THE MACKENZIE GEWEX STUDY (MAGS)

BASIC INFORMATION AND CRITICAL CHARACTERISTICS OF THE
MACKENZIE RIVER BASIN AND ITS ENERGY AND WATER FLUXES

by

Terry W. Krauss
(Version - August 16, 1995)

CONTENTS

LIST OF FIGURES .................................................... 3
LIST OF TABLES ..................................................... 4

INTRODUCTION ..................................................... 5
OVERVIEW OF OBJECTIVES OF GEWEX .................................... 5
OVERVIEW OF THE MACKENZIE GEWEX STUDY (MAGS) .................. 5

THE MACKENZIE BASIN .............................................. 5
OVERVIEW ................................................................... 5
HISTORICAL BACKGROUND ........................................ 6
PHYSIOGRAPHIC FEATURES ........................................ 6
VEGETATION AND WILDLIFE ......................................... 7

REGIONAL WATER BALANCE .......................................... 7
INTRODUCTION ...................................................... 7
TEMPERATURE ....................................................... 8
PRECIPITATION ..................................................... 8
EVAPORATION ..................................................... 9
RUNOFF ........................................................... 9
SEASONAL VARIATIONS IN RUNOFF .................................. 10
STORAGE .......................................................... 11
PERMAFROST ..................................................... 12
GROUND WATER ................................................... 12
FRESHWATER ICE COVER .......................................... 13
VERTICALLY INTEGRATED ATMOSPHERIC MOISTURE FLUXES ....... 13
CUMULATIVE ERRORS IN WATER BALANCE COMPUTATIONS ....... 14

REGIONAL ENERGY BALANCE .......................................... 15

MAGS DATA SOURCES .................................................. 17
INTRODUCTION TO OPERATIONAL NETWORKS .................... 17
LIST OF FIGURES

Figure 1: Map of Canada showing the Mackenzie Basin.
Figure 2: The Mackenzie Basin and its sub-basins.
Figure 3: Land cover map of Mackenzie Basin.
Figure 4: Map of Canada and northern regions classifications.
Figure 5: Annual mean daily temperature.
Figure 6: Mean daily temperature during Summer.
Figure 7: Mean daily temperature during Winter.
Figure 8: Mean annual precipitation from Johnstone (1983).
Figure 9: Mean annual precipitation from Kite et al. (1994).
Figure 10: Mean annual precipitation from the CCC-GCM II.
Figure 11: Mean monthly precipitation in Summer.
Figure 12: Mean monthly precipitation in Winter.
Figure 13: Mean annual total snowfall.
Figure 14: Mean maximum depth of snow.
Figure 15: Mean snow depth on the ground at end of February.
Figure 16: Mean annual lake evaporation.
Figure 17: Mean annual derived evapotranspiration.
Figure 18: Daily mean flows of the Mackenzie River at Arctic Red.
Figure 19: Average monthly hydrographs (1973-1990) at Ft. Simpson, Norman Wells, and Arctic Red.
Figure 20: Runoff coefficients for the Mackenzie Sub-basins.
Figure 21: Distribution and limits of permafrost in Canada.
Figure 22: Mean maximum ice thickness on lakes.
Figure 23: Mean maximum ice thickness in rivers.
Figure 24: Mean freeze over date on lakes.
Figure 25: Mean freeze over date on rivers.
Figure 26: Seasonal and mean water vapor flux of the Mackenzie Domain.
Figure 27: Locations of meteorological stations.
Figure 28: Locations of hydrometric stations.
Figure 29: Locations of Environment Canada and Flight Service meteorological stations.
Figure 30: Locations of NWT renewable resources forestry stations.
Figure 31: Locations of automated weather stations in the western NWT.
Figure 32: Upper-air stations of North America.
Figure 33: Upper-air stations of the Mackenzie Basin plus locations of proposed special MAGS sounding sites, and model synthetic sounding sites.
Figure 34: RFE model GCIP/MAGS domain (50 km grid resolution).
Figure 35: RFE model BASE regional domain (25 km grid resolution).
Figure 36: SEF model global domain (approximate 110 km grid resolution).
Figure 37: US, NMC ETA model domain for North America.
Figure 38: ETA model grid showing model Mackenzie Sub-Basins.
Figure 39: ECMWF domain over the Mackenzie River Basin.
LIST OF TABLES

Table 1: Major sub-basins, lakes, and deltas in the Mackenzie Basin.
Table 2: Monthly and annual discharge for the Mackenzie River at Arctic Red.
Table 3: Summary results of several water-balance studies.
Table 4: Summary results of several energy-balance studies.
Table 5: Satellite remote sensing platforms, data, and researchers.
Table 6: RFE model output parameters.
Table 7: MC2 model output parameters.
Table 8: Variables used in land surface modelling in the CCC GCM.
INTRODUCTION

The purpose of this document is to bring together a collection of basic scientific information about the Mackenzie River Basin and its hydrological cycle. This information is intended to facilitate the planning of the collaborative, multi-disciplinary research required to accomplish the goals of the Mackenzie GEWEX Study (MAGS).

OVERVIEW OF OBJECTIVES OF GEWEX

The Global Energy and Water Cycle Experiment (GEWEX) was initiated by the World Climate Research Programme (WCRP) as an internationally coordinated group of activities aimed at improving our understanding of the role that the water cycle and energy fluxes play in the global climate system. The objectives of the Canadian GEWEX Programme are: To contribute to the international GEWEX Programme in areas of special Canadian interest and expertise, and to contribute towards the better understanding and prediction of changes to Canada’s water resources arising from climatic change. GEWEX activities within Canada are within the purview of the Canadian Climate Programme and the Canadian Global Change Programme.

A central goal of the Canadian GEWEX is to develop the ability to model the water and energy balances of the Canadian Arctic Basin. The results of Canadian GEWEX will be an improved understanding of cold region, high latitude hydrological and meteorological processes, and the role that they play in the global climate system. One important aspect of this will be an improved ability to model the fresh-water flux into the Arctic Ocean.

OVERVIEW OF THE MACKENZIE GEWEX STUDY (MAGS)

As a complement to the GEWEX Continental-scale International Project (GCIP) in the Mississippi Basin, a series of large-scale hydrological and related atmospheric and land-atmosphere studies is being conducted within the Mackenzie River Basin called the Mackenzie GEWEX Study (MAGS). Within the Mackenzie Basin, there are many important cold-region phenomena such as snow and ice processes, permafrost, Arctic clouds and radiation interactions, etc., that will be essential components of any global climate system model. The Mackenzie and Mississippi Basins taken together provide a true continental area in which to test and validate macro-scale hydrological models.

THE MACKENZIE BASIN

OVERVIEW

The Mackenzie is one of the great river basins of the world, ranking tenth largest by drainage area, twelfth by sediment discharge, and fifteenth by mean annual
discharge (Milliman and Meade, 1983). The Mackenzie River flows through the northwestern part of Canada into the Beaufort Sea of the Arctic Ocean. A map showing the location of the Mackenzie River Basin is shown in Figure 1. The Mackenzie is the fourth largest river in North America and the largest North American river basin emptying into the Arctic Ocean (Milliman and Meade, 1983), with an area of 1.787 million km² or almost 20% of the total Canadian land mass.

The entire Mackenzie River system, the second largest in North America, after the Mississippi-Missouri system, is 4,240 km long. Settlements along its course include Fort Providence, Fort Simpson, Fort Norman, Norman Wells, Fort Good Hope, Inuvik, and Aklavik. In the Mackenzie Valley, the largest settlements include Yellowknife (1991 population, 15,179), the capital of the Northwest Territories (NWT) , Inuvik (population, 3,206), Hay River (population, 3,206), and Fort Smith (population, 2,480). The Mackenzie Basin is home to some 50,000 Aboriginal Peoples. The primary resources of the NWT are its wildlife, minerals (lead, zinc, and gold are important revenue producers), and petroleum and gas potential.

Although the river is frozen from November to June, during the ice-free season it is used for navigation. Transportation of barges loaded with petroleum from Norman Wells and uranium ore from the Great Bear Lake mines is the Mackenzie's principal economic function. The only rail link with the south terminates at Hay River. A limited road system links the Mackenzie Valley to northwestern Alberta, and Inuvik was linked to Yukon roads in 1979. Fort Simpson was linked to the Alaska Highway in 1984.

HISTORICAL BACKGROUND

Historically, the Mackenzie River was explored by Sir Alexander Mackenzie in 1789; the delta and coastal area were charted by Sir John Franklin (1825-26). The region became notorious during the great Alaskan gold rush of 1897-1899, which brought about 30,000 adventurers during the two years. Many uninformed travellers died on the journey to the Klondike as a result of the misguided information which enticed them to travel from Edmonton to Dawson via the Mackenzie River system (Michener, 1988).

PHYSIOGRAPHIC FEATURES

The hydrologic regime of the Mackenzie Basin is influenced by the major physiographic regions (Western Cordillera, Interior Plain, Precambrian Shield and Arctic Coastal Plain), permafrost which covers a significant portion of the basin, and vegetation which varies from boreal forest to Arctic and alpine tundra. The highest peak in the Mackenzie Mountains is 2,773 m (9,098 ft).

The basin is composed of six major sub-basins (Athabasca, Peace, Great Slave, Liard, Great Bear, and Peel); three major lakes (Athabasca, Great Slave, and Great Bear); and three major deltas (Peace-Athabasca Delta, Slave River Delta, Mackenzie Delta). Of these sub-basins only the Peace River is regulated to a significant degree. A
map showing the six major sub-basin boundaries is given in Figure 2.

Table 1 lists the areas for the major subbasins, lakes, and deltas in the Mackenzie Basin.

Table 1: Major subbasins, lakes and deltas in the Mackenzie Basin (Mackenzie River Basin Committee (1981a).

<table>
<thead>
<tr>
<th>SUBBASINS</th>
<th>Area (km²)</th>
<th>LAKES</th>
<th>Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Athabasca</td>
<td>307,000</td>
<td>Lake Athabasca</td>
<td>7,987</td>
</tr>
<tr>
<td>Peace River</td>
<td>302,000</td>
<td>Great Bear Lake</td>
<td>30,963</td>
</tr>
<tr>
<td>Great Slave Lake</td>
<td>380,000</td>
<td>Great Slave Lake</td>
<td>26,829</td>
</tr>
<tr>
<td>Liard River</td>
<td>277,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Great Bear River</td>
<td>158,000</td>
<td>Peace-Athabasca Delta</td>
<td>6,070</td>
</tr>
<tr>
<td>Mackenzie River</td>
<td>363,000</td>
<td>Slave River Delta</td>
<td>310</td>
</tr>
<tr>
<td>Total</td>
<td>1,787,000</td>
<td>Mackenzie River Delta</td>
<td>12,000</td>
</tr>
</tbody>
</table>

VEGETATION AND WILDLIFE

Basin land cover types are: coniferous forest (35%), mixed wood forest (19%), transitional forest (19%), Arctic & alpine tundra (7%), lakes and rivers (7%), deciduous forest (6%), barren lands (5%), and agriculture land (2%). A map showing a recently revised land cover for the Mackenzie Basin from Gong et al. (1994) is given in Figure 3.

