Hydrometeorological modelling in Norway

Summary of seminar 9-10 December 2015 in Lillehammer

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REPORT

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Sammendrag: The main objective of the HYDMET project is to develop a national research team (SAK) that is given the task to identify the need for important research, methods, and experimental and operational observations for application in hydrometeorological modelling for forecasting and projections of changes in climate and hydrology. This report summarizes presentations and discussions at a national seminar in Lillehammer, 2015.

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Preface

Hydrometeorology is an area of large scientific and societal importance, including risk reduction related to floods, droughts and landslides in the present and future climate. Operational services, research and/or teaching in hydrometeorology is hosted by several institutions in Norway. Evaluation reports for geosciences, written by an international committee in 2011 and a national committee in 2014 for the Research Council of Norway (RCN), identified a need to develop a common research language, which can only be reached by day-to-day joint research and development by MET Norway and NVE with support by UiO, UiB and NMBU. The major research topics identified were hydrometeorological forecasting aimed at relieving flood risk and supporting optimized energy, and water resources management under climate change. The HYDMET project was funded in a subsequent call in order to follow up the recommendations.

The main objective of the HYDMET project is to develop a national research team (SAK) that is given the task to identify the need for important research, methods, and experimental and operational observations for application in hydrometeorological modelling for forecasting and projections of changes in climate and hydrology. The main outcome of the HYDMET project is a final report/action plan that identifies important research topics and actions needed to improve SAK within hydrometeorology in Norway.

To reach this goal, the HYDMET project organised a national seminar on 9-10 December 2015 in Lillehammer, where Norwegian researchers from NVE, MET, UiO, NMBU, NTNU, NILU, Statkraft, SINTEF Energy, Norwegian Computing Center, Uni Research, met with international experts from ECMWF (UK), MetOffice (UK), SMHI (Sweden), Irstea (France) to discuss important research topics within hydrometeorology as well as current education programs and future research needs. In total, 45 persons participated in the seminar, including five international experts. The seminar was a mean to connect researchers in hydrometeorology and help to improve the synergy between the strategic plans for institutions and research groups.

The outcome of the seminar is summarized in this report, which presents the current knowledge base and important topics for future research.

Oslo, February 2017

Morten Johnsrud
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Summary

The HYDMET project is a follow-up of the Research Council of Norway (RCN) Geosciences evaluation and funded by RCN under the program ISP geosciences. The primary objective of HYDMET was to develop a national research team (SAK) that has as task to identify the need for important research, methods, and experimental and operational observations for application in hydrometeorological modelling for forecasting and projections of changes in climate and hydrology. The HYDMET project organised a national seminar on 9-10 December 2015 in Lillehammer. This report provides a summary of presentations and discussions at the seminar.

Firstly, this report provides a summary of current status for hydrometeorological modelling in Norway and four European research institutes, as seen by the researchers representing them. The status provides an overview over operational services, models in use, laboratories and research infrastructure, research topics, research projects, bachelor and master programs, and master and PhD theses.

Secondly, this report points to important topics for future research as briefly summarized below:

- **Observations - new networks, sensors and testbeds**: There is a urgent need to maintain existing and complement with new hydrometeorological testbeds, which cover different land uses and climates and aim to measure the complete energy balance and water fluxes between the land-surface and the atmosphere (e.g. atmospheric moisture fluxes, profiles of temperature and moisture, evapotranspiration, precipitation, radiation, temperatures, etc), using a range of platforms and sensors covering point to regional scales. Private meteorological stations and citizen data need to be explored.

- **Modelling – coupling and parameterizations**: Two-way coupling of hydrological and meteorological models and improved model parameterizations are needed. Important processes include (i) precipitation and its spatial and temporal variability, (ii) vegetation dynamics and interaction with the hydrometeorological system (iii), cryospheric processes, (iv) evapotranspiration and energy balance in cold environment, (v) soil moisture zone and groundwater processes, (vi) runoff, (vii) integrated hydraulic models for lakes and rivers, and (viii) urban flooding and drainage (that requires high space and time resolution).

- **Assimilation – merging models and data:** There is potential to assimilate more data into models, in particular snow data, soil moisture, river discharge, lake levels, and land-use/vegetation. This requires improved assimilation algorithms and better representations of observations in the models.

- **Tailoring to end-user:** Post-processing/downscaling/bias-correction of forecasts and climate change projections makes the model output useful for end users. Stochastic methods that keep the consistency between variables across space, and that tailor the predictions to the end-users needs are identified as important topics for the future.

- **Research to application**: In order to increase value of research results, and education and reduces time to market for innovation and competency transfer, the pathways

from results in research projects to applications in operational models can be shortened by keeping consistency and transferability between models and methodologies applied in research, education, operationally and among end-users.

- **Databases, repositories and coordination:** There is a need for better coordination of model development and implementation into operational services, and for sharing observations and model outputs. Sharing and integrating data, model outputs and model codes require an administrative system for managing the codes, common coding standards, quality control, documentation (metadata), and willingness to work closer together.

Thirdly, this report summarizes SAK within the area of hydrometeorology in Norway by identifying existing strategic research areas within institutions (internal research funding and strategic projects), and existing co-operation between institutions (e.g. bilateral co-operation, research projects, co-supervision, adjunct positions).

Finally, the report identifies topics that should be given greater emphasis in teaching. There is potential for improved coordination of teaching at the national level by (i) sharing information about courses between universities, (ii) increasing the mobility of both students and teachers, and (iii) sharing teaching materials and computer codes for exercises, which can be used across disciplines and universities. Teaching should emphasize the combination of field studies and modelling experiments, and Master and PhD theses could, to a larger degree, address operational applications and use the models, software and hardware from the operational forecasting systems. Hydrometeorology needs students who have high qualifications in numerous disciplines, e.g. mathematics, physics, statistics or chemistry and possess computer and instrument skills.

The HYDMET project has established the web-site www.hydmet.no, where the presentations at the seminar are published.

1 Introduction

The HYDMET project is a follow-up of the Research Council of Norway (RCN) Geosciences evaluation (Wilson, et al., 2011; Hov et. al., 2014) and funded by RCN under the program ISP geosciences. The primary objective of HYDMET is to develop a national research team (SAK) that has as task to identify the need for important research, methods, and experimental and operational observations for application in hydrometeorological modelling for forecasting and projections of changes in climate and hydrology.

The secondary objectives of HYDMET are to:

1) Identify the potential for the improvement of and research topics for hydrometeorological forecasting for reducing flood risk and the optimization of renewable energy production.

2) Identify the potential for the improvement of and research topics for the optimization of water resource management under climate change conditions.

3) Improve the synergy between the strategic plans for institutions and research groups.

4) Identify topics to be given greater emphasis in education.

The outcome of the HYDMET project is a final report/action plan that identifies important research topics and actions needed to improve SAK within hydrometeorology in Norway.

The HYDMET project organised a national seminar on 9-10 December 2015 in Lillehammer. The presentations and discussions at the seminar focused on the secondary objectives 1), 2) and 4) by discussing the following topics:

i. What is the current status for
    a. operational forecasting and climate change projections,
    b. ongoing research collaboration, projects, and research infrastructure,
    c. bachelor and master programs in hydrometeorology,
    d. PhD and Master theses in hydrometeorology.

ii. What is the potential for improvement and the key research challenges (methods, models, infrastructure) in hydrometeorological forecasting and climate projections with respect to flood risk reduction, renewable energy production and water resources management?

iii. How do we facilitate collaboration, division of responsibility, and concentration (SAK) within our own institutions as well as with cooperating institutions?

iv. Which topics should be given greater emphasis in teaching?

To answer these questions, five invited speakers provided their view on the status of hydrometeorology in Europe. The invited speakers were Martin Best, Met Office, UK; Fredrik Wetterhall, ECMWF, UK; Maria-Helena Ramos, Irstea, France; and Patrick Samuelsson and Ilias Pechlivanidis, SMHI, Sweden, all renowned for their work within the field and most also having operational experience. These talks were followed up by key persons from MET, NVE, UiO, UiB, NMBU and NTNU presenting key challenges as they see them. The seminar then continued with discussions in groups following the "world café method" and concluded with a plenary discussion. The seminar program and a list of participants is given in Appendix 1.

This summary report focus on research and teaching at MET, NVE, UiO, UiB, NMBU, and NTNU. Co-operation between the first four institutes is recommended by the evaluation report for geosciences (Hov et al, 2014) and NTNU was included due to their strong position in hydrology. There are relevant teaching and research activities at other universities, university colleges, and research institutes in Norway (e.g. UNIS, UiT, UiA, and others), but including these institutes were out of the scope for the HYDMET project.

For framing the HYDMET project, we defined hydrometeorology as a branch of meteorology and hydrology that studies the transfer of water and/or energy between the land surface and the lower atmosphere, including studies on snow and glaciers. In a broader frame, hydrometeorology is closely linked to other earth sciences, and it is not possible to draw a sharp border between hydrometeorology and other earth sciences. In the HYDMET project, we have, in particular, excluded hydrogeology, land-slides and avalanches, since these topics are treated in parallel SAK seminars.

Following the seminar, the organizing committee arranged a smaller workshop in December 2016 where we, based on the seminar, developed a 5-year action plan for SAK within hydrometeorology. Relevant topics were formalized obligations, common strategies, joint research projects and applications, as well as plans for education and joint supervision of students. The organizing committee consisted of: Kolbjørn Engeland and Elin Langsholt (The Norwegian Water Resources and Energy Directorate, NVE), Jørn Kristiansen and Eivind Støylen (The Norwegian Meteorological Institute, MET), Lena M. Tallaksen, Frode Stordal and Chong-Yu Xu (University of Oslo, UiO).

2 Presentations from invited speakers

Five invited speakers presented experiences from hydro-meteorological modelling from their institutions:

- Martin Best (MetOffice), *Organization of and research focus in hydrometeorological modelling in the UK.*
- Fredrik Wetterhall (ECMWF), *Ensemble modelling in hydrometeorology, challenges and benefits.*
- Maria-Helena Ramos (Irstea), *Probabilistic forecasting for the hydropower industry.*

- Patrick Samuelsson and Ilias Pechlivanidis (SMHI), *Operational hydrometeorological modelling for forecasting and projections at SMHI.*

They were all asked to base their presentations on the following topics:

- Short status on current practice (operational forecasting and projections).
- What has been your main improvement recently implemented (operational forecasting and projections), and what do you see as important next steps (potential for improvements)?
- How do you facilitate collaboration, division of responsibility, and concentration (SAK) within your own institution as well as with cooperating institutions?
- What are the key research challenges (methods, models, experimental research infrastructure)?

2.1 Organization of and research focus in hydrometeorological modelling in the UK

Presented by Martin Best (UK MetOffice).

The current practice

In the of summer 2007, a major flood event caused by uncharacteristically extreme rainfall hit large parts of England and Wales. In total, 13 people died, 55,000 homes and businesses were flooded, and there was a loss of essential utilities in some regions, e.g., power (Walham sub-station) and water (Mythe water treatment works). The loss to the country's economy was, in the region, of £3 billion in damages. As a result of the 2007 flooding, a review report was prepared and presented in 2008 by Sir Michael Pitt (the Pitt review), focussing on the potential for improvement to flood risk management. The number of recommendations within the report included the following: (i) The Environmental Agency and the Met Office should work together, through a joint centre, to improve their technical capability to forecast, model and warn against all sources of flooding; (ii) The Met Office and the Environment Agency should issue warnings against a lower threshold of probability to increase preparation lead times for emergency responders. As a result of these recommendations, the Flood Forecasting Centre (FFC) was established between the Met Office and the Environment Agency. The aims of the FFC are (i) to deliver a 24/7 hydrometeorological service enabling all stakeholders to be better prepared for flooding; (ii) to understand its customers, take a lead in the integration of flood services and help these customers understand how they can make best use of the products and services; (iii) to further develop forecasting capabilities; and (iv) to develop and promote the FFC as a centre of expertise in hydrometeorology. The FFC was established as a pilot in 2009 and became permanent, after business case approval, in the following year. It has been fully operational, based at the headquarters of the Met Office, since 2011, providing streamlined services.

The FFC determines the flood risk of an event using a probabilistic approach. The hydrometeorologists employ a subjective analysis by combining (i) the outputs of NWP models (both deterministic and ensembles), (ii) guidance from the Met Office chief and deputy chief meteorologist, (iii) observations from raingauge and radar, (iv) an in house grid based rainfall/runoff - routing model for the whole of the UK (G2G), (v) the Environment Agency's regional flood forecasting teams' catchment rainfall/runoff -

routing models, (vi) pre-determined rainfall depth-duration thresholds (especially for rapid response / surface water impacts), and (vii) conference calls with the Environment Agency's flood forecasting teams (to determine catchment sensitivity, etc). The flood risk assessment is derived using a flood risk matrix, which is based upon the likelihood of the event and its potential impacts, with four risk levels; very low, low, medium and high. The forecasts are presented on maps of the UK showing areas with differing flood risk levels along with accompanying descriptive text for the impact within the area.

Ongoing research

The winter of 2013/2014 delivered a number of severe weather events. The impact on society from high winds and persistent rainfall were manifested through various components of the environmental system, including high waves, coastal surge and flooding, saturated land, tidal locking and surface and groundwater flooding. This illustrates the integrated nature of the environmental system in the causes of flooding events. As a result, current ongoing research is focused upon coupling existing forecasting model components, i.e. land surface, atmosphere, ocean, waves and biogeochemistry, through a project to develop the UK Environmental Prediction (UKEP) system. This is a collaborative effort between the Met Office, two of the National Environment Research Council (NERC) centres (the Centre for Ecology & Hydrology (CEH), National Oceanography Centre (NOC)) and Plymouth Marine Laboratory (PML).

Increased computational resources enables improvement to forecast skill (for atmospheric, ocean or land systems) through a number of options. These include (i) improved spacial resolution, (ii) better understanding of uncertainty from increased forecast ensemble members, or extended forecast lead times by increased duration forecasts, (iii) better use of observations through new data assimilation techniques, and (iv) increased complexity in the forecast model dynamics, physics or technical requirements. Developments to the UK weather forecast system over the past 5-10 years have delivered an operational deterministic model with1.5 km horizontal resolution and ensemble members at 2.2 km resolution over the UK. This offers a level of local detail and an understanding of uncertainty that increases the ability to deliver appropriate warnings for severe weather related events. The UKEP project has been set up to explore the benefits from increased complexity through improved physical model components combined with the representation of feedbacks between the various environmental components. The aim is to have a better understanding of the impact of feedbacks on forecast model evolution and establish if this has the potential to lead to improved forecast capabilities.

To accelerate progress, a prototype project to build and evaluate a fully coupled system has been established. The model components included in the prototype project are the Unified Model for the atmosphere, JULES for the land surface, NEMO for the coastal sea shelf and WaveWatchIII for waves. Later versions of the system will include the ERSEM model for marine ecosystems. The OASIS3-MCT coupler is used for the atmosphere-ocean-wave components. Other couplings (e.g. UM-JULES, NEMO-ERSEM) are more direct at the compiled-executable level. The capability of the JULES land surface model has been extended to include a river routing scheme, in order to provide consistent linkage between the atmosphere and sea, closing the water cycle. Offline evaluation of hydrological parameter settings and comparison to other hydrological models continues at

CEH. Developments to the hydrology are anticipated in the next coupled configuration of the model components (UKC2). Key messages from initial results from the UKC1 atmosphere-ocean-land coupled system focusing on a winter case and a summer case are that (i) the model runs and produces sensible outputs, (ii) atmosphere-ocean coupling has little impact within the specific case studies, although equally the coupling has not noticeably degraded performance, and (iii) there is some sensitivity to coupling ocean parameters, with more work required to quantify the benefits (if any) for the studied cases.

This work has several challenges. One important challenge is the technical integration and coupling of a diverse set of models from disparate communities and code designs. However, the aim is to build a flexible, easy to use system with a high degree of modularity and transparency in order to being able to set up model configurations with various components and interactions enabled. This is a laudable and necessary ambition, but a challenging one to deliver in reality, in particular when developments depend on existing code and library bases. This remains work in progress. A second challenge is the evaluation and verification of simulations, especially of improvements from feedbacks due to coupling the components are small. This gives us a challenge towards being able to evaluate any differences with available observations, particularly in the near-coastal regions, where observations are typically sparse, but the impacts of coupling could be most important. Note case studies are all 'free running' (no data assimilation) in the prototype project. In time, if heading towards operational implementation, it will be important to understand the impact of coupling systems using different data assimilation schemes of varying sophistication and with varying amounts of available observations across each component.

Key research challenges:

The traditional motivation of land surface modelling has been to provide boundary conditions of momentum, heat and moisture to the atmosphere. As such, these models have been developed in order to minimise errors in these fluxes. For the hydrological community, the focus of modelling has been at the other end of the terrestrial water cycle, i.e., accurate predictions of streamflow. However, both communities are actually trying to solve the same problem, which is to represent the whole the terrestrial water cycle. As such, the key research challenge for the future will be to design and develop the next generation of land/hydrological model that considers all aspects of the terrestrial water cycle and aim to minimise errors across all components. Achieving this will require these two communities to work closely together, each applying their skills and knowledge to the problem.

