We thank J. Kjellsson and two anonymous referees most sincerely for the time and large effort they expended on a thorough review of our manuscript. Their valuable comments will definitely improve the quality of a revised paper.

In the following, the referees' comments are shown in blue.

Response to Referee #1

The trajectories of 6 surface drifters are compared to simulations of circulation by two numerical models in the German Bight. For one model, the numerical simulations of drifter tracks include direct downwind slip or Stokes drift estimated from a wave model. This inclusion appears necessary to compensate insufficient vertical resolution of the model. Substantial model errors, that dominate at low winds, are explained in terms of inaccurate Eulerian currents and lacking representation of the sub-grid scales processes by the models. The limit of trajectory predictability is also addressed. This paper is clear and well written, although some parts can be substantially shortened to increase readability (see below). The scientific topic is interesting and the comparison between drifter observations and simulations is done rigorously. The results show that when using a model with reduced vertical resolution, direct windage or Stokes drift must be added in order to better predict surface drift. However, the explicit inclusion of Stokes drift does not produce an added value compared to a simple parameterization of wind-induced slip.

I recommend publication of this manuscript in Ocean Sciences after minor revision and after the authors have addressed the following specific comments.

Page 4:

Paragraph 2.1.

Please add the sampling frequency of the drifters.

Positions were monitored at least every 30 minutes. Text in Section 2.1: "*Three drifters could successfully be tracked for between 40 and 54 days. In order to conserve battery power, an initial sampling rate of about once every 15 min was later reduced to once every 30 min*."

Was there a drogue presence sensor?

Drifters had no drogue pressure sensors (now mentioned in Section 2.1).

Are you sure that the drogued-drifters kept their drogue during their entire drift?

Unfortunately, we could not be sure. We address the issue in the last paragraph of the discussion. The manuscript reports indications that in particular drifters 8 and 9 may have experienced technical problems towards the end of their journey (cf. third from the last paragraph of the discussion).

What is "R = drag area in water / drag area in air" for the drogued drifters?

Now added in Section 2.1: "*The ratio of drag area in the water to drag area outside the water was 33.2 for the MD03i and 16.9 for the ODi model, respectively.*"

Page 8:

Paragraph 3.1 Line 9. Change "a view day" to " a few days"

Thanks, has been corrected.

Pages 12 to 19.

Paragraph 3.2. The descriptions of the observed and simulated drifts for the different periods is too long and the reader might be bored reading all these details. I suggest to shorten these 4 pages of text by at least 50% to increase readability.

We accomplished this reduction by a removal of too many details. Another option (suggested by referee #3) would have been moving parts of the material to an appendix. However, this would destroy the clear chronological order of the description, which enables a quick scan for specific events while skipping others. It would also imply a shift of corresponding figures. These figures, however, provide relevant information, which referee #2 even suggested to expand. We followed his advice and complemented Figs. 7 and 8 by a third figure (Fig. 9) so that now 12 instead of 8 example days can be shown (we compensated for that by a removal of Fig. 6, which just combined panels from different figures in the appendix). As a result, the reader is now less often forced to switch to supplementary material.

Page 20:

Figure 9. Histograms represent the frequency of occurrence in selected classes of parameters. I would use the word "bar" instead of "histogram" to show distances versus time in Figure 9a and d.

Has been changed as suggested.

Response to J. Kjellsson (Referee #2)

1 Summary

The manuscript describes an experiment with surface drifters and model simulations in the German Bight. The goal is to assess the realism of the BSHmod and TRIM models. The authors compare six observed surface drifters (tracked for about 30-40 days) with simulated drifters using the two models. They find discrepancies between observations and models and discuss what could have caused them.

2 Overall comments

The manuscript is very well written with only a few misspellings and somewhat confusing sentences. While it is good that the authors give a detailed account of the drifter experiments, the main text makes a lot of references to maps in the supplementary material, which is split into multiple files and pages. I would recommend adding an extra plot or two in the main text where some results can be shown so that the reader does not have to go back and forth between the paper and supplementary material so often.

We agree that this is a problem. We tried to solve it by displaying now 12 example simulations (Figs. 7-9) rather than just eight (Figs. 7 and 8 in the original manuscript). To compensate for the additional figure, we removed the former Fig. 6, which just re-combined panels from different figures in the appendix. We believe that the additional figure much improves readability of Section 3.2, which has also been shortened by about 50 %.

I recommend this paper be accepted for publication after dealing with a few minor comments.

3 Specific comments

Parameters for including wind effects

How did the authors chose the parameters in Section 2.2.3? Did the authors try a few different values and tune the fields to match observations in this study, or was the tuning done in another study? If the parameters were tuned in another study, please cite that study and add a comment on how well it worked. If the parameters were tuned for the data in this study, the observations and models are not really independent and a validation can not be made. In the Discussion, the authors hint that no tuning was made. What was the motivation for choosing these values?

The following extra paragraph has been added at the end of Section 2.2.3, addressing this important issue:

"*The assumed strengths of either wind forcing or Stokes drift resulted from trying to achieve an overall eastward displacement of simulated drifters that roughly agreed with observations. This approach must not be confused with sound model calibration, which seems impossible based on the very limited data available. Models perform differently during different periods and it is hard to distinguish, for instance, between deficiencies in the hydrodynamic model and implications of imperfect atmospheric forcing. Also independent data needed for model validation are not available. However, already the simple approach enables an appraisal of how successful drifter simulations will depend on a distinction between wind drag and Stokes drift.*"

At the end of the first paragraph of Section 3.2 this important aspect is emphasized once more: *"A key effect of the inclusion of extra wind or wave effects is the intensification of westward transports in agreement with wind directions that occur most often. One should remember that achieving reasonable agreement between overall strengths of these transports in simulations and observations was the criterion which led to specific values we assigned to α or β in Eq. (1) (see Section 2.2.3)."*

Page 1:

Line 21: "Lagrangian transport simulations also provide . . . "

Changed

Line 22: remove "for instance"

Changed

Page 2:

Line 3: ". . . as many of the input . . . "

Changed

Line 9: "However, the Eulerian surface currents . . . "

Changed

Line 10: "In cases of necessity, drifter simulations . . . "

Changed

Line 12: ". . . 5 m deep top layer. Therefore, even for an ideal . . . "

Changed

Line 13: ". . . of hydrodynamic currents."

Changed

Line 14: ". . . 1m deep layer".

Changed

Line 24-25: I found this sentence a bit confusing. "Although provided with . . . for instance.". Do the authors mean that the wave model is forced with the same atm forcing as the ocean model, and the Stokes fields are added "offline", i.e. after the ocean model and wave model fields have been integrated and stored? In that case, why not write something like "Stokes drift is calculated from the wave model using the same wind forcing as used in the ocean model."

The paragraph has been revised following also your suggestions: "*Waves and resulting Stokes drift were calculated using the wind forcing also employed for hydrodynamic simulations with TRIM*."

Page 3:

Line 32-34: I found this sentence unclear. "After simulations . . . 25 h length." I understand drifters are split into 25 h segments, but what is meant by "different model setups explored the range of possible effects"? How were the setups different, and what were the effects?

Has been revised: "*First, full simulated trajectories are presented using currents from TRIM or BSHcmod, the latter also combined with wind drag and Stokes drift, respectively. A more detailed* …"

Page 4:

Line 11: "of the drifter"

Changed

Page 6:

Line 8: "Eulerian model currents can usually not fully reproduce observed currents"

Sentence has been revised.

Line 17: How was α chosen? See comment above.

A new extra paragraph at the end of Section 2.2.3 now addresses this issue (see above).

Line 18: remove "a" and change "parts" to "part".

Changed

Line 21: ". . . when model currents used do . . . "

Changed

Line 22: How was 0.6% chosen? See comment above.

Again, the new extra paragraph at the end of Section 2.2.3 now addresses this issue (see above).

Line 23: "(1m deep top layer)"

Changed

Page 7

Line 10: I think Fig 4 is defined before Fig 3?

Yes, thank you for this hint! Sequence of the two figures has been changed.

Line 12: "A principal component analysis (PCA) was performed on the residual currents, focusing on the inner German . . . "

Changed

Page 8

Line 9: "a few days"

Corrected

Line 12-15: I found the two sentences really hard to read. "For each . . . existing observations." The time bar does not really show anything that has to do with the release of simulated drifters. I think the first sentence should be something like "The time bars show the durations of the surface drifters and different colours indicate subjectively identified drift regimes." The second sentence I think means that the time bars start at midnight, while simulations start at 13:00. Why not start the time bar at 13:00?
We agree. The modified Fig. 4 (now Fig. 3) now shows exact travel times of observed drifters. This made the rather complicated explanation you mention obsolete.
Line 29: ". . . of about 20 km from drifter 8".
Changed

Page 11
Line 7: "extreme drift speeds". It is hard to judge whether the drift speeds are extreme by just looking at maps. Could the authors include a time series plot of drift velocities instead, or a probability density function for speeds? Fig. 10 and 11 show this, so I would recommend moving that plot this section and perhaps include more drifters in it.
We followed this suggestion and moved former Fig. 11 to this section (now Fig. 6). The figure has also been expanded, now combining data for the four most important drifters 5, 6, 8 and 9.
Line 9: "moderate drift velocities". Again, hard to judge just by looking at maps.
A reference to Fig. 6 (former Fig. 11) is now included.
Line 20: How were these parameter values chosen? See comment above.
Described of parameter choice was improved. See our answers to the above comments.

Page 12:
Line 2: Somewhere here it might be good to remind the reader about how TRIM and BSHmod are different.
The following sentence was added: "*It appears that combining BSHcmod currents for a 5 m depth surface layer with either windage or Stokes drift brings corresponding simulations closer to both observations (Fig. 4) and simulations based on Eulerian surface currents from TRIM with 1 m vertical resolution (Fig. A4)*."

Page 16
Line 2-4:"Although . . . Eulerian currents." It is an important statement that adding wind effect gives the correct direction for drifter 7. It would be good with a plot or at least some numbers in the text where the the drift is shown for observations, TRIM, BSHmod and BSHmod+W (only TRIM and BSHmod+W shown in Fig 7).
The sentence was reworded to avoid misunderstanding ("*Comparing simulations based on BSHcmod+W (Fig. 8(a)) with those based on BSHcmod (SM2) reveals that the deviant simulation of drifter #7 arises from spatial variation of BSHcmod currents.*"). The deviating displacement simulated for drifter 7 is produced by differences in Eulerian currents. At the same time, adding wind forcing improves simulations of both drifter 7 and the neighboring drifters 5, 6 and 8 (as to be expected from the more large scale nature of wind fields). The additional figure for BSHcmod you are asking for is available from supplement SM2 (Please note: In SM2 we corrected all headers, now reading BSHcmod and TRIM, respectively. Former headers BSH_TOPLAYER and TRIM_3D_TOPLAYER were confusing. All data remained unmodified). In addition, supplement SM4 provides the results from using Stokes drift. Unfortunately, it seems hardly feasible to include these figures for one single situation into the main manuscript.

Page 17
Line 28: "An exception is drifter 9 . . . "
The whole sentence was removed to shorten the manuscript as requested by referee #1.

Page 18
Line 5: ". . . drifter 9 does not."
Sentence does no longer exist.
Line 16: "Although wind speeds can be relatively strong (not shown), strengths of 25 h. . . "
Again, the sentence was removed.
Line 20-22: "Note, however . . . locations.". I could not understand what is meant here.
Whole sentence removed.
Line 23: ". . . caused by the fast west-northwest movement of drifter 8, not shared by drifters 5 and 6 (SM3)."
Changed
Line 26: "A four-day period . . . "

The phrase has been deleted.

Line 32: "A particularly fast movement of drifter 8 is observed on days 34 and 35. On day 35, drifter 8 also drifts more westward than drifter 5 and 6."

First sentence was removed, second changed accordingly.

Page 19:

Line 13: "Southwesterly winds cause a transition towards a strengthened . . . "

Changed, but we kept the 'freshening', so it reads now "*Freshening southwesterly winds strengthen a cyclonic circulation.* "

Line 30: "Currents in TRIM representative of a surface layer of 1m depth had drift velocities similar to those observed (Fig 9)."

Changed into (Note that figure labels changed): "*Magnitudes of TRIM surface currents, representative of a layer of 1 m depth, were generally similar to those observed (Fig. 10(a))*."

Page 20:

Fig 9: Why is BSHmod not shown in Fig a, or why are current speeds not shown in Fig b? It would be good to see what effect adding the wind effect actually has, i.e. what are the relative magnitudes of Eulerian currents and added wind effects? Also, the authors should consider showing probability distributions of errors in displacement and angles in order to condense the information. Does the error in angle have a zero mean or are the errors predominant in one direction? Does one model have smaller errors than the other?

We agree that the relative magnitudes of Eulerian currents and wind/wave effects are important information. Unfortunately, Fig. 9 (now Fig. 10) is already rather complex and one must be careful not to overload it. However, the manuscript provides the information you are asking for in Figs. 10 and 11 (now 12 and 6). From Fig. 10 (now 12) it can be seen that both windage and Stokes drift are much smaller than total Eulerian currents including tides. According to Fig. 11 (now 6), however, they become much more significant when considering residual currents (i.e. 25 h averages). The two figures also nicely show the mostly similar effects of windage and Stokes drift.

In response to the second part of your comment we introduced an additional figure (Fig. 11) that shows for both model approaches distributions of model errors:

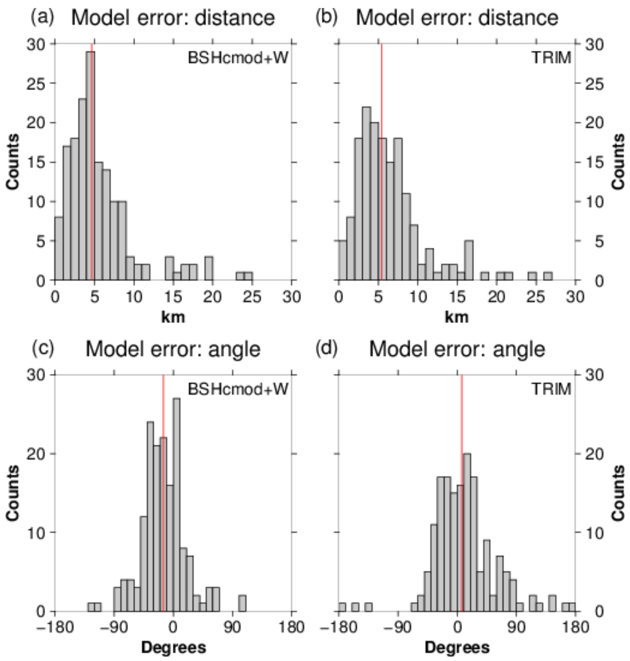

Figure 11. *Distribution of model errors in 25 h drifter simulations. Histograms are based on 164 simulations in total for drifters #5, #6, #8 and #9. Referring to drift simulations based on BSHcmod+W and TRIM, respectively, panels (a) and (b) evaluate spatial separations shown in Fig. 10(a). For the same set of 164 simulations, panels (c) and (d) evaluate directional errors from Fig. 10(d). Red lines indicate median values (4.6 km and 5.4 km in (a) and (b); -15 degrees and 7 degrees in (c) and (d)).*

We doubt that the differences between the two models are statistically significant given the fact that the 164 simulations contributing to the distribution in Fig. 11 were made under very different environmental conditions. We discuss that in the revised manuscript.

Page 21

Line 9: what does "currents will generally not parallel winds" mean?

Replaced by: "*currents will generally not be in the direction of winds*"

Line 15: ". . . may be one of the reasons why simulated trajectories resemble each other . . . "

Changed

Line 19-20: "Both TRIM and BSHcmod are unable to reproduce the specific . . . "

Changed

Line 24: ". . . they start with small initial separations $O(1-10\text{m})$.

The suggested change is part of a reformulation: "*Ohlmann et al. (2012) start with O(5-10 m) initial separations to resolve initial non-local dispersion with exponential growth of the mean square pair separation, driven by eddies larger than the distance between the two drifters*."

Line 29: "However, this separation might have been triggered . . . "

Changed

Line 34: "could imply accelerated spatial separation". Why? How? I would rather say "and relative dispersion measured using drifters of different types may not reflect the diffusivity of the flow."

The sentence was revised accordingly.

Page 22

Line 4: "The subsequent separation rate of about 3 km per day . . . "

Changed

Line 7: ". . . modelling was undertaken to . . . "

Changed

Line 19: Somewhere here I think a discussion is warranted about the differences in wind forcing in TRIM and BSHcmod. What is the temporal and spatial resolution of the wind data? Do they capture variations on the same spatial and temporal scales?

Descriptions of BSHcmod and TRIM (Sections 2.2.1 and 2.2.2) have been extended accordingly. In both models atmospheric forcing is provided on an hourly basis. At this point, we added a sentence mentioning that more frequent HF radar observations might possibly enhance variability of drift simulations.

Line 20: Again, how were the parameters for your wind effects chosen. See comment above.

The parameter specification has already been addressed a couple of times (for instance, our response to your next comment below or our response to your comment at the very beginning of your list of comments). Therefore we do not see the need for getting back to this point in this paragraph that does not explicitly mention any wind parametrization.

Page 24

Line 1-4: Here the authors touch upon how the wind parameters were chosen, but it is not clear. Was the Stokes drift parameter chosen so that Stokes drift would be of similar magnitudes as windage effects?

The following sentences were inserted to explain this in some more detail: *"The criterion we applied for selecting α or β is that the overall eastward displacement of a drifter's location should roughly agree with that observed. A convincing confirmation of our selection was that the strength factors we chose worked consistently well for all drifters."*

Page 25:

Line 1: "Fig 10 also shows magnitudes . . . "

Changed

Line 4-5: "Variations of maximum drift speeds indicates that movements along different branches of . . . "

Changed

Line 14: "Fig 10(a), magnitudes of drift velocities were smoothed using a 25 h moving average of hourly data"

The important point is that the original velocity vectors were smoothed rather than just their magnitudes. After restructuring the order of figures, the sentence now occurs together with Fig. 6: "*Fig. 6 provides magnitudes of velocities for drifters #5, #6, #8 and #9, calculated from velocity vectors smoothed using a 25 h moving average of hourly data*."

Line 31-32: "Note that . . . wave effects." I think the authors mean they add Stokes and wind effects offline, i.e. after the Eulerian currents have been stored. Why not write "Note that the Stokes drift and windage was calculated offline and added to the Eulerian currents after the model had been integrated and the fields stored."

We followed this suggestion

Page 26

Line 2: What bulk formulas were used to include wind forcing in the TRIM and BSHcmod models? Same or different? Could the choice of bulk formula impact the results?

In Sections 2.2.1 and 2.2.2 it is now mentioned that the same parametrization of wind forcing is used in both models.

Line 9: "Two crucial and outstanding questions are a) are the drifters' behaviours representative of surface . . . "

Changed

Page 27

Line 1: "To fully disentangle . . . "

Changed

Line 11: "Possible reasons for the deviant behaviours of drifters 8 and 9 can only be speculated. "

Changed

Page 28:

Line 3: Could power spectra of kinetic energy show how important the sub-grid scale motions are?

We doubt that that would be successful. One must not forget that measurements were collected under very different wind conditions so that the data would have to be partitioned accordingly. Embarking on such detailed analysis and its uncertainties would open a new discussion beyond the scope of the present paper.

Line 8: ". . . wind speeds in this case. "

Changed

Line 19-23: This bit is hard to understand. I think it needs some rewriting. The sentence "Keeping in mind . . . Stokes drift" should probably be split into two sentences. Also "Accordingly . . . marine currents" should probably be split as well.

The paragraph has been reformulated, sentences have been shortened.

Response to Referee #3

This paper presents a comparison of the model BSHcmod and TRIM with six nearsurface drifters with little or no windage. The paper is well written (albeit too lengthy), the English is good and the figures are readable. I would recommend publication after minor corrections.

We suppose that concerns about the length of the paper relate to Section 3.2. Please see our response to the last comment below.

Comments

- The work shows that the BSHcmod needs the addition of either about 50% of the surface Stokes drift or about 0.6% windage. The authors concede that this is probably a reflection of the poor vertical resolution of the model as much as it reflects missing windage and/or Stokes drift. I would recommend clarifying that the Stokes drift really *is* missing whereas the windage is probably negligible as the drifter is subsurface save for the antenna.

