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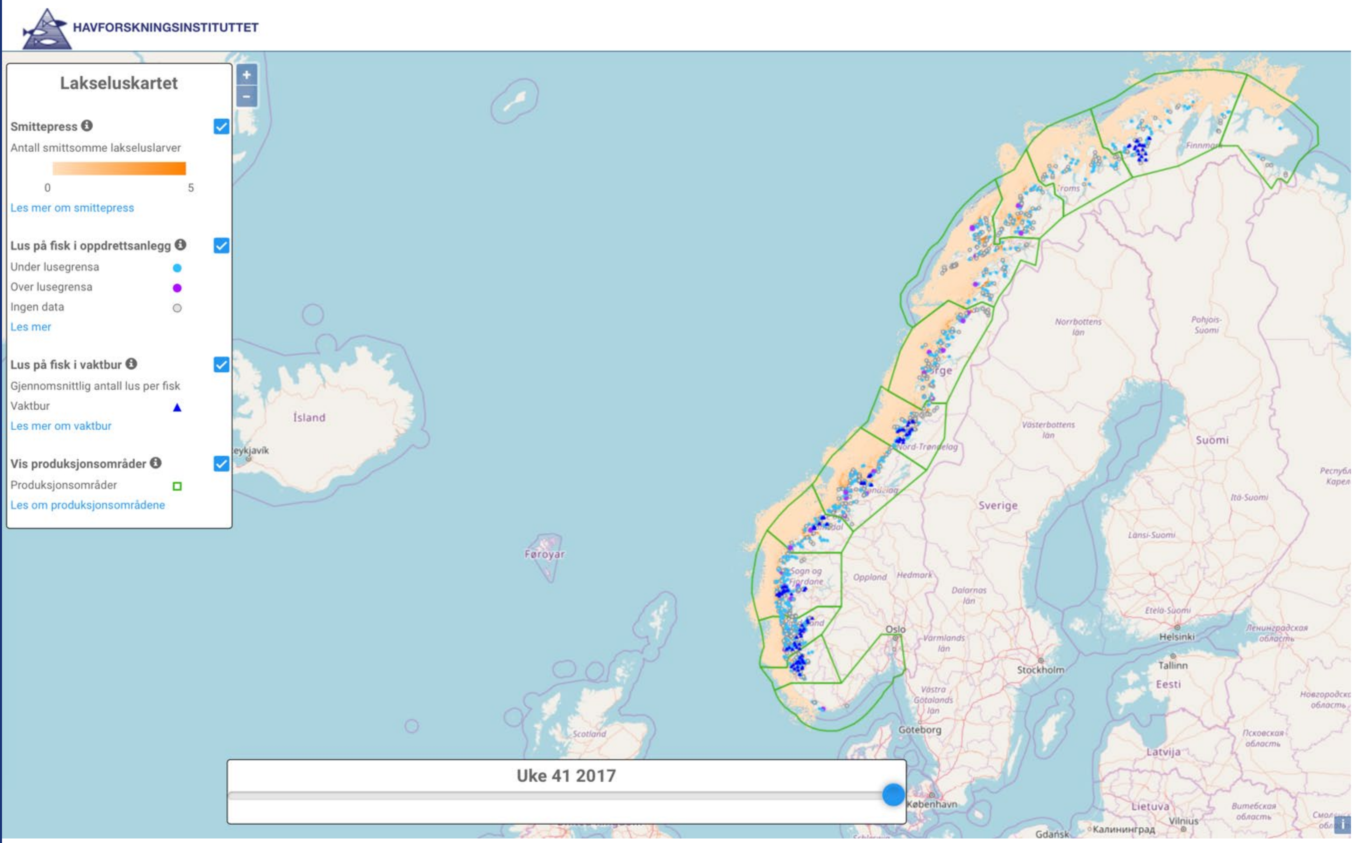

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Title (Norwegian and English):
Modellering av lakseluskopepoditter langs norskekysten – sammenligning mellom gammel og ny partikkelspredningsmodell

Modelling salmon lice copepodids along the Norwegian coast – comparing old and new particle tracking models

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Summary (Norwegian):
Målet med dette arbeidet er å evaluere forskjellen mellom den gamle *fortran* LADiM partikkelspredningsmodellen og den nye *python*-versjonen. Begge modellene bruker samme informasjon om lusebiologi og produserer geografisk fordeling av infektive lakseluskopepoditter hver time. Resultatene er relativt like, forskjellene er mindre enn 4 % for kopepodittkonsentrasjonen, og enda mindre når resultatene aggregeres i tid og rom. Vi konkluderer med at sammenligningen er tilfredsstillende og nye LADiM er velegnet til bruk i trafikklyssystemet.

Summary (English):
The purpose of this work is to evaluate the difference in the results from the old *fortran* LADiM particle tracking model and the new *python* version. Both models use the same salmon lice biological parameters and output from the models are hourly values of geographical distribution of infective salmon lice copepodids. The results are similar, differences are less than 4% for the copepodids concentration and even smaller when aggregated over space and time. We conclude that the comparison is satisfactory and the new LADIM is well suited for use in the traffic light system.

Emneord (norsk):
1. lakselus
2. spredningsmodellering
3. trafikklyssystemet

Subject heading (English):
1. salmon lice
2. particle tracking modelling
3. traffic light system

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Content

1 Introduction

The aquaculture of salmon in Norway has increased substantially the last ~30 years and today around 1.2 million tonnes of fish are produced. At any time 500-700 of the more than 1000 registered sea farms are in operation along the Norwegian coast from Agder to Finnmark (Figure 1). This increase in number of farmed fishes has not been without stressors on the wild ecosystem, and the growth in abundance of the salmon louse parasite (*Lepeophtheirus salmonis*) population due to ~500 times more potential hosts, is identified as a major problem.

The Norwegian government has an ambition of a continued growth of the aquaculture in Norway, but the industry needs to be sustainable and without critical influences on the wild ecosystems (Anon 2015). A new management system of the salmon aquaculture has been established where the carrying capacity of the wild fish for salmon lice within 13 production zones along the coast will determine whether the salmon production can increase or even be reduced (the "traffic light system"). To determine the colour of the "traffic light" (green = growth, yellow = status quo, red = decrease) several independent methods to assess the sustainability are used. This includes observational data and numerical model results. Also, several scientific institutions are involved in the collection of information and evaluation of the results. Finally, an expert group is appointed to assess the available information, including the model results as described in this paper, and recommend the traffic light colour later to be formally determined by the Ministry of Commerce and Fisheries every second year.

The Institute of Marine Research has over a long time period developed and established a numerical model simulating salmon lice growth and dispersion in Norwegian fjords and coastal waters (e.g. Asplin et al., 2004; Asplin et al., 2011; Asplin et al., 2014; Johnsen et al., 2014; Johnsen et al., 2016; Skarđhamar et al., 2018). Today the model system is used for both scenario experiments and for operational assessment of salmon lice infestation pressure based on reported numbers of salmon lice nauplii (larvae) released from fish farms and high-resolution currents, water temperature and salinity from an ocean current model. The results are validated against sentinel cages (Sandvik et al., 2016) and wild fish data (Myksvoll et al., 2018), and we find a relatively good agreement between model results and the various observations with correlation coefficient values around 0.7.

Although the salmon lice dispersion model is fully operational and with sufficiently accurate results, there are a continuously ongoing work to further improve the performance and especially get a better knowledge of the uncertainties in the results. One recent step has been to reprogram the particle dispersion section of the model system from the old *fortran* version to an updated *python* version. The latter is distributed freely on GitHub (https://github.com/bjornaa/ladim).

Theoretically we expected the newer model to be a slightly improvement, but a comprehensive comparison was required to point out and understand the differences, as well as to examine their importance for earlier conclusions. Thus, the two model versions were set up as equal as possible, and 2017 was chosen as the test year.

The purpose of the present report is 1) to ensure that the new model version has been successfully implemented and gives reasonable results in accordance to the results from the old model version, and 2) to highlight how the small differences in the model code influence on products delivered to advisory assessment.

2 Methods

The modelling system consists of several sub-models providing necessary input. We use a mechanistic approach where all relevant processes, from the details of the water mass movements to salmon lice behaviour, are reproduced as accurate as possible. Thus, we use a suite of various models and data sources feeding into each other in a cascade.

2.1. The fjord and coastal ocean current model system

The current model system contains models for atmospheric forcing, freshwater runoff and open boundary conditions towards the ocean in addition to the model for the current itself. Atmospheric forcing, i.e. wind, pressure, temperature, humidity and precipitation, is produced using the WRF model, developed by the National Center of Atmospheric Research (NCAR) (https://www.mmm.ucar.edu/weather-research-and-forecasting-model; Skamarock et al., 2008). Realistic values on a 3 km horizontal grid are produced and stored at 3-hour intervals and subsequently imported to the current model. The river runoff is based on modelled discharge from the 247 main Norwegian catchment areas that drain to the sea. The Norwegian river discharges are modelled by NVE (Norwegian Water Resources and Energy Directorate) using a distributed version of the HBV-model with 1 km horizontal resolution (Beldring et al., 2003). Note that river discharges are estimated from natural variations in weather climate, and there are no modifications due to regulations by damming. Daily averaged currents, hydrography and water level from a 4km x 4km resolution ROMS hindcast simulation was applied as open boundary conditions (see more details in Lien et al., 2014) by using a mix of radiation-nudging boundary conditions (Marchesiello et al., 2001). The tidal forcing was applied along the open boundaries and interpolated from the global TPXO7.2 (Egbert and Erofeeva, 2002).

The coastal circulation model is the Regional Ocean Modeling System (ROMS) which is an open source model developed at Rutgers University and UCLA with extensive usage by scientific communities world-wide (e.g. Shchepetkin & McWilliams, 2005; Haidvogel et al., 2008, or see http://myroms.org). In Norway, also the Meteorological institute use the ROMS model in their operational forecasts. The ROMS model solves the three-dimensional primitive hydrodynamical equations using the hydrostatic approach. The computational grid is square in the horizontal and has terrain following generalized sigma coordinates in the vertical with a free surface.