The predominant subarctic forest of spruce, pine, birch, and larch provides habitat for moose, caribou, bears, and beavers, whereas musk-oxen, caribou (in summer), and Arctic foxes live on the tundra. Other species contributing to the fur industry include marten, mink, polar bear, and lynx. The fishing industry consists principally of trout, Arctic char, and whitefish.

REGIONAL WATER BALANCE

INTRODUCTION

The land surface water balance is given by:

\[ R = P - E \pm \Delta S \]
where R is runoff, P is precipitation, E is evaporation and sublimation, and ΔS is the change in storage. Monitoring the hydrologic cycle requires measurement of precipitation, evapotranspiration, and runoff. An improved understanding of the hydrological cycle requires additionally, determination of the controlling factors for the hydrologic cycle, and quantification of the interactions between vegetation, soil, topography and the hydrologic cycle components.

On an annual basis, it is usually assumed that ΔS is equal to zero. Annual values for each component in equation 1 can be approximated from existing data sets. However, due to limitations in the existing data and significant errors in these, few published studies have calculated the water balance at shorter time steps. In addition, the spatial variations in these components are not well known.

TEMPERATURE

Air temperature is perhaps the variable most commonly used to characterize the cold, northern regions. Köppen's (1936) classification considered this to include: a mean temperature of the coldest month not exceeding -3°C and no more than 4 months with a mean temperature greater than 10°C. The common terms "Arctic" and Subarctic are also based simply on coldness criteria (e.g., Washburn, 1953). The arctic classification refers to those regions where the mean temperature for the warmest month remains below 10°C and the mean annual temperature below 0°C. The SubArctic refers to those regions where the mean temperature of the warmest month is above 10°C but no more than 4 months have a mean temperature exceeding 10°C. A map showing the approximate boundaries of the various "northern" regions is given in Figure 4. Maps showing the annual mean daily temperature, mean daily temperature during summer (May-Sept.), and mean daily temperature during winter (Oct.-April), are given in Figures 5, 6, and 7 respectively.

PRECIPITATION

Precipitation ranges from less than 300 mm/yr in the northwestern sections of the Mackenzie Basin, to between 300 to 400 mm/yr in the extreme southern sections of the basin, to as high as 1600 mm/yr in the Cordillera. The mean annual precipitation for the entire Mackenzie Basin is approximately 410 mm/yr (Canada, Fisheries and Environment, 1978).

Since most station measurements are made at low elevations, the regional averages of precipitation for the mountainous regions of the Mackenzie are underestimated. Different climatological analyses have yielded different spatial distributions of precipitation. A map of the mean annual precipitation from Johnstone (1983) is given in Figure 8. This can be compared with the results of Kite (1994 personal communication) showing the recorded mean annual precipitation for the period 1961-1990 in Figure 9. For comparison purposes, the climatological precipitation from the Canadian Climate Centre's GCM II are shown in Figure 10 (Kite, 1994 personal communication). The mean monthly precipitation during summer and during winter are given in Figures 11 and 12 respectively (Johnstone, 1983).
A serious bias also occurs due to the undercatch of snow by gauges in windy conditions. Procedures to correct historical national gauge measurements for wind, wetting, and evaporative losses have been documented by Goodison et al., 1994. Results indicate that actual annual precipitation is 50 to 100% greater than measured for Arctic stations north of 65°N, and 20 to 25% greater for stations south of 65°N. The primary reason for the larger differences between measured and corrected precipitation at High Arctic stations is the number of trace amounts at these locations (Metcalfe et al., 1994).

Over the Mackenzie Basin, a significant portion of the annual precipitation falls as snow, varying from 32% at Edson, Alberta to 57% at Inuvik. Snow storage of a large portion of the annual precipitation for between 5 and 8 months of the year is therefore an important component of the water cycle of the basin. Snowmelt runoff during the spring dominates the basin hydrograph. A map showing the mean annual total snowfall (cm) 1951-1980 is given in Figure 13. The mean maximum depth of snow in cm is shown in Figure 14 (Findlay, 1978) and a map showing the mean snow depth on the ground (cm) measured at the end of February is given in Figure 15 (Johnstone, 1983).

**EVAPORATION**

Estimated open water evaporation from ponds, shallow lakes, and reservoirs varies from between 500 and 600 mm/yr in the southern portions of the Mackenzie Basin, to less than 200 mm/yr in the northern sections of the basin (Canada, Fisheries and Environment, 1978; Morton, 1983b). Estimates of regional evapotranspiration for the Mackenzie Basin vary between 350 and 400 mm/yr in the south, to 100 mm/yr in the north (Canada, Fisheries and Environment, 1978; Morton, 1983a). The applicability of both techniques (Pan method and Morton method) to northern environments has only undergone limited testing. A map showing the mean annual lake evaporation is given in Figure 16, and a map showing the derived evapotranspiration is given in Figure 17 (den Hartog and Ferguson, 1978).

Total evaporation calculated as the residual of the water balance for the Mackenzie basin is 237 mm/yr, or approximately 58% of the total precipitation input to the basin.

**RUNOFF**

Runoff varies from less than 100 mm/yr in the southern portions of the Mackenzie basin, to 100 to 200 mm/yr in the northern portions of the basin, to over 1000 mm/yr in the southern cordillera (Canada, Fisheries and Environment, 1978). Total discharge from the Mackenzie Basin can be estimated from separate measurements for the Mackenzie and Peel Rivers. Mean annual values for an approximately 20 year period are 9,088 and 692 m³/s respectively (Canada, Environment Canada, 1990), for a combined total of approximately 9,780 m³/s or 308 km³/yr. Mean annual runoff per unit area is therefore 173 mm/yr, or approximately 42% of total precipitation input to the basin.
Although the annual water balance provides important information on the regime of the Mackenzie Basin, the seasonal variations in flow are probably more important to the social, ecological, and economical use of the basin.

The Mackenzie River integrates the runoff of four runoff regimes from the major subbasins in the Mackenzie Basin (Marsh and Prowse, 1993). Four common regime types are typical for the permafrost and mountainous sections of the Mackenzie Basin. According to Church (1974) these are described as:

i. Arctic-nival regimes: In areas of continuous permafrost the spring snowmelt dominates the annual hydrograph, and runoff from summer rain is generally small since precipitation is low in magnitude. Winter streamflow is usually very low or non-existent due to limited groundwater contribution. This regime is only found in the coldest, northern and northeastern sections of the Mackenzie Basin.

ii. Sub-Arctic nival regimes: are also dominated by spring snowmelt, but summer rainstorms may produce floods similar in size to the spring snowmelt peak flows. With the occurrence of discontinuous permafrost, groundwater contributions increase, and winter flow may be larger. Such regimes are typical of much of the pre-cambrium shield, interior plains, and cordilleran rivers of the Mackenzie Basin.

iii. Muskeg regimes: occur where drainage is poor due to low relief or the existence of an impermeable substrate. Muskeg streams are characterized by a large water-retaining capacity, and therefore, significant flow attenuation. These regimes are typical of the interior plains where 24% to 75% of the area is covered by wetlands. Permafrost may play a significant role in controlling the distribution of wetlands.

iv. Proglacial streams: in these streams, snowmelt runoff is important, but instead of a brief spring peak, flow increases throughout the snowmelt period and then continues to increase as meltwater is contributed from higher sections of the glacier dominated basin. Within the Mackenzie Basin, proglacial streams are limited to the higher areas of the western cordillera. Very little information is available on the portion of total flow which is contributed from glacial streams in the Mackenzie Basin.

Table 2 summarizes the monthly minimum, mean, and maximum flows. The resulting regime of the Mackenzie River would best be described as Sub-Arctic nival, with: a dominant spring flood with maximum flows up to 34,000 m$^3$/s or 3.7 times the mean annual flow; significant summer peaks due to rainfall runoff (up to 32,100 m$^3$/s or 3.5 times the mean annual flow), and discharge which continues throughout the winter (with minimum flows of 3,220 m$^3$/s or 0.4 times the mean annual flow). Only the Peace River tributary is regulated, however, this only results in a slight shift in the annual hydrograph, raising average flow during low flow months, and lowering summer and fall
flows (Wiens, 1991).

Table 2: Monthly and annual discharge for the Mackenzie River at Arctic Red River. The basin area at this point is $1.66 \times 10^6$ km$^2$.

<table>
<thead>
<tr>
<th>Month</th>
<th>Minimum, m$^3$/s</th>
<th>Mean, m$^3$/s (mm)</th>
<th>Maximum, m$^3$/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>2170</td>
<td>3,676 (5.9)</td>
<td>5,240</td>
</tr>
<tr>
<td>February</td>
<td>2610</td>
<td>3,490 (5.1)</td>
<td>4,470</td>
</tr>
<tr>
<td>March</td>
<td>2290</td>
<td>3,220 (5.2)</td>
<td>4,360</td>
</tr>
<tr>
<td>April</td>
<td>2040</td>
<td>3,259 (5.1)</td>
<td>4,930</td>
</tr>
<tr>
<td>May</td>
<td>2100</td>
<td>12,834 (20.7)</td>
<td>34,000</td>
</tr>
<tr>
<td>June</td>
<td>11,900</td>
<td>21,102 (32.9)</td>
<td>31,800</td>
</tr>
<tr>
<td>July</td>
<td>9,850</td>
<td>17,986 (29.0)</td>
<td>32,100</td>
</tr>
<tr>
<td>August</td>
<td>7,870</td>
<td>14,141 (22.8)</td>
<td>28,000</td>
</tr>
<tr>
<td>September</td>
<td>7,730</td>
<td>19,400 (30.3)</td>
<td>11,439</td>
</tr>
<tr>
<td>October</td>
<td>3,620</td>
<td>9,205 (14.9)</td>
<td>12,500</td>
</tr>
<tr>
<td>November</td>
<td>1,730</td>
<td>4,929 (7.7)</td>
<td>12,400</td>
</tr>
<tr>
<td>December</td>
<td>1,680</td>
<td>3,551 (5.7)</td>
<td>5,180</td>
</tr>
<tr>
<td>Year</td>
<td>1,680</td>
<td>9,088 (172.7)</td>
<td>34,000</td>
</tr>
</tbody>
</table>

The daily mean flow of the Mackenzie River at the Arctic Red station over the period 1973-82 and 1983-92 is given in Figures 18a and 18b respectively (Kerr, 1995). Average hydrographs for the 1973 to 1990 period for hydrometric stations at Ft. Simpson, Norman Wells, and Arctic Red are shown in Figure 19 (Lawford, 1994). Runoff coefficients defined as the average discharge/precipitation ratio for the period 1973-1990 for the various sub-basins of the Mackenzie are shown in Figure 20 (Lawford, 1994).

**STORAGE**

On an annual basin it is often assumed that changes in storage are zero. However, that is not always the case and long term fluctuations in groundwater, lake, and glacial storage can occur. For example, the major impact of glaciers is to store water during cold and/or wet periods, and to release water during warm periods. The
magnitude of annual or seasonal changes in storage in the Mackenzie Basin is not known.

