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Simulating spreading of salmon lice with Ladim

HOW LONG SIMULATIONS ARE NECESSARY FOR A 'REPRESENTATIVE' SPREADING

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1 Introduction

When creating a salmon farm, knowing where salmon lice can spread from that location is of interest. Using LADIM (Lagrangian Advection and Diffusion Model) one can get an estimate of this, but the question remains of how a simulation should be done, to get a general spreading field. Specifically, for how long a period should the simulation run. As the regional distribution could depend on the length of the simulations, a period should be found so that the distribution doesn't change significantly for longer simulations, the hope being that this would capture the general variability around the site.

There is also a question of whether the result of such simulations depend on the start day within a year, and whether different years would give different results.

The purpose is, given a location where lice can be released, to be able to quickly assess which areas could see a high concentration of salmon lice. To do this one needs a given period of a certain length to use as a 'normal period', that should give a representative result for that location.

2 Methods

2.1 Numerical models

The salmon lice growth and advection model is a modified version of a Lagrangian Advection and DIffusion Model (LADIM), which has been used at the IMR for about 20 years (Ådlandsvik and Sundby 1994). Hourly values of simulated currents, salinity and temperature from a coastal ocean model are used by the salmon lice model, interpolated linearly to a sub-grid position. The salmon lice model simulates particles swimming up during daytime and down during night, to resemble behaviour found in experiments (Johnsen 2011). The vertical speed at which they move due to this factor was set to $1 \times 10^{-4}\,\mathrm{m\,s^{-1}}$, and the limit for the amount of light was set to

$0.1\,\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$ – more light, and they move up in the water column, less light and they move down. The first three pelagic larval stages of the salmon louse are simulated, and the duration of the first two nauplii stages are estimated to be 50 degree days and the infectious copepodid stage is estimated to be between 50 and 150 degree days (Asplin et al. 2011). LADIM was configured to release three particles each hour[1], while the timestep was set to 180 s. The horizontal and vertical diffusion coefficients were set to $0.2\,\text{m}^2\,\text{s}^{-1}$ and $8 \times 10^{-6}\,\text{m}^2\,\text{s}^{-1}$, respectively. Output from the salmon lice model with information of the particles position, age, temperature and salinity were given every hour.

The coastal ocean model is based on the Regional Ocean Model System (ROMS, www.myroms.org, Shchepetkin and McWilliams 2005; Haidvogel et al. 2008). This is a state-of-the-art three-dimensional, free-surface, primitive equation numerical model using a generalized terrain-following s-coordinate in the vertical. The coastal model use a horizontal grid resolution of 800 m and is denoted the NorKyst800 model system (Albretsen et al. 2011). NorKyst800 data for three years, 2009, 2010 and 2011 has been used for this work.

2.2 Simulations

Simulations were done for a series of locations in western Norway. Locations in or near three of the major fjords, Boknafjorden, Hardangerfjorden and Sognefjorden, were chosen, as well as other places. Some locations were close to the open ocean, others were 'hidden' among islands or in fjords (fig. 1).

Most simulations were done for 2009, starting in January, April and July. The length of the simulations ranged from 30 days to 270, with a step of 30 days. As all simulations were done within the year, those starting in July were no longer than 180 days.

For some locations (P1, P3, P5, see fig. 1), simulations were also done for the years 2010 and 2011, and with a length of 360 days, starting in January. Finally, a single three year long simulation was done for these same three locations. In this case just one particle was released per hour.

2.3 Quantifying results

The output from LADIM are arrays containing the position and age in degree-days for each released particle at each hourl. For this case, only particles with an age of 50–150 degree days, *i.e.* infectious copepodites, have been considered. To get a concentration, the number of 'observations' in each grid cell are counted. The position of a single particle each hour is denoted an observation. Hence, each particle is counted multiple times, potentially also several times in the same grid cell.

To quantify the amount of spreading, two measures are introduced:

[1] Due to an error in a script, some cases had just two particles per hour. These are (*location–year*) P1–2010, P4–2010, P5–2010, P12–2009, P13–2009, P14–2009.

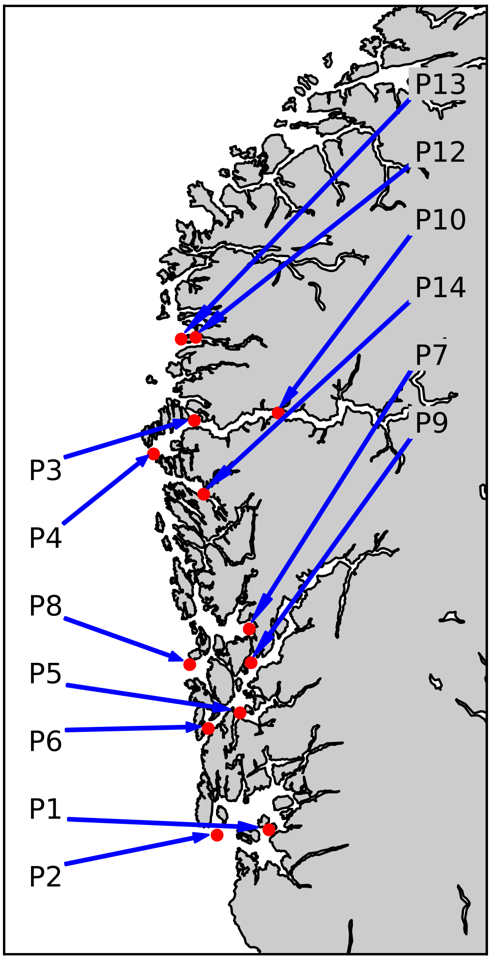


Figure 1: The western coast of Norway, with the locations of the simulations labeled.

Table 1: Short description of the locations labeled in fig. 1.

Punkt	Skildring
P1	Boknafjorden, between islands
P2	Boknafjorden, near open ocean
P3	Sognefjorden, close to mouth
P4	Sognefjorden, near open ocean
P5	Hardangerfjorden,
P6	Hardangerfjorden, close to mouth
P7	Bjørnafjorden, inner part
P8	Bjørnafjorden, near open ocean
P9	Hardangerfjorden, south of Tysnes
P10	Sognefjorden, middle part
P12	Svanøy, inside
P13	Svanøy, outside
P14	Fensfjorden

- The radius around the point of release needed to contain N% of the total number of observations.

- The number of grid points needed to contain N% of the total number of observations, when the grid points with the highest numbers of observations are considered.

