Surface drifters and model trajectories in the Baltic Sea

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Abstract

Results from recent deployments of surface drifters in the Baltic Sea are presented. Surface-drifter motion is compared to model-generated trajectories originating at discrete points along the drifter tracks. The absolute dispersion (*i.e.* the distance from initial point as a function of time) is found to be somewhat underestimated by the model trajectories. A severe underestimate of the relative dispersion (pair separation) due to the limited resolution of the model is also noted. However, relative dispersion is 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 is found. A discussion on the impact of these results on future trajectory modelling in the Baltic Sea is also provided.

Short title: Comparing observed and synthetic drifters.

Key words: Surface drifters, Lagrangian trajectories, regional ocean model, Baltic Sea, transport, dispersion, TRACMASS.

1 Background

Tracing Lagrangian trajectories is a powerful tool for understanding and diagnosing motion in both atmosphere and ocean. They can extract information about transport and dispersion that, in some sense, is hidden in the 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 *et al.*, 2011), 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 others, 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 about the temperature and the ambient atmospheric pressure in regions where observations are scarce.

As the use of model trajectories in ocean studies has increased, so has the need to validate the model trajectories with observations. Studies have compared model trajectories generated with velocity fields from an ocean general circulation model (OGCM) to surface drifters in the North Atlantic (Garraffo *et al.*, 2001; Lumpkin *et al.*, 2002; McClean *et al.*, 2002), and the world oceans (Döös *et al.*, 2011). Although these researchers used different models, and different drifter data sets, a common conclusion is that the mean flow is overestimated in some places, and underestimated at some other places, but on the whole agree fairly well. Another common finding for all studies is that the spread of particles and/or flow variability (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 both 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 *el 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).

For the Baltic Sea, there have been several studies using model-simulated Lagrangian trajectories (Jönsson *et al.*, 2004; Döös *et al.*, 2004; Soomere *et al.*, 2010; Engqvist *et al.*, 2006), but the realism of these model trajectories has, to the authors' knowledge, never been assessed. The lack of such assessments is partly an effect of there being very few Lagrangian observational data available, this due to the heavy traffic and the small horizontal extent of the basin where the mean depth is more than 18 m. The risk of a surface drifter getting caught up in too shallow waters or colliding with a ship is much higher in the

Baltic than in the world oceans. Although some drifter experiments have been 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 parameterizations and higher horizontal resolution is needed.

The aim of the present study is to, for the first time, compare surface-drifter data from the Baltic Sea with model trajectories simulated using fields from a regional ocean model. We will study both transport and dispersion, *viz.* both single- and multiple-particle statistics, and also examine the behaviour of the trajectories. A discussion of the origin and the nature of the model-observation differences is also provided. The deployed surface drifters, the model trajectories, and the ocean model are described in next section. The results of the validation are presented in the subsequent section, leaving the final section for discussion, conclusions, and future outlooks. The Lagrangian statistics are described in the appendix.

2 Observed and modelled trajectories

2.1 Surface drifters

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

Two pairs and two triplets of surface drifters were deployed at two locations in the Baltic Proper. The deployments were all made from the ferry M.S. Silja Festival, during cruises between Stockholm and Riga. Data for this study were collected until 17 September 2011. The two pairs were deployed on 14 July and 17 August 2010, 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 trajectories of the surface drifters are shown in Fig. 1.

2.2 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 are computed off-line, *i.e.*, after the fields from the RCO model have been integrated and stored. This allows for faster and less memory-consuming computations, but the temporal resolution is only 6 hours. Data are 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 are 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 reaches a depth shallower than 18 m is removed from the statistics.

The RCO model is a regional ice-ocean circulation model based on the global OCCAM model (Meier *et al.*, 2003). In our data set, RCO has been run using observed river runoff and atmospheric forcing from ERA-40 (Uppala *et al.*, 2005). The atmospheric forcing is 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. Data from RCO are available every 6 hours with a 2 nm horizontal resolution and at 41 model levels for the years 1961-2005. As data are not available for the years 2010 and 2011, and we cannot argue for any past year being more-or-less similar to those years, we chose to simulate model trajectories in all model years. To retain seasonal consistency, model trajectories were started at the same hour, day, and month as the observed surface drifters. However, as the ice-extent of the Baltic Sea can differ from year to year and affects surface floats, all winter data (December-February) are removed from both the observations and model data.