Simulations for the Norwegian coast, the NorKyst800, use an 800 m x 800 m horizontal grid resolution and 35 vertical levels with a relatively dense resolution in the upper 10-20 m. Currents, salinity and temperature are stored hourly to be used for particle dispersion in the salmon lice model. This model set-up is described in Albretsen et al., (2011).

2.2. The particle tracking models

Two particle tracking models, confusingly both named LADiM, are used. LADiM is an acronym for Lagrangian Advection and Diffusion Model. The old LADiM code is written in *fortran* and was first used in Ådlandsvik and Sundby 1994. The present version is running off-line based on result files from the ROMS model, in our case the NorKyst800 simulation described above. It has a choice of advection schemes, Euler Forward and Runge-Kutta 4th order and a random walk diffusivity.

The old model code has not been properly documented and has not been subjected to any version control system. As a result, maintenance and further development of the model have become difficult. It was therefore decided to make a new model code. The *python* programming language with the numpy library was chosen for this task because of demands for flexibility and ease of extension. The new LADiM code is open source, the code is available on GitHub, https://github.com/bjornaa/ladim and the documentation on “Read the Docs”, https://ladim.readthedocs.io. Basically, the new model performs the same tasks as the old, running offline with forcing from a regional ocean circulation model, a choice of advection schemes and optional random walk diffusivity.

One of the improvements in the new LADiM is larger flexibility, the possibility to use different ocean models for forcing and the possibility of applying different individual-based modules (IBMs) for vertical migration or other behaviour of the particles. Using modern software development tools, such as source control, the maintenance of the model is greatly simplified. Some minor new technical features, such as restart functionality, simplified the undertaking of these long simulations. The *python* implementation has comparable running time as the *fortran* version. This may be surprising as *python* has a reputation of being slow. The reason is that the running time is limited by I/O (i.e. reading output files from the coastal circulation model). This gives no performance drop as the same NetCDF library is used by both *fortran* and *python*. Also, the *python* version is more computationally efficient since dead copepodites are eliminated from the simulation.

The individual-based model (IBM) used here for salmon lice growth and advection is described in e.g. Asplin et al. (2014) and Johnsen et al. (2014). Particles, representing salmon lice *L. salmonis* during its planktonic stages, are released at each salmon farm site and transported based on the currents from the current model. The age and position of each louse are stored every hour and used to calculate the density field of infective lice particles (i.e. copepodid particles). All particles that hits the offshore grid boundary are excluded from further analysis.

The model particles represent salmon lice as super individuals, i.e. one particle represents many salmon lice with similar dispersion properties. In the present study, five super particles are released at each farm every hour. The number of nauplii released from each farm in the model domain is estimated from the average number of lice pr. fish, the number of fish and the water temperature data reported by farms. Assuming each female louse to hold 300 eggs, we quantify the lice larvae production at each farm according to the models in Stien et al. (2005). The weight of each super particle is adjusted based on this. Wild salmonid fish as a source for salmon lice are neglected.

We use state-of-the-art knowledge to parameterize the behaviour, growth and mortality of salmon lice (Johnsen et al., 2016, Myksvoll et al., 2018). All simulated lice particles have an absolute swimming speed of 0.5 mms^{-1}. The swimming is upwards during daytime and passive at night, overridden by downwards swimming if the ambient salinity is too low. Particles are given a random movement component, both vertically and horizontally at each time increment to represent turbulence on a sub-grid scale. Mortality was parameterized at a constant rate of 17% per day, as estimated by Stien et al. (2005). The lice are infective from 40 to 170 degree-days.

In the post-processing process, we aggregate the number of infective lice per grid cell, vertically integrated over the upper 2m (wild fish are assumed to reside mainly un the upper 2m), divide by the grid area, and express the lice concentration as number of lice copepodids per m^2 per day.

For the simulations presented here we have tried to make the models behave as equal as possible. However, some differences are unavoidable. The old *fortran* LADiM has a bug in the implementation of the Runge-Kutta scheme. The bug is not severe, the scheme is still consistent, but not strictly fourth order. The new LADiM is without this bug.

More important is the treatment of land and bottom. In the new code the behaviour is simple, if a particle is about to go on land it is not moved. If it is about to go under the bottom, it moves to the new position, but the particle depth is reset to 99% of the bottom depth. In the old model this treatment is different. If a particle is about to go onto a land cell or there is a land cell towards right, the particle is not moved. If a particle hits the bottom or if one of the four closest cells to the target position is shallower than the particle depth, it is not moved. As a result, particles in the old model are less likely to end up in cells neighbouring land, with a bias away from shores to the west and north (in the NorKyst800 grid). The old behaviour is judged as theoretically questionable and it is a deliberate decision not to use it in the new model.

A technical detail of the new *python* LADIM is the alive switch, which means the ability to kill particles older than the age of interest. Whereas the old *fortran* LADIM continued to calculate the position of particles older than the scope of interest, the new version does not do this, making the new *python* LADIM more computational efficient to run. This should not influence the model results as they only include particles within an age range.

Table 1. *Overview of parameterizations in the two model versions*

	OLD	NEW
Source code	*fortran*	*Python*
Advection scheme	4th Runge Kutta (with bug)	4th Runge Kutta
Horizontal diffusion	0.15 m²/s	0.15 m²/s
Vertical diffusion	0.001 m²/s	0.001 m²/s
Land handling	good enough	better
Alive switch	no	yes

2.3. Calibrated model products

The output from the salmon lice modelling system is the hourly geographical distribution of salmon lice copepodid concentration and is the most obvious variable to compare before implementing the new model version in the management system.

The copepodid concentration can vary relatively rapid due to the varying currents with eddies and fronts. However, the copepodid density maps give a good impression of the relative distributions and has shown good correlation with lice on fish in sentinel cages (Sandvik et al. 2016). To quantify the impact of lice on wild fish, the copepodid concentration has to be “translated” into absolute numbers related to mortality or degree of influence. Thus, to quantify the infestation pressure on wild salmonids, we have developed two products from the concentration fields: "The infestation pressure map" and "The virtual smolt population".

The infestation pressure map is constructed from the time series of salmon lice concentration in the upper 2m of the water column and in each horizontal grid cell for a given period of time. Based on observed infestation of salmon smolt in sentinel cages we determine threshold levels for high, medium and low infestation (Sandvik et al., 2016). From empirical observations of smolt infestation in sentinel cages in the Hardangerfjord, we have found a threshold for high infestation pressure being 1.5 copepodids pr. m^2 in 80% of the 3 by 3 horizontal grid nodes around the actual node. Thus, a fish that reside in a node reaching this threshold during any time period (shorter for higher concentration, longer for lower), will most likely be infested with more than 10 lice. By selecting relevant time periods, e.g. an assumed feeding period for sea trout, we can assess the infestation pressure based on the model results.

The virtual smolt model assumes that salmon smolt migrate from the river into the coastal ocean. A large number of virtual smolt are sent through the model domain (copepodids integrated over the 2 upper meters), and interaction with the variable distribution of copepodids are recorded. We assume the smolt population to migrate in a certain time period during spring and summer, earlier in the southern Norway than in the northern Norway. The time when the individuals starts to migrate can be modified and also the swimming route. The final result will be the aggregated mortality of the virtual smolt population from the given river. Details can be found in Johnsen et al. (2018).

2.4. The simulations

We have simulated the concentration of salmon louse copepodids for spring and summer of 2017 using realistic currents updated hourly and sources of lice from the farms in operation. Identical experiments with both the old and the new LADiM code were performed, meaning that the number of released lice from all farms is exactly the same and the settings are as shown in Table 1.

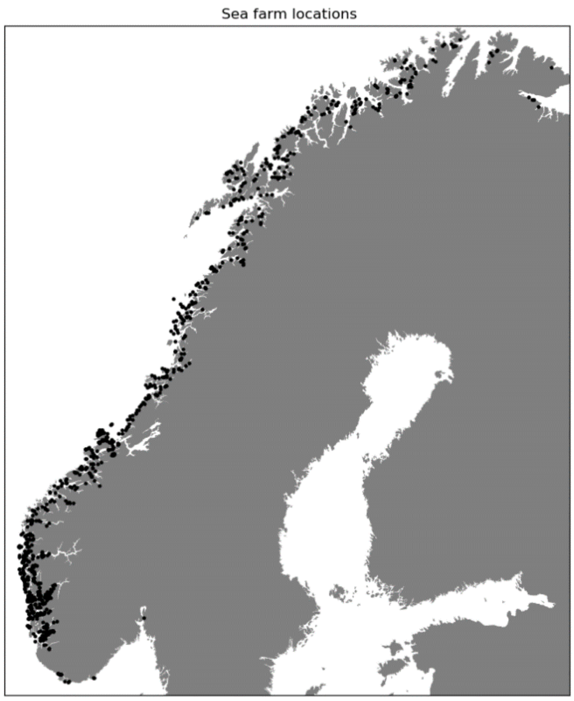

Figure 1. *Locations of the fish farms that act as a source for salmon lice in the simulations.*

3 Results

Identical results between the two simulations should not be expected. The random properties of the diffusion implementation will give differences between the two simulations even with the same model. The output from the model is aggregated over the upper 2m, differences in vertical distribution can therefore also affect the results shown here. In addition, the differences in the land/bottom treatment are expected to be visible.

Only a subset of all available figures will be presented as examples, and the rest are found in Appendix. The results are presented for the established 13 production areas for salmon aquaculture along the Norwegian coast, since these are the relevant regions for estimating lice induced mortality on wild salmonid fish in the so-called "Traffic light system".

