Climate and Hydrology in Mountain Areas

Editors

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List of Symbols

$\widehat{A}$	Fuzzy number of variable or parameter A
a	coefficient or empirical parameter
a_r	ratio
a^l, a^c & a^r	Characteristic left, center and right values, respectively, of a triangular fuzzy number $\widehat{A}$
$[a^l(\alpha), a^r(\alpha)]$	$a^l(\alpha)$ and $a^r(\alpha)$ indicate the lower and upper bounds of the interval $\widehat{A}(\alpha)$ at any α-level in the interval [0,1]
b	coefficient or empirical parameter
C_*	effective heat capacity of the surface ($\mathrm{J\,m^{-2}\,K^{-1}}$)
$C_{*,\mathrm{snow}}$	effective heat capacity of snow ($\mathrm{J\,m^{-2}\,K^{-1}}$)
C_e	bulk moisture transfer coefficient
$\widehat{C}_\mathrm{fc}$	Soil moisture capacity until field capacity of the soil profile (mm)
C_h	bulk heat transfer coefficient
$\widehat{C}_\mathrm{tp}$	Total capacity of the soil profile. The maximum storage capacity of the bucket model (mm)
c	velocity of the electromagnetic waves in the void ($\mathrm{m\,s^{-1}}$)
c_p	specific heat content of air at constant pressure ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
D	hydraulic diffusivity ($\mathrm{m^2\,s^{-1}}$)
$D(\theta)$	Hydraulic diffusivity in the porous medium ($\mathrm{L^2T^{-1}}$, $\mathrm{m^2\,s^{-1}}$)
D_0	constant with the dimensions of the hydraulic diffusivity ($\mathrm{m^2\,s^{-1}}$)
D_f	density of the forest canopy
$\widehat{D}_\mathrm{tp}$	Total depth of the soil profile to an impervious layer (mm)
d	displacement height (m)
E	evaporation (kg)
E_cum	cumulative evaporation (m)
E_F	frozen soil moisture content ($\mathrm{kg\,m^{-2}}$)
E_g	ground evaporation ($\mathrm{kg\,m^{-2}\,s^{-1}}$)
E_i	istantaneous evaporation ($\mathrm{m\,s^{-1}}$)
E_L	liquid soil moisture content ($\mathrm{kg\,m^{-2}}$)
E_s	snow evaporation rate ($\mathrm{kg\,m^{-2}\,s^{-1}}$)
E_TOT	total evaporation rate ($\mathrm{kg\,m^{-2}\,s^{-1}}$)
E_v	evaporation flux ($\mathrm{m\,s^{-1}}$)
EL_e	latent turbulent heat flux ($\mathrm{W\,m^{-2}}$)
ET	evaporation and transpiration ($\mathrm{mm\,day^{-1}}$)
$\widehat{E}$	Daily potential ($\widehat{E}_p$) or actual evapotranspiration ($\widehat{E}_a$) ($\mathrm{mm\,d^{-1}}$)
e_0	vapour pressure (hPa)
e_s	saturated vapour pressure (Pa)
F	Fractional Vegetation Cover
F_{ms}	correction term for diffuse radiation due to multiple scattering between ground and sky (dimensionless)
F_{sk}	correction term for diffuse radiation from the sky (dimensionless)

F_t	correction term for the angle of incidence of sun on the slope (dimensionless)
f_v	skyview factor (dimensionless)
G_e	Shape parameter (Reynolds and Elrick, 1991) (−, −)
H	Hydraulic head (L, m)
H_c	soil column depth (m)
H_{geo}	Geodetic head (L, m)
$h, h(t), h^*$	Water level inside the infiltrometer (L, m)
h_{sun}	theoretical maximum duration of subshine hours (h)
I	interception (mm)
$I_{\max}$	storage capacity (mm)
I_p	interception of liquid precipitation (mm)
I_s	interception of solid precipitation (mm)
I_{sc}	solar constant ($\mathrm{W\,m^{-2}}$)
$I(t)$	Cumulated drawdown of the water inside the infiltrometer (L, m)
IDW	inverse distance weighting method
$K, K(\theta)$	Hydraulic conductivity ($\mathrm{LT^{-1}}$, $\mathrm{m\,s^{-1}}$)
K	the value of k such that probability function of T_k becomes zero
K_a	apparent dielectric constant (−)
K_{HI}	horizontal hydraulic conductivity
K_s	Saturated hydraulic conductivity ($\mathrm{LT^{-1}}$, $\mathrm{m\,s^{-1}}$)
K_{VI}	vertical hydraulic conductivity
K^*	short-wave radiation budget ($\mathrm{W\,m^{-2}}$)
$K\downarrow$	incoming solar radiation ($\mathrm{W\,m^{-2}}$)
$K\downarrow_{\text{snow}}$	solar flux penetrating the snowpack ($\mathrm{W\,m^{-2}}$)
k'	z-axis unitary vector, positive upward (−, −)
k_b	degree-day factor for ice ablation ($\mathrm{mm\,d^{-1}\,{}^\circ C^{-1}}$)
k_d	degree-day factor for ice ablation under debris ($\mathrm{mm\,d^{-1}\,{}^\circ C^{-1}}$)
L	wave guide length (m)
$L(t)$	Length of the saturated soil depth (L, m)
L^*	long-wave radiation budget ($\mathrm{W\,m^{-2}}$)
$L\downarrow$	long-wave downward radiative flux ($\mathrm{W\,m^{-2}}$)
$L\uparrow$	long-wave upward radiative flux ($\mathrm{W\,m^{-2}}$)
$L'\downarrow$	long-wave radiative flux reflected from surrounding slopes ($\mathrm{W\,m^{-2}}$)
L_e	latent heat of evaporation/sublimation ($\mathrm{J\,kg^{-1}}$)
L_{f}	latent heat of fusion of water ($\mathrm{J\,kg^{-1}}$)
L_H	cumulative loss/gain in the soil volumetric water content storage (m)
L_{inf}	Soil length inside the infiltrometer (L, 0.10 m)
L_s	latent heat of sublimation ($\mathrm{J\,kg^{-1}}$)
M	number of observations in a day
M_a	moleculary mass of dry air
M_{F}	frozen soil moisture ($\mathrm{kg\,m^{-2}}$)
M_{S}	melting rate of snow ($\mathrm{kg\,m^{-2}\,s^{-1}}$)
M_{snow}	snow mass ($\mathrm{kg\,m^{-2}}$)
M_t	snowmelt from the trees (mm)
m	Archie exponent; describes the effect of porosity on resistivity change for different materials (−)
$\widehat{m}_f$	Melt factor for snowmelt processes at thaw conditions ($\mathrm{mm\,K^{-1}}\,\Delta t^{-1}$)
N	number of days
n	saturation exponent; describes the effect of saturation on resistivity change (−)
n'	Surface unitary vector, positive outward (−, −)
P	precipitation (mm)
P_0	threshold precipitation (mm)
P_a	atmospheric pressure (Pa)