PERMAFROST

Permafrost is defined as ground that is continuously below 0°C for two years or more. Permafrost covers approximately one-quarter of the land surface of the world and one-half of Canada. For much of northern Canada, it plays a significant role in the terrestrial portion of the hydrological cycle because it restricts moisture exchanges between surface water and deep ground water (Prowse, 1990).

Permafrost distribution is controlled by a combination of climatic, geological, hydrological, topographical, and botanical factors. The spatial extent and distribution of permafrost, broadly extrapolated from a meagre spatial data set, is shown in Figure 21. The thickness, temperature, and horizontal extent of permafrost undergoes a gradual transition northward. The boundary between continuous and discontinuous permafrost approximates the position of the -8.5°C mean annual air isotherm. The southern limit of permafrost is generally accepted as coinciding with the -1°C mean annual air isotherm. In the continuous zone, permafrost thickness generally increases with latitude from approximately 100 m at the southern limit to 1000 m in the far north.

Of all the factors affecting permafrost, water is the most significant. In liquid form, the combination of high absorption of solar radiation, ease of turbulent mixing, and high thermal capacity serve to develop significant summer heat storage and hence, significant ground warming. During the winter, most large lakes and rivers with appreciable flow do not freeze to the bed and hence, many rivers and lakes have unfrozen areas or taliks beneath them which permit the linking of the surface and ground water. In the solid form, as snowcover, water has dual conflicting roles in affecting permafrost. Because of its low thermal conductivity, snow inhibits ground freezing during the cold winter months but its high albedo delays thawing and warming of the underlying ground in the spring. In contrast to the effect of large water bodies on permafrost occurrence, the restriction of infiltration and recharge of water by permafrost over areas of low relief can lead to the formation of extensive muskegs and ponds. In many cases, the location of surface drainage-divides and the presence of perched water-tables depend on permafrost topography.

GROUND WATER

The supply, availability, distribution, and quality of ground water in the North is controlled, to a large degree, by the presence of permafrost. This impermeable layer controls both the recharge to underlying aquifers and the discharge to surface water systems. Suprapermafrost water is the most widely spread, occupying the seasonally-formed active layer and unfrozen zones beneath lakes and rivers. Water obtained from such sources offer only a seasonal supply, are easily contaminated and, in the case of active-layer water, are high in organic content. Intrapermafrost water exists within thawed zones between perennially-frozen layers. Subpermafrost water is found
beneath permanently frozen ground, usually in either bedrock or deep glacio-fluvial deposits. Alluvial and glacio-fluvial deposits, which can contain any of the three permafrost water types, provide good ground water supplies for many northern communities within the discontinuous permafrost zone. Progressing northward, such deposits become less accessible with increasing permafrost, although deep bedrock aquifers can produce high-quality water, especially within the high-recharge zone adjacent to the western mountains. Within the Northwest Territories, almost half of the total water supply comes from ground water. In the Yukon, 22% of the total water supply comes from ground water (Hess, 1986).

**FRESHWATER ICE COVER**

Freshwater ice seasonally covers most lake and river systems in Canada, ranging from periodic skims of ice in the more southerly temperate regions to mean thicknesses in excess of 2 m on high-latitude northern lakes and rivers. The mean maximum ice thickness on lakes and rivers is shown in Figs. 22 and 23 (1.14 and 1.15) respectively (Allen, 1977). The mean dates of freeze-over and completion of ice clearance on lakes and rivers is shown in Figs. 24 and 25 (1.16 and 1.17) respectively. Duration of the river-ice season is less than that of lake ice because river ice is first to break-up in the spring. In the northern portions of the basin, the channels begin to freeze in October with a complete ice cover forming by January in all portions of the Mackenzie Basin.

The northward advance of river-ice break-up in the territories occurs on average at a rate of approximately 0.3 degrees of latitude per day (Prowse and Onclin, 1987). Since the Mackenzie and its main tributaries flow in a northerly direction from areas of relative warmth to a colder environment, melt tends to progress in a downstream direction. The resulting flood wave often progresses downstream more rapidly than the melt conditions, and the flood wave encounters thick, resistant ice covers, resulting in very large ice jams (Andres and Doyle, 1984; Prowse, 1986). These ice jams are responsible for exceptionally high water levels, and result in the flooding of numerous towns.

Complete clearance of lake ice does not always occur in the far North and multi-year ice periodically develops on some lakes because of the brevity of melting seasons. Similarly, some forms of ice cover can remain on streams and rivers until late summer and, in some years, form multi-year accretions.

**VERTICALLY INTEGRATED ATMOSPHERIC MOISTURE FLUXES**

Walsh et al. (1994) used high-latitude rawinsonde data for 18 years (1973-1990) to compute the atmospheric moisture flux convergence for the Arctic Ocean and Mackenzie River drainage basins.

The seasonal and annual mean inflow (or outflow) along the boundary of the Mackenzie domain (from Walsh - private communication), is shown in Figure26. These
analyses suggest that the net inflow is largest across the southern and western boundaries; net outflow occurs through the eastern boundary; inflow is greatest from the west during June, July, August, and greatest from the south during September, October, November.

The moisture flux convergence was found to be positive in all months over the Arctic Ocean, but occasionally negative during summer over the Mackenzie Basin. Evaporation deduced from the moisture flux convergence and independent data on precipitation, makes a much greater contribution to the atmospheric moisture budget of the Mackenzie domain during summer. The equivalent areal averages of the 18 year annual mean moisture flux convergence, precipitation, and evaporation were found to be 24.9, 33.6, and 8.7 cm yr\(^{-1}\) respectively for the Mackenzie domain. The moisture flux convergence appear to overestimate P-E (and hence runoff) in the Mackenzie Basin because several key rawinsonde stations near the western boundary are located on the Pacific side of the drainage divide. Portions of the onshore moisture fluxes at these stations are lost as precipitation in upslope flow prior to the airflow's entry into the Mackenzie Basin. Also, negative values of the derived evaporation for the winter months imply that the station-based estimates/observations of regional precipitation are too low by at least several centimetres per year.

**CUMULATIVE ERRORS IN WATER BALANCE COMPUTATIONS**

There are serious anomalies in the large-scale water balance over northern Canada due to errors in the precipitation and runoff databases. These problems are exacerbated in the Mackenzie because of the widely spaced weather and runoff stations, extreme weather conditions, the general lack of roads, and problems due to ice and snow. The water balance calculations by Haas (1991) demonstrated that precipitation must be increased by 14 to 100% to obtain a water-storage curve with no trend. Generally the correction factor increased the further north the study area. Water balance studies are limited often to only one station per area which may in fact not be representative of their respective river basins. In addition, there are also problems with streamflow and evapotranspiration measurements and estimates.

The summary results of the water-balance calculations by Haas (1991), Kite et al. (1994), and Walsh (1994) are presented in Table 4.

<table>
<thead>
<tr>
<th>Area</th>
<th>Precipitation (mm/yr)</th>
<th>Evapotranspiration (mm/yr)</th>
<th>Run-off (mm/yr)</th>
<th>Precipitation adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fort Smith</td>
<td>414.7</td>
<td>272.8</td>
<td>29.5</td>
<td>14</td>
</tr>
<tr>
<td>Norman Wells</td>
<td>434.9</td>
<td>192.8</td>
<td>303.2</td>
<td>54</td>
</tr>
<tr>
<td>Inuvik</td>
<td>293.1</td>
<td>186.1</td>
<td>81.3</td>
<td>30</td>
</tr>
<tr>
<td>Watson Lake</td>
<td>447.5</td>
<td>230.2</td>
<td>205.0</td>
<td>14</td>
</tr>
<tr>
<td>Whitehorse</td>
<td>371.7</td>
<td>184.6</td>
<td>179.0</td>
<td>40</td>
</tr>
</tbody>
</table>
The regional energy balance exerts a major control on northern hydrological regimes as an important influence on snowmelt, in providing the energy to drive the evapo-transpiration process and through the regulation of heat flow into the substrate, which ultimately controls the amount of permafrost melting in the active layer. A good overview can be found in Rouse (1990). Evapotranspiration/precipitation ratios show, on an annual basis, magnitudes in the order of 0.4, 0.5, and 0.2 in the Subarctic, Low Arctic, and High Arctic respectively. For the snow-free period only, corresponding ratios are approximately 0.7, 1.0, and 0.9 (Price and Woo, 1988; Rouse, 1984c; Woo et al., 1983b). Evapo-transpiration thus comprises a major component in the surface water balance especially in the snow-free period. Up to 18% of the net all-wave radiation available at the surface is employed in melting of the active layer in ice-rich permafrost during the thaw period, whereas during freeze-back, this energy is released leading to a prolonged zero curtain effect (Rouse, 1984b; Halliwell and Rouse, 1987).

The energy balance at the surface is given by:

\[ Q^* = Q_E + Q_H + Q_G + Q_M \]

in which \( Q^* \) is net all-wave radiation, \( Q_E \) is latent heat flux, \( Q_H \) is sensible heat flux, and \( Q_M \) is the latent heat of melt for snow and ice surfaces. The ground heat flux, \( Q_G \) can be subdivided into:

<table>
<thead>
<tr>
<th>Komakuk Beach</th>
<th>346.5</th>
<th>190.9</th>
<th>220.1</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shingle Point</td>
<td>425.8</td>
<td>211.8</td>
<td>221.6</td>
<td>50</td>
</tr>
<tr>
<td>Mackenzie Basin Average (recorded)</td>
<td>394</td>
<td>223 (residual)</td>
<td>171</td>
<td>none</td>
</tr>
<tr>
<td>Mackenzie Basin Average (CCC0GCM II)</td>
<td>779</td>
<td>507</td>
<td>294</td>
<td>none</td>
</tr>
<tr>
<td>Mackenzie Basin Average (SLURP-Kite, 1994)</td>
<td>476</td>
<td>279</td>
<td>162</td>
<td>calibrated simulation</td>
</tr>
<tr>
<td>Mackenzie Basin Average (Walsh, 1994)</td>
<td>336</td>
<td>87</td>
<td>249</td>
<td>implied errors indicate precip. too low by several cm/hr.</td>
</tr>
</tbody>
</table>
\[ Q_s = Q_s + Q_l \]

with \( Q_s \) representing the storage of sensible heat and \( Q_l \) the storage of the latent heat of fusion in the ground ice. The Bowen ration (\( \beta \)) is both a measurable term and a diagnostic term which can describe the evapotranspiration behaviour of the surface, and is defined as:

\[ \beta = \frac{Q_H}{Q_E} = \gamma \frac{\Delta T_a}{\Delta e} \]

in which \( \gamma \) is the psychrometer constant. \( \Delta T_a \) and \( \Delta e \) are the vertical air temperature and vertical vapour-pressure gradients taken over the same height intervals (\( \Delta z \)) within the surface boundary layer.

The atmospheric fluxes are defined as:

\[ Q_H = -\rho C_p K_H \frac{\Delta T_a}{\Delta z} \]
\[ Q_E = -\rho C_p \gamma K_w \frac{\Delta e}{\Delta z} \]

in which \( \rho \) is air density, \( C_p \) is the specific heat of air, and \( K_H \) and \( K_w \) are the turbulent transfer coefficients for sensible and latent heat. These equations can be made operational in the form of aerodynamic flux equations (Halliwell and Rouse, 1989) in which the turbulent transfer coefficients are replaced by the log-linear wind profile, Von Karmans’s constant, and a correction for atmospheric stability.

