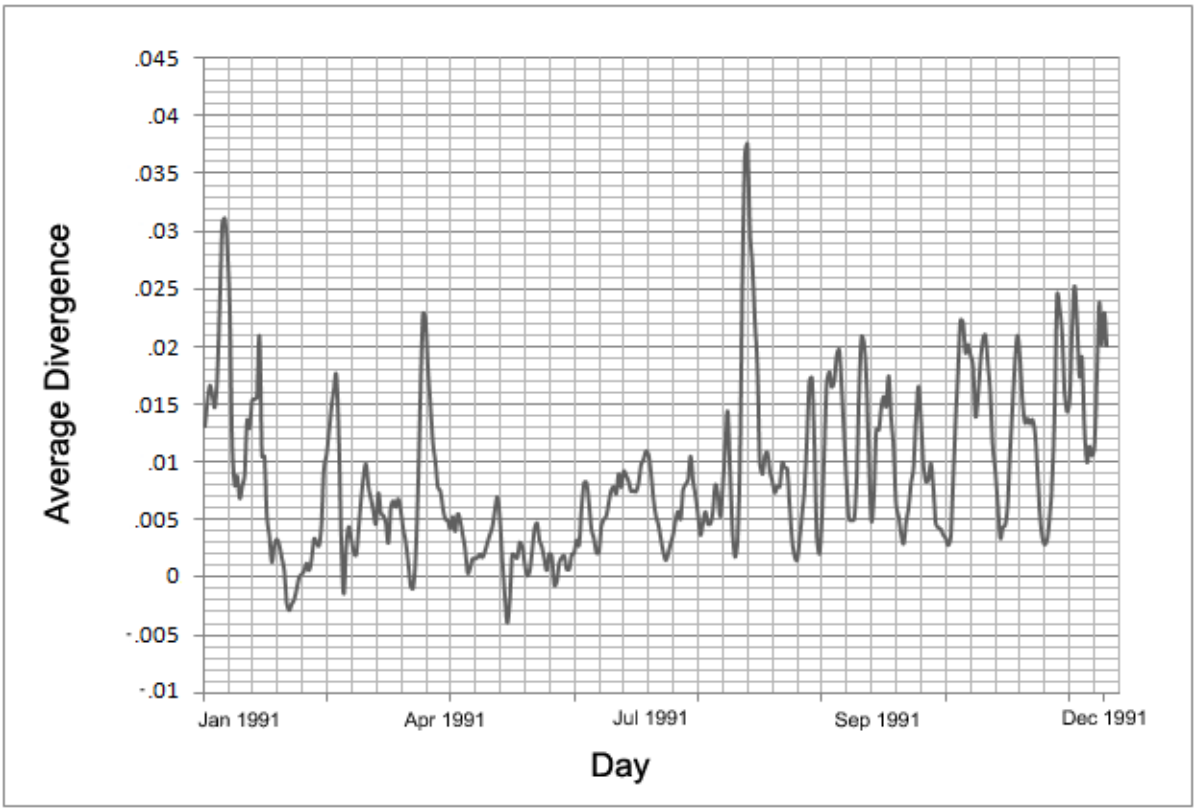

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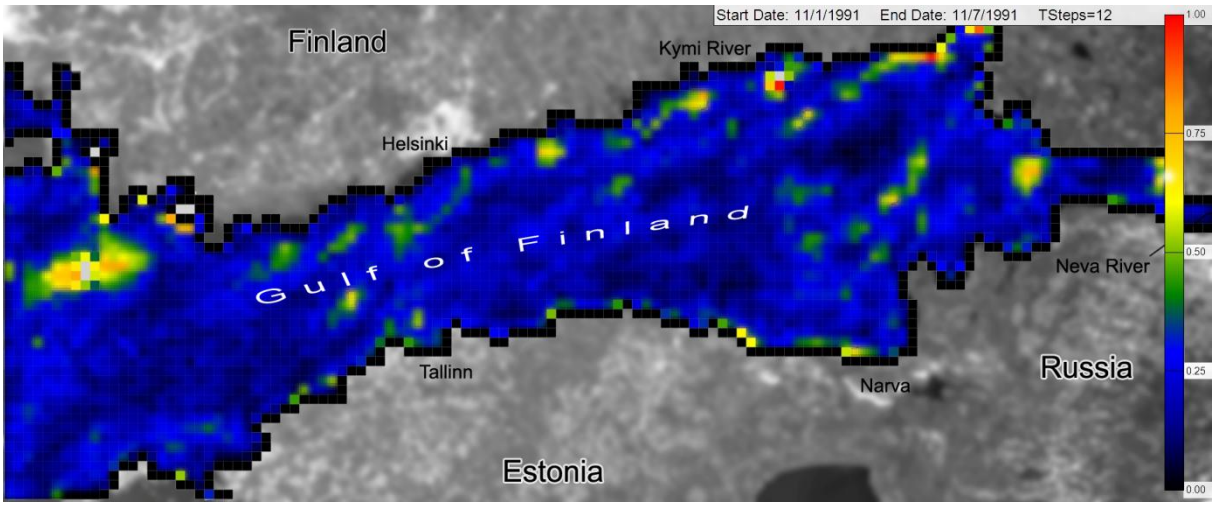
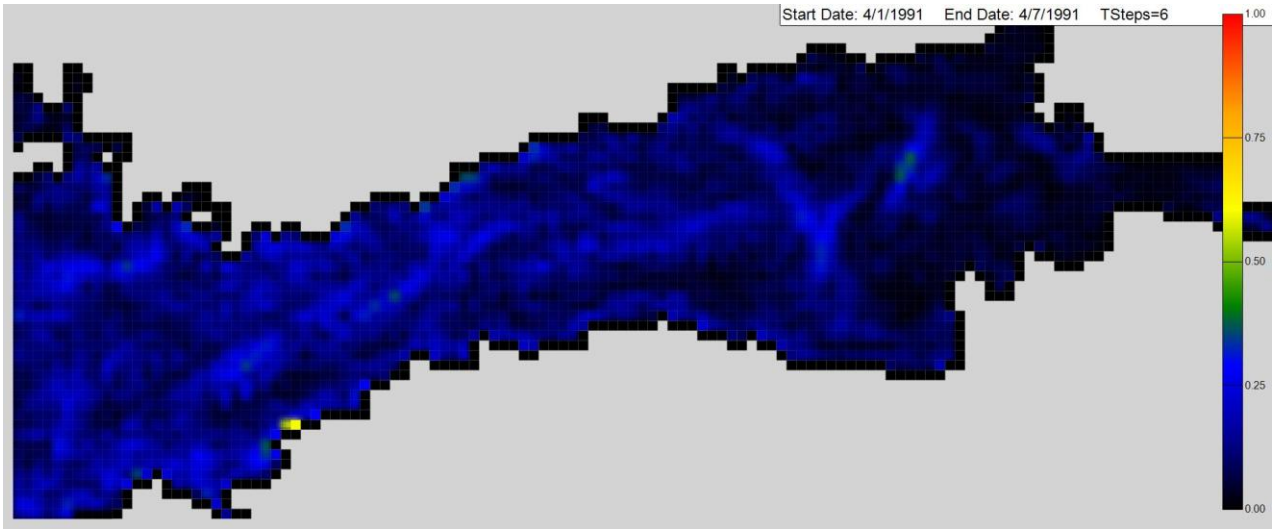


Figure 4. Average compressibility of water surface in the Gulf of Finland for one week in November 1991 calculated using t_w =48 hours.