P_{BH}	precipitation observed at the base house (mm)
P_c	snow falling from the trees (mm)
P_{cum}	cumulative precipitation (m)
P_f	ground precipitation inside a forest canopy (mm)
P_h	precipitation in a single time step (mm)
P_i	instantaneous precipitation ($\mathrm{m\,s^{-1}}$)
P_{L}	liquid precipitation rate ($\mathrm{kg\,m^{-2}\,s^{-1}}$)
P_r	precipitation rate ($\mathrm{mm\,s^{-1}}$)
P_{S}	solid precipitation rate ($\mathrm{kg\,m^{-2}\,s^{-1}}$)
P_{snow}	cumulative precipitation of the snowfall event (mm)
P_Z	precipitation at altitude Z (mm)
P^*	Orographic Precipitation
$\widehat{P}$	Daily precipitation falling as rain ($\widehat{P}_{\mathrm{r}}$) or snow ($\widehat{P}_{\mathrm{s}}$) ($\mathrm{mm\,d^{-1}}$)
p	Pressure ($\mathrm{ML^{-1}T^{-1}}$, kPa)
p_{sfc}	surface pressure (hPa)
Q	Streamflow (Total Runoff) ($\mathrm{m^3\,s^{-1}}$)
Q^*	all-wave surface radiation budget ($\mathrm{W\,m^{-2}}$)
Q_{diff}	diffuse solar radiation ($\mathrm{W\,m^{-2}}$)
$Q_{\mathrm{diff},f}$	diffuse solar radiation in the forest canopy ($\mathrm{W\,m^{-2}}$)
Q_{dir}	direct solar radiation ($\mathrm{W\,m^{-2}}$)
$Q_{\mathrm{dir},f}$	direct solar radiation in the forest canopy ($\mathrm{W\,m^{-2}}$)
Q_{e}	latent heat flux ($\mathrm{W\,m^{-2}}$)
Q_H	sensible turbulent flux per unit area ($\mathrm{W\,m^{-2}}$)
Q_{h}	sensible heat flux ($\mathrm{W\,m^{-2}}$)
Q_l	incoming infrared radiation ($\mathrm{W\,m^{-2}}$)
$Q_{l,f}$	incoming infrared radiation in the forest canopy ($\mathrm{W\,m^{-2}}$)
Q_o	Observed discharge at closure section (crisp value) ($\mathrm{mm\,d^{-1}}$)
Q_{s}	Subsurface Flow ($\mathrm{m^3\,s^{-1}}$)
Q_{sfc}	heat storage term ($\mathrm{W\,m^{-2}}$)
Q_{snow}	heat flux through the snowpack ($\mathrm{W\,m^{-2}}$)
$\widehat{Q}_{\mathrm{bf}}$	Daily baseflow ($\mathrm{mm\,d^{-1}}$)
$\widehat{Q}_{\mathrm{in}}$	Daily interflow ($\mathrm{mm\,d^{-1}}$)
$\widehat{Q}_N$	Daily snowmelt at thawing conditions ($\mathrm{mm\,d^{-1}}$)
$\widehat{Q}_p$	Modeled discharge at closure section ($\mathrm{mm\,d^{-1}}$)
$\widehat{Q}_{\mathrm{se}}$	Daily saturation excess runoff ($\mathrm{mm\,d^{-1}}$)
$\widehat{Q}_{\mathrm{ss}}$	Daily sub-surface runoff ($\mathrm{mm\,d^{-1}}$)
q	Apparent velocity of the fluid in the porous medium ($\mathrm{LT^{-1}}$, $\mathrm{m\,s^{-1}}$)
q_{air}	specific humidity at the screen level ($\mathrm{kg\,kg^{-1}}$)
$q_{\mathrm{sat,sfc}}$	saturation specific humidity at the surface ($\mathrm{kg\,kg^{-1}}$)
R	thermal resistance of debris ($\mathrm{m^2\,{}^\circ C\,W^{-1}}$)
R^2	coefficient of determination
R_a	aerodynamic resistance of the canopy ($\mathrm{s\,m^{-1}}$)
R_c	thermal resistance for critical debris thickness ($\mathrm{m^2\,{}^\circ C\,W^{-1}}$)
$R_{\mathrm{eff}}(Q)$	Model efficiency according to Nash and Sutcliffe (1970) (−)
$R_{\mathrm{eff}}(\log Q)$	Model efficiency according to Nash and Sutcliffe (1970) using logarithmic runoff values (−)
R_{off}	total runoff ($\mathrm{kg\,m^{-2}}$)
RH	relative humidity (dimensionless)
RH_f	relative humidity in the forest canopy
$R_{Z/R}$	Rainfall intensities, used in Z/R-relation for weather radar data adjustment ($\mathrm{mm\,h^{-1}}$)
r	Radius of the infiltrometer (L, m)
r_S	Soil moisture ratio; S is a fraction of C_{fc} (1)
S	fraction of the pore space occupied by liquid water (−)