The net all-wave radiation \( Q^* \) can be expressed in terms of its component fluxes as:

\[ Q^* = K_l (1-a) + L_l - L_i \]
\[ = K^* + L^* \]

in which \( a \) is surface albedo, \( L_l \), \( L_i \), and \( L^* \) are the incoming, outgoing and net long-wave radiation respectively and \( K_l \) and \( K^* \) are the incoming and net solar radiation. Trend lines of \( K_l \), \( K^* \), \( Q^* \), and \( L^* \) are plotted in Figure 8.1 using measured data from stations in Canada (Rouse, 1990). In the figure, Subarctic refers to the mixed open-forest tundra lands which lie north of the main boreal forest and Arctic refers to the open tundra north of the tree line.

Table 8.4 summarizes select data for the subarctic, Arctic tundra, and arctic glaciers (Rouse, 1990). In the subarctic and in the arctic tundra, \( Q^* \) during the melt and postmelt season is large and triggers atmospheric and ground fluxes which are large. The subsurface heat flux in summer is sizeable. Bowen ratios are large, even during melt and for wet surfaces in summer. In this respect, the high latitudes differ from temperate latitude counterparts because of strong surface and atmospheric resistances to evapotranspiration.
<table>
<thead>
<tr>
<th>Area</th>
<th>Season</th>
<th>Q*</th>
<th>(QG+QM)</th>
<th>(QG+QM)/Q*</th>
<th>QE</th>
<th>QH</th>
<th>β</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-arctic</td>
<td>melt summer</td>
<td>10.9</td>
<td>0.6</td>
<td>6</td>
<td>6.1</td>
<td>4.2</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11.3</td>
<td>0.8</td>
<td>6</td>
<td>6.0</td>
<td>4.5</td>
<td>0.75</td>
</tr>
<tr>
<td>Arctic tundra</td>
<td>melt summer</td>
<td>7.0</td>
<td>1.9</td>
<td>27</td>
<td>2.9</td>
<td>2.2</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10.7</td>
<td>1.3</td>
<td>12</td>
<td>5.1</td>
<td>4.3</td>
<td>0.84</td>
</tr>
<tr>
<td>Arctic glaciers</td>
<td>summer</td>
<td>2.8</td>
<td>5.8</td>
<td>207</td>
<td>-0.5</td>
<td>-2.5</td>
<td>5.0</td>
</tr>
</tbody>
</table>

**MAGS DATA SOURCES**

**INTRODUCTION TO OPERATIONAL NETWORKS**

As of 1989, there were 181 hydrometric and 115 climate stations operated by Environment Canada within the combined Yukon and NWT. Due to ongoing water survey and climatological program reductions by Environment Canada and its partners, the number of hydrometric and climate stations is being reduced. Discussions are ongoing regarding the maintenance of as many stations as possible of interest to GEWEX within the Mackenzie Basin. The locations of Mackenzie Basin meteorological stations from the AES National Archive catalogue is shown in Figure 27 and the hydrometric stations are shown in Figure 28. A breakdown of the various participating agencies and their respective stations is given in the following section.

**CLIMATOLOGICAL NETWORKS**

In the western portion of the NWT, there are six major contributors to the real-time meteorological and climatological data base (Lukawesky, 1994):

i. Environment Canada weather stations
ii. Transport Canada Flight Service Stations (FSS)
iii. Arctic Community Airport Radio Stations (CARS)
iv. NWT renewable resources
v. Volunteer climatological stations

Stations which have been documented by Environment Canada are assigned a climatological station number. Data collected and processed through Environment Canada’s quality control procedures are archived and listed in a climatological station catalogue. The number of volunteer climatological stations in the NWT is very small.

Figure 29 shows the position of the Environment Canada and Flight Service Stations. Figure 30 shows the position of the NWT renewable resources forestry
stations, which provide seasonal information in support of forest fire detection and control. Figure 31 shows the locations of automated stations within the western NWT.

UPPER AIR NETWORK

The locations of the two-a-day upper-air "rawinsonde" stations in North America are shown in Figure 32. Only the stations at Inuvik, Norman Wells, Ft. Nelson, and Ft. Smith are located within the Mackenzie Basin boundaries. Stations at Whitehorse, Prince George, Edmonton "Stoney Plain", and The Pas are located near the perimeter of the basin. Figure 33 shows a close-up view of the Mackenzie Basin and the locations of the existing upper air stations, plus the locations of 4 special upper air stations at Dawson, Lupin, Peace River, and Ft. Simpson as part of the proposed "enhanced" observation periods for MAGS in 1997/98. Also shown in the figure are quadrilaterals representing the sub-basins as well as the locations of the proposed model synthetic sounding sites for large scale atmospheric modelling studies.

NATIONAL CLIMATE ARCHIVE

Up to date information from the National Archives can be made available in print or electronic copy through the Climate Information Branch of the AES in Downsview Ont. or Regional Environmental Services offices of DOE.

HYDROMETRIC DATA

According to the World Meteorological Organization guidelines (WMO, 1981), the recommended hydrometric-station density for polar zones ranges from one per 5,000 to 20,000 km², equally divided among catchments greater than and less than 10,000 km². The stations density is 1:8,000 km² for the Yukon, and 1:29,000 km² for the NWT with 68% and 58% respectively of the stations located on catchments less than 10,000 km². Wedel (1986) suggested that it could be argued that a lower station density is sufficient for the larger catchments in the NWT since many basins are predominantly permafrost with low precipitation and evapotranspiration. Only 21% of the discharge stations have records longer than 30 years in length and it must be mentioned that even these long time-series may have serious omissions, inconsistencies, and inadequacies, particularly during the freeze-up and break-up periods.

Water Survey of Canada daily streamflow and lake level data for virtually all Canadian stations for the entire period of record is available on the CD-ROM called HYDAT which is updated annually.

OTHER DATA

As of 1984, the network of ice reporting stations comprised only 29 river and 61
lake locations. The snow-survey network in northern Canada is also meagre. The 1986 summary report lists only 74 official reporting snow surveys in the north; 20 within the NWT and 54 in the Yukon.

There is currently no co-ordinated glacier-survey program operating in northern Canada, although some long-term studies have been carried out by the Geological Survey of Canada, Energy Mines and Resources; National Hydrology Research Institute, and some universities (e.g. Univ. British Columbia, Univ. Ottawa, Trent Univ., Univ. Colorado, and others).

Water quality monitoring in the north is conducted at 20 standard hydrometric stations of Environment Canada and at approximately 70 industrial and municipal water-use operations licensed by the Dept. of Indian Affairs and Northern Development (DIAND).

SPECIAL HYDROLOGICAL PROCESSES RESEARCH BASINS

GEWEX hydrological research basins are located in four general areas:

a. Inuvik,
b. Prince Albert National Park, and
c. Wolf Creek.
d. Ft. Simpson. note: The fourth research "wetlands" basin near Ft. Simpson is being instrumented during 1995.

INUVIK, NWT

There are two main "types" of data presently being collected in the Inuvik area. The first is the standard river stage and level measurements collected by the Water Survey of Canada office located in Inuvik. The second includes the research data collected by the National Hydrology Research Institute at two research basins.

Water Survey of Canada (WSC) River discharge data has been collected at a large number of basins in the Inuvik area since the early 1970's when a WSC office was established in Inuvik. Previous to that, streamflow data were not collected on a routine basis in the Inuvik area. The following streams are currently monitored by WSC:

1. Rengleng River (1,310 km²),
2. Caribou Ck. (625 km²),
3. Cabin Ck. (133 km²),
4. Havikpak Ck. (approx. 35 km²),
5. Trail Valley Ck. (68 km²),
6. Hans Ck. (337 km²), and
7. Freshwater Ck.

These small drainage basins are all located on the east side of the Mackenzie Delta, and offer reasonable access. These seven drainage basins offer a unique sequence of drainage basins along a transect which crosses the Arctic treeline. Basins
1 to 4 are located south of the treeline, and the vegetation is dominated by northern Boreal forest. Basins 5 to 7 are located north of the treeline and the vegetation is dominated by arctic tundra.

In addition, to the above rivers, WSC monitors a number of larger basins in the vicinity of Inuvik. These include:

(1) Mackenzie River at Arctic Red River (1,660,000 km²),
(2) Arctic Red River (18,600 km²),
(3) Peel River (70,600 km²),
(4) Anderson River (56,300 km²),
(5) Babbage River (1,510 km²), and
(6) Firth River (5,710 km²).

These rivers drain a variety of topographic and vegetation classes, and all provide a significant input of freshwater to the Beaufort Sea/Arctic Ocean.

Data from all of the above mentioned rivers are available directly from the Water Survey of Canada, and the historical record is available on the CD-ROM called HYDAT.

National Hydrology Research Institute (NHRI): NHRI has developed a research program at Havikpak Ck. and Trail Valley Ck. NHRI conducts additional measurements of discharge at these two basins. This additional data greatly enhances the WSC discharge data during breakup when standard techniques for determining discharge are of limited use. This enhanced data is reported with the standard WSC data. However, it only began in 1992 for Trail Valley Ck. and 1993 for Havikpak Ck.

NHRI has installed a recording weather station at Havikpak Ck. and Trail Valley Ck. The Trail Valley site is located on rolling upland tundra, while the Havikpak site is located in a broad river valley with stunted black spruce. Each station records: wind speed at 4 levels to a height of 3 m, wind direction, air temperature, relative humidity, blowing snow at 1 level, snow depth, net radiation, incoming and outgoing solar radiation, air pressure (Trail Valley Ck. only), and soil temperature at 4 depths down to 0.5 m depth. In addition, a Nipher snow gauge is installed to measure total winter snowfall. At the Havikpak Ck. site, monthly snow surveys are carried out near the weather station.

In addition, NHRI conducts a variety of research type measurements within the Trail Valley Ck. basin. Some examples include: Bowen ratio measurements for evaporation determination, late winter snow surveys for determining mean snow storage, energy balance over melting snowcovers, soil moisture determination using twin probe gamma or TDR, measurements of changes in snowpack properties during the melt period, air photography of changes in basin snowcover over the melt period, measurements of water flux through the snowcover, and ground truth measurements for satellite and aerial remote sensing.

PRINCE ALBERT NATIONAL PARK, SK.
NHRI also has installed several instrumented towers in the Bear Trap Creek Basin within Prince Albert National Park. Research sites have been set up at: old clear cut region (approx. 10 yrs old); new clear-cut region (approx. 2 yrs. old); aspen forest stand; and mature spruce forest stand.

Data collected include air temperature, humidity, barometric pressure, wind speed and direction, rainfall, snowfall, incoming and outgoing radiation, net radiation, snow depth, blowing snow, soil temperature and soil heat flux.

WOLF CREEK, YUKON

The Wolf Creek Research Basin project was initiated in 1992 to provide a dedicated site to carry out applied research in a mountainous watershed in the Yukon sub-Arctic. The initiative is funded by the Department of Indian and Northern Affairs Canada (DIAND) Arctic Environmental Strategy Program with support from Environment Canada through NHRI in order to address GEWEX scientific issues.

