Surface drifters and model trajectories in the Baltic Sea

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Results from recent deployments of surface drifters in the Baltic Sea are presented. For the first time ever, the realism of model-generated trajectories was assessed by a statistical comparison with trajectories of SVP drifters. The absolute dispersion (i.e. the distance from the initial point as a function of time) was found to be somewhat underestimated by the model trajectories. A severe underestimation of the relative dispersion (pair separation) was also noted, which may, to some extent, be due to the limited resolution of the model. However, the relative dispersion was also found to be very dependent on the initial separation of the model trajectory pairs. After filtering the inertial oscillations, a good agreement of the velocity auto-correlations between the drifters and model trajectories was found. A discussion on the impact of these results on future trajectory modelling in the Baltic Sea is also provided.

Background

Tracing Lagrangian trajectories is a powerful tool for understanding and diagnosing motion in both the atmosphere and ocean. They can prove useful for extracting Lagrangian information such as transport and dispersion from Eulerian fields. Knowing the origin and destination of a water particle, as well as the spread of several particles, is highly relevant for estimating the fate of oil spills (Soomere et al. 2010) or living organisms (Corell 2012), as well as for planning rescue operations or finding lost goods. Lagrangian trajectories, if in large enough quantities, can also be used to track entire water masses (Döös 1995, Blanke & Raynaud 1997, Döös et al. 2004), or to map the mean flow (Richardson 1983), and dispersion (Pizzigalli et al. 2007) characterising the ocean. For these reasons and more, there are thousands of satellite-tracked drifters in operation in the world oceans at various depths. This vast number of Lagrangian observations constitutes an invaluable global data set of transport and dispersion properties, while also providing data on the temperature and ambient atmospheric pressure in regions where observations are scarce.

As the use of model-simulated trajectories in ocean studies has increased, so has the need to validate them with observations. Studies have compared model trajectories generated using velocity fields from an ocean general circulation model (OGCM) with surface drifters in the North Atlantic (Garaffo et al. 2001, Lumpkin et al. 2002, McClean et al. 2002), and the world oceans (Döös et al. 2011). Some of these studies binned the Lagrangian velocities from the surface drifters to obtain fields that could then be directly compared with the Eulerian fields from the OGCMs, while some simulated Lagrangian trajectories using the model-simulated velocity fields and compared them with the surface drift-
ers. Although the studies used different models, and different drifter data sets, a common conclusion is that the Eulerian velocities and/or Lagrangian transport is overestimated in some places, and underestimated at some other ones, but on the whole agrees fairly well. Another common finding for all studies is that the spread (separation) of particles and/or variability of the Eulerian flow (equivalent to eddy kinetic energy) is underestimated by the models. This, in turn, results in errors in both transport and dispersion. The discrepancies between model results and drifter data are often attributed to the model having coarse resolution in time and space, thus missing smaller-scale motions. Results from of McClean et al. (2002) and Döös et al. (2011) suggest that model velocities agree better with those derived from drifter data when the model resolution becomes higher. Döös et al. (2011) and Iudicone et al. (2002) found that the spread increases with finer model resolution. Furthermore, it is often suggested that part of the low variability of the flow could be explained by the coarse temporal resolution of the atmospheric wind forcing (Garraffo et al. 2001, McClean et al. 2002). The fact that the atmospheric forcing is often taken at the height of 2 m, and not at the ocean surface, and that the relationship between surface currents and surface wind is rather complex, may also lead to some discrepancies.

For the Baltic Sea, there have been several studies using model-simulated Lagrangian trajectories (Jönsson et al. 2004, Döös et al. 2004, Engqvist et al. 2006, Soomere et al. 2010), but very few attempts to assess the realism of these model trajectories. Gästgifvars et al. (2006) compared actual trajectories of “Current Spy” drifters, which are shallow (< 1 m deep), with forecasted trajectories driven by fields from various ocean models using operational winds. Within three days, the forecasted trajectories compared relatively well to those observed. However, this study used only a few shallow drifters for no more than three days, and was limited to the Gulf of Finland. The lack of larger assessments is partly an effect of very few Lagrangian observational data available for the entire Baltic Sea, this due to the heavy traffic and the small horizontal extent of the basin where the mean depth is sufficient for SVP drifters to travel. The risk of a surface drifter running aground in too shallow waters or colliding with a ship is much higher in the Baltic than in the world oceans. Although some drifter experiments were conducted in the Gulf of Bothnia (Håkansson & Rahm 1993, Launiainen et al. 1993), the data have not been used to validate any regional ocean-circulation model.