S_{max}	maximum snow interception (mm)
S_w	fraction of water remaining unfrozen at subfreezing temperatures or unfrozen water content (−)
$SW\downarrow$	short-wave downward radiative flux (W m^{-2})
$SW\uparrow$	short-wave upward radiative flux (W m^{-2})
$\widehat{S}$	Soil water storage; re-scaled soil water storage $\widehat{S}'$ is carried over from time step t to $t+1$ (mm)
$\widehat{S}_N$	Storage of snow water equivalent in the snowpack (mm)
s	local slope
s_e	Effective saturation (−, −)
T	temperature (°C)
T_0	initial temperature (°C)
T_0	reference temperature (°C)
T_0'	reference temperature corresponding to ρ_0 (°C)
T_{air}	air temperature (K)
$T_{air,f}$	air temperature in the forest canopy (K)
$T_{air,sl}$	air temperature at screen level (K)
T_d	dew point temperature (K)
$T_{f,C}$	temperature at the freezing point (°C)
T_{fK}	freezing temperature (K)
T_g	ground surface temperature (K)
T_g	soil temperature
T_{his}	historical temperature over 24 h (K)
T_k	temperature at the kth times (°C)
T_{max}	maximum air temperature (K)
T_{mean}	mean daily air temperature (K)
T_{min}	minimum air temperature (K)
T_n	temperature on the nth day (°C)
T_s	snow surface temperature (K)
T_{sfc}	surface temperature (K)
$\widehat{T}$	Mean daily air temperature (°C)
$\widehat{T}_{crit}$	Critical mean air temperature: threshold between frost or thaw situations and rain or snow events (°C)
$\widehat{T}_{pos}$	Daily mean air temperature. If $\widehat{T}_{pos}$ is below $\widehat{T}_{crit}$, then $\widehat{T}_{pos}$ is set to $\widehat{T}_{crit}$ (°C)
t	time (s)
$\widehat{t}_c$	Catchment response time of the total runoff process (days)
$\widehat{t}_{c-bf}$	Catchment response time of the baseflow component (days)
$\widehat{t}_{c-in}$	Catchment response time of the interflow component (days)
u	wind speed (m s^{-1})
u^*	dimensionless composite variable of space and time (−)
u_f	wind speed inside the forest canopy (m s^{-1})
$\overline{u}$	mean wind speed (m s^{-2})
V	volume of seasonal snow melt runoff
V	constant with the dimensions of the velocity (m s^{-1})
V_a	anemometer-level wind magnitude (m s^{-1})
v	velocity of the electromagnetic wave in a medium (m s^{-1})
W	total soil moisture (liquid and frozen) (kg m^{-2})
W_F	frozen soil moisture content (kg m^{-3})
W_L	liquid soil moisture content (kg m^{-3})
X	dimensionless hydraulic diffusivity (−)
x_o	Organic matter (MM^{-1}, −)
Y	degree-day sum (°C d)
Z	altitude (m)
Z_{radar}	Radar reflectivities observed with a weather radar, used in Z/R-relation

z	height above ground (m)
z	vertical space coordinate (positive downward) (m)
z_0	roughness length (m)
$z_{0,\mathrm{sfc}}$	surface roughness height (m)
$z_{0,\mathrm{snow}}$	snow roughness height (m)
z_e	roughness element height (m)
z_m	measurement height above ground (m)

