Ming-ko Woo
Editor

Cold Region Atmospheric and Hydrologic Studies
The Mackenzie GEWEX Experience

Volume 1: Atmospheric Dynamics

with 136 Figures

Springer
Preface

The geography of Canada makes it one of the best locations in the world for cold region atmospheric and hydrologic studies: its high latitude and high mountains, proximity to oceans in the Arctic and cold temperate zones, a broad assemblage of landscape and vegetation, and numerous lakes and rivers. For years, Canadians have conducted research on cold regions, either individually or in small groups, thus accumulating rich experience and ample expertise in the far North. Creation of the Global Energy and Water Cycle Experiment (GEWEX), under the auspices of the World Climate Research Program, provided an external impetus for large-scale collaborative research. Canada responded to this initiative by creating the Mackenzie GEWEX Study or MAGS that focused on the cold region. It was recognized at the early stage of MAGS that the atmosphere and the hydrosphere are strongly linked. A concerted effort of atmospheric and hydrologic scientists is beneficial, if not essential, to a successful large research program. In this regards, investigation conducted by a group of scientists and engineers of MAGS was entirely relevant and timely. This study, carried out between 1994 and 2005, had the research objectives of (1) understanding and modeling the high-latitude energy and water cycles that play roles in the climate system, and (2) improving our ability to assess the changes to Canada’s water resources that arise from climate variability and anthropogenic climate change.

So vast a world region that is under the influence of intense and persistent coldness cannot be covered by a contingent of Canadian researchers over a decadal time horizon. The Mackenzie River Basin and its vicinity in northwestern Canada, occupying an area of about two million square kilometers, was adopted as the preferred research location. It offers a wide assemblage of environments, including mountains and plains, tundra and forests, lakes and wetlands, and winters landscapes of snow, ice and frost. Its climatic continentality is accompanied by pronounced external influences, notably from the Pacific Ocean. The Mackenzie area presents a diversity of atmospheric and hydrologic conditions with their attendant research problems to challenge the MAGS investigators.

With increasing pressure of development, the previously neglected northern areas in many circumpolar nations have come to the fore. The cold region with its permafrost, snow and ice that are sensitive to climate
warming, and with its ecosystem that is vulnerable to disturbances, must be developed in a considered fashion to enable environmental sustainability. Information needs to be gathered and sound knowledge should be available for proper planning and operational purposes. Furthermore, the cold region is acknowledged to be highly sensitive to variations and changes in the climate. The effects of its atmospheric and hydrologic feedback extend well beyond the confines of the high latitudes to influence the global movements of water and energy. There are large uncertainties regarding how the cold region responds to the impetus of changes imposed by nature and human. Progress in cold climate research would contribute to improved understanding of how the system behaves, hence enabling better preparation for and appropriate adaptation to these changes.

MAGS attempted to increase our knowledge of the North. All its projects placed an explicit or implicit emphasis on improving the current understanding of the cold region atmospheric and hydrologic processes. Results from process studies were incorporated into atmospheric, land surface and hydrologic models so as to better represent and predict the cold region phenomena. Importantly, knowledge of the processes can be used to explain the occurrence of physical features or events in other world cold areas. Many algorithms developed are applicable universally. Considered this way, MAGS contribution appeals to a much broader audience than the title Mackenzie implies.

Water and energy budgets are one major means to characterize the hydroclimatology of a world region. MAGS undertook detailed analyses and mapping of components of the energy and water cycle to quantify the fluxes and stores in the atmosphere and in the hydrosphere. Closely associated with the water and energy balance studies was research on the mechanisms that convey heat and moisture, leading to improved understanding of large scale airflows, clouds and precipitation, snow and ice regimes, runoff generation, and lake dynamics. The instruments of scientific enquiry included field observations, remote sensing, modeling and statistical analyses, capitalizing on the cross-disciplinary collaborative opportunities and the asset of Canadian expertise on cold region research.

Research is useful if, in the end, the results are broadly disseminated. While it is satisfying for MAGS investigators to see their research efforts unified into a single publication, it is far more important that the results are made available to and used by a community of environmental scientists, resource managers, policy makers, instructors and students of the cold regions. Such is the goal of this book.

