SNOW AND CLIMATE

The extent and variability of seasonal snow cover are important parameters in the climate system, due to their effects on energy and moisture budgets, and because surface temperature is highly dependent on the presence or absence of snow cover. In turn, snow-cover trends serve as key indicators of climate change.

In the last two decades many new methods and techniques have become available for studying snow–climate relationships. Satellites provided the first capability for monitoring snow-cover extent at continental and hemispheric scales, enabling the investigation of synoptic-scale snow cover–climate linkages. This global view of snow cover has been accompanied by rapid advances in snow modeling physics to represent snow cover and snow processes in Global Climate Models (GCMs). These advances have changed the way we look at snow cover, and the main goal of this book is to provide an up-to-date synthesis of the current state of snow–climate science that reflects this new perspective. This volume will provide an excellent synthesis for researchers and advanced students.

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SNOW AND CLIMATE

Physical Processes, Surface Energy Exchange and Modeling

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This book is dedicated to the memory of Professor Donald M. Gray, (1929–2005), Chairman of the Division of Hydrology, University of Saskatchewan, and editor (with David Male) of the *Handbook of Snow: Principles, Processes, Management and Use* (1981), which is one of the earliest books to include a complete review of snow physics, accumulation and ablation processes and associated meteorology and climatology. Don pioneered the study of snow in Canada with an insistence that its study include a strong physical and observational basis, the full coupling of the mass and energy equations and consideration of atmospheric as well as surface processes. His contributions to this book are greatly appreciated.

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Preface

While the idea of a book with a focus on snow and climate had been discussed for several years previous, it first took formal shape at a meeting of the International Commission on Snow and Ice (ICSI) of the International Association of Hydrological Sciences (IAHS) in Victoria, British Columbia, Canada in 1996. At that time, a group was formed within the ICSI Division of Snow Cover and Avalanches (chaired by Eric Brun) to begin work on an outline of a state-of-the-art book that would focus on the relationships between snow and climate. A basic outline of the book was developed and section leads were assigned to coordinate the development of detailed outlines of each individual chapter. We recognized that the study of snow and climate was a rapidly evolving science and that there were new demands for detailed representations of snow processes to provide an up-to-date understanding of the physical processes in snow and to support modeling for climate change scenarios. The earlier *Handbook of Snow* (Gray and Male, 1981) provided excellent information on the principles, processes, management, and uses of snow, but no similar book had been published in the intervening two decades. Because we envisioned that this book would perhaps be the only example of an overview of snow and climate available, we agreed that the audience should be broad. Our intent is that this new scientific and comprehensive treatment of the subject of snow and climate becomes a fundamental reference text for university undergraduate and graduate students as well as a reference guide for instructors in secondary schools to assist them in teaching about snow and climate. Because of the world wide interest in snow and snow processes among winter recreationists and much of the general public living in cold regions, this book should also offer a source of basic information for those with only a limited scientific background. Regardless of audience, the fundamental purpose of this book is to introduce the basic scientific principles that enable us to understand the relationships between snow and climate.

Researchers have long been aware of the important role of snow in the climate system. For example, studies on snowfields in Scandinavia were undertaken by

Sverdrup (1935) and Wallen (1949). Later, Houghten (1954), Budyko (1956), and Geiger (1959) included the effect of snow in their studies of the surface heat balance and the associated snow–albedo feedback while Lamb (1955) was one of the first to look at the synoptic-scale influence of snow cover. Williams (1975) was one of the first to explore the influence of snow cover on atmospheric circulation and climate change. In the decades since these studies, many new methods and techniques have become available to study snow–climate relationships. Satellites provided the first capability for monitoring snow-cover extent at continental and hemispheric scales, thus enabling the investigation of synoptic-scale snow cover–climate linkages. This global view of snow cover was accompanied by rapid advances in snow modeling physics to represent snow cover and snow processes in Global Climate Models (GCMs). These processes have changed the way we look at snow cover, and the main goal of this book is to provide an up-to-date synthesis of the current state of snow–climate science that reflects this new perspective.

