Modelled distribution of salmon lice in a Norwegian fjord

Lars Asplin [1,2], Karin Boxaspen [1] and Anne D. Sandvik [2]

Abstract

Salmon lice is a huge problem for both wild and farmed salmonid fish in fjords. An assessment of salmon lice in a fjord system will bring forward the knowledge of wild salmonid fish stocks and help manage salmonid fish farming. Numerical models have been used to produce time series of salmon lice distribution in the Norwegian fjord Sognefjorden. Currents and hydrography were calculated from a high resolution, three-dimensional ocean model. Inside the fjords, detailed wind forcing was necessary, and these winds were produced by a meso-scale atmospheric model. The distribution of salmon lice was calculated by a three-dimensional particle advection model including temperature dependent growth. The model results show that the variability in salmon lice distribution is huge for the Norwegian fjord areas, with spreading of lice with the currents ranging from 0 to 100 km within only a few days. We will show the simulated encounter rate of salmon smolt on its way to the ocean and salmon lice, and show how different locations of fish farms affect this.

Keywords: *salmon lice, sea lice, fjords, numerical modelling*

1: Institute of Marine Research, P.O.Box 1870 Nordnes, 5817 Bergen, Norway.
2: Bjerknes Centre for Climate Research, Geophysical institute, Allegt. 70, N5007 Bergen
email: lars.asplin@imr.no, karin.boxaspen@imr.no, anne@gfi.uib.no

Introduction

Sea lice populations on farmed salmon and trout in the northern hemisphere will mostly consist of *Caligus elongatus* and *Lepeophtheirus salmonis*. They are both copepoda of the family *Caligidae* eating mucus, skin and blood of their host, thus creating lesions, osmoregulatory problems and secondary infections. The predominating species in Norwegian waters is *Lepeophtheirus salmonis* reffered to as salmon lice. The developmental stages of *L. salmonis* have been described (Kabata, 1979; Johnson and Albright, 1991a; Schram, 1993) and aspects of the general biology are documented (Wootten *et al*.; 1982, Tully, 1989; Johnson and Albright, 1991b; Pike and Wadsworth, 1999; Boxaspen and Næss, 2000). The seasonal variability of temperature affects both reproductive output (Ritchie *et al*., 1993) and developmental time for egg strings and larvae (Boxaspen and Næss, 2000; Heuch *et al*. 2000; Nordhagen et al. 2000).

Since 1989 epizootics of salmon lice have been observed several times on wild salmonids in the major farming areas of Atlantic salmon (Ireland, Scotland and Norway) (Birkeland, 1996; Grimnes, 1994). Salmon lice *(Lepeophtheirus salmonis)* seem to represent a major problem for the survival of many wild Norwegian salmon fish stocks. Especially the smolt on its way from the rivers in Norwegian fjords towards the ocean will have to pass a long fjord with possibly a large stock of salmon lice. Premature return to rivers of heavily infested trout and salmon raise the question of the overall effect on the wild fish population. Salmon lice ectoparasitic on salmonids are also by far the largest problem in production of Atlantic salmon *(Salmo salar L.)* in most producing countries (Canada, Chile, Ireland, Scotland and Norway).

The salmon lice pass three pelagic stages in its life cycle. In the first two larval stages, the lice grow and in the third stage it becomes infectious and ready for attaching to a salmonid fish. Typically the first two stages last 5-10 days and the third stage about 20 days, depending on the ambient temperature. If the lice fail to find a host, it will die at the end of stage three. Three factors are the most important for the problem of salmon lice on wild salmon in fjords:

1. The production of salmon lice,
2. The distribution of salmon lice within the system,
3. The amount of brackish water in the fjord.

As to the production of salmon lice, a female louse can typically produce several hundreds of eggs on a weekly basis. The large number of fish farms on different locations in the fjords is probably the main source area for the salmon lice larvae. Once pelagic, the salmon lice are mostly drifting passively with the local currents, although it is likely that a certain vertical behaviour takes place. Thus, a detailed knowledge of the currents is necessary to determine the distribution of the lice in the fjord system. A manifold of forcing acts on the fjord water, with especially wind as important along with tides, freshwater driven flow and various wave intrusions from the ocean. Finally, the salmon lice seem to in some degree to avoid brackish water with salinity less than ~24. In years of much brackish water, the wild smolt will be better protected from the salmon lice. The paper describes a method for estimating the distribution of salmon lice in the Sognefjord, the largest fjord in Norway.