Greek

α	surface albedo (dimensionless)
α	Sorptive number (L, m^{-1})
$\alpha_{\mathrm{nir,sfc}}$	near-infrared surface albedo (dimensionless)
$\alpha_{\mathrm{nir,snow}}$	near-infrared snow albedo (dimensionless)
α_{nm}	variable (either one or zero)
α_{snow}	albedo of the snow surface (dimensionless)
$\alpha_{\mathrm{s,sfc}}$	albedo of the visible spectrum at the surface (dimensionless)
$\alpha_{\mathrm{s,snow}}$	snow visible albedo (dimensionless)
α_T	temperature coefficient of resistivity ($^\circ C^{-1}$)
$\alpha_{Z/R}$	empirical parameter of the Z/R-relation for weather radar data adjustment (−)
$\beta_{Z/R}$	empirical parameter of the Z/R-relation for weather radar data adjustment (−)
β_{BR}	Bowen ratio
β_{e}	evaporation factor
γ_w	Water unitary weight ($ML^{-2}T^{-2}$, 9806 $N\,m^{-3}$)
ΔQ_{m}	latent heat storage change ($W\,m^{-2}$)
ΔQ_{s}	energy storage within the snowpack ($W\,m^{-2}$)
Δz	snow depth (m)
$\Delta^l(\alpha)$	Interval between $a^l(\alpha)$ and a^c at any $\alpha \in [0, 1]$; same for $\Delta^r(\alpha)$
δ_{snow}	snow fraction at the surface (fraction)
ε	emissivity (dimensionless)
ε_f	emissivity of the forest (dimensionless)
ε_r	relative dielectric permittivity (−)
ε_{s}	surface emissivity (dimensionless)
ϑ	normalized soil volumetric water content (−)
ϑ_i	vertical soil volumetric water content profile at the time origin (−)
ϑ_0	volumetric water content at the upper boundary (−)
θ	soil volumetric water content (%)
θ_l	local horizon angle (radians)
θ_M	maximum value of the soil volumetric water content (%)
θ_m	minimum value of the soil volumetric water content (%)
θ_{res}	Residual volumetric water content ($L^3\,L^{-3}$, −)
θ_s	soil volumetric water content at the saturation (%)
θ_{sat}	Saturated volumetric water content ($L^3\,L^{-3}$, −)
$\widehat{\theta}_{\mathrm{fc}}$	Field capacity (1)
$\widehat{\theta}_{\mathrm{pwp}}$	Permanent wilting point (1)
κ	Karman constant
λ	wavelength of radiation (µm) λ
λ	Pore-size distribution index (−, −)
λ_f	frontal area index (dimensionless)
λ_{snow}	heat conductivity of snow ($W\,m^{-1}\,J^{-1}$)
μ	Level of presumption
μ_r	relative magnetic permeability (−)
Φ	porosity (−)

Φ_h	horizontal component of the volumetric water content flux ($m\,s^{-1}$)
Φ_z	vertical component of the volumetric water content flux ($m\,s^{-1}$)
$\widehat{\phi}$	Soil porosity (1)
φ	azimuth (radians)
ρ	electrical resistivity (Ωm)
ρ_0	reference electrical resistivity corresponding to T_0 (Ωm)
ρ_{a}	density of air ($kg\,m^{-3}$)
ρ_f	electrical resistivity of a partially frozen material (Ωm)
ρ_i	electrical resistivity of the same material in unfrozen state (Ωm)
ρ_p	electrical resistivity of the water in the pore space (Ωm)
ρ_{snow}	snow density ($kg\,m^{-3}$)
ρ_{w}	density of water ($kg\,m^{-3}$)
σ	Stefan-Boltzmann constant ($W\,m^{-2}\,K^{-4}$)
Ψ	Matric potential ($ML^{-1}T^{-1}$, kPa)
Ψ_b	Bubbling pressure ($ML^{-1}T^{-1}$, kPa)
ψ	matric potential (m)
$\psi(\theta)$, $\psi(s)$	Water retention relationship (L, m)
ψ_b	Bubbling pressure (L, m)
ψ_s	air entry potential (m)
ω	diurnal frequency (s^{-1})
ω_p	precipitable water (cm)

Special

$(+)$	Symbol of fuzzy addition; all fuzzy arithmetic operations are symbolized with brackets, e.g.: $(+)$, (Σ), $(-)$, $(\bullet)$, $(\div)$, $(=)$, $(>)$, $(\leq)$ and $(\neq)$
$[\bar{\ }]$	Long term mean annual value
$\langle\bar{\ }\rangle$	Long term mean monthly value
$[\ ]$	Annual value
$\langle\ \rangle$	Monthly value
no brackets	Daily value

