Ming-ko Woo

Editor

Cold Region Atmospheric and Hydrologic Studies

The Mackenzie GEWEX Experience

Volume 2: Hydrologic Processes

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with 162 Figures

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Cover photograph: Ice jam formed during spring breakup at the mouth of Liard River near Fort Simpson

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Editor's Note

The circumpolar areas are crucially important to the global environment as they play the dual roles of being the harbinger of and a contributor to climate change. A rising clamor for environmental information on such areas is evident in scientific and media publications. Yet, relative to the temperate zones, the cold regions remain under-studied. There exists a need to improve knowledge of the cold region sciences, and atmospheric and hydrologic sciences are of no exception. This book was prepared with the purpose of sharing the experience of a team of Canadian researchers with the practitioners and stakeholders, residents and environmental managers, educators and students of the cold regions.

A good understanding of the physical processes and enhanced capability to model the regional atmospheric and the hydrologic conditions are the keys to environmental preservation and resource sustainability in the circumpolar areas. However, the cold environment presents a challenge to atmospheric and hydrologic research. The low temperatures test the endurance of field workers and their instruments; the distance of these areas from large urban centers raises the cost of logistics and reduces the availability of measured data. In 1994, a group of researchers from academic and government institutions embarked upon a major collaborative program, using the large and complex Mackenzie River Basin in northern Canada as the focal point to study the atmospheric and hydrologic phenomena of the cold regions. The goals of this project, known as the Mackenzie GEWEX Study or MAGS, were: (1) to understand and model the high-latitude energy and water cycles that play roles in the climate system, and (2) to improve our ability to assess the changes to Canada's water resources that arise from climate variability and anthropogenic climate change.

The Mackenzie Basin has many of the physical attributes common to cold regions worldwide. Results from MAGS investigation including the enhanced understanding of the atmospheric and hydrologic processes, the improved and developed models, and the data collected using novel and conventional methods, are largely applicable to other circumpolar areas. This publication is a documentation of the research outcomes of MAGS. For a study that spanned over a decade (1994–2005), MAGS yielded an immense amount of information, too extensive to be accommodated within one publication. Thus, this book is divided into two volumes. Volume I of this book, entitled "Atmospheric Processes of a Cold Region: the Mackenzie GEWEX Study Experience", concentrates on the atmospheric investigations. Volume II is a complementary report on the hydrologic aspect. To provide continuity with Volume I, a synopsis of its chapters is presented. This information is provided in the spirit of the Mackenzie GEWEX Study which emphasizes the integration of atmospheric and hydrologic research.

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MAGS investigators have been most enthusiastic in sharing their knowledge by authoring chapters in this publication. This collective work benefits further from the reviewers of various book chapters and from members of the advisory group for ensuring its high standard. I am particularly thankful to members of our production team: Michael and Laurine Mollinga, Robin Thorne and Laura Brown. Their dedication and efficiency contributed tremendously to shaping the materials into the final book format.

Ming-ko Woo

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List of Acronyms

AL	Aleutian Low
AMSR	Advanced Microwave Scanning Radiometer
AO	Arctic Oscillation
AVHRR	Advanced Very High Resolution Radiometer
BALTEX	Baltic Sea (GEWEX) Experiment
BERMS	Boreal Ecosystem Research and Monitoring Sites
BOREAS	Boreal Ecosystem-Atmosphere Study
CAGES	Canadian GEWEX Enhanced Study (Sept. 1998 to July 1999)
CANGRID	Environment Canada's gridded monthly surface climate dataset
CCCma	Canadian Centre for Climate modelling and analysis
CCRS	Canadian Centre for Remote Sensing
CERES	Clouds and Earth's Radiant Energy System
CLASS	Canadian Land Surface Scheme
CMC	Canadian Meteorological Centre (of Environment Canada)
CRCM	Canadian Regional Climate Model
CRYSYS	Cryosphere System in Canada
CSE	Continental Scale Experiment (of GEWEX)
DEM	Digital Elevation Model
DIAND	Department of Indian Affairs and Northern Development
DYRESM	A 1-D Dynamic Reservoir Model
EC	Environment Canada
ECMWF	European Centre for Medium-range Weather Forecasts
ELCOM	A 3-D hydrodynamic model
ENSO	El Niño and Southern Oscillation
ERA	European Reanalysis of Global Atmospheric data (from ECMWF)
ERA-40	40-year Global Reanalysis data from ECMWF
GAME	GEWEX Asian Monsoon Experiment
GAPP	GEWEX Americas Prediction Project (formerly GCIP)
GCIP	GEWEX Continental-scale International Project
GCM	Global Climate Model; or General Circulation Model
GEM	Global Environmental Multi-scale Model
GEWEX	Global Energy and Water Cycle Experiment
GFDL	Geophysical Fluid Dynamics Laboratory
GHP	GEWEX Hydrometeorology Panel

