Interactive comment on "Sea ice inertial oscillation magnitudes in the Arctic basin" by F. Gimbert et al.

Anonymous Referee #1
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General Comments:
This paper provides some measures of the strength of inertial oscillation in sea ice drift as a proxy for the degree to which the ice is in free drift or constrained by internal stresses. While generally well presented, there are a number of major and minor corrections that should be made.

Specific comments:
The magnitude of the inertial, oscillations presented here is the relative magnitude, that is relative to the magnitude of the mean drift speed.

We agree with the reviewer that the measure we propose in this paper to evaluate the magnitude of inertial oscillations is a relative measure. However, this measure is not relative to the mean drift speed, i.e. the advection part of the motion (Fourier component at frequency 0), but is relative to the mean of the norm of the velocity, which thus depend on all frequencies.

I recommend that the mean drift be removed from each "window" before the FFT is computed.

Considering the case of a buoy in free drift driven by both inertial rotation and advection, the recommendation by the reviewer is consistent. Indeed, whatever the advection velocity, only the peak at the inertial frequency would remain in the Fourier spectrum, and M would be equal to 1.27 in that case (instead of actually varying between 1 and 1.27, see below).

However, two remarks can then be made:

1. still considering the ideal case of a buoy driven by rotation and advection, and adding damping linearly related to the buoy's velocity(this term explains most of the attenuation of the inertial amplitude created by ice-ice interactions within the pack, as explained in Gimbert et al., JGR, 2012), to remove the mean drift velocity is not pertinent anymore. Indeed, the equations of motion in that case are:

$$\dot{u} = \omega_0 v + \frac{\tau}{\rho h_i} - k_c v$$
$$\dot{v} = -\omega_0 u - k_c u$$

   where u and v are the EW and NS velocities of the buoy, ω_0 is the Coriolis parameter, $\tau = \rho_a C_a (U_a)^2$ is the wind forcing (where U_a is the wind velocity, C_a the ocean drag coefficient and ρ_a the air volumetric mass), ρ is the ice volumetric mass, h_i is the ice thickness and k_c is a friction coefficient modelling the damping of inertial oscillations.

   The Fourier spectrum of the velocities integrated numerically from these latter equations is shown in Figure 1, for various values of the friction coefficient k_c.

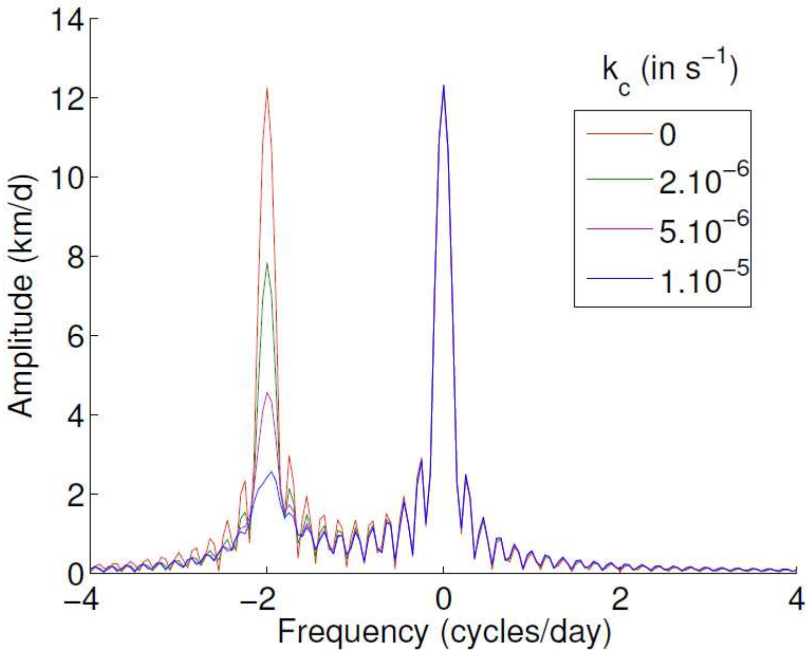

Figure 1: Fourier spectrum of the buoys' velocities, considering various values of k_c, obtained by integrating equation 1 numerically. Parameter values considered here: φ = 90°, $\omega_0 = 1{,}4.10^{-4}$ rad/s^{-1}, $u_0 = 0$ m/s, $v_0 = 0$ m/s, $\rho_a = 1$ kg/m^3, $\rho = 1000$ kg/m^3, $C_a = 0.0012$, $U_a = 2.5$ m/s, $h_i = 2$ m

The internal ice friction k_c acts to depress the peak at the inertial frequency *f*=-2 cycles/day almost without affecting the peak at *f*=0 (advection velocity). Thus, removing the mean drift component in our analysis would lead to $M \approx 1.27$ whatever the ice friction considered, which is obviously not suitable in our study, as we built *M* to be sensitive to the magnitude of k_c.

