Towards a combined meteorological-hydrological forecasting system

Assimilation of in-situ and satellite snow data for hydrological forecasting in Sweden - a hydropower case study

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SMHI – Swedish Meteorological and Hydrological Institute
Met-Hyd collaboration for surface DA at SMHI

- Land surface model (parts of) – SURFEX.

- Data assimilation method – EnKF.

- Observations – towards raw radiances / backscatter.

Work together in research projects:

- SNSB: DA for satellite-based measurements of the hydrosphere
- EU H2020: IMproving PRedictions and managment of hydrological Extremes

Collaboration with NILU, Météo France and HIRLAM partners.
ASSIMILATION OF SATELLITE-BASED MEASUREMENTS OF THE HYDROSPHERE - TOWARDS A COMBINED METEOROLOGICAL-HYDROLOGICAL FORECASTING SYSTEM

SYNOP, runoff satellite radiances → Soil & hydrology SURFEX, HYPE EnKF → Upper air analysis HARMONIE (AROME)

AMS R2 (GCOM-W1)  MIRAS (SMOS)  SAR (Sentinel-1)
EU IMPREX 2015-2018

IMproving PRedictions and management of hydrological Extremes

- SYNOP, runoff satellite products
- Soil & hydrology SURFEX, HYPE EKF / EnKF
- Upper air analysis HARMONIE

Soil moisture from ASCAT, SMOS and AMSR2.

Snow water equivalent from H-SAF / GLOBSNOW / NASA (SSMIS, AMSR2)
Harmonie MetCoOp

AROME cycle 38h1.b2
2.5 km, 750 x 960 grid points, 65 levels
3D-Var, fc +60 hours
8 an + 8 fc per day @ 00,03,...,21
ECMWF boundaries
Surface DA: CANARI-OI_main
SURFEX

Version 8

- Stable OpenMP implementation.
- ISBA-ES “Explicit snow” with multi layer snow packs.

Two patches (low and high veg) to match CMEM observation operator.

Couple with hydrological model

- Extend HYPE surface model with SURFEX.
- Introduce SURFEX river routing via OASIS.
- Interface with topological databases (e.g. Hydro1k).
Remote sensing data and observation operators

Sentinel-1/SAR-C: wet snow, snow extent, (dry snow?)
- S1A_EW_GRDM_1SDH
- Extra Wide swath mode VV+VH and HH+HV, ca 25 x 80 m
- MEMLS3&a by Proksch et al. (2015)

GCOM-W1/AMSR2
soilm (7 Ghz), deep (10, 19 GHz), moderate (37 GHz), shallow snow (89 GHz)
- L1SGRTBR
- Level 1R V,H, ca 40 x 60 km
- Community Microwave Emission Modelling Platform (CMEM): 1 – 20 Ghz
- FASTEM + RTTOV?

SMOS/MIRAS, L band 1.4 GHz: soil moisture
- MIR_BWSD1C
- Level 1C Browse Brightness Temperatures, dual (or full) polarization,
  ca 50 x 50 km, ISEA 4-9 hexagonal grid.
- CMEM + FASTEM (water)?
First technical test: AMSR2 level 1C, 6.9 GHz
Spatially correlated errors in the forcing

\[ x_k = fc_{48} - fc_{24} (m \times 1) \]

\[ X = [x_1, \ldots, x_n] (m \times n) \]

\[ B = XX^T (m \times m) \]

\[ B_s = X^TX = E_s D_s E_s^T (n \times n) \]

\[ XX_s (XX_s)^T = XX^T = B \]

\[ = E_l D_s E_l^T , \quad E_l = X \hat{E}_s (m \times n) \]

\[ z = E_l D_s^{1/2} e , \quad e \in N(0, I) \]

\[ E\{zz^T\} = E_l D_s E_l^T = B \]

\[ m \times n \approx npar \ast 500 000 \times n \]
16 columns of B (t2m), fc48-fc24: 20140401-1231
Four examples of spatially correlated t2m errors (z)

These are not fc48-fc24 differences, but samples drawn using $z = E_1 D_s^{1/2} e$, $e \in N(0, I)$
Creating an initial SURFEX ensemble (spin-up)

HARMONIE + random errors

SURFEX

\[ x_i + z_i \quad i = 1 \ldots k \]

HARMONIE + random errors

SURFEX

\[ x_i + z_i \quad i = 1 \ldots k \]

HARMONIE + random errors

SURFEX

\[ \ldots \]

How many members (k) are called for?
How long time do we need to run to spin up a sufficiently rich ensemble?
Questions

NWP

Alternative (EnKF or En2DVar) DA for t2m and rh2m?