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Nomenclature

Symbol	Description	Section	Value	Units (SI)
a	Parameter, saturation vapor pressure	2		hPa
a_1	Parameter, effective thermal conductivity	4		W m^{-2} K^{-1}
a_2	Parameter, albedo weight function	4		m^{-1}
a_3	Parameter, albedo weight function	4		m^{-1}
a_4	Parameter, dimensionless sensible heat flux	3		
a_5	"Saltation efficiency" coefficient	3	0.68	m s^{-1}
A	Specific surface of snow	2		m^2 m^{-3}
b	Parameter, saturation vapor pressure	2		
b_1	Parameter, effective thermal conductivity	4		m^6 kg^{-1} s^{-3} K^{-1}
B	Bowen ratio H_S/H_L	3		
B_*	Lower limit for Bowen ratio	3		
c	Parameter, saturation vapor pressure	2		°C
c_1	Parameter, apparent change in roughness length	3	0.1203	
c_2	New snow drift coefficient	3	0.8×10^{-4}	s^3 m^{-2}
c_{susp}	Mass concentration of suspended snow	3		
c_{can}	Canopy closure	3		
$c_{p,a}$	Specific heat of air at constant pressure and at 273.15 K	2, 3	1005	J kg^{-1} K^{-1}

Symbol	Description	Section	Value	Units (SI)
$c_{p,i}$	Specific heat of ice at constant pressure and at 273.15 K	2, 3	2114	J kg^{-1} K^{-1}
$c_{p,\ell}$	Specific heat of water at constant pressure and at 273.15 K	2	4217	J kg^{-1} K^{-1}
$c_{p,s}$	Specific heat of snow at constant pressure	2		J kg^{-1} K^{-1}
C	Shape factor	2		m
C_{hq}	Bulk transfer coefficient	3		
C_D	Bulk transfer coefficient for momentum	3		
C_H	Bulk transfer coefficient for heat	3		
C_Q	Bulk transfer coefficient for water vapor	3		
C_{DN}, C_{HN}, C_{QN}	Parameters, bulk transfer coefficients in terms of the bulk Richardson number	3		
d	Geometrical grain size or diameter	2		m
d_{opt}	Optical grain size	2		m
D_g, D_a	Diffusion coefficient of water vapor in air	2, 3		m^2 s^{-1}
D_s	Diffusion coefficient of water vapor in snow	2		m^2 s^{-1}
D_{bs}	Horizontal blowing snow transport	3		kg m^{-1}
D_{salt}	Saltating transport of blowing snow	3		kg m^{-1} s^{-1}
D_{susp}	Suspension transport of blowing snow	3		kg m^{-1} s^{-1}
E	Sum of sublimation and evaporation rate at surface	3		kg m^{-2} s^{-1}
E_{subl}	Surface sublimation rate	3		kg m^{-2} s^{-1}
E_{evap}	Surface evaporation rate	3		kg m^{-2} s^{-1}
E_{bs}	Sublimation rate of blowing snow	3		kg m^{-2} s^{-1}
f	Parameter, compaction	2		
F	Heat flux	2		W m^{-2}
f_s	Weight function for albedo	4		
g	Acceleration due to gravity	2, 3	9.81	m s^{-2}

Symbol	Description	Section	Value	Units (SI)
G	Ground heat flux	3		W m^{-2}
G_g	Enhancement factor for grain growth	2		m
h	Capillary rise	2		m
$h_{S,b}$	Portion of bare ground sensible heat advected to a snow patch	3		W m^{-2}
h_*	Lower boundary for suspended snow (upper boundary for saltating snow)	3		m
$\tilde{h}$	Mass transfer coefficient	2		m s^{-1}
$\mathcal{H}$	Internal energy of the snowpack	3		J m^{-2}
H_L	Latent heat flux	3		W m^{-2}
H_P	Energy flux carried by precipitation and blowing snow	3		W m^{-2}
H_S	Sensible heat flux	3		W m^{-2}
$H_{S,b}$	Sensible heat flux over bare ground	3		W m^{-2}
$H_{S,s}$	Sensible heat flux over a completely snow-covered fetch	3		W m^{-2}
H'_S	Dimensionless sensible heat flux	3		
HN_w	New snow depth due to blowing and drifting snow	3		m
HS, H	Depth of snowpack, snow depth	2, 3, 4, 5		m
I	Snow interception	3		kg m^{-2}
I_1	Interception before unloading	3		kg m^{-2}
k	Thermal conductivity	2		W m^{-1} K^{-1}
k_a	Thermal conductivity of air	3		W m^{-1} K^{-1}
K_ℓ	Permeability of the interconnected water pathways in wet snow	2		m^2
K_F	Cryoscopic constant for water	2	1.855	K kg mol^{-1}
k_{cl}	Snow clump shape coefficient	3		
k_{eff}	Effective thermal conductivity	2		W m^{-1} K^{-1}
k_i	Thermal conductivity of ice	4		W m^{-1} K^{-1}
K	Intrinsic or saturated permeability	2		m^2
K_k	Permeability of phase k in unsaturated wet snow	2		m^2
K_{rk}	Relative permeability of phase k in unsaturated wet snow ($=K_k/K$)	2		
$L_{i\ell}$, $L_{\ell i}$	Latent heat of fusion for ice at 273.15 K	2, 3	3.335×10^5	J kg^{-1}