2. In reality, the Fourier spectrum of buoys' velocities is richer than in the ideal case with pure advection and rotation (only *f*=0 and *f*=-2 per day, then). Thus, a buoy exhibiting strong mean drift is likely to also exhibit larger velocities at all frequencies, leading the removing of advection velocity to be obsolete regarding all the other velocities at other frequencies that would also remain larger.

A loose pack could have both strong inertial oscillations and a strong mean drift, giving small M values.

This is actually not that trivial. We believe that reviewer 1 has been misled by our supposedly "pedagogic" example proposed in page 2191 (see remark 2191-11 of reviewer 1 below).

Let us consider the configuration mentionned by reviewer 1, that consists of a buoy trajectory made of two velocities that are the mean drift velocity U and the inertial rotation velocity V obtained in very loose pack conditions, i.e. with no internal friction expected by ice-ice interactions (free drift case). In that case, U and V do not vary independently, but are correlated. A strong mean drift would lead to a proportionally strong inertial rotation velocity.

To be more quantitative, this proportionality is examined more thoroughly in the following, by writing the equations of motion of a buoy in free drift submitted to a wind external forcing along one direction (here the X direction):

$$\begin{aligned}\dot{u} &= \omega_0 v + \frac{\tau}{\rho h_i} \\ \dot{v} &= -\omega_0 u\end{aligned} \qquad (1)$$

The general solution of equation (1) is

$$\begin{aligned}u(t) &= A\cos(\omega_0 t + \phi) \\ v(t) &= -\frac{\tau}{\rho_i h_i \omega_0} - A\sin(\omega_0 t + \phi)\end{aligned} \qquad (2)$$

where *A* and *Φ* are constants inferred from initial conditions.

In any case, the advection velocity is $U = -\tau/(\rho\ h_i\ \omega_0)$, while the rotation velocity is $V = A$, and thus depends on initial conditions.

1. In the case of no initial velocity, i.e. $u(t=0) = 0$ and $v(t=0) = 0$, we have $V = A = -\tau/(\rho\ h_i\ \omega_0) = U$, and thus obtain $V/U = 1$, whatever the value of τ considered. Thus, in the case of a strong mean drift as proposed by reviewer 1, obtained by strong wind forcing, the buoy will exhibit proportionally strong inertial rotation velocity such that *M* always equals 1.

2. In the case of a non-zero initial velocity, the problem can be split into two different configurations

   a. The initial velocity is directed along the wind direction ($u(t=0) = u_0$ and $v(t=0) = 0$) In that case, we get

   $$V = \frac{-\frac{\tau}{\rho_i h_i \omega_0}}{\sin(\arctan(-\frac{\tau}{\rho_i u_0 h_i \omega_0}))} = \frac{u_0}{\cos(\arctan(-\frac{\tau}{\rho_i u_0 h_i \omega_0}))}$$

   and we can show that, whatever the value of u_0 with respect to τ, we obtain $|V/U| \geq 1$, and thus $M \geq 1$. Thus, the case $M<1$ is never obtained.

   b. The intial velocity is directed perpendicular to the wind direction ($u(t=0) = 0$ and $v(t=0) = v_0$)
   In that case, we get

   $$V = \frac{\tau}{\rho_i h_i \omega_0} + v_0$$

   and, $|V/U| \geq 1$, i.e. $M \geq 1$, if $v_0 \geq 0$ or $|v_0| \geq 2\ \tau/(\rho\ h_i\ \omega_0)$

Thus, in the northern hemisphere, to get $|V/U|<1$, i.e. $M<1$, in free drift conditions, we have to consider an initial buoy's velocity directed perpendicularly to wind forcing, oriented in the clockwise sense with respect to wind sense, and having an absolute velocity lower than $2\tau/(\rho\ h_i\ \omega_0)$. As the initial advection velocity is induced by previous wind conditions, this case would correspond to one where the wind direction would be unchanged and where the amplitude of the wind responsible of the oscillation would be of the order of magnitude of the wind responsible of the initial advection velocity.