As an initial step towards such a goal, work is underway to try to link the land surface model JULES to the hydrological model SHETRAN. The aim is to use the turbulent flux calculations for momentum, heat and moisture from JULES, whilst utilising the hydrological capabilities of SHETRAN. Additional work has also been undertaken to demonstrate that the inundation model LISFLOOD can be coupled to JULES for appropriate regions.

In addition to developing the next generation of land/hydrological model, another challenge will be to utilise all available observations to constrain the model through data

assimilation techniques. This will include assimilating snow cover/mass, soil moisture from various sources and observed streamflows.

How to facilitate collaboration

One of the main aspects to facilitating collaboration is to ensure that the technical tools are in place in order to remove as many barriers as possible. As an example, the JULES model (https://jules.jchmr.org/) has been designed to be a community land surface model. The JULES model is used as the land surface component of the Met Office Unified Model for forecasting, climate and earth system predictions, but in addition it can also be run independently as a standalone model using atmospheric forcing. This enables the community to not only run the model, but also contribute towards the longer term scientific development. Hence, it is continually improving, placing it firmly at the cutting edge of land surface modelling.

JULES includes important land surface processes and their interactions (surface energy balance, hydrological cycle, carbon cycle, dynamic vegetation, etc.) and thereby provides a tool for assessing the impact of specific process on the ecosystem as a whole, e.g. the impact of climate change on hydrology, and to study potential feedbacks. JULES is available to any researcher, free of charge. This has led to a large and diverse community from across the globe using JULES to study land surface processes on a wide variety of temporal and spatial scales. The development of JULES is governed by a community process, and is presided over by a management committee comprised of organisations providing significant resources for the ongoing development of JULES. Figure 1 is a sketch of the governance structure for the JULES community.

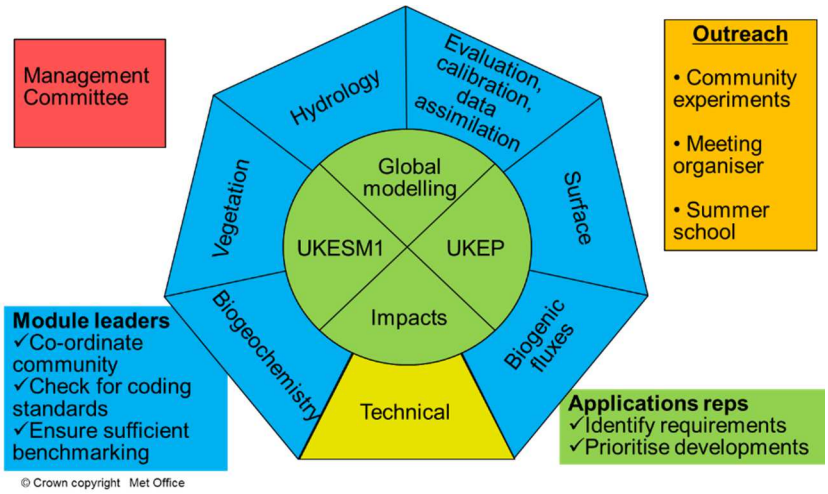

Figure 1. The governance structure for the development of JULES.

It is important to recognise that in order to maintain JULES as a leading land surface community model, it is important to ensure that the governance of the code and the technical infrastructure are well managed. For JULES this includes a rigorous testing procedure for all new code developments to ensure the robustness of the code base, whilst providing tools and training to ensure that this is not a difficult task for users and developers within the JULES community. This provides an opportunity for researchers to

not only contribute towards a leading land surface model, but also towards leading weather and earth system models.

2.2 Ensemble modelling in hydrometeorology, challenges and benefits

Presented by Fredrik Wetterhall (ECMWF, Reading, UK)

The development of the European Flood Awareness system (EFAS), an early warning probabilistic flood warning system across Europe, was presented. EFAS has over 50 partners that receive notifications of upcoming floods and in turn provide observations, feedback of performance and needs for decision makers. EFAS has the largest collection of hydro-meteorological observations in Europe. EFAS is transboundary on the European scale and aims to provide information both for decision makers and forecasters at the national and European level. EFAS provides probabilistic flood warnings for river basins larger than 2000 km^2 with lead times up to 15 days. Promotion of novel tools, techniques and data sets (e.g. satellite data) is also a key purpose of the project. EFAS is also used by the Emergency Response Coordination Centre (ERCC) of the European Commission to provide comparable information across Europe and is a useful tool for the anticipation of crisis management by the civil protection, aid and assistance during crisis. EFAS is part of the COPERNICUS Emergency Management Service, which also includes flood mapping and a forest fire warning system. ECMWF is also running a pre-operational global flood awareness system (GloFAS), which provides global flood forecasts based on the ECMWF weather forecasts (globalfloods.eu). GloFAS started in 2011 and is planned to go fully operational in 2017.

The EFAS system consists of a model chain that starts with a multi-model meteorological ensemble forecast which is pre-processed before applied to a hydrological model (LISFLOOD). The outputs are then post-processed and translated to warnings to exceeding thresholds calculated from the model climatology. The forecasts are continuously verified and the users provide feedback which is used to improve the system. EFAS provides warnings both for riverine floods and flash floods. Forecasts and warnings are published on the EFAS user interface, and warnings are also sent by email to partners.

Recent advances include improved flash-flood routine, increased post-processing, explicit inclusion of lakes and reservoirs, impacts-based forecasting (population, flood damage potential etc.), landslide susceptibility forecast and a seasonal outlook, and assessment of monetary benefits from EFAS.

The planned improvements include to extend the lead time to 15 days, increase the spatial domain, make monthly outlooks and increase the spatial resolution. Increasing resolution is expected to improve forecasts by improving the physics of the models. There is ongoing work to create a global flash-flood forecast system. The future EFAS could use multi models (NWP and hydrological), and data assimilation (e.g, remotely sensed water levels) for updating the hydrological model.

The team at ECMWF, with operational responsibility and working on further development of EFAS, consists of 8 persons. The team has a high degree of specialisation. The success of EFAS relies on: engaging with the international community (e.g HEPEX, Global flood partnership), establishing research collaborations (e.g. EU projects, guest researchers and PhD students), and using new technologies. EFAS organises annual meetings, which are opportunities to meet forecasters and get feedback from users, present new ideas and provide training. It is an important forum for building trust and confidence in the system.

Seven important challenges were discussed:

1: Making the most of data. How can we use new data sources to improve our model? How can we develop automated quality-control algorithms for DA? How can data assimilation take advantage of the expertise of the forecaster? How can forecasters make use of new sources of data? What is the point at which quality-control systems are sufficiently skilful? How can we make optimal use of sparse station networks, remotely sensed retrievals, and numerical weather prediction products?

2: Exploring the predictability. Exploring the predictability– find skill where others tell you there is none. What are the limits of predictability in space and time?

3: Quantifying the uncertainty. How to best assess the uncertainty to optimize skill? The uncertainties originate from meteorological forcing and initial conditions, observations, model parameterizations, model structures etc. and these uncertainty sources can be combined in different ways.

4: Getting the numbers right. How can the performance of hydrologic forecasting models be quantified? We need to have a discussion about benchmarking and skill:

No skill: The Hydrological Ensemble System is consistently worse than a set benchmark.

Naïve skill: The forecast system is skilful against a too simplistic benchmark. More challenging (difficult to beat) benchmarks could be designed.

Real skill: No benchmark which can be implemented at a lower cost than the operational system can beat my forecast system.

5: Turning forecasts into effective warnings. What are the best methods for the communication of probabilistic forecast? Urban Myth I: there is a single decision. Several measures can be used depending on lead time and flood severity. Urban Myth II: we cannot implement a decision framework based on probabilities. Which forecasting tasks can/should be automated?

6: Impact-based warnings. What are the potential impacts of a forecast event?

7: The holy grail of forecasting: Seamless Predictions of Natural Hazards (Figure 2).

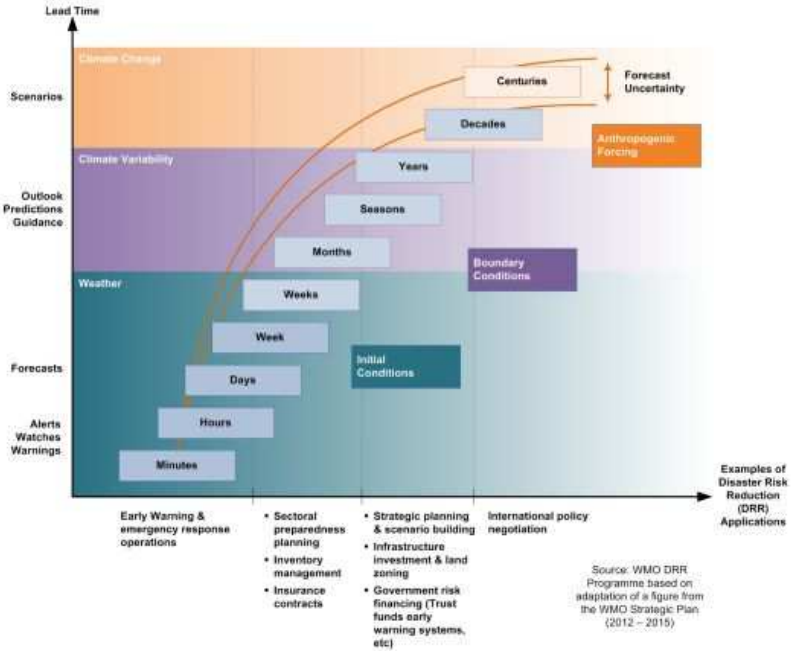

Figure 2 Seamless forecasting – the holy grail. Source: WMO DRR programme (http://www.wmo.int/pages/prog/drr/) based on adaptation of a figure from the WMO Strategic plan (2012-2015).

2.3 Probabilistic forecasting for the hydropower industry

Presented by Maria-Helena Ramos, Irstea, France

Maria-Helena Ramos represented Irstea, which is a National Research Institute of Science and Technology for Environment and Agriculture in France. Irstea has three scientific departments: 1: Water, 2: Land and 3: Eco-technologies. There are two groups working with hydrology and hydropower, one in Antony and one in Lyon, and the cooperation is, or has been, in particular with EDF and CNR in France, Hydro-Quebec in Canada, and Cemig in Brazil.

The focus of the presentation was hydrological forecasting with the hydropower sector as an end-user. Hydropower production has a strong interaction with (i) climate and weather, via the hydrological cycle, which provides the water and streamflow for power production, (ii) the demand that is in parts explained by weather, (iii) other renewable energy sources, (iv) other water uses via multi-purposes reservoirs or catchment upstream-downstream interactions, and (iv) other hydropower companies in shared river networks, transboundary catchments and for governance aspects (responsibilities, resources, legal instruments, actor network, etc.)

Flood and inflow forecasts are needed to ensure safety and security of installations (hydro-meteorological extremes/ threshold exceedance, anticipation), meet environmental standards (hydro-meteorological extremes), improve water resources management (inflow volumes/reliability), and optimize the production of power plants (inflow volumes).

Streamflow forecasts have three characteristic time horizons. (i) Short term forecasts are often deterministic hourly forecasts up to 24 hours ahead based on high resolution NWP models. These forecasts are important for dam safety. Medium-term forecasts are for 1 day to 14 days ahead. Typically, the seven first days are often deterministic forecasts, although some hydropower companies are already implementing ensemble forecasts at these ranges, whereas the 14day forecasts are given as ensembles. Both are based on NWP models, possibly in combination with statistical models. These forecasts are important for water management and optimization of power production. (iii) Long term or seasonal forecasts are from14 days to 6 months ahead and are typically probabilistic forecasts based on climatology. These forecasts are important for assessing future dam inflows and low flow risks.

For the optimization of hydropower production, the hydrometeorological forecasting activity is an essential element to provide forecasts of future streamflow, energy demand and energy prices. The information is used to optimize the management of reservoirs and the power production, with the objective to maximize income. The application of hydrometeorological forecasting systems for the optimization of hydropower production raises several needs and opportunities. Concerning weather forecasts, probabilistic approaches need to be more widely used, possibly by using mixed forcing (deterministic, ensembles, analogues). Especially challenging is the forecasting of extremes and the location of strong precipitation events. For hydrological modelling, the initial condition (snow coverage) is important, and distributed modelling becomes more relevant in order to capture spatial patterns of forcing and runoff production. Hydrological forecasts will still rely on bias correction and both pre- and post-processing in order to provide reliable forecasts for the needs of the hydropower users. In the application of statistical techniques for post-processing model outputs, attention must be paid to the space-time (intra/inter variable) interdependencies, which is challenging today. The role of human expertise and real time forecast verification will need to be integrated with pre- and post-processing approaches. The evaluation of the economic value of forecasts is useful for targeting new forecasting approaches, assessing the importance of system's improvements, or defining the allocation of resources (human and financial). Some studies have been done on this topic, but more applied research is needed to better evaluate the links between forecast quality and value in the hydropower sector. For the integration of renewable energy sources (RES), the role of reservoir hydropower systems or run-off-the-river combined with other (variable) climate-related RES deserves more in-depth investigation. For climate change impacts at regional/local scales, non-stationarities (resource planning), dam design (security), sectoral integration (co-governance, nexus) are important topics.

A study addressing the economic value of forecasts illustrates, for a case study for EDF in France, the challenges in evaluating the value of forecasts for the hydropower sector. EDF has an operational 7-day ensemble-based forecasting chain since end 2010, based on ECMWF EPS, Météo-France deterministic forecasts, analogue-based methods, and post-processing techniques for bias correction. A conceptual hydrological model is used to transform precipitation and temperature into streamflow. Within EDF, there is a strong interaction between forecasters and end users (dam operators and energy optimization/ energy market teams). Additionally, the forecasting chain is marked by a strong role of human expertise.

The case-study was performed in 11 catchments (100 – 3000 km^2) in south-Eastern France, by modelling inflow to existing reservoirs. The main use of these reservoirs is hydropower production, although some have also significant uses for irrigation and tourism. They catchments studied are located in the main French mountain chains and have a strong snow influence. The hydrological regime is characterized by dry summers and wet autumn to spring periods.

A heuristic model was developed by Irstea and EDF to illustrate the impact of different forecasts (deterministic, ensembles, climatology) in the optimization of power production, where each reservoir was characterized by a storage capacity coefficient and a maximum turbine capacity coefficient. The actual energy prices were given to the model for a 4-year period, running from 2005 to 2008, and the effect of different reservoir inflow forecasts was investigated with respect to the added economic value they bring. The results indicated a higher gain when using ensemble forecasts comparatively to the case where deterministic forecasts are used. The differences were especially important when the reservoir capacity was low. The tool, consisting of a heuristic algorithm connected with a simulation model for reservoir rules under constraints, presented the advantage of being adaptable and allowing to investigate the effects of different inflow scenarios and different characteristics of reservoirs and power systems.

Further developments include to (i) apply this approach to a larger data set of catchments in order to gain more insights into strong events / seasonal behaviour, (ii) review some of the approximations considered (constraints, use of probabilistic information from ensembles, production costs, etc.), and (iii) assess the impact of post-processing streamflow in the economic value obtained from the heuristic model.

2.4 Operational hydrometeorological modelling for forecasting and projections at SMHI

Presented by Patrick Samuelsson and Ilias Pechlivanidis (SMHI),
The presentation was divided in two parts focusing on a number of developments within meteorological modelling (Patrick Samuelsson) and hydrological modelling (Ilias Pechlivanidis).

Part I - meteorological modelling

Until recently, numerical weather prediction (NWP) land-surface modelling has focused on surface-atmosphere energy fluxes (e.g., during HIRLAM). Hydrology process description is needed for this, but has, in itself, not been the focus. Runoff is produced by HIRLAM but is essentially not used as input to other models (e.g., routing), for river discharge validation, or forecasting. The HIRLAM surface model is a tightly integrated part of the atmospheric model system and cannot be easily used for any offline applications. HIRLAM precipitation and temperature is used as input to hydrological models like HYPE. Surface assimilation technique is based on optimum interpolation, which is difficult to extend to new observational data sets and more sophisticated land processes.

Currently, and since March 2014, Sweden and Norway run operational NWP forecasts together within the framework of MetCoOp using the model system HARMONIE (AROME+SURFEX). The surface part of HARMONIE, SURFEX, is far more complex

and flexible than the corresponding surface model in HIRLAM. SURFEX can be used offline and provides more developed vegetation, snow and hydrological processes. A data assimilation system utilizing Ensemble Kalman Filter is under development. HARMONIE is also used as climate model. The operational MetCoOp system has the following features:

- HARMONIE Cycle 38h1.2
- 3D-Var + surface analysis
- 2.5 km hor. res. / 65 vertical layers
- Lat. bound. ECMWF-HIRES (1hr)
- +66 hours at 00,06,12,18 UTC

The MetCoOp Ensemble Prediction System has the following specifications:

- Cycle 40h1.1
- MetCoOp domain, 2,5km hor. Res.
- AROME atmospheric physics + SURFEX surface physics
- 1 control member + 9 perturbed SLAF members
- Lead time: +48hr

The focus of upcoming and future activities will be on (i) the MetCoOp Ensemble Prediction System (EPS) that will go operational in 2016, and (ii) combining non-traditional observations in NWP (e.g. river discharge, Leaf-Area Index, soil moisture, snow properties, freshwater levels, etc.) with assimilation methods (e.g. Extended and/or Ensemble Kalman Filter) and with models where relevant processes are included (e.g. multi-layer snow and soil, prognostic LAI, snow/vegetation combination, lake/river physics and dynamics, ground water).