Symbol	Description	Section	Value	Units (SI)
$L_{\mathrm{iv}}, L_{\mathrm{vi}}$	Latent heat of sublimation for ice at 273.15 K	2, 3	2.838×10^6	J kg^{-1}
$L_{\ell\mathrm{v}}, L_{\mathrm{v}\ell}$	Latent heat of evaporation for water at 273.15 K	2, 3	2.505×10^6	J kg^{-1}
L_{ji}	Latent heat of phase change from phase j to phase i	2		J kg^{-1}
$\mathcal{L}_{\mathrm{L}}$	Snow load	3		kg m^{-2}
$\mathcal{L}_{\mathrm{L,o}}$	Initial snow load	3		kg m^{-2}
$\mathcal{L}^*_{\mathrm{L}}$	Maximum canopy snow load	3		kg m^{-2}
$\mathcal{L}_{\mathrm{L,b}}$	Maximum snow load per unit area of branch	3		kg m^{-2}
L_{O}	Obukhov length	3		m
L_{N}	Net flux of longwave radiation, $L\downarrow + L\uparrow$	3		W m^{-2}
LAI	Winter leaf and stem area index	3		m^2 m^{-2}
$\mathrm{L}^*_{\mathrm{L}}$	Maximum canopy snow load	3		kg m^{-2}
$L\downarrow$	Downward component of longwave radiation	3		W m^{-2}
$L\uparrow$	Upward component of longwave radiation	3		W m^{-2}
m	Parameter, water saturation (van Genuchten)	2		
M	Molality of species	2		mol kg $^{-1}$
m_{p}	Mass of single blowing snow particle	3		kg
$\dot{m}$	Mass growth rate of snow particle	2		kg s^{-1}
$\mathcal{M}$	Snow mass per unit surface area	3		kg m^{-2}
n	Parameter, water saturation (van Genuchten)	2		
Nu	Nusselt number	3		
N_{Re}	Particle Reynolds number	3		
p	Pressure	2		Pa
p_{a}	Atmospheric or air pressure	2		hPa or Pa
p_{e}	Air-entry pressure	2		Pa
p_k	Pressure of constituent k	2		Pa
$p_{\mathrm{a}\ell}$	Capillary pressure or pressure drop $(p_{\mathrm{a}} - p_\ell)$ across air/water interface	2		Pa

Symbol	Description	Section	Value	Units (SI)
p_{ij}	Pressure drop ($p_i - p_j$) across i/j interface	2		Pa
$p_{\mathrm{v,sat},k}$	Saturation vapor pressure over a flat surface with respect to constituent k	2		hPa
$p'_{\mathrm{v,sat},k}$	Saturation vapor pressure over a curved surface with respect to constituent k	2		hPa
P	Precipitation rate	3		kg m^{-2} s^{-1}
$\mathcal{P}$	Accumulated precipitation	3		kg m^{-2}
Pe	Peclet number	2		
P_{bs}	Probability of blowing snow occurrence	3		
q	Phase change thermal source term	2		W m^{-3}
Q	Specific humidity	3		kg/kg
Q_{o}	Specific humidity at the snow surface	3		kg/kg
Ra	Rayleigh number	2		
r_{pt}	Particle radius	3		m
$r_{\mathrm{pt,n}}$	Nominal snow particle radius	3	0.0005	m
r_{p}	Tube radius or equivalent pore radius	2		m
r_{g}	Snow grain radius	2, 3		m
Ra_{crit}	Critical Rayleigh number for onset of convection	2		
Re	Reynolds number	3		
Ri_{B}	Bulk Richardson number	3, 4		
R_{v}	Gas constant for water vapor	2	461.50	J kg^{-1} K^{-1}
R_{F}	Freezing rate	3		kg m^{-2} s^{-1}
R_{M}	Melt rate	3		kg m^{-2} s^{-1}
R_{N}	Net radiative flux at the snow surface, $S_{\mathrm{N}} + L_{\mathrm{N}}$	3		W m^{-2}
R_{runoff}	Runoff rate at snow–soil interface	3		kg m^{-2} s^{-1}
s	Liquid water saturation (θ_ℓ/ϕ)	2		
s_{i}	Irreducible or immobile liquid water saturation	2		
s^*	Effective liquid water saturation $[(s - s_{\mathrm{i}})/(1 - s_{\mathrm{i}})]$	2		
S	Phase change mass source term	2		kg m^{-3} s^{-1}
Sh	Sherwood number	3		