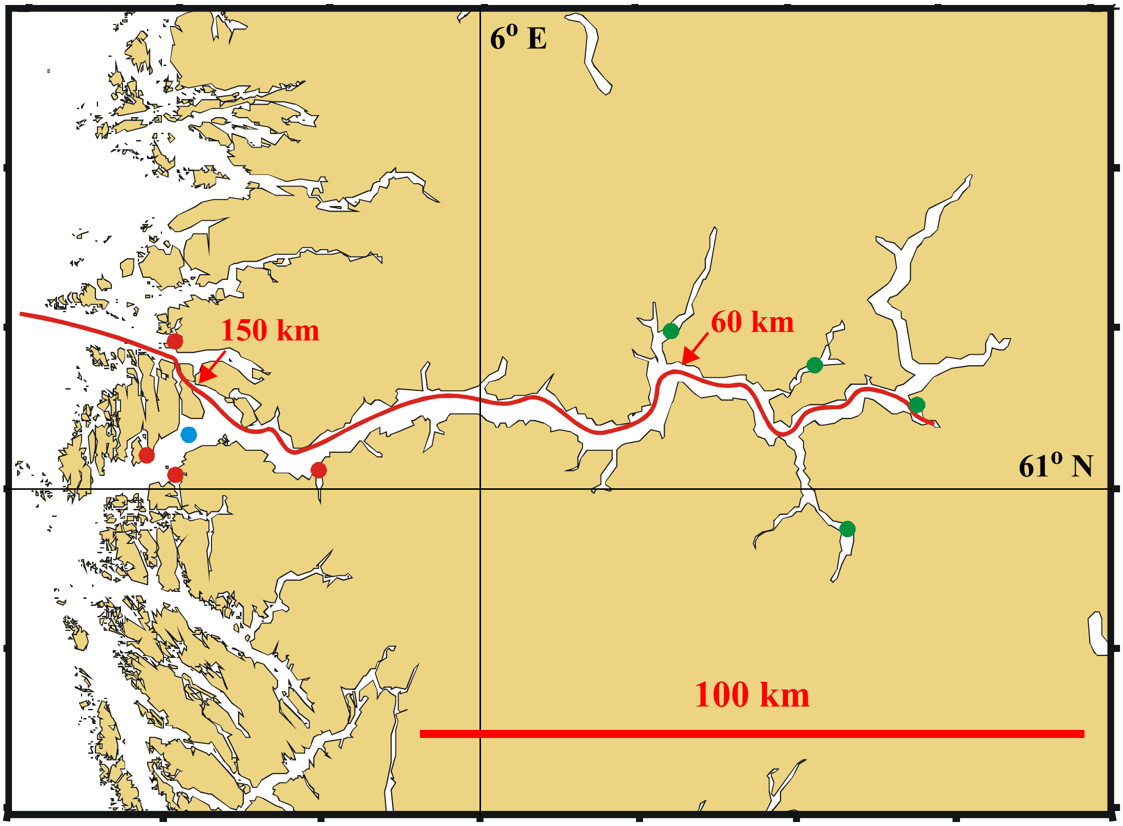

Figure 1. The Sognefjord area on the western coast of Norway. Shown on the map are red and green dots indicating source locations for salmon lice in the model experiments, the blue dot indicating the position of the current meter and the red line showing the migration route of the salmon smolt.

Materials and methods

Growth and advection (distribution) model for salmon lice

The growth and advection (movement) of the salmon lice in the first three pelagic stages are modelled.

We will use degree days as a measure of growth for the salmon lice in the model, based on a laboratory study briefly outlined below.

Salmon lice (*Lepeophtheirus salmonis*) egg strings were collected from farmed Atlantic salmon at a local slaughterhouse. The gravid females were removed from the surface of the fish and transferred to the hatchery in containers with seawater. The egg strings were detached and placed in hatching units floating in a running seawater bath. The hatching and holding units were kept at controlled temperatures (6, 8, 10, 12 and 14°C). Newly hatched salmon lice were harvested every day and each day-batch was kept separate in holding units to keep track of the animals' age. From the time the larvae reached the infectious stage (copepodid) and onwards groups of 200 live larvae were harvested at intervals and introduced into tanks with salmon free of the parasite. To ascertain the settling ability of the salmon lice the salmon were gently netted out of their tanks and anaesthetised and the successful settled salmon lice were registered. This was done two to three weeks after infection according to temperature when the salmon lice would have reached their second to third attached stage (chalimus II/III).