For future development, the French SIM model system could be an inspiration, as illustrated in Figure 3 below. The SIM modelling system consists of three main modules. (i) SAFRAN is a meteorological analysis tool and provides the atmospheric forcing needed for (ii) the energy and water balance modelling in ISBA-SURFEX, and (iii) MODCOU is a hydrological model accounting for the sub-surface dynamics.

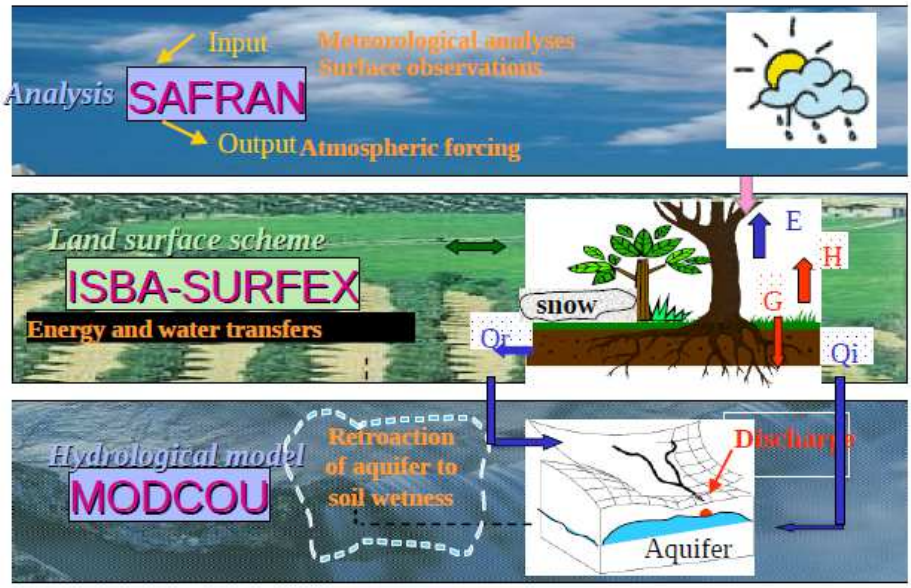

Figure 3. The three important modules for the French hydrometeorological SIM modelling suite (based on a figure on the CRNM web-site for the Safran-Isba-Modcou suite: http://www.umr-cnrm.fr/spip.php?article424&lang=en).

A Nordic hydrometeorological system could include combinations of similar components: (i) Coupled to NWP/climate model or offline with interpolation/downscaling to higher resolution and/or spatial/time correction or boundary layer processes. Possible candidates are MESAN analysis system + STRÅNG radiation analysis, MetCoOp operational + EPS HARMONIE-Climate. (ii) Land surface model with the OASIS coupler for deep and surface runoff, ground water, flooding, irrigation, etc. SURFEX is then a candidate. It has Nature-Town-Lake-Sea, Nature potential: 19 patches, multi-layer snow and soil, dynamic vegetation. (iii) Hydrological ground water and routing model, e.g. HYPE "light" or CaMaFlood.

Assimilation development needs: Currently, SMHI performs optimal interpolation (OI) of observed near-surface quantities, such as T2m, rh2m, and snow, and performs column wise OI for increments. Future plans are to include a 3D Ensemble Kalman Filter (EnKF) surface assimilation system. Satellite products exist for, for instance, snow and soil moisture, but a proper assimilation method is needed to utilize the raw satellite radiances/backscatter via observation operators (based on model quantities). Each radiance, however, needs its unique observation operator. Questions remain, such as: How to create the ensemble for the surface variables? What processes/variables are needed from the surface model for the observation operators?

Assimilation of river discharge data and EO fresh-water is to be included in the long term plans, but also requires inclusion of hydraulic processes in the modelling systems.

Surface model/SURFEX development needs: Currently in NWP, SMHI uses SURFEXv7, which has: force-restore with 2 and 3 layers for soil temperature and moisture, respectively, composite snow layer (D95), town-energy balance, and very simple inland water. SURFEXv8 provides the potential to utilize: diffusion soil scheme (~14 layers) (thin top layer), explicit snow scheme (default 12 layers) with snow crystal based albedo

formulation, multi-energy balance with separate canopy vegetation and ground/snow, ISBA-A-gs prognostic LAI, town-energy balance, explicit lake model (Flake) with prognostic ice, OASIS coupler for, e.g., hydrological models.

Hydrology/routing development needs: Currently, the Swedish hydrology uses the HYPE model (as compared to e.g. TRIP, CaMaFlood, MODUCO). The model is well developed for Nordic conditions, where a delay factor due to lakes is well considered, but the hydraulic component, where river flow speed depends on water level, is not included. Hydrology/routing components that need improvements are those necessary to consider hydraulic processes for assimilation of EO water levels. For the assimilation of observed river discharges, the routing system must be very precise with respect to the river network. Until now, no automatic system supports such level of preciseness. A potential hydro/routing system for OASIS coupling is HYPE "light" (routing part of Swedish, European and Arctic HYPE applications, i.e. only lake and river part of model).

Physiography development needs: Physically-based distributed models like SURFEX are, in general, more dependent on detailed physiography data than semi-distributed conceptual models like HYPE. Currently, in Nordic NWP, the model resolution is 2.5 km and uses 1 km resolution of landuse (ECOCLIMAP), 1 km (50 m) topography, and 10 km (1 km) sand/clay. In the future, new high-resolution and detailed physiography is needed, in particular for detailed downscaling. More details in land-use types are also needed, e.g. 90% of Stockholm is represented as two town types only. Land-use characteristics need updates, e.g. town character parameters like building height/shape.

Part II – hydrological modelling

SMHI is responsible for the national hydrological forecasting services (short to medium range (up to 10 days in the future) and seasonal forecasts (up to 7 months in the future). The presentation addressed the so called "Hydrological water factory", which describes the entire modelling chain from data acquisition to the generation of water services, i.e., the forcing data and model used, dissemination of forecasts, and the institute's current and future scientific directions in the field of hydrology. Medium-range hydrological forecasting is performed for Sweden and Europe. Additionally, SMHI acts as part of the dissemination centre in Europe for EFAS. At the national scale, the hydrological models used are the HBV and the HYPE models. The models' forcing inputs are based on databases of gridded precipitation and temperature that are provided as: (i) interpolation of quality assured observations (for Sweden), and (ii) based on weather models in combination with observations (for Europe). For the medium range forecasts, both deterministic (from SMHI and ECMWF) and ensembles (from ECMWF) are used. Observations from water levels in the lakes/reservoirs and/or rivers, river discharge, and snow information are assimilated in a number of basins in Sweden (direct replacement or assimilation through Kalman filters). This information has proven to be very useful to river flow downstream predictions, particularly when the river is regulated.

The flood forecasts are disseminated as (among other methods) maps showing the return period of the forecast discharges, together with the thresholds of critical warning levels (2.5, 5, and 10 years return period). For basins with observations, graphs of observed, simulated and forecast discharge are shown. In addition, a scenario approach/tool is used

to address the practical question "*how much rain is needed for the model to reach a warning level?*" and hence easily assess if the forecast precipitation can potentially result in a warning; such results are also shown on a map. Ensemble forecasts are further used for estimating, in a probabilistic manner, the hydrological response and its potential for flood generation. Ensemble forecasts based on ECMWF are used to assess the probability of floods for a number of lead days and up to 10 days in the future.

The scientific directions include: (i) Hydrometeorological modelling at fine temporal and spatial resolution for intense precipitation (1-hr), (ii) Hydro-climatic projections and climate services, and (iii) Assimilation of in-situ and satellite data. The information that is currently available on the impact of future climate on water resources is often at the large-scale (continental, national). Such information is produced during research projects, and quite often involves identification of climate impact indicators, which are linked to the end-user needs, whilst the information is tailored at variables and statistics of interest (long-term mean conditions, extremes, such as floods, water scarcity, droughts, and seasonality). These studies have been very useful to point out that climate change will result in a number of challenges at different geographical domains, and therefore there is a need to further analyse the climate impact information at the regional/local scale for decision making. Also, there could be differences in results/conclusions between large and local scale impact assessments; hence the needs to addressing the question of which study should one accept. There is therefore a need for tailored products, addressing climate model ensembles, bias adjustment methods, hydrological modelling ensembles, and embracing important weather variables and/or climate indices relevant to the end-users.

Hydrological modelling at fine temporal resolution is motivated by extreme rainfall events. The HYPE model was further developed and setup to run on a 1-hour temporal resolution using a new high resolution precipitation product based on precipitation radars and automatic precipitation gauges. Current efforts further focus on addressing the potential of microwave links in such services, particularly at regions with a sparse precipitation gauge network.

SMHI has given focus on exploring the potential of in-situ and earth observations for assimilation in hydrological modelling. Apart from the common variables (most of the time these are in-situ observations) that have been assimilated for a number of years, e.g. snow depth, water levels and discharge, new variables (driven by earth observations) include soil moisture, fractional snow cover, snow water equivalents, snow depth, and high resolution water level data in rivers and lakes. The development of data assimilation is mainly addressing the assimilation of different types of snow measurements, i.e. snow depth measurements performed by SMHI (daily measurements at points), SWE point data observed by hydropower companies in points (bi-weekly) and snow courses (once per year) as well as satellite products (CryoLand) that provides fractional snow cover (1x1 km) and SWE (25x25 km).

2.5 Key messages from the invited speakers

Below, a summary of the key aspects addressed by the invited speakers is given.

Short status on current practice (operational forecasting and projections)

- **Coupling of models**: The current practice for operational forecasting and projections is to use a "one way" chain of models, sometimes combined with post-processing (meteorological forecasting -> processing -> hydrological forecasting -> processing).
- **Assimilation**: this is standard in meteorological forecasting models. For hydrological models, when present, data assimilation concerns observations from water levels in the lakes/reservoirs and/or rivers, river discharge, and snow data (point observations, snow courses and satellite data).
- **Ensembles:** hydrometeorological ensembles, combined with post-processing, are becoming increasingly common for operational forecasting, both for floods and for operation of hydropower dams. The risk of a forecast event is assessed using a probabilistic approach, and often also includes a subjective analysis (human expertise) in both sectors of flood forecasting and dam operations.
- **Addressing the needs of society:** Major flood events have initiated improvements of flood forecasting services. The hydropower industry also needs reliable forecasts and the quantification of the economic gains achieved from using these forecasts in their decision-making process. Training and meetings are also important aspects to be considered. Under the European EFAS system, ECMWF organizes annual meetings with forecast users, which is an opportunity to make users meet forecasters and get feedback, to present new ideas and to provide training. It is an important forum for building trust and confidence in the forecasting system.

What has been your main improvement recently implemented (operational forecasting and projections), and what do you see as important next steps (potential for improvements)?

- **Coupling of models:** A prototype project to build and evaluate a fully coupled system for hydrometeorological forecasting has been established in UK, based on the Unified Model for the atmosphere, JULES for the land surface, NEMO for the coastal sea shelf and WaveWatchIII for waves. The French SIM model system could be an inspiration for coupling atmospheric and hydrological models. The SIM modelling system consists of three main modules: (i) SAFRAN (analysis), ISBA-SURFEX (land surface model), and MODCOU (ground water model).

- **Processes**: Increasing resolution is expected to improve forecasts by improving the physics of the models. One example is an improved flash-flood routine at EFAS.

- **Assimilation**: More data could be assimilated into models (e.g. river discharge, Leaf-Area Index, soil moisture, snow properties, freshwater levels etc.) and assimilation methods could be improved (e.g. Extended and/or Ensemble Kalman Filter) within models where relevant processes are included (e.g. multi-layer snow and soil, prognostic LAI, snow/veg combination, lake/river physics and dynamics, ground water).

- **Ensembles:** The use of multi-models (from both NWP and hydrological models) can enhance flood and drought risk assessment.

- **Addressing the needs of society**: More types of weather-related natural hazards could be forecast, e.g., landslide susceptibility forecasts, and the forecasts could become more impact-based (water levels, flood damage potential, etc.). The lead time could be extended to 15 days, and monthly outlooks can be provided and be useful to several sectorial applications. Finally, to justify the need for improved forecasting techniques and their value in the decision-making processes of several users, one could also assess the monetary benefits from forecasts and forecasting services.

How do you facilitate collaboration, division of responsibility, and concentration (SAK) within your own institution as well as with cooperating institutions?

Model development as a framework for facilitating SAK has been exemplified in several of the presentations. The development of a community model like JULES needs a governance structure. Linking new components (e.g. SHETRAN and LISFLOOD into JULES) into a community model is an effective way to encourage collaboration.

The development of operational services is also used as a framework for facilitating SAK. The development of EFAS, for instance, builds on engagement with the international community (e.g HEPEX, Global flood partnership), and research collaborations (e.g. EU projects, guest researchers and PhD students).

What are the key research challenges (methods, models, experimental research infrastructure)?

Several key research challenges have been identified, including:

- Coupling of models in order to account for feedbacks (as opposed to a one way chain of models).
- Improvement of process representation in earth system models.
- Assimilation of more observations into models, like river streamflow, soil moisture, snow cover.
- Modelling and measurements at high spatial and temporal resolution for extreme events in urban environments.
- Meeting the needs of the society: we need to make our forecasts and climate change projections more useful by using post-processing methods and impact-based forecasts, and we also need to emphasize their usefulness and the socio-economic benefits they bring.
- Seamless forecasting was suggested as the “holy grail”.

3 Summary of presentations from national institutions

Presentations of Norwegian key institutions working within hydrometeorology were given by John Burkhart and Frode Stordal, University of Oslo (UiO), Jørn Kristiansen and Anita Verpe Dyrrdal, The Norwegian Meteorological Institute (MET), Stein Beldring, The Norwegian Water Resources and Energy Directorate (NVE), Helen French, Norwegian University of Life Sciences (NMBU), Asgeir Sorteberg, University of Bergen (UiB), Tone Muthanna, Norwegian University of Science and Technology (NTNU). They were given five topics to address. The first two only concerned the universities

i. Number of master and PhD students (still studying) with relevant topics. (You could provide a table with names and topic/title). Could you also make a statistics of number of students the previous 5 years?

ii. Brief overview over bachelor- and master programs in hydrometeorological modelling

iii. Brief status on existing R&D (forecasting, climate change), which models, methods and observations are used).

iv. What are the main research challenges (methods models, research infrastructure)

v. How do you organize collaboration, share of work and concentration (SAK) in your institution and with collaborating institutions?

3.1 Masters and PhDs

Number of Master and PhD students the last 5 years are provided in Table 1 (Masters) and Table 2 (PhDs). Details of candidates and the topics for their PhDs are given in the Appendix 2. Note that this overview is not necessarily balanced between the institutions since the interpretation of hydrometeorology is not very sharp, and since information from all departments is not included (e.g. earth science at UiB, geography at NTNU and Biology at UiO).

For master theses, we see that UiO and UiB supervise all masters within meteorology, whereas masters with topics from hydrology is given at all universities. Precipitation is a common topic for masters in both meteorology and hydrology. Glaciology and avalanches is also covered by UiO and UiB, whereas snow hydrology, permafrost, and landslides is mainly covered by NTNU and UiO. Masters in urban hydrology is given by NTNU and NMBU, and ground water and water quality is covered by NTNU, UiO, UiB, and NMBU. Note that the information in Table 1 is not necessarily complete since masters on hydrometeorological topics could be given at severel departments within the universities.

For the PhD theses we see meterology at UiB focus mainly on precipitation processes, whereas meteorology at UiO (related to hydrometeorology) focus more on land surface parameterisations. NTNU has currently a focus on the engineering side and application of hydrology as in hydropower planning and operation and civil engineering. NTNU and NMBU has also a focus on urban hydrology (due to an ongoing centre for research-based

innovation (SFI)) whereas climate change impacts on hydrology and water resources management has been a focus in many of the finished PhD projects at NTNU. Snow hydrology is covered at UiO and has also over time had a strong focus at NTNU related both to climate change, hydropower, snow loads on infrastructures.

Table 1: Number of ongoing master projects and the number of finalized projects for the period 2011-2015

University	Institute	ongoing / 2011-2015	Topics
UiB	GFI	7/11	Meteorology-precipitation (10), Meteorology-evapotranspiration (2), glaciers (2), Hydrology (4)
UiB	GEOG.	9/22	Glaciers (22), Meltwater (2), Groundwater (4), Floods (3)
UiB	GEO.	14/41	Glaciology (4), glaciers (12), avalanches (4), hydrology (13), floods (5)
NMBU	IMV	1 /11	Precipitation (1)
NMBU	IMT	17/100?	Lakes and water quality (11), Sediments (2), Precipitation (1), Ground water and water quality (3)
NTNU	IVM	8/25	Urban-hydrology (precip) (3), Precipitation-runoff modelling (5)
NTNU	GEOG	5/10	
UiO*	GEO	12/46	Glaciers (11), Permafrost (7), Snow (12) Precipitation/temperature (3), Discharge (2), Hydrological modelling (3), Flood (2), River Ice (1) Avalanches (6), Water quality(1), Meteorology (10)

*Does not include theses related to hydrogeology that is reported in a parallel project, and exclude theses in meteorology not related to land surfce processes.