Abbreviations

PDD	positive degree-day sum
JSPS	Japan Society for the Promotion of Science
SD	standard deviation
DEM	digital elevation model
EFFS	European Flood Forecasting System
ISBA-CROCUS	energy balance-snow model
SVAT	soil-vegetation-atmosphere transfer model
GCM	Global Circulation Model
NWP	Numerical Weather Prediction
LAI	leaf area index
DTM	Digital terrain model
SCA	snow covered area
SRM	Snowmelt Runoff Model
NVE	Norwegian Water Resources and Energy Administration
CDD	cumulative degree-days
PACE	Permafrost and Climate in Europe
DC	direct current
MAAT	mean annual air temperature
SVAT	soil-vegetation-atmosphere transfer
NWP	numerical weather prediction
SOP	Special Observing Period
LUT	Look-Up Tables
MD	mean differences
CM	Chiew and McMahon
NS	Nash and Sutcliffe
ET	evaporation and transpiration
SHAW	Simultaneous Heat and Water
WRCCRF	Wind River Canopy Crane Research Facility
LAI	leaf area index
WRRS	Wind River Ranger Station
EC	eddy-covariance
ROI	Region Of Influence
TCEV	Two Component Extreme Value
LSS	land surface scheme
CLASS	Canadian Land Surface Scheme
GUH	geomorphological instantaneous unit hydrograph
GIS	geographic information system
MGS	Mackenzie GEWEX Study
CAGES	Canadian GEWEX Enhanced Study
RMS	root mean square
TAC	tracer aided catchment
ET	evapotranspiration
DEM	digital elevation models
ERU	Evaporation Response Units
HRU	Hydrological Response Units
RCM	Regional Climate Model
GCM	Global Circulation Models
SEBM	surface energy balance model
DOY	Days of Year
F	fractional vegetation cover
LAI	leaf area index
NDVI	normalized difference vegetation index
SFRM	Subsurface Flow Routing Model
LSHM	Land Surface Hydrology Model
LSFRM	Lateral Subsurface Flow Routing Model
DEM	Digital Elevation Model
USGS	United States Geological Survey
ECMWF	European Center for Medium Range Forecast
LAI	leaf area index
NDVI	Normalized Difference Vegetation Index
AVHRR	Advanced Very High Resolution Radiometer

Introduction: Climate and Hydrology in Mountain Areas

Undoubtedly, the mountain regions of our world are the main hydrological and climatological triggers or pertubators of the water cycle as well as of complex meteorological patterns including phenomena such as the production or inhibition of rainfall. In terms of their role as water towers, mountain regions form an important supply of snow and/or rain-fed water to the lowlands. In terms of climate, mountain systems develop a considerably complex system of their own, influenced by the often characteristically narrow, deeply incised valleys. It is rare though, to find comprehensive work that combines both the hydrological and climatological aspects of mountain catchments. The purpose of this book is therefore to bring together a very diverse group of scientists from all over the world to present their multidisciplinary research in contrasting mountain environments. This effort was developed by Carmen de Jong in cooperation with Roberto Ranzi and David Collins during the International Year of the Mountains 2002 and is based on cross-disciplinary mountain sessions at EGS/EGU meetings, a diverse team of supportive meeting participants and invited scientists. The ultimate goal was, firstly, to provide a platform for discussion amongst highly motivated and trendsetting mountain groups from different origins and secondly, to combine two hitherto separately treated subject matters – that of hydrology and climatology in mountain areas. Although hydrology and climatology appertain to two separate disciplines, it is important to acknowledge the fact that in nature they are inseparable and that enough crosscutting areas exist that cannot ignore their mutuality. It is not always easy to bring together the different disciplines, but as long as scientists are cooperating strongly in the way observed in this group of authors, such endeavours are possible.

This book covers a wide range of mountain chains including the Alps, Black Forest, Himalayas, Tien Shan, Giant mountains, Norwegian mountains, Laurentian highlands, Appalachian mountains, Rockies, Andes, and Cascade mountains (see Figure 1). From the distribution of study areas covered, it is obvious that several African mountain ranges and other mountains of the southern hemisphere are missing in this volume. It is hoped to incorporate these in future editions.

The graph below (Figure 2) illustrates the correlation between study-area size and elevation. There is a clear lack of studies carried out in the higher altitudes and only six study sites have an average catchment elevation above 4000 m. Amongst these, all except one have catchment areas below 100 km^2. In future, it may be favourable to concentrate research on larger catchments at higher altitudes.

The book is divided essentially into five parts: (1) snow and ice melt, (2) soil water and permafrost, (3) evapotranspiration and water balance, (4) coupling meteorology and hydrology, and (5) climate change impact and mountain hydrology.

Roger Barry introduces the book with a review on alpine climate change and cryospheric responses. In the first section, Rijan Kayastha and his co-authors deal with methods for calculating snow and ice melt in the Himalayas and Pratap Singh and Lars Bengtsson assess methods for interpolation and extrapolation of snow-covered areas using air temperatures in the same region. In contrast, Javier Corripio and Ross Purves introduce a particularly intriguing study on snow and ice penitentes in the central Andes. Uli Strasser then shows how sub-grid parameterization and a forest canopy model can serve to improve snowmelt runoff modelling in the humid, French Alps.

In the second section, Christain Hauck and his co-authors present a coupled geophysical and meteorological approach for monitoring permafrost in the Swiss Alps, while Daniel Bayard and Manfred Stähli monitor the effects of frozen soil on groundwater recharge in the same mountain ranges. A study on the water balance in surface soil is presented by Marilena Menziani and her

