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Climate change impact on the river ice regime in a Norwegian regulated river

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The ice conditions in a future climate have been investigated in a regulated, shallow river by using a process-based 1D model, Mike-Ice. River ice processes depend on hydrological, climatic and morphological inputs. The study uses a chain of modeling tools to derive the input forcings in the future climate and transform catchment precipitation to river ice in a regulated river system. The modeling tools are a Gridded HBV for rainfall-runoff modeling, nMAG for the reservoir and hydropower operation and finally Mike-Ice to model the river ice. High-resolution gridded data of 1km x1km, a finished product of the Norwegian Meteorological Institute (DNMI) has been used to drive the models in the study. The gridded data is created by dynamically downscaling three emission scenarios from two GCMs, HadAm3H SRES A2, B2 and ECHAM4 SRES B2 using the HIRHAM atmospheric regional climate model (RCM) followed by bias adjustment based on observation data to provide better representation of local climate. The study reveals that winter flow is increased and summer flow is decreased with the peak occurring a month earlier in the future scenario. Similarly, hydropower production will be increased for winter period in the future climate. The winter flow will be increased considerably from the unregulated local catchments. Further, the duration of water temperature < 0.1 ^{0}C and frazil ice duration is decreased in most of the locations in the river reach. The reduced frazil ice duration implies less surface ice and probably less anchor ice. The study suggests that there will be a reduced ice cover extent in the reach. A sensitivity test has been done by keeping the future meteorological input with I) current flow conditions, and II) current flow and water temperature input. Sensitivity result for instance, on frazil ice duration suggests flow and water temperature inputs are even more important factor compared to climatic input for the correct simulation of the river ice regime.

1 Introduction

Norwegian hydropower is characterized as high-head, large storage capacity, and can be important for intermittent load balancing in an increasing renewable energy system of a future Northern European market. In a changing climate hydropower operation can be affected both positively and negatively (Prowse *et al.*, 2011) in cold regions because of hydropower ice linkages . Further, the ice conditions in regulated rivers in the future would also be affected by the both climatic change and hydropower operational strategies. Particularly, winter and ice formation could be operational bottlenecks in a more variable electricity production. The typical ice related problems include intake blockage due to frazil clogging, water storage due to anchor ice dams, ice runs/ jams in bypass reaches and the problems can result in big revenue losses (Gebre *et al.*, 2013).

Despite its importance for sustainable infrastructure operations, there is a lack of assessment methods and models of river ice (Andrishak and Hicks, 2008), which can be due to the complex nature of river-ice process. Very few studies exist in literature that explore the impact of future climate on river ice regimes (Beltaos and Prowse, 2009). Andrishak and Hicks (2008) simulated the ice regime of the Peace River using the river ice model River1D for the study of climate change impacts. They found that by mid-21 century, there is a potential for a significant reduction in the duration and extent of ice cover making the river impassible for a longer period.

We have studied the impacts of climate change on the ice regime in a regulated river by using a one dimensional river ice model, Mike-Ice (Thériault *et al.*, 2010). The river system consists of a complex hydropower system with 5 hydropower plants, 3 large reservoirs, and a number of small reservoirs and brook intakes. The study involves a comprehensive set of models, as the climate change signal in the form of precipitation and temperature in the basin is transformed down to ice in the river. The chain of the modeling setup consists of estimating the future flows in the basin, transforming the flow through the hydropower system, estimating the flow at power plant outlets and finally, running the river ice model using hydrological and meteorological input forcing. Input forcing for the hydrology as well as for river ice modeling is extracted from two different General Circulation Models (GCMs) using the A2 and B2 future emissions scenarios and we evaluated changes in the ice regime towards the end of the 21st century. The simulation results from the future climate are compared with the current conditions to evaluate the expected changes in the ice conditions and how this will influence hydropower operation.

2 Material and methods

2.1 Study area

The study is focused on the regulated river Orkla located in mid Norway (63^0 17’ N, 9^0 50’E). The hydropower system (figure 1b) make the basin a good case for studies of hydrological, thermal and ice regime changes due to regulation. The basin has a drainage area of nearly 3,053 km^2 with mean annual runoff of 70 m^3/s. Figure 1 (a) illustrates the detailed features of the basin.

2.2 Study frame work

The climate change impact on the ice regime is accomplished with three main work components.

- Establish a hydrological model in current climate and estimate future flow regime using distributed climate change forcing (Temperature and Precipitation)
- Simulate the hydropower system to estimate the future outflow from the power plants and local inflow using input from hydrological model.
- Simulate the ice conditions using Mike-Ice, river ice model.

The details of each component, associated linkages and sources of input forcing for the models are graphically represented in figure 2 and additional descriptions are given in the subsequent chapter.

2.3 Delta change (Change factor) setup

The gridded historical and future scenarios for the study are available from the Norwegian Meteorological Institute (DNMI). DNMI generated fine-scale future scenario data by dynamic downscaling Atmosphere-Ocean Global Circulation Models (AOGCMs) results using a regional climate model (RCM), as it better represents the regional climate (Iversen *et al.*, 2001). Moreover, DNMI further developed a methodology to adjust the fields by applying correction factors based on observations producing high resolution climate projections of 1kmx1km (Engen-Skaugen, 2007). The adjusted method reproduces the mean monthly values and standard deviations based on daily observations. We computed delta change between the control period (1961-1990) and the future scenarios (2071-2100) on adjusted gridded data. The mean monthly delta changes have been calculated in each grid and applied correspondingly to each grid of the daily observation of 1kmx1km to derive the future scenarios. We used the results from two different GCMs, Hadley Center (HadAm3H), with the A2, B2 future emissions scenarios and ECHAM4/OPYC3, with the B2 scenario. In the associated graph legends the scenarios are represented as HADA2, HADB2, and MPIB2 respectively.

2.4 Hydrological model

In Scandinavia the HBV hydrological model (Bergström *et al.*, 2002) is commonly used for inflow estimation. In this study we have used the HBV model in the ENKI Framework (Kolberg and Bruland, 2012) distributed in a 1km x 1km grid, which permits using the gridded input directly in the hydrological model. The model is established with catchment delineated inputs (gridded precipitation and temperature daily time step) for the basin at the Syrstad gauge, where historical flow data exist. The processing of the gridded data such as cropping, masking, and statistical computation for quality checks are carried out using R (R Core Team, 2013) . The potential evaporation for all the cases (current condition and future scenarios) are computed using the Thornthwaite method (Olsson *et al.*, 2011). The hydrological model has been set up for the 10 years 1971-1980. The first five years are used for calibration and the last five years for validation. The model is evaluated using the Nash Sutcliff performance criteria. The future flow at Syrstad is simulated using the calibrated parameters for the current condition. The future period is 2081-2090 for all the scenarios.