The copepodid were infectious from the first day, showed a slow rise of infectiousness over the coming days but then the infection declined to a point where only 1 to 2 salmon lice could be found on the salmon. This indicates a diminished ability over time to successfully make the transformation from copepodid to the next stage. This corresponds with the fact that the salmon lice do not eat before finding the appropriate host and will therefore burn out over time. At low temperatures this process takes longer time but correlated to degree days the salmon lice will be infectious about 50 degree days after hatching and meet their point of no return at 200 degree days.

The salmon lice, represented by a large number of passive particles in the model, are advected using the average current for the upper ~20 m based on the ocean model results. Hourly values are used, capturing also the tides. Smaller scale variability is parameterized by a random walk diffusion, where each particle is given an individual axi-symmetric Gaussian random velocity every time step. The diffusion coeffisient is 5 $m^2 s^{-1}$.

Currents observations

Water currents observations at 10 m depth in the period May 7 to June 21, 2002, were performed by an Aandreaa RCM7 current meter. Mean values over a 10 minutes period were recorded. The location of the mooring was at the sill area (170 m depth) in the outer part of the fjord, shown by a blue dot on the map (Figure 1).

Atmospheric model, MM5

The MM5 is a limited-area, non-hydrostatic, σ-coordinate model designed at Penn State and National Center for Atmospheric Research (NCAR) to predict meso-scale atmospheric circulation. A detailed description of MM5 is given by Dudhia (1993). For the coastal areas of western Norway, MM5 is configured with two domains of horizontal grid resolution 9 and 3 km respectively. The innermost domain covers an area including both the Sognefjord and the Hardangerfjord. The MM5 simulation is performed with 23 vertical levels, where the lowermost level for the main prognostic variables is at about 38 m above ground, and the top level is set to 15 km.

The following physical parameterizations are activated in MM5; a non-local turbulence parameterization (Hong & Pan, 1996), a simple soil model, a radiation parameterization scheme taking into account the effects of clouds on short-wave and downward long-wave radiation (Benjamin, 1983), an upper radiative boundary condition (Grell *et al.,* 1994), and a microphysics with cloud water, rain and ice as prognostic variables. Arakawa-Schubert cumulus parameterization is used for the 9 km domain, while convection is assumed to be solved explicitly in the 3 km domain.

MM5 is initialized with analysis of upper air and surface data from the European Center for Medium Range Weather Forecasts (ECMWF), and lateral boundary values are included every 6 h during the integration. The two domains run separately in a one way nesting routine, and the time step is 27 and 9 s, respectively. Relaxation zone is used as lateral boundary condition for the 9 km domain, while the innermost domain is updated every coarse-mesh time step.

Results from the 3 km domain is interpolated into an 800m horizontal grid, matching the ocean model area.

The Bergen Ocean Model (BOM)

The numerical model used for the simulations in the Sognefjord is the three-dimensional, primitive equation, time-dependent, σ-coordinate, ocean circulation model named the Bergen Ocean Model. The BOM is developed by Berntsen *et al*. (1996). The prognostic variables of the model are three components of velocity, potential temperature, salinity, surface elevation and two variables representing turbulent length scale and turbulent kinetic energy. The BOM has an embedded turbulence closure submodel (Mellor and Yamada, 1982). The governing equations are the equations for conservation of mass, momentum, temperature and salinity, along with the hydrostatic equation in the vertical and an equation of state relating salinity and potential temperature to potential density. The equations are solved by finite difference techniques on a staggered Arakawa C-grid. The time differencing is explicit.

The Sognefjord area is discretized on a 800 m horizontal rectangular grid using 230 x 195 grid squares. Vertically, 21 grid nodes were used, with the grid size (expressed in *z*-coordinates, assuming no surface elevation) increasing from 0.25 m in the upper few metres to a maximum of 100 m in the lower layers where the maximium bottom depth is 400 m (being fixed to this value for numerical reasons, although the maximum depth in the Sognefjord exceeds 1200 m).

The initial conditions were of no water velocities and no surface elevation. The salinity and temperature fields were horizontally homogeneous, but with piecewise linear stratification typical for a spring situation (Table 1).

Table 1: Initial vertical values for salinity and temperature

Depth [m]	Salinity	Temperature [^{o}C]
0	31.0	8.0
100	34.5	8.0
200	35.0	7.5
300	35.0	7.5

The open boundaries towards the coastal ocean were updated using a so-called Flow Relaxation Scheme (Martinsen and Engedal, 1987) by values of sea surface elevation, horizontal velocities, salinity and temperature every 30 minutes simulated interpolated from results of a coastal ocean model covering the Skagerrak and the Western Norwegian coast. The horizontal grid resolution of this coastal area model is 4 km. Open boundary condition for the 4 km model is obtained from results of an even larger ocean model, covering the whole North Sea with a 20 km resolution horizontal grid.