  We are not sure whether we got the referee's comment right. What is meant by "Stokes drift really *is* missing"? Indeed Stokes drift wasn't taken into account when running BSHcmod and TRIM. For BSHcmod (for which a coupled setup exists) this is now explicitly mentioned at the end of the first paragraph of Sections 2.2.1: "*The option to include Stokes drift from surface wave models (as described in Dick et al., 2001) is not activated operationally so that effects of Stokes drift are also not included in archived surface current data.*"

  Another question is to which extent Stokes drift affects surface drifters in the experiment. Simulations with wave model WAM provide an estimate of the strength of Stokes drift. For more details see our response to the next comment.

- The TRIM results should be studied a little further. Please consider adding Stokes drift to these as well and report which percentage works best. This would help answer the question of how much the Stokes drift really should contribute to an object which sits in the upper metre or so of the water column. Ideally the Stokes drift should be vertically averaged over the upper metre (see Li et al, 2017), but a Stokes drift representative of the midpoint (say 0.5 m) will probably be close enough.

Of course we also did experiments with variable strengths of windage and Stokes drift in combination with TRIM. The problem is that (as with BSHcmod) a real calibration of factors α and β in Eq. (1) is impossible as errors are very different during different periods of time (with different wind conditions). Following recommendations of referee #2, we introduced a new paragraph at the end of Section 2.2.3 which explains the way strengths of windage and Stokes drift, respectively, were specified: *"The assumed strengths of either wind forcing or Stokes drift resulted from trying to achieve an overall eastward displacement of simulated drifters that roughly agreed with observations. This approach must not be confused with sound model calibration, which seems impossible based on the very limited data available. Models perform differently during different periods and it is hard to distinguish, for instance, between deficiencies in the hydrodynamic model and implications of imperfect atmospheric forcing. Also independent data needed for model validation are not available. However, already the simple approach enables an appraisal of how successful drifter simulations will depend on a distinction between wind drag and Stokes drift."*

If we would add a description of "calibration" experiments for TRIM, the same would have to be shown for BSHcmod. In our opinion, this would definitely overload the paper. And, what is more, additional effects of windage or Stokes drift for TRIM are identical with those for BSHcmod, as in both cases the same fields (calculated offline) are just superimposed upon Eulerian currents from the respective model.

Our study shows that effects of windage and Stokes drift can hardly be disentangled based on an experiment like the one we describe. Combining both effects would add another degree of freedom uncontrolled by data. Even if windage for the drifter is negligible (which seems a reasonable assumption, as the referee mentions), the poor vertical resolution of archived BSHcmod data may be remedied by kind of windage for the 1 m depth surface layer. Adding Stokes drift is an alternative option having the same effect. At the end of the first paragraph of the conclusions we added a remark regarding a similar problem when using HF radar currents: *"In a similar way, Ullman et al. (2006) attributed a bias of trajectories predicted based on HF radar currents not to a drifter leeway but rather to the fact that effective depth of HF radar measurements exceeded that of surface layer drifters."*

Although we cannot really answer the question of how much Stokes drift really contributes, it is nevertheless interesting to note that the 50% factor we chose for a reduction of surface Stokes drift is of the order of magnitude that should be expected for an object drifting in a 1 m depth surface layer. In the discussion we had already referred to a paper by Röhrs and Christensen regarding the decrease of Stokes drift with depth (last paragraph on page 23 of the original manuscript). We now added another sentence (highlighted below) stating explicitly that these values are roughly consistent with the assumed 50% factor: *"Based on these formulas, Röhrs and Christensen (2015) calculated in the context of a drifter experiment in the Barents and Norwegian Sea that an average Stokes drift of 8.9 cm/s at the surface contrasted with an average of 3.7 cm/s at 1 m depth. For the present study we neither applied theoretical profiles nor conducted an in depth model calibration.* ***However, in the light of the above numbers, the 50% factor α in Eq. (1) we chose for BSHcmod+S seems a reasonable value for drifters representing a surface layer of about 1 m depth.****"*

We added the reference Li et al. (2017) the referee provided. In their Eq. (23), Li et al. show Stokes drift being proportional to 10 m winds. The factor of 1.6 % is consistent with the data we provide in Fig 9(b) of the original manuscript (Fig. 10(b) in the revised manuscript).

- Please mention in the text after Eq (1) that the full windage is actually a rotation (called the leeway divergence) and not simply a factor *β*.

We added an explanation of why a drift component perpendicular to the downwind direction was not included: *"Eq. (1) describes windage (or leeway) as a drag in downwind direction, neglecting any crosswind lift component. Such lift component depending on the specific overwater structure of a drifting object is crucial for search and rescue (Breivik and Allen, 2008}. For surface drifters used in experiments, however, these effects should be negligible."*

- Section 3.2 is too lengthy. Please consider moving some of this verbiage to an appendix.

This comment agrees with a comment of referee #1 who suggested an abbreviation of Section 3.2 by 50%. After a removal of too many details we actually achieved this. We believe that moving part of the listing to an appendix would not improve readability as it would destroy the clearly structured chronological listing, enabling a quick scan for specific events while skipping others. It would also imply a shift of corresponding figures. These figures, however, provide relevant information, which referee #2 even suggested to expand. We followed his advice and complemented Figs. 7 and 8 by a third figure (Fig. 9) so that now 12 instead of 8 example days can be shown (we compensated for that by a removal of Fig. 6, which just combined panels from different figures in the appendix). As a result, the reader is now less often forced to switch to supplementary material.

References

- Allen, A. and J. V. Plourde, 1999: Review of Leeway: Field Experiments and Implementation. Tech. Rep. CG-D-08-99, US Coast Guard Research and Development Center, 1082 Shennecossett Road, Groton, CT, USA, available through http://www.ntis.gov.

This report is cited in Breivik and Allen (2008). We did not add the reference as our specific study does not deal with search and rescue problems.

- Li, Q., B. Fox-Kemper, Ø. Breivik, and A. Webb, 2017: Statistical Models of Global Langmuir Mixing. *Ocean Model*, **113**, 95–114, 10.1016/j.ocemod.2017.03.016.

This article has been added as another reference for a constant ratio of surface Stokes drift and 10 m winds.

Surface drifters in the German Bight: Model validation considering windage and Stokes drift

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Abstract. Six surface drifters (drogued at about 1 m depth) deployed in the inner German Bight (North Sea) were tracked for between 14 and 54 days. Corresponding simulations were conducted offline based on surface currents from two independent models (BSHcmod and TRIM). Inclusion of a direct wind drag (0.6 % of 10 m wind) was needed for successful simulations based on BSHcmod currents archived for a 5 m depth surface layer. Adding 50 % of surface Stokes drift simulated with the third generation wave model WAM was tested as an alternative approach. Results resembled each other during most of the time. Successful simulations based on TRIM surface currents (1 m depth) suggest that both approaches were mainly needed to compensate insufficient vertical resolution of hydrodynamic currents.

The study suggests that main sources of simulation errors were inaccurate Eulerian currents and lacking representation of sub-grid scale processes. Substantial model errors often occurred under low wind conditions. A lower limit of predictability (about 3-5 km per day) was estimated from two drifters that were initially spaced 20 km apart but converged quickly and diverged again after having stayed at a distance of 2 km and less for about 10 days. In most cases, errors in simulated 25 h drifter displacements were of similar order of magnitude.

1 Introduction

Lagrangian particle tracking is a natural choice when origins or destinations of drifting objects (or water bodies) need to be known. Such methods have been developed for a wide range of applications (see Mariano et al., 2002). Examples from oceanography are simulations of physical dispersion (Schönfeld, 1995; Sentchev and Korotenko, 2005), possibly augmented by specific source and sink terms (e.g. Puls et al., 1997). In ecosystem modelling, Lagrangian transport models have been employed to better understand the process of non-indigenous species invading an ecosystem (Brandt et al., 2008), the risk of toxic algae blooms (Havens et al., 2010) or larval transport and connectivity being crucial to spatial fishery management (e.g. Nicolle et al., 2013; Robins et al., 2013). Lagrangian transport simulations ~~provide also~~ also provide a basis for more comprehensive individual-based models of fish recruitment (e.g. Daewel et al., 2015)~~, for instance~~.

Obviously, the quality of Lagrangian drift simulations has a particularly high practical relevance in the context of emergency operations like search and rescue (Breivik et al., 2013) or organizing efficient combating of oil spills (Broström et al., 2011; Maßmann et al., 2014). Modelling of surface drifter trajectories is particularly challenging as many of the input factors needed are poorly known. Often drift properties of ~~the search object~~ search objects can only be estimated (Breivik et al., 2013). The present study refers to a drifter experiment conducted in the inner German Bight (North Sea) during May-July 2015. Corresponding offline drift simulations based on archived currents from two different models were undertaken to assess the degree of uncertainty that must reasonably be expected in this region.

The surface drifters deployed are ideal in the sense that their exposure to a direct aerodynamic force from wind ~~(leeway or windage (Breivik and Allen, 2008))~~ (leeway or windage; Breivik and Allen, 2008) seems negligible. However, ~~already~~ also Eulerian surface currents used can be a major source of uncertainty. The circulation model BSHcmod, this study mainly focusses on, is run operationally. In cases of necessity~~drift~~, drifter simulations will be based on an re-gridded archived version of model predictions with near surface currents representative for a 5 m ~~depth surface~~ deep top layer. Therefore even for an ideal surface drifter, introducing a direct wind drag can be helpful as a means of compensating insufficient vertical resolution of ~~marine~~ hydrodynamic currents. The second hydrodynamic model employed in this study, TRIM, was set up with a 1 m ~~surface~~ deep top layer. Comparing drift simulations based on outputs from the two different models helps assess uncertainties possibly related to the vertical resolution of near surface currents.

More complex impacts of winds on surface currents may be mediated via waves (Perrie et al., 2003; Ardhuin et al., 2009). Röhrs et al. (2012) found evidence that predictability of drift trajectories can be improved by the inclusion of numerical wave modelling. On the other hand, Stokes drift and other wave effects are often neglected in operational systems. According to Breivik and Allen (2008) the main reason for this is that wave processes are already taken into account by empirically tuned windage coefficients that summarize ~~the deflection~~ changes of an object's trajectory induced by combined impacts of both winds and waves. The situation can differ in nearshore regions, where wave refraction directs wave induced transports towards the coast (Sobey and Barker, 1997).

A key objective of this study is checking whether explicit inclusion of Stokes drift calculated with the state-of-the-art wave model WAM improves ~~simulations. Although provided with consistent atmospheric forcing, the wave model is run in a stand alone mode rather than fully coupled as in Staneva et al. (2016), for instance.~~ drift simulations. Assessing the necessity to distinguish between effects of ~~a~~ direct wind drag and Stokes drift is essential to avoid over-parametrization. Waves and resulting Stokes drift were calculated using the wind forcing also employed for hydrodynamic simulations with TRIM. However, we did not explore effects of including wave-current interactions into hydrodynamic simulations (Staneva et al., 2016).

Horizontal grid resolutions of the two hydrodynamic data sets (900 m in BSHcmod and 1.6 km in TRIM) allow for a proper representation of mesoscale eddies in the region of interest. However, simulations may miss relevant sub-mesoscale processes. According to Kjellsson and Döös (2012) the underestimation of eddy kinetic energy by ~~a~~ Eulerian flows is a common finding of many model validation studies. This deficiency could be fixed by a transition to an advection-diffusion equation, introducing an additional stochastic random walk term. In this context, specification of the proper eddy diffusivity as function of grid resolution poses a major problem. There are, however, also concerns regarding the simple theoretical concept. For the advection-diffusion approach being valid, a spectral gap should separate processes on the scale resolved from sub-grid scale processes. Such gap may often not exist (see De Dominicis et al., 2012, for instance).

Garraffo et al. (2001) compared the statistics of drifter observations in the North Atlantic with those of drift simulations based on Eulerian velocities from a model with about 6 km horizontal resolution. Without a stochastic model of sub-grid scale actions they found simulations to underestimate eddy energy. Simulated absolute dispersion being too low was also reported by Kjellsson and Döös (2012) evaluating drifters deployed in the Baltic Sea. Referring to global ocean data, Döös et al. (2011) tuned random turbulent velocity in their drift model to achieve better agreement between relative dispersion of simulated trajectories and corresponding observations. However, they found this approach being too simple for a reasonable reproduction of Lagrangian properties.

More sophisticated analyses of the relative dispersion of pairs of particles try to distinguish the regimes of *local dispersion* driven by eddies comparable in size to the distance between two drifters and of *non-local dispersion* driven by eddies with scales much larger than this distance (e.g. Koszalka et al., 2009). Beron-Vera and LaCasce (2016) conducted such an analysis for data from the Grand Lagrangian Deployment experiment (GLAD), in which more than 300 drifters were deployed in the Gulf of Mexico. Drifter launch positions spaced from 100 m to 15 km apart allowed to study sub-mesoscale dispersion characteristics in much detail. However, referring to experimental data in the southwestern Gulf of Mexico, Sansón et al. (2017) show that for large initial distances the probability density functions of pair separations get dependent on prevailing mesoscale circulation patterns. This aspect seems particularly relevant for the present study~~, as variations~~. Variations of the residual current regime in the inner German Bight can very well be approximated in terms of only 2-3 degrees of freedom, depending on prevailing winds (Callies et al., 2017). Tidal currents dominate short term transports.

The data available for this study (six drifters, tracked between 9 and 54 days) ~~do not provide a basis~~ are insufficient for studying features of oceanic turbulence. Therefore in the present model validation study, stochastic simulation of sub-grid scale processes will not be considered. Ohlmann et al. (2012) provide an example that even an accurate reproduction of mean drifter pair separation does not necessarily imply good agreement between observations and corresponding simulations. According to Coelho et al. (2015), models used in the aforementioned GLAD experiment in the Gulf of Mexico had limited success capturing the observed drift patterns. Barron et al. (2007) provides a list of typical separation rates in different regions worldwide. For an experiment in the Ria de Vigo estuary in NW Spain, Huhn et al. (2012) reported simulation errors that were relatively small compared to those typically found in the open ocean. This study tries to provide a realistic estimate of how reliable operational forecasts in the German Bight, another shelf sea region, can be expected to be. This includes gaining preliminary indications for regions where the deterministic part of a model needs improvement.

The paper is organized as follows: Section 2 documents how observations were taken (Sect. 2.1) and how corresponding model simulations were performed (Sect. 2.2). Section 2.3 describes two data sets ~~characterizing residual currents variability~~ used for characterizing residual current variability in the German Bight on a daily basis. Results (Sect. 3) are presented in two parts: Sect. 3.1 provides a synoptic description of all drifters deployed and places observations into the context of ambient atmospheric and marine conditions; Sect. 3.2 provides the analysis of how corresponding model simulations match observations. ~~After simulations based on different model setups explored the range of possible effects, a~~ First, full simulated trajectories are presented using currents from TRIM or BSHcmod, the latter also combined with wind drag and Stokes drift, respectively. A more detailed evaluation of ~~simulation errors is~~ model performance is then based on subdividing drift trajectories into segments of 25 h length. Results are discussed in Sect. 4, main conclusions provided in Sect. 5.

2 Material and Methods

2.1 Drifter observations

In May 2015 a total of nine drifters were deployed at different locations in the German Bight (North Sea) during the FS Heincke cruise HE 445. The raw data are freely accessible at Carrasco and Horstmann (2017). Table 1 specifies each drifter's launch position and launch time as well as its last position, the total ~~lengths of its observed~~ length of its trajectory and the simple linear distance between its initial and final location. Drifters #2, #3 and #4, travelling for only few days, were ignored for this study. All drifters obtained their positions via the Global Positioning System (GPS) and communicated them to the lab via the ~~global full ocean coverage bidirectional~~ satellite communication network Iridium. Three drifters could successfully be tracked for between 40 and 54~~days.~~ days. In order to conserve battery power, an initial sampling rate of about once every 15 min was later reduced to once every 30 min.

Two different drifter types were utilized (cf. Table 1). The first drifter type, MD03i, from Albatros Marine Technologies (Fig. 1(a)) is cylinder shaped with a diameter of 0.1 m and a length of 0.32 m. Only ~ 0.08 m of ~~such~~ the drifter protrude from the water surface when deployed (Fig. 1(b)). The second drifter type, ODi from the same manufacturer (Fig. 1(c)), has a spherical shape with 0.2 m diameter, about half of it protruding from the water surface. The ratio of drag area in the water to drag area outside the water was 33.2 for the MD03i and 16.9 for the ODi model, respectively. To both drifters a drogue with 0.5 m length and diameter (e.g. Fig. 1(a)) was attached 0.5 m below the sea surface. Due to this drogue and the small sail area exposed to winds above the water surface, drifter movements are supposed to be representative for currents in a surface layer of about 1 m depth. It must be noted, however, that drifters deployed had no drogue presence sensors.

2.2 Drifter simulations with PELETS-2D

For drifter simulations we used the Lagrangian transport module PELETS-2D ~~(Program for the Evaluation of Lagrangian Ensemble Transport Simulations (Callies et al., 2011))~~ (Program for the Evaluation of Lagrangian Ensemble Transport Simulations; Callie developed at Helmoltz-Zentrum Geesthacht (HZG). The PELETS algorithm was designed for particle tracking on two-dimensional unstructured triangular grids. As both models underlying this study use regular grids, the grid topology was pre-processed, splitting each rectangular grid cell into two triangles. Neither the number of nodes nor the information content of underlying hydrodynamic fields is affected by this formal procedure. The integration algorithm used is a simple Euler forward method. Particle velocities are updated (linear interpolation between two neighbouring nodes) each time a particle leaves a cell of the triangular grid. If no edge is reached within the maximum time step of 15 min, velocities are updated based on linear interpolation between three nodes.

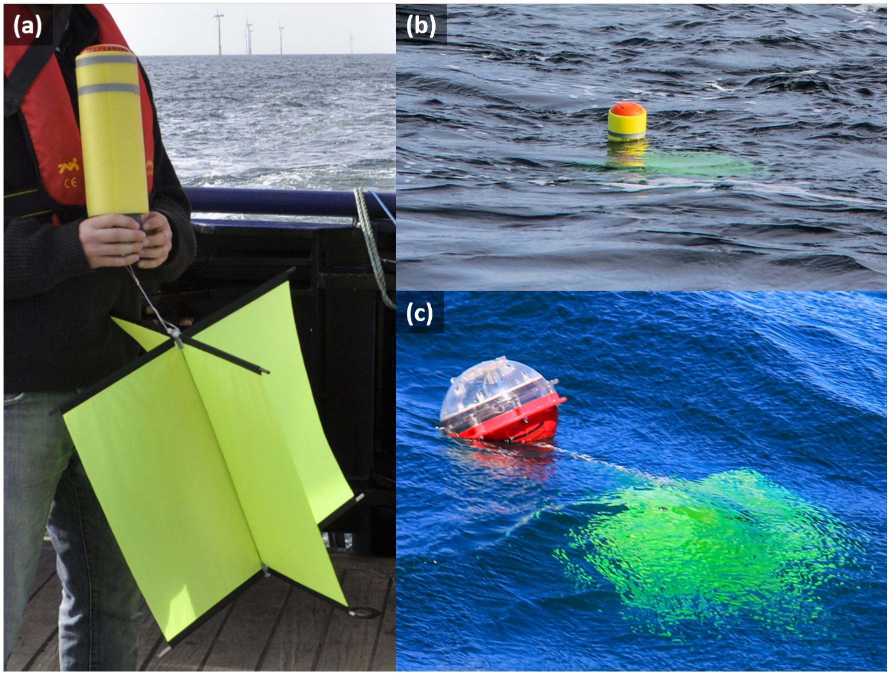

Figure 1. Drifter types MD03i (panels (a) and (b)) and ODi (panel (c)) used during the experiment. Both drifter types were photographed shortly after launch so that the drogue had not yet settled.