Regional ocean circulation models for the Baltic Sea have hitherto been validated against data from individual moored instruments. Meier (2002) compared model-simulated temperatures and salinities with observations, and found fair agreement, although the number of observational stations was quite small. The quality of the atmospheric forcing has also been assessed. Höglund et al. (2009) showed that the wind fields used to force the regional ocean model were underestimated and applied a gust correction. The correction gave better results statistically, but for individual stations this deficiency remained, and the study concluded that better boundary-layer parameterisations and higher horizontal resolution is needed.

The aim of the present study was to, for the first time ever, systematically compare statistics from surface-drifter data from the Baltic Sea with that from model trajectories simulated using fields from a regional ocean model. We studied both transport and dispersion, viz., both single- and multiple-particle statistics, and also examined the behaviour (e.g. velocity auto-correlation and integral time scales) of the trajectories. A discussion of the origin and the nature of the model-observation differences is also provided. It needs to be stressed that the study did not attempt to compare the observed and modelled trajectory tracks, but rather to compare their statistics. Also, the surface-drifter data used give information about currents at the 12–18 m depth, implying that the actual surface drift would not be investigated.

**Observed and modelled trajectories**

**Surface drifters**

The drifter data were collected using the SVP-B (Surface Velocity Program) drifters (Lumpkin and
Pazos 2007), where B indicates that they were equipped with a barometer. All the drifters were manufactured by the Marlin-Yug Ltd., Sevastopol, Ukraine. They adhere to internationally recognised standards and are approved by NAV-OCEANO (The Naval Oceanographic Office) as conforming to the WOCE (World Ocean Circulation Experiment) norms. They consist of a surface float containing a data transmitter, a barometer, a thermometer, and a battery, with an attached tether line leading down to a hollow drogue at the depth of 12–18 m. This design in meant to make the drifters follow sub-surface currents despite the effects of wind and waves on the surface float, where the GPS for tracking is situated. Data — including position, SST, atmospheric pressure, and state of the drifter — are transmitted every hour, and stored in the Argos network. If, for some reason, drifter data are not available for a certain period of time, the data are interpolated linearly between the two nearest points in time when data were available. Transfer of data is made via the Argos satellite communication systems.

The surface float is not necessarily completely submerged when in the water, which may lead to a drift not representative of the water mass transport. This drift may be due to wind, surface currents, Langmuir currents, Stokes drift, or other forces acting on the surface float. Also, it must be taken into consideration that waves may affect the float. The water-following capability of SVP drifters has been assessed in some studies, e.g. by attaching a current meter to the drifters (Niiler et al. 1995). SVP drifters have been found to represent water mass transport better than many other drifter types, due to their design, where the drag force on the drogue is much larger than that on the tether line and the surface float (Pazan and Niiler 2001). Drifters of this kind generally have a drift of < 0.5 km day⁻¹.

Three pairs and two triplets of surface drifters were deployed at three locations in the Baltic Proper. All deployments were made from the ferry m/s Silja Festival, during cruises between STOCKHOLM and Riga, except the last pair, which was deployed near the Estonian coast in the Gulf of Finland. The three pairs were deployed on 14 July and 17 August 2010, and on 7 November 2011, and the two triplets on 9 June and 10 August 2011. As ships collided with four out of the first seven drifters, the second triplet was deployed at a point closer to the Swedish coast, where the ship traffic was thought to be less frequent. The last pair consisted of drifters that had been previously deployed in the Baltic Proper, and were re-deployed in the Gulf of Finland. The last transmission of the drifter data occurred on 19 November 2011. The trajectories of the surface drifters are shown in Fig. 1, and the surface-drifter deployment positions and lifetimes are given in Table 1.

