Final author response for the manuscript tc-2015-233 submitted on 20 Apr 2016 with the title:
"Arctic sea ice diffusion from observed and simulated Lagrangian trajectories"
by Pierre Rampal, Sylvain Bouillon, Jon Bergh, and Einar Ólason

Anonymous Referee #1

Dear referee,

First of all, we would like to thank you for your insightful comments and suggestions, which helped us improving our manuscript. Below, you will find your original **comments in bold**, our answers in red and the **added text** to our manuscript in **bold red**.
Please note that our new manuscript containing all the changes we made is attached as a supplementary material to the present document.

Review of revision of "Sea ice diffusion in the Arctic ice pack: a comparison between observed buoy trajectories and the neXtSIM and TOPAZ-CICE sea ice models" (now called "Arctic sea ice diffusion from observed and simulated Lagrangian trajectories") by Rampal et al.

This is an entirely different manuscript now with the main focus on the Lagrangian drifter analysis. It extends the analysis of Rampal et al. (2009) to longer time series (until 2011) and gives recommendations and examples for using the computed diffusivities, time scales and derived searching radii.

The authors replied to my comments and concerns adequately and changed the manuscript accordingly. The authors toned down the comparison between models, although a little bit of biased interpretation of the figures remains, see below for details and examples. In my opinion, the manuscript is now mostly well written (a few language comments are in the annotated pdf, these are mostly recommendations or suggestions), has a clear structure and reads well. I recommend a minor revision in which I would ask the authors to address the points below.

ll238: I see the nearly "ballistic" regime (although the slope is really below 2) and the transition to slope 1, but what happens above 10days, when the IABP curve levels off even more to below 1 (almost 0.5)? I think this should be discussed to guide the reader.
This remark is fully justified. The problem detected by the reviewer comes from the fact that the autocorrelation function (shown in Figure 3 of the manuscript) was constantly negative for Tau larger than 8 days, leading to a stronger than expected decrease of the slope of the fluctuating displacement variance, as properly reported by the reviewer. The origin of the problem originates from using an inappropriate (too small) averaging scales, and was not detected by the criterion on the variation of the integral time scale proposed in Rampal et al. (2009). We now propose a better criterion than the one used in Rampal et al. (2009) to define the appropriate

averaging scales. We choose the averaging scales that minimize the difference between the computed fluctuating variance and the one predicted by the theory in the Brownian regime. We also found out that the values for the appropriate averaging scales may strongly depend on the weighting average used to define the mean drift. In Rampal et al. (2009), the weighting coefficients depended on the rank and the distance to the target position and time. In our manuscript it only depended on the distance to the target position and time. As these assumptions on the rank and the distance to the target position and time are not strongly supported, we now use a simple average without any specific weight. This new method is explained in the text and gives a much better match with the theoretical slopes.

ll426, Fig7

I find it very hard to see these features in the plots. I see that TOPAZ tends to be faster and neXtSIM tends to be slower, but in terms of pattern, I don't clearly see (from Fig7) how TOPAZ does something wrong where neXtSIM does it right. There are cases when TOPAZ is obviously off the data (e.g. the position of the BG is wrong in 2007/8 and 2009/10), but also cases when neXtSIM is not so great, either (e.g., there are vectors at 90deg angles with the observations). I am not sure why this form of assessment is required and how it helps the manuscript.

We agree that the use of the term "pattern" is not appropriate. We actually wanted to emphasis that the overestimation of the drift in the TOPAZ results is not homogeneous but mainly located along the CAA.

We remove the term "feature" and imprecise statement like "reproduce well the mean circulation", and we limit the discussion to the year 2007-08, where differences are obvious, while saying that: "For the other winters, it is less obvious to distinguish clear differences in the quality of the simulated mean drift fields."

ll441, Fig8

Here, in contrast to the fluctuating speed pdfs in Fig9 (see below), I clearly see the difference between the model results and that the neXtSIM mean drift pdf is nearly exponential as opposed to the TOPAZ mean drift pdf.

Yes, it was the case but this result was impacted by the uncorrect choice of averaging scales. The results are now less striking but more solid.

We discuss in detail the differences between the 3 distributions.

ll459, Fig9

I find it hard to impossible to see any significant difference between the TOPAZ and the neXtSIM results in Fig9 (as opposed to Fig8, where the difference is clear), definitely not why one should be exponential and the other isn't. I suggest to rephrase the text to objectively describe the figure or change the representation in order to avoid any misunderstanding.

Yes, we agree that the statement was exagerated. The distribution from neXtSIM follows an exponential distribution but only in the range 0 to 30 cm/s.

We now better describe the distributions.

Referee Report:
tc-2015-233-referee-report.pdf
We took all the remarks and corrections in red made in the pdf (tc-2015-233-referee-report.pdf).

Only the following remarks requires a dedicated answer:

I see the nearly "ballistic" regime (although the slope is really below 2) and the transition to slope 1, but what happens above 10days, when the IABP curve levels off even more to below 1 (almost 0.5)? I think this should be discussed to guide the reader.
See our answer above
We correct that issue by redoing the analysis.

Something is either wrong or clumsy, please check: "The TOPAZ model has been found "sufficiently eddy permitting" in the North Atlantic but this does not apply to the Arctic where the Rossby radius is about 5–15km in the Nansen and Canadian basins and can be as small as 1–7 km in the shelf seas where density stratification is weak or in shallow waters (Nurser and Bacon, 2014)."
We remove the sentence. It was not useful.

I find it very hard to see these features in the plots. I see that topaz tends to be faster and nextsim tends to be slower, but in terms of pattern, I don't clearly see (from Fig7) how Topaz does something wrong where nextsim does it right. There are cases when Topaz is obviously off the data (e.g. the position of the BG is wrong in 2007/8 and 2009/10), but also cases when nextsim is not so great (e.g., there are vectors at 90deg angles with the observations). I am not sure why this form of assessment is required.:
" The TOPAZ model generally overestimates the mean drift field and does not correctly reproduce the spatial patterns. In particular the size of the Beaufort Gyre is often overestimated and the model does not reproduce the low drift speed along the Canadian Arctic Archipelago, which are due to significantly thicker and more 430 ridged ice. The mean ice drift simulated by the neXtSIMmodel reproduces well the mean circulation patterns, slightly underestimates the magnitude of the Beaufort Gyre but reproduces well the almost immobile pack ice north of the Canadian Arctic Archipelago."
See our answer above

Here, I clearly see the difference between the model results and that the nextsim mean drift pdf is nearly exponential as opposed to the topaz mean drift pdf, but not for the fluctuating speed pdfs (see below) + I find it hard to impossible to see any significant difference between the topaz and the nextsim results in Fig9, definitely not why one should be exponential and the other isn't.
See our answer above

On Figure 11: but the pattern is similar, isn't it, with low values near Canada and high values near Siberia? Does the low ice volume of topaz lead directly to low diffusivity? Looks a little like it and may be worth mentioning somewhere.
Yes.
We add a figure showing observed and simulated sea ice thickness for the winter 2007-08, and we discuss the link with the diffusivity fields in the text.

and the external forcing itself, and the strength parameterisation (or is that part of the "rheology"?)
On: " The misrepresentation of the sea ice thickness distribution in the Arctic by TOPAZ is likely not a problem related to the sea ice thermodynamics model but rather to the sea ice dynamics model and more specifically to its rheological component which controls the formation of leads and ridges by determining the mechanical response of the ice pack to external mechanical forcings."
Yes, we do not have the necessary information to speculate on the origin of the bias in sea ice thickness seen with TOPAZ.
We remove that part of the discussion.

it may also be caused by the internal stresses, surface stress etc. I cannot think of a reason to believe a-priori that the rheology that works well for thick ice, works similarly well for thin ice. The same applies to the TOPAZ results. The rheology may be inappropriate for thick ice (as suggested in the text) and for thin ice.
On: " This misrepresentation may thus come from the oceanic forcing which comes from the TOPAZ reanalysis."
Yes, we do not have the necessary information to speculate on the origin of this misrepresentation.
We remove that part of the discussion.

fortuitously fitting …
(because an underestimation is compensated by an overestimation?) on:"The underestimation of the fluctuating variance is compensated by the overestimation of the integral time scale, leading to long-term displacement variance fitting very well the observations."
We do not think this is fortuitous but rather coming from a lack of variability in the forcings or a misrepresentation of the inertial oscillations. Both mechanisms could induce a weaker variance and longer integral time scale.**No change.**

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Anonymous Referee #2

Dear referee,

First of all, we would like to thank you for your insightful comments and suggestions, which greatly helped us improving our manuscript. Below, you will find your original **comments in bold**, our answers in red and the **added text** to our manuscript in **bold red**.
Please note that our new manuscript containing all the changes we made is attached as a supplementary material to the present document.

General Comments

This is a follow-up review of the TCD manuscript with the title "Sea ice diffusion in the Arctic ice pack: a comparison between observed buoy trajectories and the neXtSIM and TOPAZ-CICE sea ice models" by the same authors. I support the new direction of the manuscript away from the model intercomparison. This is much clearer and focused now. How the results are presented now is, in my opinion, much more useful for a wider audience. The current TC manuscript is, however, quite different from the TCD one. As there were no contributions in the TCD open discussion besides the ones from the reviewers I don't think this is a problem.

I have a few specific comments listed below, which should be addressed. The comparisons between the two model systems is presented in a fairer way. I, however, still miss a clear statement that many of the observed differences between the model systems could as well originate from external causes (different initial conditions, atmospheric forcing, and ocean) than from causes intrinsic to the model (different rheology). Some of these points are touched at different locations of the manuscript but only partly in the discussions section (see also my comment there). Due to the setup of this study this question cannot be answered definitely, which should be clearly stated.

We now start the discussion section of section 3 by a note on the objectives and limitations of the comparison of model outputs to observations.
Changes: New introduction of the discussion in section 3

After these points are addressed I recommend the publication of the manuscript in The Cryosphere.

Specific Comments

Abstract: The abstract reads much better now. However, a few more concrete quantitative results could be mentioned, e.g., …

L61, eq1: C is not defined
Corrected

L103-104: Don't understand this sentence. What do you mean with "interest of"? reformulate
Corrected

L105: This is not a good argument for the restriction to winter. Oil spills in summer are more likely and would need similar information on the time scales looked at here. I think you must have another reason to restrict your analysis to winter. Please clarify.
This statement about the criticality for the oil spill comes from the extensive review made by Drozdowski et al. (2011), which is a reference for oil-spill in ice-infested waters.
No change

L106: full name and reference for IABP
Corrected

L115: model runs
Corrected

Figure 1: More useful than the individual buoy tracks, which one cannot distinguish anyway, would be a density plot showing how many buoys existed in a particular region. From the figure one might get the impression that the buoys are quite evenly distributed over the Arctic Basin, which they are not.
We have added two panels to Figure 1, one showing the number of buoys and one showing the number of records.

L132: Please mark this "Central Arctic domain" in Fig. 1
Done

Figure 2: Mentioning the used L and T in the caption would it easier to understand the figure.
Corrected

L162: For your statistical analysis it actually doesn't matter but your constructed x and u are shifted by 6 hours from the original buoy times. Do you take that into account for your model inter-comparison?
Yes, as explain in the text the same decomposition method is applied to the 3 datasets.

We add : “with the exact same number of positions” to “three comparable datasets with the exact same number of positions are obtained” to be make it more evident.

L171: circle
Corrected

L193: 1.4 days according to the figure. Which one is correct?
Corrected

L208: is C eq C_q? mention what C(tau) is, also t_1 was not mentioned yet I believe.
We add: “Note that the subscript q is dropped when dealing with only one particle. C is then the same as C_q.”
And
“where t_1 is any instant of time in the life time of the particle”

L234: Hm, in Fig 4 the “Brownian” regime seems to converge to a slope smaller than 1. Maybe comment on that.
Yes, that issue was also raised by reviewer 1, and lead us to redo the analysis from the beginning.
Corrected

L242-244: and what are the asymptotic values? How can the reader check your “evaluation”?
Corrected by adding:
“(indicated by the green lines in Figure 4)”

L253: even if you are not showing the complete analysis here you should at least say how you checked the stationarity. Just to say that you checked it is not enough.
Corrected by adding:
“by comparing $\langle u'^2(t) \rangle$ to the mean values $\langle u'^2 \rangle$”

L258: mention why Rampal2009b is twice too low.
Corrected by adding:
“We do not know the reason for this inconsistency.”

L267-269: repeat time scale values and diffusivity values you found here again.
Corrected

Figure 5: it’s hard to derive anything from the black lines in the left part. Maybe thinner or less lines.
We plot less lines now.

Table 1: Maybe add the percentages for 1, 2, and 3 STD in the caption (in case people don't know by heart). Then all needed information are also together here.
Corrected by adding:
"Note that we checked that about 68.9\%, 95.9\% and 99.6\% of the fluctuating displacements are smaller than 1, 2, and 3 standard deviations."

L301: trend of what?
Corrected by adding:
"in the mean speed"

L357-358: check sentence; repetition
Corrected

L427-429: Cannot see that spatial patterns are less well reproduced in TOPAZ? Just looks faster. It might be true but from this figure you cannot make this conclusion. You would need a more detailed analysis or stick to the speed difference. Maybe mention again that this was observed before in another study.
We agree that the use of the term "pattern" is not appropriate. We actually wanted to emphasis that the overestimation of the drift in the TOPAZ results is not homogeneous but mainly located along the CAA.
We remove the term "feature" and imprecise statement like "reproduce well the mean circulation", and we limit the discussion to the year 2007-08, where differences are obvious, while saying that: "For the other winters, it is less obvious to distinguish clear differences in the quality of the simulated mean drift fields."

Figure 8: it says mean speed in the caption but fluctuating speed under the y-axis. What is correct?
Corrected

L444-445: don't understand this sentence. Maybe describe in a few more words.
Corrected

L447-458: don't understand this whole paragraph. The IABP buoys in Fig. 9 clearly follow the Gaussian distribution (dashed line) and not the exponential as described in this paragraph. Please clarify.
There was a mistake in the caption. The dashed line represents indeed the exponential distribution.
The caption is corrected now.

L462: there is still a mix-up of Gaussian and exponential distribution here. Anyway, add some comment why also the neXtSIM speeds do not follow the same distribution as IABP for >30cms if you have any idea about that.
Corrected by correcting the caption and improving the discussion section.