Hence, while the first method can include grid points with very few, or none, observations, the second will include only those areas where the concentration is highest. For most of the following, a relatively high amount for N was used, *i.e.* 80% or 90%.

In addition, maps with the distribution of particles shown as filled contour plots are generated, for a more qualitative description. For these maps, the number of observations in a grid cell are normalized by dividing with the total number of particles that are released.

3 Results

3.1 General results

When considering all observations, the lice can spread over very large areas, both in fjords around the release point, and out into the North Sea. However, most of the observations are done in a much smaller area. On average, about 18% of the grid points with observations will have 90% of the total number of observations. Hence, most of the area covered by lice will have very few observations. An example of this is seen in fig. 2. The left panel shows all observations, while the right panel only shows the area with the highest concentration, amounting to 90% of all observations. Note that the map in the left panel shows a much larger area than that on the left.

3.2 Radius/number of grid points vs. length of simulation

Figure 3 shows how the two measures introduced in section 2.3 changes with the length of the simulation at the different locations in 2009, for $N = 80$, fig. 4 has such plots for P1, P3 and P5 in 2010 and 2011. While the curves from the different locations have different shapes, the general trend seems to be that as simulations become longer than about $6(\pm 1)$ months, the curves level out. Not all locations demonstrate this, however, and few are as smooth as those from P1 in 2009 (first panel of fig. 3). Some may level out sooner, after four or five months, while some may not level out much at all. Similar behaviour, if perhaps a little less clear, is seen for $N = 50$. Differences between start dates are sometimes very small for longer simulations, sometimes larger.

The curves for different points show different behaviours. Some cases demonstrate an increase in radius/number of grid points as simulations become longer, while other cases demonstrate the opposite. In some cases, such as seen for P1 in 2009 (first panel of fig. 3), the values can be near constant as the simulation time increases beyond a certain length. Finally, some can fluctuate somewhat, as seen for P6, the sixth panel of fig. 3.

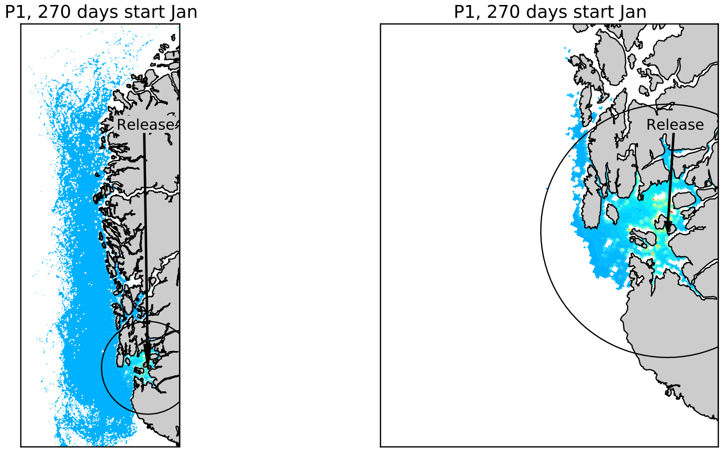


Figure 2: Maps for demonstrating that large areas have few observations. Both maps show results for the same simulation, starting January 2009, lasting 270 days. The left panel indicates all observations, while the right panel only shows the area of highest concentration amounting to 90% of all observations. Note the different areas covered by the maps. The circle indicates the radius around the release point that envelopes 90% of the observations (cf. section 2.3).

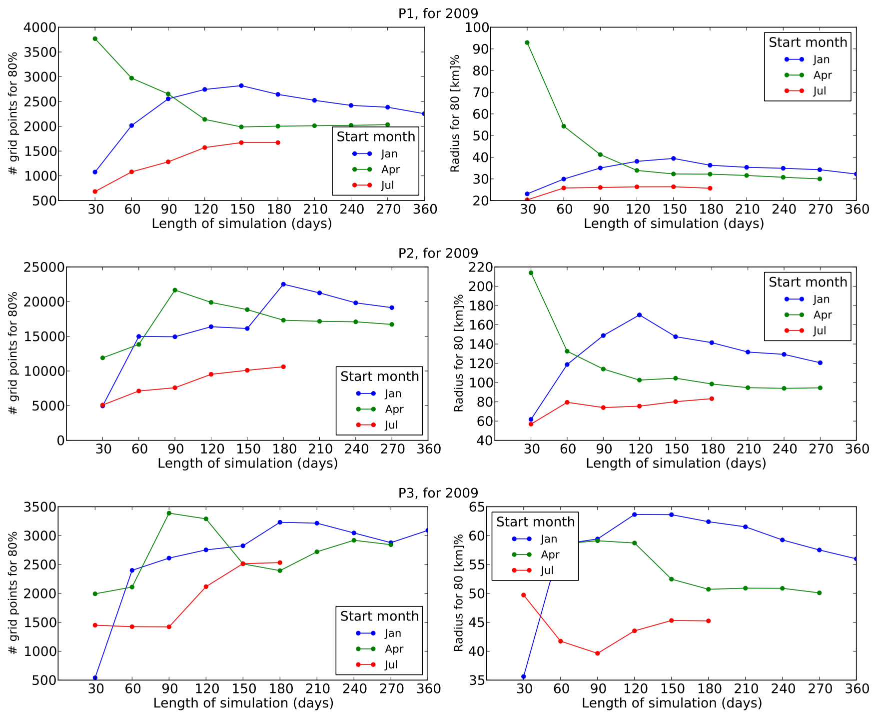


Figure 3: (ctd.)