3.1. The total number of salmon lice copepodids

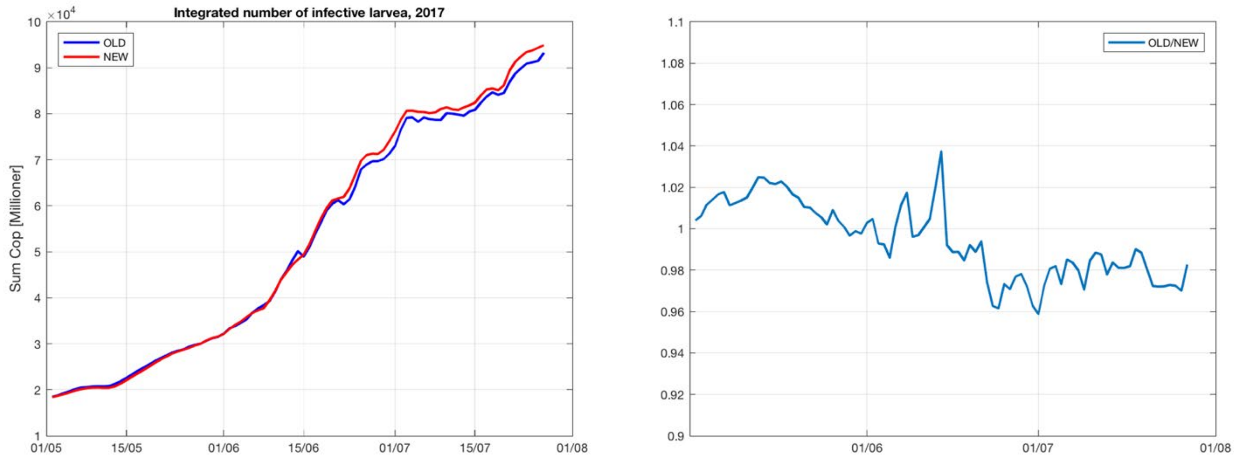

Figure 2. *The total number of copepodids to the left and their ratio to the right.*

The copepodids in the simulations are particles with age between 40 and 170 degree-days. The total number of copepodids from the two model implementations (old *fortran* and new *python* LADiM) follow a similar increasing pattern during the spring and with a maximum in late July (Figure 2, left panel). Until mid-June the difference in total number of copepodids is modest and less than 2% (Figure 2, right panel). The difference increases slightly after that and levels out at approximately 3% more copepodids in the simulation with the new LADiM code.

The source terms are identical. The ±4% difference between the simulations is therefore caused by changes in horizontal movement of the particles. Particles experiencing different temperature will be in the copepodid stage at different times, while differences in salinity may influence particle depth which feeds back again on the movement.

3.2. Vertical and horizontal distribution of lice copepodids

The basic result of the modelling system is the geographical distribution of the planktonic salmon lice in time. Hourly distributions are normally stored, but the distribution is often presented as the aggregated concentration over longer time periods (days to months).

As the currents in fjords and along the Norwegian coast are strongly stratified, with respect to temperature, salinity and currents, it is important to position the particles realistically in the vertical to obtain correct distribution patterns. In accordance to observations salmon lice are parameterized in the model to swim in the vertical to obtain a position close to the surface, and to avoid water of low salinity by sinking down. Description of the modelled vertical behaviour is given in detail in Myksvoll et al. (2018). The mean distribution for copepodids during the simulation period for the new *python* LADiM is shown in Figure 3. As the vertical lice behaviour is parameterized in similar manner as in the old *fortran* LADiM the vertical distribution from the new *python* LADiM is very similar to the distribution from the old *fortran* LADiM (Johnsen et al., 2014).

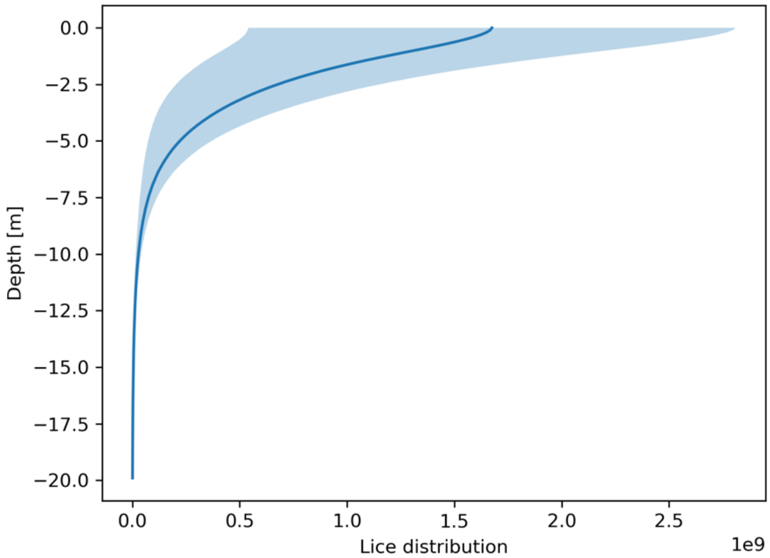

Figure 3. *Vertical distribution of salmon lice from and new model. Blue line gives the overall mean distribution of salmon lice (Lepeophtheirus salmonis) copepodids, the shaded area marks the mean value +/- standard deviation.*

In general, the old and the new LADiM models produce similar results and provide the same horizontal distribution pattern of high lice concentration areas (Figure 4). The largest differences are seen close to land, in narrow fjords and in the vicinity of the largest sources i.e. the farms. The higher concentration in the new model on the north side of the Boknafjord and the old model on the south side of the Bjørnefjorden may be induced by the bias in the land treatment in the old model. The difference in land treatment causes the lice to be redistributed within the same area. Even though there are significant differences locally, the regional lice distribution is very similar between the two simulations.

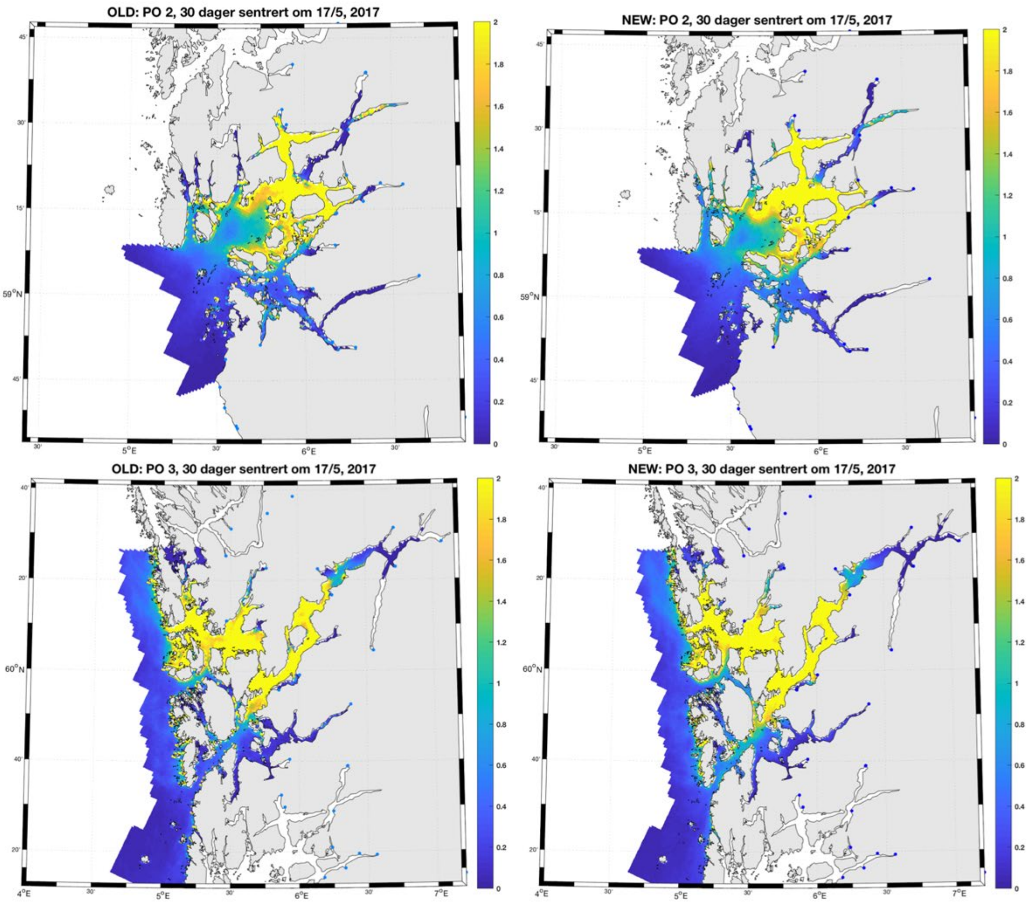

Figure 4. *Copepodid concentration in production areas 2 and 3 aggregated for 30 days centred around May 17, 2017. Results from the old LADiM on the left and the new on the right.*

3.3. Infestation pressure map

The infestation pressure map is a way to illustrate the area of elevated infestation pressure in various parts of the fjord and coastal areas (Figure 5). Typically, the infestation pressure will be highest in the areas with the most fish farms, and the detailed distribution will depend on the current conditions for the relevant period. As for the distribution of the copepodids (Figure 4), the infestation pressure maps from the simulations with the old and the new LADiM are not identical, but nevertheless highly comparable.

Figure 6 shows the running mean of the area with elevated infestation pressure from production area 2 and 3. The green lines indicate the timing of smolt migration from the rivers towards the ocean (peak migration (solid line), start and end of migration (dashed lines). This figure clearly shows that the new LADiM produces a larger area of elevated infestation pressure than the old version. The difference is small in the beginning of the season and increases through time.