Wind forcing is 6 hourly fields from the 3 km MM5 model simulation.

To include the effects of solar radiation, the surface temperature all over the model domain is relaxed towards the open boundary condition values with a relaxation period of 10 days. This ensures a warming of the water masses close to the climatology.

River runoff from 36 rivers and power plants were included in the simulation. The runoff values are daily mean observations from a few rivers collected by the Norwegian Water Resources and Energy Directorate, while others are estimates based on the observations. Especially runoff values from regulated rivers have been difficult to get, as this is regarded as a commercial secret for the hydro electric power companies.

Results

Observations vs. modelled currents

It is necessary that the modelled currents to some degree is consistent with observations of the real flow in order to trust the model results and to use them for further studies as this salmon lice distribution study. However, we do not expect the model results to match the observations perfectly, as there are too many uncertainties both in the model results and in the observations. Still, we will demand that the statistical values of mean flow and standard deviation are comparable, which is true for the current observation period May 7 to June 21 2002 (Table 2).

Table 2: Comparison of the statistics of current meter observations and numerical model results for the period May 7 to June 21, 2002, in the Sognefjord.

	mean EW-component (m s^{-1})	standard deviation EW-component (m s^{-1})	mean NS-component (m s^{-1})	standard deviation NS-component (m s^{-1})
Current meter observation	0.05	0.12	0.03	0.11
Numerical model	0.03	0.15	0.06	0.12

As to the direct comparison of the time series of observed and modelled currents (Figure 2 and Figure 3) the match is still quite good.

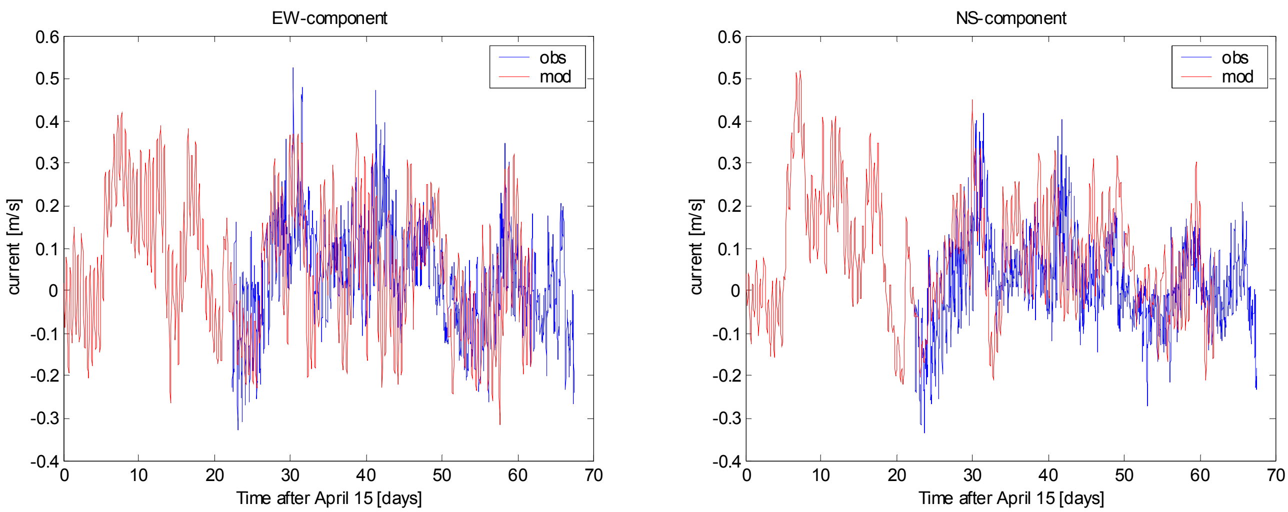

Figure 2. Time series of east-west (EW) and north-south (NS) components of velocity from the current meter mooring position in the sill area of the Sognefjord (Figure 1) for the model (hourly values, red line) and the observations (10 minute values, blue line).