2.5 Hydropower model

nMAG is a computer program for simulation of hydropower and reservoir operation with the capability of handling a system consisting of multiple reservoirs, hydropower, and inter-basin transfers (Killingtveit, 2005). The simulation is carried out for 19 years for the period 1985-2003. Average annual energy from nMAG simulations and actual energy production are compared and discrepancy is found close to 4.8%. The comparison assures that the hydropower features are reasonably well represented in the nMAG setup. The simulation of the future has been carried out for all the scenario for 10 years. Estimated total flow at Brattset, and at the Grana outlet from nMag is used as input for Mike-Ice model.

2.6 Ice model

The Mike-Ice is a comprehensive process-based 1D river ice model, developed in collaboration between Danish Hydraulic Institute (DHI) and Le Groupe-Conseil Lasalle Inc. The ice processes module of the model is a plug-in the Mike 11 hydrodynamic module. Mike-Ice simulates the hydrodynamic, water temperature, frazil production, ice cover formation from border ice progression and juxtaposition of drifting ice. The water temperature can simulate both with and without supercooling mode. For more description about the model refer to (Thériault *et al.*, 2010 , Timalsina *et al.*, 2013- in review). The simulation has been carried out for nine winters on each scenario (present and future). The current condition is simulated from the winter 2000-01 to winter 2008-09. The ice model domain covers the reach between Brattset outlet to Bjørset dam, but ice changes presented here is related to the Grana outlet – Bjørset dam reach which is considered most important for the hydropower operation.

2.6.1 Input data

The discharge output from nMAG and the daily water levels measured at Bjørset have been used as boundary conditions. The mean daily water levels computed from the measurements have been used also for future simulations since the water level variations at the intake are small. The water temperature at the upstream boundaries at Brattset and Grana was collected from Norwegian Water Resources and Energy Directorate (NVE). Short gaps in the hourly water temperature data set were filled by linear interpolation, but for a longer period in November 2008 missing data have been filled by multivariate regression. Since data for the reservoirs is scarce, we attempted to establish a relation between water temperature, air temperature and flow to predict the water temperature at the upstream boundaries in the future climate which proved difficult. We therefore used changes of mean monthly withdrawal water temperature estimated at nearby reservoir, Follsjøen from the My-Lake model (Gebre *et al.*, -in prep) to estimate the future water temperature from the Grana reservoir and the upstream of Brattset reservoirs. Air temperature used for the current period is measured by the power company at Syrstad. For the future, a delta change of mean monthly air temperature between 1975s and 2085s has been computed and this is used in a linear model to scale the measured air temperature to the future scenario. Further, the precipitation measured at Syrstad and Rennebu is averaged and used for the current simulation and a similar approach as for the air temperature has been used to define the future scenario. Moreover, the Mike-Ice equation has been adjusted to estimate net shortwave radiation by comparing the measurement of the winter 2010-11 and 2011-12 in the study area. The adjusted equation is used to compute the net solar radiation. The basin averaged mean monthly delta change cloud cover is computed from 25km X 25km DNMI data, and a delta change has been added to measured cloud cover at Oppdal to derive the future scenario.

2.6.2 Sensitivities

The model ice process sensitivity due to hydrological and meteorological inputs has been tested by two different setups. Firstly we simulated observed inflow water temperature at Brattset and Grana for future climate. Secondly we simulated with current inflow and current water temperature in the future climate. Together these give us an indication on the relative importance of meteorology, hydrology and input temperature on the ice formation.

3 Results

The mean daily flow comparison of the current and future condition shows that winter flow is increased considerably whereas the summer flow is decreased, and is the same from mid-June to beginning of November in all the scenarios (Figure 3). Between the GCMs, ECHAM4 is wetter compared to HADA2 and HADB2 for most of the period. The hydropower production and reservoir simulation results shows that total flow downstream of Brattset is increased significantly during winter (Figure 4) in the future climate, and there is also considerable spill of water from Storfossen dam. The Grana outlet will also have increased flow following increased discharge from Grana power plant as well as increased lateral flow from the catchment between Brattset and Grana in all the scenarios (Figure 5).

The number of days with water temperature < 0.1 ^{o}C varies from 16.3 days at Aunhølen (close to Grana outlet) to 52.3 days at Bjørset in the current condition. This is significantly shortened in all the scenarios (Figure 6). The Aunhølen will have nearly 1.5 days with water temperature < 0.1 ^{0}C whereas at Bjørset nearly 15.2-17.4 days for all the scenarios. The frazil plot shows that duration of frazil production at Aunhølen is 16.9 days, and is increased downstream up to 42.7 days at Hårråøya and decreased to 9.4 days at Bjørset dam in the current conditions. The frazil duration in the future climate is reduced considerably. The frazil duration at Aunhølen is only 2-3 days and at Hårråøya 16.8-19.8 days. At Bjørset dam we have 9.4 days with frazil in the current climate (controlled by ice cover formation on the intake), and in the future this is increased to 10.1 -11 days for all the scenarios (Figure 7). The variability among the scenarios is very small, in the range of 2~3 days. Additionally, the percentage of ice cover reach is nearly 13% in the current climate, and shrinks to ~ 4% in the future climate (Figure 8).

The sensitivity test setup I shows the duration of water temperature < 0.1 ^{0}C is 3.5-4.5 at Anunhølen, 20.9-25.8 days at Bjørset in the future climate (Figure 9). Similarly the frazil duration is 6-7.2 days at Aunhølen , 25.2-29.1 days at Hørråøya and 12.5-15.22 days at Bjørset for all the scenarios (Figure 10). The sensitivity test setup II shows that the duration of water temperature < 0.1 ^{0}C is 8-9.1 days at Aunholen and 29.1-32.9 days at Bjørset for all the scenarios (Figure 11). Similarly, the duration of frazil (>0.1%) is 11.7-12.3 days at Aunhølen and then increases linearly up to 31.7-34 days at Hårråøya, then decreased to 6.7-9.7 days at Bjørset (Figure 12 and Figure 13).

4 Discussion and conclusion

The basin averages precipitation is increased by 2.6% and 4.2% in Hadley A2, B2 respectively, and 14.3% in ECHAM4/B2 and temperature increases 3.3 ^{o}C, 2.6 ^{o}C and 2.9 ^{0}C in the respective scenarios compared to baseline (1961-1990) by the end of the century. The associated hydrological changes from the study shows that there will be possibly slightly decreased mean discharge for Hadley A2, B2 but increased in ECHAM4/B2 in future climate. The decreased mean discharge in first two scenarios is due to increased evaporation from the open area compared to increased precipitation. The increased flow in ECHAM4/B2 is due to significant increased precipitation in ECHAM compared to the Hadley scenarios. Further, the spring peak flow is nearly one month earlier compared to current condition and the finding is comparable to previous studies from Norway and other Scandinavian counties. The flows are increased substantially over winter and early spring because of snow melt and more precipitation as rainfall because of increased air temperature.