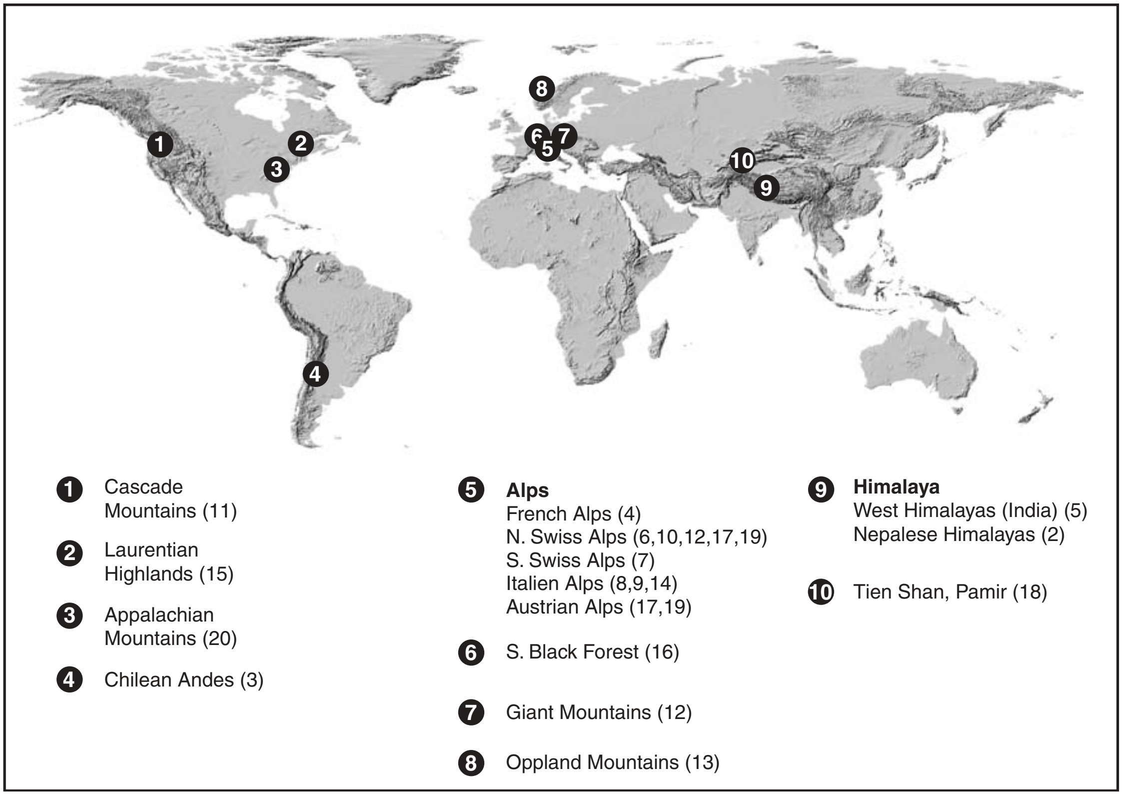

Figure 1 Location of catchments and experimental sites presented in this book. Chapter numbers associated with mountain ranges are indicated in brackets

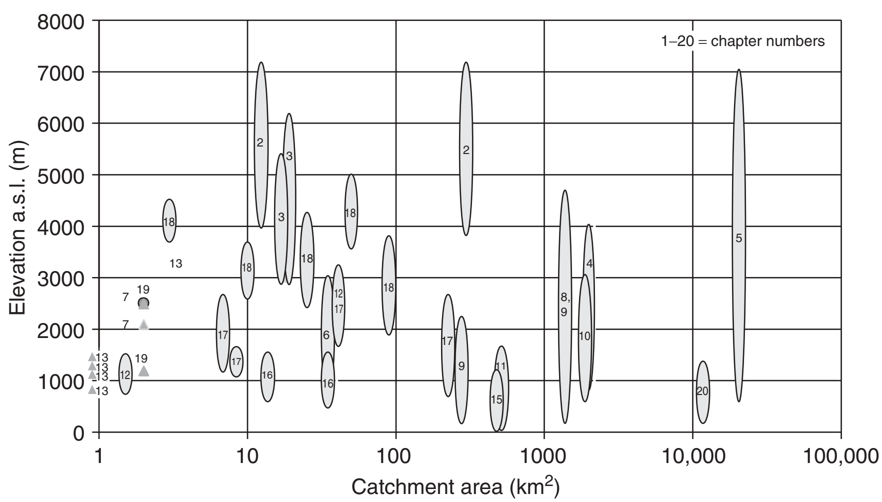

Figure 2 Relation between catchment size and mean catchment altitude for the study sites presented in this volume

co-authors with a combined analytical and measurement approach for an alpine valley in Italy, whereas Stefano Barontini and his co-authors describe saturated hydraulic conductivity and water retention relationships for mountain soils in the same mountain chain.

Gerald Eder introduces the third section with a relatively new approach of water balance modelling using fuzzy parameterization in the Austrian Alps. There is a jump then to Cascade mountains in Washington, USA, where Timothy Link and his co-authors monitor the water relations in an intensively instrumentized old growth douglas fir stand. This is followed by another field-based study by Carmen de Jong and her co-authors, where measurements of condensation and evapotranspiration are compared for the Giant Mountains in Poland and the Swiss Alps. Jörg Löffler and Ole Rößler describe an integrated approach for measuring and modelling the hydrology and ecology of mountain basins in Central Norway.

The fourth section is introduced by an overview from Baldassare Bacchi and Vigilio Villi on runoff and floods in the Alps, emphasizing precipitation and runoff formation in addition to flood frequency analysis. In this section, Charles Lin and his co-authors use an interesting coupled meteorological and hydrological modelling approach based on geomorphological principals for flood simulation in the mountainous Sageunay basin in eastern Canada. Stefan Uhlenbrook and Doerthe Tetzlaff assess convective precipitation using operational weather radar as a tool for flood modelling in the Black Forest, Germany. Geomorphological zoning as a tool for improving the coupling of hydrology and meteorology is proposed by Carmen de Jong and her co-authors for the Austrian and Swiss Alps.