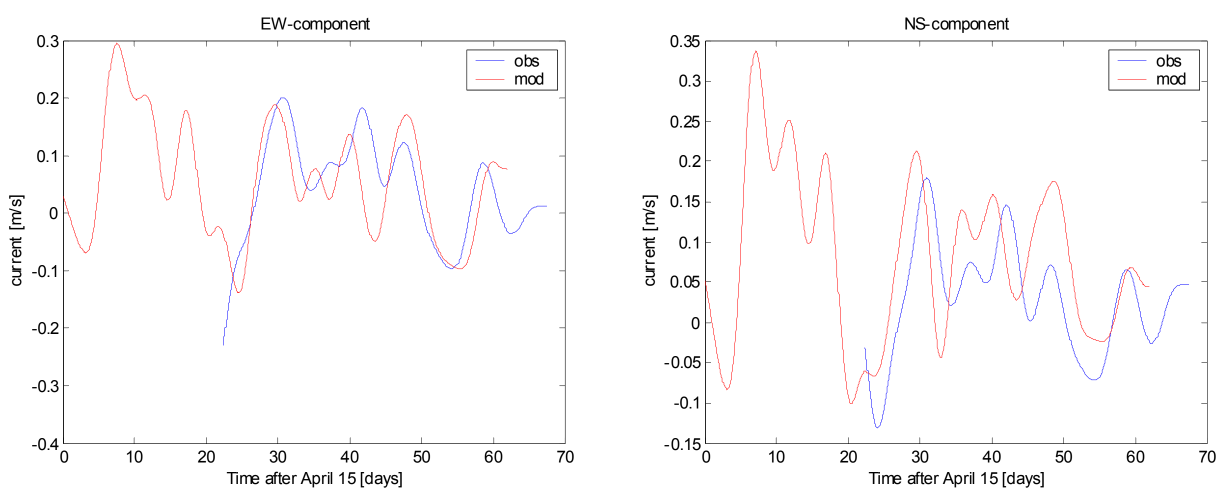

Figure 3. Time series of east-west (EW) and north-south (NS) components of 5 days low-pass filtered velocity from the current meter mooring position in the sill area of the Sognefjord (Figure 1) for the model (red line) and the observations (blue line).

Experiments with the salmon lice distribution model

From the modelled hourly currents for the period April 15 to June 16, 2002, an infinity of drift experiments can be performed by varying the timing and position of salmon lice sources. However, to illustrate the distribution potential of salmon lice in this area, three experiments where we have released batches (500 salmon lice individuals) at four locations in the outer part in the fjord and on the coast were performed. The experiments differ by the release date of the salmon lice: April 15, May 1 and May 15 (Figure 4). The results show that after 75 degree days (~10 days) and 125 degree days (~17 days) the individual salmon lice movement ranges from almost no distance at all to completely out of the area, i.e. a distance more than ~100 km. The distribution pattern for the three release dates also differs, as a result of the large variability of the currents.