The following equation is used for simulating drifter location $\boldsymbol{x}$ as function of time t:

$$\frac{d\boldsymbol{x}}{dt} = \boldsymbol{u}_E + \alpha \boldsymbol{u}_S + \beta \boldsymbol{u}_{10m} \tag{1}$$

Here $\boldsymbol{u}_E$ denotes ~~the~~ Eulerian marine surface currents calculated with either BSHcmod (Sect. 2.2.1) or TRIM (Sect. 2.2.2)~~.~~ ~~Components~~ $\cancel{\alpha \boldsymbol{u}_S}$, $\boldsymbol{u}_S$ is the surface Stokes drift obtained from wave model WAM and $\boldsymbol{u}_{10m}$ is the 10 m height wind vector. Coefficients α and $\cancel{\beta \boldsymbol{u}_{10m}}$ ~~represent additional contributions from Stokes drift and direct wind drag, respectively (~~β are weighting factors (cf. Sect. 2.2.3). ~~Within~~ Eq. (1) describes windage (or leeway) as a drag in downwind direction, neglecting any crosswind lift component. Such lift component depending on the specific overwater structure of a drifting object is crucial for search and rescue (Breivik and Allen, 2008). For surface drifters used in experiments, however, these effects should be negligible.

Throughout this study, Stokes drift and wind drag will not be considered in combination but rather as alternative options. Therefore at least one of the two weighting factors α and β in Eq. (1) will always be set to zero.

Drift paths were calculated offline based on archived data. Sub-grid scale turbulence effects implemented in PELETS-2D in terms of random movements were deactivated.

2.2.1 BSHcmod

BSHcmod is run operationally by the Federal Maritime and Hydrographic Agency (BSH) on a two way nested grid for North and Baltic sea. A description of the 3D model ~~in geographic coordinates~~ can be found in ~~Dick and Kleine (2007). Spatial~~ Dick et al. (2001). Horizontal resolution in the German Bight is about 900 m, the vertical coordinate is dynamical (Dick et al., 2008). Atmospheric forcing of BSHcmod is taken from the regional model COSMO-EU ~~(Consortium for Small-Scale Modelling (Schulz and Schättler, 2014))~~(Consortium for Small-Scale Modelling; Schulz and Schättler, 2014). This operational atmospheric model of the German Meteorological Service (DWD) has a spatial resolution of 7 km~~.~~, output is stored on a hourly basis. For BSHcmod, winds are interpolated to a 15 min model time step. The parametrization by Smith and Banke (1975) is used to include wind stress. The option to include Stokes drift from surface wave models (as described in Dick et al., 2001) is not activated operationally so that effects of Stokes drift are also not included in archived model output.

Archived surface current data represent approximately the upper 5 m of the water column. Higher resolution output of the operational model BSHcmod (version ~~-~~4) was re-gridded accordingly, conserving transport rates. Time resolution of archived data is 15 min. Although operationally BSHcmod is run in combination with its own Lagrangian transport module (Maßmann et al., 2014), for the present study this module was replaced by PELETS-2D which provides convenient interfaces to both BSHcmod and TRIM.

2.2.2 TRIM

TRIM solves the hydrodynamic equations on a Cartesian grid, allowing for coastal regions falling dry. Casulli and Stelling (1998) provide a description of the numerical implementation, extensions with regard to parallelization and nesting can be found in Kapitza (2008). After three refinements nested oneway into a coarse grid with 12.8 km resolution covering the north-eastern Atlantic, North Sea and Baltic Sea, resolution in the German Bight is 1.6 km. The FES2004 tidal model (Lyard et al., 2006) is used to determine tidal signals at the lateral boundaries of the outer coarse grid. ~~Wind~~ Hourly values of wind and sea level pressure are taken from COSMO-CLM hindcasts (Geyer, 2014), which resulted from a regionalization of global NCEP/NCAR Reanalysis 1 data (Kistler et al., 2001) using a spectral nudging technique (von Storch et al., 2000). ~~Wind~~ Similar to BSHcmod, wind stress was parametrized according to Smith and Banke (1975), a parametrization validated from gentle breeze to gale force winds. An evaluation of TRIM simulations on a 6.4 km grid (first of three refinements applied in the present study) can be found in a recent model intercomparison study regarding simulations for the whole North Sea (Pätsch et al., 2017).

2.2.3 Effects of winds and waves

~~Eulerian marine~~ Simulated Eulerian currents can usually not fully ~~account for observed drifter movements~~reproduce observed currents. Additional wind effects may manifest themselves in different ways. This study explores the strengths of windage effects and Stokes drift as alternative tuning parameters for optimizing simulated drift trajectories.

Hourly fields of surface Stokes drift were simulated with the third generation spectral wave model WAM (WAMDI-Group, 1988; Komen et al., 1996), extending an existing wind-wave hindcast for the years 1949-2014 ~~(Groll and Weisse, 2016)~~ (Groll and Weisse, 2017) and including surface Stokes drift as a new element of archived model output. Wave simulations were driven with the same COSMO-CLM hindcast also used for ~~simulations with TRIM~~ TRIM simulations. The wave model was used in a nested mode, with the finer spatial resolution of about 3×3 nautical miles over the entire North Sea. Wave breaking and depth refraction were enabled. A more detailed description of the wave simulation and its validation is given by Groll and Weisse (2017). For the present study, ~~an explicit~~ no assumption about the vertical profile of Stokes drift (Breivik et al., 2016, for instance) was ~~replaced by a simple~~ made. Instead, the empirical weighting factor α in Eq. (1) was used to translate surface Stokes drift obtained from WAM into a value relevant for drifters that represent displacements in a surface layer of say 1 m depth. Choosing $\alpha = 0.5$ resulted in a reasonable overall fit with observations (see below).

Windage (or leeway) effects occur when ~~a~~ drag resulting from ~~parts~~ part of a drifter being exposed to the wind is not fully compensated by a drogue attached to the drifter. Generally, the direct influence of winds on the drifter type used in this experiment is supposed to be small as long as the drogues attached are in a proper condition. However, specification of windage effects may also be needed when ~~marine~~ model currents used do not adequately represent the surface layer drifters are immersed in. An extra wind drift parametrised as 0.6 % of 10 m wind velocity was used in combination with archived BSHcmod currents averaged over a 5 m depth surface layer. By contrast, drift simulations based on TRIM output (1 m ~~depth surface~~ deep top layer) were performed without taking into account additional wind effects.

The assumed strengths of either wind forcing or Stokes drift resulted from trying to achieve an overall eastward displacement of simulated drifters that roughly agreed with observations. This approach must not be confused with sound model calibration, which seems impossible based on the very limited data available. Models perform differently during different periods and it is hard to distinguish, for instance, between deficiencies in the hydrodynamic model and implications of imperfect atmospheric forcing. Also independent data needed for model validation are not available. However, already the simple approach enables an appraisal of how drifter simulations will depend on a distinction between wind drag and Stokes drift.

2.2.4 Analysis of 25 h drifter displacements

Comparing simulated trajectories with concurrent observations enables a qualitative assessment of a model's ability to reproduce overall drift patterns. However, accumulation of possibly intermittent simulation errors makes it difficult to localize the origin of major deviations in either space or time. Therefore, a series of short term (25 h) simulations was started once per day (13:00 UTC) from each drifter's observed location at that time. The short term simulation errors were analysed against the backdrop of prevailing winds and residual currents (cf. Sect. 2.3).

2.3 Characterization of residual currents on a daily basis

BSH classifies the residual circulation in the German Bight (between 53.25° N and 55.5° N and between 6.5° E and 9.0° E) on a daily basis, referring to surface currents from ~~the operational model BSHcmod.~~ [1] ~~The classification~~BSHcmod. The

[1] ~~http://www.bsh.de/de/Meeresdaten/Beobachtungen/Zirkulationskalender_Deutsche_Bucht/index.js~~

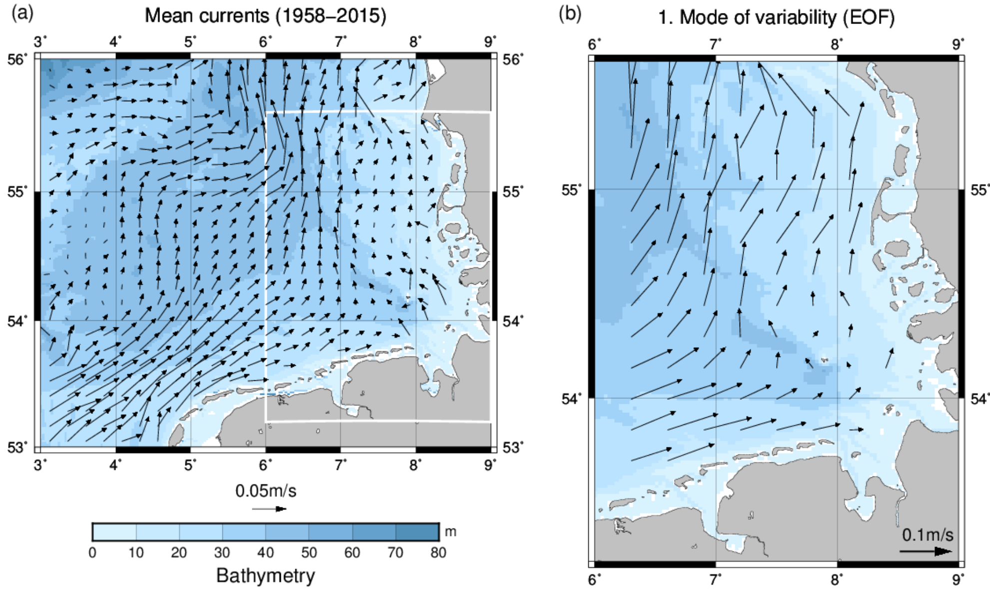

Figure 2. (a) Mean currents in the inner German Bight, calculated running a 2D-version of model TRIM for the period Jan 2014 - Aug 2015. (b) Leading mode of variability (1. EOF, cf. von Storch and Zwiers (1999)) of daily 25 h mean currents obtained from a PCA restricted to data from the white box region in panel (a) (Callies et al., 2017). Vector densities in the two plots do not represent spatial resolution of the underlying model (1.6 km). Vectors in the right panel are scaled in such a way that the EOF represents an anomaly that would arise from the first principal component (PC_1) assuming the (positive) value of one standard deviation.

classification[1] is performed manually based on subjective assessments of 24 h averages. The small deviation of the averaging interval from two tidal periods does not affect the analysed frequency distribution of circulation patterns. Most frequent are a cyclonic circulation with a pronounced inflow at the south-western border and outflow at the northern border, a reverse anticyclonic circulation, and a category with variable current patterns. Cyclonic circulations correspond with what is observed in the long-term mean (cf. Fig. 2(a)). Six specific directional types with currents towards the E, W, N, S, NW, and SE play only minor roles. They are related to strong local winds and for statistical purposes combined into just one class. Due to topographical constraints, SW and NE patterns do not occur. Fig. 3 includes results of the BSH classifications for the period relevant in this study.

An alternative analysis is based on the 2D-version of TRIM. Slightly different from the above approach, Callies et al. (2017) defined residual currents as 25 h means (close to one lunar day = 24.8 h). ~~These fields were than subjected to~~ A principal component analysis (PCA) was performed on these residual currents, focusing on the inner German Bight (east of 6.0° E and south of 55.6° N, see Fig. 2(b)) and excluding inshore areas with a bathymetric depth of below 10 m. Corresponding data are freely accessible at Callies (2016). Figure 2(b) displays the leading mode of variability (first Empirical Orthogonal Function (EOF), cf. von Storch and Zwiers (1999)). The time series of corresponding principal component PC_1 is shown in Fig. 3. The

[1] http://www.bsh.de/de/Meeresdaten/Beobachtungen/Zirkulationskalender_Deutsche_Bucht/index.js

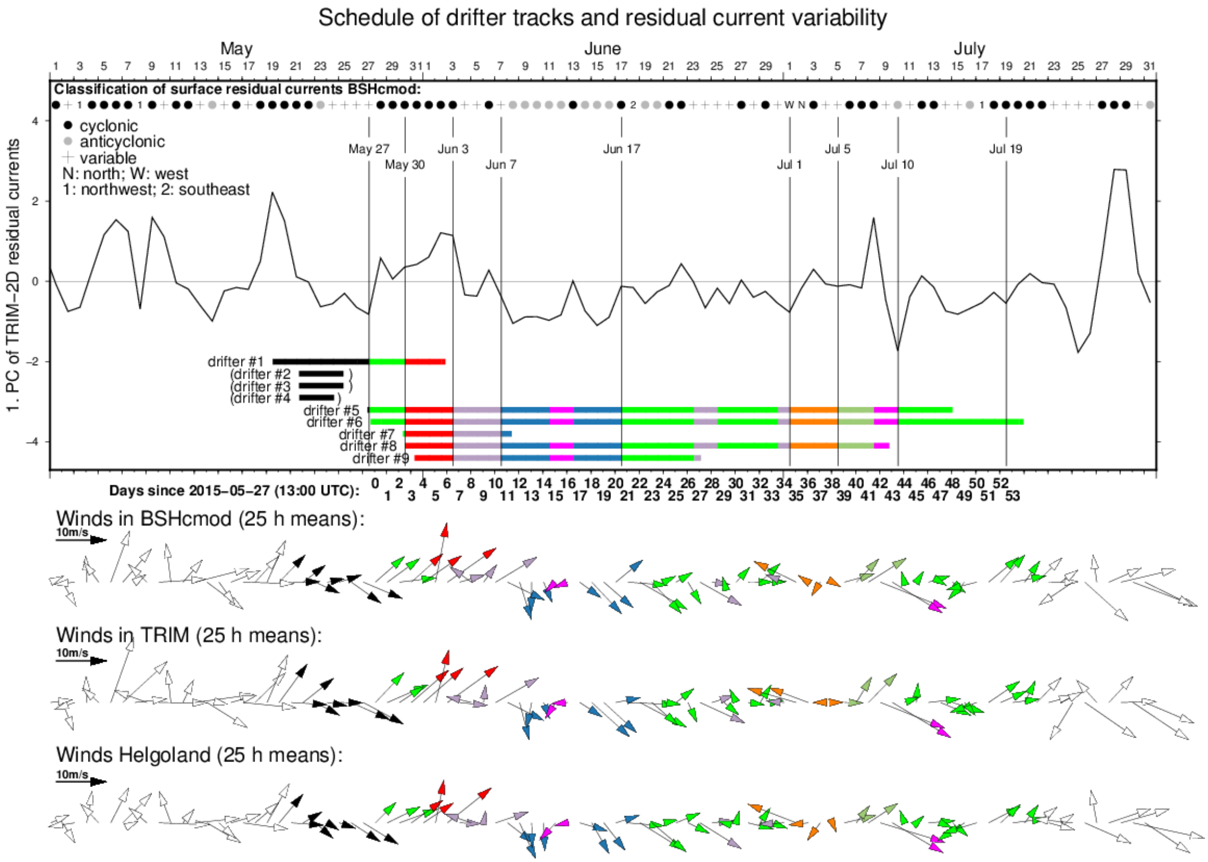

Figure 3. ~~Observed trajectories of six drifters deployed at~~ Time bars indicate for each drifter the ~~locations indicated by black crosses. Drift paths~~ period for which corresponding simulations were ~~segmented using the~~ performed (drifters #2, #3 and #4 were disregarded in this study). A colour code ~~introduced~~ defined in Table S1 (supplementary material) was used for time segmentation. ~~The numerical data underlying this plot can be found~~ Symbols at the top represent the classification of daily surface residual currents based on BSHcmod. In addition the time series of the leading principal component (PC_1) of 25 h mean currents simulated with TRIM-2D is shown (see Sect. 2.3). PC_1 values were normalized with their standard deviation during the years 1958-2015. Positive PC_1 values represent a strengthening of the cyclonic regime, negative values its weakening or even reversal (cf. Fig. 2(b)). 25 h mean wind vectors (10 m height) used in the ~~supplementary material~~two model systems (both extracted for location 55° N and 7° E) are contrasted with observations on the island of Helgoland (54.10° N / 7.53° E).

~~interpretation~~ structure of the dominant ~~anomaly pattern EOF_1 (it explains~~ residual current anomaly pattern (explaining more than 70~~% of residual current variabilityin the area) is a strengthening or weakening (even reversal) of~~ % of variability) roughly agrees with that of long-term mean residual currents ~~(~~in the area of the white box in Fig. 2(a)~~), depending on whether values of PC_1 are positive or negative~~.

3 Results

3.1 Observations

Figure ~~4 shows six observed drifter trajectories, disregarding the tracks of drifters #2, #3 and #4 that were recorded for just a view days.~~ 3 places drifter schedules into the context of variable atmospheric winds and marine residual currents. Time bars show travel times of all nine surface drifters. To facilitate a synopsis of synchronous drifter movements, the time coordinate was ~~subjectively segmented,~~ segmented, subjectively assigning different colours to periods with different drift behaviour. In this context, a continuous daily index was introduced, counting days since when the first 25 h simulation for drifter #5 was started on May 27 at 13:00 UTC (cf. Table S1~~).~~

~~Figure 3 places drifter schedules into the context of variable atmospheric winds and marine residual currents. For each drifter, a segmented time bar covers all 25 h simulations started every day at 13:00 UTC (cf. Sect. 2.2.4). Time bars slightly truncate the times drifters were tracked, due to a disregard of hours before 13:00 on the day a drifter was deployed and of those 25 h simulations that would extend beyond existing observations.~~ , supplementary material). To represent atmospheric forcing used in BSHcmod and TRIM, respectively, simulated 10 m winds at location 55° N and 7° E near the centre of the study area are shown together with observations on the island of Helgoland (54.10° N / 7.53° E). All wind vectors represent 25 h means and are plotted at the center of the respective 25 h interval starting at 13:00 UTC. The winds from three different data sources are in reasonable agreement with each other.

Figure 3 also includes the representation of a) the subjective classification of daily mean BSHcmod surface currents and b) the first principal component (PC_1) of 25 h mean currents simulated with a 2D version of TRIM (cf. Sect. 2.3). Positive values of PC_1 (~~or~~ i.e. amplitudes of the anomaly pattern shown in Fig. 2(b)) indicate a strengthening of the mean cyclonic circulation, negative values refer to its weakening or even reversal. Although the two representations of residual current variability have different roots (different models, surface layer vs. vertical means, subjective vs. objective, different atmospheric forcing), a clear correspondence between the two representations is discernible. ~~While cyclonic~~ Cyclonic hydrodynamic regimes and positive values of PC_1 tend to coincide with winds from the southwest, while anticyclonic circulations and negative PC_1-values are mainly driven by winds from the northwest (Callies et al., 2017).

