Workshop on Cold Regions Hydrology
Innsbruck, Austria, 28-30 April, 2010

Session Summaries and Discussions

- $CoReH_2O$
- Snow Accumulation Patterns - Observations and Models
- Snow Backscatter Theory and Inversion Methods
- Snow Processes - Measurements and Models
- Field Experiments on Microwave Signatures and Snow Retrievals
- SAR Signatures of Snow and Ice
- Regional Snow Models and Data Assimilation
- Hydrological Modelling
- Satellite Systems for Snow Observations
- Poster Presentations
  Posters contributed to the theme of each session.

Session/Discussion Report: SNOW ACCUMULATION PATTERNS - OBSERVATIONS AND MODELS

Chairs: *P. Etchevers, D. Yang*

The presentations covered the following topics:

- Input data and limitation
  - Wind data and wind fields
  - Precipitation data - quantity and quality
  - Bias correction of precipitation i.e. impact to model results and water balance
  - Spatial interpolation methods, key factors to snow distribution
- Snow drifts and basin hydrology model
  - Progress: very detailed snow-processes models
  - Drift effects on runoff processes and ecology
  - Snow redistribution over the storms vs. blowing snow

Poster presentations:

- Fresh snow density
- Snow albedo: vegetation litter effects
- Soil heat and snow melt
- Long term mountain snow pack simulation in climate change
- Snow energy balance in forest – burned vs. healthy conditions

The discussion focused at the following main questions:

1) What are the main gaps in our understanding of climate – snow cover – hydrology interactions and feedbacks over the cold regions? What can we do via remote sensing, modeling, and in-situ observations to fill the gaps?
2) What are the major changes in snow cover accumulation and melt patterns/processes in a warming climate? What are the impacts of these changes to regional water resources and ecosystem functions?

Gaps and Issues: Observations

- Data availability is not satisfactory
  - Precipitation data : quality, density¸ gaps even in populated areas – a good fundamental input data missing is precipitation (snow vs. rain) – then we can look at how we could redistribute spatially.
  - Need better wind fields for snow transport and sublimation.
  - Radiation data; particularly in the Arctic almost no data on incoming shortwave and longwave radiation for better energy balance of snow.
  - Ground water info
- Need to develop methods to improve spatial interpolation of input data (precipitation,…)
- Satellite mission on observing snowfall – how can we use model (reanalysis) to provide first guess for snowfall mission because of need to separate from snow already on the ground.

Gaps and Issues: Models

- Some processes need better understanding
  - Snow redistribution (by wind, avalanches)
  - Patchy snowpack processes (interactions between snow free/covered areas)
  - Turbulent fluxes above snow,…
- Strategy for snow models complexity (data and application-dependent)
- Scale issue: up-scaling detailed snow processes modeling from local to large scale models
- Concern expressed about using local/basin scale models (detailed) into continental scale for GCMs.

Session/Discussion Report: SNOW BACKSCATTER THEORY AND INVERSION METHODS

Chairs: S. *Yueh, M. Kern*

The session was concerned with snow backscatter theory and inversion methods and both presentations and posters provided valuable input for the discussion.

Due to the complexity of natural snowpack, **single-layer to multi-layer multi-scattering models need to be developed and validated** with in situ ground measurements. The models should represent the physical state of the snowpack with all/most of its heterogeneities. One approach, which was presented at the workshop, is to divide the snow pack into several layers along its vertical profile and interactions between layers with different dielectric properties are calculated. A problem that needs to be addressed is the **number of layers that can effectively be represented** by such a model and the errors that arise by simplifying the layering structure from multiple-layers to single/dual layers. Simplification is necessary as remote sensing tools such as CoReH2O can only provide few independent samples of the snowpack (CoReH2O: VV, VH in two frequencies). It is also necessary to study variations of the input parameters on these multi-layer models (sensitivity analysis).

Currently, a number of different retrieval methods and approaches exist. Direct inversion methods were found to be rather sensitive to noise and solutions may not be unique. Empirical and semi-empirical techniques are tailored to specific regions and are often robust; though their representation for larger regions need to be studied in more detail. Statistical inversion methods may be a good approach for the retrieval of the main parameters such as SWE and snow albedo but further work is needed. Firstly, the input parameters and assumptions in the methods need to be stated and tested. Secondly, the robustness and representativeness of the methods with respect to varying input/output parameters needs to be analyzed. It was clearly mentioned that a single method alone may not be able to solve the necessary parameters but tailored strategies depending on the land/surface conditions could be needed. Furthermore, it was recommended that the complexity of the methods shall be tested again ground/airborne measurements so that a good comprise is found.