L494-498: do you have any argument for that? How do you discriminate the thermodynamic and dynamic influence on the thickness distribution in TOPAZ? This sentence should be removed if not substantiated.
Corrected by removing the sentence

L513: remove "slight". I, for example, find it substantial. Why not repeat the numbers for the mean difference again here (also for TOPAZ), then the reader can make their own judgement: neXtSIM -0.45cm/s (-xx%); TOPAS +0.93cm/s (+yy%)
Corrected

L530: the discussion section would be a good place to discuss the effect of different forcing and initial condition for the two model systems on the observed differences between them:
- neXtSIM: artificially adapted ice thickness distribution towards thicker ice at the beginning of season -> can explain slower drift
- ASR accordingly to Bromwhich et al. has more realistic surface wind -> also could partially explain differences in mean speed and statistical properties
- with the thicker ice and ASR as forcing neXtSIM clearly performs more realistic compared to observations than TOPAZ. If this improvement mainly originates from the (a) different initial conditions, forcing, and ocean or (b) the sea ice model itself (different rheologies and thermodynamics) cannot be answered. (last part could also go to the conclusions)
As already raised by the reviewers, the setups analysed here do not allow for a clear distinction between the causes of the differences between the simulated and observed trajectories.
We add this clarification at the beginning of the discussion of section 3:
"The goal of the present analysis is not to compare the model systems themselves but to illustrate how the simulated motion fields differ from observations and what would be the impact of using such model outputs to force passive tracers models to study for example trajectories of pollutant trajectories in sea ice. The differences between the simulated and observed motion may be due to many factors, ranging from the internal characteristics of the sea ice models (their rheology, drag parameterisation,...) to external causes, such as the initial conditions, atmospheric forcing and impact of the ocean. To distinguish the effects of each factor would require to run the same model with different initial conditions, forcings and set of parameters, or to run different models in the same configuration (initial conditions, forcings, parameters,...). Other diagnostics than the diffusion analysis would also be necessary. For example, the effect of the rheology would be better analysed by applying dispersion analysis (double particle diffusion) as in \citet{Rampal2008} as it directly relates to sea ice deformation. Nevertheless, even if the present analysis cannot clearly distinguish the sources of the differences between the simulated and observed trajectories, it provides pertinent information on the quality of the simulated trajectories."
We also add the sentence proposed by the reviewer to the conclusions.

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Anonymous Referee #3

Dear referee,

First of all, we would like to thank you for your insightful comments and suggestions, which greatly helped us improving our manuscript. Below, you will find your original **comments in bold**, our answers in red and the **added text** to our manuscript in **bold red**.
Please note that our new manuscript containing all the changes we made is attached as a supplementary material to the present document.

The authors Rampal, Bouillon, Bergh, and Olason have revised their manuscript now entitled "Arctic sea ice diffusion from observed and simulated Lagrangian trajectories" significantly and with great success following the suggestions of the reviewers. This is now an excellent paper on sea ice drift, well structured, well written, and with a clear message. The study now focuses on sea ice diffusion with the application to pollutant dispersion. The model comparison of TOPAZ and neXtSIM, which previously was a concern shared by all reviewers, has been improved and its presentation has been reduced to a useful addition of the paper.

The paper is now in good shape to be accepted for publication in The Cryosphere. This said I list a number of suggestions, mostly regarding wording, but also some necessary corrections that the authors may want to consider before publication.

Important corrections/suggestions:

There are three references to the mean diffusivity of the sea ice cover (line 194, Fig. 3 and line 537), which I think should be consistent but currently read 1.0 x 103, 1.1 x 103 and 1.2 x 103. Same holds for the integral time scale mentioned in Figure 3 (see comment below).
Corrected

Figure 6: I am not sure what "Nr. 119" etc. means. Is this the number of buoys/floats for each winter? If yes, then better use "N=119" referring to sample size and state this in the caption.
Corrected

Figure 8: the x-axis label should read "mean speed"; fluctuating speed is shown in Figure 9.
Corrected

Figures 8 and 9: I think the dashed line is the exponential fit and the dotted line depicts the Gaussian function. Currently the caption states the opposite. If I am right, just correct he captions of Figures 8 and 9. Otherwise, the statements in the main text are somehow wrong or hard to agree with.
Corrected

It would be extremely helpful for the discussion in Chapter 3 if the authors would provide a contour plots of the ice thickness distribution of all three data sets. Since this is for Chapter 3 it should be an average of winters 2007-2010. For the TOPAZ and neXtSIM simulations this can easily be provided. For the observed ice thickness one could either check availability of satellite derived estimates or use the PIOMAS distribution (which the authors use to adjust their neXtSIM initialization). The maps could either be provided as additional panels within Figure 11 or as a separate Figure. Alternatively, a rough hint at the thickness distribution could be added to the existing maps in Figure 11 as black contours on top of the color patches, then maybe just roughly 1 to 3 m in 0.5m increments.
Yes.
We add a figure showing observed and simulated sea ice thickness for the winter 2007-08, and we discuss the link with the diffusivity fields in the text.

Wording throughout the paper:

Use "search area" and "search radius" instead of "searching area" and "searching radius"
Corrected

Not sure what The Cryosphere guidelines say, but I think using parenthesis when referencing Equations is common: "Equation (1)" instead of "Equation 1".
Corrected

Comma usage with respect to variable names should be consistent throughout the paper, e.g. 'variable, X …' or 'variable, X, … ' or 'variable X …'; personally I prefer the latter.
Corrected

Line by line suggestions:

line 3: “At the surface, …” otherwise the sentence implies accidents at the seafloor or at great depth but omits ship damage.
Corrected

line 6: “random” or “chaotic” better than “unpredictable fluctuating”; otherwise correct to “unpredictably fluctuating”
Corrected

lines 8-10: remove parentheses; add “Eulerian” to “… neXtSIM and the Eulerian coupled ice-ocean …” to stress this major difference of the two models; and remove “run on two different configurations”, because this is already implied (and details are given later).
Corrected

18: “… may differ from or agree well with …”
Corrected

19-20: “illustrates the usefulness of first applying a diffusion analysis … modeling systems that include … before using these …”
Corrected

25ff: replace ‘render’: “…facilities may hamper access to the polluted area for several months (D. et. al., 2011). These conditions also make the detection…”
Corrected

29ff: “… under the sea ice and, therefore may be transported by the ice over … (RC, 1997). In this context, improving the understanding of sea ice trajectories is crucial for risk assessment … in Arctic seas. Passive tracer modeling …”
Corrected

51f: “mean (predictable)” and “fluctuating (unpredictable)”; additional information or definition should be given in parentheses
Corrected

72: align Equation (3) with left text border
Corrected

75: add ‘the’: “… term similar to the Coriolis term”
Corrected

81: “Nevertheless, such properties have been used to reproduce …”; drop speculation about future use here
Corrected

84: “Alternatively, the advection-diffusion equation (Eq. (1)) could be …”; add comma and reference
Corrected

87: replace “/” with “or”: “simulated or observed”
Corrected

91: “ … or defined such that it accounts for the unresolved …”
Corrected

100: replace “Those” with “These”
Corrected

105: “… winter conditons, as this season has been identified to be most critical for oil …”
Corrected

114f: “… is done for two simulations obtained from two different models.” Different models implies possibility of diverting configurations; details are given later correctly.
Corrected

132: consider to add a bold red outline to map in Figure 1 depicting the region described here. Then, add a reference to Fig. 1 to this sentence (after “80˚N”).
Corrected with a blue line.

137: this sentence states an unfortunate limitation of the study as presently most of the Arctic Ocean is dominated by first-year ice (and will be in the future). Drastically said, it may render the numbers presented later in the study useless for future application by stakeholders. The authors need to discuss this issue more (in section 2.5) or/and refine the wording of this sentence.
We add these sentences:
“Before using these estimates, one should remind that they are given for the whole Arctic basin and for the whole period 1979-2011 and may then differ from estimates computed for specific regions and time periods. Also as the IABP buoys are mainly deployed on multi-year ice, these estimates may not be valid for seasonal ice and for future applications.”

141: “Before being published, however, the buoy positions …”
Corrected

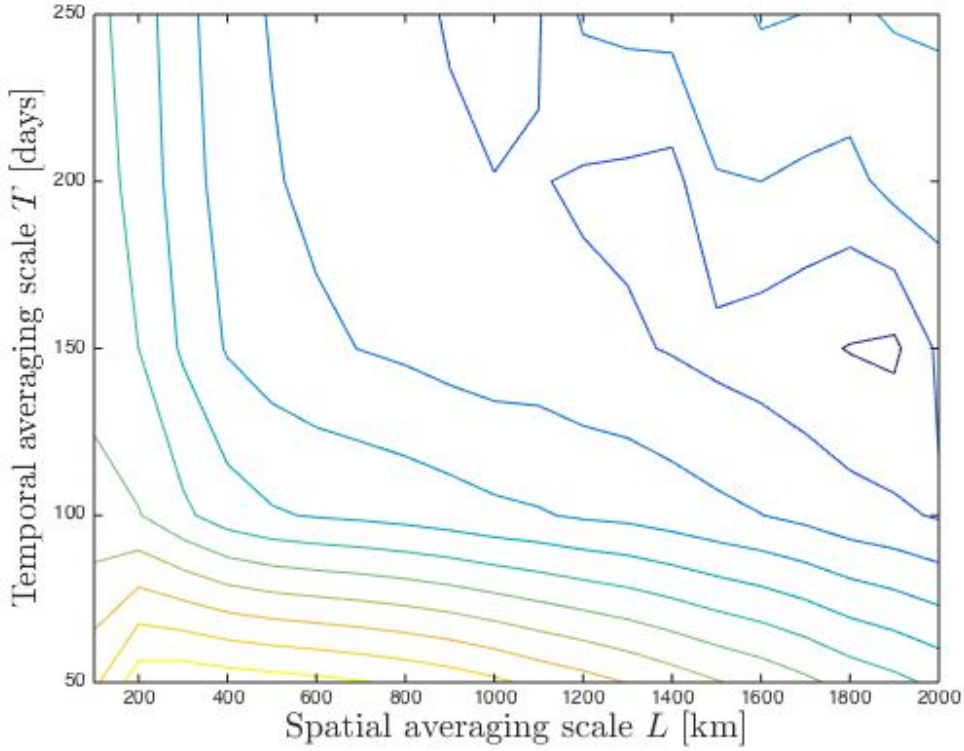
157: the bold line in Figure 2 depicting the mean should be drawn even thicker
Corrected

162: “By repeating this for all the available buoys …”

Corrected

171: “circle” instead of “cercle”
Corrected

178 and 195f: Figure 3 only shows the example of L=400 km and T=165 days. It would be nice to see whether this choice is truly optimal. My first thought of adding more lines of other (L,T) pairs to Figure 3 is not optimal. I rather urge the authors to show Lambda as function of L,T in a new panel added to Figure 3, a contour plot. In line 195 you discuss a plateau that such a plot could potentially show and that would much help to trust he argument in lines 178 and 195.
We follow the first suggestion of the reviewer and add the lines for the lowest and largest averaging scales analysed here (L=100 km and T= 50 days and L=2000 km and T= 250 days) to better illustrate the effect of the averaging scales on the autocorrelation function. The second suggestion could also be followed by adding the following figure to the paper, but we leave the decision to the editor. This figure shows how the difference between the computed displacement variance and the theoretical one depends on the averaging scales. L=1000 km and T=250 days is defined as optimal as it corresponds to the local minima of the deviation that has the smallest spatial averaging scale. In the revised manuscript, the new method to define the optimal averaging scales is described in the text without this figure.
Change: See the corrected figure and the new paragraph explaining the method to define the optimal averaging scales.



193 Lambda=1.5 days does not match Lambda=1.4 given in Figure 3. These numbers should be consistent. (same for diffusivity K)
Corrected

193/194: drop sentence "Note that the diffusivity …discussed in Section 2.3." here and add a similar statement in Section 2.3 itself.
Corrected

199: should this rather be C & T 1985 (instead of 1984) as in line 38? Also, please check if C&T '84 is cited elsewhere (I think not), i.e. when changing this line remove the paper from the references list.
No, it iscorrect, C & T, 1984 and C & T, 1985 are two different papers.

199: split sentence: "… mean circulation. This enables …"
Corrected

203: "… properties of the medium by …"; use singular
Corrected

212: remove "." After Equation (3) as sentence is continued

Corrected

214: ‘time much shorter’ sounds weird, better use “time periods shorter than” or “time much smaller than”; same for ‘time longer than’ in line 218

214: replace “we are” with “the particle is”
Corrected

217: remove parentheses and replace ‘comes’ with ‘results’: “This simply results from …”
Corrected

222: remove parentheses: “…, i.e. where fluctuating ….uncorrelated.”
Corrected

224: I suggest to add statement about mean diffusivity presented in Figure 3 here: “For the example given in Figure 3 a mean diffusivity of 1.1 x 10^3 m^2s^-1 was computed.”
We remove the mean diffusivity, it was not usefull.

240 split sentence: “… integral time scale Lambda. With Lambda=1.4 days we find a time scale similar to the one …”
Corrected

244: “… constant alpha), for which we find a good match.”
Corrected

244-247: the statement about the work of Rampal et al. 2009 “whereas the magnitude presented … to the coming discussion.” does not belong here where new results are presented but should be moved to Section 2.5 Discussion instead. Same for lines 257-259 “Note that the value … in their study.”
Corrected

256 Here, Table 2 is referenced before Table 1. Please switch order of Tables so that Table two becomes Table 1.
Corrected

263: replace “a season” with “6 months”, which is close to 165 days and somewhat more precise than ‘a season’.
Corrected

272: replace “values” with “magnitudes”
Corrected

274: make this statement stronger by using “is a crucial” rather than “may be a crucial”
Corrected

280: drop “We checked that” from beginning of sentence
Corrected

284: rephrase and split this sentence: “For forecasts longer than a few days, typically only the mean ice drift can be trusted. Then, the long-term average standard deviation provided here could be used …”
Corrected

286: “For example, the search area could be defined …”
Corrected

290: should refer to Table 2 here after switching Table sequence.
Corrected

294: replace “non-predictive” with “unpredictable” to be consistent
Corrected

302: “… represented by a single mean value derived from these decades”
Corrected

307: add ‘the’: “… of the two sea-ice(-ocean) modeling platforms…”
Corrected

315: “However, as sea ice, especially compact pack ice, does not behave …”
Corrected

319: remove ‘the’ from “used for the oceanic drifters”; and split sentence: “… (D. et . al. ’12). This approach consists of …”
Corrected

340: replace “one” with “single”, i.e. “single-thickness-category sea ice model”
Corrected

345: replace “run” with “used”
Corrected

348: “… TOPAZ simulations analyzed in the following start on …”
Corrected

349: replace “coming” with “extracted”

Corrected

350: you may drop "free-run" here as this has been made clear above
Two different simulations are presented in Sakov et al. (2012), one in free-run and one with data assimilation. It is then important to indicate that we start from the simulation in free-run.
No Change

350ff: the sentence sounds like wind is the only atmospheric forcing field applied but I guess there must also be temperature and possibly parameters for a radiation budget. Please rewrite to either "The applied wind forcing is the …" or state the other forcing fields as well.
Corrected by listing the variables

353: "The TOPAZ model in free-run mode has been …"
Corrected

356: split sentence: "… platform (not yet documented). The same value is also used here."
Corrected

357: "… in the free run is generally underestimated and has reduced horizontal gradients, i.e. shows too thin ice in areas of thick ice and too thick ice where the ice should be thin"; drop 'inversely'
Corrected

359: "… TOPAZ reanalysis, which applies assimilation of ???, but the total …" insert assimilated quantities (if too many, just say 'applies assimilation').
Corrected

363 add comma: "…shelf sea, where …"
Corrected

365: drop 'here' in "…model is here performed …"
Corrected

365: "hourly sea ice velocity": is this saved as hourly mean or snap shot? If saved as mean, say "hourly mean sea ice velocity"
Corrected

371: "… similar results to computing the float positions during run-time with the advantage …"
Corrected

378: “salinity. While still being under development, the model is already used in an experimental …”
Corrected

388: add ‘reanalysis’ to “… TOPAZ reanalysis ice thickness …”
Corrected

389ff: “… covered with ice. As the modeled ice volume of the TOPAZ reanalysis is known to be too low (S. et al., ’15), we increased … given by the PIOMAS model (Z & R, ’03) on September …”
Corrected

395: “TOPAZ reanalysis”
Corrected

400: Please add the temporal resolution of the ASR forcing. This is important when later discussing the lack inertial motions in the simulations.
Corrected

404: “… May onwards (Rampal …)”
Corrected

405 replace “look at” with “analyse”
Corrected

407: really ‘no’ bias? I guess it is a very small bias, probably negligibly small, i.e. “… showing only a negligible bias in the 3-day drift…”; aslo drop “s” from “3-days”.
Corrected

409: merge and shorten sentences: “… Eulerain fields due to the remashing techniques applied (see Rampal …”
Corrected

415: drop ‘the’ and add ‘float’: “Figure 6 shows maps with all the buoy/float trajectories …”
Corrected

416f: “… datasets. The three winter subsets from 2007 to 2010 are much … reference data set of 1979-2011 analysed in Section 2.1.”
Corrected

432: I think from Figure 6 it is not very clear that neXtSIM is superior (except for the discussed thick ice area north of the CAA), the judgement seems subjective. I just

suggest to add a note, which also helps to introduce the following analysis, such as: "Both models seem to have advantages and disadvantages and ice motion patterns may also be affected by the different wind forcing applied, thus a more objective measure of the quality of the ice velocity simulation is needed."
We limit the discussion to the year 2007-08, where differences are obvious, while saying that: "For the other winters, it is less obvious to distinguish clear differences in the quality of the simulated mean drift fields."