Modelled trajectories

The model trajectories were computed using the Lagrangian trajectory code TRACMASS (Döös 1995, Blanke & Raynaud 1997) driven by velocity fields from the Rossby Centre regional Ocean climate model (Meier et al. 2003). TRACMASS trajectories were computed off-line, i.e., after the fields from the RCO model had been integrated and stored. This allowed for faster and less memory-consuming computations, but the temporal resolution was only six hours. The data were obtained at any position and time using linear interpolation between grid points. TRACMASS is fully Lagrangian in the sense that trajectories are traced in 3D. Here, model trajectories were locked vertically, and horizontally driven...
by a weighted average of the currents between 12–18 m, to better resemble the conditions experienced by the surface drifters. To simulate drifters being stranded, any model drifter that at some point in time reached a depth shallower than 18 m was removed from the statistics.

The RCO model is a regional ice-ocean circulation model based on the global OCCAM model (Meier et al. 2003). RCO is often used for longer simulations, and not for forecasting, i.e. it is generally not used to actually track lost goods or pollutants. There are ocean forecast models e.g. HIROMB (Funkquist and Kleine 2007) that better serve these purposes. However, the particular configuration of trajectory code (TRACMASS) and OGCM (RCO) was used in many previous studies (Döös et al. 2004, Jönsson et al. 2004, Engqvist et al. 2006, Soomere et al. 2010, Corell 2012), implying the need for validation. In our data set, RCO was run using observed river runoff and atmospheric forcing from ERA-40 (Uppala et al. 2005). The atmospheric forcing was downscaled using the Rossby Centre regional Atmosphere model, RCA (Kjellström et al. 2005). Here, the model grid covers the Baltic Sea with an open boundary in the Kattegat. The data from RCO were available every six hours with a two nautical mile horizontal resolution and at 41 model levels for the years 1961–2005. As the data were not available for the years 2010 and 2011, and since it cannot be argued for any past year being more-or-less similar to those years, it was chosen to simulate model trajectories in all those model years, except 1961 and 2005 as the data sets for those years were incomplete. To retain seasonal consistency, model trajectories were started at the same hour, day, and month as the observed surface drifters.

One surface drifter was active during the winter 2010/2011. According to the available sea-ice charts, the drifter was not in contact with any sea ice, meaning that the data could be used. However, the extent of sea ice in the Baltic Sea can differ from year to year and also be somewhat different in RCO as compared with observations. Thus, all winter data (December–February) needed special treatment when calculating model trajectories and comparing with surface-drifter trajectories. It could be possible to include only ice-free model trajectories from the winters 1962–2004. However, when calculating averages over all model trajectories in a specific year, this would mean that some years include trajectories from the generally windy winter seasons and some would not. Hence, for fair comparisons between the years, all winter months (DJF) were removed from both the observations and the model data. In total, this does not change the amount of data by much, since only one drifter was active during the winter 2010/2011. Validation of the winter data could of course be done separately.

### Table 1

<table>
<thead>
<tr>
<th>Drifter number</th>
<th>Initial long./lat.</th>
<th>Start date</th>
<th>Lifetime (days)</th>
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<td>20.6984°E/58.3559°N</td>
<td>14 July 2010</td>
<td>96</td>
</tr>
<tr>
<td>2</td>
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<td>14 July 2010</td>
<td>102</td>
</tr>
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<td>3</td>
<td>20.6977°E/58.3568°N</td>
<td>17 August 2010</td>
<td>317</td>
</tr>
<tr>
<td>4</td>
<td>20.6971°E/58.3567°N</td>
<td>17 August 2010</td>
<td>11</td>
</tr>
<tr>
<td>5</td>
<td>20.7002°E/58.3539°N</td>
<td>9 June 2011</td>
<td>22</td>
</tr>
<tr>
<td>6</td>
<td>20.6976°E/58.3532°N</td>
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<td>7 November 2011</td>
<td>12</td>
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### Comparison of observed and modelled drifters

The 12 surface drifters yielded equally many time series of the single-particle statistics pre-
sent in the Appendix, but of very different lengths. To obtain more statistics, and of equal
duration, the surface drifters were divided into
segments of $2^8 = 256$ hours, resulting in 76
segments for the data period 14 July 2010–19
November 2011 (the starting positions of the
segments are marked by dots in Fig. 1). The
drifters also gave nine time series of pair sepa-
rations, also of very different lengths, but these
data could not be divided into segments, since
the drifters should initially be paired. The long-
est pair yielded data for 96 days, while the short-
est lasted 11 days.