EnKF

Ensemble Kalman Filter for SURFEX – from N 1D to 1 ND. Cycling members?
How to introduce systematic perturbations? Time shifts?
Need for adding horizontally/vertically correlated errors to the SURFEX state?
How to assimilate runoff observations – long time window EnKF?

Observations and observers (obop)

How to make Sentinel-1 data fit HARMONIE scale – work with pdf:s?
How to make HARMONIE fit scale of SMOS/AMSR2 – footprint/antenna func?
Water emissivity at SMOS freq, FASTEM? RTTOV for AMSR2 37 and 89 GHz?
Assimilation of in-situ and satellite snow data for hydrological forecasting in Sweden - a hydropower case study
EO and in-situ snow data in Sweden

Forcing data
- P, T interpolated (4x4 km²)
- Elevation EU-DEM (25x25 m²)

Snow data
- SMHI snow depth stations (point, daily)

Hydropower companies:
- SWE point data (bi-weekly)
- Snow courses (once per year)

Satellitdata (GlobSnow, CryoLand, etc)
- Fractional snow cover 1x1 km²
- Snow water equivalent 25x25 km²
Distributed hydrological model (HBV-type)

- 4x4km² model-grid
- 0.1°x0.1° SWE-grid

Runoff forecast basins:
- In-situ SWE data
- In-situ snow depth
Assimilation of point observations in a distributed model

Distributed model $X_d(x, y, z)$

Point model $X_p(x, y, z)$
HOPE model application
• Simple HBV type of snow/soil model on the 4x4 km2 PTHBV grid
• Up to 160 SLC classes for different snow accumulation/melt regimes
• Runoff is aggregated for the VRF forecast areas in Lule river, Skellefte river, Ume river, Ångerman river and Indals river.

Snow data
• SMHI snow depth stations
• VRF/VF/SVF snow water equivalent point data at regulation dams
• CryoLand SWE and Snow cover (satellite)
• Local runoff estimated for each forecast area
Two options for snow data integration:

1) Evaluation of Model and Data agreement

\[ K_{GE} = \text{agreement in terms of mean value, standard deviation and correlation} \]

2) Model state-updating using EnKF (Evensen, 1994)

\[ X^a = X^p + K(Y - HX^p) \quad K = \frac{C_{xy}}{C_{yy} + R} \]

All model states (non only snow) updated as a function of covariance between the states and the 'innovation' in the snow variables

Important that model and data do not disagree too much!
In general a very good agreement between model and satellite data throughout Sweden.

However, the temporal variability is different in the most alpine part of the mountains in northern Sweden.

Transmissivity model is well-adapted to boreal forests.
CryoLand SWE vs S-HYPE modellen
Pan-European SWE product (FMI)

- **Good agreement** in central part of middle and northern Sweden:
  - Forests
  - Non-mountain areas

- **Correlation is high** (except for the south)

- **Variability and Mean value differs:**
  - In the south (little snow and lakes)
  - along the east coast
  - western mountain range

- **Problem for the satellite or model?**
  - Mountains, surface water, coastal areas, spatial distribution of snow
Good example: Abiskojokki, northern Sweden.
Both SWE and FSC data improve stream flow simulations
### Spring flood forecast assimilation experiments

- 5 test areas
- 6 year snow observations (2010-2015)
- Initialization for forecast start dates 15/2, 15/4 och 15/6 assimilating:
  - Local runoff (Q)
  - Snow water equivalent (SWE) – in-situ
  - Snow depth (SD) – in situ
  - Snow fraction area (FSC) – from CryoLand