433: remove "also"
Corrected

434: add "more objectively." to end of sentence after '…mean drift'.
Corrected

437: add "(dashed line)" after '… an exponential function'. -> see also my main comment about likely mixed up explanation of dotted and dashed lines in captions of Figure 8 and 9.
Corrected

438: "… follow an exponential distribution but has similarity to a Gaussian function (dotted line), and has a mean value …"
Corrected

460: add "but are much closer to the Gaussian fit." At end of sentence after 'an exponential distribution'.
Corrected
462: "… within the velocity range 0 to …"
Corrected

464: remove "here"
Corrected

468 the reference should be "(Table 1)" after switching the tables
Corrected

478f: "… Archipelago (i.e. as small as about 0.3 x 10^3 m^2s^-1) and the larger values in the Beaufort and East Siberian seas (1.5 – 2.5 x 10^3 m^2s^-1)."; please check the magnitudes for the IABP data again, to me it looks like the minimum is rather around 0.2 – 0.3 than 0.5. And also add numbers for the larger values (I switched Bft. And East Sib. on purpose to because East Sib. has the larger magnitudes.
Corrected

494 "(mean drift speed smaller than …)"

Corrected

501f: "ocean model, which overestimates the size and misplaces the center of the Beaufort Gyre compared to …"
This sentence is not used anymore and has been removed.

510: remove "well" after 'represent' and instead add "much better" at end of sentence.
Corrected

512: "… are underestimated, however, just as in …"
Corrected

514: "may thus originate from the oceanic forcing adapted from the TOPAZ reanalysis. Moreover, effects by using different wind forcing cannot be excluded as well."
Corrected

518f: add comment about temporal resolution of wind forcing not sufficient to excite inertial motions. To trigger inertial motions forcing time step must be smaller than 1h.
We change the sentence into:
"These too long integral time scales may also partly come from missing physics or too weak coupling (e.g., too low frequency in the coupling and forcing) in the model setups, that may lead to a misrepresentation of the inertial oscillations that impact 12-hourly drift statistics. "

528: "… integral time scale. This may allow to maintain the good performance …"
Corrected

533-535: shorten: "… and we confirm the results of Rampal et al. (2009b) that the appropriate … and 165 days. We additionally verify …"
Corrected

536: numbers given should be consistent with Figure 3 and associated discussion in main text.
Corrected

540: add explanation for meaning of 3 std. dev.: "… to 3 standard deviations of the fluctuating displacement, which would include the polluted area with 99% confidence, we find that… " This is meant for stakeholders who may want to apply your numbers.
Corrected

553: "… sea ice model output before using it for …"; use singular instead of plural
Corrected

568: “exponential distribution – like the observations – an reproduce …”
Corrected

582: “… (mean circulation of the atmosphere and ocean, spatial … “
Corrected

584: replace “whose the respective roles” with “which”
Corrected

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Arctic sea ice diffusion from observed and simulated Lagrangian trajectories

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Abstract. Due to the difficult access, an oil spill occurring in ice-covered regions of the ocean in fall or winter may persist for several months and therefore could affect large areas and impact the local ecosystems. ~~When reaching~~ At the surface, the oil accumulates under the ice cover or in leads before being trapped in the new ice formed. Oil spill risk assessment and response planning then need to be based on an accurate description of the long term mean sea ice circulation and the effect of the ~~unpredictable~~ unpredictably fluctuating part of the sea ice motion. In this study we characterise sea ice drift by applying a Lagrangian diffusion analysis to buoy trajectories from the International Arctic buoy Program (IABP) dataset and from two different models~~(~~, the standalone Lagrangian sea ice model neXtSIM and the Eulerian coupled ice-ocean model used for the TOPAZ reanalysis~~) run on two different configurations~~. By applying the diffusion analysis to the IABP buoy trajectories over the period 1979-2011, we confirm that sea ice diffusion follows two distinct regimes (~~"ballistic" and "Brownian"~~ballistic and Brownian) and we provide accurate values for the diffusivity and integral time scale that could be used in Eulerian or Lagrangian passive tracers models to simulate the transport and diffusion of particles moving with the ice. We discuss how these values are linked to the evolution of the fluctuating displacements variance and how this information could be used to define the size of the ~~searching~~ search area around the position predicted by the mean drift. By comparing observed and simulated sea ice trajectories for three consecutive winter seasons (2007-2011), we show how the characteristics of the simulated motion may differ ~~or fit~~ from or agree well with observations. This comparison illustrates the ~~utility of using~~ usefulness of first applying a diffusion analysis to evaluate the output of ~~modelling system that includes~~ modeling systems that include a sea ice model before using ~~them~~ these to simulate the transport of passive tracers in sea ice.

1 Introduction

The increasing activities in the Arctic seas (e.g. shipping, fishing, and oil and gas exploration and exploitation) enhance the risk of pollution in a region where ecosystems are already under threat from the amplified effects of climate change. The extreme conditions (e.g., presence of ice, extreme cold, high winds, and the Polar night) and the long distance from well-equipped facilities may ~~render~~ hamper access to the polluted area ~~difficult or even impossible for long periods of time (even longer than 6 months in winter)~~ for several months (Drozdowski et al., 2011). These conditions also ~~render~~ make the detection of the pollution challenging, and slow or even stop the natural and artificial degradation processes. In addition, the pollutants are often trapped in or under the sea ice and, therefore ~~,~~ may be transported by the ice over large distances before being released (Rigor and Colony, 1997). In ~~that context, better understanding the trajectories~~ this context, improving the understanding of sea ice ~~(and then of the passive tracers following it) could be~~ trajectories is crucial for risk assessment and response planning related to pollutant release in Arctic seas. ~~Note that passive tracer modelling~~ Passive tracer modeling in sea ice has also other applications, for example to study biology and its link with pollutants (e.g. Borgå et al., 2002; Pfirman et al., 1995) or to estimate the age of the Arctic sea ice cover (e.g. Fowler et al., 2004; Hunke, 2014).

Sea ice motion can be viewed as a superposition of a mean circulation and turbulent-like fluctuations (Rampal et al., 2009b). Using such decomposition for studying pollutant transport by sea ice was already proposed by Colony and Thorndike (1985) who analysed sea ice drift data covering the period 1893-1984 while using arbitrary averaging scales (90 years and 1500 km) to define the mean motion. By using a denser sea ice drift dataset covering the period 1978-2001 and the theoretical framework introduced by Taylor (1921) for the analysis of turbulent fluids, Rampal et al. (2009b) proposed a methodology to rigorously decompose sea ice motion into mean and turbulent-like fluctuating parts. The appropriate averaging scales (about 400 km and 5.5 months for winter conditions) were found small enough to clearly separate the inter-annual variability of the mean circulation from the fluctuating motion due to passing atmospheric perturbations, local oceanic eddies and inertial and tidal motion. This approach based on the analysis of single particle trajectories has been widely used to study diffusion properties ~~from~~ of Lagrangian drifters in the ocean (see e.g., Zhang et al., 2001; Poulain and Niiler, 1989) and is now becoming a standard analysis tool for sea ice dynamics ~~(Lukovich et al., 2011, 2015)~~(Lukovich et al., 2011, 2015; Gabrielski et al., 2015).

Single particle analysis (here referred to as diffusion analysis) is particularly useful for characterising long-term trajectories as it clearly decomposes the motion into ~~a mean /predictableand fluctuating/unpredictable~~mean (predictable) and fluctuating (unpredictable) parts (Colony and Thorndike, 1985). It also allowed Rampal et al. (2009b) to show that sea ice diffusion exhibits a clear transition from the so-called ballistic regime to the Brownian regime. This transition is also typical of turbulent fluids and is due to the fast decay of the ~~velocities~~ velocity autocorrelation function. The information coming from the diffusion analysis (mean flow and diffusivity) statistically describe the ensemble

of all the potential trajectories that a particle, released at a given location at an unknown time during a season, could follow, and may then be sufficient to produce a probabilistic forecast of tracer transport.

To simulate tracer transport, one can use continuous or discrete passive tracer models. Continuous models are usually based on the following advection-diffusion equation:

$$\frac{\partial C}{\partial t} + \bar{\mathbf{u}} \cdot \nabla C = \nabla \cdot (K \nabla C), \tag{1}$$

where $\bar{\mathbf{u}}$ is the mean velocity field~~and~~ , K is the corresponding diffusivity ~~(LaCasce, 2008)~~and C may describe either the tracer concentration or the probability to find the tracer in a given position after a given time (positional probability) as explained by LaCasce (2008). One can also use discrete passive tracer models for which the displacement dx_i in the i direction is defined for independent objects. The simplest approach, known as the "random walk" model or zeroth order model, is strictly equivalent to the advection-diffusion equation of continuous models and simply defines dx_i by

$$dx_i = \bar{u}_i dt + \sqrt{2}\sqrt{\langle u_i'^2 \rangle} dw_i, \tag{2}$$

where u_i' is the fluctuating velocity in the i direction and dw_i is a ~~Weiner~~ Wiener process. The first order approach is also often used as it can represent the transition between the ballistic and the Brownian diffusion regimes by applying the stochastic term on the evolution of the velocity, leading to the following set of equations:

$$dx_i = (u_i + \bar{u}_i) dt \tag{3}$$

$$du_i = -\frac{1}{\Gamma_i} u_i dt + \sqrt{\frac{2}{\Gamma_i}} \sqrt{\langle u_i'^2 \rangle} dw_i. \tag{4}$$

where Γ_i is the integral time scale in the i direction. First-order approaches can also successfully reproduce the loops often seen in surface drifter trajectories by adding a rotation term similar to the Coriolis term.

These approaches have been widely used to study the spread of pollutant and other tracers by eddy turbulence in the ocean and atmosphere (see LaCasce, 2008, for an extensive review). ~~However, using~~ Using such approaches to simulate the spread of sea ice would be inappropriate because ~~of the characteristics of~~ sea ice motion fields ~~which~~ are intermittent in time and discontinuous in space~~. Such approaches may still be used and have been used to reproduce~~ , but is valid for reproducing the statistics of individual sea ice trajectories. The "random walk" model was for example used in Colony and Thorndike (1985) with a mean field and statistics on the fluctuations derived by ~~(Colony and Thorndike, 1984). Alternatively the advection-diffusion equation could be used as a stochastic differential equation where C describes the probability for a particle to be in a given position after a given time.~~ Colony and Thorndike (1984).

Another way to use passive tracer models is to replace the mean field $\bar{\mathbf{u}}$ in Equations ~~1, 2~~ (1), (2) or (3) by simulated or ~~3 by simulated/~~observed Eulerian velocity fields. This approach is widely used with passive tracer models directly forced by motion fields simulated by an hydrodynamical model

(e.g. Nudds et al., 2013), given by a reanalysis (e.g. Gearon et al., 2014) or derived from satellite observations (e.g. Fowler et al., 2004). The diffusion term (or in the discrete models, the Wiener process term) is either neglected or defined ~~to account~~ such that it accounts for the unresolved part of the fluctuating motion. The unresolved part of the motion could be analysed with the methodology proposed by Dominicis et al. (2012) for ocean surface tracer ~~modelling~~modeling, which consists of comparing the characteristics of the fluctuating part of observed trajectories to the ones of trajectories given by a tracer model forced by model output.

Before using one of these approaches one needs to answer a few questions: What are the right averaging scales to define the mean motion field? What are the statistical properties of the fluctuating part of the motion? Is there a transition between different regimes of diffusion? Are the mean and fluctuating parts of the motion correctly reproduced by the forcing field? If not, could this indicate that some processes are missing in the forcing velocity fields? If the fluctuating part is not well reproduced could it be compensated by adding extra terms in the tracer equation? ~~Those~~ These important questions are not always answered before running tracer models forced by sea ice velocity fields and this could strongly impact the validity of the studies based on such results.

In this paper, we demonstrate the ~~interest~~ utility of applying Lagrangian diffusion analysis ~~on~~ to sea ice trajectories in the context of passive tracer ~~modelling~~modeling. The analyses presented in this paper are restricted to winter conditions, as ~~it~~ this season has been identified as more critical for oil spill recovery operations (Drozdowski et al., 2011). In Section 2, we apply the same method as in Rampal et al. (2009b) to the ~~IABP buoys~~ International Arctic buoy Program (IABP) dataset for the period 1979-2011 ~~.~~ (Rigor, I. G. Compiled by Polar Science Center. 2002. IABP Drifting Buoy Pressure, Temperature, Position, and Interpolated Ice Velocity, Version 1. subset C. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. http://dx.doi.org/10.7265/N53X84K7. January 2015). This reference dataset is analysed to get an overall picture of the characteristic of the mean and fluctuating ~~part~~ parts of the motion for the Central Arctic domain and to derive the quantities (diffusivity, Lagrangian integral time scale, etc.) needed for tracer models. This section also includes a discussion on how to predict the evolution of the fluctuating displacements variance, which could be used to define the size of the ~~searching~~ search area around the trajectory predicted by the mean drift. In Section 3, we follow the methodology proposed by Dominicis et al. (2012), which consists of applying the diffusion analysis to observed and simulated trajectories to evaluate the merits of using these simulated fields for tracer ~~modelling~~modeling. This evaluation exercice is done for ~~two different simulations obtained with for~~ simulations obtained from two different models~~run in different configurations~~. Section 4 sums up the main conclusions.

2 Diffusion analysis on a reference dataset

In this section we present the theoretical framework of the diffusion analysis by showing its application to the IABP dataset from 1979 to 2011 as a reference. Results and theory are then compared and discussed in the context of passive tracer ~~modelling~~modeling. This is the same analysis as that already done by Rampal et al. (2009b), except that we use the 12-hourly buoy positions data ~~(Rigor, I. G. Compiled by Polar Science Center. 2002. IABP Drifting Buoy Pressure, Temperature, Position, and Interpolated Ice Velocity, Version 1. subset C. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. http://dx.doi.org/10.7265/N53X84K7. January 2015) and~~ instead of the hourly data and extend the analysis period up to 2011. The results we obtained are ~~very~~ similar to those reported in Rampal et al. (2009b), but additional evaluation and discussion ~~is presented in subsection 2.4~~ are presented in subsections 2.4 and 2.5.