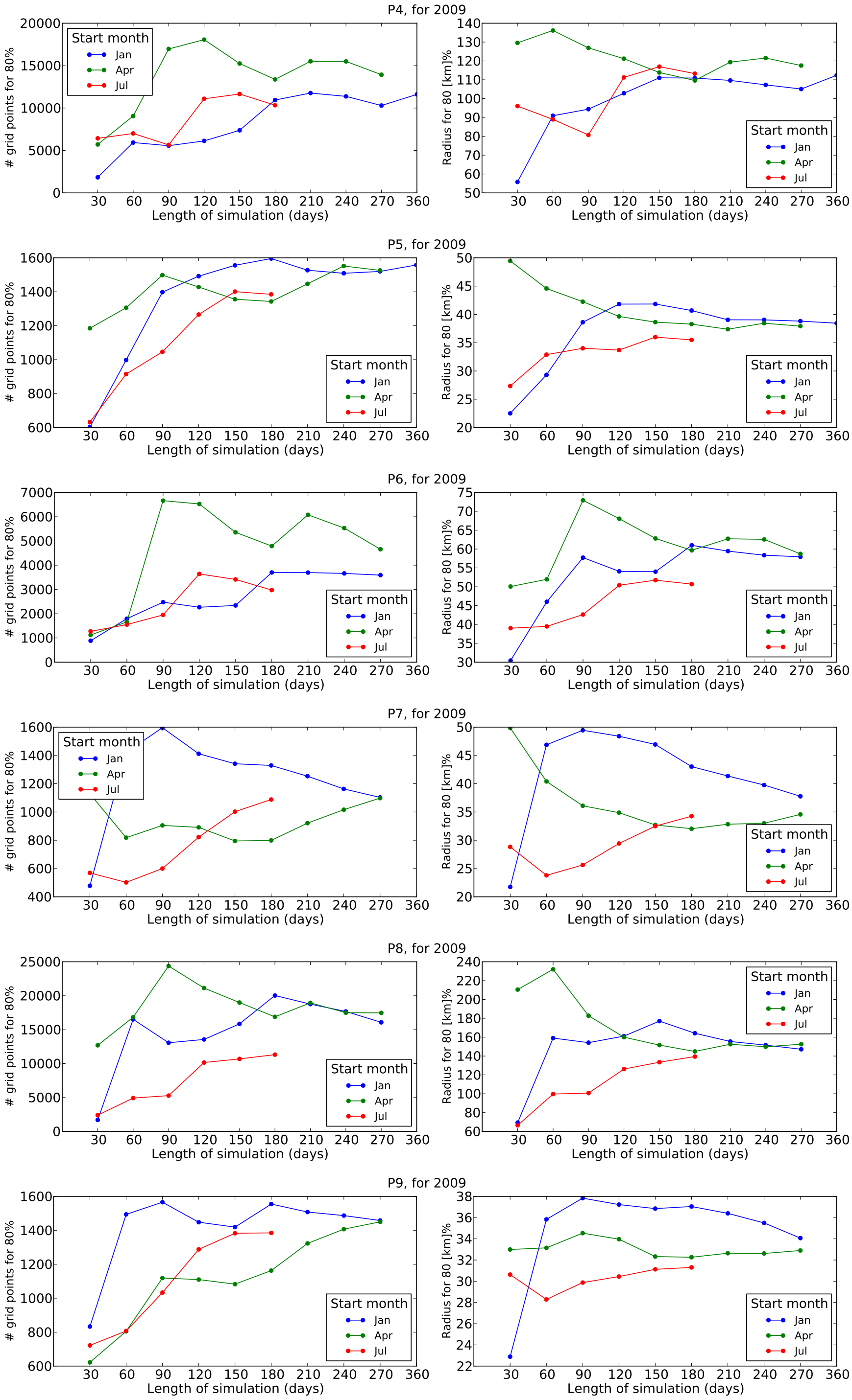

P4, for 2009
P5, for 2009
P6, for 2009
P7, for 2009
P8, for 2009
P9, for 2009
grid points for 80%
Radius for 80 [km]%
Length of simulation (days)
Start month
Jan
Apr
Jul

Figure 3: (ctd.)

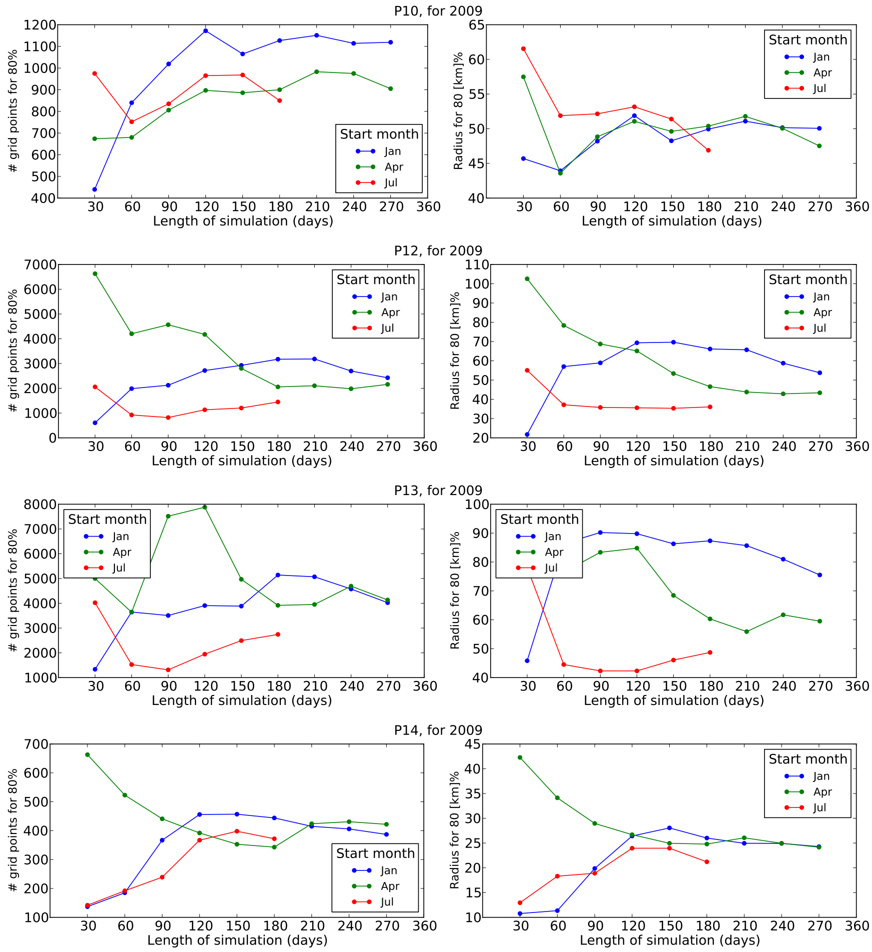


Figure 3: Examples from all locations of how the radius in kilometres around the release point and number of grid points required for 80% of the observations vary with the length of the simulation in 2009. Note different limits on all *y*-axes.

Considering maps showing the area with the highest concentration, one can see that as simulations become longer, maps from those starting in January and those starting in April become more alike. Usually, the general shape and orientation of the areas are the same, the difference is in the extent of the areas.