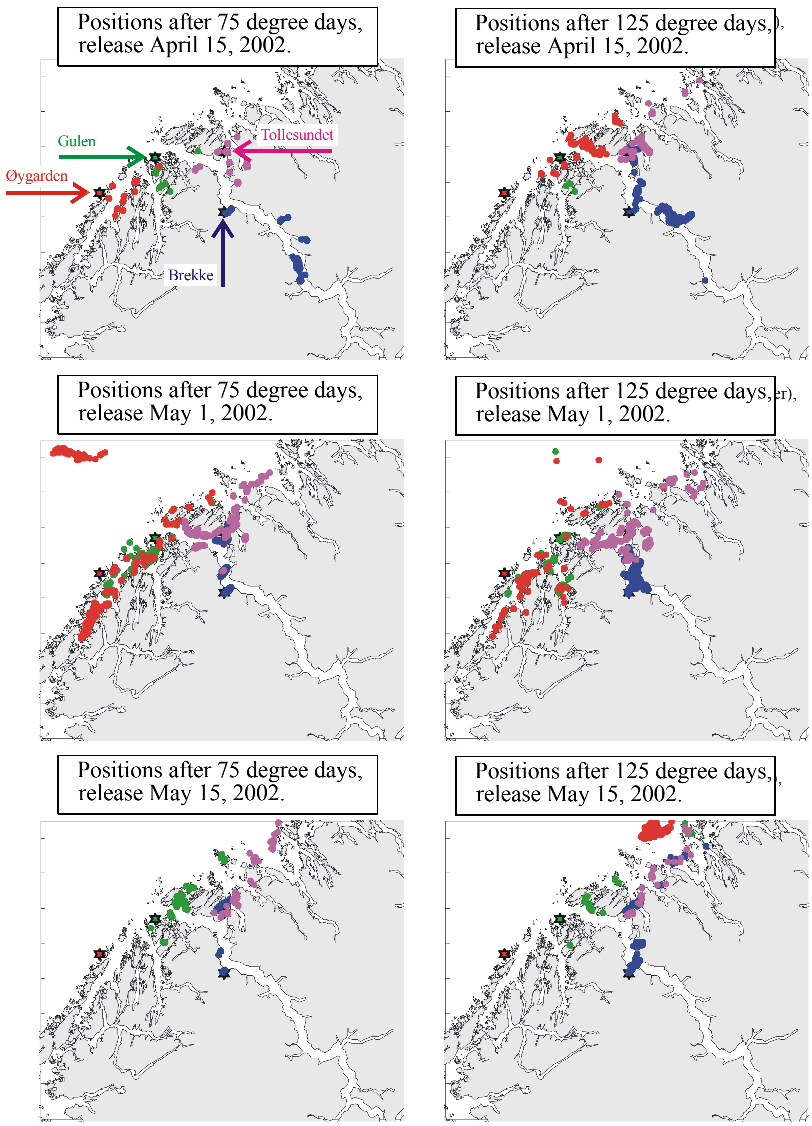

Figure 4. Distribution of salmon lice batches from four different locations (Øygarden, Gulen, Brekke and Tollesundet) and for three different release times (April 15, May 1 and May 15, 2002) after 75 degree days (~10 days, left column) and 125 degree days (~17 days, right column). Hourly values of currents from the numerical model are used for the salmon lice advection.

As an attempt to assess the encounter rates between the salmon lice and a migrating smolt, six new experiments were performed. The migrating smolt were given a predefined migration route from the river in the inner part of the fjord to the outer coastal ocean (red line, Figure 1) and a given a migration speed of ~20 km pr. day. The smolt started its migration at three dates: May 5, May 15 and May 25. Two different salmon lice distribution regimes were modelled: Four sources in the outer part of the fjord (red dots, Figure 1) and four sources in the inner part of the fjord (green dots, Figure 1). Batches of 100 salmon lice individuals every 7th day were released, starting at April 25. The results show that salmon lice originating in the outer part of the fjord is more dangerous for the smolt as those from the inner part of the fjord (Figure 5). Even though the total number of salmon lice and smolt encounters is higher for the experiments with salmon lice sources in the inner part of the fjord, the hazard is less since either the salinity of the water is less than 24 or the salmon lice do not have an age making it infectious. An exception is for the smolt leaving at May 25, which runs into a pool of infectious salmon lice in the outer part of the fjord (Figure 5, Figure 6).

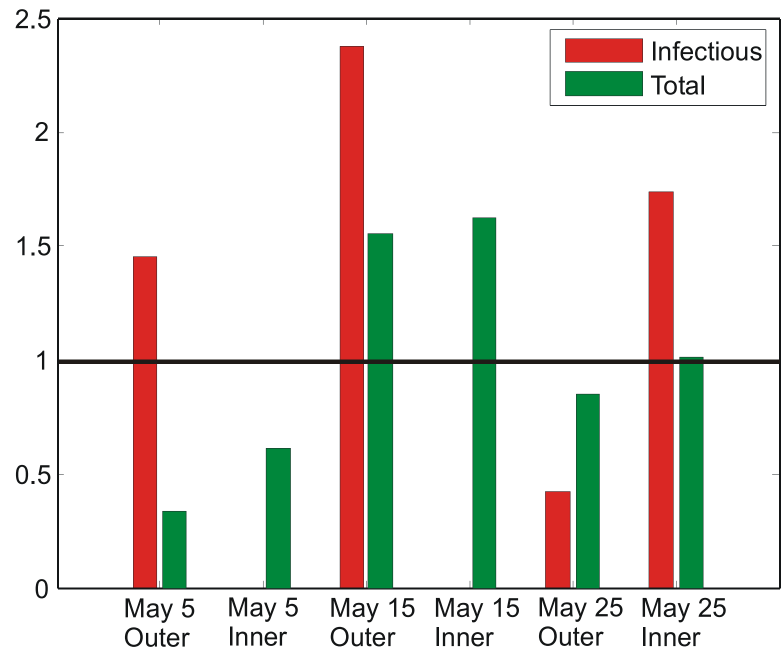

Figure 5. The total number of salmon lice and smolt encounters for the six smolt migration experiments. The numbers are normalized by the mean value for the infectious and total encounters respectively. The red bars indicate encounters when the salinity is above 24 and the salmon lice has an age between 50 and 200 degree days.

In more details, the model indicates salmon lice and smolt encounter at only a few geographical locations, after ~60 km and ~150 km (Figure 6). These areas coincide with fjord bends or narrowings, indicating this is a convergence or retention area for the salmon lice.