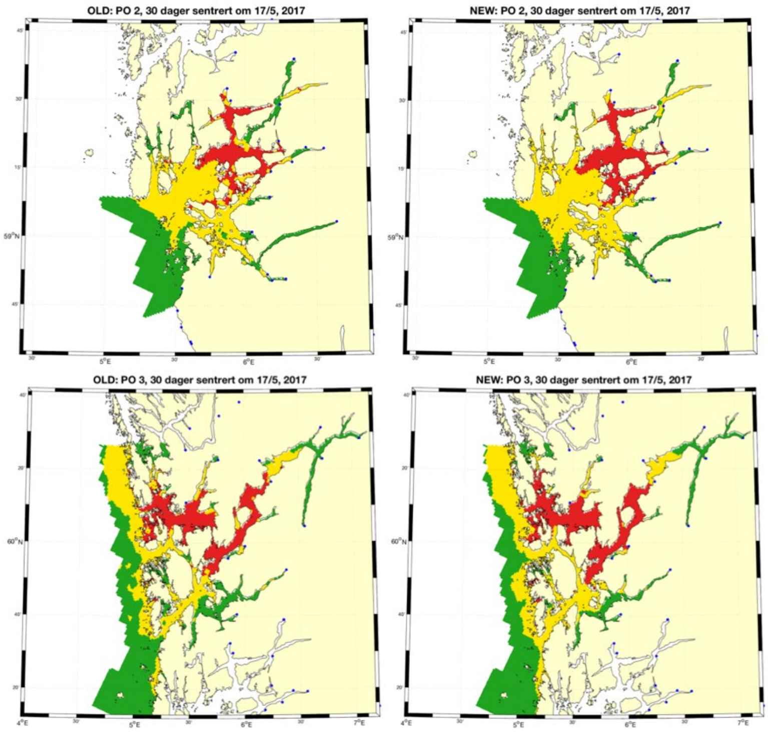

Figure 5. *Infestation pressure map for production areas 2 and 3 for 30 days centered around May 17, 2017. Results from the old LADiM on the left and the new on the right. Red colour is high infestation pressure, yellow is medium and green is low.*

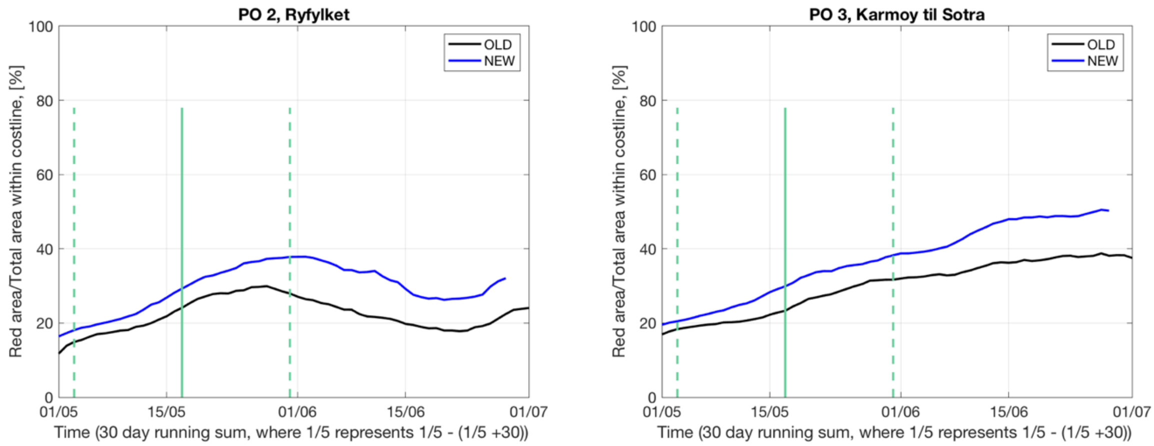

Figure 6. *Running mean of the area with high infestation pressure (red colour in Fig. 5) for production areas 2 and 3 for old (black) and new (blue) model simulations.*

3.4. Virtual smolt model

The virtual smolt model is a useful tool when evaluating the carrying capacity in the 13 production areas along the Norwegian coast. The smolt migrates from the rivers, through the lice-exposed fjord and towards the open ocean. As the smolt passes through regions of high salmon lice infestation pressure, these lice get attached to the fish. We model individual smolts along specific routes and count number of lice attached to every fish when the fish has reached the open ocean. The output from the model is compared with trawl data from the fjord and calibrated accordingly (Johnsen et al. 2018). From the number of lice on all the fish, we can calculate lice-induced mortality from Taranger et al. (2012). In total are 1000 fish released from 401 rivers along the Norwegian coast, and hence we can estimate the lice-induced mortality in all populations.

Figure 7 shows the mean intensity of lice on smolt migrating from all the 401 rivers, as calculated with the virtual smolt model. The old model version is displayed on the x-axis and the new model version on the y-axis. Most of the river estimates follow the diagonal, meaning the two models compare well, however there are some variability in the predicted lice level between the rivers. The percentage difference between the number of lice from the new and old model was calculated. The mean shows an increase from old model version to the new model version of 10 %, whereas the median increase is 0 %. The difference between mean and median indicates an uneven distribution of lice level between the rivers. The root mean square error (RMSE) for mean intensity between the model simulations was 1.1.

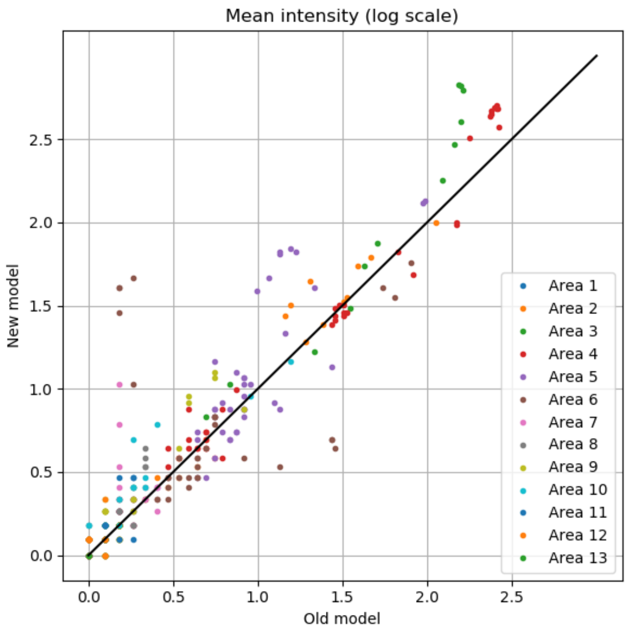

Figure 7. *Comparison between new and old LADiM of mean intensity of lice from the various rivers in the 13 Production Areas along the Norwegian coast.*

Figure 8 shows estimated lice-induced mortality on the smolt populations in specific rivers in production area 2 and 3, the other areas are shown in the Appendix. Here we find relatively similar results when comparing the old version (left) with the new version (right). However, there are discrepancies on individual rivers, but the overall assessment of the areas is not different.

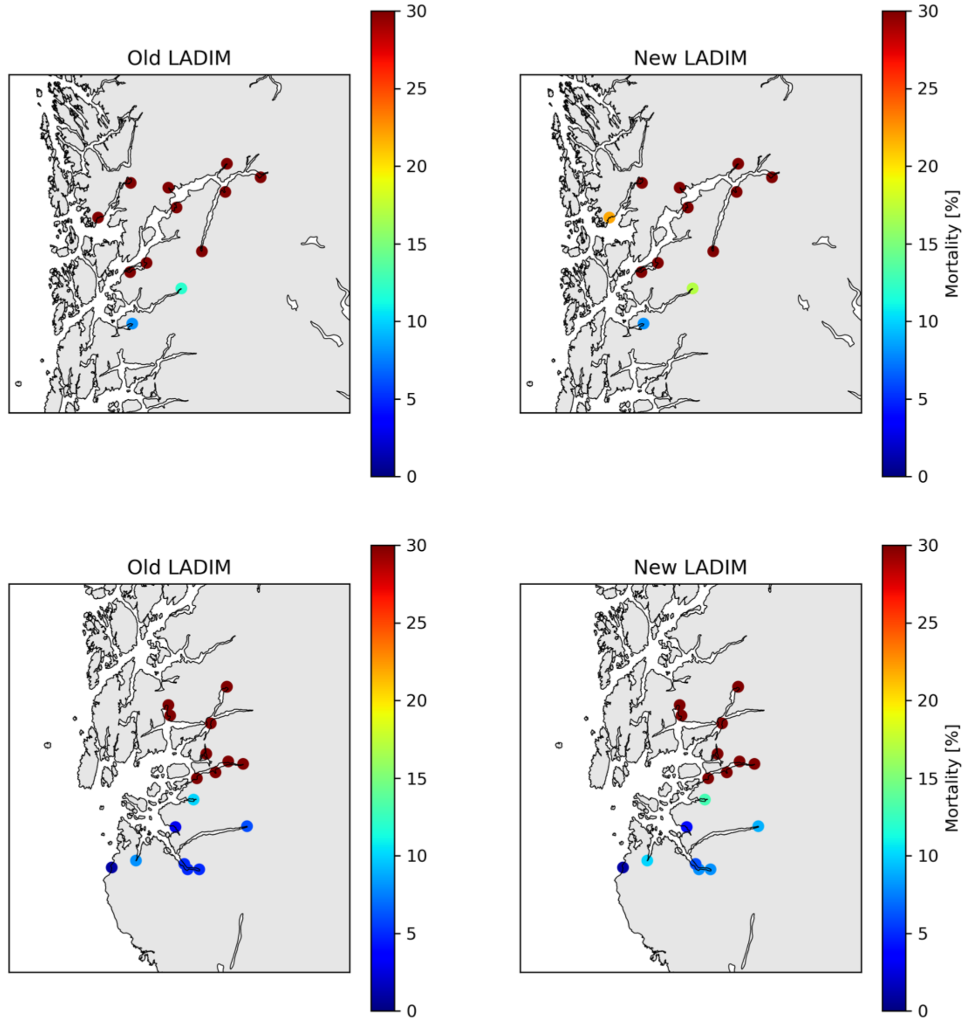

Figure 8. *Estimated mortality of the salmon populations migrating from individual rivers using the old LADiM model (left) or the new (right) for rivers in Production area 2 and 3.*

4 Discussion

4.1. Summary

The purpose of this work is to evaluate the difference between the results from the old *fortran* LADiM particle tracking model and the new *python* version. Both models use the same salmon lice biological parameters and output from the models are hourly values of geographical distribution of infective salmon lice copepodids. The only difference between the two simulations is the particle tracking algorithms with bottom and land treatment. Here, the new model has not copied the bug in the advection scheme or the unfortunate implementation of the bottom and land handling. The random walks used in the implementation of diffusion also contribute to differences between the simulations. However, the differences should not be too large.