GRACE	Gravity Recovery and Climate Experiment
GPCP	Global Precipitation Climatology Project
GRDC	Global Runoff Data Center
GSC	Geological Survey of Canada
GTOPO-30	Global 30 Arc-Second Elevation Data Set
HYDAT	Hydrometric Data from Environment Canada
ISBA	Interactions Soil-Biosphere-Atmosphere (land surface scheme)
ISCCP	International Satellite Cloud Climatology Project
LiDAR	Light Detection And Ranging
MAGS	Mackenzie GEWEX Study
MBIS	Mackenzie Basin Impact Study
MC2	Mesoscale Compressible Community Model
MEC	Modèle Environnemental Communautaire (of CMC)
MODIS	Moderate-Resolution Imaging Spectroradiometer
MRB	Mackenzie River Basin
MSC	Meteorological Service of Canada
NARR	North American Regional Reanalysis (from NCEP)
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Prediction
NESDIS	National Environmental Satellite, Data and Information Service (NOAA)
NOAA	National Oceanographic and Atmospheric Administration
NRC	National Research Council of Canada
NRCan	Natural Resources Canada
NSIDC	National Snow and Ice Data Center
NSERC	Natural Sciences and Engineering Research Council
NWP	Numerical Weather Prediction
NWRI	National Water Research Institute
NWT	Northwest Territory, Canada
PBSM	Prairie Blowing Snow Model
PDO	Pacific Decadal Oscillation
PIEKTUK	York University blowing snow model
PNA	Pacific North American Oscillation
RadarSat	Canadian Space Agency satellite designed to study polar regions
RCM	Regional Climate Model
RFE	Regional Finite Element model

RIVJAM	River ice jam model
SAR	Synthetic Aperture Radar
ScaRaB	Scanner for Earth Radiation Budget
SPOT	Satellite Probatoire d'Observation de la Terre
SEF	Canadian Global Spectral Forecast model
SLURP	Semi-distributed Land Use-Based Runoff Processes (hydrological model)
SMMR	Scanning Multichannel Microwave Radiometer
SRES	Special Report on Emissions Scenarios
SSM/I	Special Sensor Microwave Imager
TOPAZ	TOPgraphic PArameterZation
WATCLASS	A coupled model of WATFLOOD and CLASS
WATFLOOD	University of Waterloo river basin model
WCRP	World Climate Research Program
WEBS	Water and Energy Budget Study
WSC	Water Survey of Canada

Chapter 1

Synopsis of Atmospheric Research under MAGS

Ming-ko Woo

Cold regions present a challenge to atmospheric and hydrologic research. Their low temperatures test the endurance of field workers and their instruments; their distance from large urban centers raises the cost of logistics and reduces the availability of measured data. Yet, these regions are sensitive to climate variability and change and are prone to accelerated human activities. Improved understanding of the physical processes and enhanced capability to model the regional atmospheric and hydrologic conditions are the keys to their environmental preservation and resource sustainability.

Volume I of this book documents the atmospheric research on the cold environment, principally of the Mackenzie River Basin (MRB) in northern Canada. Volume II is a complementary report on the hydrologic aspect of this cold region. To provide continuity with Volume I, a synopsis of its chapters is presented. This information is provided in the spirit of the Mackenzie GEWEX Study (MAGS) that emphasizes the integration of atmospheric and hydrologic research.