Figure 4 shows six observed drifter trajectories, disregarding the tracks of drifters #2, #3 ~~and~~ and #4 ~~were disregarded in this study). The colour code defined in Table S1 was used for time segmentation. Symbols at the top represent the classification of daily surface residual currents based on BSHcmod. In addition the time series of the leading principal component (PC_1) of 25 h mean currents simulated with TRIM-2D is shown (see Sect. 2.3). PC_1 values were normalized with their standard deviation during the years 1958-2015. Positive PC_1 values represent a strengthening of the cyclonic regime~~that were recorded for just a few days. A feature shared by at least four drifters (#5, ~~negative values its weakening or even reversal (cf. Fig. 2(b)). 25 h mean wind vectors (10 m height) used in the two model systems (extracted for location 55° N and 7° E) are contrasted with observations on the island of Helgoland (54.10° N / 7.53° E).~~

#6, #7 and #8) is a general displacement towards the northeast. Concerning drifters #6 and #8, an interesting special situation occurs during June 7-16 (~~or~~ days 11-20). ~~When~~ Figure 5 shows the distance between the two drifters as a function of time. At

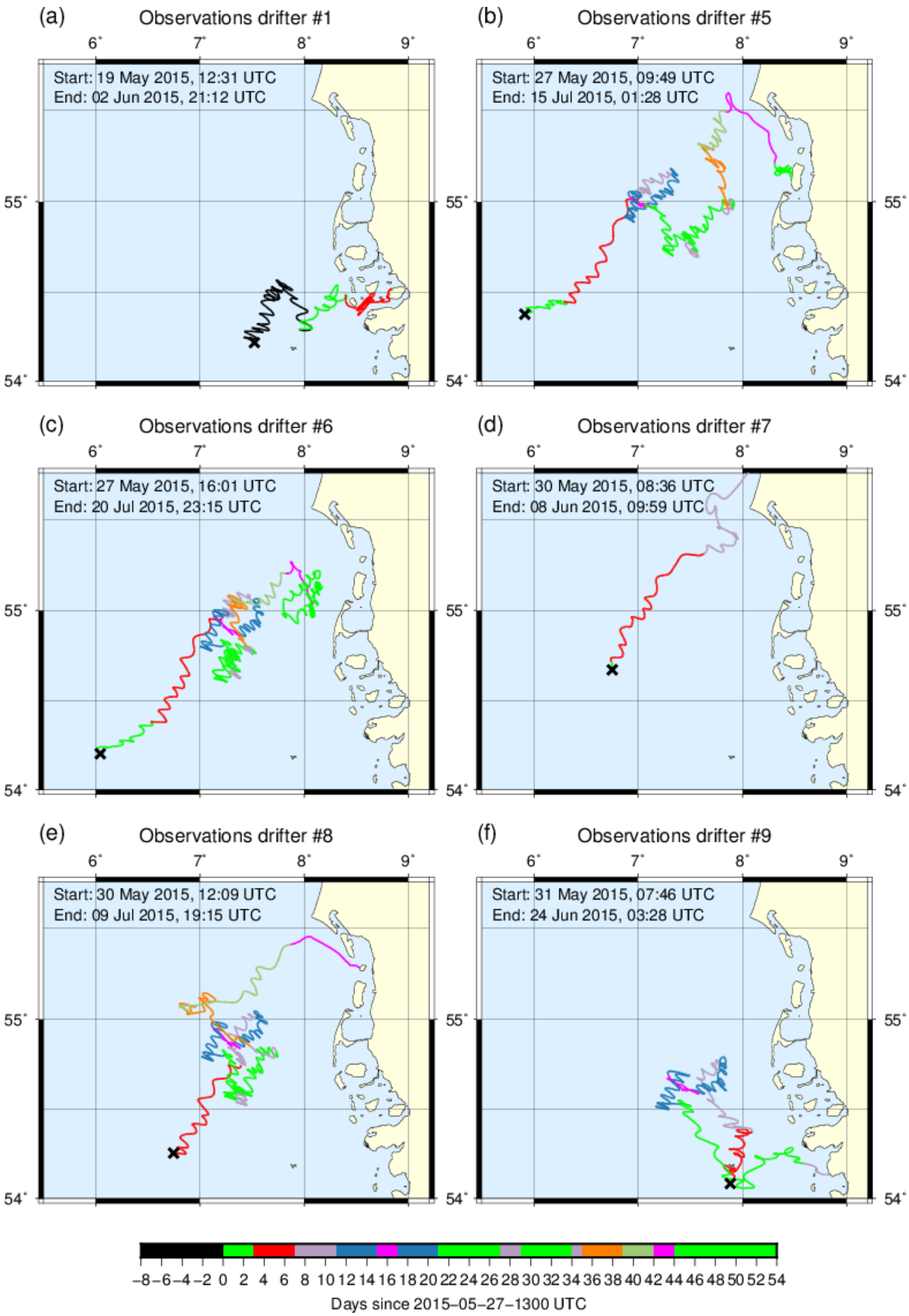

Figure 4. ~~Time bars indicate for each drifter~~ Observed trajectories of six drifters deployed at the ~~period for which corresponding simulations~~ locations indicated by black crosses. Drift paths were ~~performed (drifters~~ segmented using the colour code introduced in Table S1. The numerical data underlying this plot can be found in the supplementary material.

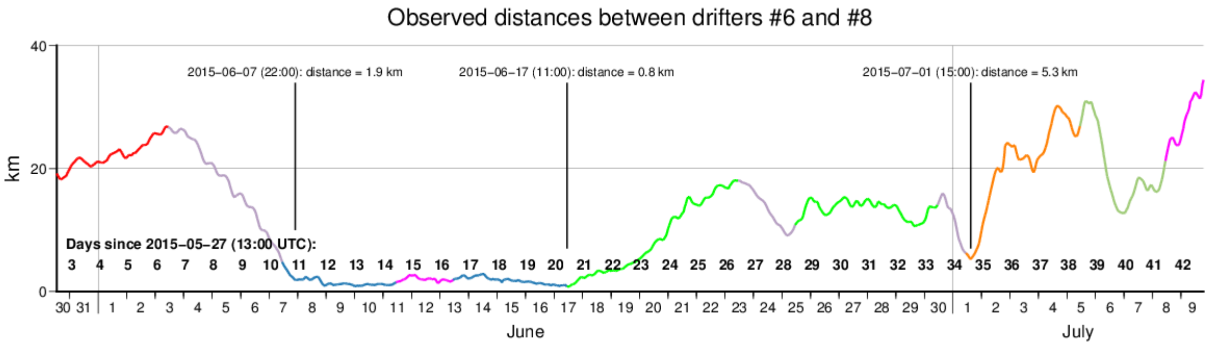

Figure 5. Observed distances between drifters #6 and #8. Colours refer to those specified in Table S1.

the deployment of drifter #8 ~~was deployed~~ (May 30, day 3), drifter #6 already travelled for nearly 3 days and was located at a distance of about 20 km ~~. Within~~ from drifter #8. During the next 4 days the two drifters further separated. On June 4 (day 8), however, they suddenly started converging quickly. From June 8 (day 12) onwards, drifters #6 and #8 stayed at a distance of less than 2 km for nearly 10 days. ~~Distance between the two drifters as a function of time is shown in Fig. 5.~~ Just after the distance had reached its minimum (about 800 m), the drifters started to separate again. Other short periods of fast convergence occurred later but never again the two drifters came that close. During the last 8 days of their joint journey (starting at around day 35) the distance between the two drifters showed particularly large oscillations ~~.~~ (Fig. 5).

~~According to~~

Fig. ~~4, a feature shared by at least four drifters (~~6 provides magnitudes of velocities for drifters #5, #6, #~~7 and~~ 8 and #~~8) is a general displacement towards the northeast. This movement is~~ 9, calculated from velocity vectors smoothed using a 25 h moving average of hourly data. Drifter movements are particularly fast in the beginning (days ~~3-6~~5-6), brought about by persistent south-westerly winds and a corresponding cyclonic circulation at ~~this~~ that time (Fig. 3). Other periods with particularly fast movements occur around day 35 and days 42-43. In the former case, strong winds from the southeast trigger a very fast separation of drifters #6 and #8 (cf. Fig. 5). In the latter case, north-westerly winds give rise to extreme drift speeds in south-east direction. Drifters #5 and #8 are already in nearshore areas at that time (Fig. 4).

In their central parts, drifter trajectories #5, #6 and #8 exhibit variable drift directions but mostly moderate drift velocities ~~. Although structures are complex~~ (Fig. 6). Although trajectories are complex (Fig. 4), they show resemblance, explicable by moderate distances between the three drifters. ~~Drifter~~ In the beginning of its journey drifter #9, started further away in the south-east of the domain, behaves more differently ~~, although some structural~~ (days 4-9, cf. Fig. 6). A much better coherence with other drift paths ~~can still be distinguished. In particular this applies for~~ is found during days 11-20 (June 7-16) characterized by the close proximity of drifters #6 and #8. The journey of drifter #1 has just a small overlap with those of other drifters, the drifter is soon trapped within the entrance to tidal basins ~~.~~ (Fig. 4(a)).

~~Observed distances between drifters #6 and #8. Colours refer to those specified in Table S1.~~

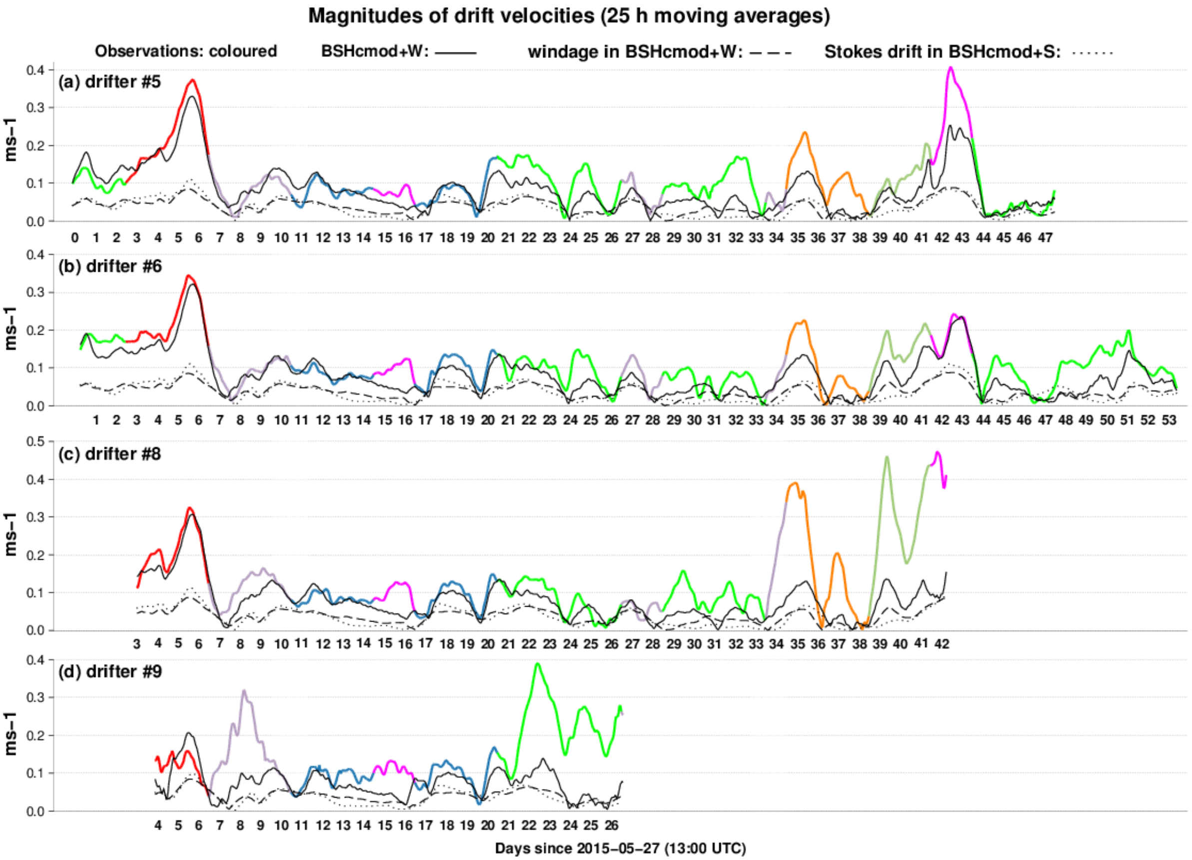

Figure 6. Magnitudes of 25-h moving averages of drift velocity vectors, considering drifters #5, #6, #8 and #9. Magnitudes of observed velocity vectors (coloured) are compared with simulations based on BSHcmod+W. In addition, magnitudes of windage (in BSHcmod+W) and Stokes drift (in BSHcmod+S) are shown. All model values were interpolated to observed (not simulated!) drifter locations prior to averaging.

Further details of observed trajectories will be addressed in Sect. 3.2 together with a presentation of corresponding simulations.

3.2 Simulations

~~Taking drifter #5 as an example, Fig. ?? compares the simulation~~ Figures in the appendix compare drift simulations based on TRIM (Fig. A4) with three different ~~simulations~~ approaches based on BSHcmod. The three ~~different~~ setups are a) just Eulerian currents (BSHcmod, Fig. A1), b) Eulerian currents plus windage (BSHcmod+W, ~~windage parametrized as 0.6 % of 10 m winds~~Fig. A2) or c) Eulerian currents plus ~~50 % of surface Stokes drift simulated independently with wave model WAM~~ Stokes drift (BSHcmod+S~~).Corresponding simulations for all six drifters can be found in the appendix (Figs. A1-A4~~, Fig. A3). Numerical data displayed in the graphs are provided as supplementary material. It appears ~~from Fig. ??~~ that combining BSHcmod currents for a 5 m depth surface layer with either windage or Stokes drift brings corresponding simulations closer to ~~those~~ both observations (Fig. 4) and simulations based on Eulerian surface currents from TRIM ~~.~~ with 1 m vertical resolution (Fig. A4). A key effect of the inclusion of extra wind or wave effects is the intensification of westward transports in agreement with wind directions that occur most frequently. One should remember that achieving reasonable agreement between overall strengths of these transports in simulations and observations was the criterion which led to the specific values we assigned to α or β in Eq. (1) (see Section 2.2.3).

~~Top: trajectories of drifter #5, simulated based on currents from (a) BSHcmod and (b) TRIM, disregarding extra effects of winds or waves. Bottom: Simulations based on BSHcmod including either (c) windage (BSHcmod+W) or (d) Stokes drift (BSHcmod+S). Corresponding observations are shown in Fig. 4(b). Figs. A1-A4 in the appendix show corresponding simulations also for all other drifters. Underlying numerical data are also provided as supplementary material.~~

~~A more detailed assessment of model performance is enabled by analysing~~ Analysing short-term drifter displacements on a daily basis enables a more detailed assessment of model performance. Simulations of 25 h drift paths (cf. Sect. 2.2.4) were initialized on every day 0-53 (cf. Table S1) at 13:00 UTC. Full sets of corresponding plots are provided as supplementary material~~, referring to the different model setups also shown in Fig. ??. Each of four sets of plots (SM1-SM4) contains information for all days 0-53~~. The first collection (SM1) shows 25 h drifter displacements that were observed. The second (SM2) compares corresponding simulations based on either BSHcmod or TRIM Eulerian currents with these observations. The third (SM3) is similar except that BSHcmod currents are complemented by parametrized windage (BSHcmod+W). Finally, the fourth collection (SM4) compares ~~two~~ BSHcmod simulations including either windage (BSHcmod+W) or Stokes drift (BSHcmod+S).

Drawing on the material from SM3, Figs. 7~~and 8~~, 8 and 9 present results for ~~eight~~ twelve selected days, comparing simulations based on TRIM surface currents with those based on BSHcmod+W. Each panel combines all drifters that are available at the respective time. Observed drifter displacements are coloured in agreement with Table S1.

Concentrating on the four drifters that travelled longest, ~~histograms~~ bars in Fig. 10(a) show daily values of ~~separations~~ separation between observed and simulated end points of 25 h drift paths, referring again to simulations with either TRIM or BSHcmod+W. To show the relative importance of drift errors, total distances covered according to observations or simulations are also included. Figure 10(d) shows the angles between observed and simulated drifter displacements. Time series (25 h means) of wind speeds used in TRIM and BSHcmod (and also BSHcmod+W) are shown in Fig. 10(b) together with surface Stokes drifts from wave model WAM. Figure 10(c) copies observed Helgoland wind vectors from Fig. 3.

The following description highlights some key aspects of drifter observations and concurrent simulations during different sub-periods of the experiment. ~~The description focusses on simulations based on either BSHcmod+W or TRIM (cf. SM3 for the full set of results).~~

Days 0-6 (27 May - 2 June): ~~The period is~~ A period characterized by cyclonic residual currents increasing in strength (Fig. 3). Driven by winds mainly from southwest, drifters move fast towards a north-eastern sector. ~~After about one week, simulated locations of drifter #5 (Fig. ??) and drifters #6, #7 and #8 (Figs. A2 and A4) are in reasonable agreement with observations (Fig. 4). The 25 h drifter displacements reveal that by and large both models capture observed drift~~

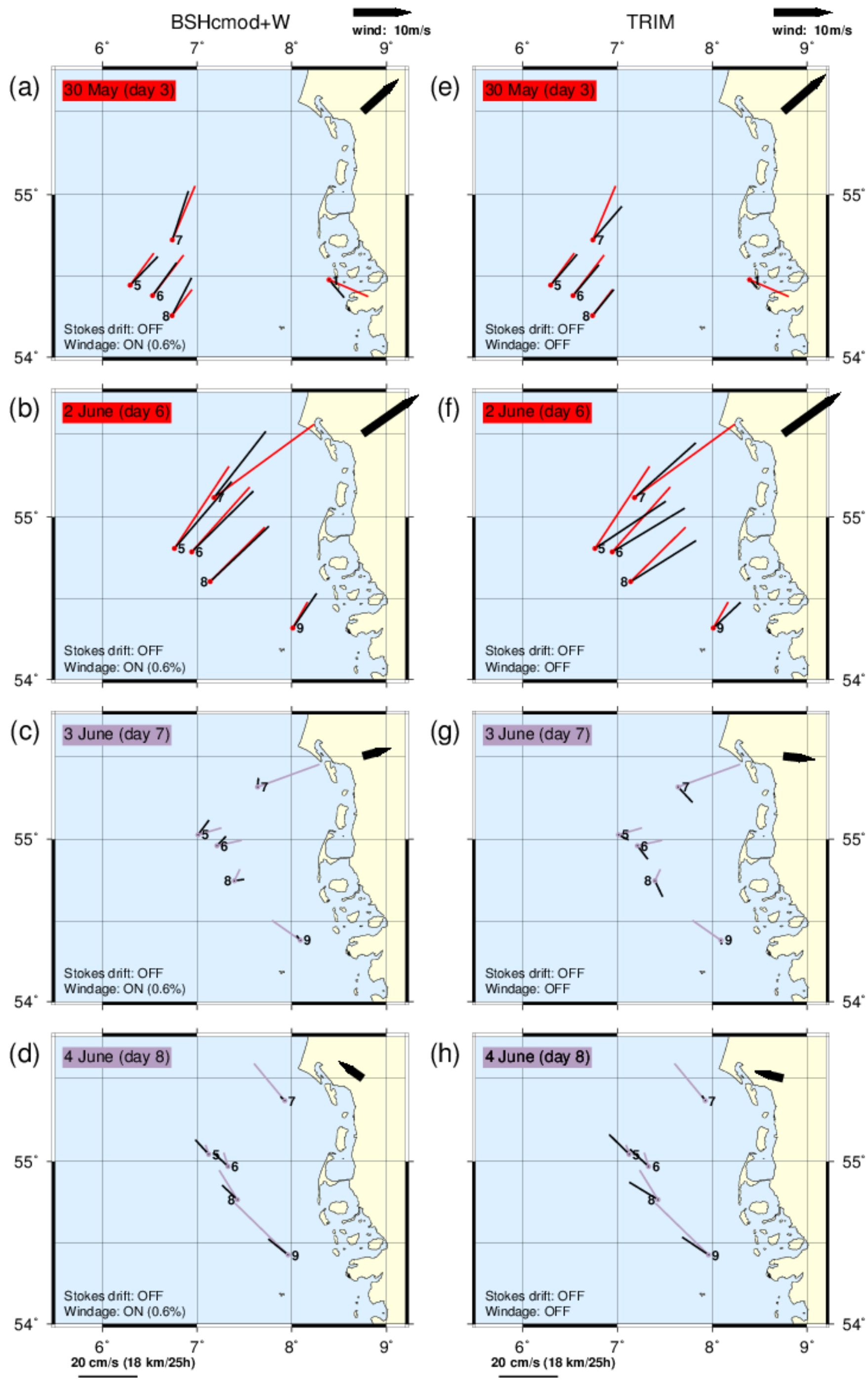

Figure 7. Observed 25 h drift paths (coloured in agreement with Table S1) are contrasted ~~with~~ against concurrent simulations (black) based on BSHcmod+W (a-d) or TRIM (e-h). For four selected days, panels combine all drifters observed at the time of the plot. All drift distances were converted into 25 h mean drift velocities. Note that the length scales shown do not correspond with the spatial scale of the geographic map. Vectors in each panel's top right corner indicate the mean wind velocity vector at 55° N and 7° E derived from the respective atmospheric model used.