As supported in the paper, we are in reality mostly sensitive to inertial oscillations during storm conditions, thus associated to large gradients in directions and amplitudes of wind, leading to consider that the effect commented above, that leads to $M \leq 1$ in free drift conditions, is not likely to occur.

Thus, in a general way, we do not think removing the advection prior to compute *M* values is appropriate.

Moreover, because misleading, our ‘pedagogic’ example proposed in page 2191 has been removed from the revised manuscript.

English usage is generally quite good, but an editor should be asked to review the manuscript. For example pluri-annual should be multi-annual throughout

OK, done

and there are
other incorrect or awkward usages.
Strike “magnitude” from the title

OK, done

Page 2184-8. What does “disconection” mean in this context?

Disconnection -> fragmentation (modification done)

2188-21: mention Kwok (2003) found significant oscillations in the same region, so it depends on when you look.

We agree with the reviewer that significant oscillations, as for example observed by Kwok (2003), could be reported in the same region considering another period of observation, as the strength of oscillations also depends on several variables that show strong variability in time and space, such as the degree of fragmentation of the ice cover, the storm activity, ... We here voluntarily selected, as an example, a trajectory that does not exhibit any oscillations, in order to introduce the method.

But reviewer 1 is right, recalling this by citing Kwok (2003) at that stage allows to point out the variability with respect to time and space of the strength of inertial oscillations, thus to introduce the statistical approach we adopt in the rest of the study. A clarification on this point has been added in the paper at page 10 line 3-9.

2190-4: The notation is very confusing here.

OK, equation (7) of the previous paper version has been removed and a simplest form is proposed (page 11 line 15 of the updated version).

2191-2: Shouldn’t Wcur be weighted by g(t) here and why have you switched to an integral instead of the summation used before?

The reviewer is right, as $W_{cur}(t)$ is computed over buoys velocities that are discrete observations in time, a summation has to be used here instead of an integral. The modification has been done in the revised version (see equation (9) on page 12).

However, $W_{cur}(t)$ is already the result of weighting the velocity by g(t), which simply “isolates” a time window. Equation (11) (2191-2), that the reviewer refers to, defines the mean of the norm of the displacement.

2191-11: This discussion will be very different if you first remove the mean drift because then U=0.

We apologize, but we think that this paragraph of page 2191 misled the reviewer, since, in order to reproduce artificial trajectories, we allow the mean drift velocity *U* and the inertial rotation velocity *V* to vary independently. Actually, this case does not specifically refer to realistic configurations, especially the free drift one. Indeed, the objective in this paragraph was purely "pedagogic", trying to show how *M* may vary with the trajectories' geometry. In this section, we arbitrary made *V* to vary with respect to *U* (which is, only in this case of the two motion components, the only velocity with which *V* is normalized), assuming that damping processes that depress V infer within the buoys trajectory.

As already explained above, we decided to remove this section, especially as other pedagogic examples are already given in preceding sections (selecting real buoys trajectories, whether being oceanic or ice tethered).

2095-21: I see little similarity with the usual ice concentration maps.

We here provide open water concentration maps obtained when concentration values are sampled at buoy positions over the same time periods considered in the paper. An open water concentration value is obtained for each buoy location as done in paragraph 4.2, and a spatial average following equation (13) is performed, as with M values. Following the suggestion of reviewer 1, a threshold on sum(w i,j) is now considered and taken equal to 1000.

Figure 2 shows the open concentration maps obtained for summers of periods 1 and 2.