In a mission such as CoReH2O, it was recommended to use of the **temporal evolution of the snowpack** (e.g. in a simplified Kalman filter approach) in the retrieval method since the repeat cycle of the mission is relatively short (3 and 15 days). Assumptions can then be made on the temporal changes within the repeat cycle and therefore, the retrieval algorithm robustness can be improved.

An important aspect that was discussed in the session is the **effect of vegetation**. It was shown that vegetation can have a significant impact on the propagation of the radar signal at X-and Ku-band, depending on its structure, biomass, water content and cover fraction. Furthermore, the attenuation of the signal coming from snow cover is different depending on the type of vegetation. In a dedicated presentation, it was shown that for herbaceous vegetation or short vegetation the influence on the backscattering signal is not significant – thus the retrieval algorithm does not need to be modified. For dense forest, on the other hand, the effect of vegetation dominates the signal and reduces the possibilities to effectively retrieve snow parameters. The discussion clearly emphasized the need to further study the effect of vegetation.

A general topic that was touched in the discussion was the **definition and understanding of snow grain size**. It became clear in the presentations that different definitions are commonly used and that campaigns do not necessarily use the same approach to determine the effective snow grain size. Improvements in definition, understanding and standardization is suggested.

Further issues addressed in the discussion:

- The need for a common understanding and definition of snow grain size, based on standardized measurements. Grain size is a main parameter for backscatter forward modelling and inversion.
- Effect of layering structure shall be studied (theoretically, experimentally). There was a discussion of how many layers can be useful in modelling, and how many can be identified in fieldwork. Most sensors have footprints greater than the depth of the snow, so that detail of the snowpack structure is usually lost. It seems that all the detailed snowpack information gathered in fieldwork cannot be coded into models, which currently use simple single- or several-layer schemes. In reality, if SWE is the desired parameters, we may be more interested in change, as the lower layers can be expected to be changing only slowly.

- There should be comparisons and consultation between measurements and modelling by different groups. It was pointed out that the CoReH2O algorithm relies partly on following temporal changes over a season (ideally from bare ground).
- Vegetation effects are important for retrieval of snow parameters. Further developments for quantifying vegetation effects in forward models and to account for these effects in the inversion are needed.
- Use shall be made of the temporal evolution of the snow pack in the inversion method. This is important for parameterizing the metamorphic state for inversion both due to constructive and melt metamorphism.
- Methods for upscaling snow parameters from in situ measurements to the satellite scale should be developed and validated.
- Direct assimilation of radar backscatter values into process models is considered to be premature. Based on present state of knowledge the general applicability of such an approach is questionable.

Session/Discussion Report: SNOW PROCESSES - MEASUREMENTS AND MODELS
Chairs: *R. Essery, C. Duguay*

The discussion focused at the following main questions:
1) The Representation of which snow processes needs to be added or improved in current snow models, and what measurements are needed to enable this?
2) How can the different scales of snow processes, measurements and model applications be reconciled?
3) What is the appropriate level of complexity for snow process models in particular applications? How can this be determined?

In the discussion the importance of the following issues was addressed, in order to advance snow process modelling:

- Getting the right answer from models for the right reasons without having to tweak – look at assimilation more carefully than we have done in the past.
- Need closer collaboration between data providers and modelers with less models but over more cases – data assimilation may be one way; e.g. how canopy is considered in different models is different (def. necessary).
- Need to know better about the workings of models rather than just the outputs generated by them; operational groups that researchers work with are usually interested by output, not details of the models, as long at accuracies are well documented.
- Operational hydrology needs new young people who are opened to the use of new models rather than the old way – need long-term partnership with operational community.
- To convince operational community we need to show them that new models give better results.
- Researchers who develop models should more easily recognize the limit of their models – need to make suggestions to improve models of others.
- Need to examine more the sub-pixel issue to reconcile scales.
- Need to capture meteorological gradients (e.g. winds) to compare to wind models and then use observations to downscale their predictions.

Session/Discussion Report: FIELD EXPERIMENTS ON MICROWAVE SIGNATURES AND SNOW RETRIEVALS
Chairs: E. Malnes, A. Wiesmann

Oral presentations reported on field experiments in field experiments with active and passive microwave sensors in North America (Canada, Colorado, Idaho) and in Finland. Poster presentations provided further details on some of these experiments, and reported on further experiments with active sensors performed in the Alps. In addition, new observation techniques were introduced, including an UAV Ku-band SAR platform and TDR imaging of seasonal snow.