To generate model results for the single-par-
ticle statistics, each surface-drifter segment was
simulated by 36 Lagrangian trajectories starting
at the same hour, day, and month as the seg-
ment. Four of these trajectories were started in
the same grid box as the surface-drifter segment,
and four were equally spread (horizontally) in
each of the eight adjacent grid boxes. As each
grid box is roughly two nautical miles wide, this
can be seen as a trajectory “cloud” of roughly
three-nautical-mile radius around each surface
drifter segment. This takes into account the vari-
ability around the starting point of each drifter,
and the large numbers of model trajectories give
clearer statistics. This yielded in total $36 \times 76 = 2736$ trajectories. The simulations were repeated
for each of the available full-model years in
RCO (1962–2004). The trajectory positions were
stored every hour in order to have the same tem-
poral resolution as the surface drifter data.

The absolute dispersion $D_A(t)$ (Fig. 2), i.e.
the displacement from the origin as a function of
time, was calculated with Eq. a1 (see Appendix)
for each of the surface drifter segments and each
of the model trajectories. It is clear that the aver-
age absolute dispersion for the drifters is gener-
ally higher than for the model years. To examine
the differences in greater detail, the average of
the absolute dispersion after 256 hours for the
surface drifter segments and all model years was
calculated (Fig. 3). Again, after 256 hours there
is a discrepancy: the average absolute dispersion
of the model trajectories in most model years is
smaller than that of the surface drifters. Also, the
10th percentile in most model years is below that
of the drifter segments, and the 90th percentile
is lower during most years. It should be noted
that the 90th percentile is more variable than
the 10th. According to these results (see Fig. 3),
the average absolute dispersion after 256 hours
was 37.2 km for the drifters, and the multi-year
model average ± SD = 31.0 ± 3.8 km. Hence,
the drifter data is ~1.6 SD above the multi-year
model average. These results indicate that the
model-simulated Lagrangian velocities may be
too low as compared with the observed ones.
For this reason, the probability density func-

![Fig. 2. Mean absolute dispersion for segments of surface drifters deployed in 2010 and 2011 (black line), and model simulated trajectories for the years 1962–2004 (colored lines). Absolute dispersion increases with time, but is slowly leveling out. The mean absolute dispersion for the model trajectories in the different years is generally lower than that of the drifter segments.](image-url)
Fig. 3. Mean absolute dispersion for each model run after 256 hours. The red line is the mean absolute dispersion for the surface drifter segments after 256 hours. The 10th and 90th percentiles are shown as error bars for the model years, and as dashed lines for the surface-drifter segments. The 10th and 90th percentiles of the lower absolute dispersion of the model trajectories are lower as compared with those of the drifters.

Fig. 4. Probability density function (PDF) of the Lagrangian velocities defined by Eq. a3 for surface-drifter segments and model trajectories. Thick black line is surface drifter segments, and the thinner lines are model results from different years. The lines are all normalized, so that the integral of any one line is 1. A 14-hour running mean was applied to filter out inertial motions. It is clear that irrespectively of the year, the model velocities are more confined to lower values than the observed ones.

tion (PDF) of the Lagrangian velocities was calculated (Eq. a3, see Appendix). The results indicate that as compared with the observations, the distributions of Lagrangian velocities for model trajectories are always narrower and also displaced towards lower values (Fig. 4). However, it should be stressed that observations from 2010–2011 were compared with the model data from 1962–2004. This will be discussed later.