2.1 Reference dataset

Figure 1 shows all the trajectories analysed in this section. We restrict the analysis to the winter period defined as starting the 1st of November and ending the 15th of May. Results for summer can be found in Rampal et al. (2009b). To investigate sea ice motion properties in the pack ice, we ~~restricted~~ restrict the IABP dataset to a region located in the centre of the Arctic basin (hereafter denoted the Central Arctic domain, blue line on Figure 1). This includes all buoy data north of 70°N, except between 20°W and 100°E where the southern limit is set to 80°N. In addition only buoy data from more than 100 km off the coast ~~is~~ are used. The selected data cover the whole Central Arctic basin, but the data coverage in the East Siberian and Laptev Seas is sparse (see the maps showing the number of buoys and records on Figure 1). Sea ice dynamics in coastal regions are specific with for example the presence of land-fast ice and would require a dedicated study. The IABP buoys are mainly deployed over multi-year ice and thus the conclusions from the analyses presented in this study may not be extrapolated for weaker seasonal ice.

The raw IABP buoy positions are sampled irregularly in time with a mean time interval of 1 hour, and with errors ranging from 100 to 300 m depending on the positioning system they used (Thomas, 1999). Before being ~~delivered to the scientific community~~published, however, the buoy positions are interpolated in time (using a cubic function) to form an homogeneous trajectory dataset giving for each buoy its position every 12 hours. We manually checked each individual buoy track from the IABP dataset to clean them from unrealistic "jumps" or "spikes" in the trajectories and from obvious errors of the dating system. The unrealistic "jumps" present in buoy trajectories are either due to errors in the positioning system installed in the buoy or to wrong recordings during the deployment or recovery phase of the instruments. A polar stereographic projection is used to change the IABP and virtual buoy positions from geographic to Cartesian (x, y) coordinates.

2.2 Decomposition of the sea ice motion

The IABP buoy trajectories are geometrically complex, with abrupt changes in direction (Figure 1). Therefore, it is helpful to decompose the total sea ice motion into a mean part, that should be considered homogeneous and stationary, and a fluctuating part, that should contain the unpredictable, local or non-stationary motion. This is done here by following the classical approach used to study Lagrangian particle trajectories (see for example Zhang et al., 2001). This consists of splitting each trajectory into mean and fluctuating parts by using appropriate averaging scales L and T to compute the Lagrangian mean motion at any given location and time. An example for one particular IABP buoy trajectory is shown on Figure 2.

From the list of positions $\mathbf{x}_q^i$ of a buoy q, one can evaluate its position and velocity at time $\tilde{t}_q^i = \left(t_q^{i+1} + t_q^i\right)/2$ by computing:

$$\tilde{\mathbf{x}}_q^i = \left(\mathbf{x}_q^{i+1} + \mathbf{x}_q^i\right)/2, \tag{5}$$

$$\mathbf{u}_q^i = \left(\mathbf{x}_q^{i+1} - \mathbf{x}_q^i\right)/\Delta t. \tag{6}$$

By ~~doing the same~~ repeating this for all the available buoys, we build a dataset of 12-hourly velocities and positions, from which we compute the mean and fluctuating part of the motion.

The mean velocity field $\bar{\mathbf{u}}_{L,T}(\mathbf{x},t)$ is defined for any target position $\mathbf{x}$ and time t as

$$\bar{\mathbf{u}}_{L,T}(\mathbf{x},t) = \frac{1}{\sum_{q,i} w_q^i} \sum_{q,i} w_q^i \mathbf{u}_q^i, \tag{7}$$

where L and T are the spatial and temporal averaging scales and w_q^i are weight coefficients~~defined as in Rampal et al. (2009b), i. e. as a Gaussian function of the distance in space and time to the observations~~

$$w_q^i = \begin{cases} e^{-0.5\left(\frac{\|\tilde{\mathbf{x}}_q^i - \mathbf{x}\|^2}{L^2} + \frac{|\tilde{t}_q^i - t|^2}{T^2}\right)} & \text{if } \|\tilde{\mathbf{x}}_q^i - \mathbf{x}\| \leq L/2 \quad \text{and } |\tilde{t}_q^i - t| \leq T/2 \\ 0 & \text{else.} \end{cases}$$

~~In other words,~~. In this study we use constant weights, meaning that the mean velocity is ~~defined as a weighted~~ simply defined as an average of all the 12-hourly velocities available in the dataset that are within a ~~cercle~~ circle of diameter L centred on the target position $\mathbf{x}$ and a time window of duration T centred on the target time t. The fluctuating velocities $\mathbf{u}'$ are then computed at each position $\tilde{\mathbf{x}}_q^i$ and time $\tilde{t}_q^i$ by subtracting the mean velocity $\bar{\mathbf{u}}_{L,T}(\tilde{\mathbf{x}}_q^i, \tilde{t}_q^i)$ from the total velocity $\mathbf{u}_q^i$. Both the mean and fluctuating velocities are then defined for a specific pair of averaging scales L and T. The mean and fluctuating displacements for each buoy (e.g. the one of Figure 2) are then be defined by integrating in time the mean and fluctuating velocities, respectively.

To verify that the averaging scales ~~,~~ L and T ~~,~~ are well chosen, one can check that the ensemble average autocorrelation function of the fluctuating velocities rapidly decreases and remains close to 0 for long time ~~interval~~ intervals τ, as shown in Figure 3 for ~~$L = 400$~~ $L = 1000$ km and ~~$T = 165$~~

$T = 250$ days and the IABP dataset from 1979-2011. The ensemble average autocorrelation function χ is defined as

$$\chi(\tau) = \frac{1}{\sum_q T^q_{\max}} \sum_q T^q_{\max} C_q(\tau) \tag{8}$$

where $T^q_{\max}$ is the duration of each trajectory and C_q is the Lagrangian normalized autocorrelation function for each individual trajectory, which is defined as

$$C_q(\tau) = \frac{1}{\langle u'^2_q \rangle T^q_{\max}} \int_0^{T^q_{\max}} \mathbf{u}'_q(t)\mathbf{u}'_q(t+\tau)dt. \tag{9}$$

Here $\mathbf{u}'_q(t)$ is the fluctuating velocity of the buoys q at time t and $\langle u'^2 \rangle$ is the variance of the fluctuating velocities for the whole trajectory, which is defined as

$$\langle u'^2 \rangle = \langle u'^2_x(t) + u'^2_y(t) \rangle. \tag{10}$$

~~More generally, L and T are defined as the lowest scales for which the average integral time $\Gamma = \int \chi(\tau)d\tau$ remains quasi constant (i.e., less than 1% change). Since we cannot integrate this equation to infinity, the average integral time scale is computed as~~

$$\Gamma = \int_0^{t_0} \chi(\tau)d\tau$$

~~where t_0 is the first time $\chi(\tau)$ crosses zero (see for instance Poulain and Niiler, 1989; Rampal et al., 2009b). In the example of Figure 3, $t_0 = 6$ days, meaning that fluctuating velocities are uncorrelated for larger time scales, and the integral time scale Γ is equal to 1.5 days. Note that the diffusivity ($K = 1.0 \times 10^3$ m^2 s^{-1}) for the example of Figure 3 is also given for information but will be discussed in Section 2.3. We checked by plotting Γ for different pairs of L and T (not shown) that a plateau is reached for averaging scales larger than $L = 400$ km and $T = 165$ days (as found in Rampal et al., 2009b, for the period 1979-2001), which are then the appropriate averaging scales for the data analysed here. These averaging scales are much smaller than the ones used by Colony and Thorndike (1984) to define a reference mean circulation, and this allows for a clear separation between the inter-annual variability and turbulent-like fluctuations due to synoptic scales activity of the atmosphere.~~

2.3 Application of Taylor's diffusion theory

Once the motion is decomposed into mean and fluctuating parts, it is possible to analyse the diffusion properties in the ~~media~~ medium by following the theory developed by Taylor (1921) for turbulent fluids~~by Taylor (1921)~~. Taylor's diffusion theory is valid for statistically steady and homogeneous turbulent flow without mean flow ~~, and for which the~~ and whose fluctuating velocity follows a Gaussian distribution. When following a single particle in such conditions, the variance of its fluctuating displacement ~~$\langle r'^2(t) \rangle$~~ $\langle r'^2(t) \rangle = \langle r'(t_1)r'(t_1+t) \rangle$ after a time interval t should ~~evolve as~~ be equal

to

$$\langle r'^2(t)\rangle = 2\langle u'^2\rangle \int_0^t \int_0^{t_1} C(\tau) d\tau dt_1 \tag{11}$$

where ~~$\langle u'^2\rangle$, the~~ t_1 is any instant of time in the life time of the particle and the variance of the fluctuating velocity ~~,~~ $\langle u'^2\rangle$ is constant in time. Note that the subscript q is dropped when dealing with only one particle.

For very long time intervals τ, the autocorrelation vanishes (as shown in Figure 3) and the integral of $C(\tau)$

$$\Gamma = \int_0^\infty C(\tau) d\tau. \tag{12}$$

is then a constant referred to as the Lagrangian integral time scale. Since we cannot integrate this equation to infinity, the average integral time scale is often computed as

$$\Gamma = \int_0^{t_0} \chi(\tau) d\tau \tag{13}$$

where t_0 is the first time $\chi(\tau)$ crosses zero (see for instance Poulain and Niiler, 1989; Rampal et al., 2009b). In the example of Figure 3, $t_0 = 11$ days, meaning that fluctuating velocities are uncorrelated for larger time intervals, and the integral time scale Γ is equal to 1.71 days.

Γ determines the transition between two diffusion regimes. For ~~time~~ times much shorter than Γ, ~~we are in the "ballistic"~~ the particle is in the ballistic regime and Equation ~~11 becomes~~ (11) becomes

$$\langle r'^2(t)\rangle = \langle u'^2\rangle t^2, \qquad t \ll \Gamma. \tag{14}$$

~~(this simply comes~~ This simply results from the fact that $C(\tau)$ tends to the limiting value unity for small ~~t)~~time intervals. For ~~time~~ times much longer than Γ, ~~we are in the "Brownian"~~ the particule is in the Brownian regime (also called "random walk" regime) and Equation ~~11~~ (11) becomes

$$\langle r'^2(t)\rangle = 2\langle u'^2\rangle \Gamma t + \alpha, \qquad t \gg \Gamma, \tag{15}$$

where α is a constant defined as $\alpha = -2\int_0^\infty \tau C(\tau) d\tau$ (LaCasce, 2008). We checked that this constant term is very small and can be neglected. This second regime is similar to the one driven by molecular diffusion~~(~~, i.e. ~~,~~ where fluctuating velocities are uncorrelated~~)~~.

These two regimes are clearly detected in Figure 4 where is plotted the displacement variance $\langle r'^2(t)\rangle$ computed with $L = 1000$ km and $T = 250$ days and the IABP dataset from 1979-2011, as well as the corresponding solution for the ballistic and Brownian regimes (Equations (14) and (15)). The fluctuating displacements have been computed as the integral in time of the fluctuating velocities for segment periods of 35 days.

Following Lagrangian turbulent theory, diffusivity is defined as

$$K = \frac{1}{2}\frac{d\langle r'^2(t)\rangle}{dt}. \tag{16}$$

In the ~~"ballistic "~~ ballistic regime (with Equation ~~14~~(14)), diffusivity increases with time and may be calculated as

$$K = \langle u'^2\rangle t. \tag{17}$$

In the ~~"Brownian "~~ Brownian regime (with Equation ~~15~~(15)), diffusivity (also called eddy diffusivity in that case) is constant and may be calculated as

$$K = \langle u'^2\rangle \Gamma. \tag{18}$$

Note that the values of diffusivity for turbulent fluids are generally much larger than diffusion coefficients linked to molecular diffusion.

2.4 Results

~~One way to evaluate the results of the diffusion analysis is~~ To define the optimal averaging scales, we perform the decomposition of the sea ice motion and the diffusion analysis for scales ranging from L =100 to ~~look at the computed fluctuating displacement variance ,~~ 2000 km by step of 100 km and from T =50 to 250 days by step of 50 days, and we analyse the deviation (i.e., the root mean square difference) of the obtained displacements variance (black line in Figure 4) to the theoretical solution for the Brownian regime (from $t = 20$ to 35 days) given by Equation (15) (upper green line in Figure 4). The root mean square difference as a function of L and T shows several local minima (not shown). The scales $L = 1000$ km and $T = 250$ days is defined as optimal as it corresponds to the local minima having the smallest averaging spatial scale.

With these optimal averaging scales, the computed fluctuating displacements variance $\langle r'^2(t)\rangle$ ~~,~~ ~~and to check if it fits~~ fits well with Taylor's theory. ~~The fluctuating displacement is the integral in time of the fluctuating velocities and is here computed for segment periods of 35 days.~~ As in Rampal et al. (2009b), we find a clear transition between the two diffusion regimes (indicated by the ~~dashed~~ green lines in Figure 4). In the ~~initial "ballistic "~~ ballistic regime, the displacement variance grows with t^2, whereas in the ~~"Brownian "~~ Brownian regime, the displacement variance grows with t. The time scale at which the regime transition occurs corresponds to the integral time scale ~~, Γ, which value (1.4 days) is similar to the one found by Rampal et al. (2009b).~~

~~We continue the evaluation by comparing the~~ $\Gamma = 1.71$ days. Also the magnitude of the fluctuating ~~displacement variance to~~ displacements variance compares well with the asymptotic values (indicated by the green lines in Figure 4) predicted by the theory for $t \ll \Gamma$ (from Eq. 14) and for $t \gg \Gamma$ (from Eq. 15~~, neglecting the constant α)and we find a good match, whereas the magnitude presented in Rampal et al. (2009b) are underestimated by a factor 100. This mistake, which the authors of Rampal et al. (2009b) are aware of, simply comes from a wrong conversion factor and~~

~~has no impact on the rest of their study, but is worth mentioning here, especially with regard to the coming discussion~~).

We also checked the stationarity of the variance of the fluctuating velocities ~~and found that it was~~ by comparing $\langle u'^2(t)\rangle$ to the mean values $\langle u'^2\rangle$. Having an almost stationary variance was found crucial for having a good match between the computed displacement variance and the asymptotic values predicted by the theory (not shown here). To increase the robustness and statistical significance of the diffusion analysis, we then artificially increase the number of buoy trajectories by splitting each trajectory into 35-day segments starting every 12 hours, i.e. every time a new buoy position along-track is available. By doing so, we make sure that the variance of the fluctuating velocities $\langle u'^2(t)\rangle$, where t here goes from 0 to 35 days, is almost constant~~. We checked that the relative deviation of $\langle u'^2(t)\rangle$~~, with a relative deviation to the mean values $\langle u'^2\rangle$ ~~is~~ not larger than 10%.

~~This evaluation step ensures~~ These evaluation steps ensure that the values given for $\langle u'^2\rangle$, Γ and K (see Table 1) are consistent with the theory and the analysed data, and can then been used with confidence. ~~Note that the value of diffusivity given in Rampal et al. (2009b) is twice as low as the one found here and is not consistent with the other results presented in their study.~~

2.5 Discussion

The first outcome of the diffusion analysis is to provide a simple and rigorous method to separate the mean circulation from the fluctuating motion, which can then be analysed separately. ~~By using the right temporal averaging scales (about a season) on individual buoy trajectories, Thorndike and Colony (1982) were for example able to determine that the mean circulation is directly related to the mean geostrophic wind and the mean ocean circulation with equal contribution, whereas the fluctuating velocity variance is mainly explained (more than 70%) by the geostrophic wind.~~

~~The diffusion analysis also quantifies the diffusion~~ A second outcome is to quantify the diffusion properties of sea ice that can then be compared to the diffusion properties of passive tracers in the ocean. We note that the integral time scale Γ (about 1.71 days), as well as the diffusivity K ($1.17 \times 10^3\,\mathrm{m^2 s^{-1}}$) are of the same order of magnitude as the ones found for ocean drifters (e.g., Poulain and Niiler, 1989; Zhang et al., 2001).