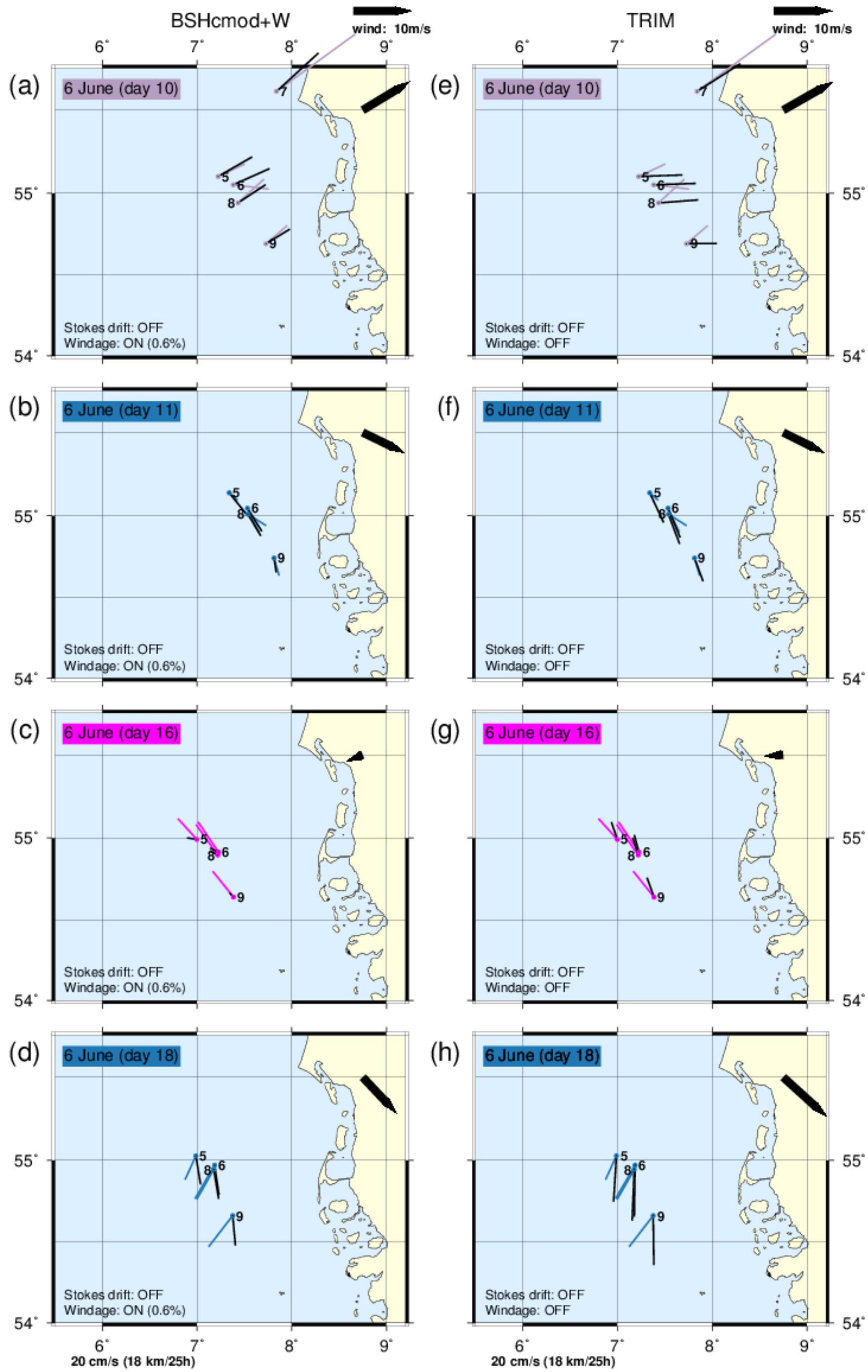

Figure 8. Continued from Fig. 7.

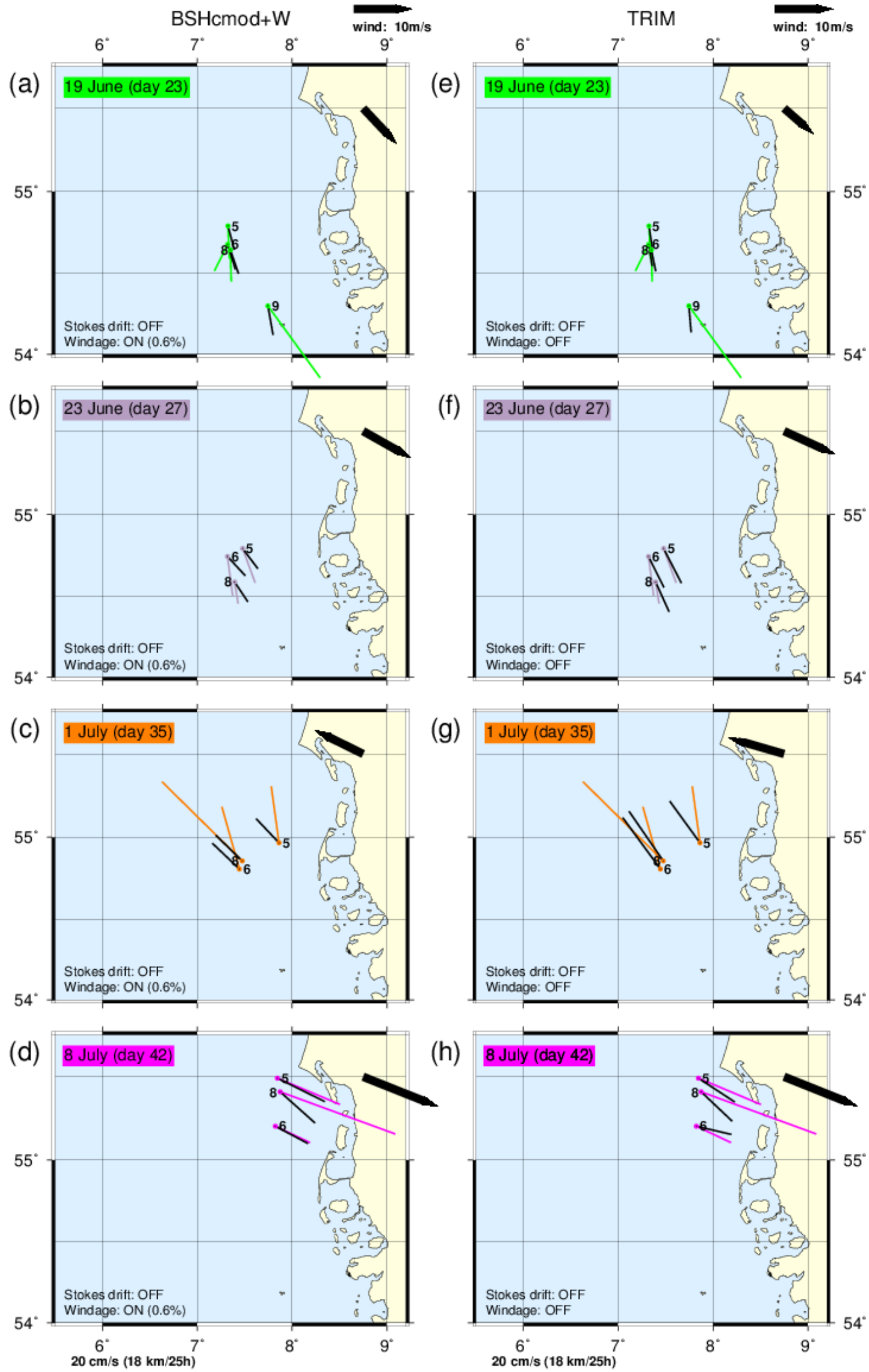

Figure 9. Continued from Figs. 7 and 8.

~~speeds reasonably well (Fig. 10(a)). Although for both models simulated drift~~ Simulated drift distances agree well with observations~~, particularly for TRIM the errors of simulated trajectory end points can be appreciable in terms of absolute values (Fig. 10(a)). However, these errors must be assessed in the light of total distances covered. According to Fig. 7(f), errors arise mainly~~ . Appreciable errors for TRIM arise from moderate directional deviations in combination with large displacements ~~. In most cases simulations are rotated to the right relative to observations. Directional mismatches tend to be larger in TRIM than in BSHcmod+W. In both models, they are largest for drifter #9 on day 4 (~~(cf. Fig. ~~10(d)and SM3~~7(f)).

~~While on~~ On day 2, neither model simulates the neighbouring drifters #5 and #6 ~~move into substantially different directions , both models predict parallel movements in a direction close to an average of the two observations~~ to move into different directions (SM3). ~~In Fig. 10(d) this leads to directional errors of opposite sign.~~ On day 3 (Figs. 7(a~~) and 7(e)), both models simulate parallel displacements of drifters #5~~,e), ~~#6 and #8 quite well, but~~ only BSHcmod+W captures the deviant direction of drifter #7. ~~Although the agreement with observations depends on the inclusion of windage, simulated differences in directions clearly arise from information in BSHcmod Eulerian~~ Comparing simulations based on BSHcmod+W (Fig. 7(a)) with those based on BSHcmod (SM2) reveals that the deviant simulation of drifter #7 arises from spatial variation of BSHcmod currents. By contrast, ~~on~~ inclusion of more large scale windage affects all drifters tracked in a very similar way. On day 6 (Figs. 7(b~~) and 7(~~,f)), the again deviant ~~direction~~ movement of drifter #7 (now rotated to the ~~other side~~opposite direction) is no longer reproduced by BSHcmod+W.

For drifter #1 simulations are generally poor. On ~~day 0 both models well reproduce its drift direction but much underestimate its drift speed (SM3). On~~ days 3-5 ~~, drifter #1~~ the drifter already enters the complex coastal bathymetry which is insufficiently resolved in both models (e.g. Figs. 7(a~~) or 7(~~,e)).

Days 7-10 (3-6 June): The strong cyclonic regime declines~~. While the residual current classification based on BSHcmod is inconclusive, values of PC_1 tend to change from positive to negative values (Fig. 3). Strong~~ , strong south-west winds first cease and then blow from different directions ~~with different strengths.After a steep decline, observed~~ (Fig. 3). Observed displacements of drifters #5, #6 and #8 take a minimum on days 7 or 8 (~~Fig.~~ Figs. 6 and 10(a)). On day 7~~directional errors of TRIM simulations are particularly large and mostly opposite to those based on BSHcmod+W (~~, major directional errors occur under variable wind conditions (Figs. 7(c,g) and Fig. 10(d)). ~~On the following days both observed and simulated drift lengths start increasing again.~~

~~According to observations,~~ Only drifter #9 ~~is the only one that~~ rotates its movement from north-east to north-west already on day 7, all other drifters follow on day 8 (~~SM3).According to Fig. 10(a),observed speeds~~ Figs. 7(d,h)). Speed of drifter #9 shows a strong peak on day 8 ~~, when drift speeds of drifters #5 and #6 take a minimum (see also Figs. 7(e)or 7(g))~~(Fig. 6). Observed drifter displacements seem to decrease with distance from the coast, a variation not resolved in ~~any of the two simulations . Simulations based on TRIM currents show for all drifters #5, #6, #8 and #9 larger displacements than BSHcmod+W simulations. But while displacements according to TRIM are still too small for the two nearshore drifters #7 and #9, displacements of more offshore drifters #5 and #6 are largely overestimated~~

~~(Fig~~simulations (Figs. 7(~~g~~d,h)). ~~Neither simulated currents nor fields of windage or Stokes drift are able to reproduce the spatial gradients.~~

~~Observed sub-mesoscale~~ Also considering Stokes drift does not help reproduce this spatial gradient (SM4). Sub-mesoscale differences in drift speed (e.g. day 8, Fig. 7(~~e~~d)) and direction (e.g. day 10, Fig. ~~7(d)) are also the reason for the~~ 8(a)) giving rise to the fast convergence of drifters #6 and #8 (Fig. 5) ~~that both modelsare unable to resolve. However, it must also be noted that the more eastern direction of the movement observed for drifter #6 on day 10 (Fig. 7(d)) is not shared by any of the neighbouring drifters moving more to the north-east~~remain unresolved in both models.

Neither model captures the ~~different~~ special behaviour of drifter #7 which continues its fast movement towards northern directions (compare Figs. A2(d) and A4(d) with Fig. 4(d)). ~~Beginning at about day 8 (Fig. 7(c)), drifter #7, deployed at a more northern location, continues its fast movement towards northern directions, while all more southern drifters considerably slow down.~~

Days 11-14 (7-10 June): Winds from the north-west or north trigger an anticyclonic circulation (Fig. 3). On day 11, the inclusion of windage much reduces errors of BSHcmod simulations for drifters #6, #8 and #9 (compare ~~panels in~~ Fig. 8(b) with SM2~~and SM3~~), mainly due to improved drift directions. Only for drifter #5, moving much slower despite its vicinity to other drifters, adding windage leads to ~~a drift velocity that is much overestimated . This overestimation also holds for simulations based on TRIM Eulerian currents (cf.~~ drift velocity on day 11 being much overestimated (Fig. ~~10(a))~~6).

~~Also during days 12-14, adding windage impairs the overall quality of BSHcmod drift simulations due to modified drift directions, despite the fact that drift speeds are improved. This seems to be the main reason why TRIM simulations tend to perform better on these three days (Fig. 10(a)).~~

Note, that after about day 12 both observations and simulations for the two drifters #6 and #8 are more or less plotted on top of each other ~~and can therefore hardly be distinguished~~ (applies to Figs. 8(~~a,e~~c,g), for instance, and various plots in the supplementary material).

Days 15-16 (11-12 June): ~~A short period with low winds from the north-east or east during which the~~ For a short time the circulation returns to ~~a~~ cyclonic orientation (Fig. 3). ~~In particular on day 16, BSHcmod+W~~ BSHcmod+W simulations much underestimate ~~observed drift speeds of all drifters~~ drift velocities to the north-west and tend to even cease on day 16 (Fig. ~~10(a) and SM3~~8(c) and Fig. 6). Due to ~~the low wind conditions, adding windage or Stokes drift (Fig. 10(b)) cannot~~ low winds (from north-east or east) adding windage could not eradicate this deficiency~~which is much less pronounced in TRIM simulations (see~~. TRIM simulations perform slightly better (Fig. ~~10(a~~8(g)).

~~In Fig. 4, excursions towards the north-west can be discerned for drifters #5, #6, #8 and #9 during days 15-16. For drifter #5, Fig. **??**(b) shows how TRIM just adumbrates such movement while all transports simulated based on BSHcmod more or less cease for the two day period.~~

Days 17-20 (13-16 June): During days 17-19 the circulation ~~returns to a anticyclonicorientation~~is anticyclonic, driven by north-westerly winds (Fig. 3). ~~On those days, simulations~~ Simulations based on either model consistently produce drift velocities that are markedly rotated to the left of ~~corresponding~~ observations (cf. Figs. 8(d,h) and Fig. ~~10(d~~10(d))~~and Figs. 8(a)and 8(e))~~.

On day 20 the wind direction ~~returns~~ turns to the south-west in BSHcmod or west in TRIM (cf. Fig. 3), the residual circulation becomes cyclonic for one day. Under ~~these~~ transitional conditions, ~~signs of directional errors substantially differ between the two models~~ directional errors are particularly high in TRIM (Fig. 10(d)~~and SM3~~).

~~Comparing TRIM simulations for drifter #5 (Fig. **??**(b)) with corresponding observations (Fig. 4(b)) reveals that TRIM currents imply too strong southward transports. This finding holds also for TRIM simulations of drifters #6 and #8 (Fig. A4). TRIM drift speeds being higher than their observed counterparts can also be discerned from Fig. 10(a).~~

Days 21-26 (17-22 June): ~~A mainly anticyclonic~~ Residual circulation gradually changes ~~into a cyclonic circulation towards the end of the period~~ from anticyclonic to cyclonic (Fig. 3). During ~~the first three days (days~~ days 21-23~~)~~, considerable errors in both BSHcmod+W and TRIM simulations resemble each other to a surprising degree (~~SM3). In particular this applies to drift directions that~~ e.g. Figs. 9(a,e)). Except for drifter #9, drift directions are typically rotated to the left of ~~observed counterparts~~ observations (Fig. 10(d)). ~~An exception forms drifter~~ From about day 22 onward drifters #~~9, for which tracks simulated with either model change from eastward~~ 6 and #8 start separating again (Fig. 5). Expectedly, neither model reproduces sub-grid scale differences in speed (day ~~21) to southward~~ 22, SM3) or direction (day 23~~) while in reality drifter #9 constantly moves towards the southeast (see also SM3)~~, Figs. 9(a,e)).

~~On day 24 both model simulations are particularly poor in that they much underestimate observed drift velocities (Fig. 10(a)) during a transition from anticyclonic to cyclonic residual currents (Fig. 3).Simulated drift angles now differ considerably between the two models (Fig. 10(d)) , although during low drift speeds already mentioned. An extreme misfit of simulations occurs for drifter #9. However, already from day~~ Starting on about day 22~~onward observed displacements of drifter #9 are much larger than their~~ , fast movements mostly in line with prevailing wind directions (e.g. Figs. 9(a,e)) and much exceeding simulated counterparts (Fig. ~~10(a)). The reason for this remains unclear. Fig. 4(f) illustrates the fast movements of drifter #9, mostly in line with prevailing wind directions. It cannot be precluded~~ 6) suggest that drifter #9 experienced some problem with its drogue. ~~The special role of drifter #9 is most pronounced on day 26. While other drifters stop moving according to both observations and simulations, drifter #9 does hardly slow down.~~

~~From about day 22 onward~~

Days 27-28 (23-24 June): On day 27 (Figs. 9(b,f)), strong winds from the north-west give rise to southern transports. Substantial differences between speeds of neighbouring drifters #6 and #8 ~~start separating again (~~(unresolved in simulations) imply a short period of their fast convergence (Fig. 5~~and SM3). On day 22 drift speeds differ, on day 23 also drift directions. As to be expected, neither model reproduces such sub-grid scale differences observed.~~

~~**Days 27-28 (23-24 June):** High wind speeds from the north-west on day 27 give rise to southern transports. Success of corresponding~~). BSHcmod+W simulations ~~(Fig. 8(b)) much depends on~~ much benefit from the inclusion of windage ~~,~~

~~which produces a more realistic drift speed.However, at the same time pushing drifter displacements more towards wind direction increases errors in drift direction (compare SM2 and SM3). Simulations based on TRIM~~ (Fig. 9(b) and SM2), while TRIM simulations are more consistent even without windage (Fig. ~~8~~9(f)).

~~Next day(day~~On day 28 ~~) winds abateand marine surface transports veer to a northeast direction. Model simulations seem to lag behind this sudden change. But there are also substantial differences between observed speeds of the neighbouring drifters #6 and #8, which implies a short period of their fast convergence (Fig. 5).~~ winds abate.

Days 29-33 (25-29 June): A period with variable wind directions. ~~Although wind speeds are not always small (not shown), strengths of 25 h averages are generally low (Fig. 10(b)) due to compensating effects on the short time scale. Model performances are poor with major errors in both directions and drift speeds.~~ Drifter displacements are generally underestimated (~~Fig.~~ Figs. 6 and 10(a))~~. Observed~~ , observed northward transports (e.g. for drifter #8, see Fig. 4(e)) are not reasonably reproduced ~~by simulations~~ based on BSHcmod+W (Fig. A2(e)) and even less ~~in simulations~~ based on TRIM (Fig. A4(e)). ~~Note, however, that simulations shown in the latter figures are not exactly consistent with 25 h simulations started from observed drifter locations.~~

Day 34 (30 June): ~~A day with a fast convergence of drifters~~ Drifters #6 and #8 converge quickly (Fig. 5)~~. This convergence is caused by the fact that~~ , caused by a fast west-northwest movement of drifter #8~~shares with drifters~~ , not shared by drifters #5 and #6 ~~neither direction nor speed of its very fast west-northwest movement~~ (SM3). No model resolves ~~the substantial differencesobserved~~these substantial differences.

Days 35-38 (1-4 July): ~~A four day period in which drifters~~ Drifters #5, #6 and #8 all move quickly into northern or northwestern directions (Fig. 4). ~~The by far largest~~ Largest drifter displacements occur on ~~the first day(day~~day 35 ~~, (~~(cf. Figs. ~~8(c) and 8(g))~~ 9(c,g) and Fig. 6) with strong winds from the southeast. ~~Drift directions are consistent with the BSHcmod classification of residual currents on 1-2 July as being directed towards the north and west, respectively (Fig. 3). Note that the counts of days used in this study are based on 24 h intervals starting at 13:00 UTC, i.e. they are shifted by about 12 h relative to the calendar days underlying the BSHcmod classification.~~

~~As already on day 34, a particularly fast movement of drifter #8 is also observed on day 35.~~ Drifter #8 ~~also drifts more westwards than drifters #5 and #6. This special behaviour underlies the very quick separation of drifters #6 and #8 at that time (Fig. 5). The drift direction of drifter #8 is~~ moving faster and more aligned with wind direction than ~~those of~~ its companion drifters ~~, possibly indicating~~ could possibly indicate problems with the drogue.

