A snowfall downscaling scheme for mountainous terrain

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To improve fine-scale snow cover modeling over mountainous terrain, an efficient downscaling scheme for coarse-scale snowfall is required.

Motivation

Coarse-scale snowfall $P_{\text{coarse}}$ of 2 mm on topography without downscaling scheme

Fine-scale modeled snowfall $P$ on topography with $P_{\text{coarse}}$ of 2 mm

$\Delta x = 30$ m

**Goal:** A snowfall downscaling scheme that takes into account wind-snowfall-topography interactions

**Recipe:**
- Generate a large, diverse data pool of modelled fine-scale snowfall distributions in mountainous terrain
- Develop statistical parameterization

**Ingredients:**

1) Large set of simulated topographies covering a broad range of topographic characteristics

2) Non-hydrostatic and compressible atmospheric model ARPS (Advanced Regional Prediction System) (Xue et al., 2001) to compute fine-scale wind fields

3) Snow transport module of Alpine3D to compute preferential deposition i.e. fine-scale snowfall distributions (Lehning et al., 2008)

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First ingredient: Simulated topographies that cover a broad range of topographic characteristics

Topographies have domain size of $L = 3 \text{ km}$, horizontal resolution of $\Delta x = 30 \text{ m}$ and cover:

- Different spatial mean slope angles $\xi$ between $10^\circ$ and $36^\circ$
- Terrain correlation length $\xi$ between $200 \text{ m}$ and $1000 \text{ m}$
- Standard deviation of elevation $\sigma$ up to $365 \text{ m}$

Three example topographies:

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**Second ingredient:** Fine-scale ARPS wind fields for all topographies

ARPS wind fields were derived for all topographies under controlled conditions (Helbig et al., 2017):

- Coarse wind speed $v_{\text{coarse}}$ of 3 and 5 m/s and fixed wind direction $wd_{\text{coarse}}$ to West
- No thermally induced circulations and turbulent structures

Generated near-surface horizontal wind speed $v_h$ and wind components, $u$, $v$ and $w$ for $v_{\text{coarse}} = 3$ m/s:

- Mean slope angle of $19^\circ$

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*Helbig et al., A snowfall downscaling scheme for mountainous terrain, EGU GA 2021, online, 19–30 Apr 2021, EGU21-13227.*
Third ingredient: Fine-scale snowfall distributions for all topographies

Fine-scale snowfall distributions using a snow transport model (Lehning et al., 2008) forced with ARPS wind fields for all topographies under controlled conditions:

- Neglected erosion, saltation, drifting snow sublimation
- Coarse snowfall $P_{\text{coarse}}$ is 2 mm, 5 mm and 8 mm; $P_{\text{coarse}}$ and $P$ are for one time step

Generated fine-scale snow deposition for $P_{\text{coarse}} = 2$ mm and $v_{\text{coarse}} = 3$ m/s:

- Mean slope angle of 19°
- Mean slope angle of 25°
- Mean slope angle of 30°

Results: Fine-scale modeled snowfall patterns

Fine-scale modeled snowfall patterns are similar, though enhanced with increasing coarse-scale snowfall $P_{\text{coarse}}$ or coarse-scale wind speed $v_{\text{coarse}}$

Modeled fine-scale snow deposition patterns for one topography (different color scales):

- $v_{\text{coarse}} = 3 \text{ m/s}$
- $v_{\text{coarse}} = 5 \text{ m/s}$

Results: Scaling factors for the snowfall downscaling scheme

Fine-scale modelled snowfall $P$ correlates well with coarse snowfall $P_{\text{coarse}}$ and

1) Fine-scale vertical wind component and a terrain slope parameter (called "wind" scheme)
2) Fine-scale slope parameter and aspect relative to coarse wind direction $wd_{\text{coarse}}$ (called "aspect" scheme)

Results: Modeled and downscaled snowfall - Spatial patterns

Downscaled snowfall $P_{\text{dsc}}$ describes spatial variability of modelled snowfall $P$ well
- Spatial patterns similar for $P_{\text{dsc}}^{\text{wind}}$ as well as for the simpler $P_{\text{dsc}}^{\text{aspect}}$
- Magnitudes are better described by $P_{\text{dsc}}^{\text{wind}}$

Modeled and downscaled snow deposition patterns for one topography with $P_{\text{coarse}} = 2$ mm:
Results: Modeled and downscaled snowfall - Per aspect and slope

Downscaled and modeled snowfall patterns are similar across all aspects and for various $P_{\text{coarse}}$
- Larger snowfall on leeside increases and lower snowfall on windward side decreases with increasing slope
- Small differences with modeled $P$ for the steepest slope angle bins

Binned per local slope angle $\xi$ with $\Delta \xi = 10^\circ$ and local aspect $\Psi$ with $\Delta \Psi = 30^\circ$:

- $P_{\text{coarse}} = 2$ mm
- $P_{\text{coarse}} = 5$ mm
- $P_{\text{coarse}} = 8$ mm

Results: Performances per aspect and slope

Overall low normalized root-mean-square error (NRMSE) for both downscaling schemes and $P_{\text{coarse}}$

- NRMSE increases with slope angles and is slightly larger on windward slopes
- Wind scheme has lower NRMSE than aspect scheme
- NRMSE similar for all $P_{\text{coarse}}$ (not shown)

Binned per local slope angle $\xi$ with $\Delta\xi = 10^\circ$ and local aspect $\Psi$ with $\Delta\Psi = 30^\circ$:

- $P_{\text{coarse}}$ = 2 mm and for $v_{\text{coarse}}$ = 3 m/s
Conclusions

• Fine-scale modeled snowfall patterns (only preferential deposition) are similar for different coarse-scale snowfall and wind speed

• Large correlations between fine-scale modeled snowfall, vertical wind component as well as terrain aspect relative to coarse wind direction

• Two statistical downscaling schemes describe new snow patterns well for downscaled coarse snowfall of 2 mm, 5 mm and 8 mm:
  1) A wind scheme performs better than a simpler aspect scheme
  2) Performances decrease slightly on windward mountain sides and for steeper slopes (larger 40°)

Outlook

• For coarse wind speed of 5 m/s errors increase especially for steeper slopes (computed for one subset of all topographies only)
  → Further investigation currently underway to better account for different coarse wind speed

• Evaluation on real data

References


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