~~Another~~ A third outcome of this analysis is to give a way to estimate the evolution of the fluctuating displacement ~~,~~ r'. The ~~values~~ magnitudes of diffusivity and integral time scale can be used to evaluate the fluctuating ~~displacement~~ displacements variance (and its standard deviation) for any time t with Equations ~~14 and 15~~(14) and (15). The standard deviation of the fluctuating displacement ~~may be~~ is a crucial piece of information for the planning of a recovery operation in the case of drifting oil or some other pollutant that is trapped in or attached to the ice, as it gives an estimate of how the size of the ~~searching~~ search area around the predicted mean drift should increase ~~through~~ with time, in a statistical sense. This is illustrated in Figure 5, which shows the evolution of the norm of the fluctuating displacement for every ~~hundredth~~ thousandth segment retrieved from the IABP tra-

jectories for the winter periods from 1979 to 2011. This norm indicates the distance between a given buoy and the trajectory predicted by the mean drift. ~~We checked that about 68.9%, 95.9~~About 67%, 96% and 99.6% of the fluctuating displacements are smaller than 1, 2, and 3 standard deviations, which means that the fluctuating displacement distribution is in the Gaussian attraction basin.

~~If an operator can only trust the mean drift, which is the case for forecast~~ For forecasts longer than a few days, ~~the information on the standard deviation~~ typically only the mean ice drift can be trusted. Then, the long-term average standard deviation provided here could be used to define the size of the ~~searching~~ search area around the position predicted by the mean drift. ~~The searching~~ For example, the search area could be ~~for example~~ defined as a circular region with a radius equal to 3 standard deviations of the fluctuating displacement. The ~~searching~~ search radius would then be about ~~90~~84 km after 5 days (corresponding to a surface area of ~~23,600~~22,200 km^2), and about ~~210~~222 km after 30 days (corresponding to a surface area of ~~133,700~~154,900 km^2). More examples are given in Table ~~??~~2.

The diffusion analysis may also be used to predict long-term (typically seasonal) sea ice trajectories based on continuous or discrete tracer models. The average mean velocity needed by the tracer model may be defined from observations taken over the last few months, whereas the term reflecting the effects of the ~~non-predictive~~ unpredictable fluctuations may be defined by the values of diffusivity and integral time scale derived from the diffusion analysis.

Compared to the analysis of the same data performed by Rampal et al. (2009b), several improvements should be highlighted. First of all, the mean velocity field is defined with a simpler weighted average which does not depend on the rank or the distance of the observations to the target point. Secondly, the criterion to define the optimal averaging scales does not depend on an arbitrary criterion of convergence but on the minimisation of the deviation from Taylor's diffusion theory. Finally, we checked that the results presented here fit with Taylor's diffusion theory. In Rampal et al. (2009b), the fluctuating displacement are underestimated by a factor 100. This mistake, which the authors of Rampal et al. (2009b) are aware of, simply comes from a wrong conversion factor and has no impact on the rest of their study, but is worth mentioning here, especially with regard to the present discussion. Note that the value of diffusivity given in Rampal et al. (2009b) is twice as low as the one found here and is not consistent with the other results presented in their study. We do not know the reason for this inconsistency.

There are, however, some limitations when using the mean motion and mean diffusivity to force passive tracer models:

- the averaging smooths out local mean circulation features such as coastal currents,
- the method is not well suited for studying dispersion as it assumes no spatial correlation,
- the diffusivity could differ spatially and be not well represented by the basin-wide mean value,

– the diffusivity could be affected by the long term trend in the mean speed identified in Rampal et al. (2009a) and may therefore not be well represented by a ~~value computed over the last four~~ single mean value derived from these decades.

These issues do not occur if the tracer models are directly forced with sea ice velocity fields representing correctly both the mean and fluctuating parts of the motion field, as well as their gradient at all scales. The diffusion analysis presented here can also help to assess the representation of the mean and fluctuating parts. In the following section such an assessment is carried out on the results of the two sea-ice(–ocean) ~~modelling~~ modeling platforms, neXtSIM and TOPAZ.

3 Diffusion analysis on observed and simulated sea ice trajectories

Model output or reanalyses are often used to directly force passive tracer models (e.g. Nudds et al., 2013; Gearon et al., 2014). In that case, it is important to check if the simulated trajectories ~~represent well~~ adequately represent the mean and fluctuating parts of the sea ice motion before pursuing an analysis of these trajectories. In some cases, a specific term is added to the tracer model (either via a diffusive term or a random perturbation) to represent the effect of the unresolved physics on the tracer evolution. When applied in the ocean, the stochastic part represents molecular and turbulent diffusive processes that are not included in the velocity fields simulated by the ocean model. However, as sea ice~~in the ice pack~~, especially compact pack ice, does not behave as a turbulent fluid, the stochastic term to be used for sea ice should not be taken to represent the same underlying physical processes as in the ocean, and therefore may have a different form ~~and/~~or be scaled with a different coefficient. In this section, we follow an approach that is frequently used for ~~the~~ oceanic drifters (e.g., Dominicis et al., 2012)~~and which~~. This approach consists of applying the diffusion analysis to observed and simulated trajectories to determine how the mean and fluctuating motion are represented and how unresolved physics could be taken into account.

3.1 Observed and simulated trajectories datasets

In this section we compare observed trajectories from the IABP dataset to trajectories of virtual buoys (here called "floats") whose motion is forced by sea ice fields coming from two different model setups. Due to limited available computational time, this analysis is restricted to three consecutive winters. The period 2007-2010 has been selected for its relatively good data coverage, with more than 40 IABP buoys recording their positions simultaneously every day.

The float simulations are initialised at the same time and position as the IABP buoys (280 individual floats). The positions of each float are sampled every 12 hours at the same time as the IABP buoys, and stop when the IABP buoy track stops or when the float enters into an area of simulated open water (sea ice concentrations less than 15%). By doing so, three comparable datasets with the exact same number of positions are obtained: i) the observed sea ice trajectories, already discussed in section 2.1, ii) the trajectories of virtual sea ice floats forced by a free run of the TOPAZ sea-ice–ocean data assimilation system, and iii) the trajectories of virtual sea ice floats simulated by the neXtSIM sea ice model.

3.1.1 TOPAZ trajectories dataset

TOPAZ is a coupled sea-ice–ocean data assimilation system (Sakov et al., 2012) used in the operational Arctic Ocean forecast platform of the European Copernicus Marine Environment Monitoring service (http://marine.copernicus.eu). It has also been used to build a 23-years reanalysis (1991-2013), also distributed by the Copernicus marine service. The ocean part of TOPAZ uses the

HYCOM model version 2.2, with 28 vertical layers, whereas the sea ice part uses a ~~one thickness category~~ single-thickness-category sea ice model whose thermodynamics are described in Drange and Simonsen (1996) and dynamics are built around a standard EVP rheology (Hunke and Dukowicz, 1997) as it was implemented in the CICE sea ice model (the Los Alamos Sea Ice Model) version 4 (Hunke and Lipscomb, 2010).

The sea-ice–ocean model of TOPAZ (hereafter called the TOPAZ model) is ~~run~~ used here in free-run mode (i.e., no data assimilation is applied) in the same configuration as in Sakov et al. (2012). The model grid covers the Arctic and North-Atlantic Oceans with a mean resolution of approximately 12 km over the Arctic. The three TOPAZ simulations ~~used here~~ analyzed in the following start on September 15th and finish on May 15th for three consecutive winters from 2007 to 2010 with initial conditions ~~coming~~ extracted from the free-run simulation described in Sakov et al. (2012). The applied atmospheric forcing fields are the ~~6-hourly 10-meter wind velocities~~ 10 m wind velocity, the 2 m temperature and mixing ratio, mean sea level pressure, total precipitation and the fraction of that which is snow, and the incoming short-wave and long-wave radiation from the ERA interim reanalysis (ERAi) distributed at 80 km spatial resolution and 6 hours temporal resolution (http://www.ecmwf.int/en/research/climate-reanalysis/era-interim, ECMWF (2011)).

The TOPAZ model in ~~free run~~ free-run mode has been evaluated in Sakov et al. (2012) and was found to overestimate sea ice drift by about 3 km day^{-1} compared to buoy data. To try to solve this issue, the frictional drag parameters for the atmosphere-ice stress has been reduced to $c_a = 0.0016$ in the TOPAZ operational platform (not yet documented)~~and we then use this value~~. The same value is also used here. The mean sea ice thickness in the free run is ~~underestimated and typically shows too thin ice in areas of thick ice and inversely, too thin ice in areas of thick ice~~generally underestimated and has reduced horizontal gradients. The sea ice thickness is slightly better in the TOPAZ reanalysis, which applies assimilation of sea surface temperature, in-situ profiles, sea ice concentration and sea ice drift, but the total volume is still too low (Sakov et al., 2015, http://marine.copernicus.eu/documents/QUID/CMEMS-ARC-QUID-002-003.pdf). ~~The TOPAZ model has been found "sufficiently eddy permitting" in the North Atlantic but this does not apply to the Arctic where the Rossby radius is about 5–15km in the Nansen and Canadian basins and can be as small as 1–7 km in the shelf seas where density stratification is weak or in shallow waters (Nurser and Bacon, 2014).~~

The float tracking with the TOPAZ model is ~~here~~ performed off-line by using the hourly mean sea ice velocity fields simulated by the model. The float-tracking system moves the floats with a simple Eulerian method. The virtual floats move in the quasi-homogeneous TOPAZ Arctic grid in order to avoid singularity errors at and around the Pole that would arise with a regular longitude/latitude grid. The sea ice velocities given by the TOPAZ model are interpolated with a bilinear method to the position of the virtual Lagrangian floats every hour. We checked that for the time scale and spatial resolution considered here, this tracking method gives similar results to ~~using an online tracking~~

~~system,~~ computing the float position during run-time with the advantage of remaining computationally efficient.

3.1.2 neXtSIM trajectories dataset

neXtSIM is a fully-Lagrangian thermodynamic-dynamic sea ice model, using an adaptive finite element mesh and a mechanical framework based on the elasto-brittle rheology (Rampal et al., 2015). Thermodynamic growth and melt of the ice are based on the zero-layer model of Semtner (1976) and the ice model is coupled to a slab ocean model, whose variables are the slab ocean temperature and salinity. ~~The model is still under development but~~ While still being under development, the model is already used in an experimental sea ice forecast platform covering the Kara Sea (https://www.nersc.no/data/nextsim-f).

The configuration used here is the same as the one presented and evaluated in Rampal et al. (2015). The model domain shares the exact same coastlines and open boundaries as the TOPAZ model described above, i.e. it covers the Arctic and North-Atlantic Oceans extending from an open boundary at 43°N in the North-Atlantic to an open boundary in the Bering Strait. The mean resolution of the finite element mesh used by neXtSIM is about 10 km. The three neXtSIM simulations used here start on September 15th and finish on May 15th, for three consecutive winters from 2007 to 2010. The model is initialised with the ice concentration derived from the AMSR-E passive microwave sensor (Kaleschke et al., 2001; Spreen et al., 2008, data obtained from the Integrated Climate Date Center, University of Hamburg, Germany, http://icdc.zmaw.de) and the TOPAZ reanalysis ice thickness, within the area ~~reported by AMSR-E as being~~ covered with ice. ~~The modelled ice volume in~~ As the modeled ice volume of the TOPAZ reanalysis ~~being known~~ is known to be too low (Sakov et al., 2015), we increased the initial thickness uniformly so that the total volume is the same as that given by the PIOMAS model (Zhang and Rothrock, 2003) on September 15th 2007, 2008 and 2009, respectively~~(Zhang and Rothrock, 2003)~~. The good performance of PIOMAS in simulating Arctic sea ice volume as compared to available observations is reported in Schweiger et al. (2011). The temperature and salinity of the slab ocean model are initialised with temperature and salinity from ~~TOPAZ~~the TOPAZ reanalysis. The model is forced with the ocean state (i.e., sea surface height, velocity at 30 m depth, and sea surface temperature and salinity) of the TOPAZ reanalysis. The atmospheric state comes from the Arctic System Reanalysis, Interim version (ASR-Interim hereafter) (http://rda.ucar.edu/datasets/ds631.4/, Byrd Polar Research Centre/The Ohio State University (2012). Accessed 01 Jan 2014). The ASR-Interim is a high resolution atmospheric reanalysis (30 km with output every 4 hours) known to reproduce particularly well the near-surface wind fields in the Arctic region (Bromwich et al., 2016).

The neXtSIM model is able to simulate correctly the observed evolution of the sea ice volume, extent and area for the freezing season (from September to May) but simulates a too rapid melt from May onwards (Rampal et al., 2015). This limitation does not impact the results of this ~~analysis~~ study

as we only ~~look at~~ analyse simulated drift in winter with simulations restarted every September. For the winter season 2007-2008, the simulated drift fields have been extensively evaluated in Rampal et al. (2015) against satellite derived products, showing ~~no~~ a high correlation (higher than 0.85) and only a negligible bias in the ~~3-days drift~~3-day drift, and a good representation of the mean circulation.

The float tracking with neXtSIM is performed at ~~run time~~run-time. The main reason for doing this is that the Lagrangian advection used in the neXtSIM model offers some additional challenges to a post-processing approach using Eulerian fields ~~. The floats positions then change as the underlying mesh moves and are interpolated onto the new mesh after each remeshing step~~ due to the remeshing technique applied (see Rampal et al. (2015) for more details on the remeshing procedure).

3.2 Results

Figure 6 shows ~~the~~ maps with all the buoy/float trajectories for each winter season from the IABP, TOPAZ and neXtSIM ice trajectories datasets. The ~~different datasets for the period~~ three winter subsets from 2007 to 2010 are much sparser and cover a smaller portion of the Arctic Ocean than the reference dataset of 1979-2011 analysed in Section 2.1. As it is not practical to directly compare the simulated and observed trajectories, we analyse separately the mean drift and the fluctuating part of the motion by applying the ~~same decomposition of the sea ice motion as the one~~ decomposition method presented in Section ~~2.1~~2.2.

The mean velocity fields for each winter season and for the three datasets are shown in Figure 7. The two main features of the Arctic-wide mean circulation are the Beaufort Gyre and the Transpolar Drift. ~~However, we note that the~~ The lowest drift speeds are observed along the Canadian Arctic Archipelago, where the ice is significantly thicker and more ridged. The strength and the extent of the Beaufort Gyre, as well as the strength of the Transpolar drift, vary from one year to the ~~other~~next. This inter-annual variability is well represented by both TOPAZ and neXtSIM. The ~~two models, however, perform differently in terms of the magnitude and the spatial distribution of the mean sea ice drift . The TOPAZ model generally overestimates the mean drift field and does not correctly reproduce the spatial patterns. In particular the size of the Beaufort Gyre is often overestimated and the model does not reproduce the~~ quality of the mean drift simulated by the two models is not constant in time nor in space. In 2007/8, the simulation with TOPAZ largely misses the low drift speed along the Canadian Arctic Archipelago, ~~which are due to significantly thicker and more ridged ice. The mean ice drift simulated by the neXtSIM model reproduces well the mean circulation patterns, slightly underestimates the magnitude of the Beaufort Gyre but reproduces well the almost immobile pack ice north of the Canadian Arctic Archipelago~~when the simulation with neXtSIM correctly reproduces it. For the other winters, it is less obvious to distinguish clear differences in the quality of the simulated mean drift fields.