Logistically the Wolf Creek basin is a very attractive research site since it is located within thirty minutes of Whitehorse and is readily accessible. The basin occupies an area of 220 km² in the southern Yukon headwaters region of the Yukon River.

Three major meteorological stations were established within the study area, one each in the three elevation-vegetation zones which characterize the basin.

a. A Black Spruce Forest research site is located at an elevation of 750 m within a mature black spruce forest stand approximately one kilometre upstream from the lower Wolf Creek hydrometric station. The 13 m high instrumented tower extends to within 2 m of the canopy.

b. A Buckbrush Taiga research site is located at an elevation of 1250 m on a gentle slope near the valley bottom. Vegetation consists of 1 to 2 m high willows and alders with scattered spruce patches spaced approximately 30 m apart. A 5 m high instrumented tower extends above the vegetation.

c. An Alpine Tundra research site is located at an elevation of 1615 m on a wind swept high alpine tundra plateau along a drainage divide at the northern edge of the basin. Vegetation at this site is sparse consisting of mosses and lichens with occasional patches of scrub willow no more than 0.2 m tall. Boulders of up to 1 m tall are scattered on the plateau. A 3 m high instrumented tower extends above the vegetation and boulders.

At each research site, instruments record air temperature, rainfall, snowfall, wind speed, humidity, incoming and outgoing shortwave radiation, net radiation, barometric pressure, snow depth, blowing snow transport, soil temperature, and soil heat flux. Precipitation instrumentation includes a tipping bucket rain gauge and a nearby Nipher
snow gauge. The instrumentation is controlled by solid state data loggers and powered by solar panels. Twenty-five point snow courses are sampled monthly throughout the winter.

A hydrometric station was activated at the Alaska Highway crossing of Wolf Creek in the spring of 1993 and will be operated continuously. Two additional hydrometric stations on upper creeks in the basin are planned for installation in 1995.

Water quality sampling was initiated at the lower Wolf Creek station in the spring of 1993 and will continue on an ongoing basis for routine parameters and metals as well as coliform bacteria. Isotope samples have been collected since September 1993.

FT. SIMPSON, NWT

The fourth research "wetlands" basin near Ft. Simpson is being instrumented during 1995. Work to date has concentrated on classification of vegetation-terrain units from LANDSAT-TM for the Ft. Simpson local region and preliminary testing of a distributed runoff model to existing hydrometric data for selected catchments (Martin River, Manners Creek, Jean-Marie River, Birch River, and Blackstone River).

REMOTE SENSING APPLICATIONS FOR HYDROLOGY

Although no purpose-built hydrological satellite has been launched, many satellites have yielded information of use to hydrologists. Pre-eminent amongst these have been meteorological satellites, and the LANDSAT series.

The polar orbiting and geostationary meteorological satellites will be the primary source of remote sensing observations for MAGS. The Geostationary Operational Environmental Satellites (GOES) series operated by NOAA will provide coverage of the Mackenzie Basin (although the look angles are highly inclined). The NOAA Polar Orbiting Environmental Satellite (POES) series, along with the US military Defense Meteorological Satellite Program (DMSP) satellite series, will provide valuable observational data from microwave remote sensing instruments. In particular, the Special Sensor Microwave Imager (SSM/I) will be used for snow water equivalent mapping, and the Advanced Microwave Sounding Unit (AMSU) (planned for launch in 1996) will hopefully be available for vertical soundings of water vapour. The Advanced Very High Resolution Radiometers (AVHRR) on board NOAA-11 and 12 satellites are very suitable for the study of the whole Mackenzie Basin and have been successfully used for multitemporal land cover mapping.

The US Land Remote Sensing Satellite (LANDSAT) and French Systeme Pour l'Observation de la Terre (SPOT) satellites will continue to provide observational data of land surface colorimetric mapping.

Determination of hydrologic variables such as soil moisture, snowpack water
equivalent, snow wetness and flood extent is not always possible at shorter wavelengths. The microwave portion of the electromagnetic spectrum (longer wavelength) offers potential for monitoring several of these variables. The advantages of microwave sensing are: all weather capability, which is important for any periodic observation; greater penetration depth into the soil or snowpack; and sensitivity to changes in the dielectric properties of materials produced by changes in water content. Synthetic aperture radars (SAR) are at the centre of current developments in microwave remote sensing and most countries involved in space borne programs are building or planning satellite SARs. In 1995 Canada will launch RADARSAT, its first Earth observation satellite. Equipped with a SAR, RADARSAT will operate at C-Band (5.3 Ghz) with horizontal transmit and receive polarization. Although it will have a five year design life, future platforms are planned to ensure a continuous data source. The sensor will have several imaging modes arising from the ability to shape and steer the radar beam over a 500 km swath.

Although the orbit repeat period is 24 days, with the 500-km wide swath substantially complete surface coverage is available after only four days, even at equatorial latitudes. With the range of imaging modes, the spatial resolution varies between 10 m in Fine mode to 100 m in ScanSar mode.

RAINSAT

The RAINSAT technique, as developed by Bellon and Austin (1986) and evaluated by King et al (1989) uses satellite data, calibrated with radar information as the ground truth, to estimate the rates of rainfall and snowfall. It is proposed to use this method to derive the daily precipitation fields over the Mackenzie River basin with a spatial resolution of 10 km. On account of the high latitudes concerned, AVHRR data from polar orbiting satellites with potentially useful information from 4 to 6 passages per day at 70°N will be used in addition to the half-hourly data from the geostationary GOES satellite. However, the geostationary satellite data will be used for comparison purposes over the more southerly section of the basin, south of 60°N. NWP output data will be used in this project to improve the RAINSAT estimates which at present are solely based on VIS-IR empirical relationships. It is anticipated that the RAINSAT technique will provide a measure of the precipitation field over the entire Mackenzie Basin.

RADAR SATELLITE STUDY OF SNOWMELT AND SOIL MOISTURE

High-resolution radar images from the ERS-1 satellite have been shown to be sensitive to snowmelt in an Alpine environment (A. Maxfield, NHRI 1992). Radar's potential for surface moisture monitoring in agricultural areas, is under active investigation by a number of studies and agencies. Studies are underway at NHRI to extend radar satellite monitoring in two stages, to (1) Tundra and (2) Boreal Forest environments in support of MAGS objectives. Monitoring the timing and distribution of snowmelt and surface moisture by radar remote sensing, will allow the initializing and updating of watershed streamflow and surface condition simulations, over a wide range
of climate zones.

**SNOW COVER AND LAKE ICE**

The research project of Walker et al. (AES) addresses the problem of determining essential snow cover variables, including extent, water equivalent, and state (Wet vs Dry), for both open and forested regions of Canada, and mapping ice cover on large lakes using algorithms based on SSMR and SSM/I brightness temperatures.

**SATELLITE OBSERVATIONS OF CLOUDS, RADIATION, AND HUMIDITY**

The research project of Garand et al. (AES) is investigating the use of NWP models and data assimilation systems, which include explicit parameterization of cloud water, combined with satellite (AVHRR cloud detection algorithm, TOVS (Television and Infrared Observation Satellite (TIROS) Operational Vertical Sounder) humidity retrievals to produce 3-D temperature and humidity fields.

**PARAMETERIZATION OF EVAPOTRANSPIRATION**

The research projects of Bussieres (AES) and Granger (NHRI) are investigating the use of GOES and NOAA remotely-sensed surface temperature data to parameterize the sensible heat flux, from which the evapotranspiration can be estimated using a simplified energy balance and feedback model.

**HYDROLOGICALLY SIGNIFICANT TERRAIN MAPPING**

The hydrologic response of permafrost affected basins is strongly affected by local differences in thermal, morphological, and vegetation factors. The research project by Pietroniro (NHRI) is using terrain classifications derived from LANDSAT TM data near Ft. Simpson to map terrain types which dominate the hydrological response. These terrain classifications will be used as input for both the SLURP and WATFLOOD distributed hydrologic models.

**CANADIAN CENTRE FOR REMOTE SENSING (CCRS) RADARSAT HYDROLOGICAL PROGRAM**

The principle objectives of the Canadian Centre for Remote Sensing (CCRS) RADARSAT hydrological program are:

i) to evaluate the feasibility of extracting information from SAR data on soil moisture, extent of snow cover (wet and dry) and snow water equivalent, river ice dynamics, flood extent and flood damage, and wetland conditions;

ii) to initiate and support research in the development of distributed hydrological models that effectively use spatial data and to develop techniques to use these data
to improve runoff forecasts; and

iii) to demonstrate the operational use of airborne and satellite based radar and other remotely sensed data for hydrological applications.

CCRS research focuses on the extraction of information on soil moisture, snow parameters and surface water conditions from SAR data and development of distributed hydrological models which can fully utilize spatial data.

The following table lists satellite data sources, approximate resolution, parameter products, and the names of Canadian GEWEX researchers involved in remote sensing studies.

<table>
<thead>
<tr>
<th>Satellite Remote Sensing Data</th>
<th>researchers</th>
<th>parameter</th>
<th>resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOAA TOVS</td>
<td>Benoit et al. Garand et al.</td>
<td>temp. and moisture profiles (exp.)</td>
<td>20 km</td>
</tr>
<tr>
<td>GOES VISSR</td>
<td>Gyakum &amp; Moore Stewart Zawadzki</td>
<td>imaging cloud cover sounding - temp. and water content</td>
<td>1-4 km</td>
</tr>
<tr>
<td>DMSP (SSM/I)</td>
<td>Walker et al.</td>
<td>ice snow water equiv.</td>
<td>12.5-25 km</td>
</tr>
<tr>
<td>Landsat (multi-spectral, seasonal images), SPOT</td>
<td>Soulis &amp; Kouwen Kite Pietroniro</td>
<td>mapping land cover</td>
<td>20-80 m</td>
</tr>
<tr>
<td>SAR (ERS-1, ERS-2, JERS1, RADARSAT)</td>
<td>Agnew et al.; Brugman et al. Maxfield et al.</td>
<td>snow cover area snow melt area ice cover soil moisture (exp)</td>
<td>30 m</td>
</tr>
</tbody>
</table>
HYDROLOGICAL MODELLING

Several hydrological models of varying complexity are presently being used by MAGS researchers.

a. The macro-scale hydrological model SLURP, running with a daily time step, will be used to assess the water balance of the Mackenzie basin (Kite et al., 1994) and that of several GEWEX research catchments near Ft. Simpson and Inuvik (Pietroniro-NHRI). SLURP is a daily distributed hydrological model in which the parameters are related to vegetation type. At each time increment, the model is applied sequentially to a matrix of grouped response units (GRU) and land covers. A GRU is a watershed component made up of a number of computational units that may or may not be contiguous (Kouwen et al., 1990). Each application of the model (GRU x land cover) is represented by three nonlinear reservoirs, one for snowpack, one for a rapid increase (combined surface storage and top soil layer storage), and one for a slow response (groundwater). Runoffs from each reservoir are accumulated from each land cover within a GRU using a time/contributing area relationship for each land class and combined runoff is converted to streamflow and routed between GRUs. Further details of the model structure are given by Kite and Kouwen (1992).

b. The meso-scale hourly hydrological model WATFLOOD will be driven over selected gauged sub-basins (Soulis). WATFLOOD will contain a version of CLASS as a preliminary step towards an integrated model.