The first volume is entitled "Atmospheric Processes of a Cold Region: the Mackenzie GEWEX Study Experience". All its chapters are listed in the Appendix. The Introduction chapter (Woo et al., Chap. 1) presents the physical setting of the Mackenzie Basin and places its cold environment in the context of the continental water and energy balances. In 1994, an interdisciplinary study began in Canada to participate in the international Global Energy and Water Cycle Experiment (GEWEX) under the auspices of the World Climate Research Program. The goals of the MAGS were (1) to understand and model the high-latitude energy and water cycles that play roles in the climate system, and (2) to improve our ability to assess the changes to Canada's water resources that arise from climate variability and anthropogenic climate change.

Szeto et al. (Chap. 2) provide a synthesis of atmospheric research contributions of MAGS. Major scientific accomplishments include improved understanding of the large-scale atmospheric processes that control the transport of water and energy into and out of the MRB; enhanced understanding of the interactions of large-scale atmospheric flows with physical features of the Basin to affect its weather and climate; and applications of research results to address climate issues in the Basin and other cold regions. This overview is a companion paper to Woo and Rouse (Chap. 2 in this Volume) which surveys the hydrologic process research undertaken under MAGS.

Most parts of the MRB are located in a center of high pressure in the winter. Ioannidou and Yau (Chap. 3) showed that MRB anticyclones are deep, warm core structures developed through an amplification of the climatological semi-permanent ridge over western North America. They are also sensitive to variation of the Pacific–North American and the Arctic Oscillations, manifested in a weaker or stronger meridional/zonal orientation of the anticyclonic activities. These anticyclones are transformed into cold core structures as they move to eastern Canada. The weather of the MRB is also strongly affected by the pressure pattern and storm systems over the North Pacific. As the Pacific airflow crosses the lofty western Cordillera and descends the mountains, adiabatic warming associated with subsidence governs the heat budget (Szeto, Chap. 4). Anomalously warm or cold winters are related to the strength of this incursion of the North Pacific air. A large winter temperature variability is linked to the interaction between this airflow and the regional environment, notably the Cordillera. On top of this variability is a significant winter warming trend in the last several decades (Cao et al., Chap. 5). Warming events are largely due to the advection of warm air from west and south of the Basin and through adiabatic descent induced by topography and by the pressure system, especially when low-level temperature inversion occurs.

Vapor flux into the MRB comes from the Pacific and Arctic Oceans. These sources also bring moisture to its southern neighbor, the South Saskatchewan Basin in the prairies, though the prairies also receive moisture flux from the Gulfs of Mexico and California, and from the Hudson Bay (Liu et al., Chap. 6). Although there are moisture exchanges between the two basins, topography and surface properties give rise to differences in their vertical profiles of moisture transport. In the MRB, there are occasions when extreme summer rainfall (>100 mm) is fed by moisture that can be traced back to the Gulf of Mexico (Brimelow and Reuter, Chap. 7). In these cases, rapid lee cyclogenesis over Alberta (associated with a 500-hPa cutoff low) and the Great Plains Low Level Jet act in unison to transport moisture to southern MRB. The transport time is 6–10 days.

Within the MRB, local evaporation is also a moisture source for precipitation (Szeto, Chap. 8). Compared with several other basins, the MRB has a precipitation recycling ratio that is below that of the Amazon (30%) but similar to the Mississippi and the Lena basins (23–25%). The ratio is expectedly higher in the summer than in the cold season, and about half of the summer precipitation in the downstream regions of these basins is derived from local evaporation.

Closely associated with precipitation is the cloud system, both features being linked to synoptic forcing conditions in the MRB (Hudak et al., Chap. 9). Intense observation at Fort Simpson (1998–99) near the center of the Basin, including cloud radar sampling, showed the common occurrence of multi-layered clouds and a reduction in precipitation due to sublimation beneath or between cloud layers. Both observation and modeling of clouds may be improved. Ground measurement of precipitation has allowed a set of precipitation–elevation relationships to be developed on the lee slopes of the Alberta foothills (Smith, Chap. 10). The monthly accumulated precipitation is linearly correlated with elevation when precipitation exceeds 70% of the long term average and this altitudinal increase depends on the total precipitation observed. Dupilka and Reuter (Chap. 11) noted the linear relationship between maximum snowfall and cloud base temperature. For Alberta exclusive of the mountains, it was found that the snow amount depends roughly linearly on the 850 hPa temperature.