3.3 Inter-annual differences

For the three tested years, there are generally differences in how the spreading field appears, see fig. 5. In the case of location P1, inside Boknafjorden, both 2010 and 2011 saw a greater transport of particles out of the fjord than in 2009, but in 2010 most of this went southwest, while in 2011 there was more transport north. In 2011, the largest transport out of the fjord occurred in the first three months. At P3, in the outer region of Sognefjorden, 2009 and 2011 saw a similar spreading north along the coast,

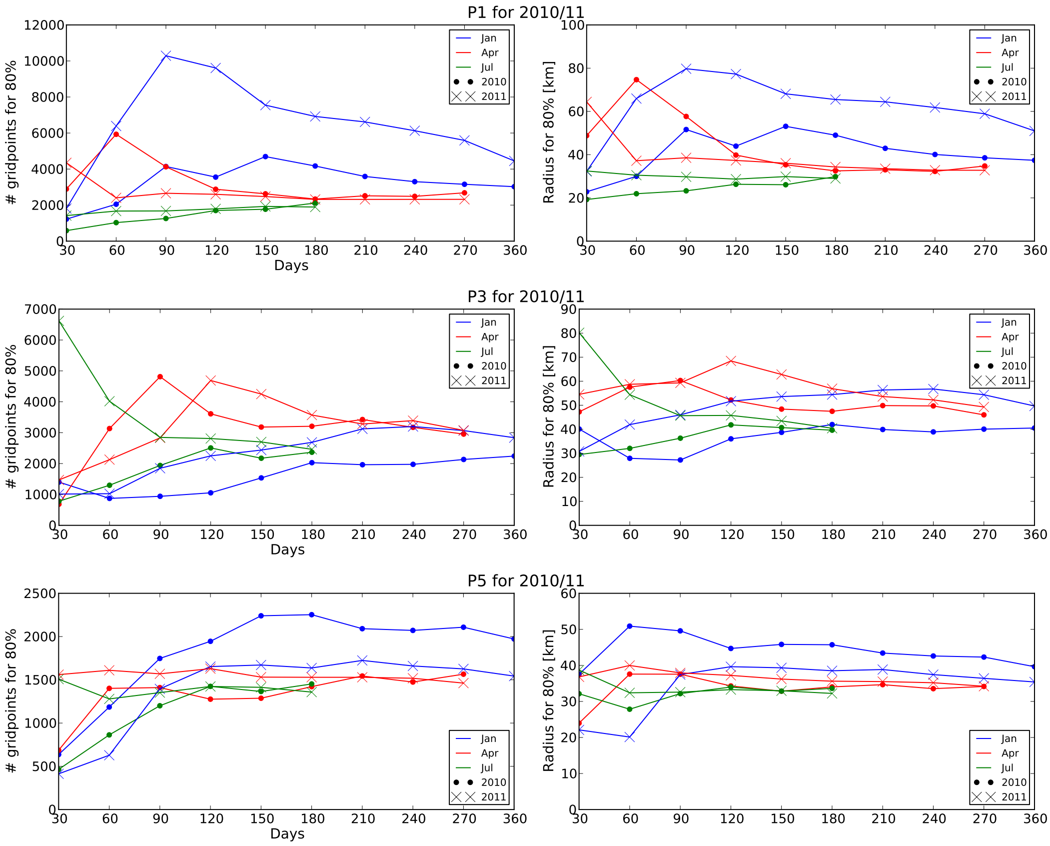


Figure 4: Examples from locations P1,P3 and P5 of how the radius in kilometres around the release point and number of grid points required for 80% of the observations vary with the length of the simulation in 2010 and 2011. Note different limits on all y-axes.

while there was less of this in 2010. When looking at the spreading into the Sognefjord however, 2010 and 2011 were similar, while in 2009 there was less spreading into the fjord. Finally, at P5, 2010 saw considerably more spreading in all directions than the two other years. 2009 and 2011 was somewhat similar, with slightly more spreading both north and west in 2011.

A similarity between the years is that several of the spots with very high concentrations are often found in the same places. By considering those areas adding up to 25% of all observations.

4 Discussion

While some lice can move far out at sea, the highest concentrations are generally found close to the coast.

That some cases see an increase in radius or number of grid points required for 80% as simulations become longer (*e.g* the blue curve in the lower panel of fig. 3), indicate that earlier months in the simulations have a current field that disperses the particles to a lesser extent.

The influence of events with strong currents on the concentration depend on when it appears in the simulations. If such an event occurs early in the simulation, it could have a relatively larger effect on the required radius, than if it occurs late, as fewer particles have been released. This is seen in the curves for P6, in the sixth panel of fig. 3. The large increase seen from 60 days to 90 days in the curve for April, is also seen in the curve for January from 150 to 180 days, but here the jump is much smaller.

As mentioned in section 3.2, there is a tendency that for simulations longer than 6–7 months the concentration field covering 80% of all observations changes little. This tendency is clearer when looking at the radius around the release point needed for N%, than when looking at the number of grid points. Figure 6 has curves similar to fig. 3, but includes simulations starting in January and April in 2009 for all locations. Figures 7 and 8 have similar curves, but for $N = 50$ and $N = 25$ instead.

Because the values for the different simulations in fig. 6 span a large range, all curves have been normalized by dividing with the value for the simulation lasting 270 days, hence all curves have value 1 here. As demonstrated by the upper panel of the figure, all the locations see relatively little change in the radius for the longer simulations. The curves for the number of grid points, lower panel, have a somewhat larger spread.

There is also a tendency for the simulations starting in January and those starting in April to become more similar for longer simulations. This could be expected, as there will be an increasing fraction of overlap between the two simulations. Yet, there are often differences between the two start times, even for simulations as long as nine months, where the overlap is six months.

In most cases, one can see that the simulations starting in January have a larger radius and higher number of grid points required to cover 80% of the observations. This could indicate that the spring months generally has a current field that disperses the particles relatively much. That is also indicated by the fact that the shortest simulations