WATFLOOD (Kouwen, 1988) is a hydrologic data-base management system that was designed to incorporate the GRU concept. The system is expressly designed for distributed modelling using remotely sensed data although it can be used with conventional meteorological and hydrometric data as well. The data base uses a Cartesian coordinate system usually aligned with the local UTM system and can easily accommodate georeferenced imagery and be connected to a GIS.

SIMPLE is the hydrological simulation model within WATFLOOD and uses the GRU approach. SIMPLE was initially designed for flood forecasting and therefore reflects the dominant short duration rainfall-runoff processes. The various modelling details associated with interception of precipitation by vegetation, surface storage, infiltration, interflow, overland flow, base flow, and routing are described further in Kouwen et al., (1990).

b. The microscale model VSAS2 will be applied over successively larger areas of the Wolf Creek research basin (Woo).

FORCING DATA FOR HYDROLOGICAL MODELLING

Assimilated 6 hour, 35 km data will be archived from the CMC's runs of the Regional Finite Element (RFE) model starting in 1995 for 5 years (Benoit - AES).
The domain will be an approximately 6000 km x 6000 km area of west-central North America that includes not only the MAGS area but also the GCIP area over the Mississippi River basin. The RFE domain (50 km grid resolution) is shown in Figure 34.

These fields will provide boundary and initial conditions for the running of mesoscale models over the MAGS area, and will also provide data for stand-alone testing of preliminary versions of the integrated atmosphere-hydrologic model. The RFE regional domain (25 km grid resolution) used during the BASE experiment is shown in Figure 35.

The precipitation fields produced by the RFE will be adjusted where orographic effects are significant on the western edge of the basin. Various techniques will be explored to generate a 5 - 10 km field, required for distributed hydrological modelling.

The precipitation fields will also be augmented by monthly summaries prepared using the RAINSAT model (Zawadzki). This method uses meteorological satellites augmented by weather radar to generate daily precipitation probabilities, which are integrated to estimate monthly precipitation totals. RAINSAT will use weather radar at (sites to be determined), adjusted using streamflow data (using techniques developed for the AES King City radar), to calibrate the satellite imagery.

During significant meteorological events, the meso-scale compressible community model (MC2) will be run (Yau). Initialized and forced by the RFE output, the runs will be at a 25 km resolution in a 2500 km x 2500 km area centred over the Mackenzie with a time step of 10 min and for a period of 7 or 8 days. Nested within these runs will be 4 or 5 1-km resolution runs over areas of significant convective activity. Output from these runs will also be used to drive the hydrological models described above.

ATMOSPHERIC MODELLING

RPN / CMC MODEL ARCHIVES

GCIP (GEWEX Continental-scale International Project) conducted a GCIP Integrated Systems Test (GIST) for summer 1994 in the Arkansas - Red River basin of the southwest portion of the Mississippi River basin. The GCIP Data Collection and Management (DACOM) Committee examined data availability for this test and requested outputs from the operational RFE (regional finite element) analysis and forecast system at CMC during this period. This includes periods of intensive observations using a dense, enhanced meso-scale network in this region. The U.S. ETA model was run at a 40 km 50 level resolution during this period, and ECMWF outputs are also to be supplied, possibly along with products from a couple of other operational and/or research groups. The GIST period ended on August 31, 1994 and the next archive period is a seasonal Enhanced Observing Period (EOP) in the same area as GIST, running from 1 April 1995 to 30 September 1995, after which the 5-year
EOP on the larger GCIP area begins. It is intended that outputs from both the regional and global systems will be archived during this EOP. The Mackenzie Basin study (MAGS) is the Canadian counterpart to GCIP, and the two projects will interact in several ways.

The overall goal of these projects (and similar ones starting in several other regions of the world) is to undertake a detailed study of the water and energy budgets, in order to improve our understanding, modelling, and prediction of them. High resolution meso-scale models are to be used to complement and compare with intensive observations from a variety of observing platforms in an attempt to produce the best possible water and energy budget analyses. Lower resolution global models will then be used to test the transferability of budgets and parameterizations to other regions around the world.

One of the main objectives of the GIST period was to set up and "shake down" the outputs and archives for the subsequent EOPs. However, there are also intensive observation periods (IOPs) in the GCIP area and in the BOREAS (Boreal Ecosystem - Atmosphere Study) region in Manitoba and Saskatchewan during the GIST period, so the collected data are also scientifically valuable. GEWEX has provided a "wish list" of outputs, but the list was trimmed by operational centres for practical reasons. RPN/CMC has started with a basic archive and is enhancing it as time goes on.

The outputs from the analysis and forecast systems are intended to complement and be compared with intensive observations in an attempt to produce the best possible water and energy budget analyses. Hence the emphasis is on moisture- and energy-related outputs during data assimilation cycles (4DDA) and short-term forecasts (0-24 hours). The list of output fields needed by GCIP researchers is given in Table 3 of Volume I of the GCIP Implementation Plan (copy available on request). The fields are divided into four types:

(A) Gridded 2-D fields, mostly comprised of surface, subsurface, and top of atmosphere (TOA) fields;
(B) Gridded 3-D atmospheric fields;
(C) Vertical profile time series at selected points; and
(D) Fixed fields.

The list is a mix of instantaneous (I), accumulated (A), and time-averaged (AVG) fields. It is understood that practical constraints imposed on operational models will dictate certain choices such as instantaneous instead of accumulated fields or vice versa, and even the unavailability of certain fields except in limited special model reruns.

RFE MODEL DESCRIPTION

The Regional Finite Element (RFE) model is used operationally at the Canadian Meteorological Centre (CMC) for the regional data assimilation and short-range forecasting. The model is an evolved version of that of Staniforth and Daley (1979) with a semi-Lagrangian treatment of advection (Tanguay et al., 1989). A unique feature of the model is its variable-resolution self-nesting capability (Gravel and Staniforth, 1992) which allows the model to be easily reconfigured with the high resolution domain over...
any given area. The model integrates the hydrostatic primitive equations using linear finite elements in all three space dimensions. It uses a variable resolution horizontal grid overlaid on a polar stereographic projection of the entire northern hemisphere. The time integration scheme is semi-implicit and semi-Lagrangian which permits the use of long time steps (operational time step is 20 min).

The following model output strategy is an adaptation of the one prepared by Ken Mitchell at NMC for the ETA model. It describes the RFE model related fields to support GCIP during GIST and the first GCIP EOP year (1995). This is a baseline data output plan, representing a core output strategy, which may be augmented with other RFE output fields as MAGS and GCIP proceed.

Each month, forecasts and analyses from the regional system will be saved on a set of cartridge tapes.

This monthly data set is divided into 3 categories of output:
I. Upper air fields (3-D atmospheric fields)
II. Surface, sub-surface, and near surface fields (2-D fields)
III. Vertical profile time series ("soundings")

For user convenience, a small set of the key fields from II will be included in I, and vice versa (as described below).

Both categories I and II will be output on the 169 X 117 50-km RFE uniform grid area shown in Figure 34. It is desirable that they eventually be packed in the GRIB format, although RPN standard files are being used to start with.

Category I fields (i.e. 3-D atmospheric) will be provided on all 25 model levels.

The following describes the detailed content and data volume of the three categories of output currently available. Other variables may be added as they become available (e.g., cloud water QC).

UPPER AIR FIELDS

A. Forecast Fields per output time

<table>
<thead>
<tr>
<th>output grid points</th>
<th>19773</th>
<th>(169 X 117 50-km grid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>output variables</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>1. U wind velocity component</td>
<td>UU (I)</td>
<td></td>
</tr>
<tr>
<td>2. V wind velocity component</td>
<td>VV (I)</td>
<td></td>
</tr>
<tr>
<td>3. Omega vertical motion</td>
<td>WW (I)</td>
<td></td>
</tr>
<tr>
<td>4. Temperature</td>
<td>TT (I)</td>
<td></td>
</tr>
<tr>
<td>5. Specific humidity</td>
<td>HU (I)</td>
<td></td>
</tr>
<tr>
<td>6. Geopotential height</td>
<td>GZ (I)</td>
<td></td>
</tr>
</tbody>
</table>
supplemental sfc flds   8
7. Surface pressure     P0   (I)
8. Surface height       MT   (Constant)
9. Skin temperature     TG   (I)
10. Surface soil moisture fraction    WG  (Constant)
11. Deep soil moisture fraction       WR  (Constant)
12. Accumulated total precip      PR   (A)
13. Accumulated convective precip   PC   (A)
14. Surface evaporation         FV   (I)

forecast cycles per day   2   (00Z and 12Z)
output times per cycle    4   (6, 12, 18, 24 hrs)

B. Six-hour first-guess fields

Same content as in I.A

analysis cycles per day   4   (00, 06, 12, 18 GMT)

C. Analysis fields

Same content as in I.B, except that the following fields (which are not directly analysed) are taken from 0 hour forecasts, and are available only at 00 and 12 GMT: omega vertical motion (WW), temperature (TT), geopotential height (GZ), skin temperature (TG), surface soil moisture fraction (WG), deep soil moisture fraction (WR), and surface evaporation (FV). There is no precipitation analysis (PR, PC).

SURFACE, SUB-SURFACE, AND NEAR SURFACE FIELDS

A. Forecast Fields per output time

output grid points   19773

output variables    28
1. Surface evaporation   FV  (I)
2. Surface sensible heat flux     FC  (I)
3. Upward TOA longwave radiation  EI  (I)
4. Upward TOA shortwave radiation  EV  (I)
5. Total cloud amount      NT  (I)
6. Skin temperature       TG  (I)
7. Soil temperature        TP  (I)(analysis,not forecast)
8. Surface soil moisture fraction  WG  (Constant)
9. Deep soil moisture fraction   WR  (Constant)
10. Percent snow cover     NE  (I)(analysis,not
forecast)

11. Sea ice mask GL (I)(analysis,not forecast)
12. Accumulated total precip PR (A)
13. Accumulated convective precip PC (A)
14. Sea level pressure PN (I)
15. Surface pressure P0 (I)
16. Surface momentum flux FQ (I)
17. 850 mb Temperature TT(850) (I)
18. 850 mb Specific humidity HU(850) (I)
19. 850 mb u wind UU(850) (I)
20. 850 mb v wind VV(850) (I)
21. 850 mb Height GZ(850) (I)
22. 500 mb Height GZ(500) (I)
23. 700 mb Vertical motion WW(700) (I)
24. 1000-500 mb mean RH <RH> (I)
25. 1000-500 mb thickness DZ (I)
26. Low altitude cloud fraction NB (I)
27. Medium altitude cloud fraction NM (I)
28. High altitude cloud fraction NH (I)

forecast cycles per day 2 (00Z and 12Z)
output times per cycle 4 (6, 12, 18, and 24 hrs)

B. Analysis fields (Actually first-guess)

analysis cycles per day 4
output times per cycle 1

VOLUMES (RPN Standard Files - to be converted to GRIB)

Analyses (6 or 18 GMT) : 7530120
(0 or 12 GMT) : 11252520

Forecasts (0 or 12 GMT) : 27805320

Per day analyses : 2 * (7530120 + 11252520) = 37565280
forecasts : 2 * 27805320 = 55610640

Total : 93175920

Per month : Total = 31 * 93175920 = 2888453520 i.e. 2888 MB.