Table 2 Number of ongoing PhD projects and finalized projects for the period 2011-2015

University	Institute	ongoing / 2011-2015	Topics
UiB	GFI	9/7	Meteorology-Precipitation (15), Hydrology (1)
UiB	GEO	5/3	Glaciers (3), Flood reconstruction (1), Hydrology (2), Storminess(1)
NTNU	IVM	6/10	Hydrology-climate-impacts (5) Urban-Hydrology (2),Hydrology-precipitation(1), hydraulic modelling (2), Hydrology-runoff (2)
UiO*	GEO	19/26	Glaciers (15), Permafrost (4), Large-scale hydrology (1). Hydrological modelling (7), Streamflow forecasting (2). Soil moisture (1), Meteorology-Precipitation (2), Meteorology – land surface(6), vegetation (1), Snow (6)

*Does not include thesis related to hydrogeology

3.2 Master and bachelor programs

The current bachelor and master programs are listed in Table 3 below, and in Appendix 3, a table with currently available courses is shown. At University of Oslo new bachelor programs will be launched autumn 2017 (meteorology and hydrology will now be part of the same bachelor program (Geophysics and Climate) and new master programs will follow (still under discussion). At University of Bergen there was a revision of the bachelor program in climate, atmosphere and ocean science in 2012/13 and of the master program in 2013/14. In 2012 a new master program in renewable energy was launched. Master programs and courses are coordinated with UiO and UNIS and J. Lacasce at UiO is used as a program sensor.

For the period 2016-2024 UiB will host the Norwegian Research School on Changing Climates in the coupled Earth System (CHESS) that builds on The Norwegian Research School in Climate Dynamics (ResClim). Participating institutions are University of Bergen, University of Oslo, University of Tromsø, the Universitety Centre in Svalbard, UNI Research, The Norwegian Meteorological institute, Norwegian Institute for Air Research and the Norwegian Polar Institute. CHESS will provide courses for PhD students, and it is open for new suggestions.

Table 3 List of bachelor and master programs concerning hydrometeorology at UiB, UiO, NMBU and NTNU. Other Universities and University colleges has study programs that are relevant.

Study programs	Level	University	Department
Water and environmental engineering	Master	NMBU	Dept. of Mathematical sciences and technology (IMT):
Environment and Natural Resources	Master	NMBU	Dept. Environmental Sciences (IMV)
Renewable energy	Master	NMBU	Dept. Ecology and Natural Resource Management (INA
Klima-, atmosfære- og havfysikk	Bachelor	UiB	Geophysical Institute
Physical Geography	Master	UiB	Department of geography
Quaternary Geo. and Palaeoclimatology	Master	UiB	Department of earth sciences
Klima-, atmosfære- og havfysikk	Master	UiB	Geophysical Institute
Energy	Master	UiB	Geophysical Institute
Hydropower development	Master	NTNU	Department of Hydraulic and Environmental Engineering
Civil and Environmental Engineering	Master	NTNU	Department of Civil and Transport Engineering
Geotechnics and Geohazards	Master	NTNU	Department of Civil and Transport Engineering
Coastal and Marine Engineering and Management	Master	NTNU	Department of Civil and Transport Engineering
Cold Climate Engineering	Master	NTNU	Department of Civil and Transport Engineering
Geology	Bachelor	NTNU	Department of Geology and Mineral Resources Engineering
Geotechnology	Master	NTNU	Department of Geology and Mineral Resources Engineering
Physics, Astronomy and Meteorology	Bachelor	UiO	Department of Geosiences
Geosciences GEO where hydrology is one specialization	Bachelor	UiO	Department of Geosiences
Physical geography, hydrology and geomatics	Master	UiO	Department of Geosiences
Meteorology and oceanography	Master	UiO	Department of Geosiences

3.3 Brief status on existing R&D (forecasting and climate change).

3.3.1 Operational hydrometeorological forecasting

The forecasting services at MET (1-3 days lead time) is based on the AROME model for two domains, both with a spatial resolution of 2.5 km. The models are operated in cooperation with SMHI for the domains shown in Figure 4. The high resolution has been successful both in terms of better precipitation forecasts and better representation of especially polar lows.

The production of weather forecasts is based on assimilating observations into the NWP model. Observations of the atmosphere, land surface and ocean from satellites, aircrafts, SYNOP-ships, weather radars, sondes, atmospheric profilers and SYNOP stations are assimilated into the NWP models. The updating cycle for forecasts is currently 3 hours. The updating cycles are illustrated in Figure 5.

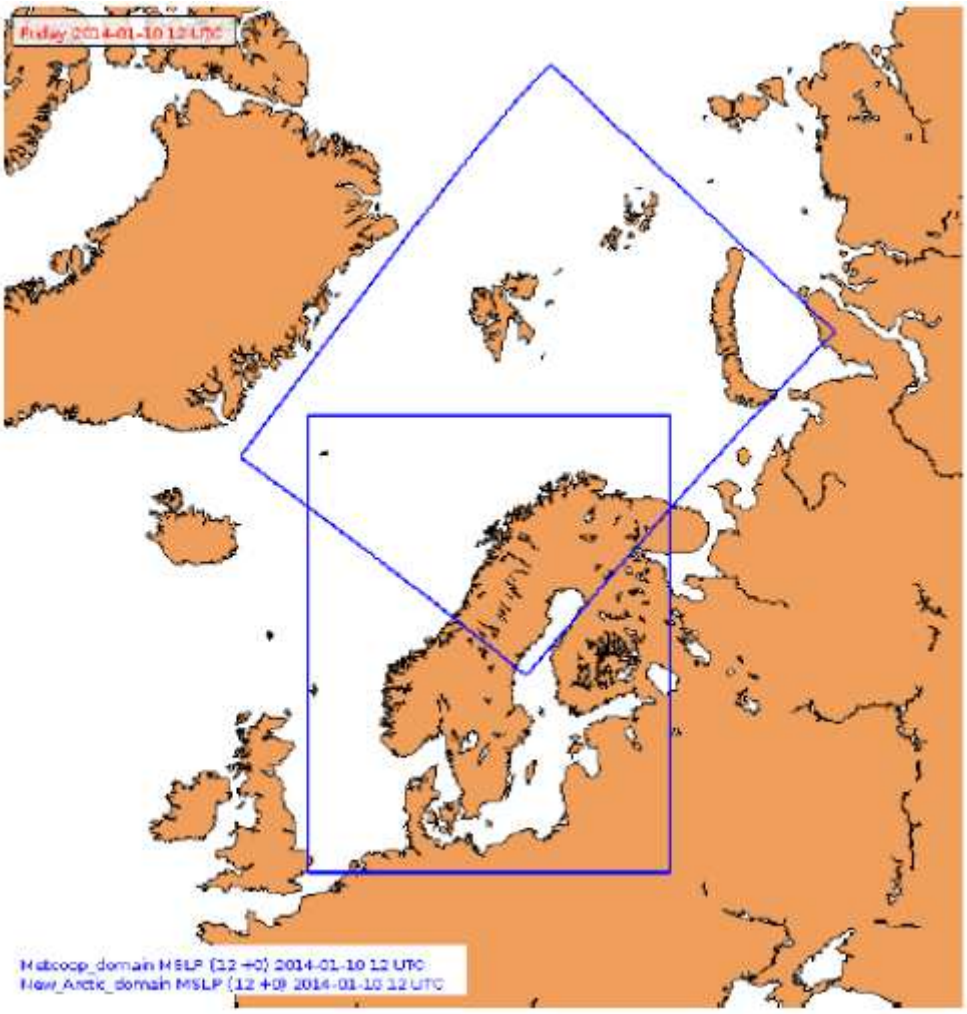

Figure 4 The domains for the MetCoop Scandinavian and arctic regions

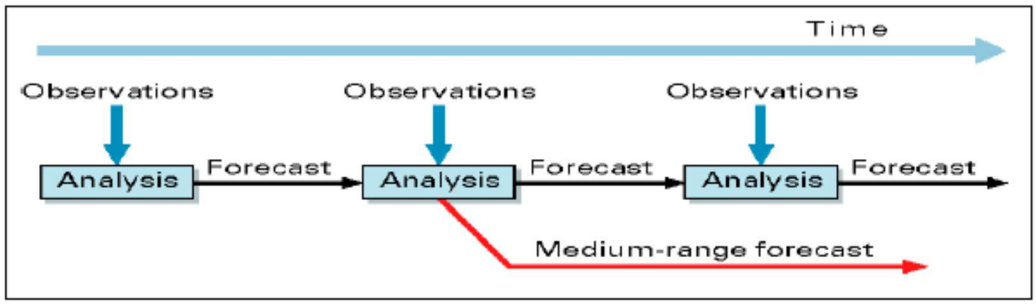

Figure 5 The updating cycle for the operational NWP model at MET.

MET has a 24/7 forecasting service always prepared to communicate with the public. Yr.no, both the app and the web-site is a successful platform for communication forecasts to the public, and is used in Norway and worldwide. For professional clients HALO (https://halo.met.no).

MET runs the national database for meteorological data and is also responsible for operating the monitoring network. Most recently the observational data from "Statens vegvesen" is included in the database

Forecasting services at NVE include several natural hazards, i.e. floods, landslides, slush slides, rockfalls and avalanches. All services are based on weather forecasts provided by the meteorological institute and are published at http://www.varsom.no/ and www.xgeo.no. The flood forecasting is based on a set of lumped catchment model HBV and DDD running on time resolution of 3 and 24 hours. The landslide forecasting is based on a moisture index from a gridded (1km) HBV model whereas the avalanche forecasting is based on the SURFEX/CROCUS model.

NVE runs the national database for hydrological data and is also responsible for operating a monitoring network of streamflow, water temperature, groundwater, soil moisture and measure mass balance for selected glaciers.

3.3.2 Climate services

A new service under development by NVE, MET and the Bjerknes Center is the Norwegian climate service centre (KKS) (https://klimaservicesenter.no/). The center aims to provide hydrometeorological data that can be used by public services for adapting to expected climatic changes, or for further research on climate change impacts on nature and society. Important products include "climate profiles" on a county level that include assessments of changes in extreme precipitation and floods. The service is relatively new, and the amount of data is expected to increase in the following years.

The services provided by KSS builds on a chain of hydro-meteorological models that include (i) outputs from global circulation models (GCMs), that are used by (ii) regional models for downscaling to a higher spatial resolutions, followed by (iii) stochastic downscaling/bias correction before the outputs are used in (iv) hydrological models in order to assess the climate change impacts on the water cycle.

3.3.3 Research topics and models

Table 6 summarize the different types of models applied to hydro-meteorological modelling tasks that are currently used at the institutions. This includes hydraulic models

(MIKE, HEC-RAS, SSIM) that model open channel flows, hydrological catchment models (HBV, DDD, GR4J, WASMOD, KiWa) that focus on the precipitation-runoff relationship, land-surface models (e.g. VIC, SURFEX / CROCUS, NOAH) that focus on the land-surface atmosphere interactions and numerical weather models and their different land surface parameterizations (e.g. WRF, AROME, NorESM) that model the energy and water balance on land surface and in the atmosphere.

The models used in operational forecasting include AROME (for meteorological forecasts) and HBV, ODM, DDD, (for streamflow forecasting) and SURFEX/CROCUS (for avalanche forecasting). The model chain for developing climate services include NorESM (GCM model), WRF, HARMONIE (dynamic downscaling), ESD (Statistical downscaling) and HBV (hydrology). The HBV, ODM and DDD are developed internally at NVE. AROME, SURFEX/CROCUS and HARMONIE is based on co-development at European meteorological institiutes (http://hirlam.org/). NorESM (http://folk.uib.no/ngfhd/EarthClim/) is developed by UiB, UiO and Met-Norway building on Community Climate System Model (CCSM) and Community Earth System Model (CESM) projects operated at NCAR. WRF (http://www.wrf-model.org/index.php) is a community based model used for both research and operational forecasting.

Table 7 below lists important research topics that are covered by the different institutions. Note that this list is not complete or following international standards of topics, but reflects the input given at the seminar. We see that there is a high focus on modelling activities at all parts of the water cycle from precipitation to cryosphere, soil moisture, evapotranspiration, groundwater and runoff.

Table 6 Summary of hydrological and meteorological models used in Norway.

Name	Model type	Users
HBV	Hydrological distributed and catchment model	NVE/UiO/NTNU
DDD	Hydrological catchment model	NVE
GR4J	Hydrological catchment model	NVE
KiWa	Hydrological catchment model	NVE
WASMOD	Hydrological gridded and catchment model	NVE/UiO
VIC	Land surface model	NVE
HEC-HMS	Hydrological distributed and catchment model	NVE
COUP	Point scale model	NVE
WRF	Numerical atmosphere model	NVE/UiO/UiB
SURFEX/CROCUS	Land surface model	NVE/MET/UiB
HEC-RAS	Hydraulic model	NVE
Mike 11	Hydraulic model	NVE
ODM	Modelling platform for hydrology	NVE
NorESM	Coupled land-ocean-atm climate model	UiB / UiO/MET
WRF-Hydro	Coupled atm-hydrology model	UiB
WRF-Chem	Numeric atmosphere model	UiO
ICAR	Simplified numeric atmosphere model	UiB
Harmonie climate	Numeric atmosphere model	MET
AROME	Numeric atmosphere model	MET/UiO

REGCM	Numeric atmosphere model	UiO
CLM	Land surface model	UiO
NOAH/NOAH-MP	Land surface model	NVE / UiO/UiB
SWMM	Urban hydrology	NMBU / NTNU
MIKE-SHE	Gridded hydrological model	NMBU
ENKI	Hydrological modelling platform	SINTEF
SHyFT	Hydrological modelling platform	Statkraft/NTNU/UiO
SSIIM	Hydraulic model (CDF-code)	NTNU
LISEM	Hydrological and sediment model	NMBU
FLEXPART	Lagrangian atmospheric trajectory model	UiB/UiO
ESD	Empirical statistical downscaling	MET
DEBAM	Distributed snow and glacier energy balance	UiO
CRYOGRID	Land surface model	UiO

Table 7 Summary of research topics covered by the different institutions in Norway.

	UIB	NTNU	MET	NVE	UiO	NMBU
Atmospheric climate	X		X		X	
Evapotranspiration	X		X	X	X	X
Groundwater hydrology	X	X		X	X	X
Soil moisture / vadose zone			X	X	X	X
Urban hydrology		X		X		X
Freshwater ecology		X				
Agricultural hydrology						X
Precipitation – modelling	X		X		X	
Ice sheet modelling	X	X	X		X	
Catchment modelling		X		X	X	X
Glacier reconstruction	X				X	
Statistical downscaling	X		X	X	X	
Glacier remote sensing	X			X	X	
Snow remote sensing	X			X	X	
Precipitation – observation	X	X	X		X	X
Glacier – observations	X			X	X	
Landslides		X		X	X	
Avalanches	X		X	X	X	
Erosion and sediments		X		X		
Renewable energy	X	X	X	X	X	
Flood reconstruction	X					
Hydropower hydrology	X	X		X	X	
Droughts				X	X	
Floods	X	X	X	X	X	x
Data assimilation		X	X	X	X	
Isotope composition	X					

3.3.4 Research infrastructure

The research infrastructure might divided into (i) the national meteorological and hydrological observation network operated by MET and NVE respectively (ii)experimental sites with detailed instrumentations and (iii) equipment and laboratories that is used in connection to field campaigns. The national network will be an essential part of both research and operational activities, is well known and documented. In the seminar, focus was on the two latter points.We start to describe the experimental sites.

3.3.4.1 Experimental sites

Skuterud test catchment (4.5 km^2) (Figure 6) with the sub-catchment Gryteland (0.27 km^2) is suited close to the Ås campus and has been monitored since 1993. Several weather variables as well as runoff is measured as well as soil moisture, snow cover and soil temperatures. This study catchments has been used in several research projects coordinated by NMBU and/or other institutes located as the NMBU campus. More details are given here:
http://www.bioforsk.no/ikbViewer/page/prosjekt/tema/artikkel?p_dimension_id=18844&p_menu_id=18851&p_sub_id=18845&p_document_id=47155&p_dim2=19697

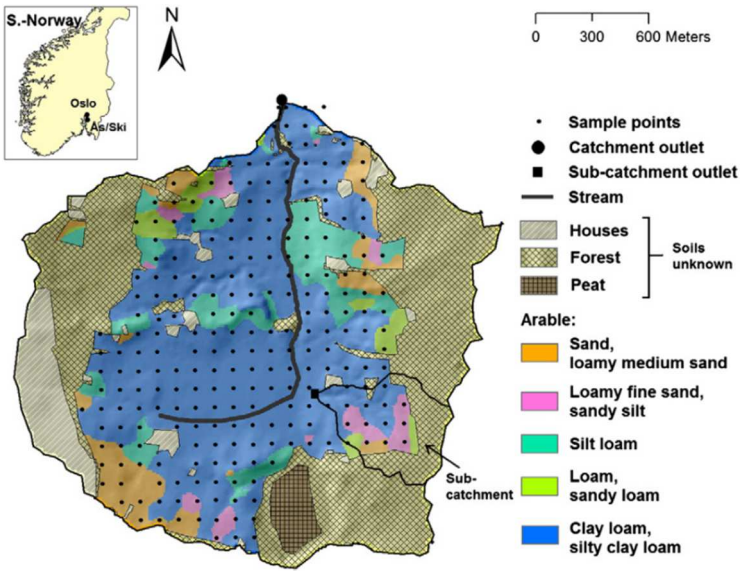

Figure 6 Map of the Skuterud catchment.

