Snow depth observations from Sentinel-1 over the Northern Hemisphere mountain ranges

The importance of snow

Snow covers ±20% of the Northern Hemisphere

Global cooling effect
• Reflects ±90% of incoming solar radiation, vegetation only 10-20%
• Reduces ground heat exchange with the atmosphere

Critical water resource
• Drinking water for >1 billion people
• 75% of the agricultural water use in western US
• Hydropower generation, industry, ...

Flood and avalanche prediction, wildlife migration, tourism, ...
Current snow depth estimates

We lack basic understanding of how much snow we have on Earth, particularly in mountain areas.

- Measurements: sparse
- Models: poor snowfall
- Passive microwave: coarse
- Airborne observations: local
Active microwave remote sensing

- Preferred frequency (Ku-band) not in space
- Adequate satellite observations only in C-band (e.g. Sentinel-1)
Sentinel-1 backscatter time series

San Juan Mountains, Colorado, USA
37.71°N, -107.51°E, 3535 m

European Alps, Austria
46.87°N, 10.71°E, 2464 m

$\sigma_0^v$ (dB)

$\sigma_0^h$ (dB)

$\sigma_0^v / \sigma_0^v$ (dB)
Snow Depth (SD) = Snow Index (SI) × Scale Factor (SF) × Snow Presence (SP)

\[
SI_t = SI_{t-1} + \frac{\Delta \sigma^0}{\Delta t}
\]

Relate change in \( \sigma^0_{vh}/\sigma^0_{vv} \) with snow accumulation/ablation

\[
SF = \frac{a}{1 - b \times FC}
\]

Rescale to snow depth and correct forest (FC) attenuation

\[
SP(t) = \{1, 0\}
\]

Mask with snow presence (1) or absence (0) from IMS

- **Processing**
  - Sentinel-1 data: Google Earth Engine and HPC
  - Full archive over Northern Hemisphere (> 20°N), updated continuously
  - 1-km² spatial resolution and ~weekly temporal resolution
  - Automated with ~5 days latency
• Snow depth measurements (point-scale) in mountain areas for Sep 2016 – Aug 2018
• 4175 grid cells with validation data
  • Global networks from NOAA (GHCN-D) and ECMWF (SYNOP)
  • Regional networks over the US, Canada, Alps, Scandinavia, Himalaya, ...
### Sentinel-1 spatial validation

#### Snow Depth (m)

<table>
<thead>
<tr>
<th>Month</th>
<th>$R_s$ overall</th>
<th>$R_s$ between ranges</th>
<th>$R_s$ within ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec</td>
<td>0.67</td>
<td>0.96</td>
<td>0.58</td>
</tr>
<tr>
<td>Jan</td>
<td>0.72</td>
<td>0.93</td>
<td>0.60</td>
</tr>
<tr>
<td>Feb</td>
<td>0.76</td>
<td>0.92</td>
<td>0.72</td>
</tr>
<tr>
<td>Mar</td>
<td>0.69</td>
<td>0.85</td>
<td>0.67</td>
</tr>
<tr>
<td>Apr</td>
<td>0.72</td>
<td>0.84</td>
<td>0.60</td>
</tr>
</tbody>
</table>
Different magnitudes

Wet snow underestimated

Insufficient Sentinel-1 data

Sentinel-1 snow depth time series
\(\geq 30\) measurements with SD > 0

- Incl. SD = 0, \(\mu = 0.77\)
- Excl. SD = 0, \(\mu = 0.65\)

\(N = 1800\)

\(\geq 1\) measurement with SD > 0

- Incl. SD = 0, \(\mu = 0.18\)
- Excl. SD = 0, \(\mu = 0.31\)

\(N = 2000\)
Inter-annual differences (Feb ‘18 – ’17)

Sentinel-1

Δ Snow depth (m)

European Alps

MERRA-2

Δ Snow depth (m)

US Sierra Nevada

Sentinel-1

Δ Snow depth (m)

MERRA-2

Snow depth (m)
- Meas. and cross-masked S-1 correlate to $R = 0.92$
- Meas. and area-wide S-1 correlate to 0.6
- Coast Mountains >100 km³ diff.

- Lack of meas.
- Himalaya discrepancy
Ongoing activities

- Algorithm improvements
  - Detecting onset of snowmelt (+ masking of retrievals afterwards)
    - Wet snow causes strong absorption of radar signal: uncertain retrievals
    - Detection: $\Delta\sigma^0/\Delta t < \text{threshold}$

February 1-7, 2018

April 1-7, 2018
Ongoing activities

- Data assimilation
  - Sentinel-1 snow depth reader implemented in NASA LIS framework
  - Next: Impact of assimilating Sentinel-1 snow depth retrievals on model simulations of snow depth and SWE, discharge, other energy/water balance components
  - Challenges:
    - Bias between modelled and observed snow depth
    - N observations depends on location: unequal updates, unequal observation uncertainties

Sep 2016 – Aug 2018
Ongoing activities

- Field campaigns
  - C-band quad-pol radars (3) deployed in Idaho and Colorado, USA (SnowEx sites)
Ongoing activities

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  - C-band quad-pol radars (3) deployed in Idaho and Colorado, USA
Ongoing activities

• Field campaigns
  • Continuous radar & snow measurements: improved understanding
    • Scattering mechanisms increasing C-band $\sigma^0_{\text{vh}}$
      • Volume scattering on anisotropic ice crystals?
      • Volume scattering on clusters of ice crystals?
      • Multi-scattering on snow layer interfaces?
      • Diffraction, forward scattering, ground reflection?
  • Scattering impacts from
    • Wet snow
    • Rain on snow
    • Ice lenses
    • Snow microstructure
    • Snow stratigraphy
    • Substrate and vegetation conditions
Conclusions

• First satellite-based snow depth observations in Northern Hemisphere mountains
  • 1-km² spatial and ~weekly temporal resolution
  • Reasonably accurate over space and time
  • Data available through https://ees.kuleuven.be/project/c-snow/

• Ongoing activities
  • Potential for data assimilation
  • Algorithm improvements
    • Wet snow detection
    • Field-campaigns with tower-based radar sensors in US Rocky Mountains

• More info
  • Website: https://ees.kuleuven.be/project/c-snow/
  • Email: hans.lievens@kuleuven.be