The total number of copepodids in the two simulations varied slightly (± 4%), as seen in Figure 2. Both simulations start with exactly the same number of particles, so this difference is caused by internal differences in advection and vertical distribution. Through both random effects and land handling the particle distributions can be shifted in time and space. This leads to differences in the number of particles that will be transported out of the model domain and differences in temperature exposure and their corresponding life span.

The differences for the model products, infestation pressure map and virtual smolt, are significant when comparing the old and the new model version. Interpretation of these results are difficult since both of these include an extra step of calibration against observations, either sentinel cages or trawl data.

4.2. Factors affecting the differences

These simulations involve a large number of processes and even the smallest difference at every calculation can add up to something larger when the total number of calculations is huge as is the case for these simulations. Thus, two models programmed in different programming languages will never be completely identical due to minor technical differences. Also, small differences in the vertical position can give an amplified signal as the shown figures only include copepodids from the upper 2m.

Particle tracking as we do it involves a correction term every time step to include a small (sub-grid scale) and generally unknown motion due to turbulence. This so-called random walk algorithm will certainly generate differences when added up through months of simulations. The differences though, should be relatively small. For the virtual smolt method however, it might be of importance if the distance between the virtual smolt and a lice patch changes 1-2 grid nodes horizontally.

Differences in land handling and random parameters cause a redistribution of particles within specific fjords, however there are minor regional differences (Figure 4). On the scale of the production areas the results are more or less indistinguishable. As individual particles are redistributed, they will experience different temperatures and have different life spans. The combined effect of redistribution and increasing temperatures cause the increasing difference between the two model simulations for the area of elevated infestation pressure (Figure 6).

4.3. The way forward

Summing up, the results from the new model are expected to be an improvement as a bug and some inappropriate decisions in the old model have been eliminated. However, we do not have data that can verify that expectation. The results are similar, differences are less than 4% for the copepodids concentration. Hence, we conclude that the comparison is satisfactory and the new LADIM is well suited for use in the traffic light system.

To ensure the highest possible quality of the model products, which are important deliverables in the management system, we have recalibrated the model product to the new model outputs. A further description of this operation can be found in Johnsen et al. (2018) for the virtual smolt model and the infestation pressure maps is under publication (Anne Sandvik, pers. comm.).

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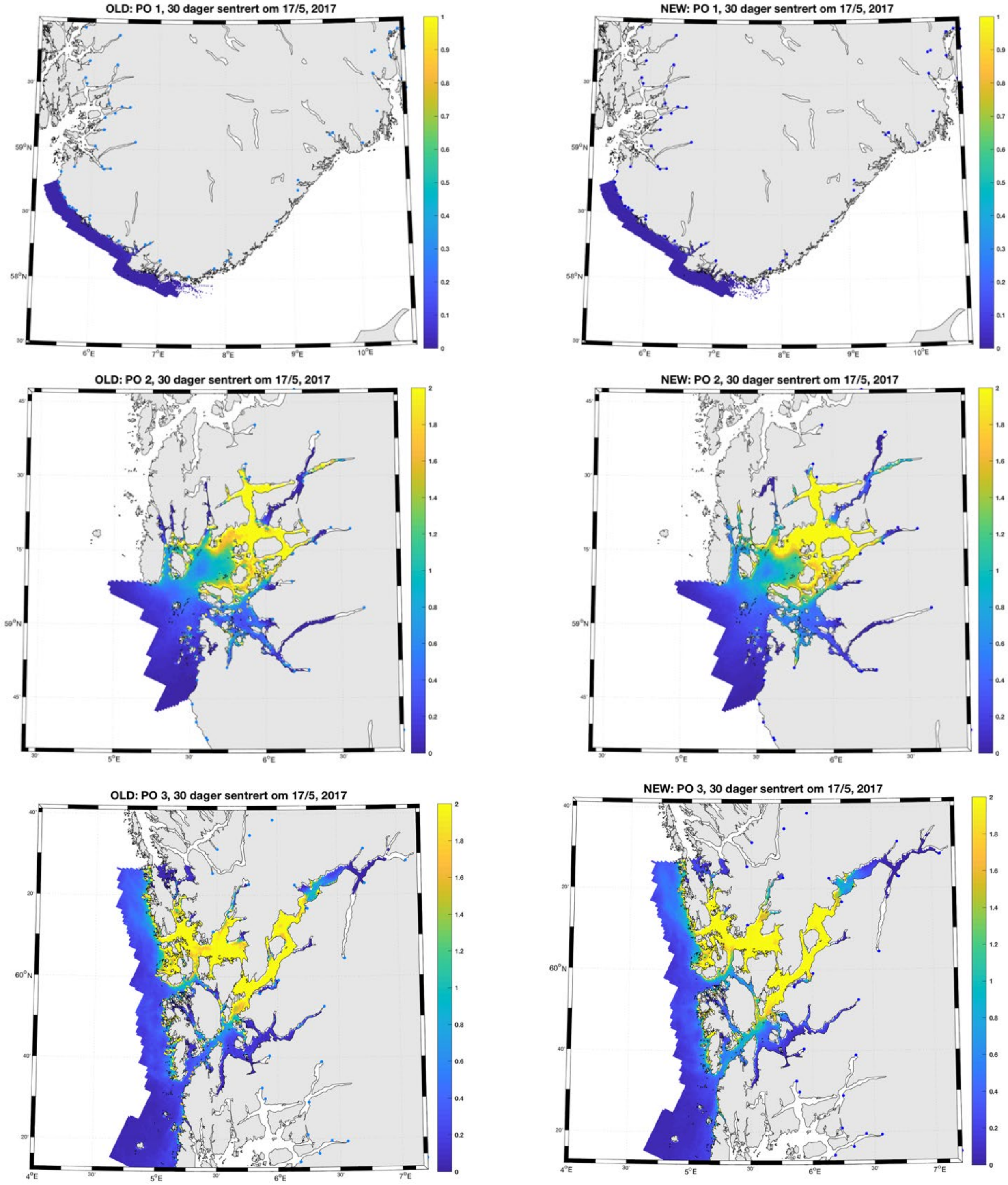
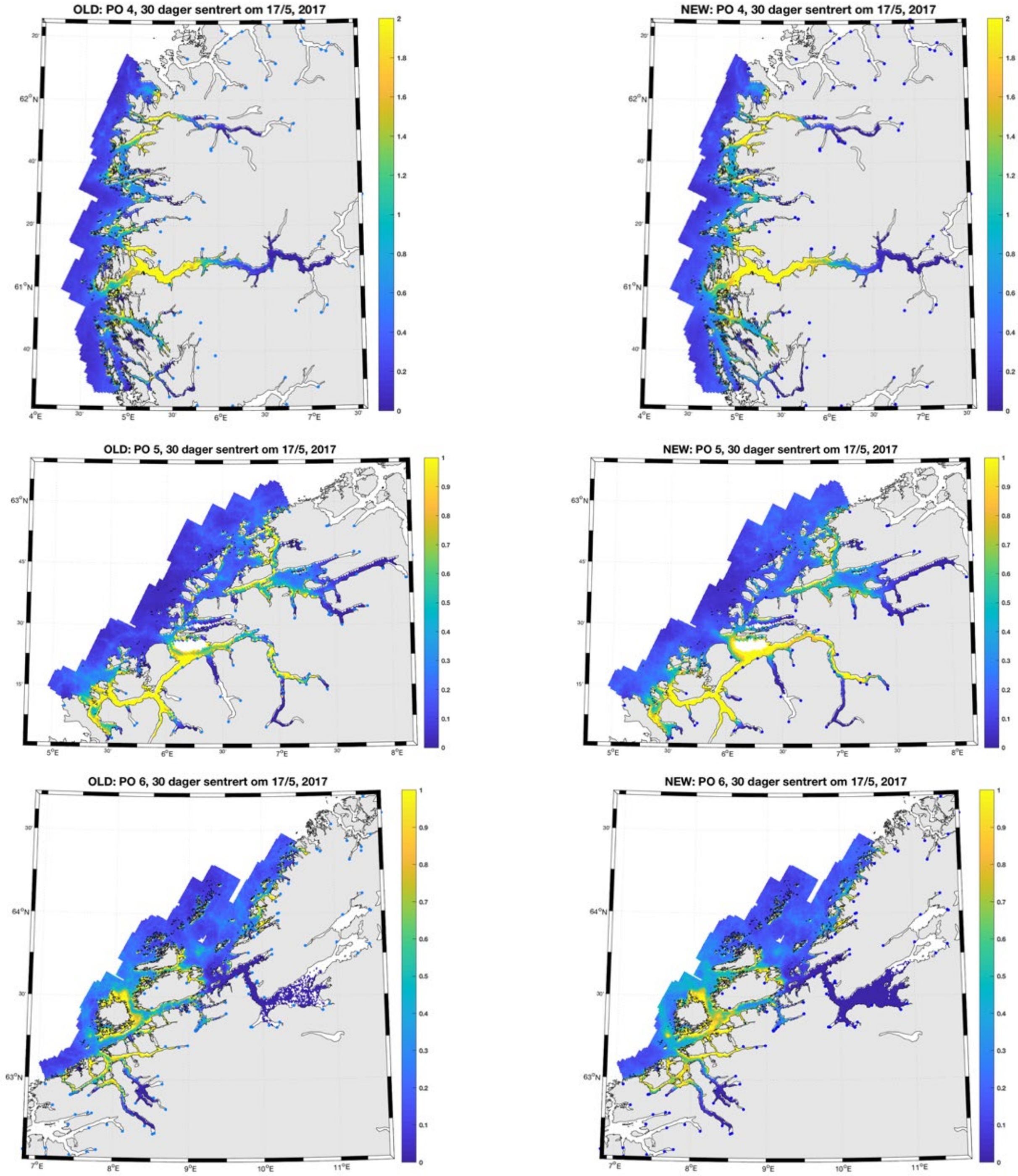
6 Appendix