The Lagrangian velocity auto-correlation was calculated for each drifter segment and model trajectory using Eq. a7 (see Appendix). The total velocity auto-correlation function is defined as the average of the zonal and meridional components. A discrepancy arose since surface drifters are subject to inertial oscillations, which in the Baltic Sea have a period of $T_{osc} \sim 14$ hours. The model velocity fields, however, were stored only every sixth hour, which is too infrequent to resolve these oscillations, although
a slight signal due to these oscillations could be found. In order to filter out the oscillations, a running mean of 14 hours was applied to the trajectory positions, similar to the procedure used by Rupolo (2007). With this filter applied, the average velocity auto-correlation for the drifters was very similar to that of the model trajectories. It is necessary to point out that the velocity auto-correlation does not take the magnitude of the velocity into account, merely how it varies in time.

The Lagrangian integral time scale, \( T_L \), was calculated for each drifter segment and model trajectory using Eq. a8 (see Appendix). The 14-hour filter mentioned above was applied to the trajectory positions before computing the time scales. Just like the velocity auto-correlations for the model trajectories agreed fairly well with those of the drifters, the PDFs of \( T_L \) also agree (Fig. 5). \( T_L \) was found to vary between half a day and two days. The velocity and acceleration time scales \( T_v \) and \( T_a \), respectively (see Appendix for formal definitions), were not included since \( T_v \) was very small for all cases, and so \( T_L = T_v + T_a \approx T_v \).

Model results for the relative dispersion, i.e. the distance between two initially paired drifters as a function of time, were obtained by starting 36 model trajectories in each of the grid boxes where the surface-drifter pairs start, thus in total \( 9 \times 36 \) trajectories for each model year (1962–2004). As relative dispersion needs at least two trajectories starting close to each other, only the complete drifter pairs could be used, and not the segments. This gave in total nine drifter pairs, and more than 5000 model pairs for each model year. The average initial separation, \( D_R(0) \), was \( \sim100 \) m for the surface drifters, and \( \sim1 \) km for the model trajectories since they were spread evenly within the same grid box (Fig. 6). The relative dispersion was found to be underestimated for this regional ocean model by one order of magnitude. Another setup, where the 36 model trajectories were started in the grid boxes adjacent to the drifter pair, so that \( D_R(0) \approx6 \) km (Fig. 7), increased the relative dispersion after 25 days by almost an order of magnitude.

**Discussion and conclusions**

The absolute dispersion was found to be significantly lower for the model trajectories than for the observed drifters. This was attributed to the model velocities being lower and less variable than those observed, as shown by comparing the PDF of Lagrangian velocities from drifters to that of the model trajectories. A 14-hour running mean was applied to filter out inertial oscillations before computing the velocity PDFs, this
to ensure that the difference was not due to the ability to resolve inertial motions. Applying the filter did not result in any significant change of absolute dispersion. There are motions in the Baltic Sea on spatial and temporal scales smaller than those resolved by the RCO model that act on the surface drifters but not on model-simulated trajectories. This may explain some part of the differences between observed Lagrangian velocities and those simulated by the model. An overall increase in model resolution would thus most likely be beneficial to some extent.

Near-surface currents in the Baltic Sea are mainly wind-driven on time scales comparable to those of the drifter segments (Leppäranta and Myrberg 2009). This implies that the discrepancies between model data and observations may, to some part, be due to the model-simulated velocities not being correctly forced by the atmospheric winds. The wind forcing for RCO
(ERA-40 winds, dynamically downscaled by the RCA model) was corrected by Höglund et al. (2009) using a parameterization of gusty winds. This, to some extent, yielded more realistic frequency distributions of the wind speeds, but does not imply that the wind at a specific point or time became more realistic. The RMS error may very well have increased with this correction. Furthermore, the study was limited to the Swedish coastal regions, as no observations over open water were available. Thus, there is no information about the quality of the wind forcing over open water, although it is likely to share some of the problems of the coastal winds.