On day 36, TRIM (but not BSHcmod) assumes the wind to persist (Fig. 3 or SM3), which results in a substantial overestimation of drifter displacements (Fig. 10(a)). ~~A comparison with~~ According to observations at Helgoland (Fig. 3)~~suggests that~~, winds used by BSHcmod~~are~~ +W seem more realistic. ~~Regarding drift directions, simulations based on either model are rotated to the left relative to observations.~~

~~On days 37-38 both models assume low 25 h mean winds (Fig. 10(b)) although on an hourly basis some short term peaks exist (not shown). For all drifters, simulations based on either model are very poor.~~ Under low wind conditions on day 37, BSHcmod+W ~~simulations predict drifter movements to cease, which contradicts observations on day 37 (SM3). According to TRIM, drifters keep moving (possibly brought about by the assumed stronger winds the day before) , but predicted drift directions much deviate from observations.~~(to a lesser degree also TRIM) very much underestimates drift speeds (Fig. 6). On day 38, drifters #6 and #8 coming to rest is well reproduced in both models ~~. Drifter #5, however, continues to move, a special behaviour that remains unresolved in both models.~~ (SM3).

Days 39-41 (5-7 July): Freshening southwesterly winds ~~bring about a transition towards a strengthened~~ strengthen a cyclonic circulation (Fig. 3). ~~A remarkable observation~~ Remarkable is the extremely fast movement of drifter #8 in reaction to this forcing (~~Fig~~Figs. 4(e) ~~). One side effect of this special behaviour is the rapid reduction of the distance to drifter #6 during day 39 (Fig. 5). While simulations~~ and 6(c)). Simulations for drifters #5 and #6 perform well, while the behaviour of drifter #8 cannot be reproduced.

Days 42-43 (8-9 July): The wind ~~veering~~ turning from southwest to northwest implies a fast transition from a cyclonic to an anticyclonic residual current regime (Fig. 3). Models perform well for ~~drifters~~ drifter #6~~and also #5, but again~~ , while simulations for drifter #8 are ~~very poor on day 42~~ again very poor (Figs. ~~8(d) and 8(h)), the last day on which drifter #8 data are available. On day 43 the fast southward movements of drifters #5and #6are reasonably well represented in both models (SM3).~~ 9(d,h) and Fig. 6(c)).

Days 44-53 (10-19 July): ~~In this final period only~~ Only drifters #5 and #6 are left, both of them already located in coastal waters. ~~Wind speeds are mostly low. Directional drift errors tend to be large and in particular at the end of the period speeds of drifter #6 are in most cases underestimated by model simulations (Fig. 10(a)). Between about day 45 and day 48 extra large differences between averages of~~ Extra large differences between wind velocities used in BSHcmod and TRIM ~~can be discerned in~~ occur (Fig. 10(b)~~. Consequences~~). Effects of a sudden reversal of the mean wind direction between ~~day~~days 50 and~~day~~ 51 ~~can reasonably be represented~~ are reasonably reflected in both models.

4 Discussion

~~Incorporating either direct~~ The model validation study suggests the assumption that inclusion of either wind drag or Stokes drift ~~proved indispensable for successful surface drifter simulations based on BSHcmod currents. The currents representative for a~~ compensates insufficient vertical resolution (5 m~~depth surface layer, integrated and archived from original BSHcmod output, could not properly represent a direct influence of winds, possibly mediated via waves. Based on TRIM currents representative for a surface layer of only~~) of surface currents in archived BSHcmod output. Magnitudes of TRIM surface currents, representative of a layer of 1 m depth, ~~drift velocities were generally larger and similar in size~~ were generally similar to those observed (Fig. 10(a)). In many cases, however, 25 h simulations based on BSHcmod+W outperformed those based on TRIM, ~~while~~ in other cases (e.g. days 13-16) TRIM simulations were ~~still~~ in better agreement with observations (Figs. 8(c,g) or Fig. 10).

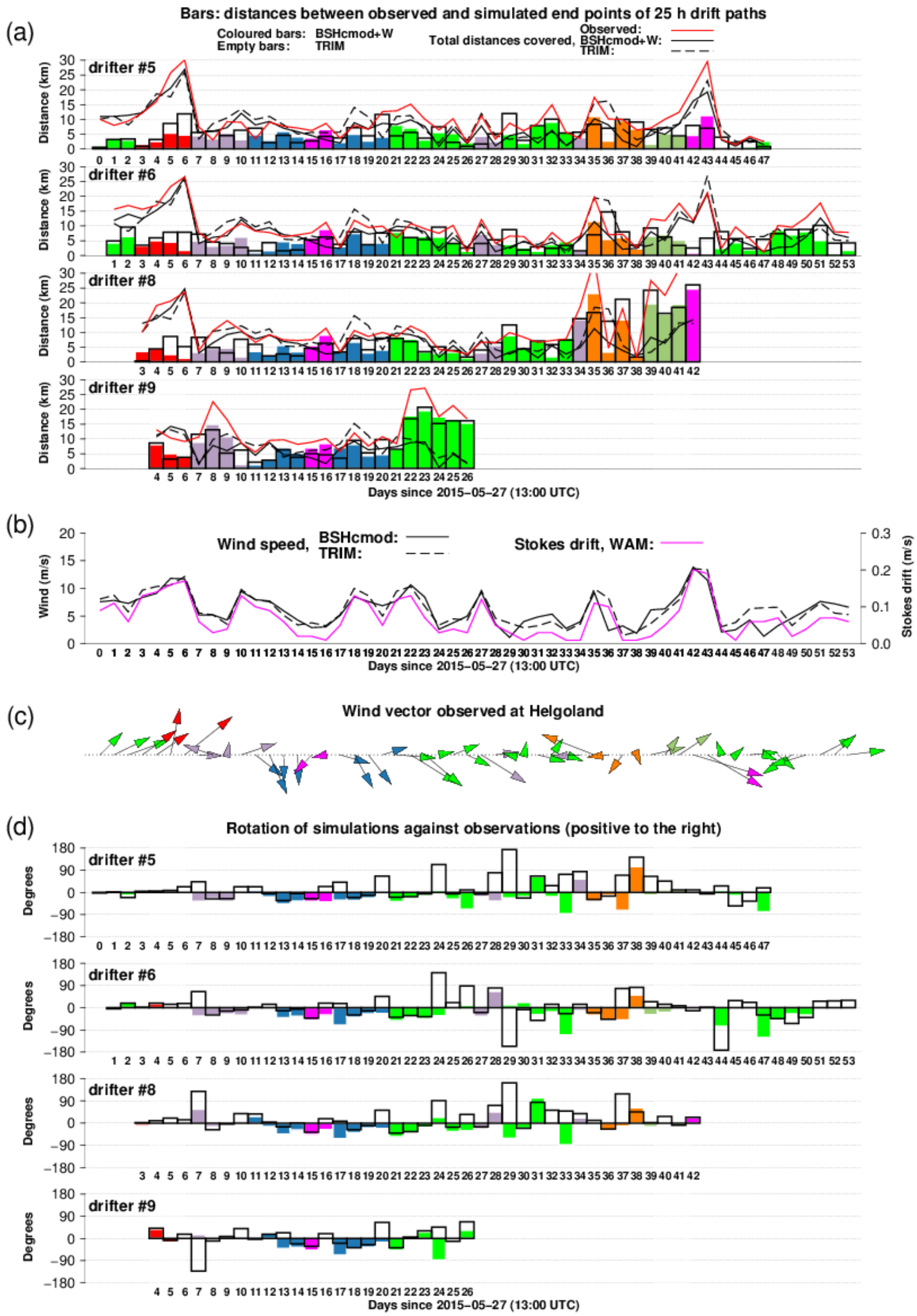

Figure 10. (a) Bars: Distances between observed end points of 25 h drift paths and corresponding simulations based on either BSHcmod+W or TRIM. All drift errors, coloured and labelled in terms of days since May 27 (13:00 UTC), are assigned to the center of the respective 25 h period. In addition, ~~the panel shows~~ lines show total distances travelled. (b) Wind speeds used in the two models and surface Stokes drifts obtained from wave model WAM. ~~All these data~~ Data were extracted for the central example location 55° N and 7° E. (c) Helgoland winds, copied form Fig. 3. (d) Angles between observed and simulated tracer displacements. Throughout the figure, all values represent 25 h averages.

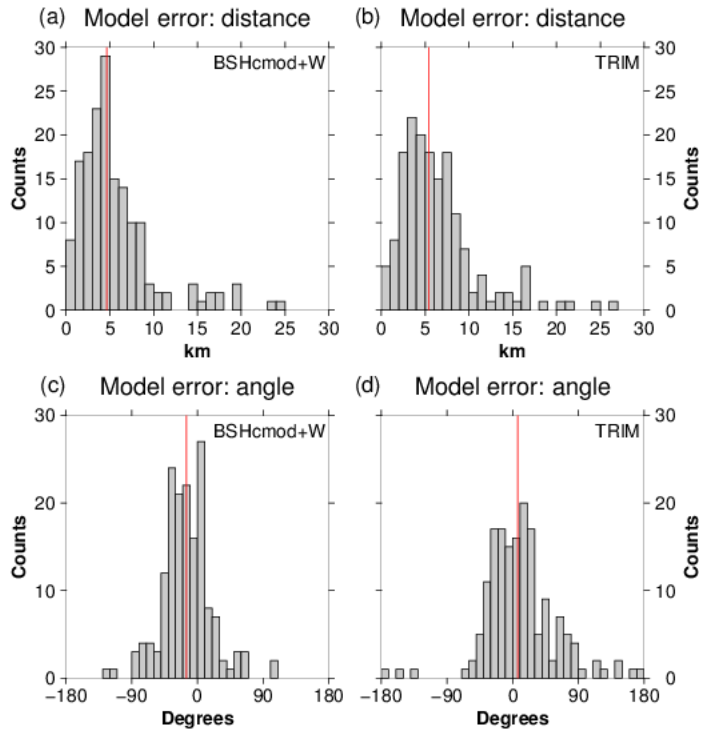

Figure 11. Distribution of model errors in 25 h drifter simulations. Histograms are based on 164 simulations in total for drifters #5, #6, #8 and #9. Referring to drift simulations based on BSHcmod+W and TRIM, respectively, panels (a) and (b) evaluate spatial separations shown in Fig. 10(a). For the same set of 164 simulations, panels (c) and (d) evaluate directional errors from Fig. 10(d). Red lines indicate median values (4.6 km and 5.4 km in (a) and (b); -15 degrees and 7 degrees in (c) and (d)).

In several other studies (e.g. Gästgifvars et al., 2006; Kjellsson and Döös, 2012; De Dominicis et al., 2012) simulated marine surface currents were found being too small, possibly also due to insufficient resolution of the marine surface layer. As a side effect, predictions may be particularly good when marine currents and winds are nearly parallel (Gästgifvars et al., 2006). The drift component most underestimated based on just BSHcmod Eulerian currents was a displacement towards the ~~northeast~~east, along the most frequent wind directions (compare Figs. 4 ~~(b) and ??(a))~~and A1). This deficiency could very effectively be remedied by adding direct effects of winds or waves. However, during periods when anticyclonic residual currents prevail (along with winds from the north-west, for instance), currents will generally not ~~parallel~~ be in the direction of winds (e.g. day 18, Fig. 8(~~a~~d,h)), unlike the situation with south-westerly winds driving a cyclonic circulation (e.g. day 3, Fig. 7(a,e)). Erroneous residual surface currents in the inner German Bight can therefore not always be fixed by simply adding windage or Stokes drift.

In both BSHcmod+W and TRIM simulations, drifter displacements were often rotated to the left of their observed counterparts, e.g. during days 13-23 (cf. Fig. 10(d) or Figs. 8(d,h)). A parametrization of wind induced Ekman drift (Röhrs and Christensen, 2015) might be explored as a means to remedy such model deficiencies including lacking representation of the Coriolis-Stokes drift (Hasselmann, 1970; Polton et al., 2005) driven by ocean surface waves. Fig. 11 shows error distributions that combine all data from Figs. 10(a) and 10(d), respectively. Median errors of drifter displacements are of the order of 5 km for both BSHcmod (4.6 km) and TRIM (5.4 km). BSHcmod+W tends to have negative directional errors (median value of about 15 degrees to the left of observations), while the median directional error for TRIM is about 7 degrees to the right. Negative deflections of BSHcmod+W simulations happen to coincide with what one would expect from a simple parametrization of windage (or Stokes drift) that neglects effects of Coriolis force. However, distributions in Fig. 11 combine simulations under very different wind conditions and directional biases are not permanent. In many cases (cf. day 18 in Figs. 8(d,h)) directional errors of the two simulations resemble each other. One must therefore be very careful to interpret shifted median values in terms of specific model deficiencies. Differences between Fig. 11(c) and 11(d) are probably not statistically significant so that we refrained from trying to incorporate and tune additional effects of Coriolis force.

Drifters #5, #6 and #8 played a central role in this study because their trajectories overlapped for 40 days, enabling tentative conclusions regarding spatial scales that affected long- and short-term drifter displacements. Wind fields resolved in numerical models (and also corresponding fields of Stokes drift) tend to vary smoothly on a regional scale. A substantial impact of winds on surface currents may be one ~~aspect contributing to the fact that~~ of the reasons why simulated trajectories resemble each other more than corresponding observations. But also ~~the~~ observed drifter paths show similarities that point to the impact of large scale forcing.

Due to bathymetric constraints and different scales of relevant processes, spatial variability of marine currents tends to be higher than that of wind fields (Röhrs et al., 2012). However, our study did not show clear effects of the higher resolution in BSHcmod regarding either space (900 m compared to 1.6 km in TRIM) or time (15 min compared to 1 h in TRIM). ~~Like TRIM , also BSHcmod proves itself~~ Both TRIM and BSHcmod are unable to reproduce the specific behaviour of drifter #7 during days 7-11, for instance (Fig. 4(d), Figs. 7 and 8). This could suggest that some relevant aspects of nearshore transports are not properly represented in both models. Surprisingly small effects of resolutions in both space and time on the metrics for Lagrangian predictability were also reported by Huntley et al. (2011).

Drifters will separate even if they ~~start together~~ are released from about the same location. Ohlmann et al. (2012) ~~performed an experiment with initial distances of~~ start with $\mathcal{O}$(5-10 m~~between drifters so as to possibly better resolve an initial phase of so-called~~) initial separations to resolve initial *non-local* dispersion ~~characterized by~~ with exponential growth of the mean square pair separation, driven by eddies larger than the distance between the two drifters. In the present field experiment, simultaneous deployments of drifters #2 and #3 were originally intended to study an example of drifter dispersion. The two drifters, both tracked over 3.7 days, stayed very close together for some time until they abruptly started to separate. ~~There were doubts, however, that~~ However, this separation might have been triggered by an unobserved interaction with the research vessel. ~~As the drifters crossed wind parks, it could also be that they had interfered with a turbulent wake related to the pile of an engine.~~ Due to such concerns, drifters #2 and #3 were excluded from the present analysis.

Fortunately, drifters #6 and #8 offered another opportunity to estimate predictability of drift trajectories. The minimum distance of only 800 m qualified the two drifters as a 'chance pair' ~~(e. g. (Döös et al., 2011)). Note~~(e.g. Döös et al., 2011). Note, however, that drifters #6 and #8 were of different types (cf. Tab. 1) ~~, which could imply accelerated spatial separation~~so that relative dispersion measured may not necessarily reflect diffusivity of the flow. On the other hand, the two drifters travelling jointly for about 10 days in a sense justifies the assumption that consequences of different designs were not essential. Also ~~Fig. 10(a) provides~~ Figs. 6(b,c) provide no evidence for ~~major differences in the overall behaviours of drifters #6 and #8~~ systematic differences in observed drift speeds during the period of interest.

From the perspective of a model with either 900 m (BSHcmod) or 1.6 km (TRIM) grid resolution, the locations of drifters #6 and #8 almost coincided for about 10 days~~(cf. Fig. 5). Thereafter the two drifters' separation increasing by a~~. The subsequent separation rate of about 3 km per day (according to visual inspection of Fig. 5) indicates a lower bound of prediction uncertainty under these specific conditions. An independent second estimate can be obtained considering the period when the two drifters converged (days 8-11). Assume that modelling ~~were~~ was undertaken to determine where an item collected on day 11 came from. Looking 4 days back in time, the two drifters #6 and #8 have separated by about 20 km, so that the uncertainty estimate (about 5 km per day) even exceeds the above value. However, the separation rate is still much lower than that reported by Huntley et al. (2011, their Fig. 3) under open ocean conditions near the Kuroshio current, considering a similar constellation with two drifters that separate after staying close for a couple of days. A wide spectrum of typical separation rates in different regions worldwide provided by Barron et al. (2007) also shows systematically larger values.

Error bounds estimated from drifter convergence/divergence will combine with model deficiencies that at least theoretically could be eliminated by model improvement or calibration. However, the above error estimates roughly fit into the general range of simulation errors found in this study (~~Fig. 10(a~~Figs. 11(a,b)). Ohlmann et al. (2012) tried to reproduce observed drifter trajectories with a Lagrangian stochastic model based on Eulerian background velocities derived from HF-radar observations interpolated to a regular $2 \times 2\ \mathrm{km}^2$ grid. Substantial discrepancies exceeding the expected level of HF radar measurement errors were found in occasional periods. On average, the separation between corresponding centres of gravity was found to be about 5 km after 24 h, a value that compares well with ~~uncertainties estimated~~ estimations from the present experiment. It remains as an open question whether the quality of predictions would be better with HF-radar observations replacing output from numerical models. Ullman et al. (2006) found skills in predictions based on currents from either a circulation model or HF radar comparable. Both Ullman et al. (2006) and Ohlmann et al. (2012) used hourly average velocities from HF radar observations, i.e. the same temporal resolution as in the present study. Higher resolution (e.g. 20 min; Horstmann et al., 2017) measurements of currents could possibly better capture short term fluctuations and enhance variability in drift simulations.

According to Koszalka et al. (2009) and Döös et al. (2011), 'chance pairs' should possibly be distinguished from pairs of drifters intentionally launched together, because their behaviour may depend on specific hydrodynamic conditions. An interesting question is what characterizes the 10 day period when drifters #6 and #8 stayed close together. The drifter convergence (days 7-10) coincided with the transition from a cyclonic to an anticyclonic residual current circulation (Fig. 3). The anticyclonic regime forced by winds from mainly the northwest dominated days 11-20, except for a short episode (days 14-16) with very low winds and a circulation returning to the cyclonic orientation for about one day. Drifters #6 and #8 started separating again when residual currents gradually returned to an either indifferent or cyclonic circulation, a process probably best represented in the time series of PC_1 in Fig. 3. So it seems that both convergence and divergence of the two drifters ~~coincide~~ coincided with reorientations of the hydrodynamic regime.

The present data are insufficient for a discussion of to which extent the drifters' observed responses to changing winds and residual currents depend on drifter location. ~~The small number of drifters can obviously not represent the spatial structure of transports.~~ Based on model simulations, however, there are promising techniques to better describe regions within which separation for drifters can be expected. Identification of Lagrangian coherent structures (LCS) is a field that developed recently (e.g. Shadden et al., 2009). Huhn et al. (2012) applied LCS to identify transport barriers for drifters in an estuary, Peacock and Haller (2013) discuss how such techniques could be used for optimizing drifter deployment in the sense of maximizing their dispersion. Olascoaga et al. (2013) used LCS to illustrate how mesoscale circulation shapes near surface transports in the Gulf of Mexico.

~~In both BSHcmod+W and TRIM simulations, drifter displacements were often rotated to the left of their observed counterparts, e.g. during days 13-23 (cf. Fig. 10(d)). A parametrization of wind induced Ekman drift (Röhrs and Christensen, 2015) might be explored as a means to remedy such model deficiencies including lacking representation of the Coriolis-Stokes drift (Hasselmann, 1970; Polton et al., 2005) driven by ocean surface waves. However, the directional bias is not permanent and it seems difficult to justify and calibrate a corresponding parametrization based on the limited amount of data from the present field study.~~

A couple of different processes can be relevant for an exchange of energy and momentum between surface waves and underlying mean currents (cf. Smith, 2006). Under open sea conditions, the probably most important process affecting near-surface drifters is the Stokes drift which arises when backward motions beneath the troughs of surface gravity waves do not fully compensate forward motions beneath the crests. However, a key observation from our simulation experiments is that for surface drifters the inclusion of an explicitly simulated Stokes drift did not produce an added value ~~compared to~~ beyond a simple parametrization of wind drag in terms of 10 m winds. According to Fig. 10(b), wind speeds used as forcing for either TRIM or BSHcmod are both highly correlated with Stokes drifts calculated with wave model WAM (based on ~~exactly~~ the same wind hindcast also used as forcing for TRIM). This similarity agrees with results reported by Drivdal et al. (2014, their Fig. 7), for instance.