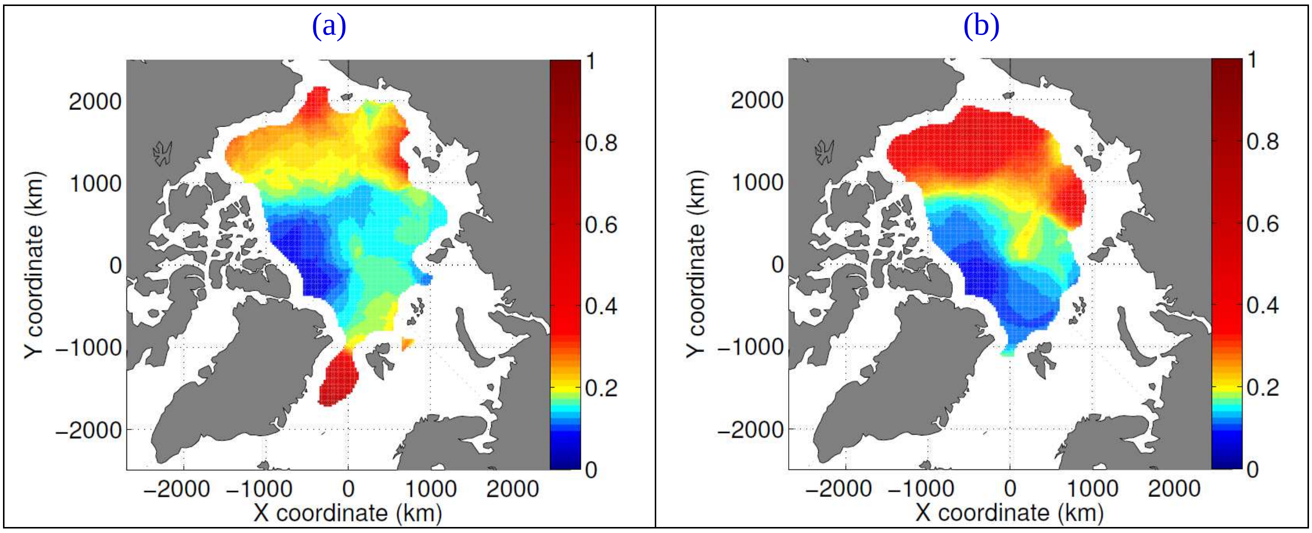

Figure 2: Open water concentration maps for summer obtained when sampling concentration at buoys positions and averaging over (a) time period 1 and (b) time period 2 defined in the paper.

Contrary to what is suggested by reviewer 1, we see quite evident similarities with the spatial repartition of M shown in the paper. Like *M*, low values of open water concentration are observed along the Greenland and Canadian coasts while large values of open water concentration are observed in the periphery of the basin, i.e. in the Beaufort, Chukchi and Laptev seas. Moreover, the evolution from period 1 to period 2 is also similar to the one observed on *M*, materialized by a slight migration of the pack zone toward the south, and an increase of the peripheral zone area, materialized by larger open water concentration values.

Finally, the correlation coefficient *R* computed between *M* values shown on Figure 13 of the paper and concentration values shown here on Figure 3 is equal to 0.57 for period 1 and 0.80 for period 2.

These informations have been added at the end of section 4.3.2 of the updated version.