However, a realistic response to atmospheric wind forcing also depends on the ability of the OGCM to give a fair mixed-layer depth, and that the forcing is implemented correctly. Meier (2002) found that, in a multi-year model average from RCO, the thermocline depth in the Baltic Proper varies between 10–20 m, which he showed to agree with observations. Similar results were found in our data set. Improvements of the wind forcing should thus focus on improving the atmosphere model (increased temporal and spatial resolution, and better parameterisations of the physical processes), and studying the wind stress parameterisations, which, in the end, could yield better results for the ocean trajectories. However, the relatively shallow thermocline in the Baltic Sea implies that some of the drifters may have half the drogue in the mainly wind-driven upper layer, and the other half in the layer below, which could result in shear affecting the drogue. How this would influence the surface drifters is uncertain, but the model trajectories were driven by a weighted average of the velocities at the depth of 12–18 m, where the grid-box depth was 3 m. Simulations where the model trajectories were driven by the velocities from only one layer, 12–15 m, or the layer 15–18 m, resulted in statistics very similar to those presented in the previous section. It is thus concluded that the relatively shallow thermocline of the Baltic Sea may affect the surface drifters differently than in the world ocean, but for the model data no significant change is found whether a drogue at depths of 12–18 m, 12–15 m, or 15–18 m is used.

The observations and the model data in this study spanned different periods (2010–2011 and 1962–2004). This is also the reason why trajectory statistics and not the trajectories themselves were compared. The statistics from the model trajectories were calculated from a rather large distribution of trajectories (some 40 years of data) while the samples of the surface-drifter segments were rather few (2 years of data). Hence, it could be the case that the years 2010 and 2011 were, in some sense, both extreme and that the model trajectories for the same period would also be at the “high end” of what is shown in Fig. 3. The observed mean absolute dispersion at the end of the drifter segments was found to be ~1.6 SD above the multi-year model mean. As ~90% of the data should be within 1.6 SD of the mean, it is thus ~5% probability that a model year would have that high mean absolute dispersion. Or, put differently, such high absolute dispersion happens once every 20 years. This could, of course, be the case for 2010–2011, but is somewhat unlikely. Note also that no clear trend can be seen in Fig. 3, and that the year-to-year variability of absolute dispersion is quite random.

Variability between the 10th and 90th percentiles was also noted. The strong year-to-year variability of the 90th percentile could reflect the much-increased absolute dispersion for some trajectories during especially windy conditions. The variability of the 10th percentile for all model years could reflect trajectories moving with some mean flow that is relatively constant for all model years. There is a clear underestimation of the 90th percentile for most model years. It is thus concluded that the model-simulated velocities are less variable than those observed. This may also be concluded from the clear model–observation discrepancies for the PDF of Lagrangian velocity, where the means of the model-simulated velocities were smaller and less variable. Future studies, when model data for 2010–2011 are available, are needed to firmly determine whether the model-simulated velocities are underestimated or not.

A 14-hour running mean was applied to the trajectory positions in order to filter out inertial oscillations for both drifters and model trajectories. The model velocities would need to be stored as frequently as the surface drifter positions in order to resolve these inertial oscillations.
equally well. The average auto-correlation functions, $R(\tau)$, for observed drifter segments and for model trajectories during different years were in good agreement (not shown). Good agreement was also found for the PDF of the Lagrangian integral time scale, $T_L$, which was determined for each drifter and model trajectory (Fig. 5). We also stated that the Lagrangian-velocity time scale was the major component of the Lagrangian integral time, $T_L \approx T_v$. In the classification introduced by Rupolo (2007), this is identified as Class 1. Class 1 is close to the “frozen turbulence regime”, where the de-correlation of the trajectories is mainly due to the spatial and not the temporal variability of the flow.

Finally, a clear underestimation of relative dispersion by the model trajectories was shown: in all model years, the mean pair separation after 25 days was $\sim 35$ km for the drifters and $< 5$ km for the model trajectories. Investigating the actual trajectories on a map (not shown) revealed that the model-trajectories essentially remained together during those 25 days and did not separate. The model trajectories were all started from the same grid box (evenly spread so that $D_R(0) \approx 1$km), but when they were initially put in separate but adjacent grid boxes ($D_R(0) \approx 6$ km), the relative dispersion increased significantly. This shows the implications of finite differences and model resolution on particle dispersion, i.e. that particles within the same grid box cannot separate, since the variation in the grid box is non-existent, which was also noted by Griffa et al. (2004) and Döös et al. (2011). Although velocities were computed in coordinates between model grid points using linear interpolation in space and time, the variability within a grid box was still much too small to disperse particles properly. Thus, we propose that increased resolution, spatial and temporal, would give more realistic relative dispersion for the model trajectories. Presently, we cannot argue for one being more important than the other, although this would be intriguing to examine.