Risvollan Urban hydrological site (Figure 7) was established in 1986 and is operated by NTNU, NVE and Trondheim municipality for studies on urban drainage in cold climate. The catchment has Continuous recording of climate, snowmelt, storm, and waste water discharge with one-minute temporal resolution. Several precipitation gauges are installed including a disdrometer and a MRR. Field observations of snow water equivalent and snow covered area is also collected**.** More details are given here:
https://www.ntnu.no/ivm/risvollan

Figure 7 The Risvollan urban catchment operated by NTNU, NVE and Trondheim municipality.

Sagelva test catchment (9.16 km^2) (Figure 8) is located in the forest outside Trondheim and has been measured since 1969. Several weather variables, runoff and snow is monitored, and there are additional data from specific field campaigns available. More details are given at https://www.ntnu.no/ivm/sagelva. Data from the catchment has been used in several Master and PhD projects.

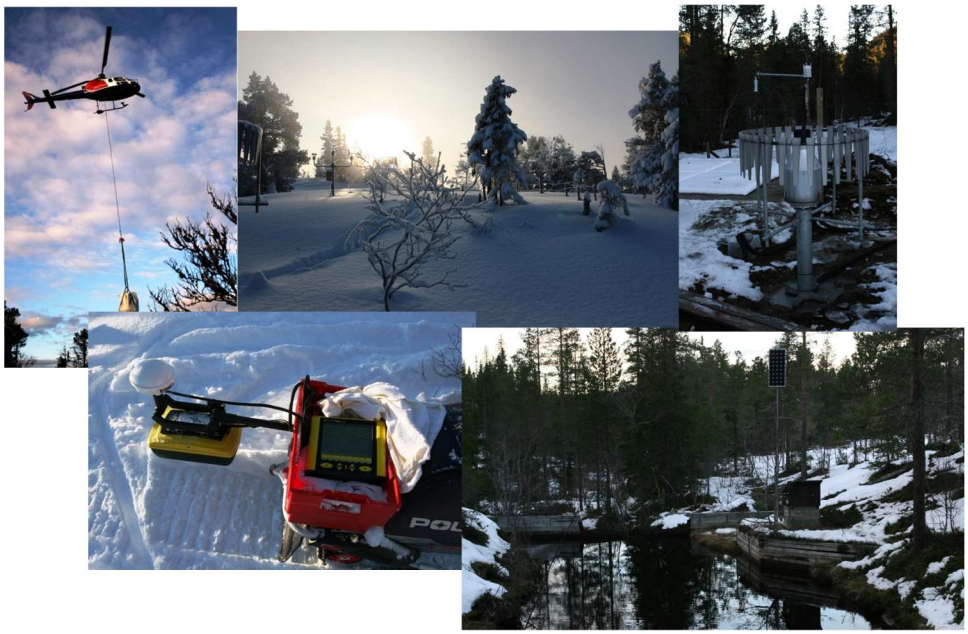

Figure 8 The Sagelva catchment located near to Trondheim and operated by NTNU.

Finse Alpine Research Center (Figure 9) is the selected site for installing the LATICE infrastructure (see section 3.5). The instrumentations for collecting data on land surface – atmosphere interaction infrastructure includes a central 10 m. climate mast (ra MET Norway reference station) extended with eddy-covariance equipment for flux measurements,, a portable Eddy-Covariance system, and a distributed wireless sensor network for climate data. The distributed wireless sensor network consists of an array of small distributed lightweight towers and communications equipment. All devices connected to the system will have access to telemetry for dissemination of data in real-time. The primary components of the system include (installed fall 2016):

1) A 10 m. mast instrumented for CO2 and H2O flux measurements.

2) A portable flux system (tripod based) for use on campaigns and for calibration and inter-comparison with the tower on a regional scale.

3) A wireless sensor network for distributed hydrometeorological and snow depth observations.

The same location there has been studies on permafrost (soil temperatures) and glacier dynamics and water balance and in 2016 also two discharge stations were installed, one in Finseelva and one in the river draining the Midtdalsbreen glacier (collaboration with NVE and UiB). The location is also used as a destination for field excursions for students. More details are given on http://www.mn.uio.no/latice

Figure 9 High resolution measurement infrastructure at Finse alpine research station, including a Flux tower (LATICE Flux), two discharge stations, seven WSN (wireless sensor network for hydrometeorological data) and ablation stakes for snow (installed fall 2016).

3.3.4.2 Equipment and laboratories

Hydraulic Laboratory is operated by NTNU. The surface of the laboratory is ca. 800 m2 . It used for running physical hydraulic models. The building has 3 hydraulic flumes, a workshop, total pump capacity of 800 l/s from a total head of 7m, 5 ADV vectrino + 2D

Laser sheet PIV, Distance laser, Sieve machine, Drying cabinet. For more details see: https://www.ntnu.no/ivm/lab/hydrauliske.

Field equipment at NTNU includes 2 Vectors, 1 hand-held ADV, 1 multi frequency ADCP, 1 single frequency ADCP, 3D terrestrial laser, Sediment traps / plates, 2 Freeze core sets, 1 Kayak for ADCP, 1 Motorboat & 1 snow scooter, 1 remote controlled boot for 2 m/s water velocity, 1 remote controlled submarine robot , 1 echo sounders, 2 echosounder with sidescan sonar, Suspended sed. Measurement device LISST SL & LISST 100.

EarthLab (Earth Surface Sediment Laboratory) is operated by UiB. Facilities for preparation and investigation of sediment samples and includes a wide rage particle size and characterization measurements as well as core scanners (CT-scanner, hyperspectral-scanner, DigiSizer, Particulate System, FlowCam, CoreWall and LIDAR-scanner). More details here: http://www.uib.no/en/earthlab

MetLab (Meteorology Laboratory) Radiation Observatory (1952-> Rain Radar Microwave temperature profiler Hot Plate Distrometer SUMO (Small Unmanned Meteorological Observer) Micrometeorological Energy Balance Stations Automatic Weather Stations Rain gauges (tipping-buckets) Eddy covariance system for moving platforms. For more details see: http://www.uib.no/en/rg/meten/53342/field-instrumentation.

FARLab Facility for advanced isotopic research for analysis of weather, climate, hydrology and biogeochemical cycling. For hydro-meteorology the isotope analysis might help explain the origin of the water in precipitation and river runoff. Examples of applications are

- Meteorology: Physical processes in the water cycle
- Glaciology: Moisture budgets of glaciers
- Hydrology: Water reservoir estimation
- Oceanography: Separation of freshwater contributions
- Paleoclimatology: Fluid inclusions in stalagmites

For more details see: http://www.bjerknes.uib.no/artikler/laboratorier

3.4 Research challenges

3.4.1 Data and infrastructure challenges

There is a need for new types of measurements that (i) fill gaps in the observations of the hydrological cycle (ii) have a high resolution in order detect the temporal variability at all time scales. Today no complete observational testbeds for hydrometeorology is available. In particular, direct measurements of evapotranspiration, i.e.by a Eddy-covariance tower, is until now missing in Norway (with the installation at Finse there is since September 2016 one such flux tower in Norway, and another one in planning at a forested site in southern Norway). This measurements will be essential in order to close the energy, and water balance based on measurements. Measurements of all components of the energy balance, e.g. radiation, is limited and should be improved.

Below the land surface more groundwater level (and soil moisture) measurements are needed in order to understand better the ground water recharge and the interactions between groundwater, rivers and lakes. A major challenge when measuring sub-surface hydrology, is the relatively large spatial variability that is not easily covered by a monitoring network, rather campaign measurements can be useful.

For urban application and small catchments (e.g. flood forecasting and prediction of design values) there is a need for measuring runoff and precipitation at a high temporal resolution. Today, there is a limited observation network for hourly (and sub-hourly) precipitation measurements and a limited amount of runoff data in small and/or urban and semi-urban catchments.

Measurements campaigns that are carefully designed in combination with model development could make it possible to develop and evaluate new model hypotheses. This requires a close co-operation between model developers and field hydrologists and meteorologists.

Finally, infrastructure for sharing both data and results from models (model data) is needed, both for researchers and for specific end-user needs. See section 3.4.5 for more discussion

3.4.2 Analysis challenges – water cycle in current climate

There is a weak momentum in coupled hydrometeorological modelling. We need a comprehensive 'earth system model' where the interactions between land surface and the atmosphere is accounted for. For hydrology it is essential to link land use and water balance. Some applications that could benefit from this is:

- Consistent water balance maps for Norway (precip., evap., runoff).
- Spatial variations in precipitation – understanding the orographic effect on precipitation.

For analysing and modelling the hydrological components in current climate, there is need for interpolated products of meteorological variables (i.e. precipitation, temperature, wind, radiation, humidity) that useful for climate research. Important challenges is to keep consistency between these variables and to make the interpolated products robust with respect to changes in the observational network (that might introduce trends and/or systematic changes in variability). We need better modelling tools for quantify hydrological effects of land use changes and measures and how they interact with variable meteorological conditions including frost.

Understanding and predicting extreme values is challenging since they are based on small samples and might be non-stationary in both time and space. Understanding non-stationarity of extremes is therefore essential for prediction design floods in ungauged catchments and for the future.

3.4.3 Forecasting

Improved flood forecasts requires improvements of (i) the resolution, (ii) data assimilation, (iii) the ensemble predictions, (iv) communication to end users.

Higher temporal and spatial resolution is especially important for urban applications. Nowcasting – forecasting the nearest 1-2 hours might become important for urban areas, and research is needed to improve nowcasting capapilities, both statistical and NWP based approaches should be considered.

For improved data assimilation, measurements and assimilation at high spatial (better than 10 km) and temporal resolution (from 1h down to the order of 10 minutes or better) is needed. To achieve this an increased use of remote sensing data, especially surface data (soil moisture and vegetation, snow, sea ice, lakes) is needed. We also need to introduce more sophisticated surface analysis algorithms like Extended/Ensemble Kalman Filter assimilation systems for various surface types and aim for a Coupled DA. In order to utilise satellite data in an optimum manner, we need to evaluate and correct systematic model errors. Data assimilation needs handling and dissemination of a large amount of data. Also for the hydrological forecasting there is a potential for improvement of forecast by looking for new methods, tools and data for merging (assimilating) observations into models, especially streamflow and snow observations.

Ensemble predictions at a higher spatial resolution, i.e. mesoscale, is needed in order to capture the limited predictability on small scale an accurate representation of the surface is of critical importance. The Arome CoOp model setup will provide a limited number of ensembles. For the flood forecasting there is a need for improvements in Ensemble predictions and in particular post-processing of spatial-temporal fields.

Presentation/communication of forecasts and warnings should be based on appropriately presented probabilistic forecasts lead to better decisions. Multiple representations (text, numbers and graphics) of the same evidence may be needed. User interpretation depends on a wide variety of factors

3.4.4 Climate change – interactions and impacts

Climate change impacts on the spatial and temporal variability of water is challenging since information is needed at a much higher spatial resolution than the climate and regional downscaling models currently achieve. For assessing impacts of climate change on the hydrological cycle there is still a need for bias correction and downscaling. The dynamic downscaling has still too coarse resolution (computer power). We therefore need collaboration between dynamical and statistical downscaling. All downscaling approaches, especially statistical downscaling, need good reference datasets for evaluation. The statistical approaches are challenging, both in terms of keeping the internal consistency between the different variables, being able to represent the extremes, and finally the stationarity of downscaling is hard to verify.

For investigating climate change impacts, we need to improve our understanding of land use change impacts on the hydrological cycle including extremes. There will be changes in snow storage, glaciers are melting, and vegetation and the human use of land surface is changing. We need to understand the interactions between these dynamic land use and cryosphere changes

3.4.5 SAK challenges

Important challenges related to national collaboration and coordination on the national level included:

- There is a too weak momentum for coupled hydrometeorological modelling, and no clear plan for a national regional hydro- meteorological modelling system.
- The meteorological and hydrological observation networks could be better coordinated.
- Concerning field experiments and data access there are no really good observational testbeds. In addition national information on measurement capabilities and coordination and storing of field campaign data could be improved. We need metadata at a national level describing which data are available, where and how to get them.
- Storage and sharing of data is challenging. Universities often do not have a good system for storing data, so maybe a national database could be used. Simple automated access to hydrological data still a problem.
- Our special competence depends on few people. Stronger national and Nordic collaboration is needed, and it is difficult to get knowledge of who is doing what. There is potential in improved collaboration within and between institutions, e.g. at UiB, there is a weak connection between paleo people and meteorologists. Another challenge is the collaboration between R&D and the services delivered to the society, e.g. «Climate services».
- Computer power is a challenge in earth system modelling.
- Access to long-term research funding. Climate research is mostly financed though relatively short-term projects (~3 years). For hydrology, the relevant research programs are FRINATEK, EnergiX Klimaforsk and Miljø2015, and the challenge here is that hydrology as a subject by itself seldom is the focus of the call, rather it feeds into specific applications.

3.5 Collaboration, share of work and concentration (SAK)

Adjunct positions: Both NVE and MET has bilateral agreements with Department of Geosciences at UiO on co-funding adjunct position within hydrology and meteorology. Currently UiO has two adjunct research positions (20%) with NVE as main employer and to professor II with MET as main employer. These positions are co-funded by UiO and NVE/MET.

Joint supervision of PhDs and masters: UiO, MET and NVE has cooperated on joint supervision of both master and PhD Students within hydrometeorology. UiB and UiO has cooperated on joint supervision of masters.

Internal resources. LATICE (Land-ATmosphere Interactions in Cold Environments) is recognized as a strategic research area by the Faculty of Mathematics and Natural Sciences at UiO. LATICE aims to advance the knowledge base concerning land atmosphere interactions and their role in controlling climate variability and climate change at high northern latitudes. The research group is hosted by the Department of Geosciences and the most of the researchers comes from the department, but also

researchers from the Department of Informatics and The Natural History Museum at the UiO participate in this interdisciplinary research group.

NVE provides resources for internal research and innovation projects based on an evaluation of internal project proposals. Some of the funding might be given to other institutions.

UiB is the major funder of EarthLab (Earth Surface Sediment Laboratory), MetLab (Meteorology Laboratory) and FARLab (Facility for advanced isotopic research). See 3.3.5.2 for details and is together with MET funding parts of the NorESM (Norwegian Earth System Model) development.

MET-NVE cooperation on forecasting of hydro-meteorological hazards. The models, tools and services related to forecasting of natural hazards is continuously improved. Each year plans for this activity is defined. Until now the focus has been on (1) improved precipitation interpolation (2) improved forecasts and (3) use of radar for estimation of precipitation.

Research and in innovation projects funded by European commission, the Research Council of Norway, and private companies (especially the energy sector), public institutions is a major framework for creating co-operation within and between institutions. Table A3 lists recent and ongoing projects with important partners whereas Table A4 provides an overview over institutions that are co-operating. E.g. for NTNU has CEDREN been a major framework for co-operation.

4 Report from Word Cafe Method discussion

The group discussions were organized by an adaption of the word café method. For each session, four questions were prepared and presented at flip-overs located in four corners of the room. For each flip-over we assigned a reporter responsible for guiding the discussion and for reporting. The participants were divided into four groups. The groups circulated along all flip-over stations and got 10 minutes for discussing each question. At the end, the reporters summarized the group discussions in plenum, and after the seminar the reporters provided a brief written summary for each question. These reports are given in the following sub-sections.

4.1 Group discussion 1 – Combining models and data

Summarized by Elin Langsholt (NVE)

Question: What are good ways for combining models and data for
(i) consistent data control
(ii) testing model hypotheses?

Many of the discussions circulated around the “holy grail” – model, a model that is unified in time and space and covers the full hydrometeorological system. Assuming the existence of such an ideal model, any data representing different states of the system, at

any temporal and spatial scale would have their counterpart in the model and, thereby be candidates for data assimilation. Important topics in this context were:

- availability of many different types of data should be strived for
- various types of data, representing different system states, other than the model output, are "anchor data". By assimilation, the model is hooked to different parts of the system, approaching a unified nature
- in a well-defined system model, assimilation of state variables can correct model output and characterize the error
- models that combine the meteorological and hydrological system should be preferred
- take advantage of the different scales of the data, e.g. the integrated nature of the stream flow vs. the point nature of the precipitation and temperature measurements. What does a point represent?
- models should be seamless, and tested on data of different scales, from urban short-term to river system scales
- Ranking: which variables are the most decisive?

The discussions also addressed the challenge to enhance data availability and creating a common data center, which is easy to use. The data center could be based on extending existing national databases (eKlima, Hydra II) or new Data Service Center. Important topics in this context are:

- standard formats
- quality controlled data
    - should be non-subjective
    - data should be tagged, according to quality/uncertainty
    - corrections must be documented
- well documented
- both data and model/algorithm tool box?
- Establish a common test bench
    - East – west, north – south, small – big
    - common reference data for identifying which model is better
    - models should be tested on the most uncertain catchments/regions

A special challenge is design of data collecting campaigns and the later use of the data:

- all relevant parts should be informed and given the opportunity to participate
- data from campaigns should be taken properly care of, for later use

Finally it is important to identify the need for new data as a part of the national monitoring network of hydrometeorological variables. Important topics then are:

- more stations, representing all regions
- high resolution data in urban catchments
- long time series
- coordinated collection of precipitation, temperature, and discharge data

4.2 Group discussion 2 – Recruitment of graduated students.

Summarized by Stein Beldring (NVE).