Symbol	Description	Section	Value	Units (SI)
S_{toa}	Solar radiation flux at the top of the atmosphere	3		W m^{-2}
SCA	Proportion of snow-covered area	3		
S_{N}	Net flux of shortwave radiation, $S\downarrow + S\uparrow$	3		W m^{-2}
SWE	Snow water equivalent	2, 3, 4, 5		kg m^{-2} (or mm w.e.)
$S\downarrow$	Downward component of solar radiation	3		W m^{-2}
$S\uparrow$	Reflected component of solar radiation	3		W m^{-2}
t	Time	2, 3, 4		s
t_{h}	Snow surface age	3		hours
T	Temperature	2, 3		K or °C
T_{d}	Melting point depression, $273.15 - T$	2		K
T_0	Melting temperature 273.15 or 0 °C	2		K or °C
T_{o}, T_0	Snow surface temperature	3, 4		K or °C
$T_{\mathrm{o,sp}}$	Ice sphere surface temperature	3		K
T_{a}	Air temperature	3, 4		K or °C
T_{s}	Snow temperature	3		K or °C
T'	Snow temperature gradient	2		K m^{-1} or °C m^{-1}
T_{mean}	Mean air temperature in layer of depth ζ_{ref}	3		K
u	Wind speed	3		m s^{-1}
u_{10}	Average hourly 10-m wind speed	3		m s^{-1}
$\bar{u}$	Mean wind speed	3		m s^{-1}
$\bar{u}_{\mathrm{crest}}$	Mean wind speed measured on a crest	3		m s^{-1}
u_*	Friction velocity	3		m s^{-1}
$u_{*\mathrm{n}}$	Friction velocity applied to small-scale non-erodible elements	3		m s^{-1}
$u_{*\mathrm{t}}$	Threshold friction velocity	3		m s^{-1}
U_I	Snow unloading coefficient	3		s^{-1}
v_i	Velocity of ice matrix	2		m s^{-1}
v_k	Flow (filter) velocity of fluid k (a = air, ℓ = water)	2		m s^{-1}

Symbol	Description	Section	Value	Units (SI)
V	Volume per unit mass or reciprocal density	2		$m^3\ kg^{-1}$
w	Vertical (wind) velocity	3		$m\ s^{-1}$
w_*	Dimensionless vertical velocity	3		
x, y, z	Coordinate system with z positive upward relative to the ground	2, 3		m
x	Spatial coordinate along the direction of flow	2		m
x_M, x_H	Parameters, similarity function	3		
X	Dimensionless distance downwind of snow patch	3		
z_{ref}	Reference height above ground	3		m
z_b	Upper boundary for suspended snow	3		m
z_o, z_0	Momentum (or aerodynamic) roughness length; surface roughness length	3, 4		m
z_H	Roughness length for heat	3		m
z_Q	Roughness length for water vapor	3		m
z_*	Scale of roughness elements	3		m
α	Snow (surface) albedo	2, 3		
α_b	Albedo of snow-free (bare) surface	4		
α_{max}	Upper limit on snow albedo	4		
α_{min}	Lower limit on snow albedo	4		
α_s	Albedo of deep, homogeneous snow	4		
β	Coefficient of solar absorption	2		cm^{-1}
$\tilde{\beta}$	Coefficient of thermal expansion	2		K^{-1}
β_{1H}, β_{1M}	Parameters, similarity function	3		
β_1	Parameter, similarity function, $\beta_1 = \beta_{1M} = \beta_{1H}$	3		
Δt	Time interval	4		s
Δx	Characteristic distance	2		m
γ_1, γ_2	Parameters, similarity function	3		
δ	Standard deviation of wind speed	3		$m\ s^{-1}$
ε	Snow infrared emissivity	3		
ε_{eff}	Effective emissivity for the atmosphere	3		
ε	Exponent, phase permeability	2		