6.1. Old and new copepodid concentration

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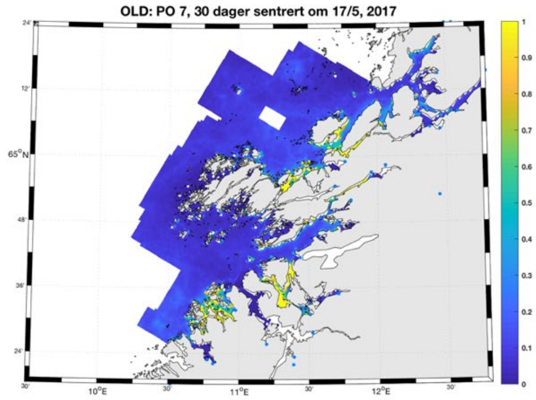
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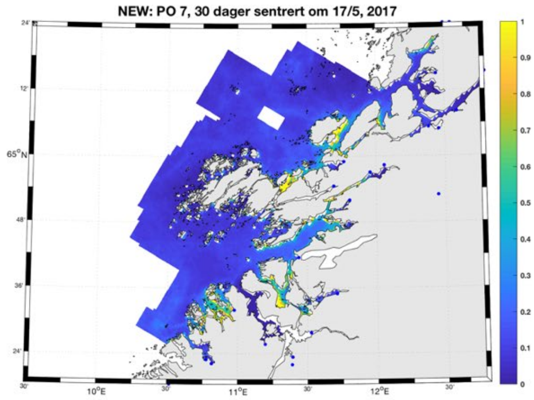
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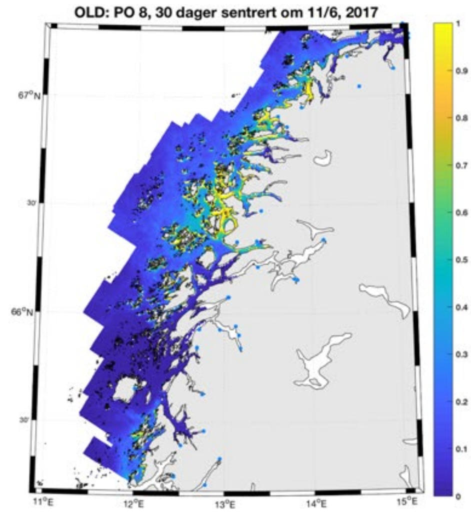
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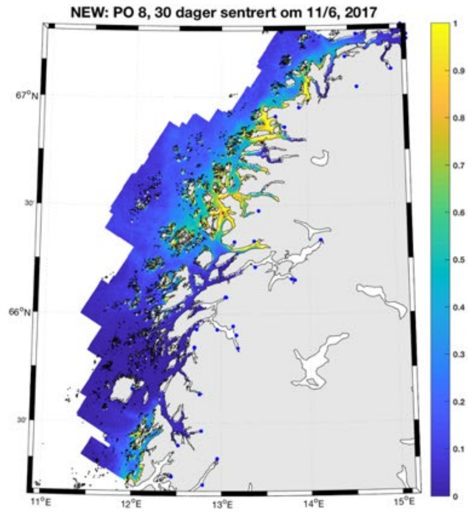
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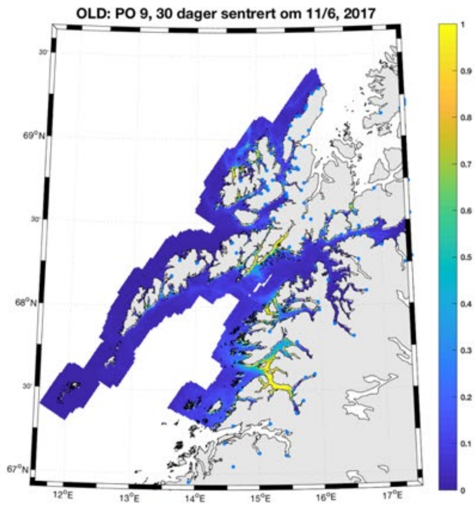
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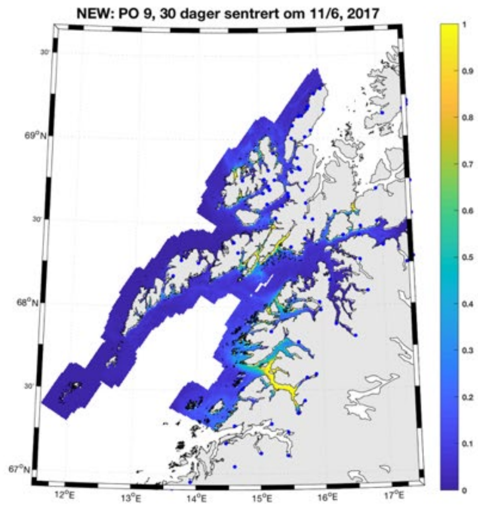
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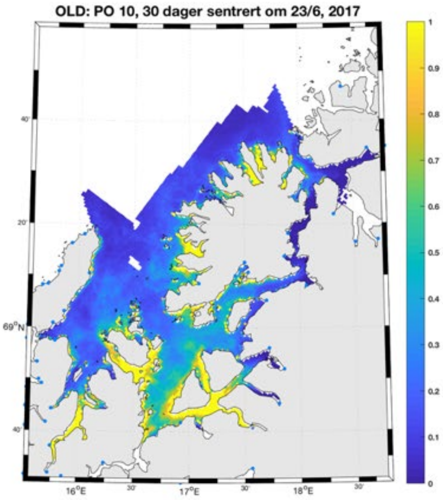