3 Comparison of observed and modelled drifters

The ten surface drifters described in the previous section, yielded equally many time series of the single-particle statistics presented in the appendix, but of very different lengths. To obtain more statistics, and of equal duration, the surface drifters were split up into segments of $2^8 = 256$ hours, resulting in 71 segments for the data period 14 July 2010 – 17 September 2011. The starting positions of the segments are marked by filled dots in Fig. 1. The drifters also gave eight time series of pair separations, also of very different lengths, but these data cannot be split up into segments, since the drifters need to be paired initially. The longest pair yielded data for 96 days, while the shortest lasted 11 days.

To generate model results for the single-particle statistics, each surface drifter segment was simulated by 36 Lagrangian trajectories starting at the same hour, day, and month as the segment for all model years. Four of them were started in the same grid box as the surface-drifter segment, and the rest were equally spread (horizontally) in the adjacent grid boxes. As each grid box is roughly two nautical miles wide, we thus released a trajectory "cloud" of roughly three nautical mile radius around each surface drifter segment. This takes into account the variability around the starting point of each drifter, and the large numbers of model trajectories give clearer statistics. The trajectory positions were stored every hour in order to have the same temporal resolution as the surface drifter data.

The absolute dispersion was calculated from Eq. (1) for each of the surface drifter segments and each of the model trajectories. Fig. 2 shows the absolute dispersion, $D_A(t)$, as a function of time, averaged over all drifter segments. Also shown is the absolute dispersion averaged over all simulated trajectories for each model year 1962-2004, since model data were not available for the years 2010-2011. It is clear that the average absolute dispersion for the drifters is higher than for any of the model years at all times. To examine the differences more in greater detail, Fig. 3 shows the average after 256 hours, with 10th and 90th percentiles, of the absolute dispersion for the surface drifter segments and all model years. Again, there is a discrepancy, where, after 256 hours, the average absolute dispersion of model trajectories in all model years is smaller than that of the surface drifters. Also, the 10th percentile in all 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. Using the results in Fig. 3, the average absolute dispersion after 256 hours is 38.7 km for the drifters, and the multi-year model average and standard deviation is 29.1 ± 4.1 km. Hence, the drifter data is more than two standard deviations above the multi-year model average. The results in Fig. 2 and 3 indicate that the model-simulated velocities are too low compared to the observed ones. For this reason, the probability density function (PDF) of the Lagrangian velocities from Eq. (3) was calculated. The results for the drifter segments and all model years are shown in Fig. 4, where the model velocity PDF is narrower and also displaced towards lower values compared to the observations. However, it should be stressed that observations from 2010-2011 have been compared to 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. (7). 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 $T_{\text{osc}} \sim 14$ hours. The model velocity fields, however, were only stored every sixth hour, which is too infrequent to resolve these oscillations, although a slight signal due to these oscillations could be found (not shown). 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 (not shown). 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. (8). The 14-hour filter mentioned above was applied to the trajectory positions before computing the time scales. Probability density functions of T_L for the drifter data and the different model years are shown in Fig. 5. 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. T_L was found to vary between half a day and two days. T_v and T_a are not shown since T_a is very small for all cases, and so $T_L \approx T_v$.

Model results for the relative dispersion were obtained by starting 36 model trajectories in the same grid boxes as the surface-drifter pairs. 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 eight drifter pairs, and more than 5000 model pairs for each model year. The average initial separation, $D_R(0)$, was ~ 100 m for the surface drifters, and ~ 1 km for the model trajectories. Fig. 6 shows the average pair separation for all drifters and model trajectories during each model year. The relative dispersion was found to be underestimated for this regional ocean model by one order of magnitude. Another set-up, where the 36 model trajectories were started in the grid boxes adjacent to the drifter pair, so that $D_R(0) \sim 6$ km, is shown in Fig. 7. This increased the relative dispersion after 25 days by almost an order of magnitude.

4 Discussion and Conclusions

We have presented results based on surface drifters deployed in the Baltic Sea during 2010 and 2011. Statistics from the drifters have been compared to statistics from trajectories generated by a Lagrangian trajectory model driven by velocity fields from the regional ocean circulation model, RCO. 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 too low and not variable enough, 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 temporal resolution.