Question 1: What are the key competencies institutions are looking for when recruiting staff?

Candidates must possess the theoretical skills that allow them to understand, analyze and predict the behavior of the land-surface-atmosphere system. They should also have high q ualifications in numerate disciplines, e.g. mathematics, physics, statistics or chemistry. For research positions it is imperative that candidates are interested, curios and take initiative in research topics in order to bring science forwards. Innovative skills and understanding of earth system processes are also required in positions where the candidate is to be responsible for operational work, but technical skills, e.g. computer and instrument skills may be equally important. Both for research and operational positions candidates must be able to convert processes to practical solutions, i.e. implementation of theories and methods in computer programs.

It is essential to be able to work as a member of a team where the combined results of the entire group are in focus.

Experience with communicating results to the public, stakeholders and media is necessary.

Documented scientific merits, e.g. academic degrees, publications, research experience, experience in tutoring and education are essential for candidates to research positions. For recruitment to PhD student positions it is necessary to consider qualifications in communicating research results as there will often not be any documentations of scientific merits. Experienced candidates must be able to formulate research questions, theories and models in a realistic manner that moves science forwards, write research project applications and lead research projects, while less experienced candidates must have the ability to acquire these skills.

Question 2. How much training is required after recruiting?

Training depends on type of position. If the candidate is expected to work as a researcher without responsibility for operational applications or forecasting the skills in theoretical, experimental and laboratory work as a scientist will have to be developed as part of the daily tasks, participation in projects, seminars, workshops and conferences. This training will necessarily have to take place as long as the candidate is engaged in research. For PhD students and other staff in recruitment positions it will be necessary to follow courses with topics that are relevant to the expected outcome of the research, either at the university where the student is obtaining the PhD degree or at other universities, research schools and seminars.

For candidates that are to be engaged in operational positions there should be training in the required procedures, e.g. data processing procedures, evaluation of results from forecasting models, decisions on when to issue forecasts, communication of results to media, authorities and the public. This training may be arranged as formal courses, but for most institutions in Norway it will require too much resources to develop and maintain a course program for a limited number of candidates. It is probably better to train the candidates in daily work with an experienced colleague as tutor.

Experts in a science should train in implementing results of their work. This can be in cooperation with an experienced tutor already engaged in similar procedures or the computer/technical staff that are responsible for maintaining the operational procedures.

The ability to be engaged in communication of results is another important field of training. This could be in the form of courses in case of media training, while training in communicating results to stakeholders can be undertaken when the inexperienced candidate is participating at meetings where experienced colleagues inform stakeholders and the public about research results.

4.3 Group discussion 3 – Recruitment of new students

Summarized by Elin Langsholt (NVE)

Question: How can we better recruit students?
- *by reaching out to the public*
- *by reaching out to secondary schools*
- *creating interest*
- *explaining which qualifications are needed after coming to university*

For recruitment from secondary school it is important to explain which qualifications are needed after coming to university. In particular, the geosciences subject in secondary school (the books used) gives a wrong impression of what geosciences are. The subject is heavily biased towards descriptive geography, and excludes the physical aspect. Geophysics should be included in the physics subject, to communicate the physical basis of geosciences, and to reach out to theoretically oriented students

In order to make geosciences visible for undergraduates in universities we might (i) participate when opportunity knocks, e.g. when schools arrange job fairs (ii) participate in programs, e.g. "Rollemodell", arranged by "Nasjonalt senter for realfagsrekruttering" (iii) make interesting arrangements for undergraduates, like "researchers night" at NTNU (iv) include undergraduates in processes suitable for that, like field campaigns, excursions etc. (v) invite teachers to continuing education e.g. field excursions. Important points to communicate to undergraduates are that geosciences is needed to meet important society needs, like climate change, geohazards etc. and that you may find a good and well paid job within geosciences. It will also help to introduce geosciences early at the universities e.g. by defining broad bachelor programs, that includes introductory geosciences topics together with e.g. physics, to catch students' interest early in the study course or like UiB, write a letter to all new students, that invites/introduces them to geosciences.

In order to recruit from other disciplines, geoscientific problems should be communicated to computer scientists, mathematicians and physicists, to bring in such experts at PhD-level.

4.4 Group discussion 4 – Linking basic research and operational applications

Summarized by Jørn Kristiansen (MET)

Question 1: How can we improve interaction between operational application and basic research?

Interaction between operational application and basic research might be improved by increasing collaboration on PhD and Postdocs between Met/NVE (operational applications) and Universities (basic research); combining basic research and operational applications in projects. There are journals dedicated to model development research (e.g. special issues such as for NorESM), and such papers could also be included in a PhD. Improved interactions requires (i) (more) operational thinking at the universities, (ii) that the operational environment becomes closer to the research front, (iii) that the operational application needs must be communicated, and (iv) that a well-defined operational production chain with preoperational suites is established.

A way to improved interaction is the use of common data in studies. This requires easy, open access to data (real-time and archive), searchable metadata, robust and reliable (e.g. SLAs) infrastructure and access control (to restricted/internal data, services and products). This would trigger curiosity and potentially be a starting point for initiative to collaboration.

On the technical side, it is important to employ common coding standards, easy-to-use models (e.g. SURFEX), and tools and benchmarking/repository.

Finally, training recourses at Met/NVE (e.g. annual training schools ala ECMWF) could educate students in good coding practices and computer science/super computing, implementing tools and develop “open” platforms (e.g. ENKI/Shyft).

Question 2: Do you have success stories on collaboration / best practice?

There are already several success stories. MET, NVE and UiO collaborate already, including co-supervising, on PhD and Postdocs. There are several common projects, both research projects and more operational projects, within hydrometeorology. This HYDMET seminar and other seminars / workshops / meetings aiming at communication between researchers. E.g. Met and UiB met to discuss, exchange ideas and establish personal relationships.

Question 3: What are the bottlenecks for collaboration?

Important bottlenecks are (i) an "imbalance" at universities between learning and producing (applied) results (ii) ambitions and requirements differ between academia and operational applications, (i.e. could operational application give credits at universities?). (iii) we compete for the same funding resources. (iv) we use different models, software and hardware.

4.5 Group discussion 5 - Hydrometeorology in teaching

Summarized by Frode Stordal (UiO)

Question: How can integration of hydrometeorology be implemented in teaching (university)?

The integration of hydrometeorology in teaching can mainly be implemented by better design and interactions on teaching in courses. Firstly, there is a potential for improved coordination of teaching at the national level. A first step is to share information about courses between universities. Then it might be a potential for increasing the mobility of both student and teachers by arranging short courses in one university that students from many universities can attend, or organise common teaching blocks that a teacher in one university can teach in several. The lecturers might also share teaching materials, and some suggestions are to (i) develop a common pool of computer codes for exercises, which can be used across disciplines and universities (ii) develop online teaching material that can be used for students to prepare before regular classes, with weight on problem solving (e.g. teaching material in wind energy FME). (iii) use multidisciplinary field sites in field work and teaching (Finse, Skuterud) (iv) develop targeted massive open online courses (MOOC) for bachelor students. (v) use researchers in the non-university institutes as guest lecturers in their field of specialty.

Potential funding sources for development: SIU (international collaboration ?), Nordic Hydrological Council, UiO/Computing in Science Education (CSE).

Shared supervision of MSc students, could take advantage of resources in the non-universities institutes, as well as letting the non-university instituted defining the research

4.6 Group discussion 6 – Climate change projections

Summarized by Chong-Yu Xu (UiO)

Question 1: What are the important research questions for climate and hydrological projections (decade to century) to be answered in the coming years?

(1) Scale mismatch between climate model's scale and hydrological need is still a remaining issue to be studied in the coming years. We need a better understanding of atmospheric and hydrological system and processes, as well as improved our modelling tools along with the improved physical understanding and better data assimilation. In particular, low accuracy of simulated extreme precipitation is to be improved.

Question 2: How do we deal with nonstationarity when predicting and estimating design values?

Nonstationarity exists in low to high order moments, in their probability distribution function, pdf, in their correlation among different processes. Stationarity and Non-stationarity is scale depended since nonstationarity in one scale may be just normal fluctuation in another. Two different modelling approaches have been followed: (1) the nonstationarity approach, and (2) the scaling approach.

Question 3: Will we need and how do we apply bias-correction?

It is well-known that climate models exhibit, systematic errors (biases) in their output due to, among others, incomplete knowledge of climate system processes and imperfection of the modelling tools. Bias correction is therefore needed. Existing bias correction methods include delta change approach, multiple linear or nonlinear regression, analogue methods, local intensity scaling, etc.

4.7 Group discussion 7 – Forecasting challenges

Prepared by Richard Moore (MET Norway, UiO)
Question: What are important research questions for forecasting (hourly to seasonal) to be answered in the coming years?
If the research community hopes to move toward seamless prediction (hourly to seasonal), there is a need to explore: (i) which information is necessary for the disparate time and spatial scales. This needs to be reflected in the ingestion of observational data (assimilation). (ii) How best to find a significant 'signal' on seasonal time scales? Is the best approach to attempt to define so-called weather regimes that can be related to sensible weather (e.g. warm/cold, enhanced precipitation/drought)? (iii) Improvement in and further use of 'nowcasting' techniques is very relevant for heavy precipitation

Improving the quantification of uncertainty (for all time/space scales) is paramount. A greater use of ensemble prediction is necessary. However, how best to approach the problem? Specifically, on short time scales / deep convection: is it better to use a dynamical EPS / statistical EPS (i.e. neighborhood methods)? Improved data assimilation techniques are needed.

Specific research areas:
• Coupled land surface / atmosphere assimilation
• RADAR for convective storms
• Improved snow cover and soil moisture data (important for both short and long time scales)
• Emphasis on fully utilizing satellite data

A better understanding of the orographic enhancement of precipitation is needed

Finally, it is important to emphasize and improve the communication of forecast data to the end users in order to mitigate damage to life and property.

4.8 Group discussion 8 – Coupling of models

Summarized by John Burkhart (UiO/Statkraft)

Question: Which strategies should we follow when coupling hydrological and meteorological models.

Coupling is not always necessary, we do not always need/want a coupled model.

A major challenge when coupling hydrological models are focused on mass balance and modelling the discharge correctly whereas meteorological models are focussed on energy balance on the land surface. In particular this is manifested in difference in the soil moisture parameterizations in hydrological and meteorological models where hydrological models us it as a "knob" to control land surface energy balance (latent and sensible heat fluxes) whereas hydrological models use it as a "knop" to control timing of mass. Coupling models requires that hydrological models move from calibration with respect to discharge towards multi-objective calibration. A coupled model might be evaluated according to the coupled covariance between model states in order to analyse the benefit of coupling. A key to coupling could therefore be to collect better observations for variables that are essential to coupling, e.g. soil moisture.

The discussions addressed the possibility to use “couplers” that are commonly applied in earth system models. The modules/sub-models are then independent and we then need a define (i) responsibilities of each module (ii) expose processes for other modules, (iii) define a common interface concerning data definitions and –formats. For this to work we need to increase data availability and derive better tools for archiving and retrieving core data. It was also asked if conceptual hydrological model have a place in a coupled system.

Conclusions

This report summarizes the presentations and discussions from the HYDMET seminar at Lillehammer in December 2015. More specifically, it provides the following answers to the questions raised in the introduction:

(i) What is the current status?

Operational forecasting and climate change projections:

- **Coupling of models**: The current practice for operational forecasting and projections is to use a “one way” chain of models, sometimes combined with pots-processing (meteorological forecasting -> processing -> hydrological forecasting -> processing).
- **Assimilation**: this is standard in meteorological forecasting models. For hydrological models, observations from water levels in the lakes/reservoirs and/or rivers, river discharge, and snow data (point observations, snow courses and satellite data) are assimilated. In Norway only snow data are assimilated into operational hydrological models.
- **Ensembles:** hydrometeorological ensembles combined with post-processing are used for operational forecasting. In Norway hydrological ensembles are, only to a little degree, used in operational services.
- The risk of forecasted events is assessed using a probabilistic approach that also include a subjective analyses (human expertise) both for flood forecasting and for dam operators.
- **Addressing the needs from society:** Major flood events has initiated improvements of flood forecasting services. The hydropower industry also needs reliable forecasts. The Norwegian climate service centre is established for providing climate change information to end-users.

Ongoing research collaboration, projects, and research infrastructure:

Ongoing research collaboration is based on both internal and external funding. The external funding is for research programs, industrial partners and public institutes. For NTNU, CEDREN has been a major framework for projects related to hydropower and environmental consequences of changes in runoff-regimes. For the coming years Klima2050 (urban hydrology) and the Norwegian hydropower center, will be important.projects. For UiO, LATICE is currently the main framework for co-operation. External funding of research projects are mainly through EnergiX or Klimaforsk.

There are four hydrological test sites Sagelva (Forested), Risvollan (urban), Skuterud (agriucutural landscape) and Finse (alpine) that cover different land surface and climates. In addition there are observational and laboratory facilities. The hydraulic laboratory is operated by NTNU, EarthLab (Earth Surface Sediment Laboratory), MetLab (Meteorology Laboratory), and FARLab (Facility for advanced isotopic research) are operated by UiB. In addition equipment for field campaigns are available at all institutes.

Bachelor and master programs in hydrometeorology.

The overview shows that both UiO and NTNU provide extensive curriculums in hydrology. UiO focuses on process understanding and advanced modelling tools (physical based and stochastic), whereas NTNU focus on hydraulic, hydropower, water supply and drainage systems. At NMBU an introductory courses is given in hydrology, followed by two more advance courses in hydrogeology. Similar, in Bergen only a few courses are given, covering karst hydrology, hydrology/groundwater and glaciology. The overview shows that there is not extensive overlap in hydrology courses, and that **c**oordination on the national level is therefore currently not a major issue, but should be kept in mind in future revisions.

The overview shows that both UiO and UiB provide extensive curriculums in meteorology, whereas At NMBU two courses in meteorology are given, including on in micro-meteorology. Coordination on the national level is currently not a major issue, but should be kept in mind in future revisions.

(ii) What is the potential for improvement and key research challenges?

Figure 10 summarises the key research challenges and their relationship, and below each component are described in more details. In addition, in Appendix 3, suggestion for a large integrated R&D project on hydrometeorological forecasting and climate projections aiming for flood risk reduction, renewable energy production and water resources management is suggested. The project suggestion was carried out as a post-conference task asking from contributions from all participants.

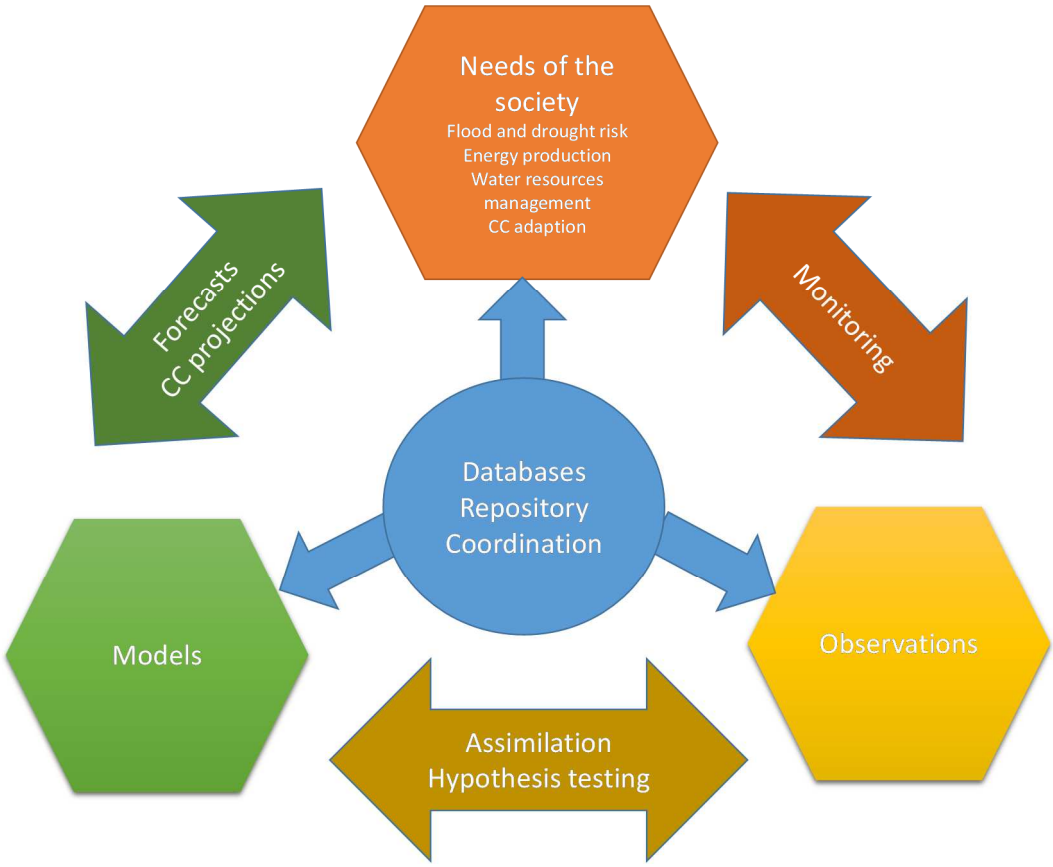

Figure 10 An overview over key research challenges in hydrometeorology and the needs fof the society.