<table>
<thead>
<tr>
<th>Område</th>
<th>Älv</th>
<th>Area (km²)</th>
<th>Snow water equivalent at forecast start (mean 2010-2015)</th>
<th>15/6 (% av 15/4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tjaktjajura</td>
<td>Luleälven</td>
<td>2256</td>
<td>376, 520, 258</td>
<td>50%</td>
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<tr>
<td>Riebnesjaure</td>
<td>Skellefteälven</td>
<td>976</td>
<td>290, 440, 147</td>
<td>33%</td>
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<tr>
<td>Överuman</td>
<td>Umeälven</td>
<td>653</td>
<td>402, 663, 236</td>
<td>36%</td>
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<tr>
<td>Kultsjön</td>
<td>Ångermanälven</td>
<td>1095</td>
<td>357, 498, 118</td>
<td>24%</td>
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<tr>
<td>Landösjön</td>
<td>Indalsälven</td>
<td>1453</td>
<td>148, 182, 11</td>
<td>6%</td>
</tr>
</tbody>
</table>
Results spring melt volume forecasts

- Assimilation until forecast start – forecast using ensemble of historical years
- Assimilation initialization is better in most cases than the reference run
- In-situ SWE and satellite based FSC is the most consistent improvement

### Relativt volymfel (%)  (medel av absolut volym fel 2010-2015)

<table>
<thead>
<tr>
<th>Prognos 15/4-31/7</th>
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<tr>
<td><strong>Område</strong></td>
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<tr>
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<td>Riebnes</td>
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<tr>
<td>Överuman</td>
</tr>
<tr>
<td>Kultsjön</td>
</tr>
<tr>
<td>Landösjön</td>
</tr>
</tbody>
</table>

| **antal lägst fel** | 2 | 3 |
| **antal < Ref**     | 5 | 1 | 4 | 3 | 4 | 3 |
Comparing forecasts 15/2  15/4 och  15/6

- Snow data assimilation important throughout winter
- Largest improvement later in the winter and through the melt period

<table>
<thead>
<tr>
<th></th>
<th>Ref</th>
<th>Ens0</th>
<th>EnsQ</th>
<th>EnsSWE</th>
<th>EnsSD</th>
<th>EnsFSC</th>
<th>EnsAll</th>
</tr>
</thead>
<tbody>
<tr>
<td>15/2</td>
<td>12.8</td>
<td>12.6</td>
<td>15.1</td>
<td>13.5</td>
<td>15.9</td>
<td>12.6</td>
<td>15.9</td>
</tr>
<tr>
<td>15/4</td>
<td>23.1</td>
<td>21.5</td>
<td>29.9</td>
<td>18.8</td>
<td>22.1</td>
<td>15.4</td>
<td>29.4</td>
</tr>
<tr>
<td>15/6</td>
<td>28.6</td>
<td>26.8</td>
<td>34.6</td>
<td>23.0</td>
<td>23.1</td>
<td>22.8</td>
<td>27.6</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th></th>
<th>Relativt volymfel (%)</th>
<th>Relativ förbättring (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15/2</td>
<td>-2</td>
<td>20</td>
</tr>
<tr>
<td>15/4</td>
<td>-7</td>
<td>37</td>
</tr>
<tr>
<td>15/6</td>
<td>-6</td>
<td>27</td>
</tr>
</tbody>
</table>
Next step: assimilate in-situ data, passive microwave data directly in the hydrological model?

Radiation emission model
Ex from Pullianen and Hallikainen (2001)

Satellite observed radiation:
- Radiation from atmosphere
- Radiation from ground (soil, snow, vegetation)

Spatial distribution of snow (from model or from in-situ data)
Conclusions

- Assimilation of satellite and in-situ snow data reduced snow melt runoff forecast errors with 5-50%.

- In-situ snow water equivalent and satellite based fractional snow cover gave the most consistent improvements when assimilated in the model.

- Further studies will be focused on assimilation of passive microwave data and in-situ data directly in the snow hydrological models.
Tack för uppmärksamheten