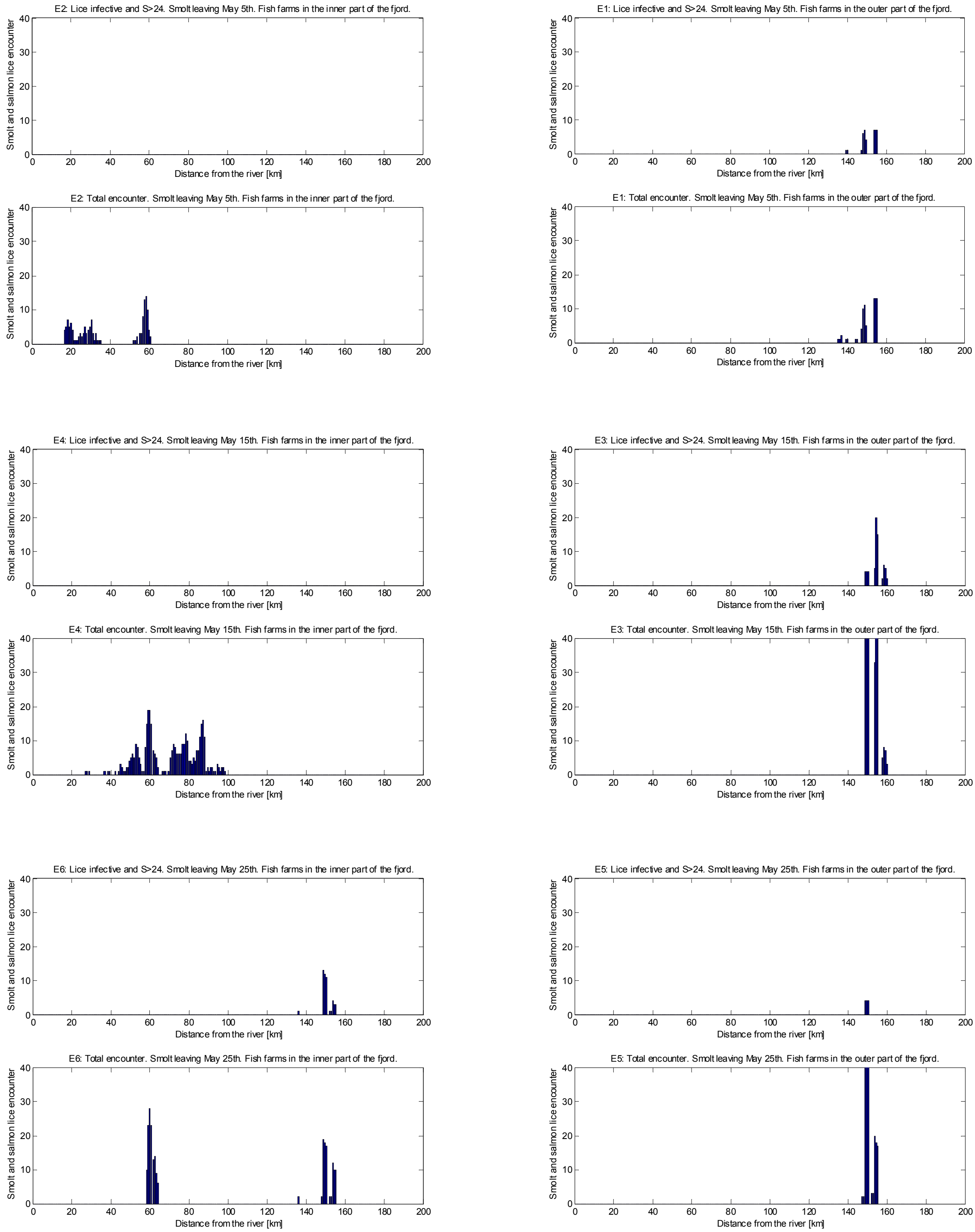

Figure 6. The number of salmon lice and smolt encounters along the migration path (the river mouth is at 0 km) for the six smolt migration experiments. The results for the experiments with salmon lice sources in the inner part of the fjord is shown in the left column, and the results from the experiments with sources in the outer part of the fjord is shown in the right column. Both results for the total number of salmon lice and smolt encounters (lower panel) and those with the salmon lice being infectious (upper panel) are shown.

Concluding remarks

The experiments with the salmon lice distribution model have shown that this tool can provide some useful information. Especially the huge potential spreading of the salmon lice and the result that salmon lice originating from the inner part of the fjord perhaps are less harmful to the smolt than those from sources in the outer part of the fjord. However, the parameter space for these kind of experiments are large, and many more experiments should be performed to provide more secure results. Particularly a more exact record of salmon lice sources should be achieved as well as results from different years.

References

Birkeland, K., 1996: Salmon lice, *Lepeophtheirus salmonis* Krøyer, infestations and implications for anadromous brown trout, Salmo trutta L. Dr. scient thesis. University of Bergen, Bergen, Norway, 20 pp. English.