From experimental data, Röhrs et al. (2012) estimated Stokes drift to be about twice as large as effects of direct wind drag. However, as the roles of direct wind drag and Stokes drift are difficult to disentangle, we did not conduct experiments with mixtures of the two processes. For the factors α or β we chose in Eq. (1), drift components from either windage or Stokes drift were similar most of the time (Fig. 6). Validating modelled wave effects based on four surface drifters deployed near the Grand Banks (Newfoundland), Tang et al. (2007) considered both processes in combination. They also found simulated Stokes drift to be linearly related to wind velocities, so that it seems ~~hardly possible~~ difficult to decide whether the about 21 % decrease of separation between modelled and observed trajectories after one day are really attributable to Stokes drift effects. According to Breivik and Allen (2008), the ~~difficulty~~ impracticality to separate Stokes drift effects from an empirically parametrized direct wind drag is a major reason why Stokes drift is neglected even in most operational search and rescue ~~(SAR)~~ modelling systems, where a realistic assessment of existing uncertainties and their origin is of utmost importance.

Tang et al. (2007) found Stokes drift being about 1.5 % of wind speed~~. This value agrees~~ , Li et al. (2017) report a value of 1.6 %. These values agree with the ratio (0.3/20) of the scales annotated on the two y-coordinates in Fig. 10(b). For low wind conditions the relative importance of Stokes drift ~~decreases~~ decreased (again in agreement with the results of Tang et al. (2007)), but in these cases the overall contributions from winds and waves are small anyway.

In particular growing young wind seas forced by local winds typically produce strong surface Stokes drifts that decline fast with depth (e.g. Röhrs et al., 2012). Breivik et al. (2016) developed an approximate method to efficiently calculate this near-surface shear, underestimated by the common assumption of a monochromatic profile. Based on these formulas, Röhrs and Christensen (2015) calculated in the context of a drifter experiment in the Barents and Norwegian Sea that an average Stokes drift of 8.9 cm/s at the surface contrasted with an average of 3.7 cm/s at 1 m depth. For the present study we ~~did not apply any theoretical profiles but just tuned a constant factor that reduces surface Stokes drift to a value suitable for the drifters deployed. The~~ neither applied theoretical profiles nor conducted an in depth model calibration. However, in the light of the above numbers, the 50~~% factor used in~~ % factor α in Eq. (1) we chose for BSHcmod+S ~~simulations did not result from an in depthmodel calibration. Its vagueness~~ seems a reasonable value for drifters representing a surface layer of about 1 m depth. Vagueness of the factor corresponds with that of the ~~windage factor~~ 0.6 % windage factor β used in BSHcmod+W. ~~In~~ Given the limited data, in both cases even most careful calibration would not lead to robust estimates~~given the limited data available.~~

~~Magnitudes of drift velocities on a hourly basis, considering drifters #5 and #6. Magnitudes of observed velocity vectors (coloured) are compared with simulations based on BSHcmod+W. In addition, magnitudes of windage (in BSHcmod+W) and Stokes drift (in BSHcmod+S) are shown. All model values are specified from either atmospheric or marine fields interpolated to observed (not simulated!) drifter locations. See supplementary material (SM5) for full times series for both drifters.~~

~~A more general question is which relative contributions of extra wind~~ . The criterion we applied for selecting α or ~~wave effects must be expected. Based on data from an experiment in northern Norway, Röhrs et al. (2012) found Stokes drift to be about 20 % of the mean Eulerian currents. For~~ β is that the overall eastward displacement of a drifter's location should roughly agree with that observed. A convincing confirmation of our selection was that the strength factors we chose worked consistently well for all drifters.

Similarity between simulations with either wind drag or Stokes drift (cf. SM4) is an implicit consequence of how parameters were chosen. According to Fig. 6, a period with major differences between contributions from either windage or Stokes drift occurs during days 30-34, when indeed simulations based on BSHcmod+W and BSHcmod+S, respectively, diverge (cf. Figs. A2 and A3). According to Fig. 4(b), however, results from model version BSHcmod+W ~~simulations of~~ seem to be more realistic. It is interesting to see that also TRIM simulations are particularly wrong in this period, producing e.g. for drifter #5 ~~we found average magnitudes of hourly Eulerian currents to be about 0.27 m/s and corresponding values for parametrized windage (last term in Eq. (1))about 0.043 m/s. The resulting relative magnitude of 16 % roughly agrees with the ratio which Röhrs et al. (2012) found for Stokes drift.~~ transports to the south-east (Fig. A4(b)) when in reality the drifter moved in a north-east direction (Fig. 4(b)).

Figure 12 compares ~~the~~ magnitudes of observed and simulated drift speeds on an hourly basis, referring to trajectories of drifters #5 and #6 during days 0-17 (see supplementary material SM5 for corresponding full time series). ~~All~~ As in Fig. 6,

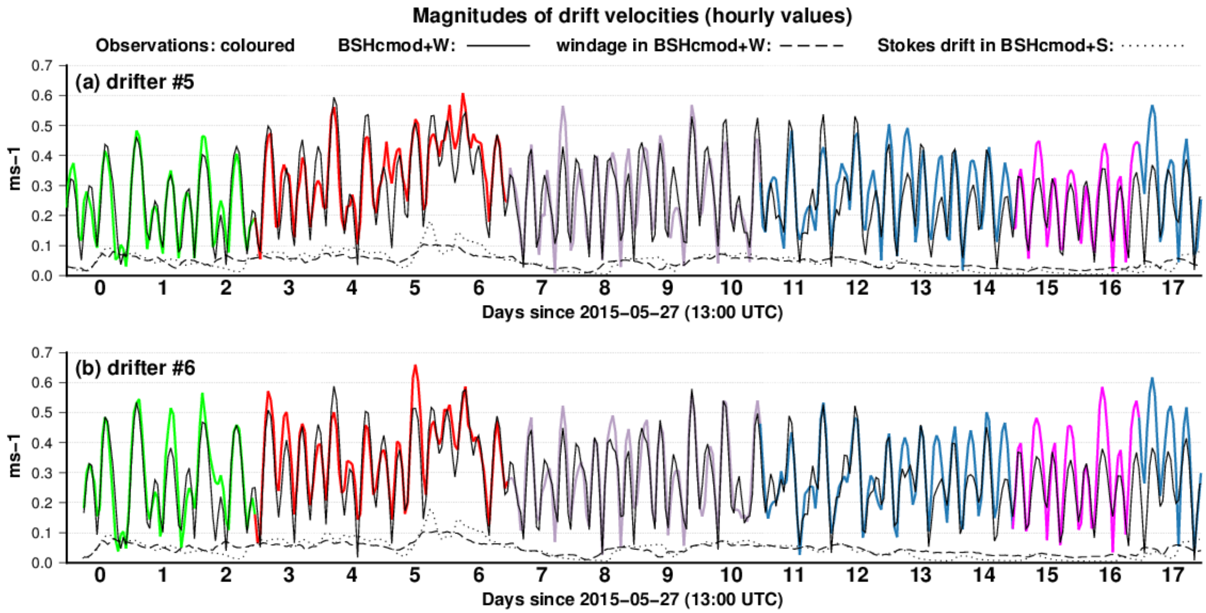

Figure 12. Magnitudes of drift velocities on a hourly basis, considering drifters #5 and #6. As in Fig. 6, magnitudes of observed velocity vectors (coloured) are compared with simulations based on BSHcmod+W. In addition, magnitudes of windage (in BSHcmod+W) and Stokes drift (in BSHcmod+S) are shown. All model values are specified from either atmospheric or marine fields interpolated to observed (not simulated!) drifter locations. See supplementary material (SM5) for full times series for both drifters.

all simulated velocity components were specified at observed rather than simulated drifter locations (i.e. no drift simulation was performed), so as to avoid the problem of spatial separation between simulations and observed counterparts. Observed and simulated drift speeds agree surprisingly well at least during about days 0-12. Nearly perfect agreement for one drifter sometimes coincides with discrepancies for the other, a possible manifestation of sub-grid scale processes (see observations at the beginning of day 5, for instance).

Together with total drift speeds, Fig. 12 ~~shows also~~ also shows magnitudes of simulated windage and Stokes drift. During most of the time, these two drift components are of similar size. More short-term pulses of Stokes drift can be discerned at days 5-6. Generally, however, contributions from both wind and waves are smooth. A removal of compensating tidal effects by averaging enhances visibility of the contributions of winds or waves (cf. Fig. 6). Note that, due to vectors having different directions, differences between total drift speeds and contributions of windage do not directly translate into magnitudes of mean Eulerian currents. For instance, a non-zero windage effect may be offset by an opposed Eulerian current. For BSHcmod+W simulations of drifter #5 we found average magnitudes of hourly Eulerian currents to be about 0.27 m/s and corresponding values for windage about 0.043 m/s. The resulting relative magnitude of 16 % roughly agrees with what Röhrs et al. (2012) found for Stokes drift. According to data from an experiment in northern Norway, Stokes drift amounted to about 20 % of the mean Eulerian currents.

In Fig. 12, both observations and simulations show regular intermittent patterns in connection with tidal cycles. ~~Alternating heights of maximum total~~ Variations of maximum drift speeds indicate that movements along different branches of tidal ellipses have components that are alternately oriented in the same or opposite direction of a superimposed non-tidal drift component. This non-tidal drift is possibly but not necessarily related to wind effects. On days 13 and 14, such non-tidal drift manifests itself more in simulations than in observations, while during days 15 and 16 alternating drift speed maxima are more pronounced in observations (in particular for drifter #6). ~~From~~ According to Fig. ~~4(c) an observed fast drifter displacement~~ 6, BSHcmod+W underestimates residual drift speeds for all four drifters tracked at that time. A fast displacement of drifter #6 to the northwest can be discerned ~~during days 15 and 16. All models failed~~ from Fig. 4(c). All models fail to reproduce this movement (~~compare~~ see Fig. ~~4(c) and Fig.~~ A2(c), for instance). Considering the small values of windage and the even smaller of Stokes drift (wind directions allow for only small fetches over the open sea), tuning these effects cannot substantially improve simulations.

~~Figure 6 provides magnitudes of velocities of drifter #5 for the full period the drifter was tracked. However, unlike in Fig. 12(a) now magnitudes of drift velocities were calculated from moving 25 h averages of hourly vectors. Removal of compensating tidal effects enhances visibility of the contributions of wind or waves. A clear correspondence between minimum drift speeds in observations and simulations can be discerned. Note that in Fig. 6, due to vectors having different directions, separations between simulated total drift speeds and contributions of windage do not directly translate into magnitudes of mean Eulerian currents. For instance, the simulated mean speed of drifter #5 nearly vanishes on day 24 (see also SM3) as non-zero windage effects are offset by opposed Eulerian currents~~ Remember that Stokes drift and windage were calculated offline and added to the Eulerian currents after the model had been integrated and the fields stored.

~~In agreement with moderating wind (Fig. 3), the overall strength of simulated windage decreases during days 11-16. The poor agreement between simulations and observations in Fig. 6 on day 11 seems surprising in the light of the good agreement in Fig. 12(a) on that day. However, the differences in Fig. 6 arise from averaging under conditions when winds veer from south-west to north-west and the hydrodynamic regime switches from a cyclonic to an anticyclonic orientation (cf. Fig. 3). Information on wind directions is not contained in Fig. 12(a). The large discrepancy between observations and simulations on days 15-16 was already addressed in the context of Fig. 12.~~

~~The period with largest differences between contributions from either windage or Stokes drift occurs during days 30-34, when indeed simulations based on BSHcmod+W and BSHcmod+S, respectively, diverge most (cf. Figs. **??**(c) and **??**(d)). According to Fig. 4(b) results from model version BSHcmod+W seem to be more realistic. It is interesting to see that also TRIM simulations are particularly wrong in this period, producing transports to the south-east (Fig. **??**(b)) when in reality drifter #5 moved in a north-east direction (Fig. 4(b)).~~

~~Note that this study and the above discussion refer to a posterior amendment of existing simulations rather than their recalculation including all wave effects.~~ Lacking success of this approach is not to say that deficiencies of drifter simulations are not related to wind conditions. The problem around days 15-16, for instance, occurs under non-stationary wind directions that affect also the orientation of the residual current regime (Fig. 3). Changes of wave induced forcing of the ocean, including sea-state-dependent momentum flux and Stokes drift (Staneva et al., 2016) affect water level, high and low water times and therefore also ocean currents.

~~Magnitudes of 25-h moving averages of drift velocity vectors, considering drifter #5. As in Fig. 12(a), magnitudes of observed velocity vectors (coloured) are compared with simulations based on BSHcmod+W. In addition, magnitudes of windage (in BSHcmod+W) and Stokes drift (in BSHcmod+S) are shown. All model values are specified from either atmospheric or marine fields interpolated to observed (not simulated!) drifter locations.~~

Röhrs et al. (2012) warn that implementing ~~the~~ Stokes drift as a simple additive component of drift velocity, parameterized in terms of wind forcing, can be inconsistent (i.e. ~~violates~~ violate conservation of both momentum and energy) if Eulerian currents were simulated without taking into account the reservoir of wave momentum and energy. ~~Although this is the case for simulations in the~~ In the present study, the exchangeability of Stokes drift and ~~a parametrized~~ wind drag indicates that the role of waves as a reservoir of momentum wasn't relevant at least during the period considered. One reason for this could be that due to limited fetches the North-Sea is less swell-dominated than other Nordic Seas (Semedo et al., 2015).

Two crucial ~~questions difficult to answer are the following:~~ and outstanding questions are a) are the drifters' behaviours ~~really representative for~~ representative of surface currents and b) can it justifiably be assumed that all drifters maintained their ideal drift properties over the whole period they were tracked. Drifter trajectories may reflect a specific exposure to winds and waves, well illustrated by the experiment reported by Röhrs et al. (2012). Edwards et al. (2006) suggested corrections to improve trajectory simulations when wind errors and characteristics of the specific drifters deployed are known. However, for the present study a tentative positive answer to the first question could be given based on the reasonable correspondence between the magnitudes of observed tracer displacements and their counterparts simulated based on just TRIM Eulerian surface currents (cf. Fig. 10(a)). On the other hand, Poulain et al. (2009) estimated a higher downwind slippage of about 1 % of the wind speed for undrogued SVP (Surface Velocity Program) drifters. In the context of an oil-drift study, Price et al. (2006) deployed CODE (Coastal Ocean Dynamics Experiment) type drifters drogued in such a way that they were supposed to capture the upper 1 m layer velocities. Referring to a report by Niiler et al. (1997), Price et al. (2006) estimated for these drifters slip velocities of the order of 0.03 m/s. In BSHcmod+W such velocity would match the parametrized wind drag at a wind speed of 5 m/s. Like contributions from wind drag, the estimated downwind slippage of drifters is supposedly much smaller than short term drift velocities in a tidally dominated regime but may nevertheless have considerable impacts on drifter displacements in the long run. To ~~strictly~~ fully disentangle effects of wind drag on water masses and drifters, respectively, ~~will hardly be~~ seems hardly possible.

Answering the second question ~~seems~~ is again difficult. The joint analysis of drifter positions and displacements in this study gave at least some indications for possible non-ideal drifter behaviour. A period of extreme velocities far beyond what models predict occurs for drifter #9 at the end of its journey (days 22-26~~).~~, cf. Fig. 6(d) and Figs. 9(a,e)). These high velocities result in a clear separation of drifter #9 from the formerly concentrated group of drifters. Probably more central for the present study is the behaviour of drifter #8. ~~Browsing the full set of daily 25 h displacements (see SM1) suggests that there might be some problems with this drifter towards the end of its journey.~~ From day 34 onward, drifter #8 showed a tendency to move faster than the neighbouring drifters #5 and #6 (e.g. days 34-35, day 37 or days 39-42, cf. Fig. 6). Strikingly, in these cases drifter #8 tended to move into directions that are more parallel to prevailing winds (see SM1). This latter observation also applies to the aforementioned behaviour of drifter #9.

~~About possible~~ Possible reasons for the deviant behaviours of drifters #8 and #9 can ~~just~~ only be speculated. The simplest explanation would be that the different type of the two drifters (and of drifter #7, which also showed a very fast movement at the end of the time period it was tracked) distinguishes them from other drifters deployed (cf. Table 1). However, this explanation is not in accord with the fact that problems did not persist throughout the whole observational period. The ~~fact that drifter #8 moved jointly with drifter #6 for ten days (Fig. 5) provides strong evidence against generally different behaviours of the two drifter types.~~

~~A~~ special behaviour of drifter #9 after about day 22 coincided with its entering a more southern region of the German Bight ~~.~~ (Figs. 9(a,e)). For this regions Port et al. (2011) identified a higher variability of surface currents, less correlated with wind conditions, which would imply that introducing either Stokes drift or an additional wind drag could probably be a less promising approach for model improvement. However, still the most probable explanation for the mismatch of observations and corresponding simulations is that the drifter experienced problems with its drogue. Unfortunately, drifters ~~could~~ had no drogue presence sensor and could also not be collected at the end of their journey to check the conditions of the devices.

5 Conclusions

Trajectories of six surface drifters deployed in the German Bight were compared with corresponding offline simulations based on hydrodynamic data from two independent models. ~~While successful~~ Successful simulations based on ~~archived BSHcmod currents representing~~ BSHcmod currents archived for a 5 m depth surface layer needed inclusion of extra wind (or wave) effects, ~~this~~ which was not the case for simulations based on TRIM currents ~~representing~~ for a 1 m depth surface layer. This suggests the assumption that the extensions in BSHcmod+W or BSHcmod+S ~~, respectively,~~ primarily acted to compensate insufficient vertical resolution in archived data. There was no convincing evidence that the drifters deployed experienced an appreciable direct wind drag. In a similar way, Ullman et al. (2006) attributed a bias of trajectories predicted based on HF radar currents not to a drifter leeway but rather to the fact that effective depth of HF radar measurements exceeded that of surface layer drifters.

On the other hand, it is striking that often errors in simulations based on TRIM and BSHcmod+W (or BSHcmod+S) closely resembled each other (e.g. day 8, see Figs. 7(~~c)and 7(g)~~d,h); or day 18, see Figs. 8(~~a)and 8(e)~~d,h)). This points to ~~general problems~~ problems shared by both models, explanation of which probably requires analyses ~~comprising~~ considering also other aspects of hydrodynamic model output.

The present study focussed on a synoptic assessment of (mainly four) drifter trajectories overlapping in time. Expectedly, differences between synchronous drift trajectories were much larger in observations than in simulations, due to unresolved sub-grid scale processes~~lacking in simulations. Characteristic spatial scales in the atmosphere and the marine system differ, so that simulated~~ . Simulated fields of wind (not including sub-grid scale weather phenomena and gustiness as important drivers for drifter dispersion) and Stokes drift are even more smooth than simulated current fields. Small-scale model data misfits can therefore obviously not be remedied employing windage or Stokes drift.

Although the small number of drifters does not enable an in depth analysis, it seems that major deficiencies of simulations often manifest themselves under low or moderate wind speeds. For instance, data from days 7-9 (cf. ~~Figs~~panels in Fig. 7~~(c) and 7(g) or SM3) suggest that at that time~~) suggest that simulations underestimate currents in coastal areas at that time. Insufficient resolution of intertidal areas could be one aspect contributing to this model deficiency. Also on days ~~24, 31 or 33 (cf. SM3),~~ 15 and 16, observed drifters moving much faster than simulated (Fig. 6) coincides with low wind conditions ~~. All these instances~~ (e.g. Figs. 8(c,g)). However, all instances also correspond with changes in wind conditions and ~~possibly also~~ transitions between different residual current regimes (~~cf.~~ Fig. 3).

On an hourly basis, contributions from windage in BSHcmod+W are often much smaller than discrepancies between simulated and observed drifter velocities (Fig. 12 or SM5), in particular under low wind conditions. When averaging over tidal cycles, relative contributions from wind forcing increase (Fig. 6). However, even small systematic errors in the simulation of oscillating tides might possibly give rise to ~~residual currents~~ erroneous residual current components similar in size to the contributions from windage. A finding that needs further analysis is whether nearshore residual currents underestimated in simulations indicate such inaccuracies in regions where tides increase with decreasing water depth.