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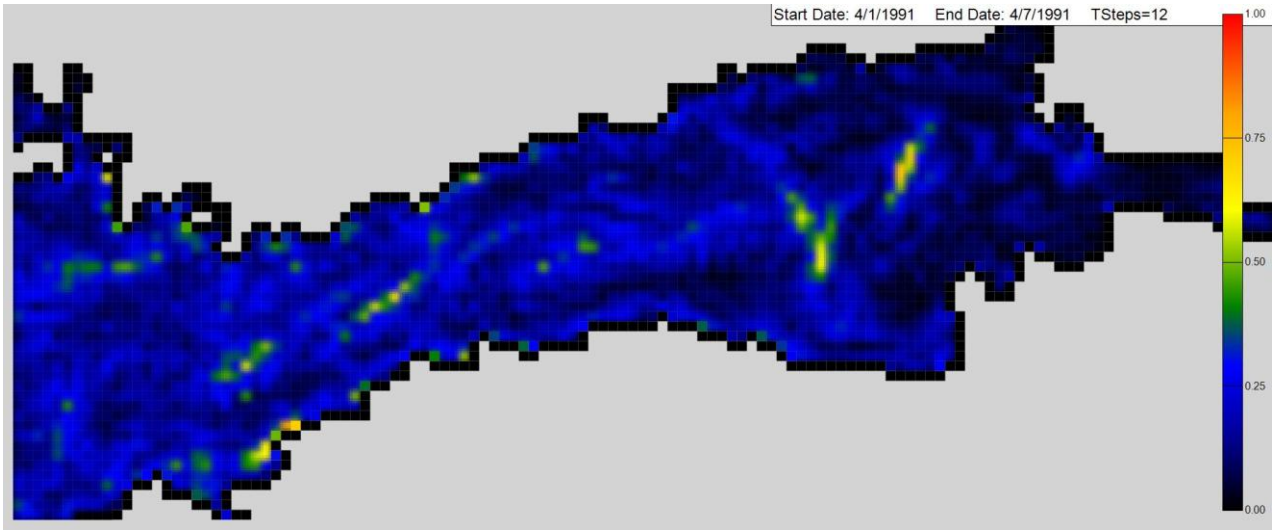
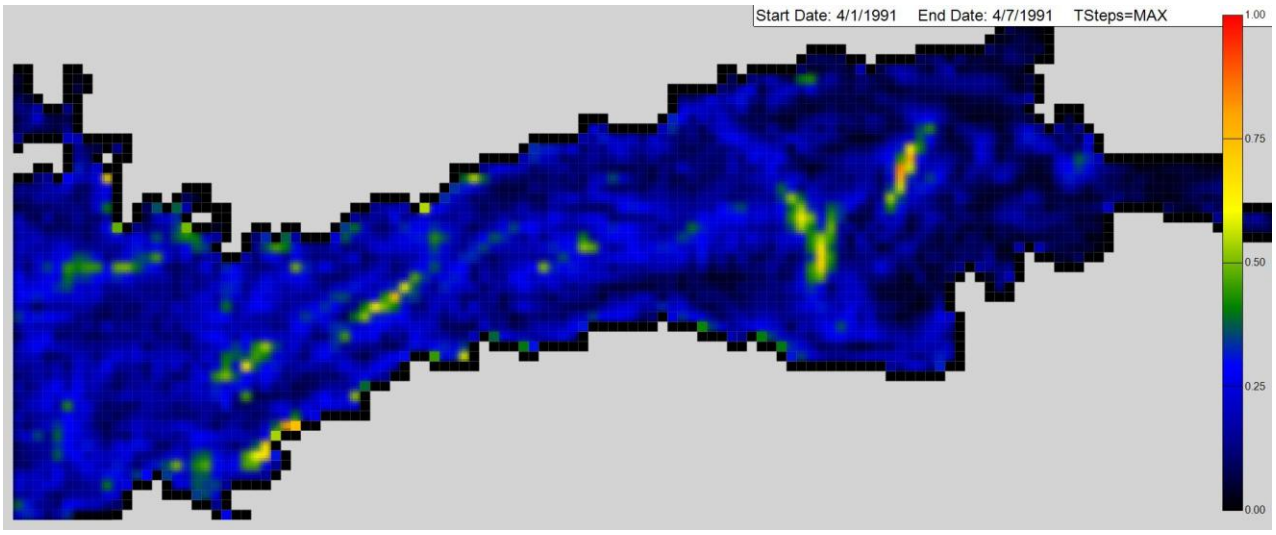


Figure 6. Average compressibility of water surface in the Gulf of Finland for one week in April 1991, calculated with the time window of 48 hours.