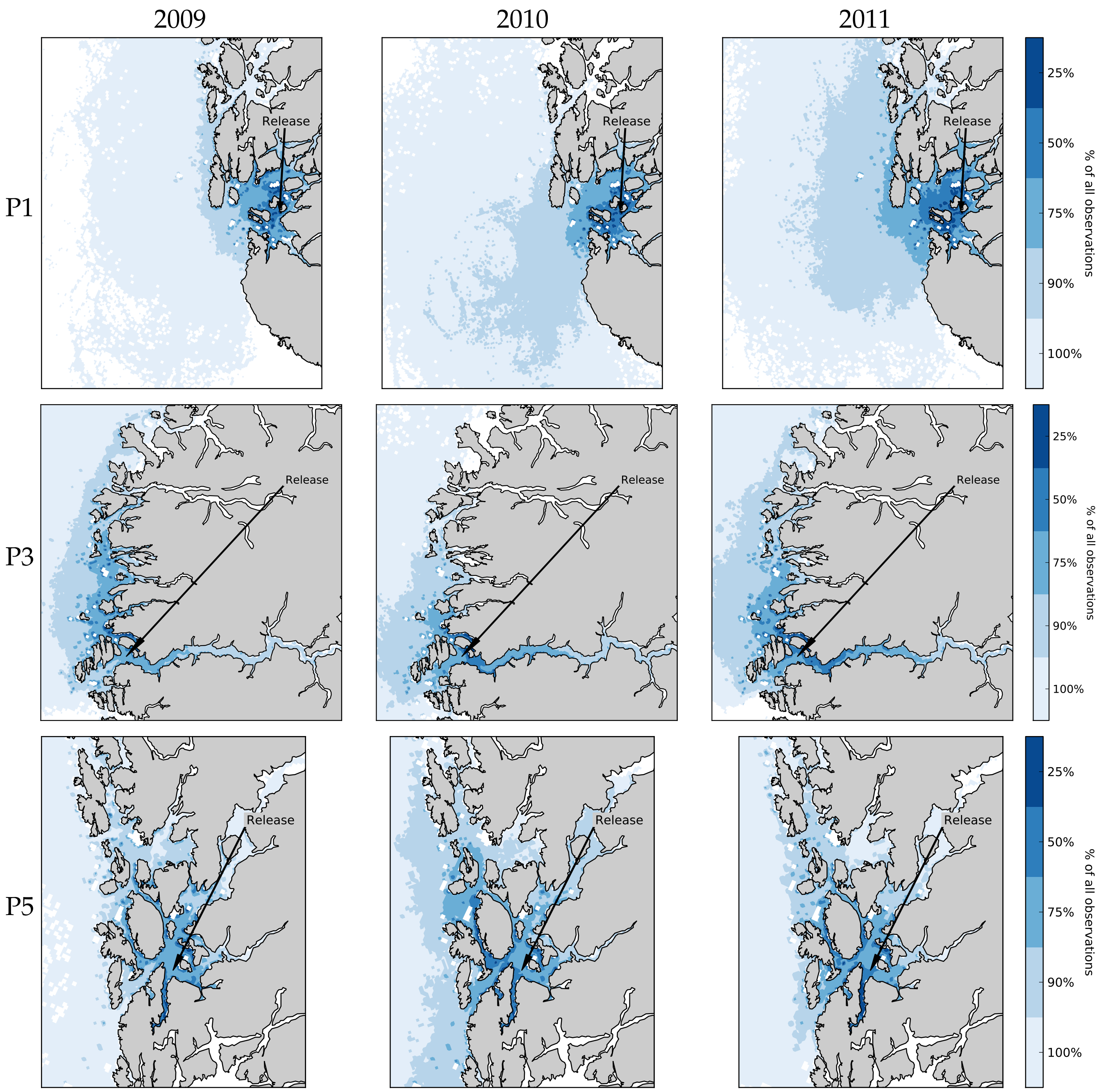


Figure 5: Maps demonstrating the difference in area when including 25%, 50%, 75%, 90% and 100% of all observations. The top row shows results for location P1, the middle for P3 and the bottom for P5. The first column shows the results for 2009, the middle column for 2010, and the right column for 2011. All simulations started in January, lasting 270 days.

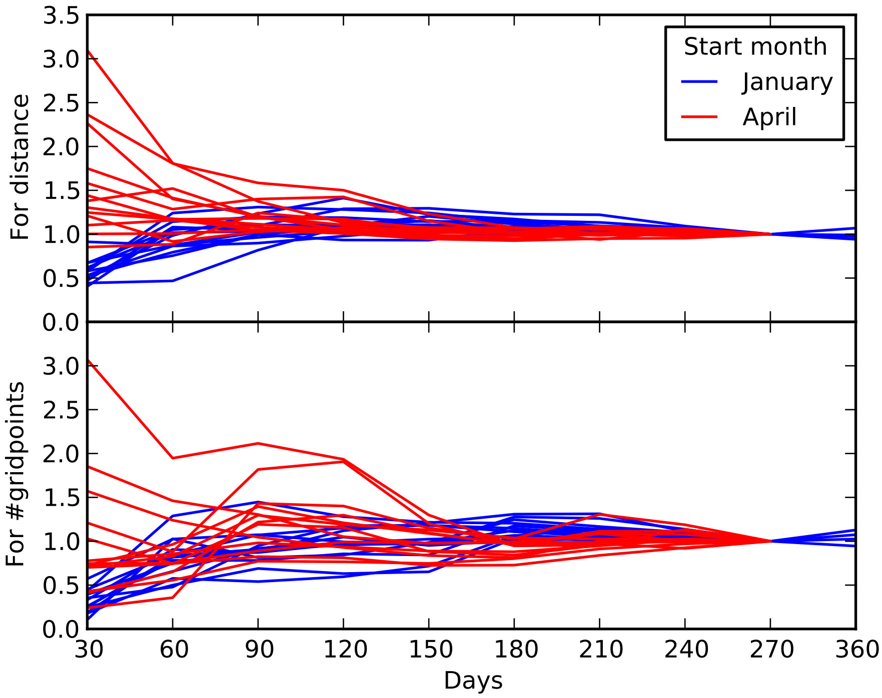


Figure 6: Curves for simulations starting in January and April, for all locations in 2009 with $N = 80\%$. The values are normalized by dividing on the value for the simulations lasting 270 days, hence, all curves have the value 1 at that point. The upper panel shows the curves for radius, the lower panel shows the curves for number of grid points.

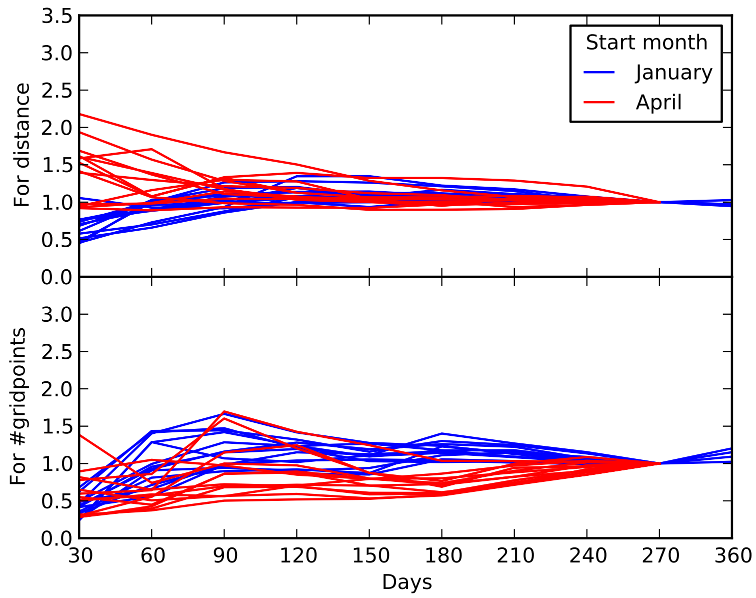


Figure 7: Similar to fig. 6, but for $N = 50\%$.