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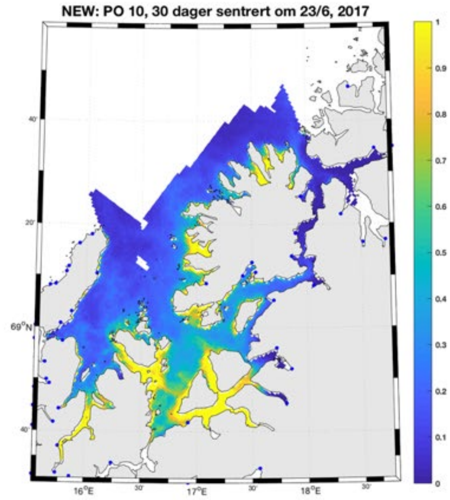
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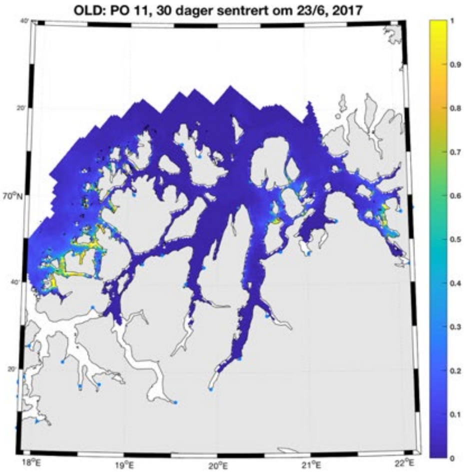
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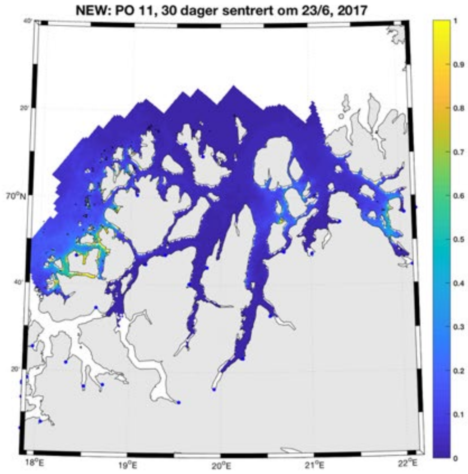
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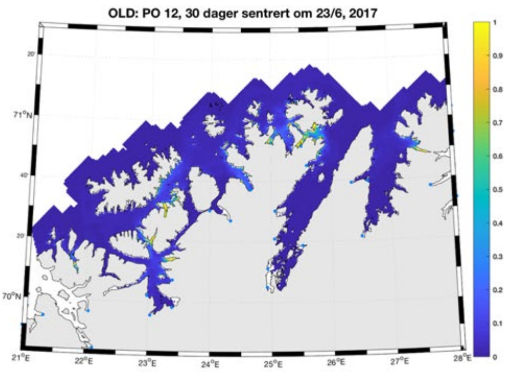
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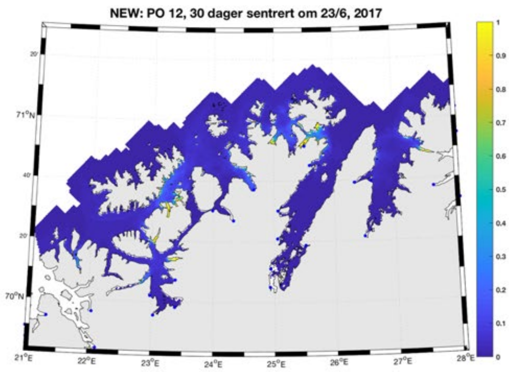
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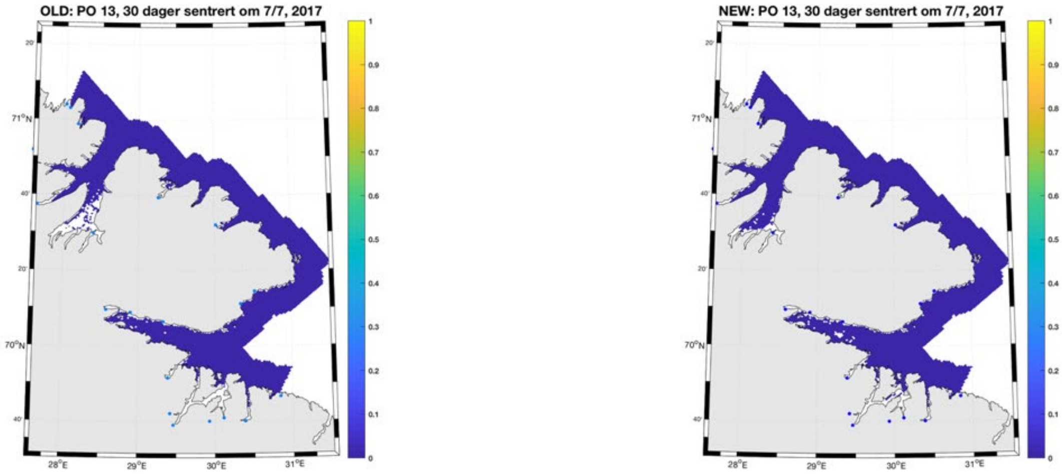
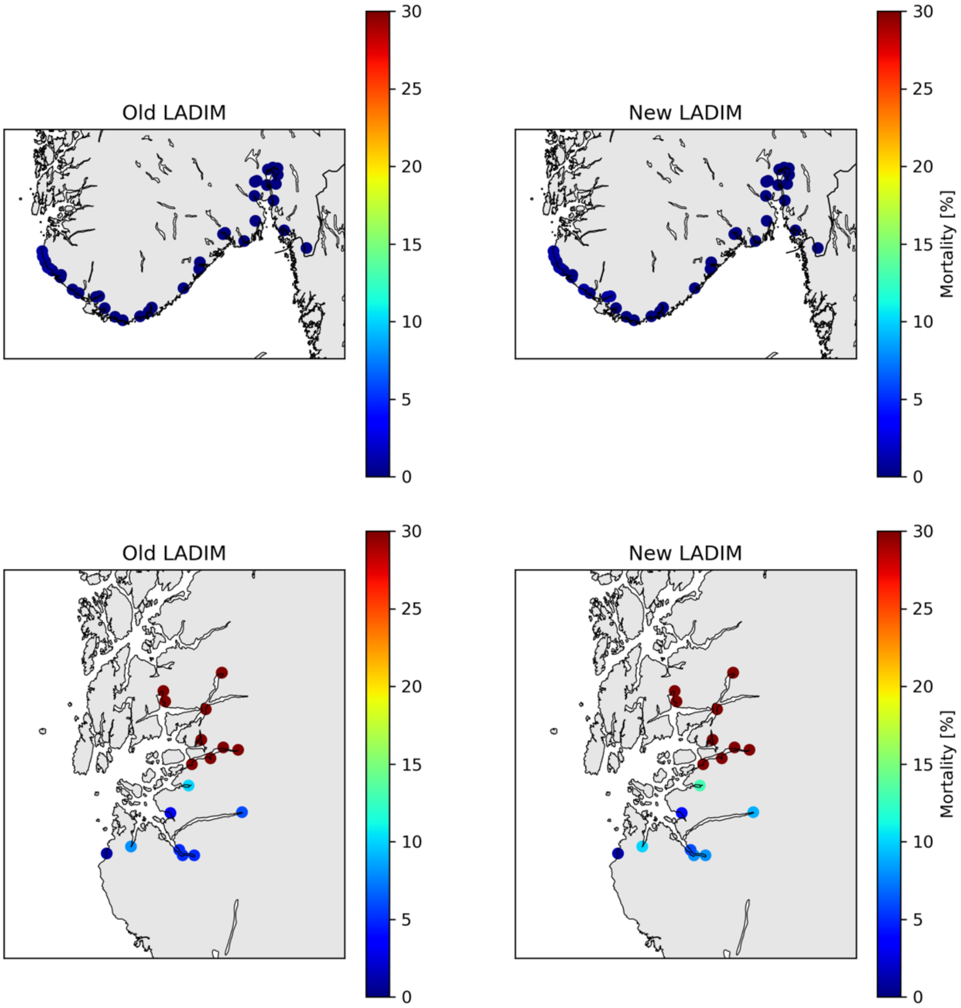
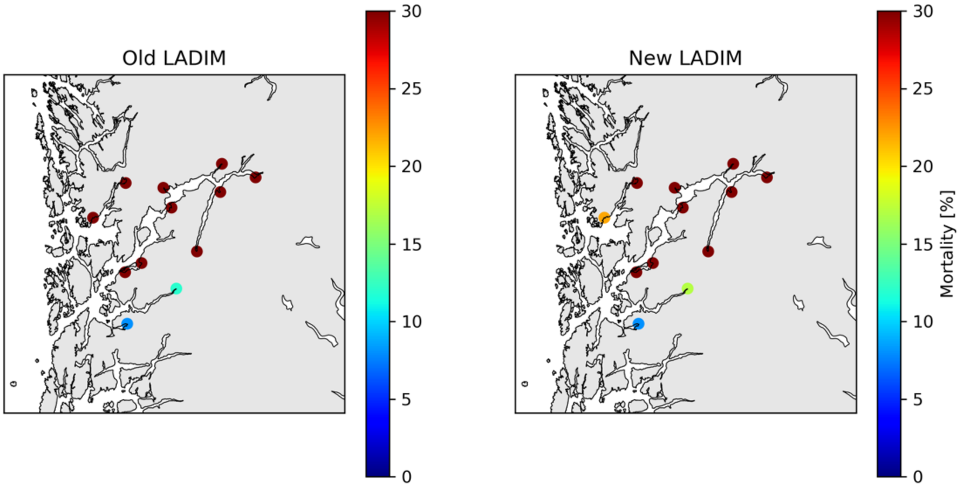