There is increased flow during winter and early spring at both Brattset and Grana plants because of water availability. Further, the local flow at unregulated catchments is also increasing both upstream of Brattset outlet and in the area between Brattset and Grana outlets during winter and also in mid-spring due to increase snow melt. For the rest of the year the flow is decreased. The study shows that there is a reduction of freezing water temperature duration (water temperature < 0.1 ^{0}C) and frazil ice duration due to changed hydrological and meteorological conditions. The results show that the river ice conditions depend on the hydropower operation upstream. The future ice conditions therefore depend on the operational strategies of the hydropower company. In this study we made the assumption that hydropower operation strategies remain similar in the future. However, as the increased spill of water at the Storfossen dam (Brattset intake) shows, there will be needs for future modifications to the operational strategies. This will influence the river ice conditions. Since a new optimization of the plant was not the purpose of this study, we have tested the sensitivity of the changes in discharge on the ice formation in the future climate.

We found that the hydrological and meteorological inputs are very important for the correct simulation of river ice process. The sensitivity results show that the hydrological input are very sensitive for the river ices processes and its realistic estimate in the future climate can reduce the modeling uncertainty. The water temperature estimates at boundaries are very sensitive for the correct modeling of river ice but the estimate of the inputs is not straight forward. The water temperatures from both unregulated catchment and from the power production at reservoir have sources of uncertainty. The estimate of water temperature from reservoir outlets for example using My-Lake model and catchment water temperature models and linking to river ice model would be valuable tools for the thermal and river ice modeling.

Only few studies exist in the literature that is comparable to the result of this study. In Canada, (Andrishak and Hicks (2008)) found less ice cover extent and duration in the Peace River in the future, the result from the Orkla study is similar to their findings. The study suggests that there is considerably less frazil ice production at most of the locations and almost unchanged at Bjørset dam. The quantity of frazil and drifting ice will be important for assessing the possible impact on hydropower operation by clogging the intake at Bjørset. Reduced frazil duration implies less surface ice, lesser extent of ice cover in the reach and reduced anchor ice in the river

This study demonstrates the comprehensive modeling work procedures applied to simulate the complex hydropower system response in future climate and associate the river ice condition in steep and fast flowing river. That is being said, there are different sources of uncertainity in our modeling work that includes: future greenhouse gasses, our understanding of the atmospheric processes, limitation of GCMs/RCMs model and followed by downscaling methodology, spatial resolution. Therefore, climate change impact studies at local scale need to be interpreted with caution. One of the measurers to reduce the uncertainty is to use different GCMs and various emission scenarios. In this study consideration of three sets of input forcing from two different

GCMs and two SRES emissions scenarios (A2 & B2), downscaled data using RCMs with higher resolution and bias correction at local scale can resolve the uncertainty to some extent. The study assumes model transferability and parameter stationarity in future climate. However, it would give at least reasonable estimate as some of the errors associated in the current and future period may cancel out.

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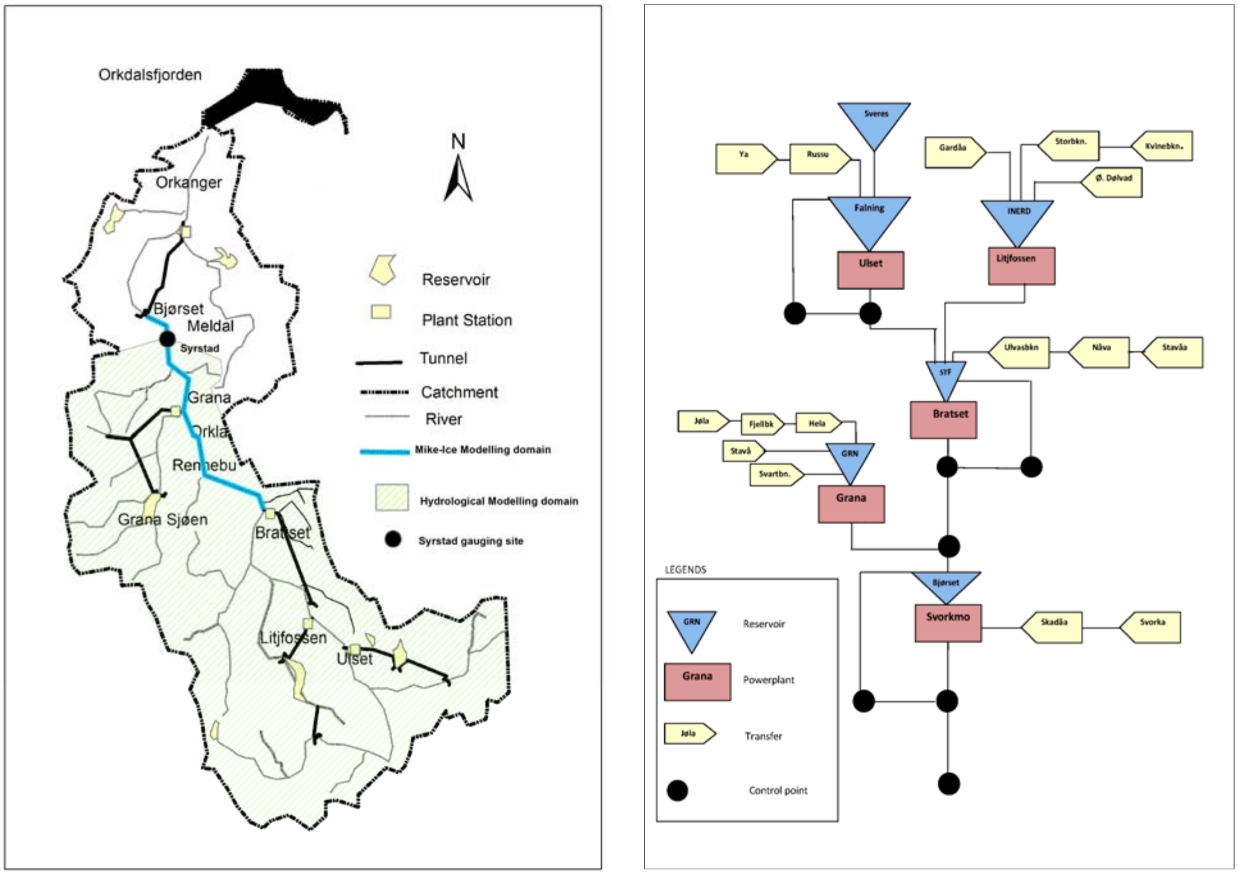

Figure 1(a): Study area in the Orkla Basin. Figure 1(b) Orkla hydropower system representation in nMAG model

