Mathematical Modeling and Microphysics of Snow Distribution

Oral Presentation

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November 9, 2022

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Outline

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Introduction

Snow

- The cryosphere comprises areas of the Earth where snow and ice cover varies with latitude, altitude, and season.
- The regions of the cryosphere includes; Snow, Sea Ice, Ocean, Frozen Ground, Glaciers, Rivers, and the Atmosphere.
- Snow is defined as "solid precipitation in the form of minute ice crystals at temperatures well below $0^{\circ}C$".
- Snow is formed when temperatures are low, and there is moisture in the atmosphere in the form of tiny ice crystals.

Introduction

Snow

Snow is a crucial part of the Earth's climate system because:

- It reflects about 80% to 90% of the total sunlight hitting its surface, which regulates the planet's temperature.
- Snow acts as an insulating blanket to the ground beneath it by preventing heat and moisture from escaping into the atmosphere.
- It reduces the risk of wildfire.

The interaction between the atmosphere and the land surface via energy and mass exchange processes makes the distribution of snow very vital.

Introduction

Seed papers

1. Rebecca Mott, Vincent Vionnet, and Thomas Grünewald. "The seasonal snow cover dynamics: review on wind-driven coupling processes". In: *Frontiers in Earth Science* 6 (2018), p. 197

2. Varun Sharma, Franziska Gerber, and Michael Lehning. "Introducing CRYOWRF v1. 0: Multiscale atmospheric flow simulations with advanced snow cover modelling". In: *Geoscientific Model Development Discussions* (2021), pp. 1–46

3. Vincent Vionnet et al. "High-resolution large eddy simulation of snow accumulation in Alpine terrain". In: *Journal of Geophysical Research: Atmospheres* 122.20 (2017), pp. 11–005

4. Gregory Thompson et al. "Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part II: Implementation of a new snow parameterization". In: *Monthly Weather Review* 136.12 (2008), pp. 5095–5115

Introduction

Snow Cover

The term "snow cover" describes the blanket of snow that covers the ground and incorporates the ideas of snow depth and area.

- Seasonal snow cover covers an average of $46 \times 10^6 km^2$ of Earth's surface (31% of the land area) annually, it functions as a water reserve in hydrological systems.
- For a continuous snow cover, Snowpack energy balance can be written as[1]

$$-\frac{dH}{dt} = Q_S + Q_L + Q_h + Q_e + Q_a + Q_G \tag{1}$$

[1] Richard L Armstrong and Eric Brun. *Snow and climate: physical processes, surface*

Introduction

- In 1995, Matthew Sturm and Jon Holmgren proposed a new classification system for seasonal snow covers.
- Each of these classes was defined by a unique textural and compositional characteristics, such as the sequence of snow layers, their thickness, density, crystal morphology, and grain characteristics.
- These classes include tundra, taiga, alpine, maritime, ephemeral, prairie.
- In the alpine region, snow is vital for solid precipitation and mountain hydrological process.

Introduction

Snow transport modes

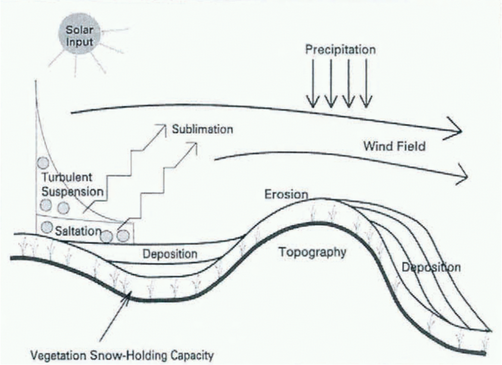

Figure: Source: A snow-transport model for complex terrain by Cambridge Press[2].

This figure represents key features of the snow-transport model.

[2] Glen E Liston and Matthew Sturm. "A snow-transport model for complex terrain".