Passive microwave data are well suited to snow cover application and Derksen et al. (Chap. 12) reviewed the performance of snow water equivalent retrieval algorithm at high latitudes. There is recent progress in understanding the impact of subgrid land cover variability, validating algorithm performance in northern boreal forest, and the development of algorithm for the boreal forest and tundra. Snow cover extent in the MRB was analyzed using satellite data, ground observation, and Canadian Regional Climate Model (CRCM) simulations (Derksen et al., Chap. 13). Consistent with air temperature trends, there are significant decreases in spring snow cover duration and earlier snow disappearance, but no significant trends for snow cover onset in the fall. An east–west gradient in the MRB shows earlier melt in the mountains, little change or slight increase in the spring snow cover in the northeast, and a cyclical behavior in the south that is linked to the Pacific–North America and Pacific Decadal Oscillation. A zone with high winter snow water equivalent (>100 mm) occurs across the northern fringe of the boreal forest. CRCM simulations indicate its correspondence with the mean monthly patterns of the 850 hPa frontogenesis forcing.

The winter snow cover is subject to blowing snow transport and sublimation. Blowing snow events are rare in the boreal forest but common in the tundra (Déry and Yau, Chap. 14). A parameterization based on the PIEKTUK-D model and the ERA-15 data provides a first-order estimate that indicates surface and blowing snow sublimation would deplete 29 mm yr^{-1} or about 7% of the annual precipitation of the MRB. Gordon and Taylor (Chap. 15) also parameterized the sublimation of blowing snow at six locations in the Basin. They predicted that up to 12% of the total snow precipitation in the Basin may be removed by this process, though these amounts could be an overestimate.

Assessment of the water and energy budget of the MRB is a major goal of MAGS. Szeto et al. (Chap. 16) provided a comprehensive climatology using remotely sensed and ground observations and several sets of reanalyzed and modeled data. The magnitude of the residuals in balancing the budgets is often comparable to the budget terms themselves and the spread of the budget estimates from different datasets is also large. However, the water budget closure for the Basin was within 10% of the measured runoff. Discussion of the sources of error and level of uncertainty suggests areas of improvement for the observation and the models.

Moisture flux convergence for the MRB showed significant yearly variations (Schuster, Chap. 17). Within the decade of 1990–2000, the 1994–95 water year had the lowest flux convergence. For some years the maximum flux convergence was at 850 hPa, implying that there was a large overall moisture flux into the MRB. However, usually the largest moisture flux convergence was at 700 hPa and this was particularly prominent in 1994–95, the year with record low discharge for the Mackenzie River.

The abundance of lakes of various sizes plays an important role in the energy and water cycling of the MRB. Rouse et al. (Chap. 18) used results of measured data to study the sensitivity of energy and moisture exchanges between lakes and the atmosphere. They found that were the Basin devoid of lakes, there would be a positive water balance for wet and average years and only a small negative balance for the driest years. If all the lakes in the region were large or medium-sized, there would be a regional evaporation increase by 8–10%.

Satellite observation and modeling are a major source of information for the study of energy budget of a vast domain. Trishchenko et al. (Chap. 19) used satellite information to examine the seasonal and interannual variability of albedo of the MRB for 1985–2004. They found a seasonal change in the broadband albedo from 0.11±0.03 in summer to 0.4–0.55 in winter, but no systematic trends because of large interannual variability, uncertainties in sensor properties, atmospheric correction, and retrieval procedures. Guo et al. (Chap. 20) compared the net surface radiation fluxes from satellite observation with those from the CRCM. They found that the latter overestimates short-wave fluxes at the top of atmosphere and underestimates the surface absorbed solar fluxes. CRCM also underestimates the outgoing long-wave fluxes at the top of atmosphere in winter. Differences were noted between the cloud fields simulated by the model and deduced from satellite measurements. Clouds and wildfire aerosols have strong influences on the radiation budgets of the MRB. Guo et al. (Chap. 21) investigated their radiative forcing at the top of atmosphere and at the surface. Overall, the cloud forcing could impact the short-wave and long-wave radiation budgets by 30–50%, both at the top of atmosphere and at the surface of the MRB region.