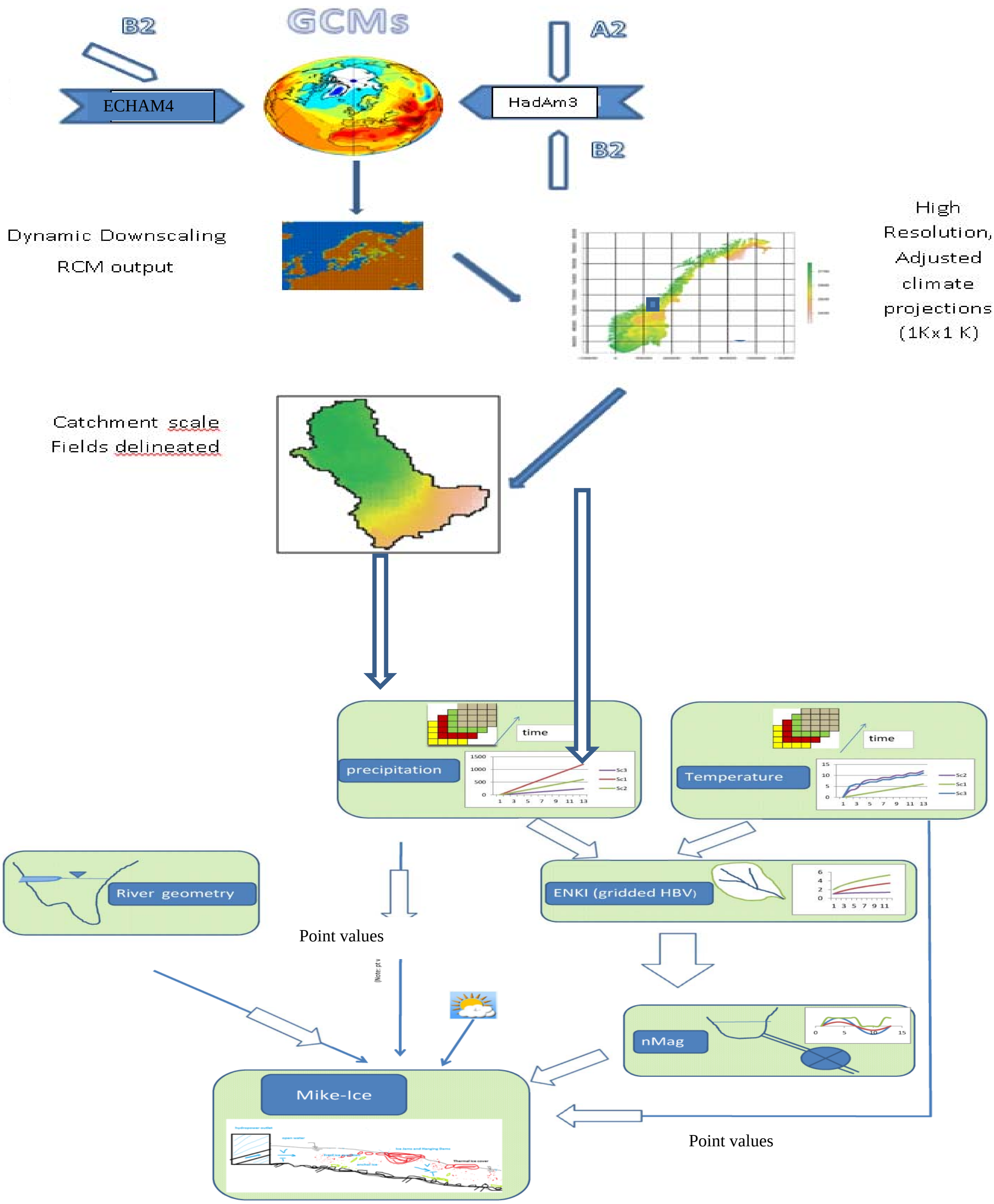

Figure 2: Comprehensive modeling framework of climate change impact on River ice Regime in Orkla

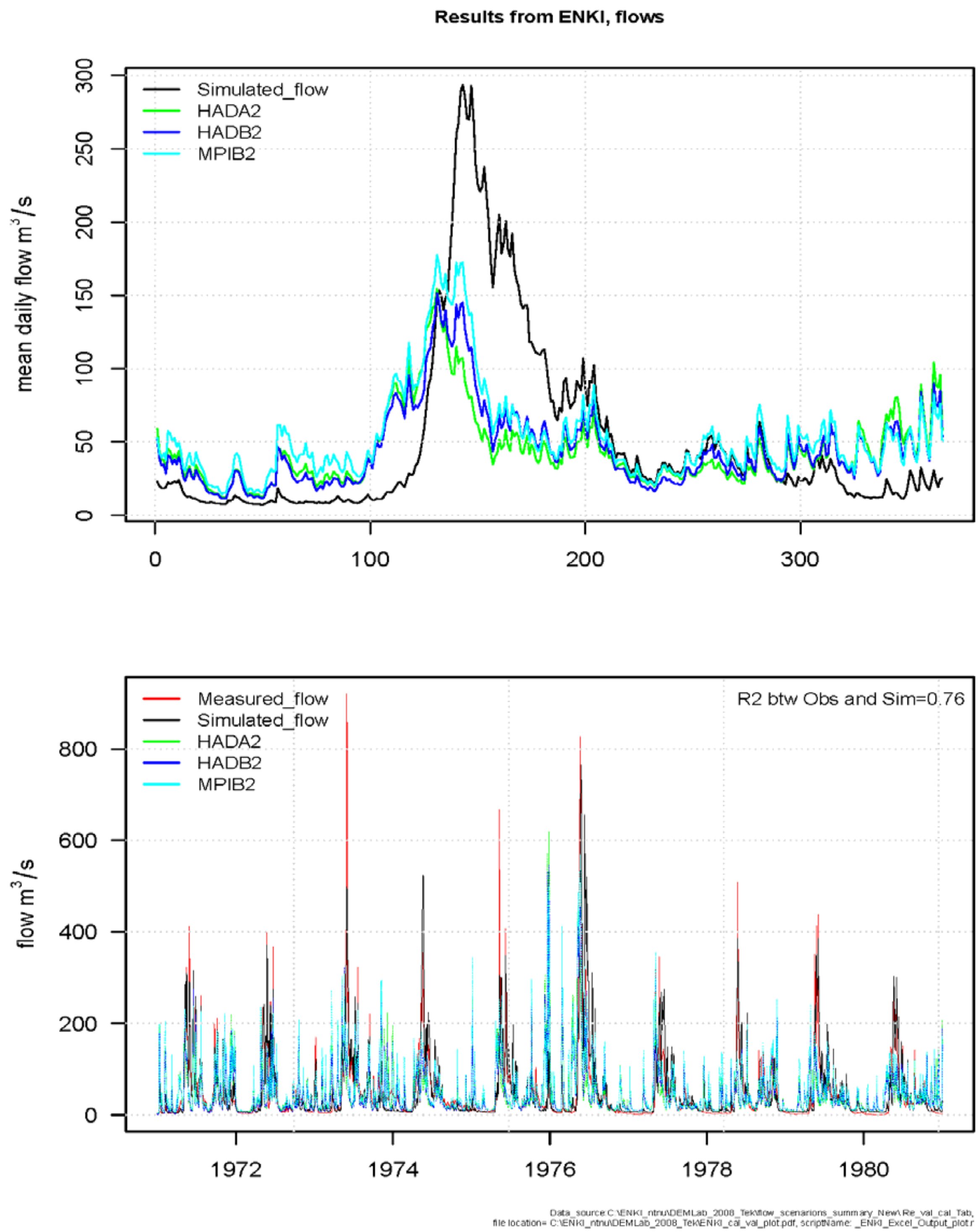

Figure 3: Results from Gridded HBV Hydrological model for the current condition and the future climates