This collaborative research venture could not have been realized without the necessary organizational structure, financial support and institutional
partnership. To coordinate the MAGS Program, a Management Board was in place, chaired by John Stone. A Science Committee with a rotating Chair and membership set the overall research agenda, facilitated and monitored research projects. An International Advisory Panel offered critical annual reviews of MAGS progress. At various times, the Panel members included Alan Betts, Denis Lettenmaier, Tetsuo Ohata, Eherhardt Rashke, John Roads and Brian Wilkinson. Ming-ko Woo, Wayne Rouse, Ronald Stewart, Kent Moore and Han Ru Cho served as the Principal Investigator at different periods and phases of MAGS. We were fortunate to have able Managers to assist in the program, information, and finance aspects: Peter diCenzo, Geoff Strong, Terry Krause, Bob Crawford and Joan Parker.

Funding from the Natural Sciences and Engineering Research Council of Canada (NSERC) has enabled all the university investigators and their students to carry out multiple years of research, and an expression of gratitude to NSERC is provided here on behalf of every one of the MAGS investigators and their trainees. We acknowledge the unwavering support, both financial and institutional, of Environment Canada through the former Atmospheric Environment Service, the National Water Research Institute and the Prairie and Northern Region. The Departments of Indian and Northern Affairs, and Natural Resources of Canada, and several Canadian universities (Alberta, McGill, McMaster, Quebec, Saskatchewan, Toronto, Waterloo and York) gave their endorsement of the program. Other sources of support are acknowledged in individual chapters.

The production of this book was facilitated by an editorial advisory team consisting of Wayne Rouse, Kit Szeto, Lawrence Martz and Ron Stewart. We are grateful to the many reviewers who provided valuable comments to ensure that all the chapters are of a high standard. The coherent appearance of this book is a result of the dedication and efficiency of the team that brought its materials into the final format. In this regard, Michael and Laurine Mollinga, Robin Thorne and Laura Brown deserve much credit and my gratitude.

Ming-ko Woo

May 2007
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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
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<tr>
<th>Acronym</th>
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<tr>
<td>SPOT</td>
<td>Satellite Probatoire d’Observation de la Terre</td>
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<tr>
<td>SEF</td>
<td>Canadian Global Spectral Forecast model</td>
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<td>SLURP</td>
<td>Semi-distributed Land Use-Based Runoff Processes (hydrological model)</td>
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<td>WATCLASS</td>
<td>A coupled model of WATFLOOD and CLASS</td>
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<td>World Climate Research Program</td>
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<td>WEBS</td>
<td>Water and Energy Budget Study</td>
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Chapter 1

The Mackenzie GEWEX Study: A Contribution to Cold Region Atmospheric and Hydrologic Sciences

Ming-ko Woo, Wayne R. Rouse, Ronald E. Stewart and John M.R. Stone

Abstract The Mackenzie GEWEX Study (MAGS) is a collaborative study with the goals of understanding and modeling the high-latitude energy and water cycles, and improving our ability to assess the changes to the water resources of northern Canada that arise from climate variability and anthropogenic climate change. The Mackenzie River Basin (MRB) was selected for a comprehensive study as it possesses many of the environmental attributes of the northern circumpolar region, offers an excellent natural laboratory for studying cold region processes, and experiences significant climate warming and large climate variability. The Basin exhibits an annual negative heat balance, low annual mean temperature and a large positive water balance that promotes large river flow, notably during the spring snowmelt period. High topography of the Western Cordillera and low relief of the central and eastern Basin exert a strong influence on the pattern of atmospheric circulation, and on the advective heat and moisture fluxes. Numerous lakes and extensive wetlands affect surface energy and water balances through evaporation enhancement. Snow, ice (river and lake), and frost are major land surface features molded by the cold climate, and they in turn have strong feedbacks to the atmospheric and hydrologic processes. One major research challenge was to piece together the energy and water budgets given limited data of reliable quality. Through the decade-long MAGS research, this challenge was met in part by intensive studies in select regions within the MRB, the use of remote sensing information and ground observations, and the development and employment of models at various scales. This book is a compilation of the knowledge gained which is equally applicable to other cold regions in the world.