In the final section, Wilfried Hagg and Ludwig Braun analyse the influence of glacier retreat on water yield in the high mountain basins of the Alps and Tien Shan. Staying in the Swiss Alps, Franziska Keller and Stephane Goyette model snowmelt under different climate change scenarios. Finally, Osman Yildiz and Ana Barros model water and energy budgets in the Appalachian mountains under climate variability and hydrological extremes.

In summary, it can be said that the studies integrate an interesting combination of field-based and modelling approaches, with several studies concentrating on the coupling of hydrology and meteorology. The large variety of approaches necessary for well-to-low-instrumented catchments are highlighted and with this comes a general appeal for more long-term monitoring programmes and field-based studies to validate model results. Since mountain regions are remote and difficult environments, a good field-based approach cannot be taken for granted. Thus, the sophistication of field and remote-sensing techniques should keep in pace with the development of modelling concepts, in particular for mountain ranges in developing countries and in arid environments.

Although this comprehensive book has seen a long way from its conception to its production, it is important to state that all chapters were sent to two international reviewers that, with few exceptions, were not authors of the book. We are very grateful to the many hours invested by these voluntary reviewers. It can be imagined that this was not always easy since the subject area is not that widespread.

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Alpine Climate Change and Cryospheric Responses: An Introduction

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1.1 INTRODUCTION

As an introduction to the following chapters dealing with changes in snow and ice conditions in high mountain regions, and their hydrological consequences, a brief overview of recent changes in alpine climates and associated cryospheric responses is presented.

Direct observations and proxy records indicate that historical and recent changes in climate in many mountain regions of the world are at least comparable with, and locally may be greater than, those observed in the adjacent lowlands, Pfister (1985). Actual and potential responses in cryospheric variable include a rise in the snowline, a shorter duration of snow cover, glacier recession, break out of ice-dammed lakes, warming of perennially frozen ground, and thawing of ground ice.

The changes – including the loss of ice core records of climate history as tropical glaciers and ice caps warm and melt water destroys the ice stratigraphy – are of scientific importance. There are also critical socioeconomic implications. These include direct effects of the changes on water resources and hydropower generation, on slope stability, and on hazards relating to avalanches and glacier lakes. Indirect effects include economic and social costs for winter tourism based on skiing and associated sports; and impacts on agricultural, industrial, and consumptive use of water that is strongly influenced by the annual cycle associated with snow and ice melt runoff.

1.2 EVIDENCE FOR CHANGES IN CLIMATE IN MOUNTAIN REGIONS

Global mean annual temperature has risen by just over 0.6°C over the last century, with accelerated warming in the last 10 to 15 years. The evidence for changes in climate in mountain areas is both direct and indirect. Observational records are available from the late nineteenth century at a number of mountain observatories, mostly in Europe (Barry 1992). They indicate that mean temperatures have risen by amounts generally comparable with those observed in the lowlands during the twentieth century; however, there are some differences in the pattern of seasonal and diurnal changes. In a survey of available high-elevation data, Diaz and Bradley (1997) present changes in zonally averaged temperatures for 1951–1989 between 30° and 70°N, versus elevation. Mean maximum temperatures increased slightly between 500 and 1500 m, with minor changes at higher elevations, while minimum temperatures rose by about 0.2°C/decade at elevations from 500 m to above 2500 m. In the Rocky mountains, Pepin (2000) documents altitudinal differences in the changes in the Colorado Front Range since 1952, with overall cooling at 3750 m but warming between 2500 and 3100 m. This results in complex changes in lapse rate. In the tropical Andes, mean annual temperature trends have been determined for 268 stations between 1°N and 23°S, for 1939–1998 (Vuille and Bradley 2000). They find an overall warming of about 0.1°C/decade, but the rate tripled to +0.32–0.34°C/decade over the last

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25 years. The warming varies with altitude, but there is generally reduced warming with elevation. This is especially apparent on the western (Pacific) slopes of the Andes.

Brown *et al*. (1992) demonstrated that lapse rates between the high plains (1200–1500 m) and three stations at 3200 m in the Colorado Rocky mountains had weakened in the daytime, but strengthened at night. Globally, the decrease in diurnal temperature range is attributed to increased cloud cover, locally augmented by changes in precipitation and soil moisture (Dai *et al*. 1999). An analysis of lapse rates in the Pennines of northern England indicates that atmospheric temperature and moisture level, cloudiness/solar radiation, and wind speed determine lapse rates (Pepin *et al*. 1999). Thus, changes in lapse rate are complex and may result solely or partly from changes in the frequency of cyclonic/anticyclonic circulation regimes. A shallower/steeper lapse rate may be expected under warmer, moister atmospheric conditions/increased solar radiation. The amplitude of diurnal change in lapse rate intensifies under anticyclonic conditions and slack pressure gradients.