The statistical distribution of the mean velocity ~~also~~ gives valuable information and can be used to evaluate the simulated mean drift more objectively. Figure 8 shows the probability density func-

tion of the mean speed ~~,~~ $\bar{U} = \sqrt{\bar{u}^2 + \bar{v}^2}$ ~~,~~ as computed from the IABP buoy data and from the TOPAZ and neXtSIM virtual buoy data for the period 2007-2010~~. The mean speed distribution from the observations~~ , as well as the Gaussian and exponential fits. None of the three distributions fits well with ~~an exponential function and has a mean value equal to 2.45~~the Gaussian or exponential distributions on the whole range of values. The mean speed distribution obtained with the TOPAZ dataset seems to have not enough values within the range 0 to 1.5 $\mathrm{cm\,s^{-1}}$ and too many values within the range 1.5 to 4 $\mathrm{cm\,s^{-1}}$. The mean speed distribution obtained ~~with the TOPAZ dataset does not follow an exponential distribution and has a mean value equal~~ from the neXtSIM dataset is close to the observed distribution within the range 0 to ~~3.38~~4 $\mathrm{cm\,s^{-1}}$, but differs for the larger values. The mean value of the observed mean speed is equal to 1.95 $\mathrm{cm\,s^{-1}}$, when the one of the TOPAZ dataset is 2.89 $\mathrm{cm\,s^{-1}}$, which is about ~~38~~48% larger than ~~the one of the IABP buoys. The mean velocities obtained~~ than the observations, and the one from the neXtSIM dataset ~~follow an exponential distribution with a mean equal to 2.00~~is 1.65 $\mathrm{cm\,s^{-1}}$, which is about ~~18~~15% lower than the observations.

When removing the mean part of the velocity field we are left with the fluctuating velocity field $u'(x)$. If the mean part is removed correctly (according to the Taylor's theory), ~~the fluctuating velocities~~ each component of the fluctuating velocity should be symmetrically distributed around zero. This is the case in our results (not shown), meaning that one can directly ~~look at the speed~~ use the norm of the fluctuating velocity instead of the components separately, without losing information. The PDFs of the fluctuating speeds are plotted in Figure 9 with the Gaussian and exponential fits indicated for reference.

The fluctuating speeds of the IABP buoys clearly follow an exponential distribution with a mean equal to ~~6.9~~6.98 $\mathrm{cm\,s^{-1}}$. ~~It is important to note here~~ The fact that the data follow an exponential distribution instead of a Gaussian distribution ~~, this~~ means that the sea ice fluctuating speed can be much larger than a standard deviation away from the (zero) mean. Such non-Gaussian distributions for fluctuating speeds are not expected for fully developed turbulence (Batchelor, 1960; Frisch, 1995) but have been observed for oceanic surface currents during energetic events associated with large organised structures such as jets and vortices. Such a signature for multi-year sea ice may indicate that sea ice dynamics are dominated by the passage of large perturbations over the Arctic, whereas less energetic features have less impact on sea ice motion. This selective sensitivity to energetic events may be related to the intrinsic properties of solids associated with threshold mechanics (Rampal et al., 2009b). This seems to be supported by the fact that for weaker seasonal sea ice, the observed fluctuating velocities rather follow Gaussian statistics (Lukovich et al., 2011).

The mean value of the fluctuating speeds from the TOPAZ setup ~~are too high on average (~~is too high by about 30% ~~) with a mean value close to 9~~ (8.97 $\mathrm{cm\,s^{-1}}$ ~~, and~~ instead of 6.98 $\mathrm{cm\,s^{-1}}$). Also their statistics do not follow an exponential distribution ~~. The~~ as in the observations but are closer to the Gaussian fit centred on the value 10 $\mathrm{cm\,s^{-1}}$, resulting in an underrepresentation of both the

very high speed (larger than 30 cm s^{-1}) and very low speed (smaller than 5 cm s^{-1}). The mean value of the fluctuating speeds from neXtSIM ~~are slightly too low (~~is too low by about 10% ~~) with a mean value equal to 6.1~~(6.2 cm s^{-1}~~and~~). The fluctuating speeds follow an exponential distribution ~~within the~~ but only in the velocity range 0 to 30 cm s^{-1}. The high speed values are missed by the two models.

Figure 10 shows the evolution of the fluctuating ~~displacement~~ displacements variance for the observed and simulated trajectories. The fluctuating displacement are ~~here~~ computed for segments of 35 days, the same as in the analysis of the reference dataset. The magnitude of the fluctuating ~~displacement~~ displacements variance is constantly overestimated ~~in~~ with TOPAZ, by about 40% in the ballistic regime and almost ~~100~~50% in the Brownian regime. This is ~~consistant~~ consistent with the fact that ~~both~~ the integral time scale and fluctuating velocity variance are overestimated by ~~about 40%~~ 15% and 30%, respectively, (see Table 1). In the Brownian regime, these overestimation are combined resulting in the overestimation of the diffusivity by about ~~100%. In~~ 50%. With neXtSIM the fluctuating displacements are underestimated in the ballistic regime but correctly reproduced for the Brownian regime. This is consistent with the underestimation of the fluctuating velocities variance by about ~~20~~23%, which is balanced in the Brownian regime by the overestimation of the integral time scale by about ~~20~~25%, leading to a diffusivity almost equal to the one coming from the observations for the same period.

Figure 11 shows the regional distribution of the diffusivity fields. The ~~diffusivity~~ results obtained with the TOPAZ setup have a correlation coefficient against the diffusivity map obtained from observations of about 0.71, but generally overestimate the diffusivity. The results obtained with the neXtSIM setup have a correlation coefficient against diffusivity map obtained from observations of about 0.85, and adequately represent the magnitude of the diffusivity.

The diffusivity field computed from the IABP buoys is not uniform and seems to be related to the spatial distribution of ~~the multi-year ice concentration and ice thickness (as shown in Kwok et al., 2009)~~sea ice thickness shown in Figure 12, with rather low diffusivity values along the Canadian Arctic Archipelago (i.e. ~~down to~~ as small as about 0.5×10^3 m^{2}s$^{\cancel{-2}-1}$) and larger values in the ~~East Siberian Sea and in Beaufort Sea. The presence of thick multi-year ice (more than 3 meters) north of the CAA may then explain the low diffusivity values (lower than 1×10^3~~ Beaufort and East Siberian seas ($1.5-2.5\times10^3$ m^{2}s$^{\cancel{-2}-1}$). ~~The results~~ The spatial distribution of the diffusivity obtained with the TOPAZ ~~setup analysed here also show a non-uniform distribution that may be related to~~ and neXtSIM setups also correlate well with the simulated sea ice thickness pattern (~~not shown). The magnitude of the diffusivity for TOPAZ is overestimated almost everywhere except for a few cells located at the boundaries of the analysed domain.The results obtained with the neXtSIM setup represent well the magnitude and spatial variability of the diffusivity.The correlation coefficient between the diffusivity map obtained~~

~~from observations and those obtained from TOPAZ and neXtSIM are equal to 0.7 and 0.85, respectively.~~ shown in Figure 12).

3.3 Discussion

The goal of the present analysis is not to compare the model systems themselves but to illustrate how the simulated motion fields differ from observations and what would be the impact of using such model outputs to force passive tracers models to study for example trajectories of pollutant trajectories in sea ice. The differences between the simulated and observed motion may be due to many factors, ranging from the internal characteristics of the sea ice models (their rheology, drag parameterisation,...) to external causes, such as the initial conditions, atmospheric forcing and impact of the ocean. To distinguish the effects of each factor would require to run the same model with different initial conditions, forcings and set of parameters, or to run different models in the same configuration (initial conditions, forcings, parameters,...). Other diagnostics than the diffusion analysis would also be necessary. For example, the effect of the rheology would be better analysed by a dispersion analysis (double particle diffusion) as in Rampal et al. (2008) as it is directly related to sea ice deformation. Nevertheless, even if the present analysis cannot clearly distinguish the sources of the differences between the simulated and observed trajectories, it provides pertinent information on the quality of the simulated trajectories.

The TOPAZ model reproduces the very basic characteristics of the Arctic sea ice mean circulation, with interannually varying Beaufort Gyre and Transpolar drift. ~~The largest differences in the mean circulation simulated by TOPAZ and the observations are~~However the averaged mean drift is overestimated by about 48%. This overestimation partly comes from missing the mean drift speed smaller than 5 $\mathrm{cm\,s^{-1}}$ that are, in the observations, localised north of the CAA in a region covered by thick multi-year ice. ~~These differences appear to be related to the local underestimation of sea ice thickness by the TOPAZ model. This localised underestimation of the mean drift greatly affects the lower part of the distribution (mean drift lower than 5~~

In the simulations analysed here, TOPAZ misses both the low (larger than 10 $\mathrm{cm\,s^{-1}}$) ~~. The misrepresentation of the sea ice thickness distribution in the Arctic by TOPAZ is likely not a problem related to the sea ice thermodynamics model but rather to the sea ice dynamics model and more specifically to its rheological component which controls the formation of leads and ridges by determining the mechanical response of the ice pack to external mechanical forcings.~~

~~The largest values of the mean circulation (mean drift larger than 15~~and high (larger than 30 $\mathrm{cm\,s^{-1}}$) ~~are underestimated in TOPAZ. Those values are localised in regions of thinner ice, where the TOPAZ system is known to overestimate sea ice thickness. This underestimation could also be due to the ocean model, especially in the Beaufort Gyre, which is reported as being too large and misplaced in TOPAZ compared to observations (Sakov et al., 2012).~~

~~Contrary to the mean drift, the long term fluctuating displacement (and equivalently the diffusivity) is homogeneously overestimated in TOPAZ. The large overestimation (by about 100%) of the long term fluctuating displacement comes from the combined effect of an excessively long integral time scale and overestimated fluctuating velocities variance. The~~ values of fluctuating speed. As the low values largely dominate the observed distribution, missing those values leads to an overestimation of the fluctuating velocities mean and variance. When combined to the overestimation of the integral time scale~~is likely due to the atmospheric forcing (ERA-interim) , which has a limited representation of the local and rapidly varying surface wind.~~ , it leads to a large overestimation (by about 50%) of the long term fluctuating displacement and absolute diffusivity.

The ~~simulations with the neXtSIM model represent well the spatial and~~ neXtSIM model also reproduces the interannually varying Beaufort Gyre and Transpolar drift. The statistical distribution of the mean circulation ~~. The nearly immobile ice north of the CAA is well represented. The~~ is close to the one obtained from the observations for the range 0 to 4 cm s^{-1}, but the largest values of the mean circulation (mean drift larger than ~~15~~4 cm s^{-1}) are underestimated, ~~just as in TOPAZ, and this may explain the slight underestimation of~~ resulting in an underestimation of about 15% of the averaged mean drift. ~~This misrepresentation may thus come from the oceanic forcing which comes from the TOPAZ reanalysis.~~

~~The spatial and statistical distributions of the fluctuating motion are also well reproduced in the neXtSIM simulations. The slight underestimation of the averaged fluctuating speed likely comes from the missing largest valuesof~~ In the simulations analysed here, neXtSIM represents well the statistical distribution of the fluctuating ~~velocities. This, as well as~~ speed until 30 cm s^{-1} but misses the higher values, leading to an underestimation of the fluctuating velocities mean and variance. When combined to the overestimation of the integral time scale, this leads to long term fluctuating variance and diffusivity having the same magnitude as in the observations.

The two model setups used here have a common deficiency at representing the fluctuating speed higher than 30 cm s^{-1}. This is likely to come from the missing local and rapidly varying ~~high~~ winds in the atmospheric ~~reanalysis~~ reanalyses (ASR-interim ~~,~~ and ERA-interim) used here to force ~~neXtSIM. It may also~~ the models. This lack of variability in the forcings may also explain the overestimation of the integral time scale seen in the two setups. These too long integral time scales may also partly come from missing physics ~~related to the absence of mechanical coupling between neXtSIM and the slab ocean underneath in our configuration. Therefore, sea ice motion features like inertial oscillations that~~ or too weak coupling (e.g., too low frequency in the coupling and forcing) in the model setups, that may lead to a misrepresentation of the inertial oscillations and impact 12-hourly drift statistics~~are not reproduced in the simulations analysed for this study~~.

It is common practice to add an extra diffusive term to the tracer evolution equation, as discussed earlier. In the case of the TOPAZ setup, adding such an extra term to the tracer evolution equation would not help, as the model already overestimates the fluctuation both in the ballistic and Brownian

regimes. Adding such a term when using the neXtSIM setup presented here may improve the evolution of the fluctuating displacement in the ballistic regime. Adding a random term would increase the fluctuating velocity variance but decrease the integral time scale. ~~Doing this may then keep~~ This may allow to maintain the good performance in reproducing the long term displacements and diffusivity fields, without impacting the long term mean drift.

4 Summary and conclusions

In the first part of the paper (Section 2), we analyse IABP buoys trajectories for the winter periods between 1979 and 2011 and we ~~confirm that the appropriate averaging scales to define the mean circulation in winter are about 400 km and 165 days. This agrees with the results of Rampal et al. (2009b), but we additionally verify that the computed displacement variance is consistent with the theory and with the estimated~~ estimate the values of the integral time scale (about ~~1.5~~ 1.7 days), the 12-hourly fluctuating velocities variance (~~73~~59 km^2 day^{-2}) and the diffusivity (~~1.2~~1.17$\times 10^3$ m^{2}s~~$^{-2}$).~~ $^{-1}$). We additionally verify that the computed displacement variance is consistent with Taylor's diffusion theory.

These information can be used in the context of pollutant tracking to evaluate the proper size for the ~~searching~~ search area around the long-term trajectory predicted by the mean drift. If one defines the ~~searching~~ search area as a circular region with a radius equal to 3 standard deviations of the fluctuating displacement, which would include the polluted area with 99.6% confidence, we find that on average the ~~searching~~ search radius should be about ~~90~~84 km after 5 days (corresponding to a surface area of ~~24000~~about 22000 km^2), and about ~~210~~222 km after 30 days (corresponding to a surface area of ~~134000~~155000 km^2). Before using these estimates, one should remind that they are given for the whole Arctic basin and for the whole period 1979-2011 and may then differ from estimates computed for specific regions and time periods. Also as the IABP buoys are mainly deployed on multi-year ice, these estimates may not be valid for seasonal ice and for future applications.

The estimates of the mean drift field, diffusivity and integral time scale computed here could also be used within a passive tracer model (either with an advection-diffusion equation or a Lagrangian stochastic approach) to estimate the probability for a particle to be in a given position after a given time. The limitations of that approach would be the excessive smoothing of local mean circulation patterns (e.g., coastal currents), the inability to represent dispersion and the potential misrepresentation of the spatial and temporal distribution of the diffusivity values.