1 Introduction

Cold regions are a major research frontier for atmospheric and hydrologic sciences. They are defined as areas where air temperature stays below 0°C for over half of a year so that snow, ice and frost are common occurrences.
Circumpolar cold regions are considered to be highly sensitive to global warming which can lead to significant changes in the environment (ACIA 2005). This sensitivity promotes alteration of the weather patterns, increased melting of snow, ice and permafrost, and shifts in the river flow regime. Such changes are especially relevant to the climate and water resources of the high latitudes. There is a clear need to enlarge the information base and to improve understanding on the atmospheric and hydrologic processes. To participate in the international Global Energy and Water Cycle Experiment (GEWEX), the Mackenzie GEWEX Study (MAGS) was created in Canada. It was designed specifically to increase our understanding of the atmospheric dynamics and the hydrologic processes of cold regions as coupled systems and to enhance our ability to model them.

Harsh climate, isolation and high cost of research have often discouraged field investigations, and most research to date has been limited in scope, focusing on particular aspects of the environment such as the climate, hydrology, vegetation or landforms (Nuttall and Callaghan 2000). However, many aspects of the natural environment are inter-connected. Atmospheric and hydrologic processes, for example, are strongly coupled. There is a need to understand the climate–hydrologic system on various spatial scales, from the local to the regional level. Recognizing this need, a concerted effort was made to study the water and energy cycles of a large cold-climate domain represented by the Mackenzie River Basin (MRB) in northern Canada, and to apply the collective Canadian expertise to address issues of climate variation and climate change in cold regions.

A primary purpose of this book is to share knowledge gained through our studies, with other researchers and students of the cold environment. It is a compilation of research achievements obtained through a decade of collaborative study. While the Mackenzie drainage basin provides the focal point for the study, the information on cold region processes, and the research methodologies developed, can be applied to other circumpolar regions. This chapter offers background information on the MRB and its relation to world cold regions in terms of physical setting, climate, and water resources.

2 The Circumpolar Cold Region

The circumpolar region has extreme seasonal radiation regimes, with negative radiation balances in the dark winter months and positive balances in the long daylight months of the summer. Atmospheric processes and air
mass dynamics are strongly influenced by these seasonal radiation balance extremes. Annually, the surface heating is restricted by large winter heat loss to the atmosphere, high reflectance of solar radiation by the snow cover in the spring, and low sun angles even in the summer season. Snowfall is an important part of annual precipitation and the snow cover often lasts over half a year. Rivers and lakes have an ice cover for much of the year, and below ground, seasonal frost and permafrost are prevalent (Fig. 1). At high elevations and on a number of Arctic islands, vestiges of Pleis-

![Map of the circumpolar region of the Northern Hemisphere showing major rivers and lakes and areas with snow on the ground for at least 180 days. Also shown is the distribution of continuous and discontinuous permafrost and the boundary of the Mackenzie River Basin.](image)

**Fig. 1.** The circumpolar region of the Northern Hemisphere showing major rivers and lakes and areas with snow on the ground for at least 180 days. Also shown is the distribution of continuous and discontinuous permafrost and the boundary of the Mackenzie River Basin.
tocene glaciation are preserved as remnant glaciers, the largest being the Greenland Ice Cap.

The cold region in the Northern Hemisphere includes both areas of high latitude and of high elevation. Two vast land masses in the circumpolar area, Eurasia and North America, surround the Arctic Ocean. Many Arctic islands occupy the perimeter of the central Arctic Basin, including Greenland which is the largest island in the world. On the continents, several major mountain chains that run approximately north-south were created at different geological times along the former edges of the Precambrian platforms. These mountains include the Western Cordillera in North America, the Scandinavian mountains in Europe, the Ural and other mountains in Siberia.

Topography focuses the major drainage into the Arctic Ocean. The northwestward flowing Yukon River is an exception. Among the five largest rivers, the Ob, Yenisey and Lena (basin areas of 2.5x10⁶, 2.6x10⁶ and 2.5x10⁶ km², respectively) are in Asia; the Mackenzie and the Yukon (basin areas of 1.8x10⁶ and 0.9x10⁶ km²) are in North America. In terms of flows from these pan-Arctic rivers, the North American contribution at 281 and 203 km³ per year for the Mackenzie and the Yukon respectively, is large, but it is moderate compared with 580, 538 and 402 km³ per year for the Yenisey, Lena, and the Ob (ACIA 2005).