In some mountain regions, monitoring of ground temperatures has begun recently. In the northern Tien Shan, permafrost ground temperatures have risen by 0.2–0.3°C over the last 25 years (Gorbunov *et al*. 2000). The depth of seasonal freezing has not changed significantly in the low mountains, but there has been a decrease in the depth between 1400 and 2700 m, while above 3000 m the depth of seasonal freezing is increasing. In the Swiss Alps, Haeberli (1994) estimated permafrost warming by about 1°C between 1880 and 1950, then stabilizing, before accelerated warming in the late 1980s to at least 1992. However, a 10-year borehole record (Vonder Mühll *et al*. 1998) indicates that warming until 1994 was largely compensated by rapid cooling between 1994 and 1996.

Proxy evidence of climatic change is available from changes in glacier size dated by lichenometry and carbon-14, from tree-ring series, and from ice cores, *inter alia.* Numerous accounts from various mountain regions exemplify these results (Luckman 1997; Luckman and Villalba 2001; Solomina 1999; Kaser 1999). These sources become even more important in mountain regions that lack direct records, or where these are of short duration, as in the Andes and other tropical regions (Barry and Seimon 2000). Diaz and Graham (1996) reported a rise of 100–150 m in the altitude of the freezing level in the atmosphere over the inner tropics (10°N–10°S) between 1970 and 1986; this is correlated with a warming in the sea surface over the eastern tropical Pacific. The characteristics of glacier energy balances in the central Andean region is addressed by Corripio and Purves (Chapter 3).

1.3 CRYOSPHERIC RESPONSES

The effects of global warming on the cryosphere in mountain areas are most visibly manifested in the shrinkage of mountain glaciers and in reduced snow cover duration. However, the responses are by no means linear. For example, warmer winters imply higher atmospheric moisture content and more snowfall is associated with an overall increase in precipitation. Records of glacier length and mass balance during the second half of the twentieth century show reductions in continental climatic regimes, but increases in maritime regimes, such as Norway, southern Alaska and coastal areas of the Pacific Northwest in Canada, and the United States. In the Tropics, the rise in freezing level noted above, as well as changes in atmospheric humidity and perhaps cloudiness, in some cases, has given rise to progressive reduction in mountain glaciers and ice caps over the last century. Particularly, dramatic changes are evident in East Africa where there has been a 75% reduction in ice area on Mount Kilimanjaro since 1912 (Hastenrath and Greischar 1997). The ice cover on East African summits will be lost within 20 years or so, unless there is a dramatic shift in climatic conditions.

In an example of subtle changes in snow cover, Böhm (1986) reported a reduction in May–September snow cover at Sonnblick (3106 m), Austria, from 82 days during 1910–1925 to 53 days in 1955–1970. The mean summer temperature was about 0.5°C higher in the second interval. However, the associated change in snow cover duration estimated from average gradients of snow cover duration and temperature lapse rate would only be about 10–11 days (Barry 1990). Such nonlinear responses may arise through local albedo-temperature feedback effects, but this still requires thorough investigation. Keller and Goyette (Chapter 19) provide scenarios of snowmelt in the Swiss Alps under climatic changes.

Large responses are expected in the annual hydrologic regime of rivers where a significant proportion of the runoff is from melt of snow cover and from wastage of ice in heavily glacierized basins. Runoff models under global warming scenarios project a higher and earlier peak of spring runoff from snowmelt and reduced flow in summer (Rango and Martinec 1998). For the upper Rhône, for example, Collins (1987) found discharge correlated with mean summer temperature; a 1°C cooling between 1941–1950 and 1968–1977 led to a 26% decrease in mean summer discharge. Warming trends will have the opposite effect, but a dominant component of runoff change in heavily glacierized basins is attributable to the reduction in ice area. Chen and Ohmura (1990) calculated an 11% decrease in runoff from a basin of the upper Rhône drainage with 66% ice cover between 1922–1929 and 1968–1972, compared with only 6% decrease in one with about 17% ice cover between 1910–1919 and 1968–1972. In the latter case, the Rhône at Porte du Scex, runoff changes responded also to changes in climate but a decrease in basin precipitation was offset by the effect of warmer summers increasing the ice melt. The introductory chapter and Chapter 18 address this topic using more recent and extensive data.

1.4 SOCIOECONOMIC CONSEQUENCES

Socioeconomic effects of changes in mountain snow and ice characteristics will be both direct and indirect. Direct effects associated with a shorter snow season and shallower snow cover will include the reduction or loss of winter sports facilities, or the necessity for enhanced reliance on snowmaking capabilities, with attendant losses of income and adaptation costs. For the Austrian Alps, losses will be exacerbated at lower elevations. Secondary effects resulting from this change may include the loss of related service activities and income at mountain resorts. Summer tourism may also be affected as scenic mountain glaciers shrink and waste away. Maintaining tourist access to the terminus of the Upper Grindelwald glacier, in retreat since the mid-1980s, for example, has necessitated the construction of a wooden stairway.

The changes in snowmelt runoff and its timing will have direct impacts on hydropower generation and impose requirements for alternative power sources. Power outages and loss of revenue by utility companies may be expected, depending upon the relative contribution of hydropower to total electricity generation. In adjacent lowland areas where spring runoff is a major source of water for irrigation and for stocking reservoirs, there may be even greater economic consequences. Changes in snow pack will also affect soil moisture levels in spring and summer, with implications for soil biota, fire risk, and the productivity of mountain pastures and forests (Price and Barry 1997).

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PART I: SNOW AND ICE MELT