Applying the filter did not result in any significant change of absolute dispersion. As the near-surface currents are mainly wind-driven on time scales comparable to those of the drifter segments (Leppäranta & Myrberg, 2009), it is suggested that this discrepancy between model data and observations is an artifact of 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. R.M.S. 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, an accurate wind forcing also depends on the ability of the ocean model to give a fair mixed-layer depth, and that the forcing is implemented correctly. Meier (2002) found that, in a multi-year model average, 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. This 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 effecting 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 depth $12 - 18$ 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. We thus conclude 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 we find no significant change whether we use a drogue at depths of $12 - 18$ m, $12 - 15$ m, or $15 - 18$ m. 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.

We again stress that we have compared surface-drifter data collected in 2010 and 2011 to model trajectories simulated during the years 1962-2004. However, we wish to argue that although we cannot compare the behaviour of a single observed drifter to its modelled counterpart, we can still draw some conclusions from the statistical behaviour. Since the near-surface currents in the Baltic Sea are mainly wind-driven, the absolute dispersion for a specific drifter segment lasting for 11 days is highly influenced by the weather during those days. For instance, it is very dependent on whether there is a low-pressure system passing over the Baltic Sea or if there is a high-pressure ridge giving calmer conditions. In some sense, the ability of model trajectories driven by RCO velocity fields 1962-2004 to agree with surface drifters released in 2010 and 2011 boils down to whether the RCA winds in 1962-2004 are similar to those over the Baltic Sea at some specific times in 2010 and 2011. Whether the winds are strong or weak on a certain day and month of a given year is quite random, and consequently there is no reason to expect that a certain drifter segment should look anything like its model counterparts. However, if there are enough drifter segments and model trajectories, there is reason to believe that they might be statistically similar, and hence distributions over a longer period of time should agree. When computing absolute dispersion for several model years, it can be expected that there will be some inter-annual variability, and that the drifter data should be within this variability. The drifter average of absolute dispersion, $D_A(t)$, was found to be more than twice this variability above the multi-year model average. A difference in variability between the 10th and 90th percentiles was also noted. The strong variability of the 90th percentile could reflect the much-increased absolute dispersion for some trajectories due to passing weather systems. The almost non-varying 10th percentile for all model years could reflect trajectories moving with some mean flow that is relatively constant for all model years. The difference in 10th percentile between model years and drifter data is so consistently large that it is unlikely to be caused by an inter-annual variability, but is more likely a systematic discrepancy between the model currents and those observed. This may also be proposed from the clear model-observation discrepancies for the PDF of Lagrangian velocity, where the model-simulated velocities had lower mean values and less variability.

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. 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 taxonomy 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, where the mean pair separation after 25 days was $\sim$ 35 km for the drifters, and $<$ 5km for the model trajectories in all model years. The model trajectories were all started from the same grid box ($D_R(0) \approx$ 1km), but if they were initially put in separate but adjacent grid boxes ($D_R(0) \approx$ 6km), the relative dispersion increased significantly. This shows the implications of finite differences on particle dispersion, 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 is 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 will 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 & Engqvist (2007) and Döös *et al.* (2011), increases the relative dispersion (not shown). The random motions introduced by the parameterisations give 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 from Fig. 3, it was found that on average the absolute dispersion in the model is only $\sim 3/4$ of the observed values. This was confirmed by simulations were 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, on average, travel 100 km in 10 days, a drifter, or a real water particle, would, on average, travel $\sim$ 130 km during this time. 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 by the model found in 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. 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 being developed at SMHI. Also, the ERA-40 data set is to be replaced by ERA-Interim, and later on by ERA-75, indicating that new regional wind-forcing fields, most likely with higher horizontal resolution and with improved model physics, will become available. 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.

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A Lagrangian statistics

The absolute dispersion is a measure of the displacement from the origin as a function of time. For a trajectory m it is defined as

$$D_A^m(t) \equiv \sqrt{\sum_{i=1}^{2} \left[x_i^m(t) - x_i^m(0)\right]^2}, \tag{1}$$

where t is the time, and i is the dimension (zonal and meridional). The average over all trajectories is $D_A(t) = M^{-1} \sum_{m=1}^{M} D_A^m(t)$. 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

$$D_R^p(t) \equiv \sqrt{\sum_{i=1}^{2} [x_i^q(t) - x_i^r(t)]^2}, \tag{2}$$

where p is the particle pair consisting of trajectories r and q. The average over all pairs is $D_R(t) = P^{-1} \sum_{p=1}^{P} D_R^p(t)$. The square of the separation ensures positive values.