Introduction

Snow transport modes

In 1992, Kosugi et al. described the three main transport modes for snow as the following:

- Reptation corresponds to the rolling of particles over the snowpack's surface. It is commonly neglected in blowing snow models.
- Saltation corresponds to the transport of snow crystals in a layer close to the ground (typical thickness: 5 – 10 cm).
- Turbulent suspension occurs in the atmosphere above the saltation layer, where turbulent eddies transport snow grains without contact with the surface.

Microphysics

- In the atmosphere, microphysics refers to the study of microscale processes that affect cloud and precipitation particles.
- The microphysics of snow entails the branch of snow physics that studies the phenomena in snow that takes place on the microscopic scale.
- Based on advancing technology, microphysics of snow incorporated into numerical models was grouped to:
  - explicit bin-resolving cloud model parameterizations
  - bulk microphysical parameterizations for modeling cloud microstructure

Microphysics

Points to consider when representing snow to use in a microphysical parameterization according to Thompson et al. (2008), are:

- Snow geometry: the density, diameter, shape, and mass of the snow particle.
- Particle Size Distribution (PSD) diagnostic method: entails how to choose values that define the relative amount of snow according to their size in the snowpack.
- PSD shape is the shape the PSD takes for its mathematical representation.

Microphysics

Suspension Modeling

- In an atmospheric boundary layer with blowing snow, the primary transport mechanisms for erosion, transport, and deposition of snow are saltation and suspension.

  The snow moisture equation is given as[3]

$$\frac{\partial q_L}{\partial t} + u_j \frac{\partial q_L}{\partial x_j} = - \left(\overline{q_L^{\prime} u_j^{\prime}} - q_L W_f \delta_{j3} \right), \qquad (2)$$

  to define precipitation as well as suspension transport.

  - q_L is the humidity (non-vapor part) in $kg_{water} kg_{air}^{-1}$

[3] Peter Gauer. "Blowing and drifting snow in alpine terrain: a physically-based numerical model and related field measurements". PhD thesis. ETH Zurich, 1999.

Snow Model Description

- Snow models compose most climate models, the overall aim of snow model construction is to develop a model of surface processes for specific applications.

- The primary task of the numerical model is to compute the time and space evolution of variables characterizing the snow conditions and their interactions with the environment based on the time integration of physical laws expressed in controlled mathematical equations.

Snow Model Description

Snow Model constituents:

1. Physical processes operating within the snowpack: these are represented by sets of equations responsible for the time evolution of the physical properties of snow under the influence of boundary conditions and the intrinsic snow properties.
2. Initial and Boundary conditions: this concerns mainly the energy and mass balance at the interface between the snowpack and the overlying atmosphere and underlying ground.

Examples of Snow Models

SNOWPACK

- SNOWPACK is a well-established snow cover model developed at the Swiss Federal Institute for Snow and Avalanche Research (SLF), Davos, Switzerland.
- The model is used for predicting snow development with fine stratigraphic details, enabling snow stability estimations.

Examples of Snow Models

SNOWPACK

- The core SNOWPACK module solves the heat equation on a dynamic finite element mesh, which evolves with mass changes of ice and snow to preserve the identity of layers[4].
- The finite element implementation is particularly valuable in describing the varying snow stratigraphy, diverse soil compositions, upper boundary conditions for mass and heat for initial snow density, or for stability corrections .

[4] Michael Lehning et al. "SNOWPACK model calculations for avalanche warning based upon a new network of weather and snow stations". In: *Cold Regions Science and Technology* 30.1-3 (1999), pp. 145–157.

Examples of Snow Models

ALPINE3D

- In 2006, Lehning et al. formed a detailed model of mountain surface processes and their application to snow hydrology known as ALPINE3D;
- It is a model for the high-resolution simulation of alpine surface processes, in particular snow processes.
- It was discovered to be a valuable tool for investigating mountain surface dynamics.
- It is currently used to investigate snow cover dynamics for avalanche warnings, permafrost development, and vegetation changes.