~~Keeping in mind that we did not consider extreme events, this~~ This study did not substantiate benefits from including ~~results of (computationally demanding) offline simulations of Stokes drift . Most of the time, directions of~~ Stokes drift simulated offline. Directions of winds and waves coincided ~~and the strength~~ most of the time and effects of Stokes drift ~~was proportional to wind speed. Accordingly, Stokes drift~~ on surface currents could successfully be mimicked ~~by windage, in TRIM even reasonably represented as an implicit part of parametrized~~ in terms of additional windage. In TRIM, such effects seemed already sufficiently parametrized as part of momentum transfer from the atmosphere to marine currents. When winds quickly abate, increase or ~~veer~~turn, waves adjust with a time lag, needing a certain fetch to fully develop. Although in these cases the different roles of winds and waves could be more marked, in the present study errors in atmospheric or marine circulation modelling seemed predominant. Nevertheless, fully coupled modelling of currents and waves (Staneva et al., 2016) could probably improve simulated surface currents, given that the vertical resolution is fine enough. It must also be kept in mind, that the present study did not include any extreme events.

The incident of two drifters converging quickly and separating about ten days later provided evidence that at least in some situations an unavoidable increase in prediction uncertainty would be of the order of 3-5 km per day, regardless of however sophisticated a model used might be. Further studies would be needed to substantiate this finding in terms of its representativity and possible dependence on specific locations or atmospheric conditions. The observed separation rate happened to roughly agree with the average magnitude of simulation errors we identified~~also for model simulations~~. More experiments would help identify the way to go for further model improvements.

Data availability. The raw data of observed drifter locations are freely available from Carrasco and Horstmann (2017).

Author contributions. J. Horstmann collected the field data. S. Maßmann provided BSHcmod currents and her experience regarding performance of the operational model. H. Kapitza produced the TRIM simulations. F. Schwichtenberg pre-processed the raw drifter data for comparison with model data. H. Klein produced the residual current classification based on BSHcmod surface currents. N. Groll conducted the WAM simulations. U. Callies prepared the manuscript with contributions from all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This work was kindly supported through the Coastal Observing System for Northern and Arctic Seas (COSYNA). Wind observations at station Helgoland were provided by the Deutscher Wetterdienst (DWD). Graphs were produced using the Generic Mapping Tools software (GMT) available from www.soest.hawaii.edu/gmt/. We appreciate valuable comments by J. Kjellsson and two anonymous reviewers that helped improve the presentation of our results.

Appendix A: Full sets of BSHcmod and TRIM simulations

In this appendix we present simulated counterparts of all observed trajectories shown in Fig. 4. The four different model setups considered are simulations based on BSHcmod (Fig. A1), BSHcmod+W (Fig. A2), BSHcmod+S (Fig. A3) and TRIM (Fig. A4). For all figures the underlying data are provided as supplementary material.

~~This work was kindly supported through the Coastal Observing System for Northern and Arctic Seas (COSYNA). Wind observations at station Helgoland were provided by the Deutscher Wetterdienst (DWD). Graphs were produced using the Generic Mapping Tools software (GMT) available from www.soest.hawaii.edu/gmt/.~~

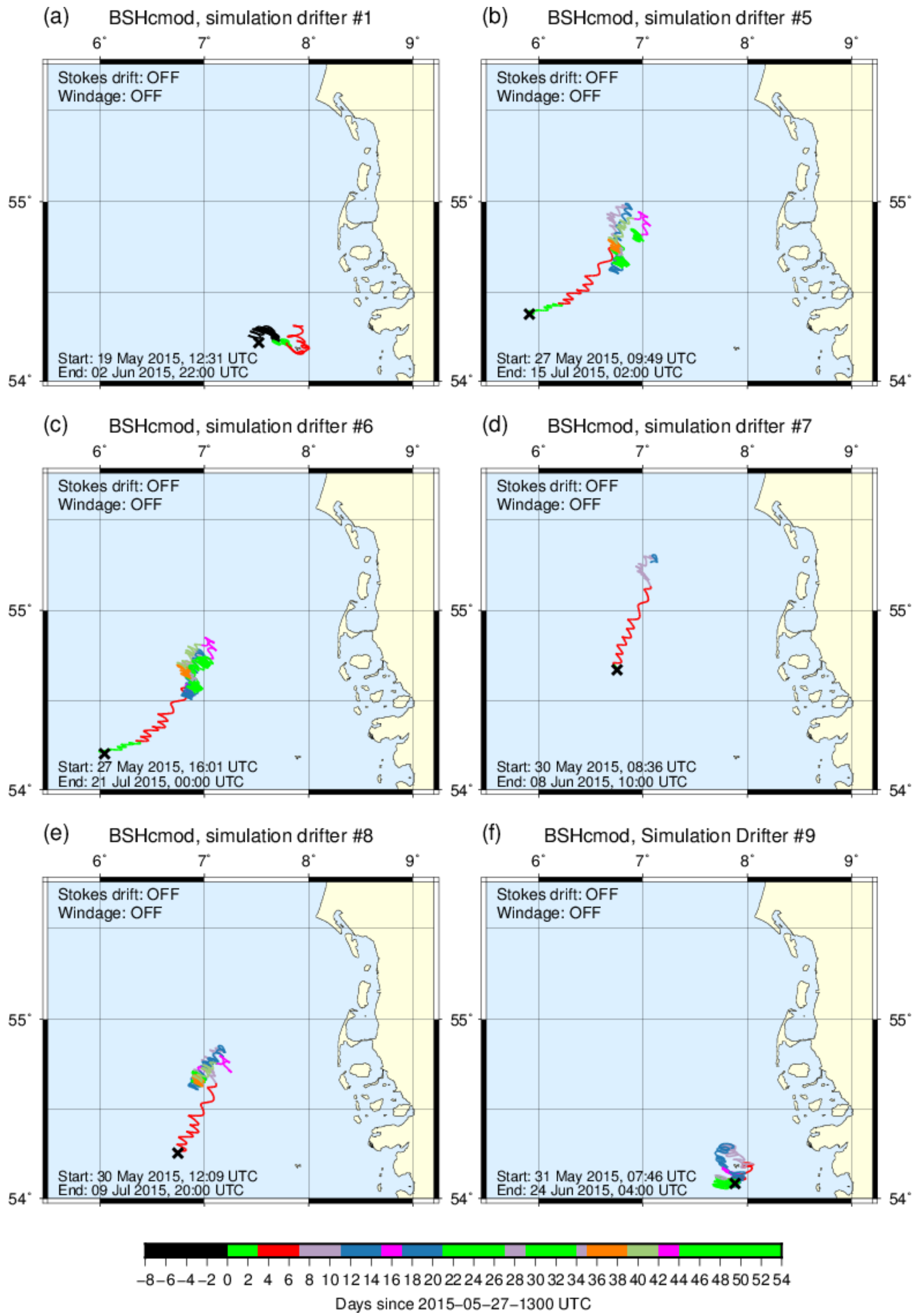

Figure A1. Simulations based on BSHcmod top layer currents, disregarding ~~all~~ extra effects of winds or waves. Black crosses indicate locations where simulations were started.

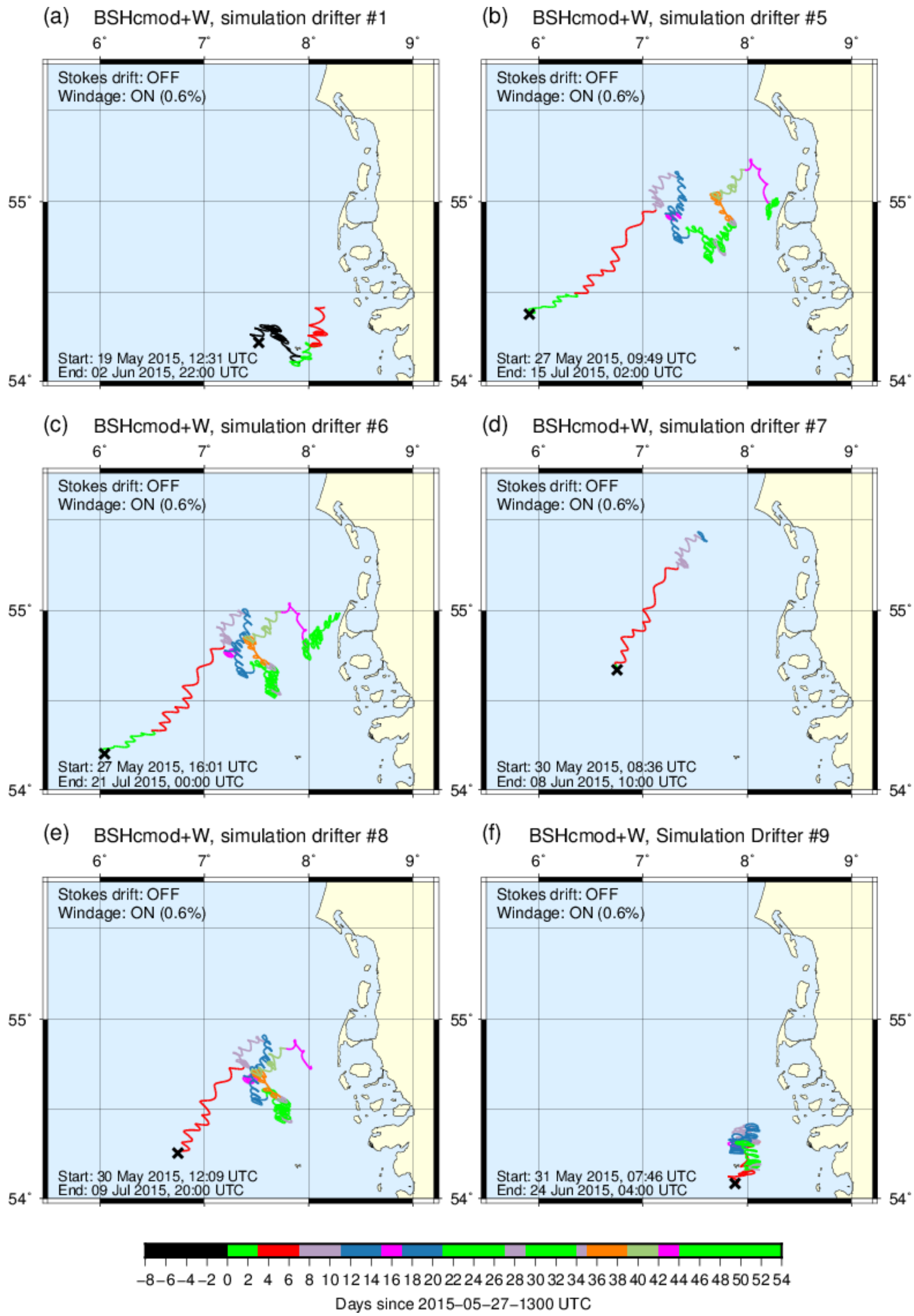

Figure A2. Simulations based on BSHcmod top layer currents plus 0.6 % of 10 m wind velocity (BSHcmod+W). Black crosses indicate locations where simulations were started.

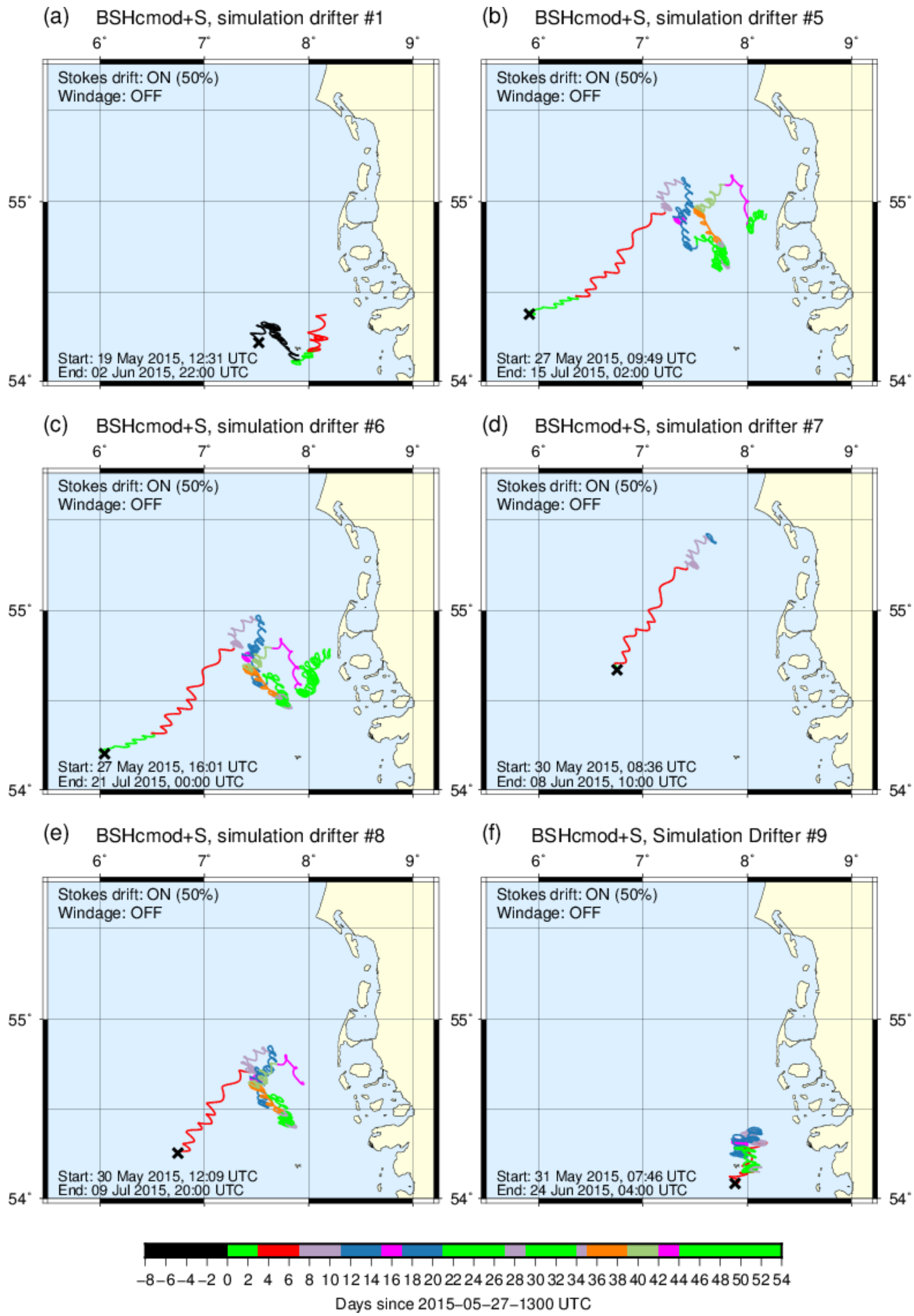

Figure A3. Simulations based on BSHcmod top layer currents plus 50 % of surface Stokes drift from WAM (BSHcmod+S). Black crosses indicate locations where simulations were started.

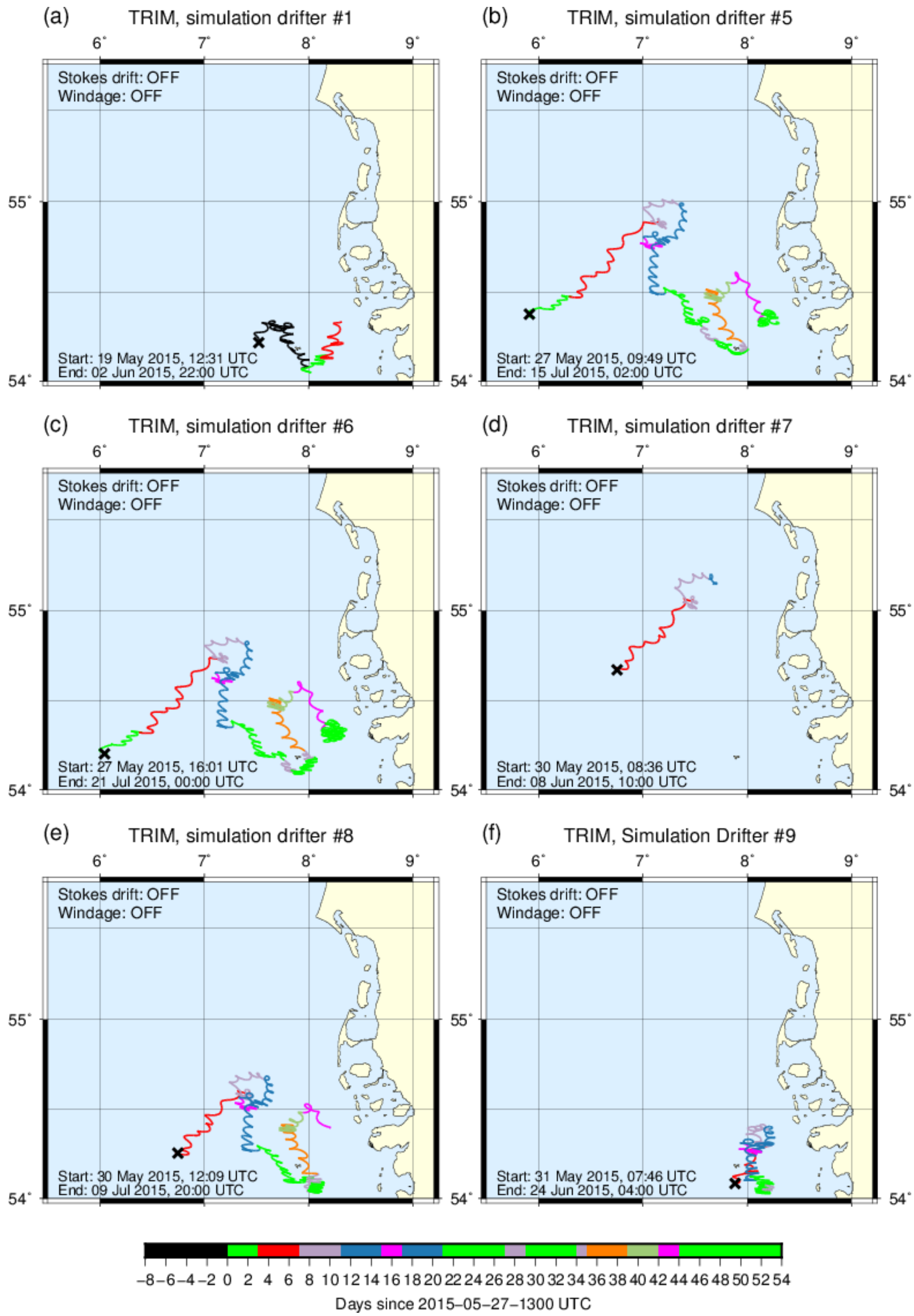

Figure A4. Simulations based on TRIM top layer currents, disregarding ~~all~~ extra effects of winds or waves. Black crosses indicate locations where simulations were started.

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Table 1. Drifters deployed in May 2015

#	Type	Start			End			Length	Dist	ΔT
		Time (UTC)	°E	°N	Time (UTC)	°E	°N	[km]	[km]	[days]
1	MD03i	May 19 (12:31)	7.5216	54.2160	Jun 02 (21:12)	8.8338	54.5180	1032.1	91.7	14.4
(2)	MD03i	May 21 (17:13)	7.1484	55.0752	May 25 (09:47)	7.3080	55.1360	87.4	12.2	3.7
(3)	MD03i	May 21 (17:13)	7.1480	55.0750	May 25 (09:59)	7.2526	55.1160	85.7	8.1	3.7
(4)	MD03i	May 21 (17:36)	7.1426	55.0786	May 24 (15:00)	7.2960	55.0626	66.6	10.0	2.9
5	MD03i	May 27 (09:49)	5.9126	54.3752	Jul 15 (01:28)	8.4680	55.1232	1264.0	184.4	48.7
6	MD03i	May 27 (16:01)	6.0446	54.2024	Jul 20 (23:15)	8.0944	55.1930	1467.7	172.1	54.3
7	ODi	May 30 (08:36)	6.7516	54.6712	Jun 08 (09:59)	8.2360	55.7702	273.2	154.6	9.1
8	ODi	May 30 (12:09)	6.7476	54.2554	Jul 09 (19:15)	8.5282	55.2812	1203.0	161.8	40.3
9	ODi	May 31 (07:46)	7.8816	54.0842	Jun 24 (03:28)	8.8360	54.1316	844.3	62.6	23.8

Type: Two drifter types used (cf. Fig. 1). Length: Sum of the lengths of linear segments connecting observed drifter locations. Dist: Linear distance between the first and the last drifter location observed. ΔT: Days between the first and the last observation. Drifters #2, #3 and #4 travelling for only few days were ignored for this study.