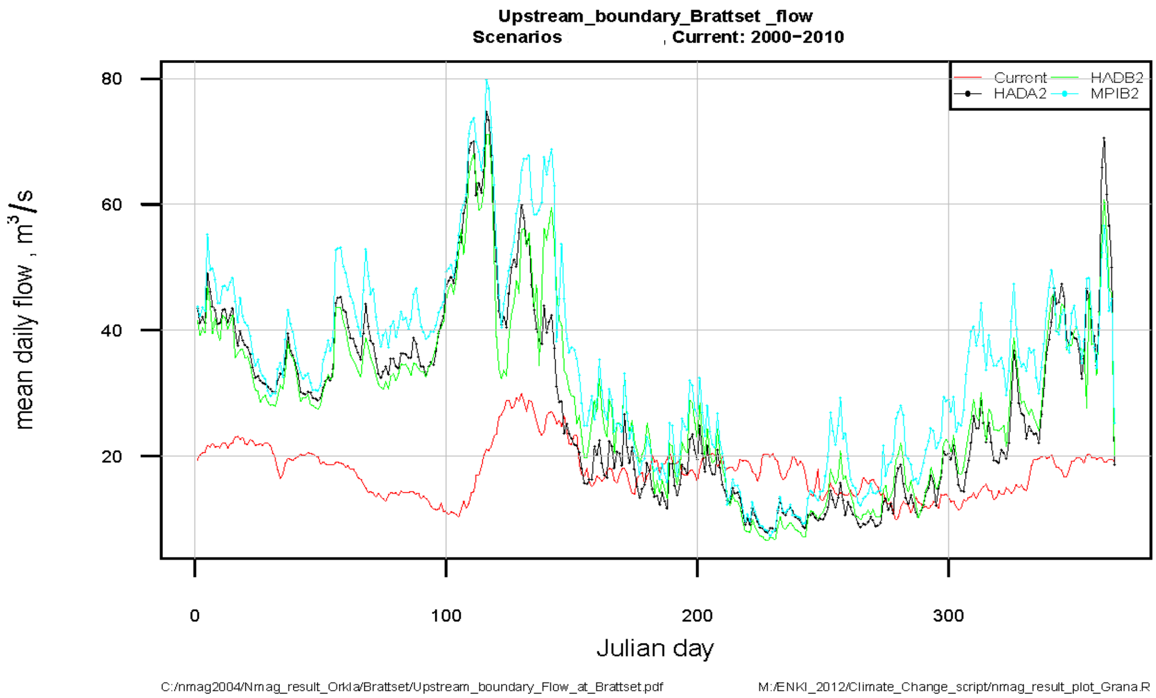

Figure 4: nMAG results i.e. Upstream Boundary at Brattset Outlet for Mike-Ice simulation (Mike-Ice simulation period is between 1- 90 and 305-365 Julian days, i.e., Jan, Feb, Mar, Nov, Dec.)

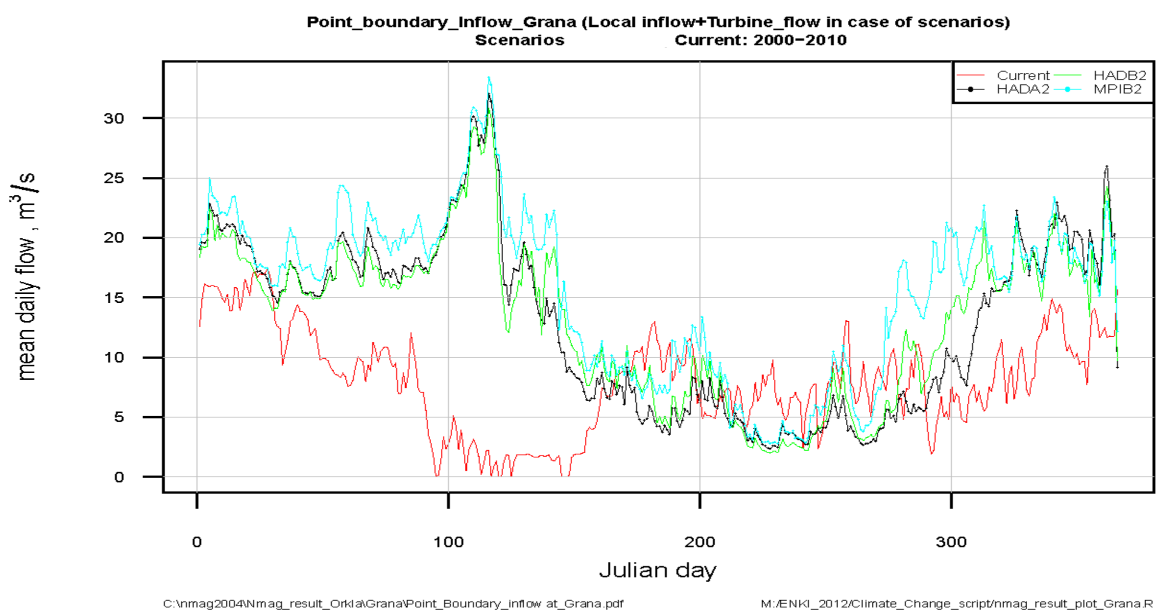

Figure 5: Point Boundary at Grana outlet for Mike-Ice simulation (Mike-Ice simulation period is between 1- 90 and 305-365 Julian days, i.e., Jan, Feb, Mar, Nov, Dec.)