It is possible to introduce some random motions when simulating the trajectories to compensate for the finite resolution of the model. Adding a parameterisation of sub-grid turbulence to the model velocities, similar to what was done by Döös and Engqvist (2007) and Döös et al. (2011), increases the relative dispersion. The random motions introduced by the parameterisations produced model results that are statistically more realistic, e.g. adding more variability to the Lagrangian-velocity PDF. For individual trajectories, however, the random motion added is in practice never correct, resulting in severely shortened Lagrangian time scales. In other words, we most likely improve the transport speed and dispersion, but loose its direction and properties.

Using roughly estimated values presented in Fig. 3, we found that, on average, the absolute dispersion in the model is only $\sim 3/4$ of the observed values. This was confirmed by simulations in which the model velocities were multiplied by 4/3, which resulted in an absolute dispersion of model trajectories similar to that of the surface drifters. This means that if model trajectories travel on average 100 km in 10 days, a drifter, or a real water particle, would during this time travel $\sim 130$ km. By the same argument, if model trajectories were estimated to reach the coast in 10 days, real water particles would make the same journey in less than 8 days. Even more problematic is the underestimation of relative dispersion (see Fig. 6). A model particle cloud of 1-km radius would, on average, grow to $\sim 2$ km in 25 days, and a cloud of 6 km radius would grow to 16 km, while the real cloud would grow to $\sim 35$ km. It ought to be noted that only the realism of currents at the 12–18 m depth was assessed. Discrepancies found at this depth could also be valid near the ocean surface, but of different magnitude. If the flow speed at 15-m depth is underestimated due to an underestimation of the wind forcing, the errors could be larger at the surface. Such conclusions could have large impacts when estimating the fate of oil spills or other pollutants.

Regional ocean model fields for 2010 and 2011 may not be available for quite some time, as RCO is being decommissioned while a new model, BaltiX, based on the ocean general circulation model NEMO (Madec 2008), is currently being developed and tested at SMHI. Also, the ERA-40 data set is to be replaced by ERA-Interim, and later on by ERA-75 (still under development), indicating that new regional wind-forcing fields, most likely with higher horizontal
resolution and with improved model physics, will become available (see Samuelsson et al. (2011) for more recent results of RCA). We hope that surface-drifter data can continue to be gathered in the Baltic Sea with more deployments, thus building an observational data set of transport and dispersion that, in the future, can be used to validate, and perhaps tune, the next generation of regional ocean climate models, while also proving usable for model inter-comparisons.

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References


Appendix. Lagrangian equations.

The absolute dispersion is a measure of the displacement from the origin as a function of time. It is defined as

\[ D_A(t) = \frac{1}{M} \sum_{m=1}^{M} D_A^m(t), \quad D_A^m(t) = \sqrt{\sum_{i=1}^{2} \left[ x_i^m(t) - x_i^m(0) \right]^2} \]  

(a1)

where \( t \) is the time, \( m \) the trajectory number, and \( i \) is the dimension (zonal and meridional). \( D_A^m(t) \) is the absolute dispersion for trajectory \( m \), and \( D_A(t) \) is the average of all trajectories. The square assures positive values.

Relative dispersion is defined here by using the separation of pairs of drifters. With the same notations as for the absolute dispersion, the definition is

\[ D_R(p) = \frac{1}{P} \sum_{p=1}^{P} D_R^p(t), \quad D_R^p(t) = \sqrt{\sum_{i=1}^{2} \left[ x_i^r(t) - x_i^q(t) \right]^2} \]  

(a2)

where \( p \) is the particle pair consisting of trajectories \( r \) and \( q \). \( D_R^p(t) \) is the relative dispersion for the pair \( p \), and \( D_R(t) \) is the average of all pairs. The square of the separation ensures positive values.