VERTICAL PROFILE TIME SERIES (SYNTHETIC SOUNDING SITES)
output variables (all values are instantaneous):
UU - U wind velocity component at each level
VV - V wind velocity component at each level
SS - Vertical velocity in sigma coordinates at each level
TT - Temperature at each level
HU - specific humidity at each level
GZ - geopotential height at each level
TK - heating rate due to convective precipitation at each level
TA - heating rate due to total condensation at each level
TA-TK - temperature tendency due to grid-scale precipitation at each level
TF - heating rate due to vertical diffusion
T2 - temperature tendency due to short wave radiation at each level
TI - temperature tendency due to long wave radiation at each level
TI+T2 - temperature tendency due to all radiation at each level
NU - cloud fraction at each level
BM - prognostic cloud fraction at each level (for Sundquist scheme only)
QK - condensation rate by convection at each level
QA - total condensation rate at each level
QA-QK - large-scale condensation rate at each level
QF - humidification by vertical diffusion at each level
TU - vertical diffusion of U component at each level
TV - vertical diffusion of V component at each level
GU - Gravity wave drag of U component at each level
GV - gravity wave drag of V component at each level
FV - surface evaporation
FC - surface sensible heat flux
FL - subsurface heat flux
FS - solar radiation flux absorbed by the ground
FI - infrared radiation absorbed by the ground
FI+FS - net incoming radiation at the surface
EI - upward TOA longwave radiation
EV - upward TOA shortwave radiation
NT - total cloud amount
TS - skin temperature
WS - surface soil moisture fraction
WP - deep soil moisture fraction
P0 - surface pressure
FQ - surface momentum flux

MC2 MODEL DESCRIPTION

MC2 is a finite difference semi-Lagrangian model solving the non-hydrostatic Euler equations on a uniform resolution limited-area grid nested in time dependent boundaries. The Mesoscale Compressible Community model (MC2) was the special operational very-high resolution forecasting guidance model used to support the field phase of the BASE experiment.
During BASE, the special model was run on a polar stereographic grid with a horizontal resolution of 15 km to 30 hours once per day, at night, after the operational RFE model with initial conditions from the 00 UTC 50-km Regional Data Assimilation System of CMC. The initialisation included parts of the BASE special observations (extra radio-sondes and surface stations) and 25 km resolution analysis for ice based on SSMI data. The regional RFE domain (25 km grid resolution) used for BASE is shown in Figure 35.

Two different configurations of parameterization schemes for physical processes were used during the experiment. From September 1st to September 11, 1994 a Kuo-type (Kuo 1965, 1974) deep convection scheme combined with a grid-scale condensation in supersaturated layers scheme was used (identical configuration to the one used by the RFE). For the rest of the experiment the MC2 version for BASE was running with a new cloud water scheme (Sundqvist, 1989) in which the liquid and solid cloud water is a predictive variable of the model. This scheme produced both deep convective (Kuo 1965, 1974) and stratiform clouds based on conditions for convective and stratiform condensation. The scheme also generates liquid and solid precipitation fluxes across the model atmosphere.

The 25 computational levels of the special model were chosen to match the same pressure values as the sigma levels of the operational RFE in a standard atmosphere.

MC2 was run on the NEC SX-3 computer of CMC. 3D model grid output of the basic fields were transmitted to Inuvik every 3 hours via a dedicated satellite uplink. About 50 MBytes per run were transmitted to the site in RPN/CMC Standard File Format and then processed locally on pressure levels before visualisation with XREC on an SGI machine.

Numerical weather archives for BASE reside on a CFS Convex system at the CMC/RPN site. The database is divided in 4 branches, each of them containing a set of files of the same type. A table of content and a lexicon at the end of this section describe the different branches of the database.

A script is under development that will permit to anyone having an access to the CMC/RPN computer network to extract data from the database.

UNITS/UNITES
BIN Binary i.e. 0 or 1 Binaire i.e. 0 ou 1
C Celsius Celsius
DAM Decametre Decametre
HR Hour Heure
K Kelvin Kelvin
KG Kilogram Kilogramme
KG/KG Kilogram of water per kilogramme
kilogram of dry air d'air sec
KT Knots Noeuds
<table>
<thead>
<tr>
<th>NOMVAR</th>
<th>DESCRIPTION</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL</td>
<td>Albedo</td>
<td>R1</td>
</tr>
<tr>
<td>AP</td>
<td>Planetary Albedo</td>
<td>Albedo planétaire</td>
</tr>
<tr>
<td>DD</td>
<td>Divergence</td>
<td>1/S</td>
</tr>
<tr>
<td>DZ</td>
<td>Thicknesses</td>
<td>DAM</td>
</tr>
<tr>
<td>EI</td>
<td>Outgoing IR flux at top ATM</td>
<td>W/M²</td>
</tr>
<tr>
<td>ES</td>
<td>Dew point spread</td>
<td>C</td>
</tr>
<tr>
<td>EV</td>
<td>Outgoing VIS flux at top ATM</td>
<td>W/M²</td>
</tr>
<tr>
<td>FC</td>
<td>Sensible heat flux at top ATM</td>
<td>W/M²</td>
</tr>
<tr>
<td>FI</td>
<td>Incoming IR flux at SFC</td>
<td>W/M²</td>
</tr>
<tr>
<td>FS</td>
<td>Solar flux absorbed at SFC</td>
<td>W/M²</td>
</tr>
<tr>
<td>FV</td>
<td>Latent heat flux at SFC</td>
<td>W/M²</td>
</tr>
<tr>
<td>GL</td>
<td>Ice cover</td>
<td>R1</td>
</tr>
<tr>
<td>GZ</td>
<td>Geopotential height</td>
<td>DAM</td>
</tr>
<tr>
<td>HS</td>
<td>Ground moisture</td>
<td>R3</td>
</tr>
<tr>
<td>HU</td>
<td>Specific humidity</td>
<td>KG/KG</td>
</tr>
<tr>
<td>LH</td>
<td>Launching height</td>
<td>M²</td>
</tr>
</tbody>
</table>
for GWD  
ME Mountains Montagnes M  
MG Land-sea mask Masque terre-mer BIN  
NC Convective clouds Nuages convectifs R1  
NE Snow cover Couverture de neige R1  
NS Stratiform clouds Nuages stratiformes R1  
NU Total clouds Nuages totaux R1  
P0 Surface pressure Pression a la surface MB  
PM Pressure on momentum Pression aux niveaux momentum PA  
PN MSL pressure Pression au NMM MB  
PR Total precipitation Precipitation totale accumulee M  
PT Pressure on thermodynamic levels Pression aux niveaux thermodynamique  
QC Cloud water mixing Rapport de melange d'eau KG/KG  
QQ Absolute vorticity Tourbillon absolu 1/S  
RN Stratiform PCPN amount Precipitation stratiforme accumulee M  
RT Total precipitation rate Taux de precipitation total M/S  
SN Convective PCPN amount Precipitation convective accumulee M  
TG Surface temperature Temperature de la surface K  
TM Sea surface temperature Temperature de la SFC de la mer C  
TP Deep ground temperature Temperature profonde du sol C  
TS Air temperature at SFC Temperature de l'air a la SFC C  
TT Air temperature Temperature de l'air C  
UU Wind component along the X-axis of the model direction de l'axe X du KT grid modele  
UV Wind speed Vitesse du vent KT  
VV Wind component along the Y-axis of the model direction de l'axe Y du KT grid modele  
WW Vertical motion Mouvement vertical PA/S  
YI Solid precipitation flux Flux de precipitation solide KG/M2/S  
YW Liquid precipitation flux Flux de precipitation liquide KG/M2/S  
ZP Roughness length Longueur de rugosite LOG(M)  

Evolution of the boundary conditions that were imposed to MC2 for each run of the experiment.
Coordinates: Sigma
Resolution : 15 km
Domain size: 1500x1500 km

<table>
<thead>
<tr>
<th>Fields Levels (mb/mb)</th>
<th>Dt (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL,GL,HS,LH,ME,MG,</td>
<td>surface</td>
</tr>
<tr>
<td>NE,TM,TP,TS,ZP</td>
<td>t = 0</td>
</tr>
</tbody>
</table>

P0           =====  =====  =====  =====

1. .99, .97, .943, .905,
 .86, .81, .758, .702, .642,
GZ,HU,TT,UU,VV,WW .578, .514, .45, .39, .335,
 .28, .23, .185, .14, .1,
 .07, .05, .03, .02, .01

prog.pres: MC2 forecasts on pressure levels.

Coordinates: Pressure
Resolution : 15 km
Domain size: 1500x1500 km

<table>
<thead>
<tr>
<th>Fields Levels (mb)</th>
<th>Dt (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT,RN,PR,SN</td>
<td>surface</td>
</tr>
</tbody>
</table>

PN           =====  =====  =====  =====

GZ,TT,ES,QC,WW,NU, 1000, 850, 700, 500, 250
YW,UU,QQ,DD,VV

prog.galc: MC2 forecasts on Gal-Chen (computational) levels.

Coordinates: Gal-Chen
Resolution : 15 km
Domain size: 1500x1500 km

<table>
<thead>
<tr>
<th>Fields Levels (metres)</th>
<th>Dt (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL,ME,TS,TM,GL,NE</td>
<td>surface</td>
</tr>
</tbody>
</table>

RT,RN,SN,TG,FI,FS      =====  =====  =====  =====

34036.50, 28979.20, 25355.33,
22138.48, 19328.65, 16800.00,
14345.04, 12311.51, 10722.96,
TT,PM,PT,UU,VV,HU, 9287.74, 7979.24, 6870.11, 3
QC,WW,NS,NC,YW,YI 5826.03, 4855.82, 3999.61,
3233.41, 2581.54, 2021.56,
1537.45, 1100.43, 728.30,
428.20, 222.23, 73.33, 0.00

anal.pres: Regional Data Analysis covering the Beaufort sea, the Chukchi sea, the Bering sea, the Gulf of Alaska and the Northern Pacific ocean down to Vancouver Island.