Most of these large basins include a range of climatic and vegetation zones, from temperate grassland (steppes in Asia, prairies in North America) in the south, through boreal forests and subarctic woodlands in the central regions, to tundra in the north. Altitudinal zonation is also conspicuous in mountainous areas, with diminished vegetation diversity and coverage at high elevations. Lakes and wetlands are common on the plains and on the Precambrian bedrock topography (National Wetland Working Group 1988; Zhulidov et al. 1997).

3 The Mackenzie River Basin

The Mackenzie River Basin (or MRB) was selected for a comprehensive study of its climate and hydrology for a number of reasons that are listed as follows. It possesses many of the environmental attributes of the northern circumpolar region, thus offering an excellent natural laboratory for studying cold region processes. It is experiencing significant climate warming, making it a good candidate to examine climatic change and variability, and their attendant effects. The MRB has a moderately dense net-
work of weather stations and streamflow gauging sites that offer 30 or more years of records. The Mackenzie is the largest river in North America flowing into the polar seas. For the MRB, there have been several studies on aspects of the physical and human dimensions that provide useful background information (e.g., Cohen 1997; Mackenzie River Basin Board 2004; Marsh and Ommanney 1991).

### 3.1 Physical Setting and Vegetation

The MRB extends from 52° to 69°N, with a total area of 1.8 million km². This represents about 20% of the Canadian land mass (Fig. 2). From west to east, it straddles three major physiographic provinces: the Cordillera, the Interior Plains and the Precambrian Canadian Shield (French and Slaymaker 1993). At the northern extremity, the Mackenzie Delta forms part of the Arctic Coastal Plain (Fig. 3a). The Western Cordillera is a mountainous region with sub-parallel ridges that trend northwest-southeastward on the western flank of the Basin (Fig. 3b). The high peaks reach from 4000 to over 5000 m. There is a large elevation range of about 1000 m between the valley floors and the mountain tops. In contrast, the Interior Plains (Fig. 3c) are flat-lying and underlain by thick glacial, fluvial, and lacustrine deposits. The Plains drop very gradually from over 800 m in the south to the Mackenzie Delta near sea level. Large parts of the Plains are occupied by wetlands and lakes, as is the Delta which also includes a maze of levee-lined distributary channels. The eastern part of the MRB is dominated by the Precambrian Shield which has an undulating topography (Fig. 3d), with bedrock outcrops sculpted by Laurentide glaciation into rounded hills, and valleys that contain wetlands and lakes.

There is a diversity of surface cover conditions in the basin (Fig. 1 in Trischenko et al. 2007). Farmlands are restricted to the lowlands in the south and the plateau and valleys of the Peace River basin. Forests cover most of the Basin. The boreal forest has a diversity of tree species, including black and white spruce (*Picea mariana, Picea glauca*), mixed with aspen and poplar (*Populus tremuloides, Populus balsamifera*), pines (*Pinus banksiana, Pinus contorta*), birch (*Betula papyrifera*), balsam fir (*Abies balsamea*) and with larch (*Larix laricina*) in poorly drained areas. There is often a rich ground cover of shrubs. The subarctic open woodland is dominated by black or white spruce, with a ground cover of lichen and low shrubs. Wetlands including bogs, fens and marshes are a common feature in the forest zones, as are ponds and lakes. Alpine tundra and barren ground are found at high elevations and Arctic tundra follows a strip of
about 50 km in width along the Beaufort Sea coast. These zones lie beyond the tree-line and the surfaces range from bare soil to coverage by herbaceous plant communities and/or shrubs.