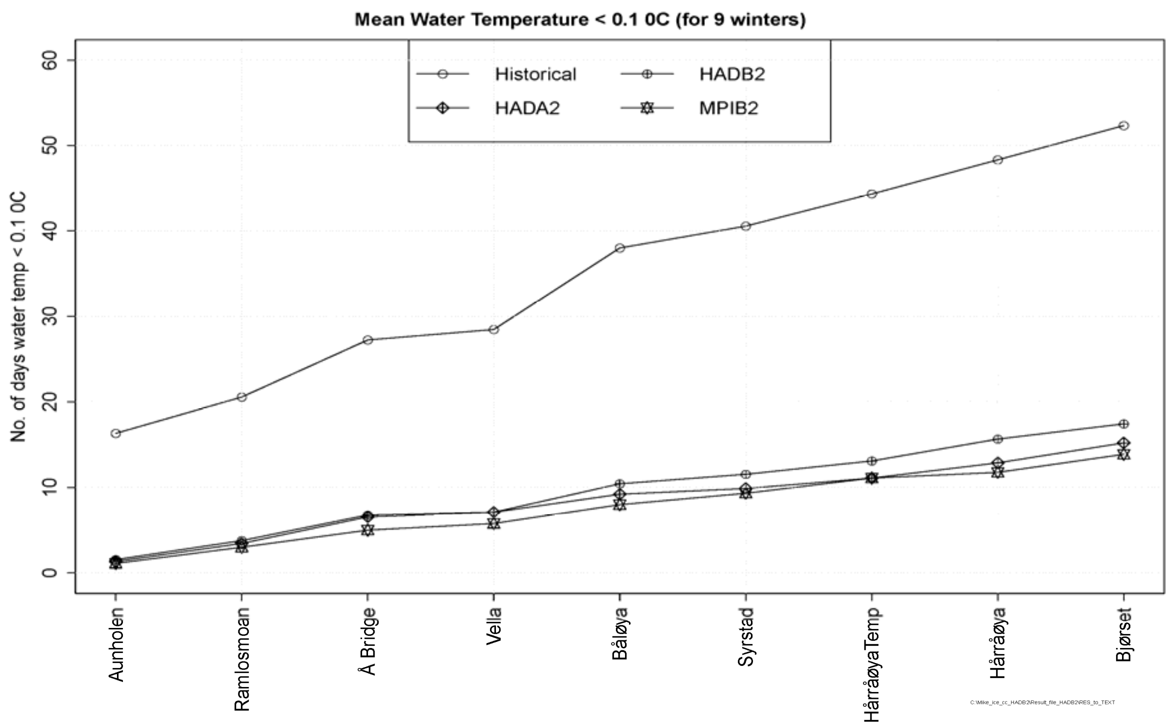

Figure 6: The water temperature < 0.1 0C duration for current and future climate

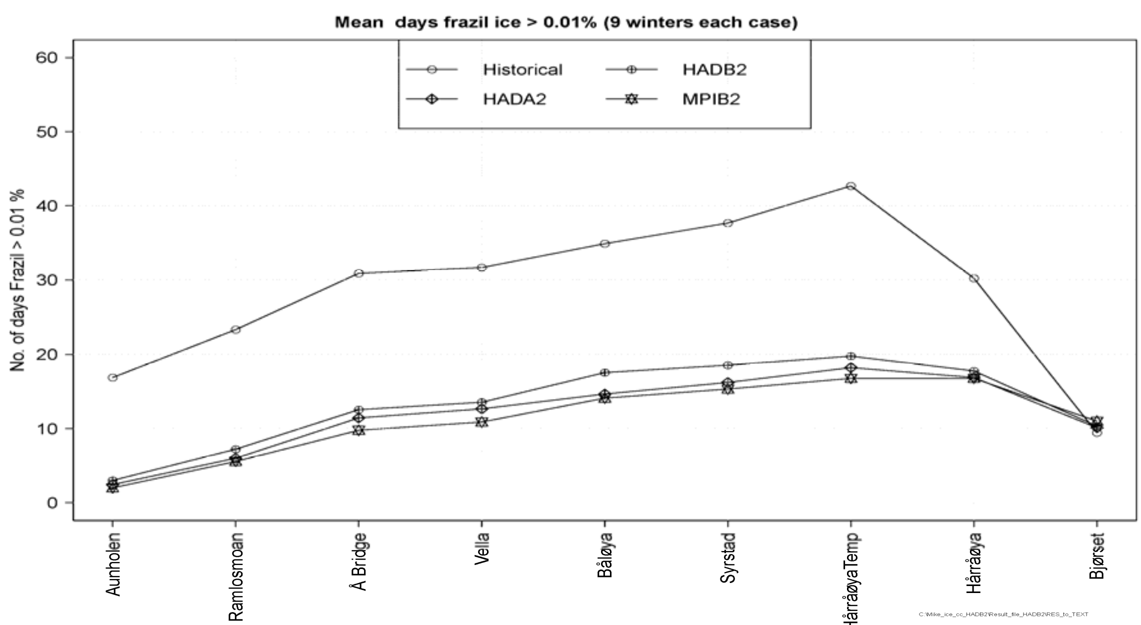

Figure 7: The frazil duration for current and future climate (the values are derived for mean of nine winters in each case)

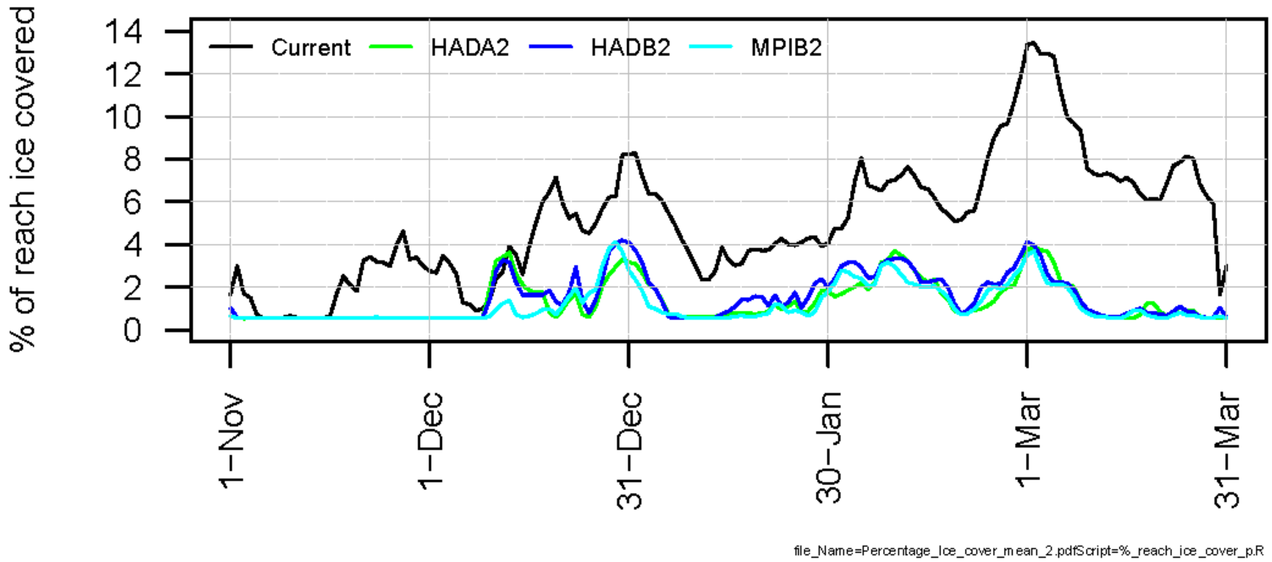

Figure 8: The percentage of reach with ice cover in the current climate and future climate (the values are daily mean from the nine winters for each case)