Coordinates: Pressure
Resolution: 50 km
Domain size: 5000x5000 km

<table>
<thead>
<tr>
<th>Fields</th>
<th>Levels (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PN, GL, TM</td>
<td>surface</td>
</tr>
<tr>
<td>GZ, TT, UV</td>
<td>250</td>
</tr>
<tr>
<td>GZ, UU, VV, QQ</td>
<td>500</td>
</tr>
<tr>
<td>GZ, TT, ES</td>
<td>700</td>
</tr>
<tr>
<td>GZ, TT, UU, VV</td>
<td>850</td>
</tr>
<tr>
<td>DZ</td>
<td>1000-500</td>
</tr>
</tbody>
</table>

**SEF MODEL DESCRIPTION**

The Canadian global spectral forecast model was developed at Recherche en prevision numerique (RPN) and is used for global data assimilation and medium- and long-range forecasts at the Canadian Meteorological Centre (CMC). The basic dynamical formulation is presented in Ritchie (1991). The model treats the global primitive equations, expressed in terms of the sigma = pressure / (surface pressure) vertical coordinate, using the spectral (S) technique in the horizontal, linear finite-elements (EF) in the vertical (Beland and Beaudoin, 1985), with a semi-implicit semi-Lagrangian time integration scheme (Ritchie, 1991). The global data assimilation and forecast system replaced the former hemispheric one in operations at CMC in March, 1991. Optimization and sensitivity tests that were performed in preparing this model for operational use are discussed in Ritchie and Beaudoin (1994). This model was originally implemented with a triangular 79-wave (T79) horizontal resolution, which was subsequently increased to T119 in June 1993, and to T199 in June 1995. In the vertical the model uses 21 levels with variable spacing in order to give higher resolution near the earth's surface in support of the boundary layer and parameterization of other physical processes. The semi-implicit semi-Lagrangian time integration scheme permits the use of a relatively large 30-minute time step even at the T199 resolution, enhancing the model efficiency.

This dynamical model is coupled with a physical parameterization that includes a planetary boundary layer based on turbulent kinetic energy, a surface layer based on similarity theory, solar and infrared radiation, large-scale precipitation, convective precipitation, and gravity wave drag. Modifications made to the physical parameterization during the development of the global system are described in Girard et al., 1991. Significant modifications were introduced in the physical parameterizations in June 1993. In particular, the Manabe-type moist convection scheme was replaced by a Kuo-type convection. Some of the parameterizations were further updated in June 1995 to correspond with those used in the operational regional finite element model, as described by Mailhot et al., 1995.
A state-of-the-art global data assimilation and forecast system is a key ingredient for modelling the water and energy balances of the Mackenzie Basin. The Canadian global spectral model (SEF) is being extended to permit direct incorporation of satellite observations relating to moisture and the coupling of the hydrologic, land-surface, and atmospheric components. Once energy and water process algorithms have been calibrated and validated in high resolution mesoscale models using the enhanced MAGS observations, their transferability to the global domain will be accomplished within the global spectral model operating with a horizontal resolution of approximately 100 km. The global numerical weather prediction system has been calibrated and verified to produce very good medium-range (5-10 days) forecasts on its current calculation grid with a spatial resolution of about 110 km. Longer (monthly, seasonal, and even 10 yr) simulations produced with lower resolution versions are being conducted in order to examine the model's systematic errors. The goal is to test a fully coupled hydrologic/land-surface/atmospheric system and use it to generate mean monthly estimates of water and energy budgets for the Mackenzie Basin.

The SEF global domain (approximately 110 km grid resolution) is shown in Figure 36.

MODEL ASSIMILATION

The moisture cycle in atmospheric models is largely determined by subgrid scale physical parameterizations which typically drive atmospheric models rather quickly to an equilibrium between evaporation and precipitation, both of which are crucial to the terrestrial water cycle. The model's moisture equilibrium may be realistic but upset in assimilation by incorrect data; on the other hand, good data may be subverted in the assimilation by systematic deficiencies and biases in the model.

Modern 4-D data assimilation systems use objective analysis techniques combined with advanced atmospheric forecast models to blend observations of varying types, timeliness, accuracy, and spatial coverage into self-consistent uniformly gridded fields of atmospheric and surface fields. For fields that are not observed (or very sparsely observed), 4DDA systems rely on the atmospheric model to generate realistic analysis based on the internal physical and dynamic coupling within the model to those fields that are observed.

US-NMC ETA MODEL

The ETA mesoscale model is the US National Meteorological Center's newest regional forecast model. Its most unique feature is its "step mountain" vertical coordinate, known as the Eta coordinate, which allows detailed representation of orography. The Eta model is a finite difference model defined on the semi-staggered Arakawa E grid. It uses a split-explicit time differencing scheme in combination with a distinctive technique for preventing grid separation. The Eta model has been tested at NMC in twice daily, on-line, real time executions of 80, 50, 40, 30, and 15 km. It has demonstrated performance superior to NMC's currently operational regional model the
Nested Grid Model. The first operational configuration model domain will cover all of North America and adjacent oceans at a nominal grid resolution of 80 km and 38 vertical levels. In its initial implementation, the first guess for the analysis will be provided by the global spectral model at T-126 resolution from the Global Data Assimilation System (GDAS). The Eta model domains for the experimental 48 km grid and respective operational output windows labelled AWIPS 214 and AWIPS 212 are shown in Figure 37.

Figure 38 shows the Mackenzie River sub-basins superimposed on the ETA model grid being used by a special atmospheric water budget study being conducted by Hugo Berbery and Gene Rasmusson at the Univ. of Maryland.

EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECAST (ECMWF) MODEL

The ECMWF produces routine global analyses for the four main synoptic hours 00, 06, 12, and 8 UTC and global 10-day forecasts based on 12 UTC data. As a forecasting center emphasizing the medium-range, the ECMWF operates with long data collection times of between 18 hr for the 18 UTC analysis and 8 hr for the 12 UTC final analysis. This schedule ensures the most comprehensive global data coverage including the southern hemisphere surface data and global satellite sounding data. The most recent version of the ECMWF forecasting system uses a 15 min time step and T213L31 (triangular truncation, resolving 213 waves around a great circle on the globe with 31 levels between the earth’s surface and 30 km altitude). Figure 39 shows the ECMWF T213 grid for the Mackenzie River Basin domain. The following parameters are associated with the model:

- orography (10 min arc resolution),
- three surface and subsurface levels (allowing for vegetation cover, gravitational drainage, capillarity exchange, surface and subsurface runoff, deep-layer soil temperature and moisture),
- clouds (high, medium, low, convective),
- stratiform and convective precipitation,
- carbon dioxide,
- aerosol,
- ozone, solar angle,
- diffusion,
- ground and sea roughness,
- ground and sea-surface temperature,
- ground humidity,
- snow fall,
- snow cover and snow melt,
- radiation (incoming shortwave and outgoing longwave),
- friction (at surface and in free atmosphere),
- gravity wave drag,
- evaporation,
- and sensible latent heat flux.
LAND SURFACE MODELLING

Since the mid-1980's, the importance of realistic treatment of the land surface in global climate modelling has increasingly been recognized. With the rise of climate change studies, a heightened awareness has been gained of the crucial role of land-atmosphere feedbacks in the global climate system (Verseghy, 1993). Over the past ten years, therefore, virtually every major general circulation modelling group worldwide has moved to incorporate a second-generation land surface scheme into its GCM. Studies done using such second-generation schemes, both in column mode and coupled to GCMs, have confirmed that the modelled climate is sensitive to the characterization of vegetation and soil parameters, and that ignoring the spatial heterogeneity of landscapes can lead to serious errors, particularly in the water balance variables.

The Canadian Land Surface Scheme (CLASS) is the second-generation land surface model developed for, and now operationally in use in, the Canadian Climate Centre GCM. Research is presently underway towards the further development and improvement of CLASS. This research includes running CLASS in coupled mode with two regional models: the MC2 research model developed at RPN, Dorval, and the Regional Climate Model (RCM) developed at l'Universite du Quebec a Montreal. Furthermore, the hydrological model SIMPLE developed at the University of Waterloo, is being coupled to CLASS for the purposes of including runoff routing in the surface water budget and modelling streamflow.

VARIABLES USED IN LAND SURFACE MODELLING IN THE CCC GCM.

Background land surface characteristics:

Vegetation:
- Diurnally-averaged visible albedo
- Diurnally-averaged near-infrared albedo
- Average height
- Annual maximum leaf area index
- Annual minimum leaf area index
- Standing mass
- Rooting Depth

Other:
- Soil visible dry albedo
- Soil visible saturated albedo
- Soil near-infrared dry albedo
- Soil near-infrared saturated albedo
- Soil fractional sand content
- Soil fractional clay content
- Thickness of modelled soil layers
- Sub-grid scale variance of topographic height
- Fractional grid square coverage of various land cover types
Variables supplied to the land surface model by the GCM:

- Incoming visible radiation
- Incoming near-infrared radiation
- Incoming direct shortwave radiation
- Incoming diffuse shortwave radiation
- Cosine of solar zenith angle
- Incoming long wave radiation
- Specific humidity of air above boundary layer
- Temperature of air above boundary layer
- Wind speed of air above boundary layer
- Surface atmospheric pressure
- Grid-cell average precipitation rate
- Latitude and longitude
- Day of year
Prognostic variables of the land surface model:

- Soil layer temperatures
- Canopy layer temperature
- Snow layer temperature
- Liquid moisture content of soil layers
- Frozen moisture content of soil layers
- Intercepted liquid water stored on vegetation
- Intercepted snow and ice stored on vegetation
- Snow mass on ground per unit area
- Snow visible albedo
- Snow near-infrared albedo
- Snow density

Land cover types commonly recognized by GCMs

- Evergreen needle leaf trees
- Evergreen broadleaf trees
- Deciduous needle leaf trees
- Deciduous broadleaf trees
- Tropical broadleaf trees
- Drought deciduous trees
- Evergreen broadleaf shrubs
- Deciduous shrubs
- Thorn shrubs
- Short grass and forbs
- Long grass
- Arable
- Rice
- Sugar
- Maize
- Cotton
- Irrigated crop
- Urban
- Tundra
- Swamp
- Bare soil
- Glacier
- Inland water
- Ocean
ACKNOWLEDGEMENTS

Since this document is a compilation of material presented elsewhere and/or provided by others, the author is indebted to many people. However, several people deserve special recognition. The author gratefully acknowledges the contributions of Dr. Philip Marsh and Dr. Terry Prowse of the National Hydrology Research Institute, Saskatoon without whose help much of the material presented in this document would have remained unknown to the author, within government reports and non-standard publications. The contributions to the atmospheric modelling section by Dr. H. Ritchie, Dr. S. Pellerin, and Dr. D. Verseghy are gratefully acknowledged and deserve special recognition. The idea and motivation for completion of this document was provided by Dr. Ron Stewart, AES Downsview and his suggestions and encouragement are appreciated.

REFERENCES


Saskatoon. 1-36.


Figure 1: Map of Canada showing the Mackenzie Basin.
Figure 2: The Mackenzie Basin and its sub-basins.
Figure 3: Land cover map of Mackenzie Basin.

LAND COVER MAP OF MACKENZIE BASIN
Remote Sensing Lab
Department of Geomatics Engineering
Figure 6: Annual mean daily temperature.
Figure 6: Mean daily temperature during Summer.
Figure 7: Mean daily temperature during Winter.
Figure 8: Mean annual precipitation from Johnstone (1983).
Mackenzie River Basin
Recorded Mean Annual Precipitation 1961 - 1990

Precipitation (mm)
200 - 299
300 - 399
400 - 499
500 - 599
600 - 699
700 - 799

Climate Stations

Figure 9: Mean annual precipitation from Kite et al. (1994).
Figure 10: Mean annual precipitation from the CCC-GCM II.