The discussion addressed issues to be considered in future field campaigns:

- Need for a common approach how to set up future campaigns and which parameters shall be measured -> suggestion for a common campaign protocol.
- Standardized methods for characterizing and quantifying snow structural properties (in particular grain size) should be developed.
- Deep snow conditions and snow on sea ice shall be further studied. For both target types effects of layering need to be assessed.
- A wide spectrum of possible snow states should be covered by experimental data.
- It was suggested that the CoReH2O mission advisory group may act as a contact point for future campaigns.
- The complexity of the snowpack was discussed. Refined profile measuring techniques and development of systematic standardized schemes are very desirable.
- Very different backscattering responses can be obtained at nadir and at oblique looks. There was a difference of opinion between whether significant off-nadir measurement is possible, with the pointing out the presence of a poster paper on the TDRi technique to do just that.

Session/Discussion Report: SAR SIGNATURES OF SNOW AND ICE
Chairs: *G. Macelloni, K. Morrison*

The session included three presentations that covered different topics on the exploitation of radar signal properties for snow and ice applications in hydrology and glaciology. In the discussion the potential of the presented techniques for specific applications was stressed, as well as the need to further consolidate and validate the methods.

Coherent Scatterers Detection for Glacier Monitoring by Means of TerraSAR-X Data. The presentation reported on the identification of persistent point scatterers in a temporal sequence of images of a fats-flowing glacier in order to determine ice motion. The points were selected based on their spectral characteristics across the radar bandwidth. The number of retrieved points was rather small. In the discussion their selection over other points in the imagery which would be expected to provide the same point response was questioned. It was pointed out that the general applicability of this technique and the advancement over other techniques needs to be studied using further data sets.

Snow Properties Retrieval in Alpine Regions With Full Polarimetric Radarsat2 Data. A temporal sequence of imagery from Radarsat-2 was examined using polarimetric decomposition techniques to determine snow parameters. The estimated parameters were compared against in suit snow data. Seasonal progressions of measured and estimated snow cover were presented over a mountainous region, in order to estimate the performance of the retrieval algorithm in discriminating snow-covered (dry and wet snow) and snow-free areas. . The work is ongoing, possibilities and constraints for broad applicability need to be investigated.

Role of Wetlands in the Seasonal Distribution of Discharge of the Poluy, Nadym, Pur and Taz Rivers. The study used information from a variety of sources and platforms to look at the variability of water discharge from wetland basins in Siberia. Radar altimetry provided the main remote sensing information, complimented by a set of non-radar platforms and ground measurements. Passive microwave measurements, providing estimates on large-scale snow accumulation, show clear relations to annual snow melt discharge. A question was whether the variability was due to natural fluctuations, changes in climate, or the recent arrival of man-made artefacts such as raised roads. The case for a significant effect from the latter-most seemed very plausible.

Session/Discussion Report: REGIONAL SNOW MODELS AND DATA ASSIMILATION

Chairs: *M. Drusch, M. Lehning*

When talking about regional snow models, it appears critical to distinguish between applications with a meteorological, hydrological or climatological focus. Since meteorological models are frequently re-initialized, it is critical to have a good SCA product for initialization but true assimilation (feeding information at multiple time points during the model run) has relatively minor impact. But even for the initialization of meteorological models, improved mechanisms need to be found, which should allow for example the assimilation of SWE. Data assimilation appears to have most benefits in hydrological models, which require a good representation of SWE distribution to achieve reliable forecasts of runoff e.g. for flood prediction.

The models need to develop in a way that they allow easy and efficient data assimilation. Currently, simple schemes such as Cressman or optimal interpolation prevail and more advanced assimilation schemes e.g. based on Kalman filtering, which would allow to adequately considering estimated observation errors, are scarce.

An often-observed problem with data assimilation is that the effect may vanish quickly, e.g. that if snow gets added to a grid point in a regional model, which has not been there before, the model often then just melts it again much too quickly. Therefore, an interesting research topic could be automatic model adaptation to produce the desired result. One such model feature that could be improved on the fly with the corresponding observations is the snow / rain partitioning of precipitation.

A fundamental problem of regional models is the question on model complexity versus grid resolution. Which processes need to be included in a model? How is sub-grid variability handled? Features that are known to cause trouble are sub-grid fractional snow cover and turbulent fluxes over snow. These issues need more work.

A number of contributions addressed the assimilation of snow parameters, i.e. the analysis of snow extent, snow water equivalent and albedo. Most presentations focussed on large scale applications and the data assimilation schemes presented were rather simple, i.e. data ingestion, Cressman interpolation or optimal interpolation schemes.