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

$$v_i(t) \equiv \frac{dx_i(t)}{dt} \approx v_{i,n} \equiv \frac{x_{i,n+1} - x_{i,n}}{t_{n+1} - t_n}, \tag{3}$$

with the same indices as before, and unit ms^{-1}. Note however that the Lagrangian velocity can only be defined in $N-1$ points. Similarly, the acceleration was calculated by finite differencing of the velocity:

$$a_i(t) \equiv \frac{dv_i(t)}{dt} \approx a_{i,n} \equiv \frac{v_{i,n+1} - v_{i,n}}{t_{n+1} - t_n}. \tag{4}$$

The unit is ms^{-2}. For the same reasons as for the velocity, the Lagrangian acceleration can only be computed in $N-2$ points.

The auto-covariance of a time-series describes the co-variance of the series with itself, lagged by a time τ. The definition of the co-variance of the zonal velocity is

$$\sigma_x^2(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_0^T u'(t+\tau)\cdot u'(t)\ dt \tag{5}$$

$$\approx \quad \sigma_{q,x}^2 = \frac{1}{N-q-1} \sum_{n=1}^{N-q-1} u'_n u'_{n+q}, \tag{6}$$

where $u'_n = u_n - \overline{u}$ and $\overline{u} = (N-1)^{-1} \sum_{n=1}^{N-1} u_n$ is a time average of the whole segment. The unit of σ_x^2 is $\mathrm{m^2 s^{-2}}$. The auto-correlation is then the auto-covariance normalised by $\sigma_x^2(\tau = 0)$, giving a dimensionless function $-1 \leq R_x(\tau) \leq 1$, since the series is completely covariant with itself for no time lag.

$$R_x(\tau) = \frac{\sigma_x^2(\tau)}{\sigma_x^2(0)}. \tag{7}$$

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 $R(\tau) = \frac{1}{2}(R_x(\tau) + R_y(\tau))$.

Using the zonal velocity auto-correlation, $R_x(\tau)$, we can compute the Lagrangian integral time of the zonal Lagrangian velocity, $T_{L,x}$.

$$T_{L,x} = \int_0^\infty R_x(\tau)\ d\tau. \tag{8}$$

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. (8), we use the point where $R_x(\tau) = 0$ for the first time 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 τ (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

$$T_v = \frac{T_L + \sqrt{T_L^2 - 4\frac{\sigma_U^2}{\sigma_A^2}}}{2} \qquad T_a = \frac{T_L - \sqrt{T_L^2 - 4\frac{\sigma_U^2}{\sigma_A^2}}}{2}, \tag{9}$$

where

$$\sigma_U^2 = \frac{1}{N-1}\frac{1}{2}\sum_{n=1}^{N-1}\sum_{i=1}^{2}(u'_{i,n})^2 \qquad \sigma_A^2 = \frac{1}{N-2}\frac{1}{2}\sum_{n=1}^{N-2}\sum_{i=1}^{2}(a'_{i,n})^2, \qquad (10)$$

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

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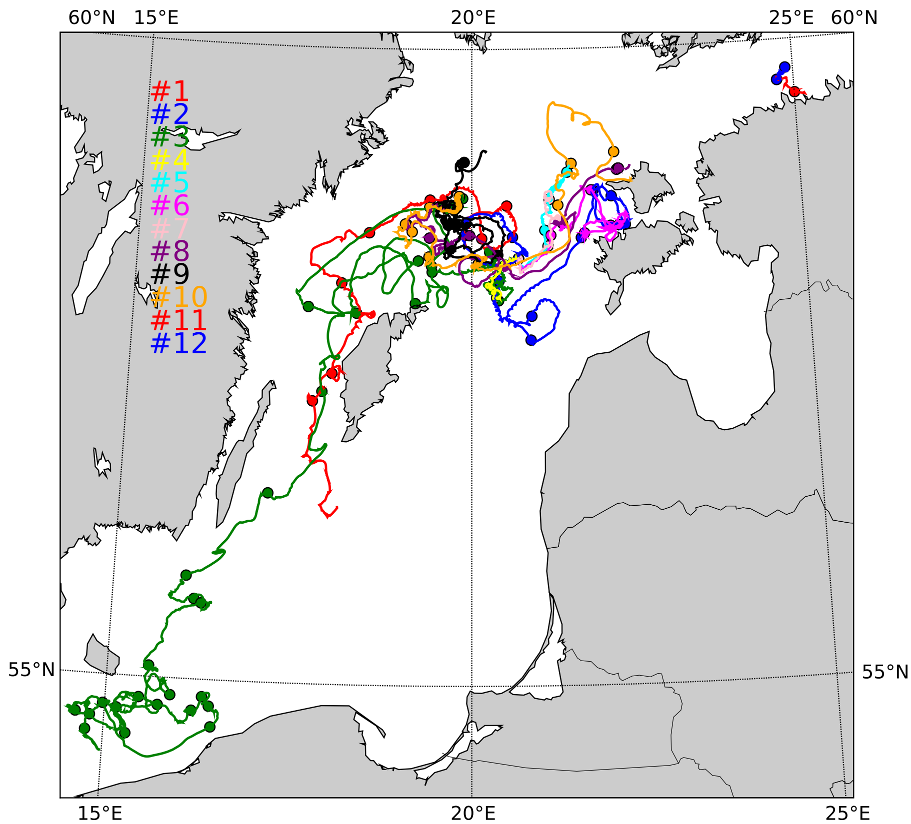