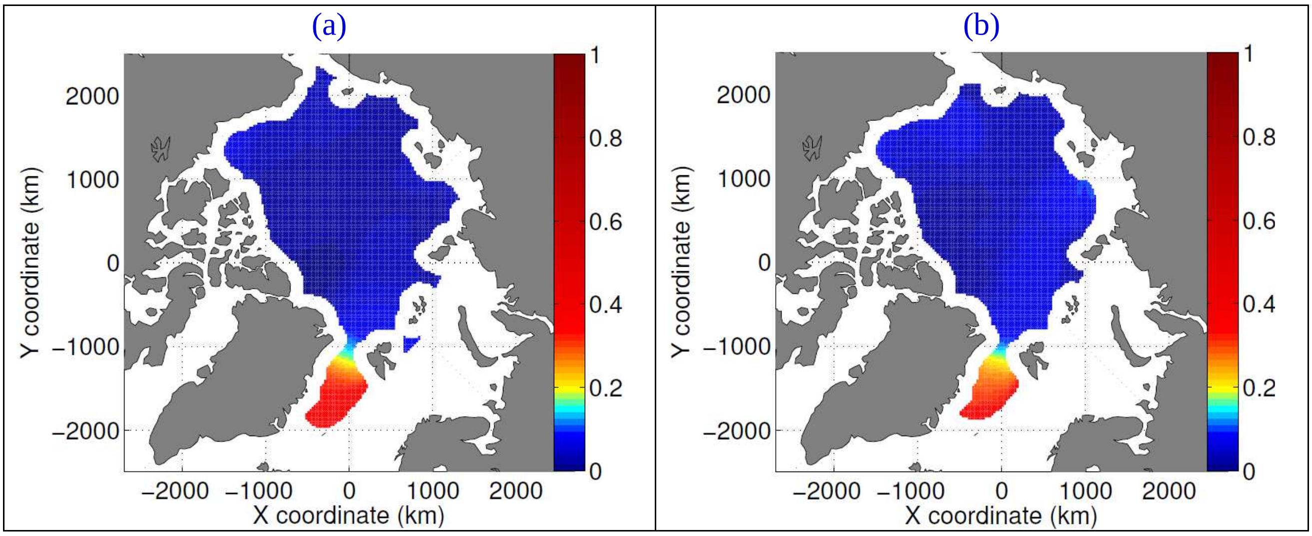

Figure 3: Open water concentration maps for winter obtained when sampling at buoy positions and averaging over (a) time period 1 and (b) time period 2 as defined in the paper.

Concerning the winter season (Figure 3), open water concentration values are very close to 0 over the whole basin, as for most of the M values. The relatively larger M values computed north of Canadian coasts could be attributed to buoys drifting along the “Circumpolar flaw lead” that consists of a sheared, thus highly fragmented, zone (Lukovich et al., JGR, C00G07, 2011).

This comment has been added in the paper (page 16 and line 5-7).

2195-13: A minimum value for the sum(w i,j) should be established. Some parts of the domain have very little data, sometimes far from the interpolation point.

We agree with the reviewer.
The introduction of a threshold on sum(w i,j) is a good suggestion. We thus performed this thresholding, by considering a minimum value for sum(w i,j) equals to 1000. Updated maps and legends have been provided in the paper.

2197-26: What is the motivation here? You are still weighting the latter years more heavily since there are more of your bins. Why not just get annual averages?

The IABP dataset has two main drawbacks, (i) a strong spatial as well as (ii) a strong temporal variability of data density. Therefore, to make sure that the increase of M values in recent years is real and does not result from sampling biases, we did the following:

(1) On section 4.3.3 and figure 14, we show that this evolution cannot result from spatial sampling bias.

(2) To tackle the problem of temporal sampling, and particularly the fact that recent years, for which larger *M* values are found in average, correspond to many more observations, we eliminated a possible effect of the number of data on the estimation of *M*-values over the entire Arctic by splitting our dataset into time windows containing the same amount of data.

2199-21: The splitting of the time series in two seems very arbitrary. Perhaps it would be better to determine the maps of the trend and only plot points with sufficient data over the whole time period to compute the trend consistently, for example that there is a minimum number of points in the early 1980's. A simple evaluation of the uncertainty in the trend might be enough and only plot points with p-value of more than 90 or 95%. The trend could include all points within a radius of, say, 400 km of each location. As it is, the uncertainty in the temporal sampling make it hard to interpret the maps.

This splitting is not arbitrary. As explained in the text, we tested where a change-point is most likely to occur, by comparing the means of the two distributions (*M* before the change point, *M* after the change point). We found, by applying this Student' t-test, that it is best to separate the times series equally in two, with a change point in 2001 – 2002. However, the goal here is neither to claim that something special happened for the ice cover in 2001-2002, nor to argue that there is a linear trend on M-values over the entire record. We only want to stress that *M* values have significantly increased over the period (a significant trend of 1.19 (± 0.34).10^{-5} yr^{-1} in summer and 5.7 (± 1.9).10^{-6} yr^{-1}in winter are computed) and especially in recent years, and that this observation cannot be explained by sampling bias and/or a change in the positioning accuracy of the buoys (see section 4.3.3).
Incidentally, note that this date (2002) corresponds (i) to a splitting of the overall dataset into two approximately equal parts in terms of amount of data, and (ii) to a date after which GPS buoys became much more numerous (so the analysis on fig. 12).

2202-7: Again, the correspondence to ice concentration is weak.

See answer above

2215: Over what region?

Ok, legend of Figure 8 has been corrected. The *M* values are computed over the central Arctic basin.