In the second part of the paper (Section 3), we analyse trajectories of virtual buoys whose motion is forced by simulated sea ice velocity fields. This approach eliminates the limitations of using tracer models forced by mean fields but relies on the good representation of the sea ice drift by the models. To illustrate how one could evaluate sea ice model ~~outputs before using them for trajectory modelling~~output before using it for trajectory modeling, we applied the diffusion analysis to three

similar datasets, one from the IABP data, one from the TOPAZ model and one from the neXtSIM model, and we compared the numbers obtained from simulated and observed trajectories.

The mean velocities in the simulations using TOPAZ are on average ~~40~~50% too high ~~, follow a Gaussian instead of an exponential distribution and do not represent correctly the circulation~~ and generally miss the very low mean drift located near the Canadian Arctic Archipelago. ~~This limitation may be largely linked to the misrepresentation of the sea ice thickness spatial distribution, with too thin ice along the CAA and too thick ice elsewhere. The fluctuating velocities mean and variance~~ The long-term displacement variance and absolute diffusivity are also overestimated ~~, even if the simulated fields do not reproduce the observed high values of fluctuating speed (larger than 40 cm s^{-1}). The overestimation of the fluctuating velocities combined to the overestimation of the integral time scale leads to an overestimation of the long-term displacement variance by about 100~~by about 50%. ~~The validity of tracer studies based on similar setups could be substantially affected by those differences compared to observations~~Using the output of this TOPAZ setup for tracer studies would produce too long trajectories and too large displacement variance, potentially affecting the conclusions of such studies.

The mean velocities in the simulations using neXtSIM are on average ~~20~~15% too low, ~~follow an exponential distribution and~~ reproduce well the ~~spatial distribution~~ very low mean drift located near the Canadian Arctic Archipelago but misses the highest values of the mean motion. The ~~fluctuating velocity's mean and variance are also slightly underestimated, which may come from the missing high values of fluctuating speed (larger than 40 cm s^{-1}). The underestimation of the fluctuating variance is compensated by the overestimation of the integral time scale, leading to~~ long-term displacement variance ~~fitting very~~ and absolute diffusivity fit well the observations. Tracer studies based on ~~similar~~ such results could be trusted except for the ballistic regime (first few days), where the simulated displacement variance is too weak.

Using the outputs of the simulations made with neXtSIM would give better sea ice trajectories than using the outputs of the TOPAZ simulations analysed here. However, if this difference mainly originates from (a) the different initial conditions, forcing, and ocean or (b) the sea ice model itself (different rheologies and thermodynamics) cannot be clearly answered. As a follow up of this study, it would be interesting to investigate the causes of the missing high values of fluctuating velocities and the overestimation of the integral time scale, first by ~~looking at~~ examining the impact of the atmospheric forcing resolution and second by ~~looking at the representation of the~~ checking how the inertial/tidal oscillations are represented by the two ~~modelling~~ modeling platforms used here. To better asses the quality of the simulated sea ice dynamics, it would be interesting to also perform a dispersion analysis as in Rampal et al. (2008) or to specifically study sea ice deformation as in Bouillon and Rampal (2015) with data from models and observations. Finally, it is worth noting that the representation of the mean sea ice circulation depends on many processes (mean circulation of the atmosphere and ocean, spatial and temporal variation of the ocean–ice and air–ice drag coefficients

as a function of the ice age/type, representation of the ocean–ice and atmosphere–ice boundary layers (McPhee, 2012), etc.), ~~whose~~ which the respective roles would also need to be further explored.

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References

Batchelor, G. K.: The theory of homogeneous turbulence, Students' edition. By G. K. Batchelor. Cambridge Monographs on Mechanics and Applied Mathematics. Cambridge (University Press), 1959. Pp. xi, 197; 28 Figures; 18s. 6d, Quarterly Journal of the Royal Meteorological Society, 86, 291–291, 1960.

Borgå, K., Poltermann, M., Polder, A., and Pavlova, O.: Influence of diet and sea ice drift on organochlorine bioaccumulation in Arctic ice-associated amphipods, Environmental Pollution, 117, 47–60, doi:10.1016/s0269-7491(01)00160-9, 2002.

Bouillon, S. and Rampal, P.: Presentation of the dynamical core of neXtSIM, a new sea ice model, Ocean Modelling, 91, 23–37, 2015.

Bromwich, D. H., Wilson, A. B., Bai, L.-S., Moore, G. W. K., and Bauer, P.: A comparison of the regional Arctic System Reanalysis and the global ERA-Interim Reanalysis for the Arctic, Quarterly Journal of the Royal Meteorological Society, 142, 644–658, doi:10.1002/qj.2527, http://dx.doi.org/10.1002/qj.2527, 2016.

Colony, R. and Thorndike, A. S.: An estimate of the mean field of Arctic sea ice motion, J. Geophys. Res., 89, 10 623—10 629, doi:10.1029/JC089iC06p10623, 1984.

Colony, R. and Thorndike, A. S.: Sea ice motion as a drunkard's walk, J. Geophys. Res., 90, 965–974, 1985.

Dominicis, M., Leuzzi, G., Monti, P., Pinardi, N., and Poulain, P.-M.: Eddy diffusivity derived from drifter data for dispersion model applications, Ocean Dynamics, 62, 1381–1398, doi:10.1007/s10236-012-0564-2, http://dx.doi.org/10.1007/s10236-012-0564-2, 2012.

Drange, H. and Simonsen, K.: Formulation of air-sea fluxes in the ESOP2 version of MICOM, Tech Rep. 125, Tech. rep., NERSC, Bergen, Norway, www.nersc.no, 1996.

Drozdowski, A., Nudds, S., Hannah, C. G., Niu, H., Peterson, I., and Perrie, W.: Review of Oil Spill Trajectory Modelling in the Presence of Ice, Tech. rep., Canadian Tech. Rep. Hydrogr. Ocean Sci. 274, 2011.

Fowler, C. W., Maslanik, J. A., and Emery, W. J.: Satellite-Derived Evolution of Arctic Sea Ice Age: October 1978 to March 2003, IEEE Geosci. Remote Sensing Lett., 1, 71–74, 2004.

Frisch, U.: Turbulence: The Legacy of A. N. Kolmogorov, Cambridge University Press, U.K., 1995.

Gabrielski, A., Badin, G., and Kaleschke, L.: Anomalous dispersion of sea ice in the Fram Strait region, Journal of Geophysical Research: Oceans, 120, 1809–1824, doi:10.1002/2014JC010359, http://dx.doi.org/10.1002/2014JC010359, 2015.

Gearon, M., French McCay, D., Chaite, E., Zamorski, S., Reich, D., Rowe, J., and Schmidt-Etkin, D.: SIMAP Modelling of Hypothetical Oil Spills in The Beaufort Sea for World Wildlife Fund (WWF), Tech. rep., Applied Science Associates and Environmental Research Consulting (ERC), South Kingstown, RI and Cortlandt Manor, NY P13-235, http://awsassets.wwf.ca/downloads/wwf_beaufort_sea_oil_spill_modelling_full_report_rps_asa.pdf, final Report, 2014.

Hunke, E. C.: Sea ice volume and age: Sensitivity to physical parameterizations and thickness resolution in the CICE sea ice model, Ocean Modelling, 82, 45–59, 2014.

Hunke, E. C. and Dukowicz, J. K.: An elastic-viscous-plastic model for sea ice dynamics, J. Phys. Ocean., 27, 1849–1867, 1997.

Hunke, E. C. and Lipscomb, W. H.: CICE model Ver. 4.1 Documentation, Tech. rep., T-3 Fluid Dynamics Group, Los Alamos National Laboratory, 2010.

Kaleschke, L., Lüpkes, C., Vihma, T., Haarpaintner, J., Bochert, A., Hartmann, J., and Heygster, G.: SSM/I Sea Ice Remote Sensing for Mesoscale Ocean-Atmosphere Interaction Analysis, Canadian Journal of Remote Sensing, 27, 526–537, 2001.

Kwok, R., Cunningham, G. F., Wensnahan, M., Rigor, I., Zwally, H. J., and Yi, D.: Thinning and volume loss of the Arctic Ocean sea ice cover: 2003–2008, Journal of Geophysical Research: Oceans, 114, doi:10.1029/2009JC005312, c07005, 2009.

LaCasce, J. H.: Statistics from Lagrangian observations, Prog. Oceanogr., 77, 1–29, 2008.

Lukovich, J. V., Babb, D. G., and Barber, D. G.: On the scaling laws derived from ice beacon trajectories in the southern Beaufort Sea during the International Polar Year - Circumpolar Flaw Lead study, 2007–2008, Journal of Geophysical Research: Oceans, 116, doi:10.1029/2011JC007049, c00G07, 2011.

Lukovich, J. V., Hutchings, J. K., and Barber, D. G.: On sea-ice dynamical regimes in the Arctic Ocean, Annals of Glaciology, 56, 323–331, 2015.

McPhee, M. G.: Advances in understanding ice-ocean stress during and since AIDJEX, Cold Regions Science and Technology, 76-77, 24–36, 2012.

Nudds, S. H., Drozdowski, A., Lu, Y., and Prinsenberg, S.: Simulating Oil Spill Evolution in Water and Sea Ice in the Beaufort Sea, in: Proceedings of the twenty-third International Offshore and Polar Engineering, pp. 1066–1071, International Society of Offshore and Polar Engineers, 2013.

Nurser, A. J. G. and Bacon, S.: The Rossby radius in the Arctic Ocean, Ocean Science, 10, 967–975, 2014.

Pfirman, S., Eicken, H., Bauch, D., and Weeks, W.: The potential transport of pollutants by Arctic sea ice, Science of The Total Environment, 159, 129–146, doi:http://dx.doi.org/10.1016/0048-9697(95)04174-Y, 1995.

Poulain, P.-M. and Niiler, P. P.: Statistical analysis of the surface circulation in the California Current System using satellite-tracked drifters, J. Phys. Ocean., 19, 1588–1603, 1989.

Rampal, P., Weiss, J., Marsan, D., Lindsay, R., and Stern, H.: Scaling properties of sea ice deformation from buoy dispersion analysis, Journal of Geophysical Research: Oceans, 113, doi:10.1029/2007JC004143, http://dx.doi.org/10.1029/2007JC004143, c03002, 2008.

Rampal, P., Weiss, J., and Marsan, D.: Positive trend in the mean speed and deformation rate of Arctic sea ice, 1979-2007, Journal of Geophysical Research: Oceans, 114, doi:10.1029/2008JC005066, http://dx.doi.org/10.1029/2008JC005066, c05013, 2009a.

Rampal, P., Weiss, J., Marsan, D., and Bourgoin, M.: Arctic sea ice velocity field: General circulation and turbulent-like fluctuations, Journal of Geophysical Research: Oceans, 114, C10 014, 2009b.

Rampal, P., Bouillon, S., Ólason, E., and Morlighem, M.: neXtSIM: a new Lagrangian sea ice model, The Cryosphere Discussions, 9, 5885–5941, doi:10.5194/tcd-9-5885-2015, http://www.the-cryosphere-discuss.net/9/5885/2015/, 2015.

Rigor, I. and Colony, R.: Sea-ice production and transport of pollutants in the Laptev Sea, 1979–1993, Science of The Total Environment, 202, 89–110, doi:http://dx.doi.org/10.1016/S0048-9697(97)00107-1, environmental Radioactivity in the Arctic, 1997.

Sakov, P., Counillon, F., Bertino, L., Lisæter, K. A., Oke, P., and Korablev, A.: TOPAZ4: An ocean sea ice data assimilation system for the North Atlantic and Arctic, Ocean Sci., 8, 633–662, doi:10.5194/osd-9-1519-2012, 2012.

Sakov, P., Counillon, F., Bertino, L., Finck, N., and Renkl, C.: Quality Information Document For Arctic Physical Reanalysis Product, Tech. rep., EU Copernicus Marine Service, Bergen, 2015.

Schweiger, A., Lindsay, R., Zhang, J., Steele, M., Stern, H., and Kwok, R.: Uncertainty in modeled Arctic sea ice volume, Journal of Geophysical Research: Oceans, 116, doi:10.1029/2011JC007084, c00D06, 2011.

Semtner, A. J.: A model for the thermodynamic growth of sea ice in numerical investigations of climate, J. Phys. Ocean., 6, 379–389, 1976.

Spreen, G., Kaleschke, L., and Heygster, G.: Sea ice remote sensing using AMSR-E 89-GHz channels, Journal of Geophysical Research: Oceans, 113, doi:10.1029/2005JC003384, c02S03, 2008.

Taylor, G. I.: Diffusion by Continuous Movements, Proceedings of The London Mathematical Society, s2-20, 196–212, doi:10.1112/plms/s2-20.1.196, 1921.

Thomas, D.: The quality of sea ice velocity estimates, Journal of Geophysical Research: Oceans, 104, 13 627–13 652, 1999.

Thorndike, A. S. and Colony, R.: Sea ice motion in response to geostrophic winds, J. Geophys. Res., 87, 5845–5852, 1982.

Zhang, H., Prater, M. D., and Rossby, T.: Isopycnal Lagrangian statistics from the North Atlantic Current RAFOS float observations, J. Geophys. Res., 106, 13 817, 2001.

Zhang, J. and Rothrock, D.: Modeling global sea ice with a thickness and enthalpy distribution model in generalized curvilinear coordinates, Monthly Weather Review, 131, 845–861, 2003.

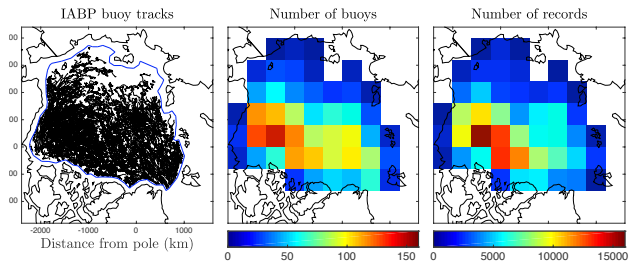

Figure 1. Buoy tracks from the IABP dataset for the ~~period~~ winter periods 1979–2011 (left panel) and the corresponding number of buoys (middle panel) and records (right panel). The Central Arctic domain is delineated by a blue line.

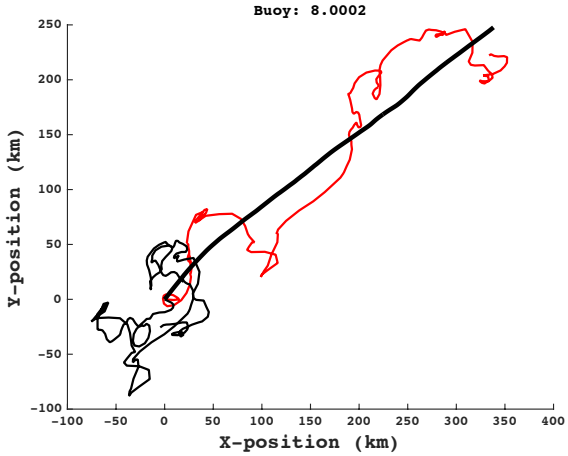

Figure 2. Example of a 35-days long trajectory from a buoy of the IABP dataset (thin red line) partitioned into a mean (thick black line) and fluctuating (thin black line) parts using the method described in subsection 2.2 and the averaging scales $L = 400$ km and $T = 150$ days. The starting point of the three trajectories is the same and arbitrarily set to be the origin of the axes.