Figure 1: Trajectories of the surface drifters as of 17 September 2011. Nine model trajectories are started from the start of each drifter segment, marked by filled dots.

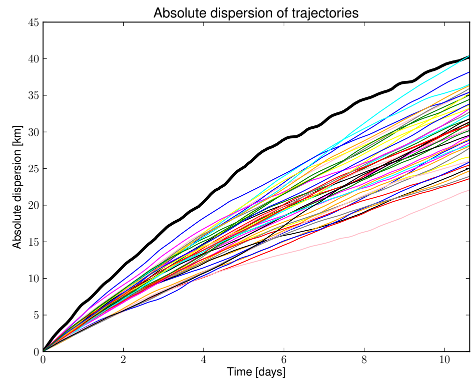

Figure 2: Mean absolute dispersion for segments of surface drifters deployed in 2010 and 2011 (thick black line), and model simulated trajectories for the years 1962-2004 (thin lines with random colors). Absolute dispersion increases with time, but is slowly leveling out. The mean absolute dispersion for the model trajectories in the different years are generally significantly lower than that of the drifter segments.

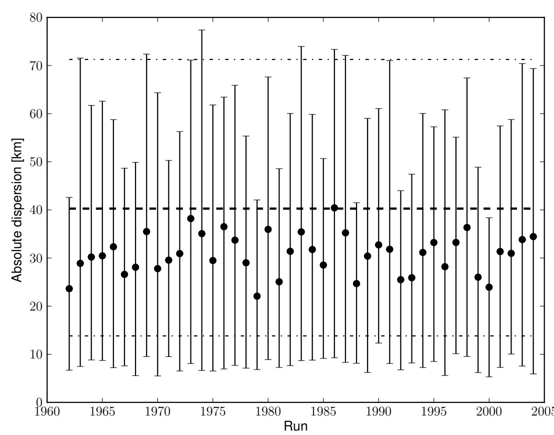

Figure 3: Mean absolute dispersion for each model run after 256 hours. The dashed line is the mean absolute dispersion for the surface drifter segments after 256 hours. 10th and 90th percentiles are shown as error bars for the model years, and as dash-dotted lines for the surface drifter segments. The finding is that the lower absolute dispersion of the model trajectories compared to the drifters is accompanied by lower 10th and 90th percentiles as well. The 10th percentile is overall lower for the model, while the 90th is more random.

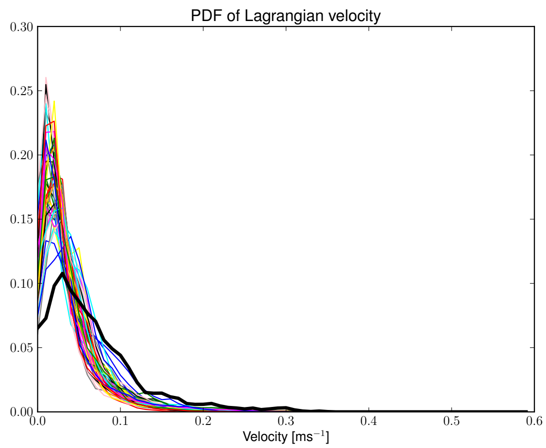

Figure 4: Probability density function (PDF) of the Lagrangian velocity defined in Eq. (3) for surface drifter segments and model trajectories. Thick black line is surface drifter segments, and the thinner lines are model results from different years. The lines are all normalized, so that the integral of any one line is 1. A 14-hour running mean has been applied to filter out inertial motions. It is clear that the model velocities are more confined to lower values than the observed, irrespectively of the year.