Most wildfires in northern Canada are started by lightning. Thunderstorms and associated lightning also play an important role in the cycling of water and energy during the warm season over the boreal and subarctic ecosystem. Kochtubajda et al. (Chap. 22) used observational datasets and model-derived products to characterize these storms and to examine their impacts on the forests and polar bear habitats. Fires peak in July but much of the burning occurs in June. The region of maximum lightning activity varies in space and time, and there is evidence that smoke from fires enhances the probability of positive cloud-to-ground lightning flashes. A tree-structured regression method successfully predicts the probability of lightning. Under a future warmer climate, more severe fire weather, more area burned, more ignition, and longer fire season are expected (Flannigan et al., Chap. 23). The burned area may increase by 25–300% and the fire season may lengthen by 30–50 days over a large of the Northwest Territories in Canada.

A final section presents contributions to atmospheric modeling. Ritchie and Delage (Chap. 24) analyzed the predictions of water and energy fluxes over the MRB by the Canadian Global Spectral Forecast model (SEF) which was used by the Canadian Meteorological Centre for weather forecasting. They found that the accumulation of precipitation-minus-evaporation is highly sensitive to initial conditions. Within SEF, the replacement of the force-restore scheme by the Canadian Land Surface Scheme (CLASS) improves the predicted energy and water budgets for the MRB, and better initialization of the CLASS variables can greatly affect its performance. CLASS was also used in the MAGS version of the CRCM, tailored for use over North America (MacKay et al., Chap. 25). Its simulation of the MRB climate was evaluated against surface observations. The model yielded an annual precipitation bias of 13% and a surface temperature cold bias of $<1^{o}$C, suggesting that the physics package developed by a coarse-resolution GCM can be used in high resolution regional climate model with minimum modification.

Volume I presents the primary atmospheric processes that occur in northwestern North America, particularly in the domain of the MRB. Many of the research methods employed, including ground based observations, remote sensing techniques and modeling approaches, are shared by hydrologic studies in MAGS. Most of the atmospheric processes summarized in this Chapter are related to or even responsible for the hydrologic activities discussed in Volume II.

Appendix

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Chapter 2

MAGS Contribution to Hydrologic and Surface Process Research

Ming-ko Woo and Wayne R. Rouse

Abstract The Mackenzie GEWEX Study (MAGS) research contributed to advancement in our knowledge on hydrologic and surface processes common to all cold regions. These include the accumulation, sublimation and ablation aspects of the snow in boreal forest and tundra areas; infiltration into and thawing of frozen soil; breakup of river ice and the associated floods. Additionally, there are several land surface features distinctive to the Mackenzie River Basin, including lakes and wetlands, mountainous topography, Precambrian Shield and organic terrain. Hydrologic knowledge on these landscapes was gained through field research, conceptualization and modeling effort. Most of these studies were carried out at a local scale that allows understanding of the physical processes through intense field and modeling investigations.

1 Introduction

As for all cold regions, snow, frost and ice exert considerable influence on the hydrology of the Mackenzie River Basin (MRB). Additionally, there are several land surface features distinctive to the Basin. They include lakes and wetlands, mountains, Precambrian Shield and organic terrain. The surface and hydrologic processes are important in the water balance through evaporation, storage and runoff. Latent heat exchanges are particularly relevant because of their roles in ground freeze-thaw, ice formation and breakup, snow sublimation and melt, and evaporation. The significant research results arising from the Mackenzie GEWEX Study (MAGS) that deal with these processes and features are addressed in this synthesis.

2 Snow Processes

The MRB is snow-covered for five to eight months each year (Hydrological Atlas of Canada 1978), with the duration increasing northward towards the Arctic coast and westward at high elevations (Fig. 1). Winter precipitation comes mainly as snowfall but rainfall can occur occasionally, particularly in the south. The snow cover is subject to sublimation loss and redistribution by drifting. Snowmelt in the spring is a major hydrologic event that triggers extensive runoff, infilling of lakes and ponds, inundation of wetlands together with river ice breakup and the flooding of riparian zones. Problems associated with the measurement of snowfall have been discussed extensively (Goodison 1978; Yang et al. 1999). The distribution of snowfall (Fig. 1) has to be interpreted with caution because of possible inaccuracies, especially due to gauge undercatch. Research carried out under MAGS has emphasized snow ablation rather than accumulation. Snow sublimation and melt were the main processes considered.