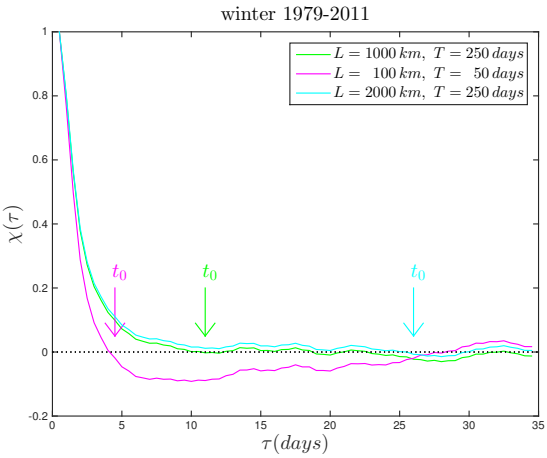

Figure 3. Ensemble ~~averaged fluctuating velocity~~ average autocorrelation function ~~for~~ of the fluctuating velocities computed from the IABP dataset for winter seasons 1979 to ~~2011.~~ 2011 with three different averaging scales. The ~~values of the integral~~ first zero-crossing time ~~scale Γ and mean horizontal diffusivity $\bar{K}$~~ t_0 is given for ~~this particular period are indicated~~indication.

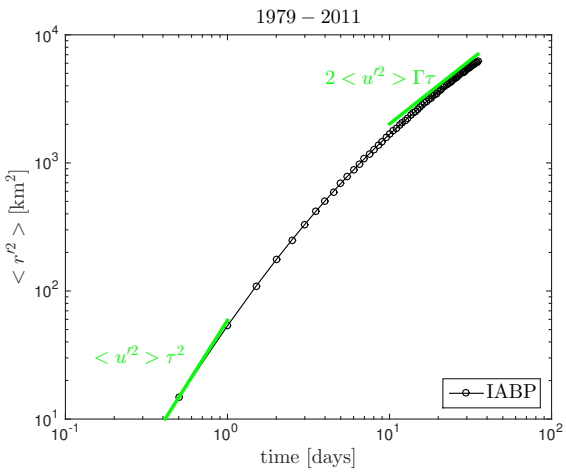

Figure 4. Ensemble mean of the variance of the fluctuating ~~displacement~~ displacements $< r'^2 >$ for the winter seasons 1979-2011 for IABP. The ~~dashed lines indicate the theoretical slopes for the two diffusion regimes: the "ballistic" regime ($\langle r'^2(t)\rangle \sim t^2$) which has a slope equal to 2, and the "Brownian" regime ($\langle r'^2(t)\rangle \sim t$) which has a slope equal to 1. The~~ green lines correspond to the equations (14) and (15) and are shown for reference.

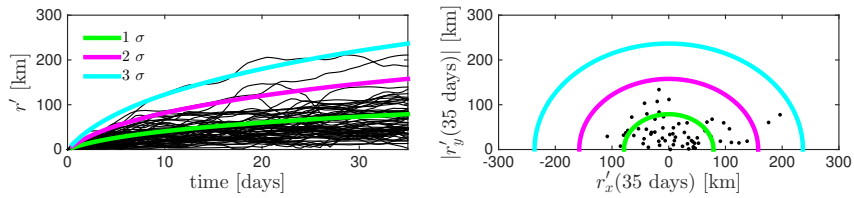

Figure 5. Time evolution of the norm of the fluctuating displacement r' for every ~~hundredth~~ thousandth 35-days segments extracted from the IABP buoys tracks for the winters 1979-2011 (left). The solid lines in color indicate 1, 2 and 3 standard deviations of the fluctuating displacement, respectively. Illustration of ~~searching~~ search area after 35 days (right) estimated statistically from the IABP buoys dataset for the period 1979-2011.

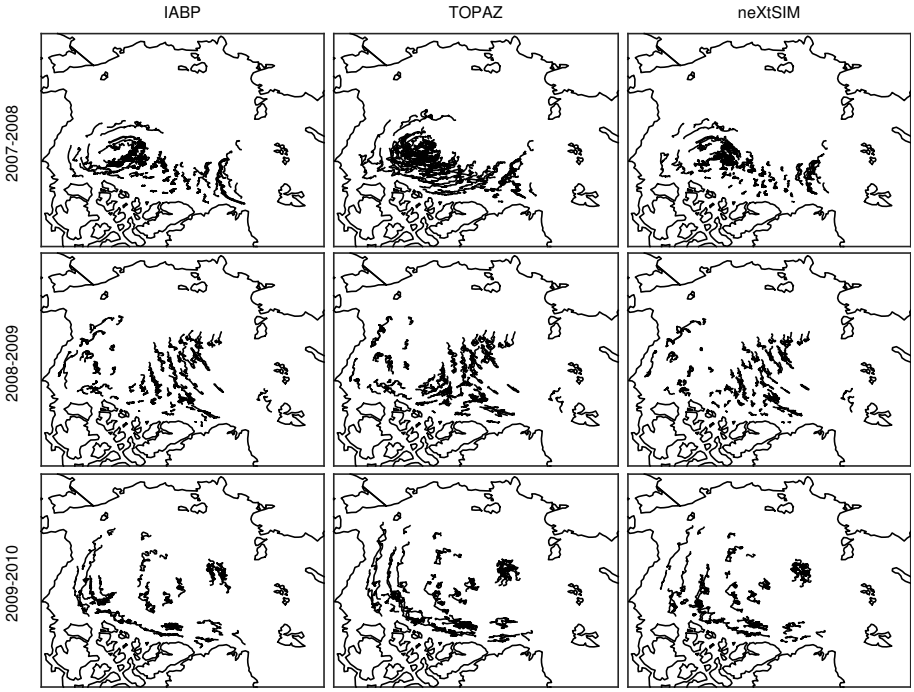

Figure 6. IABP buoys tracks (left) and their corresponding virtual tracks simulated by TOPAZ (centre) and neXtSIM (right) for the winters 2007/2008 (top), 2008/2009 (middle), and 2009/2010 (bottom).

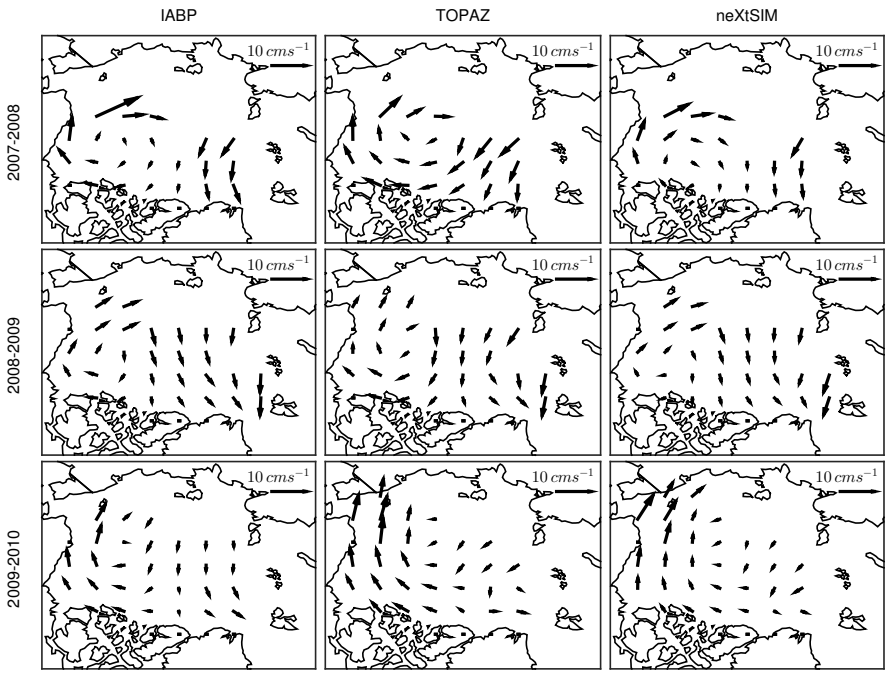

Figure 7. Mean sea ice velocity field computed from the IABP buoys dataset (left) and the corresponding floats dataset generated with TOPAZ (centre), and neXtSIM (right) for the winters 2007/2008 (top), 2008/2009 (middle), and 2009/2010 (bottom). The mean velocity vectors are computed with the averaging scales $L = 1000$ km and $T = 250$ days and are shown on a 400×400 km regular grid.

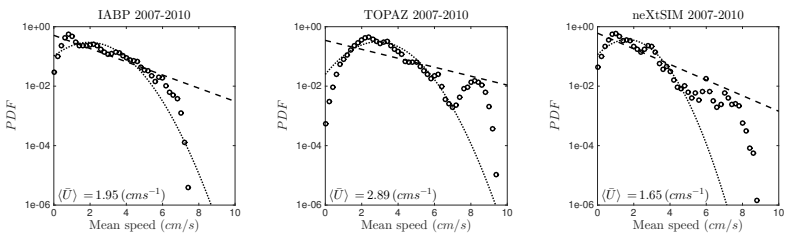

Figure 8. Probability density function of the mean speed of the IABP buoys (left), and of the corresponding virtual floats in TOPAZ (middle) and neXtSIM (right) for the period 2007-2010. The Gaussian (~~dashed~~ dotted lines) and exponential (~~dotted~~ dashed lines) fits of the data are also indicated.

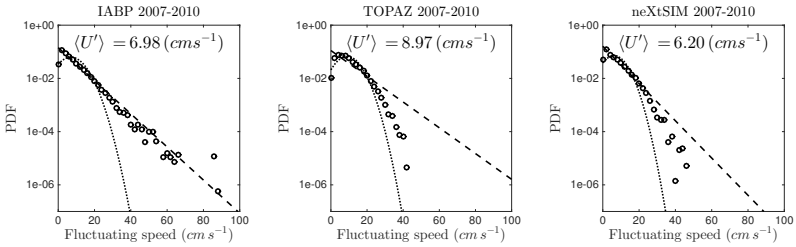

Figure 9. Probability density function of the fluctuating speed of the IABP buoys (left), and of the corresponding virtual floats in TOPAZ (middle) and neXtSIM (right) for the winter periods 2007-2010. The Gaussian (~~dashed~~ dotted lines) and exponential (~~dotted~~ dashed lines) fits of the data are also indicated.

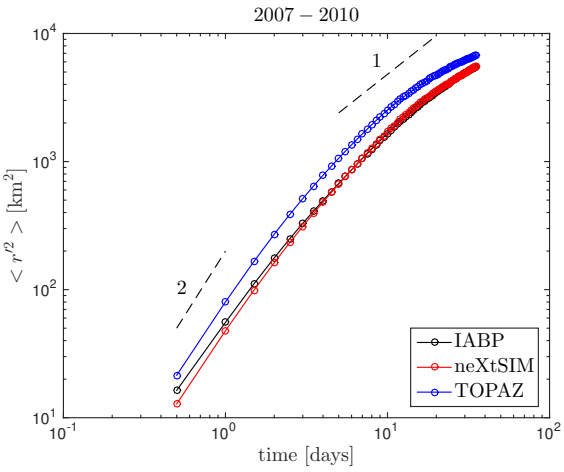

Figure 10. Ensemble mean of the variance of the fluctuating displacement $< r'^2 >$ for the winter seasons 2007-2011 for IABP, TOPAZ and neXtSIM. The dashed lines indicate the theoretical slopes for the two diffusion regimes: the "ballistic" regime ($\langle r'^2(t)\rangle \sim t^2$) which has a slope equal to 2, and the "Brownian" regime ($\langle r'^2(t)\rangle \sim t$) which has a slope equal to 1.

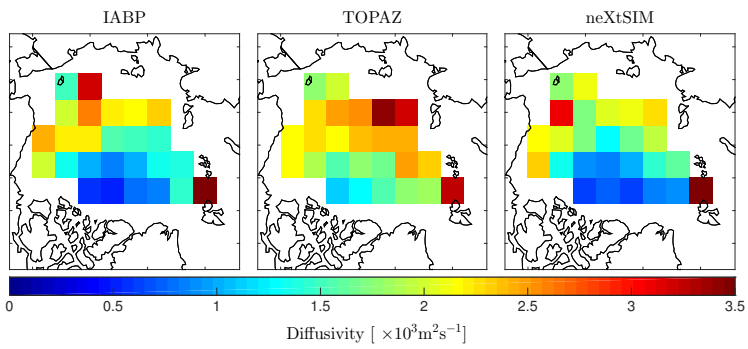

Figure 11. Diffusivity fields obtained from the analysis of the IABP buoys trajectories (left), TOPAZ floats trajectories (middle), and neXtSIM floats trajectories (right) for the winters 2007-2010. The diffusivity is averaged over boxes of 400 by 400 km.

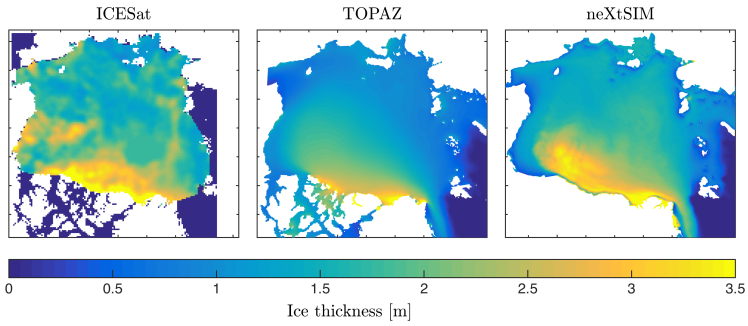

Figure 12. Mean ice thickness in the central Arctic obtained from ICESat satellite observations (Kwok et al., 2009) and the two models. ICESat results are only available in February and March of 2008, while the model results have been averaged over the winters of 2008, 2009, and 2010.

Table 1. This table ~~gives an estimate~~ shows the total number of floats (Nrf), the ~~searching radii and areas corresponding to 1~~calculated integral time scale (Γ), ~~2~~ the variance $\langle u'^2 \rangle$ and ~~3 standard deviations, respectively, and~~ the calculated diffusivity K for ~~time horizons ranging from 1 to 30 days. These numbers are averaged over~~ the ~~whole domain~~ different dataset (IABP, TOPAZ and ~~period analysed in Section 2~~ neXtSIM) and ~~should be reevaluated for specific applications,~~ time periods ~~and domains~~ used in this study. All these Lagrangian statistics were computed following the diffusion theory of ~~interest, for example by~~ Taylor (1921) and using ~~model outputs having passed~~ $L = 1000$ km and $T = 250$ days as averaging scales to calculate the ~~evaluation test proposed in Section 3.~~Lagrangian mean velocities

$Source$	$Period$	Nrf	$\Gamma(day)$	$\langle u'^2 \rangle (km^2\, day^{-2})$	$K10^3(m^2 s^{-1})$
IABP	1979-2011	1406	1.71	59	1.17
IABP	2007-2010	280	1.57	66	1.20
neXtSIM	2007-2010	280	1.96	51	1.16
TOPAZ	2007-2010	280	1.81	86	1.80

Table 2. This table gives an estimate of the search radii and areas corresponding to 1, 2 and 3 standard deviations, respectively, and for time horizons ranging from 1 to 30 days. These numbers are averaged over the whole domain and period analysed in Section 2 and should be reevaluated for specific applications, periods and domains of interest, for example by using model outputs having passed the evaluation test proposed in Section 3. Note that we checked that about 67%, 96% and 99.6% of the fluctuating displacements are smaller than 1, 2, and 3 standard deviations.

~~This table shows the total number of floats (Nrf), the calculated integral time scale (Γ), the variance $\langle u'^2 \rangle$ and the calculated diffusivity K for t~~