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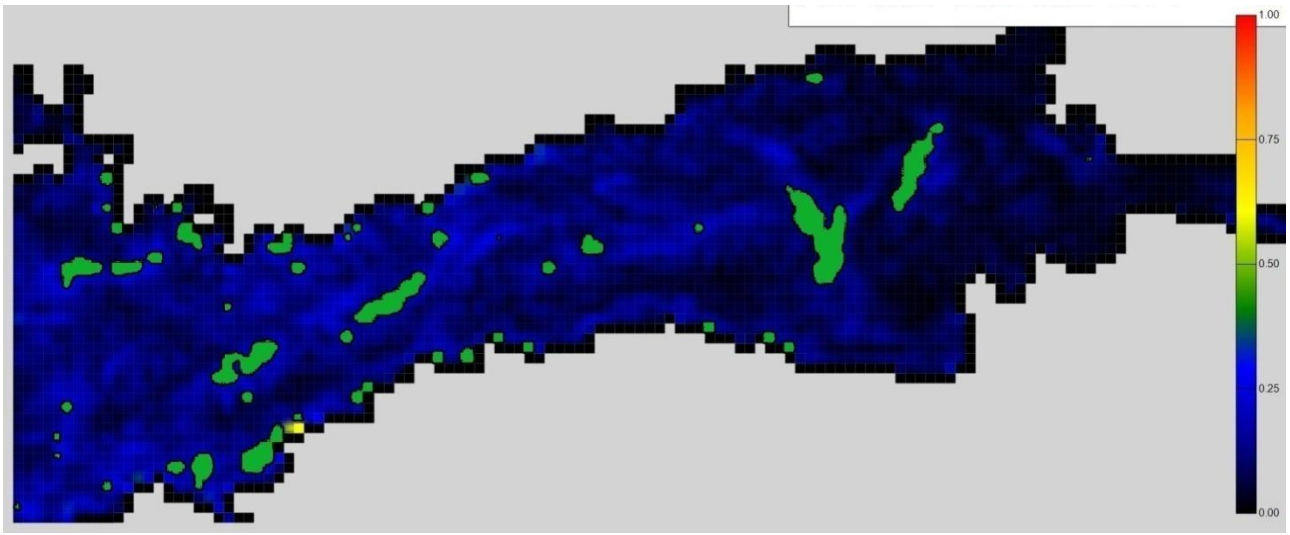

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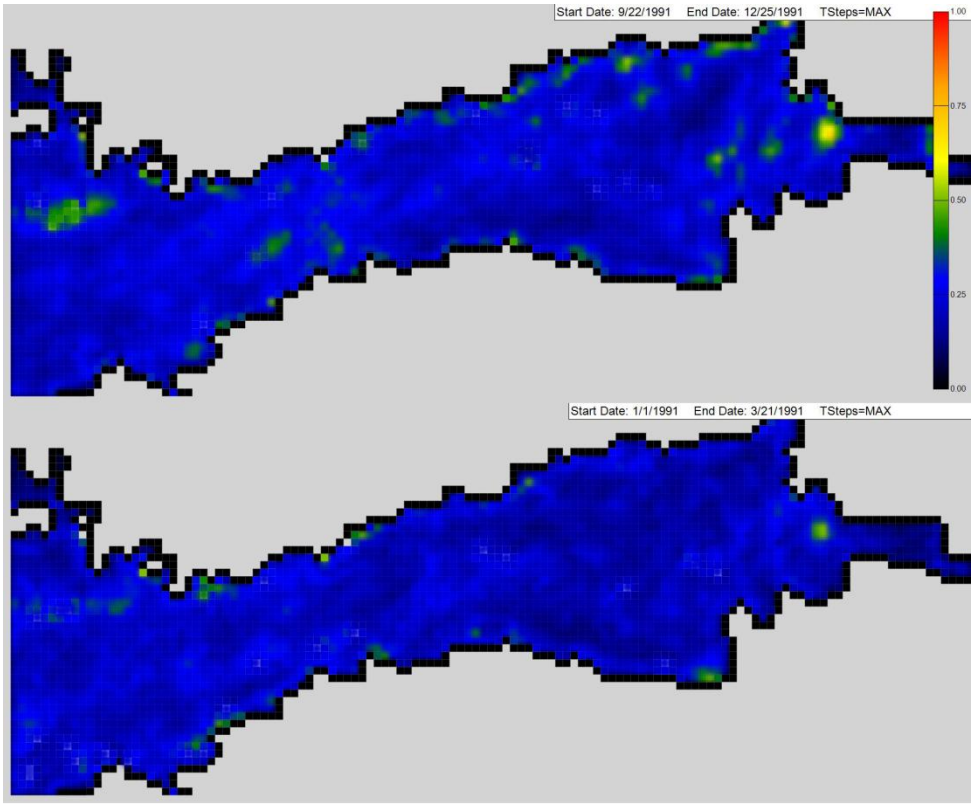

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On the compressibility of the surface currents in the Gulf of Finland, the Baltic Sea

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Table 1. Maximum values of finite-time compressibility C calculated using t_w for different seasons in the Gulf of Finland.

Season	Maximum compressibility
Spring 1991	0.4408
Summer 1991	0.5246
Autumn 1991	0.7634
Winter 1991	0.5072