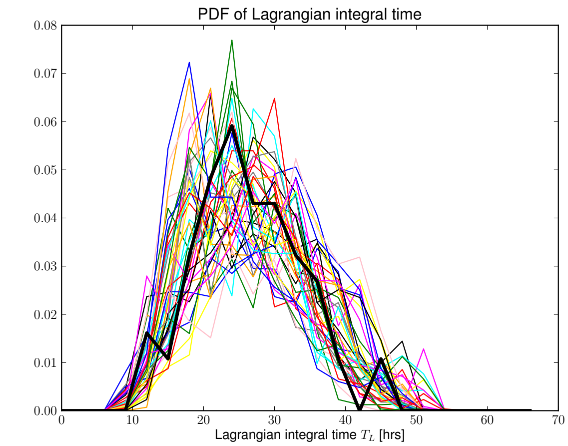

Figure 5: Probability density function (PDF) of the Lagrangian integral time, T_L, from Eq. (8), for the drifter segments (thick, black line), and for all model years (thin, colored lines). The lines are all normalized, so that the integral of any one line is 1. T_L was calculated after the trajectories had been smoothed by a 14 hour running mean to filter out the inertial oscillations. Each bin is 3 hours wide. The range of T_L is similar for both drifter data and model data.

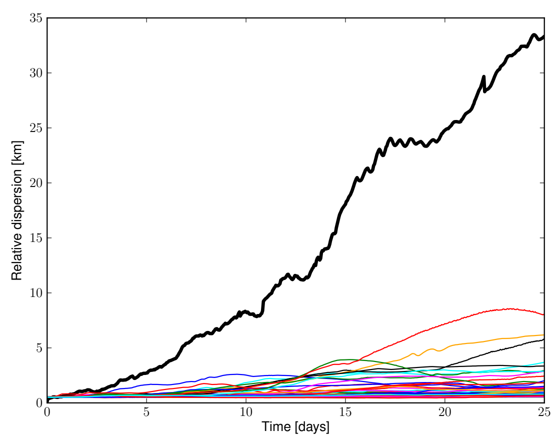

Figure 6: Relative dispersion averaged over all pairs of surface drifters (thick black line), and corresponding averages for trajectories simulated each model year (colored thin lines). Horizontal axis is time in days. Only five drifter pairs are still active after 25 days. While the surface drifters clearly have separated within this time frame, the model trajectories have not.

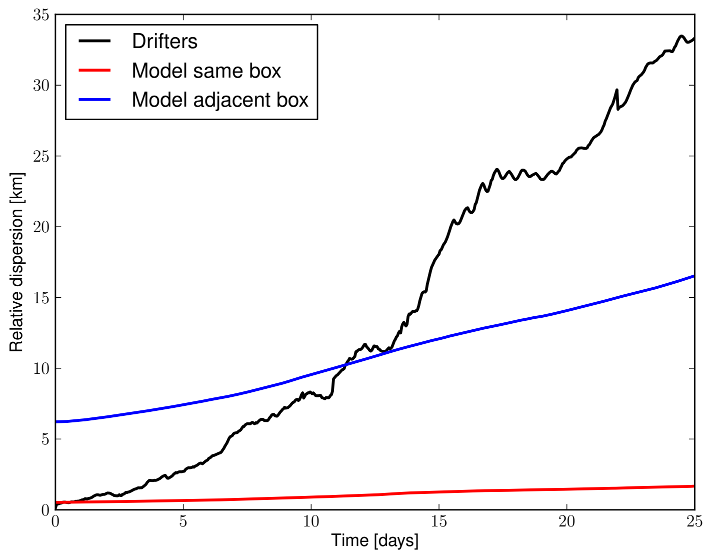

Figure 7: Relative dispersion averaged over all pairs of drifters (black line), and all pairs in all model years. Red line shows the results when pairs of model trajectories are started in the same grid box, and blue line shows the results when they start in grid boxes adjacent to each other. Model trajectories starting in different grid boxes clearly separate more rapidly than those starting in the same grid box.