During the discussion it became clear that the community recommends using derived satellite parameters at Level 2 rather than reflectance, brightness temperatures or backscatter coefficients. It was stressed that the error characteristics are reasonably well known and that a lot of research has been devoted to the validation of satellite derived snow data sets.

It was also recommended to analyse snow water equivalent and snow extent separately. Consequently data assimilation schemes for these two control variables should be developed. In current operational systems, e.g. at ECMWF and the UK Met Office, information on snow extent has been used to constrain the analysis of snow water equivalent. Another option may be to assimilate merged products, e.g. the snow water equivalent estimates produced through ESA's Globsnow project.

In general, active and passive microwave sensors have a very good capability detecting wet snow. Although this information is "binary" and the error characteristics are non Gaussian, new techniques shall be developed to incorporate this information in snow analysis schemes.

Session/Discussion Report: HYDROLOGICAL MODELLING
Chairs: *D. Marks, G. Kaser*

We need research on scaling from process-level studies to large hydrological systems, specifically in the context of remote sensing applications.
Detailed very successful research on snow and hydrological processes in cold regions in general, and mountain systems specifically has been restricted to hill-slope or small catchment scales. Very few studies have been undertaken that attempt to relate these results to larger scales or regions that are hydrologically significant, and where remote sensing applications would apply.

a. We need to encourage, and secure funding for research investigating how to scale processes, properties and measured features from the measurement scale (1m to hill-slope scale) up to 500m – 1km scales of operational satellite data products (MODIS, AVHRR).
b. We need to include direct measurement on the ground of the same radiometric features measured for aircraft of satellite (e.g. portable active radar).
c. We need to better understand the sensitivity of our models to the inherent loss of detail when the forcings are spatially degraded through either data assimilation or derivation from remote sensing.

Before remote sensing products can be effectively integrated into hydrologic assessment and modeling, we must fully characterize and understand their uncertainty in both scale and surface conditions (re: sub-grid variability).

a) In addition to direct radiometric measurement on the ground (see above), we need research aircraft of satellite data products that are on the order of the scale of variability of the processes and properties being sensed (1-50m).
b) Inversion models that rely on critical physical parameters, such as grain size, require that these are carefully defined, and consistent procedural steps for their determination developed so that they are comparable from site to site, between different countries, regions and research groups.

In an unstable climate, modeling and remote sensing should focus on patterns and distribution of water supply volumes (snow, soil moisture, ground water) and fluxes (evaporation, transpiration), rather than statistical relationships (e.g. degree-day or temperature index) to stream discharge at the outflow.
The inherent complexity of hydrological systems is overlooked when evaluating only discharge, which can occur for a variety of reasons. Modeled and measured discharge can

easily be matched for a specific year by calibration, giving the false impression that the remote sensing derived parameters are correct, and that the statistical model is performing effectively. The appropriateness of extending calibration parameters to either future conditions, or to near-by unmeasured basins is based on the assumption of stable climate and hydrological conditions across a region, which we know is not the case. Unfortunately, the transition to process-based simulation modeling has been limited by the quantity and quality of forcing data.

a) Remote sensing derived products can provide estimates of spatial patterns of snow (extent, temperature, depth, SWE) and soil moisture and temperature, and can be used to improve estimates of evaporation and transpiration. If these are properly evaluated and validated, they can be used to improve our models and assist us in moving away from calibrated, statistical models, toward simulation models based on the physics of the critical processes involved.
b) Process research must be undertaken to assess gradients and distributions of critical hydrologic parameters (radiation, precipitation & snow, wind) in response to terrain, canopy and land-cover parameters.

We need long-term (20-40 year), complete, high quality modeling and remote sensing validation data sets from sites dominated by cold-season and snow processes.

While such data are limited, there a few very well instrumented catchments globally where such data are available. These sites qualify as hydrologic observatories, where detailed and complete data is collected for a long period of time. Data on precipitation, snowfall, snow cover depth, density and distribution, soil moisture and temperature, full meteorological data (air temperature, humidity, solar and thermal radiation, wind speed and direction), ground water head, stream discharge and temperature is available from multiple sites, as is detailed topography, vegetation structure, density and height, soil thickness, and land cover. In general these sites are a) hydrologically constrained within a basin or drainage where the water balance can be closed; b) have carefully checked, corrected and filled the long-term data to create coherent modeling data sets; and c) have the long-term data stored in some sort of a database system. Most of the sites have LIDAR characterization of terrain and vegetation structure. Note: The hydrologic utility of previous remote sensing field experiments (BOREAS, CLPX I, II & III) has been reduced by the lack of complete data (specifically precipitation) to support hydrologic modeling.