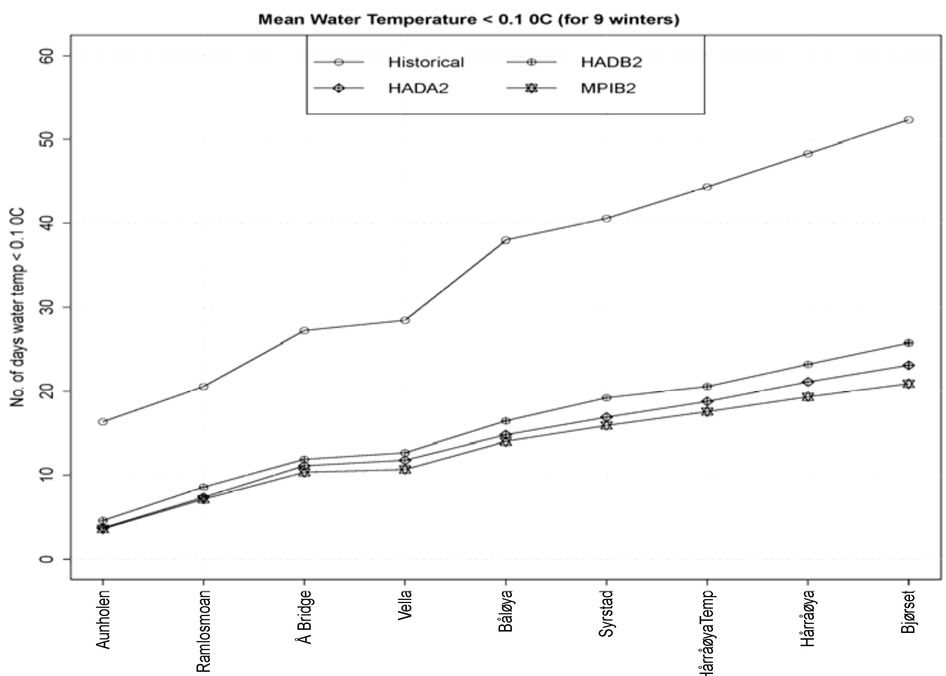

Figure 9: duration of the water temperature < 0.1 ^{0}C for the current and the future climate, keeping the same current water temperature input in future climate.

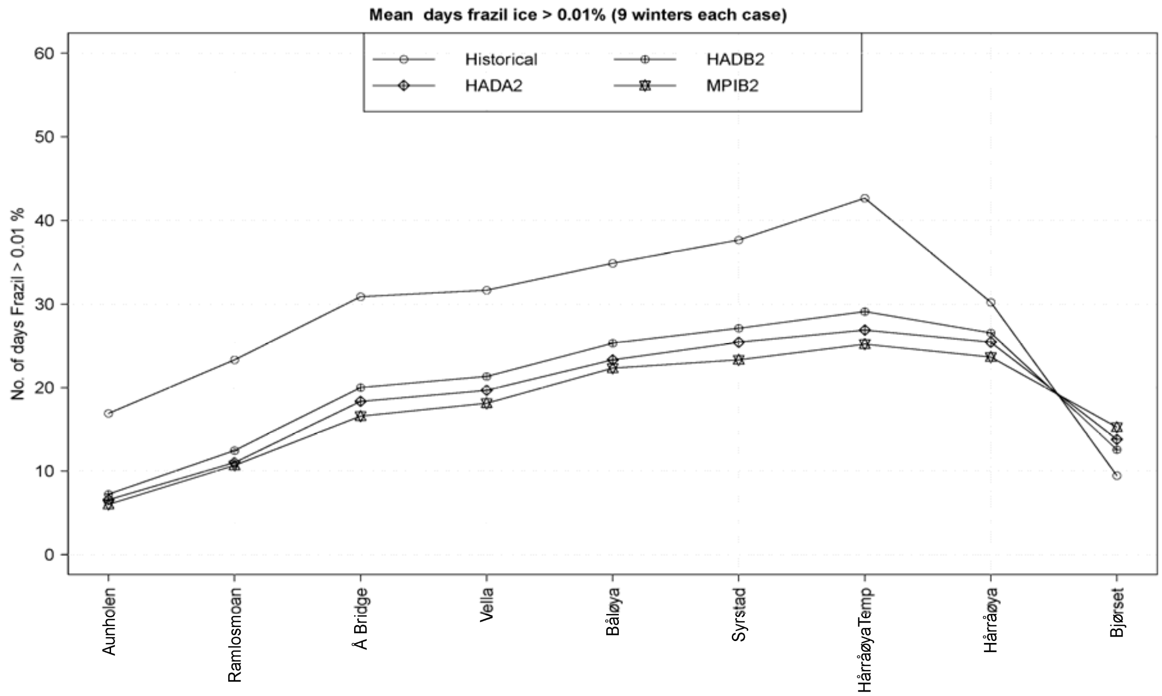

Figure10: The frazil duration for current and future climate (the values are derived for mean of nine winters in each case), keeping the same current water temperature input in future climate.

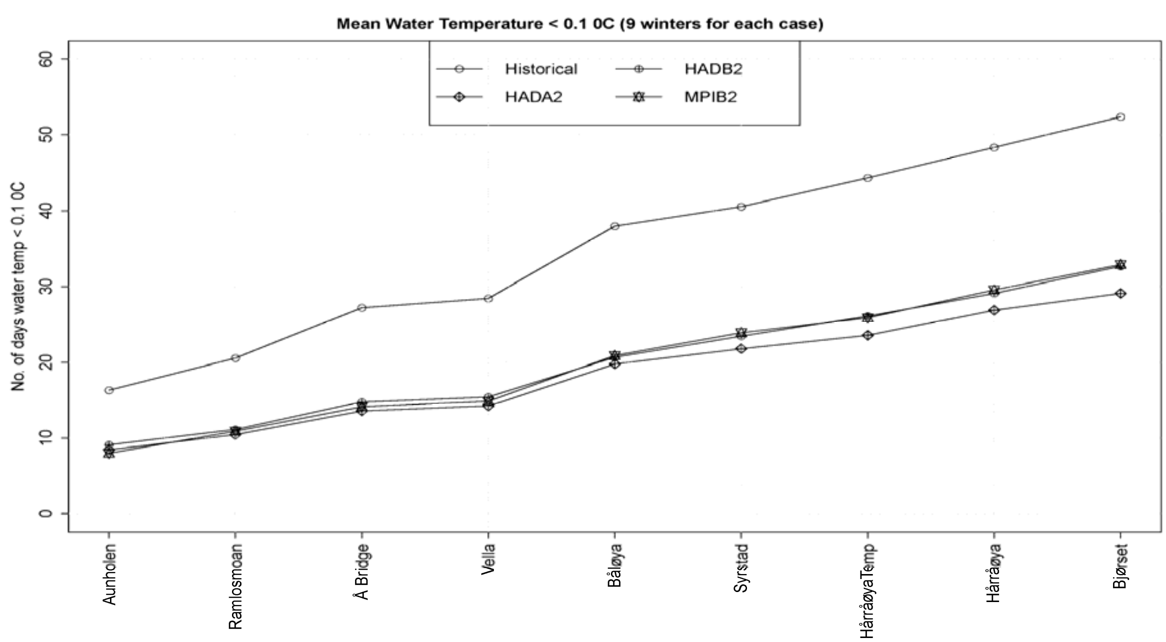

Figure 11: duration of the water temperature < 0.1 0C for current and future climate (the values are derived for mean of nine winters in each case), keeping same current water temperature and same upstream boundary flow in future climate.