Benjamin, S. G., 1983: Some effects of surface heating and topography on the regional severe storm environment. Ph.D. thesis, Department of Meteorology, The Pennsylvania State University, 265 pp.

Berntsen J., M.D. Skogen, and T.O. Espelid, 1996: *Description of a sigma-coordinate ocean model*, Fisken og havet, Institute of Marine Research, Norway, **12**, 33 pages.

Boxaspen, K. and T. Naess, 2000: Development of eggs and the planktonic stages of salmon lice (*Lepeophtheirus salmonis*) at low temperatures. *Contributions to Zoology*, **69**, 51-55.

Dudhia, J., 1993: A Nonhydrostatic Version of the Penn State-NCAR Mesoscale Model: Validation Tests and Simulation of an Atlantic Cyclone and Cold Front. *Monthly Weather Rev*iew, **121**, pp. 1493-1513

Grell, G. A., J. Dudhia and D. R. Stuffer, 1994: A description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5). NCAR/TN-389+IA, National Center for Atmospheric Research, CO, USA

Grimnes, A., 1994: Salmon lice (*Lepeophtheirus salmonis* Krøyer) infestation on Atlantic salmon (Salmo salar L.) post smolts: physiological consequences and mortal impact. Cand. scient. Department of Zoology, University of Bergen, Norway, Bergen, Norway, 33 pp.

Heuch, P.A., J.R. Nordhagen and T.A. Schram, 2000: Egg production in the salmon louse [*Lepeophtheirus salmonis* (Krøyer)] in relation to origin and water temperature. *Aquaculture Research*, **31**, 805-814.

Hong, S.-Y., and H.-L. Pan, 1996: Nonlocal boundary layer vertical diffusion in a medium-range forecast model. *Monthly Weather Rev*iew, **124**, pp. 2322-2339.

Johnson, S.C. and L.J. Albright, 1991a: Development, growth and survival of *Lepeophtheirus salmonis* (Copepoda:Caligidae) under laboratory conditions. *J.Mar.Biol.Ass., U.K.*, **71**, 425-436.

Johnson, S.C. and L.J. Albright, 1991b: The developmental stages of *Lepeophtheirus salmonis* (Krøyer,1837) (Copepoda:Caligidae). *Can.J.Zool.*, **69**, 929-950.

Kabata, Z., 1992: Copepods parasitic on fishes. Synopses of the British fauna. New series. Universal Book Services, Oegstgeest, Netherland. 264 pp.

Martinsen E. A., and H. Engedahl, 1987: Implementation and testing of a lateral boundary scheme as an open boundary condition for a barotropic model, *Coastal Eng.*, **11**, 603-637.

Mellor G.L. and T. Yamada, 1982: Development of a Turbulence Closure Model for Geophysical Fluid Problems. *Reviews of Geophysics and Space Physics*, **20**, 851-875.

Nordhagen, J., P. A. Heuch and T. Schram, 2000: Size as indicator of origin of salmon lice *Lepeophtheirus salmonis* (Copepoda: Caligidae). *Contributions to Zoology*, **69**, 99-108.

Pike, A.W. and S.L. Wadsworth, 1999: Sea lice on salmonids: Their biology and control. *Advances in Parasitology*, **44**, 234-337.

Ritchie, G., A. Mordue, A. Pike and G. Rae, 1993: The reproductive output of *Lepeophtheirus salmonis* adult females in relation to seasonal variability of temperature and photoperiod. In: Boxshall, G.A. and Defaye, D. (Editors), *Pathogens of wild and farmed fish* . Ellis Horwood. New York, USA, 153-165.

Schram, T., 1993: Supplementary descriptions of the developmental stages of *Lepeophtheirus salmonis* (Krøyer, 1837) (Copepoda: Caligidae). In: Boxshall, G.A. and Defaye, D. (Editors), *Pathogens of wild and farmed fish* . Ellis Horwood. New York, USA, 30-47.

Tully, O., 1989: The succession of generations and growth of the caligid copepod *Caligus elongatus* and *Lepeophtheirus salmonis* parasiting farmed atlantic salmon smolts (*Salmo salar L.*). *J. mar. biol. ass. U.K.*, **69**, 279-287.

Wootten, R., J.W. Smith and E.A. Needham, 1982: Aspects of the biology of the parasitic copepods *Lepeophtheirus salmonis* and *Caligus elongatus* on farmed salmonids and their treatment. *Proc.Roy.Soc.*, **81B**, 185-197.