Observations

Observations are used both for: (i) monitoring the state of the weather and components of the hydrological cycle that together with models provide an analysis or "best estimate" of the current state, and (ii) evaluating models and testing of hypotheses.

The national meteorological and hydrological observation networks are used for both (i) and (ii). In addition, there is a need for hydrometeorological test beds aim to measure the complete energy balance and water fluxes between the land-surface and the atmosphere (e.g. atmospheric moisture fluxes, profiles of temperature and moisture, evapotranspiration, precipitation, radiation, temperatures, etc) using a range of platforms and sensors covering point to regional scales. These testbeds will be complementary to the observation network. Maintenance and expansion of existing sites established for process studies in different environments (from urban to mountain and arctic) must have high priority in order to provide high quality data and time series for both (i) and (ii). Establishment of complementary sites in different land-uses and climates and temporary sites for specific studies is important. At the larger scale, increased accessibility to private meteorological stations and use of citizen data is a mean to achieve better coverage of meteorological data, but also better coverage of hydrological observations are necessary to reduce uncertainties and hydrometeorological risks in ungauged areas.

Maintenance of existing and establishment of new hydrometeorological testbeds where the complete water and energy exchange is observed requires for long-term strategies, funding and co-operation on sites.

Models

Model structure and setup: Physical properties (e.g. topography, vegetation, and soil type) generally show high spatial variability and thus large heterogeneity in system behaviour. In addition, river basins can often be strongly influenced by human activities, such as irrigation, hydropower production, and groundwater use, for which information is rarely available at high resolution in available (open) databases. This introduces additional uncertainty regarding process understanding and description. Moreover, the topographic and setup data of open datasets (i.e. water divides, weather and climatic data) are more likely to be inconsistent, erroneous, and/or only available at a coarse resolution.

Model parameterizations: The core of the models is the parametrization of processes, and several processes need special attention including (i) precipitation and its spatial and temporal variability, (ii) vegetation dynamics and interaction with the hydrometeorologicals system (iii), cryospheric processes (iv) Evapotranspiration and energy balance in cold environment (v) soil moisture zone and groundwater processes. (vi) runoff, (vii) integrated hydraulic models for lakes and rivers.,(viii) urban flooding and drainage (that requires high space and time resolution)

Coupling of models Most models applied address a subset of the earth system, and working on a common modelling platform might facilitate co-operation across several disciplines. There are several strategies to follow, either a unified model or an earth system model based on couplers that links models for different sub-systems. For a complete earth system model, computing time and available data resources are a limitation, Resolution / uncertainty / complexity / -> what is the priority?

Implementation and availability of models: To increase the value to the society of model development there need to be strong linkages between models used for research, education and operational use in governmental organizations and in the society in general. Common platforms for models and communication with users increases the relevance and actuality of model development. Research, teaching and education on models applied outside academia reduces time to market of innovations in PhD's and research projects.

Assimilation and hypothesis testing

Observations used for assimilation into models in order to providing best predictions of hydro-meteorological variables in space and time. There is a potential to assimilate more data into models, in particular snow data, soil moisture, river discharge, lake levels, and land-use/vegetation. This might require improved assimilation algorithms and better representation of observations in the models.

Forecasting and CC projections - tailoring to end-user

Forecast and climate change projections should be given as probabilistic forecasts (when appropriate) that in the end will lead to better decisions. There is still a need for post-processing/downscaling/bias-correction of models, and methods that keeps the

consistency between variables across space is still needed, and such methods requires a high quality monitoring network.

Databases, repository and coordination

There is need for better coordination and integration of model development and implementation. Sharing and integrating models requires a administrative system for managing the code, common coding standards, and quality control, and documentation (metadata).

(iii) How do you facilitate collaboration, division of responsibility, and concentration (SAK) within your own institution as well as with cooperating institutions?

- Internal resources are used for supporting strategic research areas. Such initiatives include LATICE at UiO, internal research funding at NVE and EarthLab, MetLab and FARLab at UiO. UiB and MET funding parts of the NorESM development
- Both NVE and MET has bilateral agreements with Department of Geosciences at UiO on co-funding adjunct position within hydrology (2) and meteorology (2).
- NVE, MET and NVE has cooperated on joint supervision of both master and PhD Students within hydrometeorology. UiB and UiO has cooperated on joint supervision of masters.
- MET and NVE cooperates on forecasting of hydro-meteorological hazards. The models, tools and services related to forecasting of natural hazards is continuously improved.
- Research and in innovation projects is a major framework for creating co-operation within and between institutions.
- The CHESS research schools is used for creating national courses and a network for PhD students.

(iv) Which topics should be given greater emphasis in teaching?

The integration hydrometeorology in teaching can mainly be implemented by better design and interactions on teaching in courses and by design of bachelor and bachelor programs that requires courses in both hydrology and meteorology.

There is a potential for improved coordination of teaching at the national level by (i) sharing information about courses between universities, (ii) increase the mobility of both student and teachers, (iii) share teaching materials and computer codes for exercises, which can be used across disciplines and universities.

Students should have high qualifications in numerate disciplines, e.g. mathematics, physics, statistics or chemistry and possess computer and instrument skills. Common platforms for programming should be emphasized to ease exchange of code. The teaching should emphasize the combination of field studies and modelling experiments.

Master and PhD theses could to a larger degree address operational applications and use the models, software and hardware from the operational forecasting systems.

Acknowledgements

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Appendix 1 – Seminar program

DAY 1
11:30-12:00 Registration
12:00-13:00 Lunch
13:00-13:30 Opening

• Welcome - Background and aims for the seminar. (*Kolbjørn Engeland, NVE*)

13:30-15:00 Session I Solicited presentations on hydrometeorological modelling for forecasting and climate projections (30 minutes presentation + 15 minutes discussion in plenum)
Chair: Eivind Støylen (MET)

- 13:30-14:15 Martin Best (MetOffice), Organization of and research focus in hydrometeorological modelling in the UK
- 14:15-15:00 Fredrik Wetterhall (ECMWF), Ensemble modelling in hydrometeorology, challenges and benefits

15:00-15:30 Coffee break

15:30-17:15 Session 1 continues
Chair: Lena Tallaksen (UiO)

- 15:30-16:15 Maria-Helena Ramos (IRSTEA), Probabilistic forecasting for the hydropower industry
- 16:15-17:15 Patrick Samuelsson and Ilias Pechlivanidis (SMHI), Operational hydrometeorological modelling for forecasting and projections at SMHI

17:15-18:30 Group and plenum discussions inspired by the World Café method

20:00 Dinner

DAY 2

09:00-10:30 Session 2 Hydrometeorological modelling for forecasting and climate projections in Norway (20 minutes presentations, 10 minutes questions)
Chair: Elin Langsholt (NVE)

- 09:00-09:30 John Burkhart and Frode Stordal, University of Oslo (UiO)
- 09:30-10:00 Jørn Kristiansen and Anite Verpe Dyrrdal, The Norwegian Meteorological Institute (MET)
- 10:00-10:30 Stein Beldring, The Norwegian Water Resources and Energy Directorate (NVE)

10:30-10:45 Break

10:45-12:15 Session 2 continues
Chair: Chong-Yu Xu (UiO)

- 10:45-11:15 Helen French, Norwegian University of Life Sciences (NMBU)
- 11:15-11:45 Asgeir Sorteberg, University of Bergen (UiB)
- 11:45-12:15 Tone Muthanna, Norwegian University of Science and Technology (NTNU)

12:15-13:15 Lunch

13:15-14:15 Session 2 continues
Chair: Frode Stordal (UiO)

- 13:15-14:15 Group discussions

14:15-14:30: Break

14:30-15:30 Session 3 Summary
Chair: Jørn Kristiansen (MET)

- 14:30-15:15 Plenum discussion
- 15:15-15:30 Summary and closing of seminar (Nils Roar Sælthun, *UiO*)
- 15:30 End of seminar

Table A1 Participants in the seminar

Name	Institution
Stausland, Mari Tansem	Statkraft Energi
Wetterhall, Fredrik	ECMWF- UK
Ramos, Maria-Helena	Irstea – Frankrike
Skøien, Jon Olav	JRC – Italia
Best, Martin	MET Office UK
Kristiansen, Jørn	Meteorologisk institutt (MET)
Aspelien, Trygve	Meteorologisk institutt (MET)
Dyrrdal, Anita Verpe	Meteorologisk institutt (MET)
Luijting, Hanneke	Meteorologisk institutt (MET)
Lussana, Christian	Meteorologisk institutt (MET)
Moore, Richard	Meteorologisk institutt (MET)
Singleton, Andrew	Meteorologisk institutt (MET)
Støylen, Eivind	Meteorologisk institutt (MET)
French, Helen Kristine	NMBU, IMV
Engeland, Kolbjørn	Norges vassdrags- og energidirektorat (NVE)
Langsholt, Elin	Norges vassdrags- og energidirektorat (NVE)
Colleuille, Hervé	Norges vassdrags- og energidirektorat (NVE)
Engeset, Rune	Norges vassdrags- og energidirektorat (NVE)
Hegdahl, Trine Jahr	Norges vassdrags- og energidirektorat (NVE)
Lawrence, Deborah	Norges vassdrags- og energidirektorat (NVE)
Magnusson, Jan	Norges vassdrags- og energidirektorat (NVE)
Mengistu, Zelalem	Norges vassdrags- og energidirektorat (NVE)
Müller, Karsten	Norges vassdrags- og energidirektorat (NVE)
Skaugen, Thomas	Norges vassdrags- og energidirektorat (NVE)
Wong, Wai Kwok	Norges vassdrags- og energidirektorat (NVE)
Beldring, Stein	Norges vassdrags- og energidirektorat (NVE)
Lahoz, William	Norsk institutt for luftforskning (NILU)
Thorarinsdottir, Thordis	Norsk Regnesentral
Muthanna, Tone	NTNU
Kolberg, Sjur	SINTEF Energi
Pechlivanidis, Ilias	SMHI – Sveige
Samuelsson, Patrick	SMHI - Sverige
Johansen, Stian Solvang	Statkraft
Soot, André	Statkraft
Barstad, Idar	Uni Research
Sorteberg, Asgeir	Universitetet i Bergen

Name	Institution
Tallaksen, Lena M.	Universitetet i Oslo (UiO)
Xu, Chong-Yu	Universitetet i Oslo (UiO)
Stordal, Frode	Universitetet i Oslo (UiO)
Berntsen, Terje	Universitetet i Oslo (UiO)
Burkhart, John	Universitetet i Oslo (UiO)
Kristjansson, Jon Egill	Universitetet i Oslo (UiO)
Schuler, Thomas Vikhamar	Universitetet i Oslo (UiO)
Sælthun, Nils Roar	Universitetet i Oslo (UiO)
Tang, Hui	Universitetet i Oslo (UiO)

Appendix 2 – Summarizing tables

Table A2 List of ongoing PhD projects by the end of 2015

Univ.	Department	Student	Thesis	Supervision
UiO	Geosciences	Helene Erlandsen	Assessing Land-Atmosphere coupling strength in maritime, mountainous and seasonally snow covered climate using the WRF model	NVE, MET
UiO	Geosciences	Johanne H Rydsaa	Atmosphere-hydrosphere-vegetation interactions in a boreal and artic climate	
UiO	Geosciences	Kjersti Gisnås	Permafrost modelling over different scales in arctic and high-mountain environments	
UiO	Geosciences	Torbjørn Ims Østby	Climatic mass balance of glaciers in Svalbard from observations and modelling	
UiO	Geosciences	Desirée Silvana Treichler	Estimating surplus river runoff from remotely-sensed glacier mass loss	
UiO	Geosciences	Kjetil S Aas	On the representation of fine-scale atmosphere-cryosphere interactions in weather prediction and climate models	
UiO	Geosciences	Habiba Mtongori	Climate Change and the impacts to crop-agriculture in Tanzania	
UiO	Geosciences	Irene Brox Nilsen	Detection and attribution of recent changes in surface temperature in Europe (statistical and LSM-modelling approach).	NVE, MET
UiO	Geosciences	Felix Nikolaus Matt	Aerosol deposition in hydrologic models	
UiO	Geosciences	Heidrun A. Ullerud	Mapping and distribution modelling of nature types in Norway	
UiO	Geosciences	Trine Jahr Hegdahl	Uncertainty estimation for flood-forecasting based on meteorological and hydrological ensembles	NVE, MET
UiO	Geosciences	Bikas C Bhattarai	Radiative impacts on the cryosphere and its consequence on hydropower potential	

Univ.	Department	Student	Thesis	Supervision
UiO	Geosciences	Kristoffer Aalstad	Applications of ensemble-based data assimilation methods to the cryosphere	
UiO	Geosciences	Inger Helene H Karset	Improved model treatment of stratocumulus clouds and associated aerosol-cloud interactions	
UiO	Geosciences	Peter Horvath	Statistical (DM) and physical (GDVM) modelling of vegetation in Norway	
UiO	Geosciences	J Håvard Eriksrød	Imaging radar instrument for eco/cryo hydrological data collection improving observation density and observation accuracy in remote locations	
NMBU	IMV	Ellen Kayendeke	Analysis of flood control by wetlands in lake Kyoga basin, eastern Uganda	
NMBU	IPV	Roger Holten	Pesticide fate and behaviour under Norwegian winter conditions and adaption of the MACRO model to freezing and thawing	
NMBU	IMV	NN	Lake Hydrodynamics	
NTNU	IVM	Kuganesan Siv asubramaniam	Hydrologisk modellering av flom ved ekstrem lokal nedbør	
NTNU	IVM	Aynalem Tsegaw	Noko om arealbruk og flom	
NTNU	IVM	Yisak Abdella	Quantitative estimation of precipitation from radar measurements - analysis and tool development.	
NTNU	IVM	Vladimr Hamouz	“Modelling effects of blue green infrastructure on a watershed level”	
NTNU	IVM	Erle Kristvik	”Climate change impacts on urban hydrology and water resources in Bergen ”	
NTNU	IVM	Øyvind Pedersen	3D-modellering av vannstand-vannføringskurver for ekstremflom	
UiB	GFI	9 PhD candidates	Extreme precipitation, moisture sources and residence time and hydrological modelling	
UiB	Geography	5 PhD candidates	Holocene glacier fluctuations along the western coast of Norway. Holocene storminess in Lofoten and Vesterålen. Glacier fluctuations in the Nepali Himalayas. Hydropower in a changing climate.	

Table A3 list of courses concerning hydrometeorology at UiO, UiB, NMBU and NTNU. Courses from other universities and university colleges are not included.