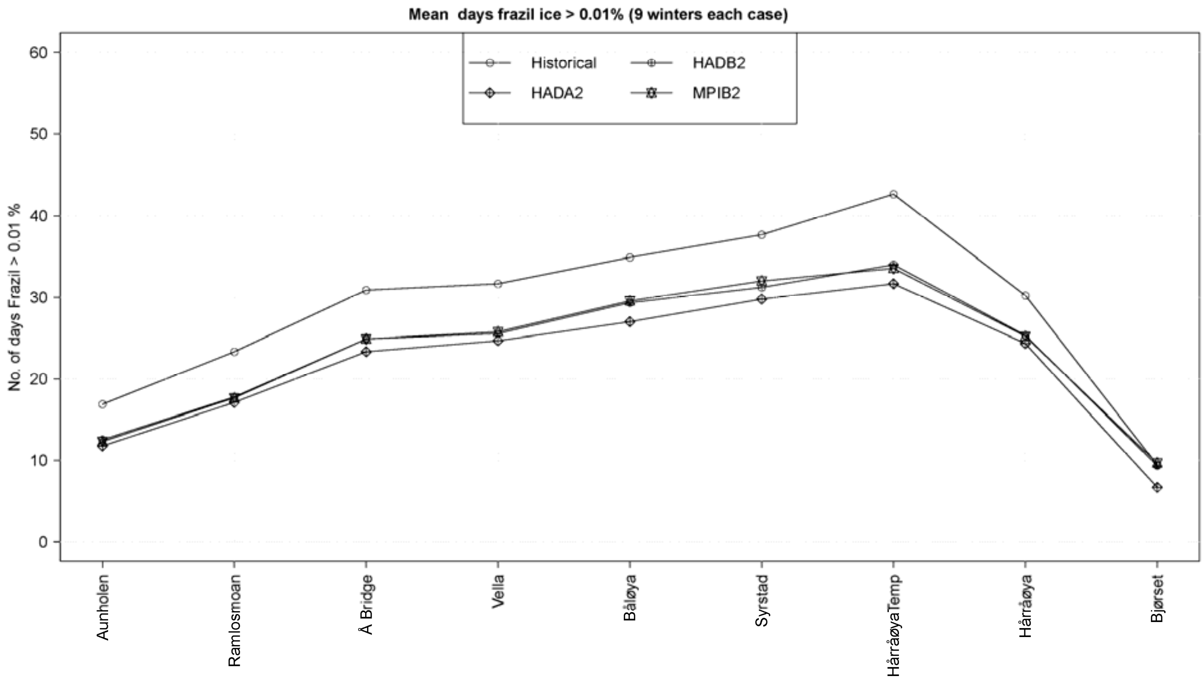

Figure 12; the frazil concentration in water column for current and future climate (the values are derived for mean of nine winters in each case), keeping same current water temperature and upstream boundary flow in future climate.

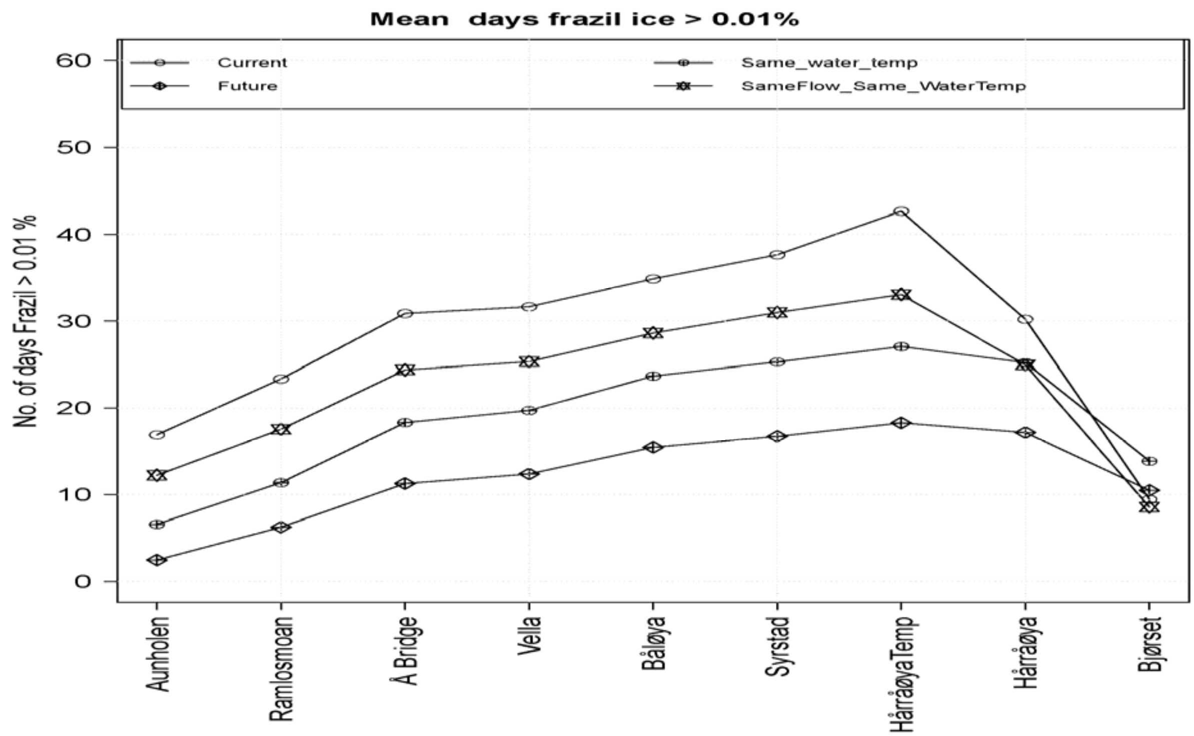

Figure 13; the frazil concentration in water column for current and future climate (the values are derived for mean of nine winters in each case), keeping same current water temperature and upstream boundary flow in future climate, this figure is the summary of the figure 7, 10 and 12.