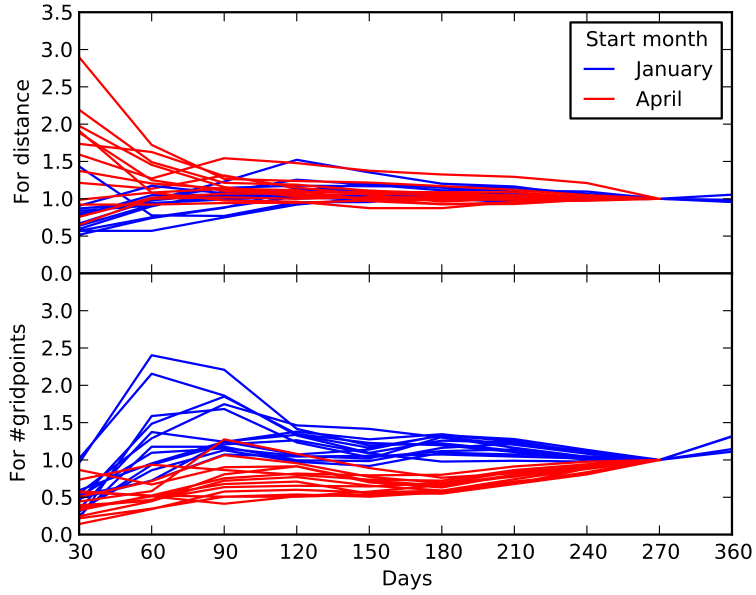


Figure 8: Similar to fig. 6, but for $N = 25\%$.

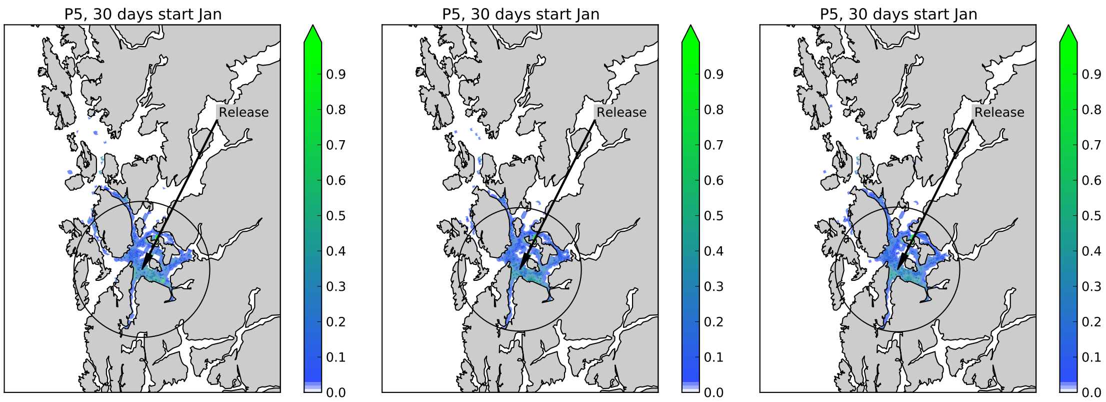
that started in April usually have a much higher dispersion than those starting in January, demonstrated by fig. 6. The relative differences are not large for long simulations though.

4.1 Inter-annual differences

The inter-annual differences make it more difficult to say what may be a ‘normal period’. Both 2010 and 2011 give a somewhat larger dispersion than 2009, but which of them is closest to an average is impossible to say without considering more years. In order to catch most of the variability around a location, a period in either 2010 or 2011, if not a combination of the two, could be considered.

4.2 Number of released particles

For the simulations done for this report, three particles were released each hour. To test the sensitivity of the results for the number of particles released hourly, some simulations were run with one and ten particles released per time step. Simulations of length 30, 120 and 240 days were done for the locations P3 and P5.



(a) One particle released per time step.

(b) Three particles released per time step.

(c) Ten particles released per time step.

Figure 9: Comparison of model runs with one, three and ten released particles per time step. Simulations started January 2009, lasting 30 days. The colored area include 80% of the observations.

In the areas with high concentrations, the coverage is very similar, exemplified by fig. 9. The maps in fig. 9 show the area of highest concentration that covers 80% of all the observations. Generally, the same area is covered in all three cases, there are just some small, scattered patches that are different. In areas with very low concentration, *e.g* out in the North Sea, the simulation with just one particle may cover less area than the ones with three and ten particles released. All tests, regardless of length and location, shows similar behaviour with regard to the ares of highest concentration,

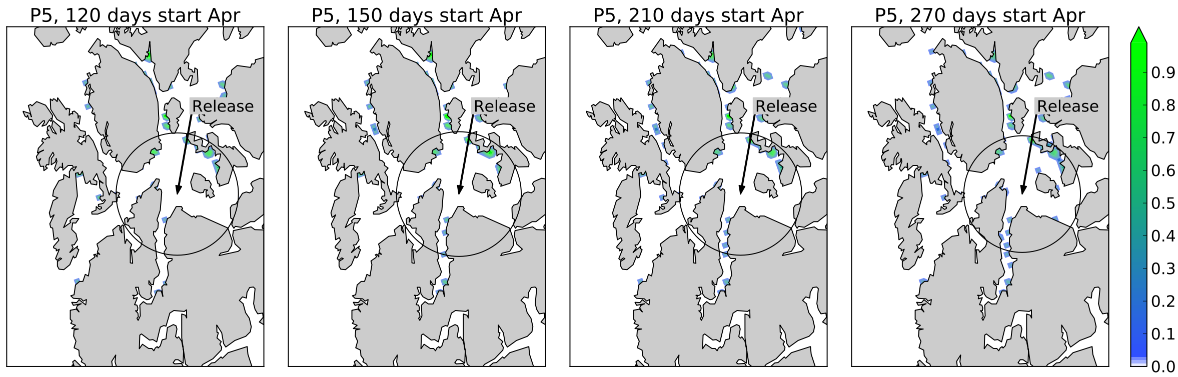


Figure 10: Close up of the spreading required for 25% of all observations, for four different length simulations at location P5, starting January 2009. Only those areas with the highest concentration are coloured.

with only minor differences depending on the amount of released particles. This was true for both $N = 50\%$ and $N = 80\%$.