a) Potential sites are the area around Davos, Switzerland (get specifics from M. Lehning and T. Jonas); the Reynolds Creek Experimental Watershed in Idaho, USA; the Marmot Creek Experimental Watershed, Alberta, Canada; the Sodankylä Arctic Research Center, Finland; other sites could be included as appropriate.
b) Research should be undertaken to quantify measurement methods, instrumentation effects and the impact of site conditions and climate effects. The objective is not so much to standardize these, but understand how and why they are different, so that reliable inter-site comparisons can be undertaken.
c) A series of coherent, comparative field experiments should be undertaken at these sites to evaluate how they are similar and how they are different. A suite of models from the cold regions hydrology community will be selected and run at all sites to compare the sites, the site data, and to determine the *state of the science* in cold regions hydrologic modeling. A particular focus would be snow deposition and re-distribution in an effort to determine features, such as persistent during storm wind-fields with subsequent patterns of snow deposition and redistribution, over multiple years at each site.

We need to undertake a significant research effort to determine how best to measure precipitation and snowfall in cold regions, and we need to form a research – operational partnership to expand precipitation measurement networks into cold regions.
The almost universal lack of precipitation data from cold regions of the world, particularly in mountainous areas, is acknowledged. Because precipitation is the primary hydrologic input, there is a critical need for snow and precipitation data, including redistribution methodologies over mountain and cold regions of the world.

a) Precipitation measurement methodologies – particularly in mountain regions – need to be evaluated as a follow-on effort to the WMO *Solid Precipitation Measurement Evaluation*. Wind-correction algorithms for hourly precipitation (rather than daily) are needed, as are alternatives to the very large Russian and Wyoming windshields. Better definitions for *wind-corrected* solid precipitation in respect to actual deposition are required.
b) Experiments at hydrologic observatories (see above) should be undertaken to determine optimum and minimally effective numbers of sites for different regions to 1) characterize *wind-corrected* precipitation, and 2) gradients of precipitation across the landscape.
c) Snow redistribution and drifting estimates should be integrated with precipitation measurement programs in cold snow-dominated regions.

Session Report: SATELLITE SYSTEMS FOR SNOW OBSERVATIONS
Chairs: *J. Pulliainen, C. Derksen*

Jessica Cherry (University of Alaska Fairbanks) provided an overview of an evaluation framework developed in Alaska for hydrometeorological products anticipated from GOES-R. The emphasis is on facilitating links to between product development and end users. The hydrological variables of interest include snow cover fraction, grain size and albedo derived with the GOESRSCAG algorithm (the GOES implementation of an existing snow fraction retrieval scheme currently applied to MODIS data), cloud top phase, cloud/snow discrimination, and estimates of low fog/cloud.

After providing an update on current CliC activities, *Daqing Yang* (WCRP CliC) summarized the status of precipitation bias correction. The issue of the high level of uncertainty in precipitation measurements was consistently raised during previous sessions. While standardized undercatch corrections were developed by WMO during the 1990's, factors such as inconsistent gauge and shield combinations between countries, station automation, and sparse station networks continue to hamper the development of hemispheric or pan-Arctic precipitation time series with defined levels of uncertainty.

Richard Kelly (University of Waterloo) described efforts to combine MODIS imagery, AMSR-E data, and in situ observations in the Yukon Territory, Canada to improve the retrieval of snow information in mountainous areas. A comparison with climate model and reanalysis derived climatologies show passive microwave data on their own have difficulty in capturing the interannual variability in snow depth in western North America. Using the Canadian Meteorological Centre daily gridded global snow depth analysis as a baseline, AMSR-E brightness temperature combinations ((10V-36V)+(18V-10V)) provided the best sensitivity to longitudinal changes in snow depth. Coarse resolution passive microwave data may have some feasibility for SWE retrieval in areas of complex terrain provided there is no mixing of dry snow, wet snow and snow-free terrain within a single grid cell. Using field observations acquired during International Polar Year, a linear mixed effects model was developed to produce high resolution 'ground-truth' information for alpine snow cover in the Yukon.

The synergistic combination of satellite optical and microwave observations for snow extent retrievals was presented by *Peter Romanov* (NOAA NESDIS; University of Maryland). Using an automated scheme, daily, global, 4 km resolution snow extent information has been produced continually since 2006. The objective retrieval scheme removes the subjectivity of the manually derived NOAA IMS snow charts. The combined use of microwave and optical information reduces uncertainty related to cloud cover, but minimizes the known limitations of microwave retrievals (underestimation of snow extent during the autumn and spring).