Symbol	Description	Section	Value	Units (SI)
ζ	Height above snow surface	3		m
ζ_{ref}	Reference height above snow surface	3		m
ζ_{ij}	Radius of curvature of i/j interface	2		m
η	Newtonian viscosity of snow	2		Pa s
η_0	Newtonian viscosity of snow at $T = 0\ ^\circ\mathrm{C}$ and $\rho_\mathrm{s} = 0.0\ \mathrm{kg\ m^{-3}}$	2		Pa s
η_k	Dynamic viscosity of fluid k	2		Pa s
θ	Contact angle between solid and liquid	2		rad.
θ_k	Volume fraction of constituent k	2, 3		
κ	Von Kármán constant	3		
κ_s	Turbulent diffusion coefficient for snow particles	3		$\mathrm{m^2\ s^{-1}}$
λ	Wavelength	2		μm
λ_p	Pore-size distribution index	2		
Λ	Leaf area index	4		
Λ	Thermal diffusivity ($k/\rho_\mathrm{a} \cdot c_{\mathrm{p,a}}$)	2		$\mathrm{m^2\ s^{-1}}$
μ_a	Kinematic viscosity of air (η_a / ρ_a)	3		$\mathrm{m^2\ s^{-1}}$
ρ_a	Density of air	2, 3		$\mathrm{kg\ m^{-3}}$
$\rho_{0,\mathrm{a}}$	Reference density of air	2		$\mathrm{kg\ m^{-3}}$
ρ_i	Density of ice	2, 3	917	$\mathrm{kg\ m^{-3}}$
ρ_k	Density of fluid or solid k	2		$\mathrm{kg\ m^{-3}}$
ρ_ℓ	Density of water	2, 3, 4	1000	$\mathrm{kg\ m^{-3}}$
ρ_{max}	Maximum permitted snow density	4		
ρ_s	Density of snow	2, 3, 4, 5		$\mathrm{kg\ m^{-3}}$
ρ_v	Density of water vapor	2		$\mathrm{kg\ m^{-3}}$
$\rho_{\mathrm{v,a}}$	Density of water vapor in air	3		$\mathrm{kg\ m^{-3}}$
$\rho_{\mathrm{v,pt}}$	Density of water vapor at particle surface	3		$\mathrm{kg\ m^{-3}}$
$\rho_{\mathrm{v,sat}}$	Saturation density of water vapor	2, 3		$\mathrm{kg\ m^{-3}}$
σ_{SB}	Stefan–Boltzmann constant	3	5.6697×10^{-8}	$\mathrm{W\ m^{-2}\ K^{-4}}$
$\sigma_{a\ell}$, $\sigma_{\ell\mathrm{v}}$	Surface tension of air/water interface	2	0.076	$\mathrm{N\ m^{-1}}$
$\sigma_{\mathrm{i}\ell}$	Surface tension of ice/water interface	2	0.028	$\mathrm{N\ m^{-1}}$
σ_{iv}	Surface tension of ice/vapor interface	2	0.104	$\mathrm{N\ m^{-1}}$
σ_{ij}	Surface tension of i/j interface	2		$\mathrm{N\ m^{-1}}$

Symbol	Description	Section	Value	Units (SI)
τ_o	Surface stress	3		N m^{-2}
τ_{atm}	Atmospheric shear stress	3		N m^{-2}
τ_n	Atmospheric shear stress on non-erodible surface	3		N m^{-2}
τ_p	Atmospheric shear stress on saltating bed of snow particles	3		N m^{-2}
τ_s	Atmospheric shear stress on stationary erodible surface	3		N m^{-2}
τ_α	Time constant for albedo	4		s
τ_ρ	Time constant for density	4		s
ϕ	Snow porosity	2		
Φ	Surface-layer similarity function	3		
χ_I	Exponent for bulk transfer coefficient	3		
ψ	Angle between direction of flow and downward vertical	2		rad.
Ψ_H	Integrated form of surface-layer similarity function for heat	3		
Ψ_M	Integrated form of surface-layer similarity function for momentum	3		
Ψ_Q	Integrated form of surface-layer similarity function for water vapor	3		

Subscripts

Subscript	Description
a	Air or atmosphere
b	Bare ground
i	Ice
i	Phase
j	Phase
k	Constituent
ℓ	Liquid water
s	Snow
sat	Saturated or equilibrium state
v	Vapor