4.3 The value for N

In the above, a cutoff of 80% has generally been used, *i.e.* the area that envelopes 80% of all observations has been considered. Figure 5 demonstrates how the area changes for different cutoff-values: 25%, 50%, 75% 90% and 100%. For the 25% cutoff, one can see that the concentration usually consists of small, unconnected patches. The same is partly true for the 50% cutoff, but when 75% is included, the area is mostly continuous. One can also see that the area that is added with a cutoff at 90% is often quite large, indicating that concentration is small.

Figures 7 and 8 has plots similar to fig. 6, but for $N = 50$ and $N = 25$. With regard to radius, both cases seem to converge quite well, while with regard to number of gridpoints there seems to be less convergence. For smaller N the spreading tends to become more 'patchy'. That there is less convergence with regard to number of grid points, could indicate that these patches vary in size or distribution. Figure 10 shows an example of this, from simulations starting in April 2009, for P5. For this case, the radius was nearly constant for simulations longer than 120 days, but the number of grid points was generally increasing for longer simulations.

The patches with the highest concentration often occur in the same locations, and they are often close to shore, but the number of such patches can vary between simulations.

4.4 Three-year simulation

Finally, a three year long simulation was done for the locations P1, P3 and P5, releasing one particle per hour. Figure 11 shows maps of the resulting concentration, while

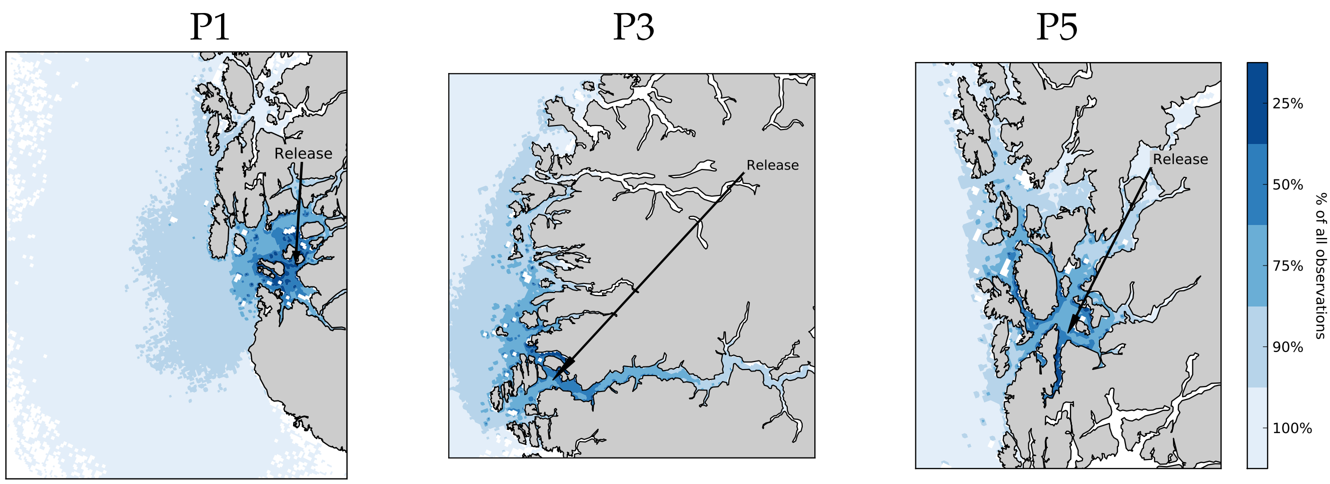


Figure 11: Maps showing the concentration after a three year long simulation, releasing one particle per hour.

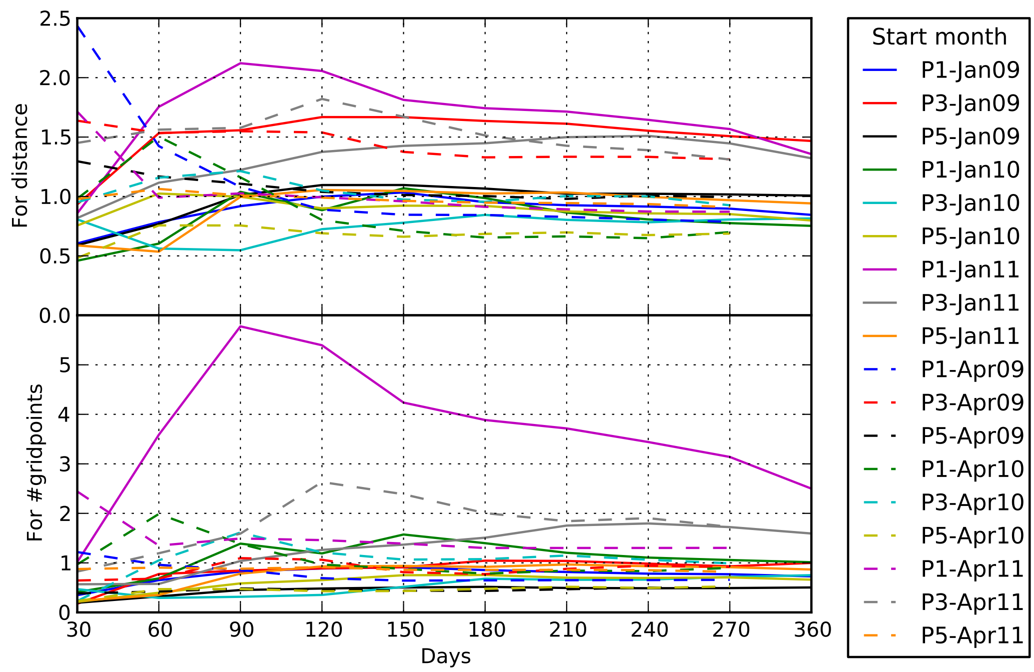


Figure 12: Curves for simulations starting in January and April 2009, for locations P1, P3 og P5, with $N = 80\%$. The values are normalized by dividing on the value for the simulations lasting three years. The upper panel shows the curves for radius, the lower panel shows the curves for number of grid points.