The Lagrangian velocity is obtained by using a non-centered finite difference

\[ v_i(t) = \frac{dx_i(t)}{dt} = v_{i,n} \equiv \frac{x_{i,n+1} - x_{i,n}}{t_{n+1} - t_n} \]  

(a3)

with the same indices as before, and the unit m s\(^{-1}\). Note, however, that the Lagrangian velocity can be defined for only \( N - 1 \) points. Similarly, the acceleration was calculated by finite differencing of the velocity (the unit is m s\(^{-2}\)):

\[ a_i(t) = \frac{dv_i(t)}{dt} = a_{i,n} \equiv \frac{v_{i,n+1} - v_{i,n}}{t_{n+1} - t_n} \]  

(a4)

For the same reasons as for the velocity, the Lagrangian acceleration can be computed for only \( N - 2 \) points.

The auto-covariance of a time series describes the covariance of the series with itself, lagged by the time \( \tau \). The definition of the covariance of the zonal velocity is
\[ \sigma^2_x(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_0^T u'(t+\tau) \cdot u'(t) \, dt \]  
\( (a5) \)

\[ \sigma^2_x = \frac{1}{N-q-1} \sum_{n=1}^{N-q-1} u'_n u'_{n+q} \]  
\( (a6) \)

where \( u'_n = u_n - \bar{u} \) and \( \bar{u} = \left( N-1 \right)^{-1} \sum_{n=1}^{N-1} u_n \) is a time average of the whole segment. The unit of \( \sigma^2_x \) is \( \text{m}^2 \cdot \text{s}^{-2} \). The auto-correlation

\[ R_x(\tau) = \frac{\sigma^2_x(\tau)}{\sigma^2_x(0)} \]  
\( (a7) \)

is then the auto-covariance normalised by \( \sigma^2_x(\tau = 0) \), giving a dimension-less function \(-1 \leq R_x(\tau) \leq 1\), since a time series is maximally covariant with itself for no time lag. The meridional component of the Lagrangian velocity auto-correlation, \( R_y(\tau) \), can be calculated in a similar fashion, and the total auto-correlation function is

\[ R(\tau) = \frac{1}{2} \left[ R_x(\tau) + R_y(\tau) \right] \]

Using the zonal velocity auto-correlation, \( R_x(\tau) \), the Lagrangian integral time can be calculated from the zonal Lagrangian velocity, \( T_{L,x} \).

\[ T_{L,x} = \int_0^\tau R_x(\tau) \, d\tau \]  
\( (a8) \)

This is a measure of the memory of a trajectory, viz., the time lag during which the Lagrangian velocity is correlated with itself. There is one value for the zonal component, and one for the meridional component of velocity. The total Lagrangian integral time is defined as the average of both components. When computing the integral in Eq. a8, the point where \( R_x(\tau) = 0 \) for the first time is used as an upper bound. This truncation is perhaps the most commonly used, due to the often noisy character of the autocorrelation function, \( R(\tau) \), for large \( \tau \) (Rupolo, 2007). Lumpkin et al. (2002) compared this approximation with several others, and found that all produced essentially the same results. It may thus be concluded that the approximation used here is a robust one.

Using the total Lagrangian integral time, \( T_L \), the velocity and acceleration time scales are defined as

\[ T_v = \frac{T_L + \sqrt{T_L^2 - 4 \frac{\sigma^2_v}{\sigma^2_x}}}{2} \quad T_a = \frac{T_L + \sqrt{T_L^2 - 4 \frac{\sigma^2_a}{\sigma^2_x}}}{2} \]  
\( (a9) \)

where

\[ \sigma^2_v = \frac{1}{N-1} \frac{1}{2} \sum_{n=1}^{N-1} \sum_{m=1}^{N-1} (u'_{m,n})^2 \quad \sigma^2_a = \frac{1}{N-2} \frac{1}{2} \sum_{n=1}^{N-2} \sum_{m=1}^{N-2} (a'_{m,n})^2 \]  
\( (a10) \)

are the variances of velocity and acceleration respectively. The time scales are thus constructed so that \( T_L = T_v + T_a \).