University	Institute	Course code	Course name
UiB	GFI	GEOF100	Introduksjon til meteorologi og oseanografi
UiB	GFI	GEOF105	Atmosfære og havfysikk
UiB	GFI	GEOF212	Klimatologi og klimaendringar
UiB	GFI	GEOF220	Fysisk meteorologi
UiB	GFI	GEOF321	Innføring i metodar for vervarsling
UiB	GFI	GEOF322	Feltkurs i meteorologi
UiB	GFI	GEOF327	Atmosfæren sin generelle sirkulasjon
UiB	GFI	GEOF328	Mesoskala dynamikk
UiB	GFI	GEOF334	Fjernmåling i mikrobølgjeområdet
UiB	GFI	GEOF345	Fjernmålingsteknikkar i meteorologi og oseanografi
UiB	GEO	GEOV221	Karstgeologi og karsthydrologi
UiB	GEO	GEOV222	Paleoklimatologi
UiB	GEO	GEOV323	Terrestrial paleoclimatology
UiB	GEO	GEOV217	Geofarer
UiB	GEO	GEOV325	Glasiologi
UiB	Geography	GEO110	Kartografi og tematiske kart
UiB	Geography	GEO111	Landformdannande prosessar
UiB	Geography	GEO112	Vegetasjon, klima og marin geografi
UiB	Geography	GEO212	Terrestriske klima- og miljøendringar
UiB	Geography	GEO215	Geografiske informasjonssystem: Teori og praksis
UiB	Geography	GEO291	Naturgeografisk feltkurs
UiB	Geography	GEO313	Naturgeografiske laboratorie- og feltmetodar
UiB	Geography	GEO314	Hydrologi og grunnvatn i naturlege og menneskepåverka miljø
UiB	Geography	GEO341	Mastergradsfeltkurs i naturgeografi
NMBU	IMT	THT261	Vannforsyning og avløpssystemer
NMBU	IMT	FYS160	Lokal- og mikrometeorolog
NMBU	IMT	FYS161	Meteorologi og klima
NMBU	IMV	VANN200	Hydrologi
NMBU	IMV	GEO220	Hydrogeology
NMBU	IMV	Geo221	Hydrogeology field course,
NMBU	IMV	Geo300	Videregående hydrogeologi
NMBU	INA	Forn300	Vind- og vannkraft
UiO	GEO	GEO4012	Literature study in geosciences
UiO	GEO	GEO4060	Fortran 2003 programming
UiO	GEO	GEF4220	Predictability of Weather and Climate
UiO	GEO	GEF4310	Cloud physics
UiO	GEO	GEF4320	Radiation and remote sensing

University	Institute	Course code	Course name
UiO	GEO	GEF4400	The Earth System
UiO	GEO	GEF4510	Atmosphere and Oceans on Computers: Fundamentals
UiO	GEO	GEF4520	Turbulence in the atmosphere and ocean
UiO	GEO	GEF4530	The General Circulation of the Atmosphere
UiO	GEO	GEO4013	Field excursion in Physical Geography and Hydrology
UiO	GEO	GEO4310	Stochastic methods in hydrology
UiO	GEO	GEO4320	Hydrological modelling
UiO	GEO	GEO4340	Fluvial hydrology
UiO	GEO	GEO4360	Field methods in hydrogeology
UiO	GEO	GEO4420	Glaciology
UiO	GEO	GEO4430	Snow, Snow Hydrology and Avalanches
UiO	GEO	GEO4441	Physical river processes
UiO	GEO	GEO4520	Advanced remote sensing and topographic analysis
UiO	GEO	GEO9440	Cryosphere modeling
NTNU	IVM	TVM4101	BM2 Vann og miljø
NTNU	IVM	TVM5140	Economic Assessment of Hydropower Projects
NTNU	IVM	TVM4850	Eksperter i team – Waterworld
NTNU	IVM	VM8107	Emner i hydraulikk
NTNU	IVM	VM8104	Emner i hydroinformatikk
NTNU	IVM	VM8109	Emner i vassdragsmiljø
NTNU	IVM	VM8206	Emner innen vann- og avløpssystemer
NTNU	IVM	VM8207	Feltkurs for vann og miljøteknologi
NTNU	IVM	VM8205	Fornyelse av vann og avløpssystemer
NTNU	IVM	TVM5160	Headworks and Sedimentation Engineering
NTNU	IVM	TVM5125	Hydraulic Design
NTNU	IVM	TVM4105	Hydrologi
NTNU	IVM	VM8105	Hydrologi, avansert kurs
NTNU	IVM	TVM4106	Hydrologisk modellering
NTNU	IVM	TVM4116	Hydromekanikk
NTNU	IVM	TVM4155	Numeriske modeller og hydraulikk
NTNU	IVM	VM8202	Overvannshåndtering
NTNU	IVM	TVM5115	Planning and Design of Dams
NTNU	IVM	TVM5135	Planning of Hydropower
NTNU	IVM	TVM5132	Prefeasibility Study in Hydropower Development
NTNU	IVM	TVM4130	Urbane vannsystemer
NTNU	IVM	TVM4126	Vannforsyning og avløp, renseteknikk, videregående kurs
NTNU	IVM	TVM4141	Vannforsynings- og avløpssystemer, videregående kurs

University	Institute	Course code	Course name
NTNU	IVM	TVM4510	Vannforsynings- og avløpsteknikk, fordypningsprosjekt
NTNU	IVM	TVM4125	Vannforsynings- og avløpsteknikk, grunnkurs
NTNU	IVM	TVM4905	Vannforsynings- og avløpsteknikk, masteroppgave
NTNU	IVM	TVM4110	Vannkjemi
NTNU	IVM	TVM4520	Vannkraft og vassdragsteknikk, fordypningsprosjekt
NTNU	IVM	TVM4128	Vannkraft og vassdragsteknikk, videregående kurs
NTNU	IVM	TVM4165	Vannkraftverk og vassdragsteknikk
NTNU	IVM	TVM4145	Vannrenseprosesser
NTNU	IVM	TVM5171	Vannressursforvaltning

Table A4: List of recent and ongoing projects in hydrometeorology

Name	Funding	Partners	Period	Aims
Norwegian Centre for Climate Services	Public service	MET/NVE/UniResearch , MDIR	2015-??	Gi beslutningsgrunnlag for klimatilpasning i Norge. https://klimaservicesenter.no/
I:Can	NFR Researcher project	NVE, NIBIO, MET	2015-2018	Provide a detailed assessment of interactions between changes in climate, land use and hydrology, as well as how such changes can influence floods, droughts and forest fires.
FlomQ	NFR innovation project	Energi Norge, NTNU, NVE, Norsk Regnesentral (NR), UiO and MET	2014-2017	The primary objective for this project is to develop a robust flood estimation framework for Norway
SnowHow	NFR Researcher project	NVE, MET, SINTEF, GLB,TE,HYDRO, E-CO	2015-2018	Improve the physical realism in snow models and making them reliable for operational hydrological simulation under a changed climate. Improve the capabilities for updating of hydrology– and snow models.
ESCYMO	NFR Researcher project	UiO, statkraft, E-CO, AE, HYDRO, GLB, GlobeSar	2015-2019	Develop competence in the area of snow distribution modeling and snow hydrology to optimize the use of water resources in a changing climate. * To provide increased capability and competence in modeling snow distribution * To provide hierarchical decision support tools using multiobjective targets for hydrologic modeling in

Name	Funding	Partners	Period	Aims
				snow dominated catchments. * To provide current and future model operators with the new competence and improved climate variability assessment tools for hydrologic modeling.
TIGRIF	NFR Researcher project	NPI, IMR, UiO	2015-2017	Assess the impact of tidewater glacier retreat on fjord circulation and ecosystems
Rcubed	NFR Researcher project	UNI-Klima, MET, NVE, and UNI-Rokkan	2016-2019	Develop and implement innovative, integrated approaches to produce reliable local-scale climate projections for communities and stakeholders in Norway.
EVOGLAC	NFR Researcher project	UiB, UiO, Statkraft, NVE	2016-2019	Develop an integrated atmosphere-glacier-hydrological modelling system, test it on the present and apply it to future climate projections for a well-monitored Norwegian glacier complex.
PostClim	NFR Researcher project	MET, NVE, Uni Research, NR	2016-2019	Improve methodology for producing tailored climate information for key Norwegian user groups
Water Balance map	NVE internal project	NVE, MET, UiO	2017-2020	Develop a consistent water balance map (precipitation, runoff and evapotranspiration) for Norway, both seasonal and annual averages.
Snow Map	NVE internal project	NVE MET	2016-2019	Significantly improved quality of the daily maps of snow conditions in Norway (published at senorge.no)
ExPrecFlood	NFR competence building project	UiB, UniResearch, MET, Sintef Energy	2015-2018	Climatic changes in short duration extreme precipitation and rapid onset flooding - implications for design values

Name	Funding	Partners	Period	Aims
LATICE	UiO strategic research area	UiO	2015-2019	Advance the knowledge base concerning land atmosphere interactions and their role in controlling climate variability and climate change at high northern latitudes. http://www.mn.uio.no/geo/forskning/grupper/latice/index.html
Improved flood forecasting	Bilateral cooperation	MET NVE		Long term cooperation on improved flood forecasting disseminated at varsom.no
CERAD	SFF	NMBU,MET	2013-2022	Develop an ecosystem based scientific approach to help protect people and the environment from ionizing radiation, with a program of targeted focused long term research https://www.nmbu.no/en/services/centers/cerad
IRIDA	Water JPI (EU)	NIBIO	2016-??	Increased understanding of ET/water balance in areas with different landuse/vegetation https://www.era-learn.eu/network-information/networks/waterworks/era-net-cofunded-call/innovative-remote-and-ground-sensors-data-and-tools-into-a-decision-support-system-for-agriculture-water-management
SoilSpace	NFR-FRINATEK	NMBU/NIBIO	2015-2018	Quantifying Soil Structure to Augment the Relevance of Laboratory-Based Soil Hydraulic Properties for Environmental Modeling
Exflood	NFR	NMBU	2010-2014	Extreme weather in small catchments: new method for flood protection

Name	Funding	Partners	Period	Aims
				http://www.bioforsk.no/ikbViewer/page/prosjekt/tema/artikkel?p_dimension_id=22783&p_document_id=72676&p_dim2=22785
Climrunoff	NFR	NMBU,Nibio, NTNU, ViaNova	2007-2009	Stormwater and roads – dimensioning for climate change
Meadowarm	NFR	NMBU/ NIBIO,NINA	2013-2016	The effects of elevated temperatures in combination with concurrent air pollution on vegetation and soils in arctic agricultural meadows will be studied. http://www.nibio.no/en/news/warming-up-northern-meadows
Klima2050	SFI	MET,NVE,NTNU,SINTEF,JBV,SVV,AVINOR, NGI	2015-2023	Reduce the societal risks associated with climate changes and enhanced precipitation and flood water exposure within the built environment. http://www.klima2050.no/
BingoN	Horizon2020	City of Bergen, NTNU	2015-2019	Provide practical knowledge and tools to end-users, water managers, decision and policy-makers affected by climate change to enable them to better cope with all climate projections, including droughts and floods. http://www.projectbingo.eu/

Name	Funding	Partners	Period	Aims
Regnbyge 3M	Multilateral	NTNU, NMBU,SINTEF, MET,NIVA, HiØ,HiB,Rosim,DOSCON, Municipality of Drammen, Oslo and Trondheim		Helhetlig optimalisering ledningsnett og renseanlegg med overvåkning, modellering og styring for økonomiske og miljømessige besparelser: Regnbyge-3Mhttp://web.rosim.no/regnbyge3m/index.php/om-regnbyge-3m/
HydroPeak	NFR-CEDREN	NTNU/SINTEF	2009-2014	Develop know-how in order to adapt the Norwegian hydropower system to support and balance the increasing volume of intermittent wind power entering the power system http://www.cedren.no/Prosjekter/HydroPEAK
EnviPeak	NFR-CEDREN	NTNU/SINTEF	2009-2013	Develop knowledge and tools to analyze, predict and mitigate environmental impacts from rapid and frequent changes in hydropower production regimes (‘hydropeaking’) http://www.cedren.no/Prosjekter/EnviPEAK
EnviDORR	NFR-CEDREN	NTNU/SINTEF	2007-2011	Develop optimal solutions to increase both salmon and hydropower production in regulated rivers. http://www.cedren.no/Prosjekter/EnviDORR
HydroBalance	NFR-CEDREN	NTNU/SINTEF	2013-2017	Provide a roadmap for large-scale energy balancing and storage from Norwegian hydropower. http://www.cedren.no/Prosjekter/HydroBalance

Name	Funding	Partners	Period	Aims
EcoManage	NFR-CEDREN	NTNU/SINTEF	2012-2015	Test, evaluate and adapt new concepts and indicators for the improved development and management of energy and water resources. http://www.cedren.no/Prosjekter/EcoManage
WISLINE	NFR-Kilmaforsk	MET,UiO,Nibio	2015-2018	Quantify climate change impact on technical infrastructure and the natural environment caused by strong winds, icing and wet snow. https://wiki.met.no/wisline/start
SnowPack	NFR-Fripro	UiB, UiO	2017-2020	Sources of the Norwegian winter season snow pack constrained by stable water isotopes
GREENICE	NordForsk	UiB	2014-2016	Impact of future cryospheric changes in Northern Hemisphere
NAWDEX		MET,UiB	2016-??	Increase the physical understanding and to quantify the effects of diabatic processes on disturbances to the jet stream near North America, their influence on downstream propagation across the North Atlantic, and consequences for high-impact weather in Europe. http://www.nawdex.ethz.ch/

Table A5 Co-operation between institutions on hydrometeorology

	Met	NVE	UiO	UiB	NTNU	NMBU	HP-sector	NIBIO	SINTEF	NILU	IFE	Muni.	UniR.	JBV/SVV/AviNor
Met		X	X	X		X	X			X				
NVE	X		X	X	X		X	X	X			X	X	X
UiO	X	X		X	X	X	X		X	X			X	
UiB	X	X	X		X		X		X				X	X
NTNU	X	X	X			X	X		X			X	X	X
NMBU	X		X		X			X	X	X	X			

Appendix 3: Research project in hydrometeorology

This description is based on inputs from William Lahoz (NILU), Idar Barstad (Uni-Research), Jørn Kristiansen (MET), Thomas Skaugen and Deborah Lawrence (NVE)

Brief:

Define a large integrated R&D project on hydrometeorological forecasting and climate projections aiming for flood risk reduction, renewable energy production and water resources management.

Flood damages and distress are caused by flooding from major rivers, surface water flooding and flash flooding. The latter two types of flooding are a direct result of intense rainfall (traditional catchment-based approaches to flood prediction are not applicable) whereas the former is related to the more predictable large-scale systems and processes including surface hydrology.

With the introduction of convection-permitting Limited Area Models (LAMs), e.g. the Harmonie model system for NWP and climate simulations, it is possible to provide useful predictions and projections by directly feeding precipitation forecasts into hydrological models. For surface water flooding, the scale of interest is even finer and it is the details of local runoff and inundation that are of interest.

Title:

Flood risk reductions and intelligent management of Norwegian and Northern Areas water resources in the changing climate of the 21st Century

Main objective:

Develop a water resources and risk reduction management system for Norway and the Northern Areas that integrates all elements in the "observations-models-forecasts-impacts" information chain.

Secondary objectives:

1. Assess the error characteristics of multiple spatio-temporal scale observations (ground-based to satellite) of the water cycle over Norway and the Northern Areas;

2. Develop a roadmap to integrate elements of the Earth System to set up a fully coupled water cycle seamless regional, high-resolution model system, including one or more of the following: (i) hydrology-land surface, (ii) land-atmosphere, (iii) ocean-atmosphere, and (iv) land-ocean-atmosphere;

3. Develop a coupled data assimilation system that uses the observational and model information provided by secondary objectives 1 and 2, and implements an advanced data assimilation system, e.g., a variant of the EnKF;

4. Develop a roadmap to integrate the coupled water cycle model system developed in secondary objective 2 with one or more of models (simplified or otherwise) describing water resources, energy resources, and economic impacts;

5. Design and implement scenario studies to assess the impact of the changing climate on flood damages and distress, the water and energy resources in Norway and the Northern Areas, and the impact of these changes on the economy of Norway and other Nordic countries.

Main design:

WP1: Observations of the water cycle.

Establish an observational test bed where the model systems are tested and compared during well-defined campaigns. The main information on a hydrological system is the signal of the integrated response of the soil moisture, i.e., runoff. Decomposing and disaggregating this signal on integrated behaviour to individual model grid points in the catchment in a consistent way has many challenges. Amongst these are the problem of direct observation of the subsurface, both the physical properties controlling fluxes and, not least, the fluxes themselves. Physical modelling of these processes at the laboratory or plot scale is not directly transferrable to the catchment scale, due to the highly heterogeneous nature of the material properties of the subsurface.

The accuracy requirements in surface flood forecasting are very challenging, as they relate to prediction of intensities; these occur only infrequently and typically affect only small areas.

Calibrate probabilistic runoff predictions to produce forecasts of flood inundation and impact, and employ this information more (or less) directly in forecast alerts.

Evaluate the potential of citizen science and observations in flood risk forecasting and management during flood events. We expect an increase in flood events in Norway with the increase in extreme weather events associated with climate change.

WP2: Coupled water cycle model.

A single, deterministic forecast or projection is unlikely to match reality owing to incompleteness of the initial state specification or system forcing, and owing to biases in the representation of physical and dynamical processes in models. For instance, for surface flood forecasting, atmospheric initial conditions typically dominate forecast uncertainties up to 6 hours ahead while boundary conditions and model perturbations are more important by 12 hours ahead.

Coupling of hydrological and meteorological models also introduces uncertainties. Within the SURFEX model, we propose to develop the subsurface and runoff dynamics of a hydrological model. This embedded hydrological model would predict runoff and realistic spatial fields of soil moisture consistent with observations and theory. We could update and verify this model using runoff observations or other sources of information (for example, remotely sensed soil moisture).

WP3: Coupled data assimilation.

Reduce the (small-scale) errors and biases introduced when interactively coupling the different elements (atmosphere, land surface, hydrology, ocean, waves) in Earth system models. This will take account of the different temporal scales of the different elements of the Earth system. We will improve the model parameterisations by use of observed information (e.g., digitised maps, satellite data, and climate model output). We will use established diagnostics from the data assimilation methodology to evaluate the skill of the coupled data assimilation system.

WP4: Coupled models of climate model/water resources and climate/economic impacts.

http://www.nrk.no/norge/finans-norge_-bekymringsfull-okning-i-naturskader-1.12727775

WP5: Scenario studies for Norway and the Northern Areas for the 21st Century.

WP6: Project management.

WP7: Training.

Programme for PhD students; Master courses; establish an annual summer school (addressing the objectives of this project) for Norway and Northern Areas PhD students and young post-docs, and other interested parties.

Impacts:

1. Improved use of observational information: monitoring of water resources; evaluation of models; high-resolution analyses of water cycle parameters;

2. Improved simulation of the water cycle using coupled models: forecasts; process studies; scenario studies;

3. Improved estimates of the state and evolution of the water cycle through data assimilation: monitoring of water resources; evaluation of models and observations; initial data for water cycle forecasts; initial data for scenario studies; risk assessment (floods, insurance);

4. Improved understanding of the response of the water cycle in Norway and the Northern Areas to the changing climate in the 21st Century;

5. Improved information for policy makers: efficient use and allocation of water and energy resources; disaster prevention and response;

6. Training of young scientists from Norway and Northern Areas in understanding and management of water resources in the changing climate of the 21st Century.

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