Examples of Snow Models

ALPINE3D

- The ALPINE3D system consists of two structural units: the input/output (I/O) part and the computation part[5].
- The I/O unit has various components: data on topography, initial vegetation, snow cover, soil conditions, the time series of meteorological conditions, simulation parameters, and a choice of output options.
- The computation consists of three core modules: SNOWPACK, SnowDrift, and energy balance, driven by the control module.

[5] Michael Lehning et al. "ALPINE3D: a detailed model of mountain surface processes and its application to snow hydrology". In: *Hydrological Processes: An International Journal* 20.10 (2006), pp. 2111–2128.

Examples of Snow Models

ALPINE3D

- The control module can turn a computation module on or off depending on the simulation parameters from the I/O part, control the simulation time, synthesize the results, and send them to the I/O part.
- The three computation modules will exchange data after each simulation time step.
- The one-dimensional SNOWPACK model was previously coupled with a three-dimensional solver in the atmosphere specifically for snow transport and a spatial description of snow atmosphere interaction to form ALPINE3D.

Examples of Snow Models

CRYOWRF

- In another approach, SNOWPACK was used in the coupling with WRF by Sharma et al. (2021). A unique coupling library was implemented to link SNOWPACK and WRF to form a coupled model called CRYOWRF.
- CRYOWRF is a fully coupled atmosphere-snowpack solver suitable for simulations in alpine and polar regions.
- CRYOWRF brings together two state-of-the-art models, with WRF being the atmospheric core of the model, while SNOWPACK, a high-complexity snow model, acts as the land-surface model (LSM).

Examples of Snow Models

CRYOWRF

Due to the non-hydrostatic dynamical core and domain nesting of WRF, the development of CRYOWRF has the following benefits:

- It enables the use of the same software package for simulations at scales ranging from the global scales with grid sizes of (50–100km) to the turbulent scales with grid sizes of (10–25m).
- It has the ability to model snowpacks at extreme resolutions, for example, when the minimum thickness of a snow layer is set at 0.001m.

Examples of Snow Models

CRYOWRF

- The SNOWPACK model allows for the intelligent merging (splitting) of vertical layers based on their similarity (strong gradients), apart from the physical processes of snow accumulation, melting, and settling.
- A notable feature of CRYOWRF is its ability to run atmospheric simulations with highly (vertically) resolved snowpacks. This allows accurate representation of thin subsurface ice layers of thickness of a few millimeters that significantly impact snow hydrology at larger scales.

Limitations of Snow Models

- Identification of the right choice of topography for the model estimation. How to account for the errors and map out such topography?
- Lack of details for reproducible results.
- Some of the models used are computationally expensive and time-consuming.
- Assumptions about the size and shape of the snow particles.

Open Research Questions

1. How do we determine the correct values of parameters to be used? Does random guess and assumption of some snow parameters affect the accuracy of the results, and under what conditions would they hold?
2. Does global warming affect the snow model's accuracy?
3. Can we choose a specific snow model based on the amount of snow we get in the study region?
4. Snow datasets involves multiple observation types, how do we know the snow datasets are most reliable?
5. How do mismatches between model grids and snow observation stations, especially in areas with complex terrain, affect land–atmosphere feedbacks?

Computing Artifact

- My computing artifact entails the convergence study of the snow transport in the suspension mode using the Galerkin Methods.
- The machinery used to solve this snow moisture equation can be found in the book[6].
- Following what Dr. Kopera taught us in his special topics class - MATH 597.
- It is on github and can be found here

[6] Francis X Giraldo. *An Introduction to Element-Based Galerkin Methods on Tensor-Product Bases: Analysis, Algorithms, and Applications*. Vol. 24. Springer Nature, 2020.

Acknowledgments

A huge thanks to my advisors (Dr. Kopera and Dr. Flores) for their helpful comments and suggestions for improving my synthesis and artifact!

My profound appreciation also goes to Yao Gahounzo and Ibrahim Alabi for the help and support rendered during this write-up.

Gratitude

Thank you for

Listening!

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