2.1 Snow Sublimation and Redistribution

Sublimation of snow intercepted on the tree canopy reduces snow accumulation on the forest floor. Tree-weighing experiments conducted in northern Saskatchewan (Fig. 2) and southern Yukon clearly demonstrated the loss of intercepted snow to sublimation, melt and shedding from the tree canopy (Pomeroy et al. 1998). Leaf area, canopy closure, vegetation type, time since snowfall, snowfall amount and the existing snow load determine the efficiency with which snow is intercepted. Cold coniferous forest canopies can store more than half of the cumulative snowfall and much of this can be lost by sublimation. Parviainen and Pomeroy (2000) developed a boundary layer model that provides a reasonable approximation of sublimation losses and the within-canopy energetics, enabling an evaluation of the role of sublimation from a boreal forest.

On the scale of a forest, Pomeroy et al. (2002) provided simple yet physically appropriate equations for estimating snow accumulation beneath forest canopies, relating canopy properties (leaf area index or canopy density) to either snowfall or snow accumulation in the clearings. For sites where mid-winter melt, snow redistribution by wind, and surface sublimation are infrequent or limited, this approach can be used to estimate the seasonal snow accumulation. Comparisons with data and results from eastern Europe and Siberia suggest that these findings are transferable.

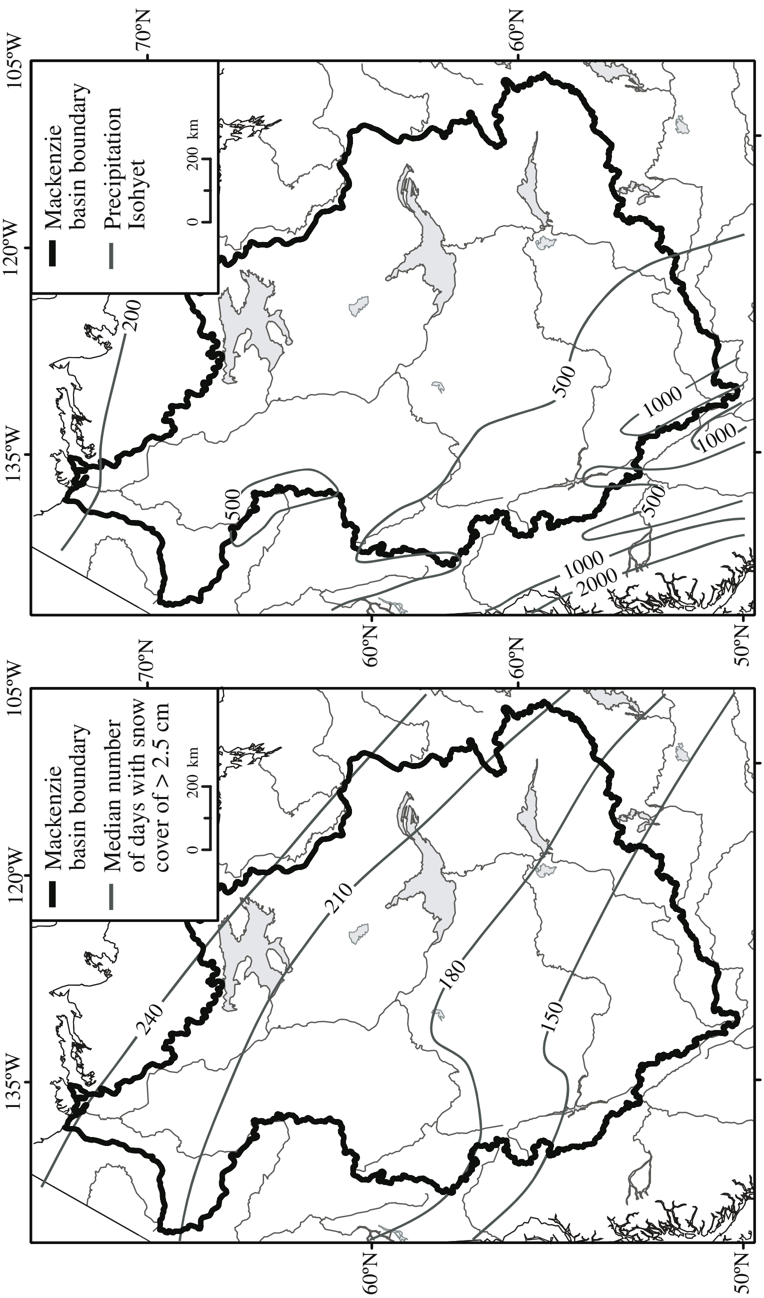