Fig. 2. The Mackenzie River Basin: its topography, major rivers and lakes
Fig. 3. Major regional landforms of the Mackenzie River Basin: (a) labyrinth of distributaries, ponds and wetlands in the Mackenzie Delta, (b) Western Cordillera with South Nahanni River deeply incised into a high plateau, (c) Fort Simpson situated on an island of the Mackenzie River that flows through the Interior Plain with low relief, and (d) undulating bedrock upland and lake in the Canadian Shield near Yellowknife. (Photos: M.K. Woo)
Fig. 3. (cont.)
3.2 Climate and Climate Variability

The MRB lies athwart the circum-global westerly wind circulation. Within this circulation, moisture transport to the northwestern coastal region of North America is accomplished by the cyclones initiated over the west Pacific, while secondary cyclones spawned from these primary cyclones are responsible for bringing precipitation to the Basin. Topography exerts a major influence on atmospheric circulation in the MRB. This is especially pronounced in the cold season when the interaction of the low-level onshore flow with the lofty Western Cordillera induces significant disturbances along the mean westerly flow to incite a stationary long wave pattern. Associated with this wave are a mean westerly transport of warm moist air into the region from the Pacific, and a mean northerly transport of cold dry air to the Basin from the Arctic (Cao et al. 2007; Szeto 2007). In the warm season, the Basin receives moisture flux from the Pacific and the Arctic Oceans, and sometimes from the Gulf of Mexico also (Liu et al. 2007); the latter can bring extreme rainfall to the Basin (Brimelow and Reuter 2007). Moisture recycling is also pronounced (Szeto et al. 2007a) as the large areas of wetlands and lakes facilitate evaporation and the mountain slopes enhance precipitation of the atmospheric moisture. Within the Basin, there is a strong precipitation gradient, with annual precipitation exceeding 1000 mm in the mountains to the southwest and decreasing to less than 300 mm in the northeast. Snowfall constitutes about 30% of total precipitation in the southern Interior Plains but over 60% in the far north and at high altitudes in the west.

As a high-latitude continental basin, the MRB is an important source region of cold continental polar air during the winter when monthly mean air temperatures range from -25 to -35°C, but daily temperature can fall below -50°C. In contrast, summer heating of the large land mass brings about high temperatures, with monthly averages ranging from 15°C in the northern to 20°C in the southern sector of the MRB. Daily high temperature can occasionally reach 30°C. One consequence of persistent coldness is the formation and maintenance of permafrost, or ground with temperatures at or below 0°C for at least two consecutive summers. Over 75% of the Basin is underlain by permafrost which is continuous north of the tree-line and discontinuous in the subarctic regions south of tree-line and in the alpine zone (Fig. 1). The entire MRB, including the non-permafrost zones, experiences seasonal ground freezing.

Temperature variations in circumpolar regions have been larger than those in the temperate and tropical areas. Records show that over the period 1950–98 the annual temperature in the Arctic region has generally in-
creased by 1 to 1.5°C, except in Eastern Canada and Greenland which experienced cooling (ACIA 2005). Reanalysis data indicate that winter temperature variability has been particularly large for the Yenisey and the Mackenzie areas (Kistler et al 2001; Szeto 2007). Mean annual temperature at Fort Simpson, located near the middle of the basin, indicates a rise of about 1°C after 1975 (Fig. 4). Simulation of temperature tendencies by several Global Climate Models confirms that the Arctic is a sensitive indicator of climate change. A scenario of a moderate future global emission of greenhouse gases, known as a B2 scenario, is expected to warm the zone 60–90°N by 3.5–5.5°C by 2100, depending on which model result is consulted (ACIA 2005).

Fig. 4. Annual temperature of Fort Simpson in Mackenzie Basin showing a sharp increase after the mid-1970s

A change in the snow cover conditions has accompanied recent climate warming (Derksen et al. 2007). Compared with the 1915–55 snow cover extent, the snow cover of the Northern Hemisphere for the period 1956–97 indicates a statistically significant decrease in March and April but an increase in November (Brown 2000). This is possibly related to cooling in November and warming in April, with a resulting shift in the snow season towards earlier dates of maximum snow depth and earlier disappearance of snow.

### 3.3 Energy and Water Budgets

A fundamental way to characterize the climate of a region is through its energy and water balances. The mean annual water and energy budgets for three large river basins along a north-south transect in the Americas are presented (Table 1) for comparison, using the results for 1988–99 produc-