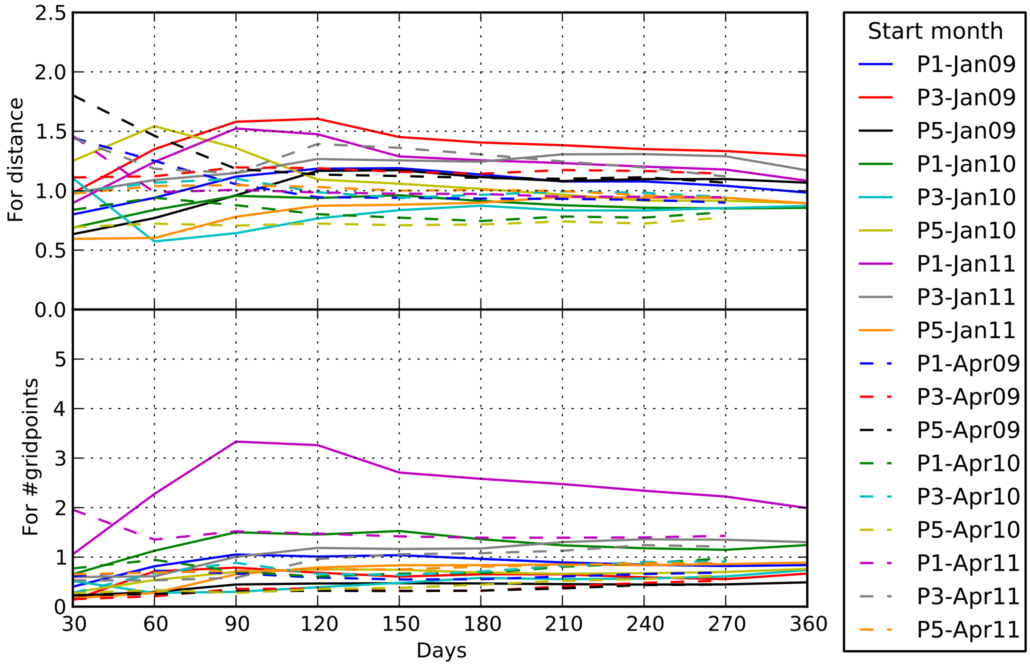


Figure 13: Similar to fig. 12, but for $N = 50\%$.

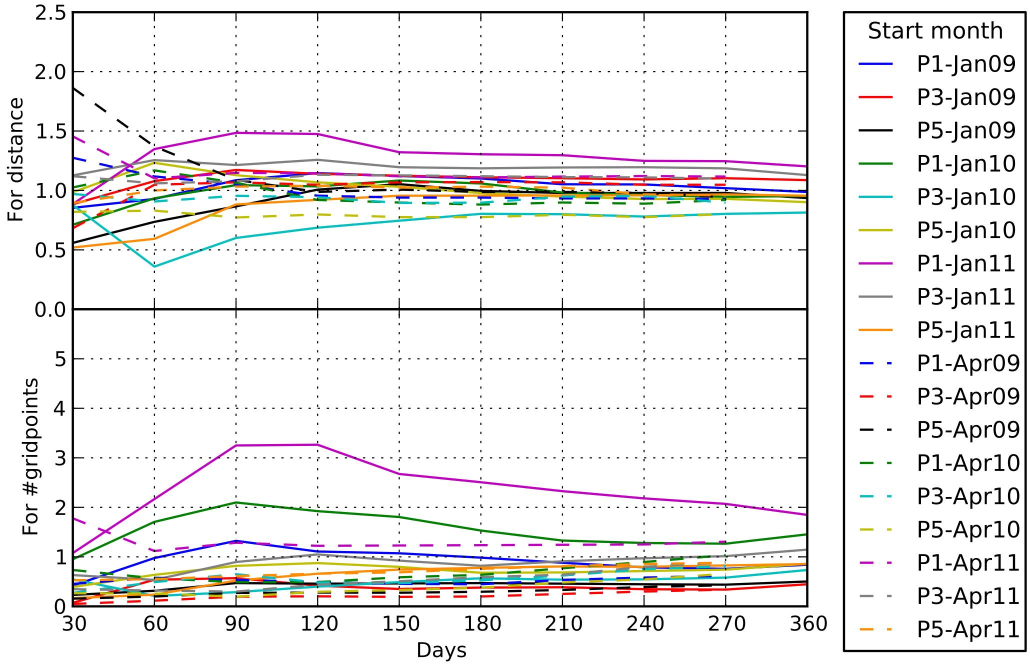


Figure 14: Similar to fig. 12, but for $N = 25\%$.

fig. 12 has a plot similar to fig. 6, but the lines are normalised by dividing with the value after three years. Therefore only lines from the locations P1, P3 and P5 are included in this figure. As simulations become longer, most of the lines cluster together in an interval between 0.5 and 1. Some cases demonstrate higher values. The one line that is much higher than all the others in the bottom panel is for simulations starting January 2011. This case saw a very wide spreading, compared to other cases, also demonstrated by the fourth panel of fig. 4.

Figures 13 and 14 shows the same as fig. 12, but $N = 50\%$ and $N = 25\%$, respectively. In both these cases, the lines for radius are distributed fairly evenly around the three-year value (*i.e.* $y = 1$), somewhat tighter in the 25% case. As simulations become around 6 months long, they vary only little related to three-year value, and most are within about $\pm 20\%$ of this, *i.e.* between $y = 0.8$ and $y = 1.2$. With regard to the number of gridpoints, most of the lines fall below the value of the three-year simulation.

5 Conclusion

Spreading of salmon lice has been modeled using LADIM and NorKyst800. While the spreading can cover large areas, most of the observations of lice are in a relatively small area, generally close to the coast. The number of particles released each hour does not seem to influence the results to any large degree, so for longer simulations in particular, 1 or 2 particles is likely enough.

The highest concentrations are generally found not in a continous area surrounding the release point, but in scattered patches. These patches often occur in the same locations, though the number of patches can vary.

Giving a definite value for how long simulations are needed for 'convergence' is difficult due to the differences in the results, both with regard to location and start time for the simulations. However, for simulations longer than about 6–7 months, the change in the concentration is generally quite small, so a simulation of that length will capture most of variability. For simulations of this length, those starting in January usually have a spread that is larger than, or similar to, those starting in April or July. To catch this larger varibility seen in the early months of the year, simulations should start in January.

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