Fig. 1. (a) Median number of days with at least 25 mm of snow on the ground; (b) Annual precipitation [mm] in the Mackenzie Basin (after Hydrological Atlas of Canada, 1978). Precipitation values should be accepted with caution as snowfall is usually underestimated

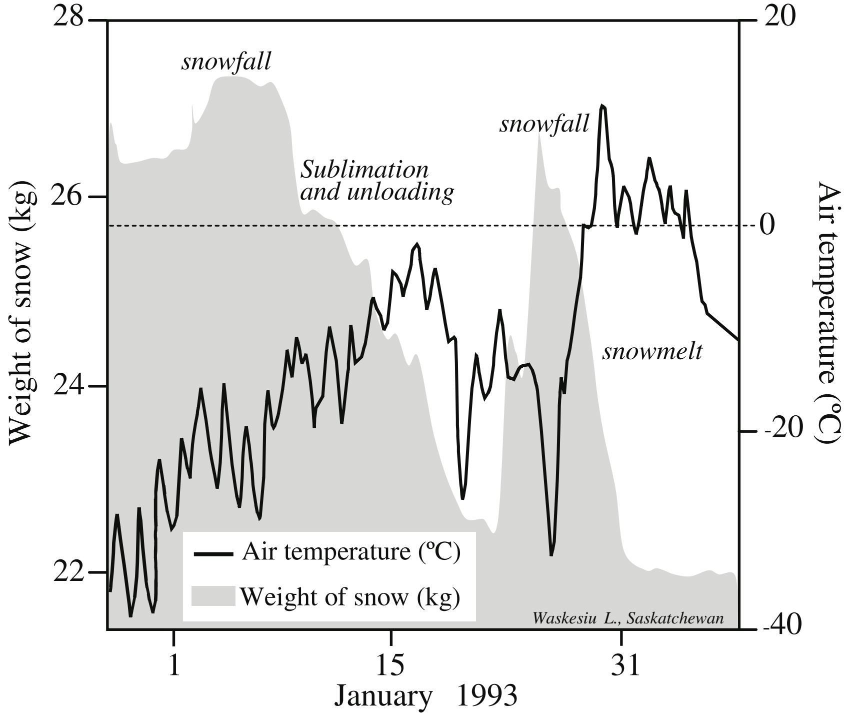

Fig. 2. Weight of snow on a 9-m tall black spruce tree as snow accumulated, sublimated, melted and slid off its canopy. Experiment was carried out in a forest in northern Saskatchewan. (Modified after Pomeroy and Gray 1995)

Snow redistribution by wind is an important process in the open terrain. Accompanying blowing snow events is the loss to sublimation by the transported snow. However, there are large discrepancies among various blowing snow models concerning the rates of sublimation loss. Essery et al. (1999), using their Prairie Blowing Snow Model (PBSM), suggested that 47% of the snow in a small tundra basin (Trail Valley Creek; see Marsh et al. 2007 for description of the basin) sublimated over a winter period. For the same study site and year, Déry and Yau (2001) utilized a version of the PIEKTUK model and indicated that the near-surface relative humidity quickly approached saturation with respect to ice; consequently sublimation becomes limited. On a regional scale, Déry and Yau (2002, 2007) used reanalysis data at a resolution of 2.5° to study the effects of surface sublimation and blowing snow on the surface mass balance. They found that surface sublimation removes 29 mm yr^{-1} snow water equivalent (SWE), or about 7% of the annual precipitation of the MRB. Taylor and