6.2. Old and new virtual smolt

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New LADIM
30
25
20
15
10
5
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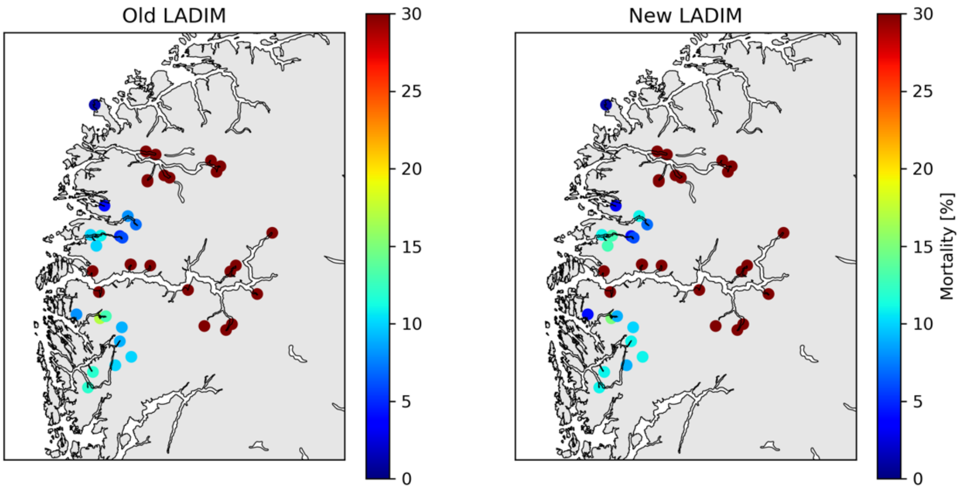
Mortality [%]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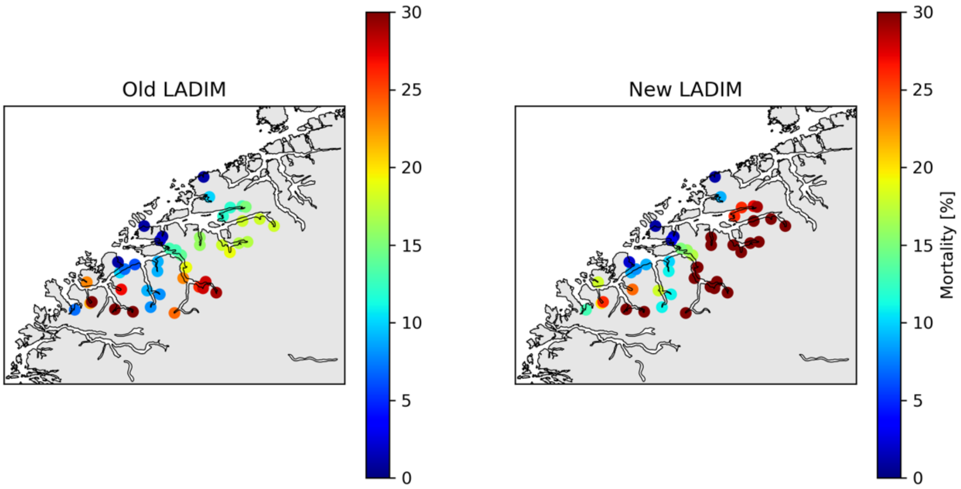
Mortality [%]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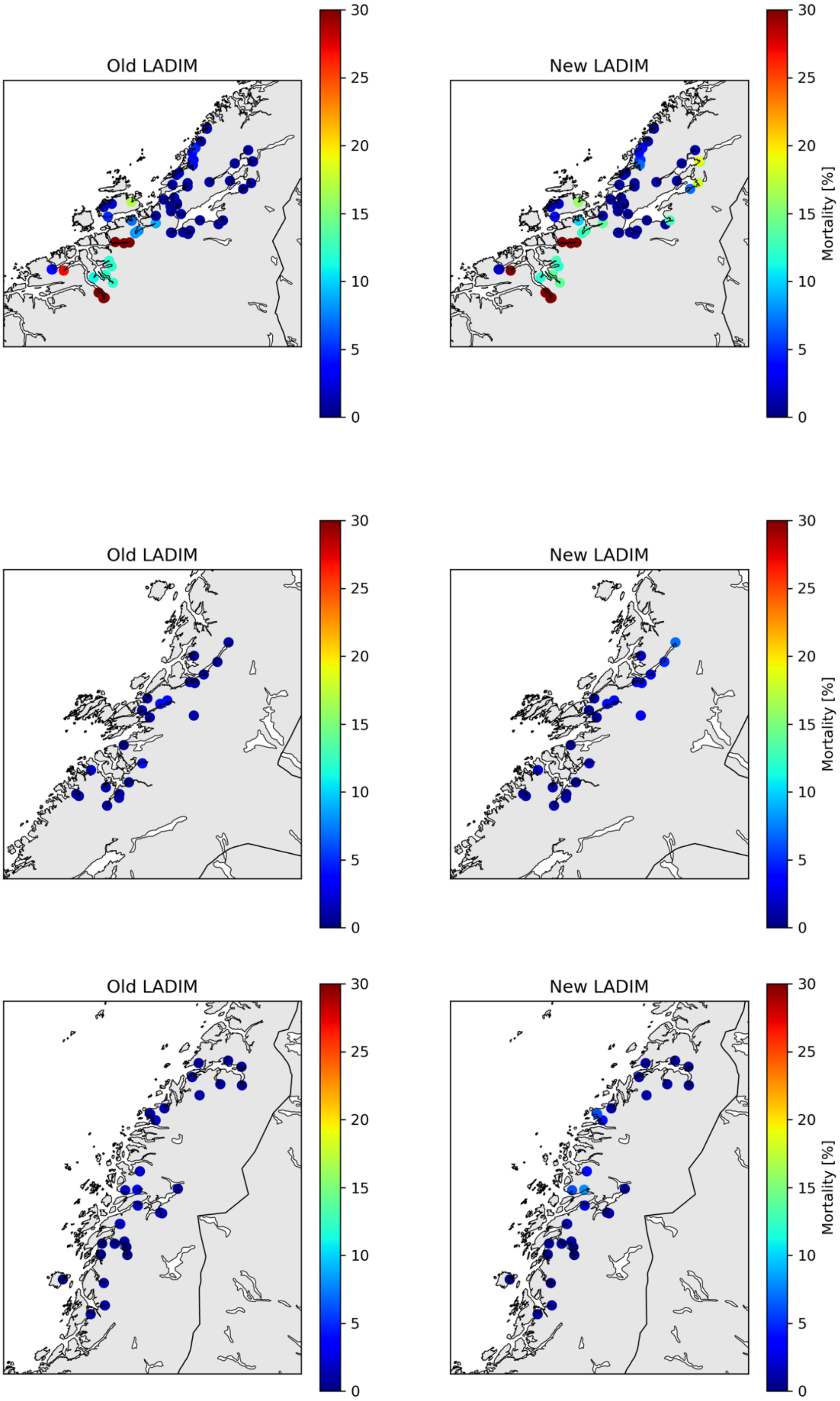
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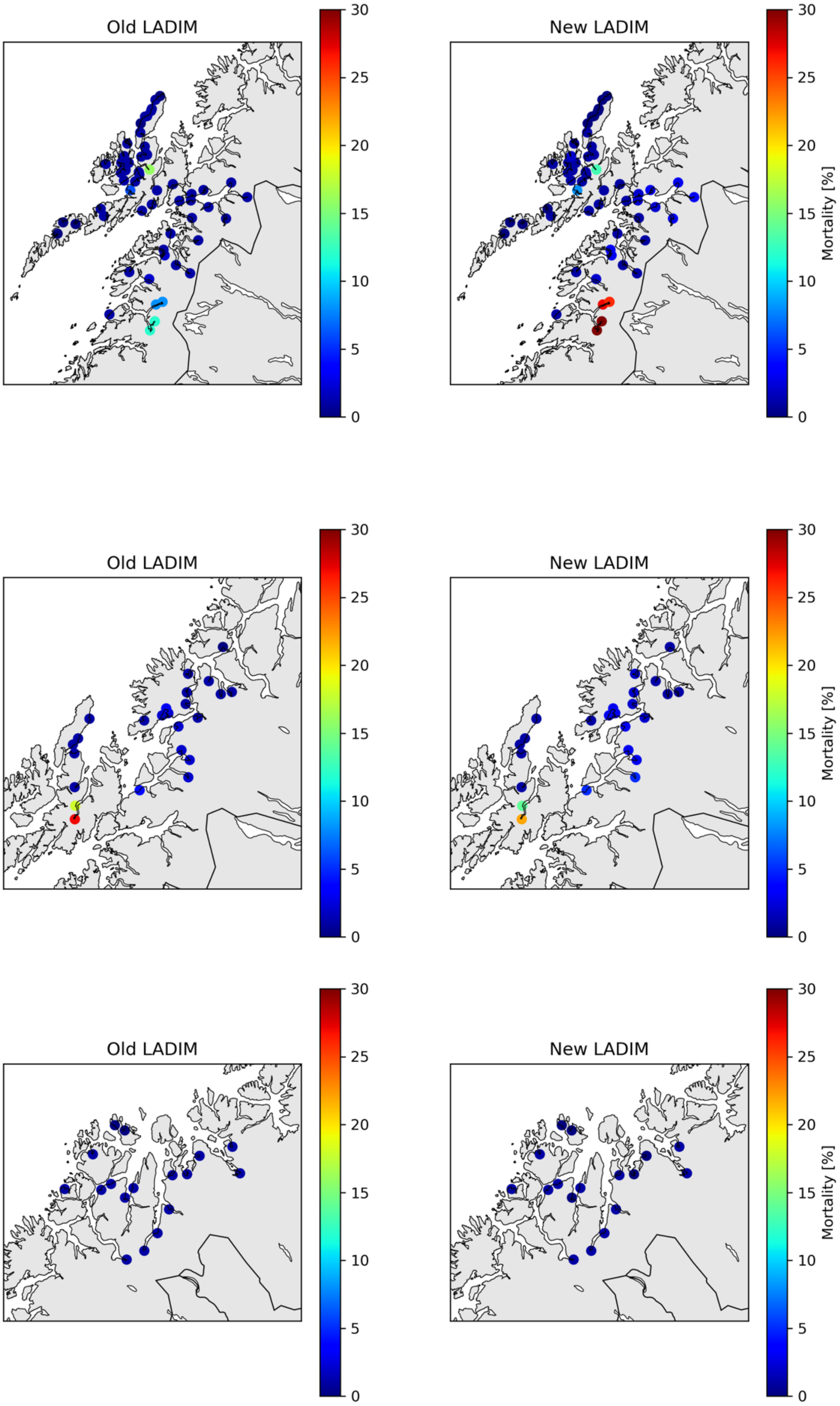
Mortality [%]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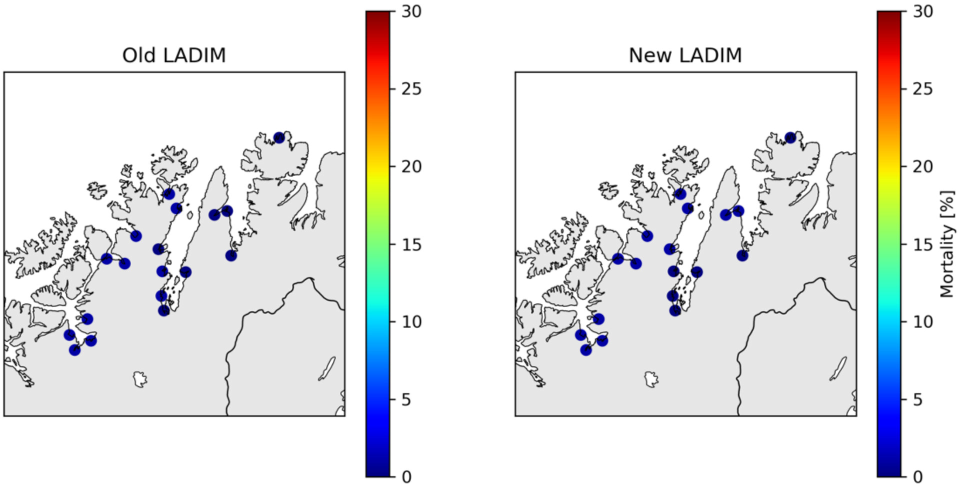
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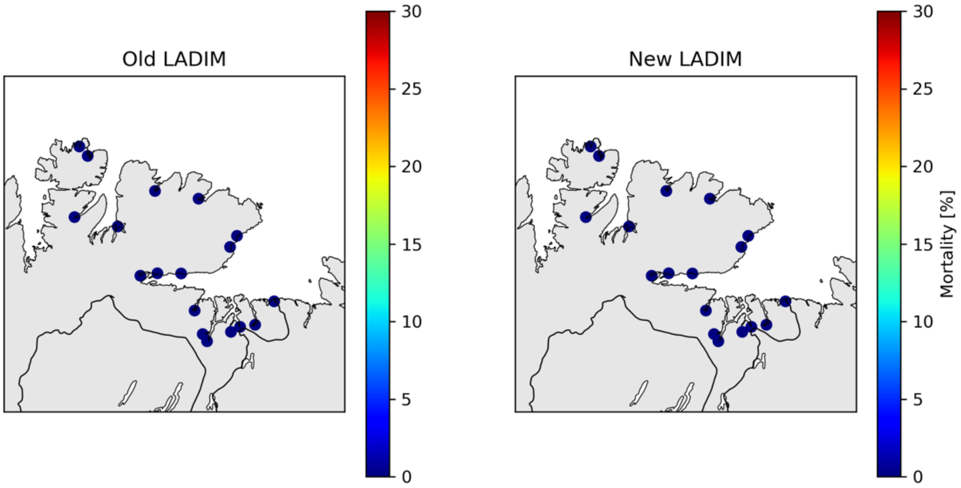
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Mortality [%]

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