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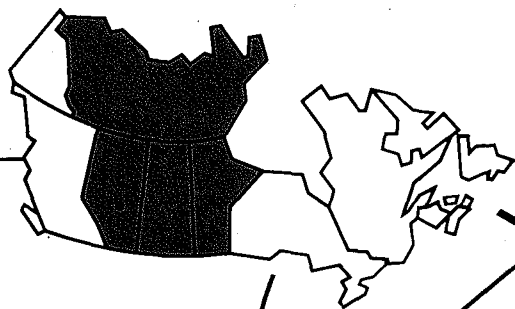
T. Singh, compiler



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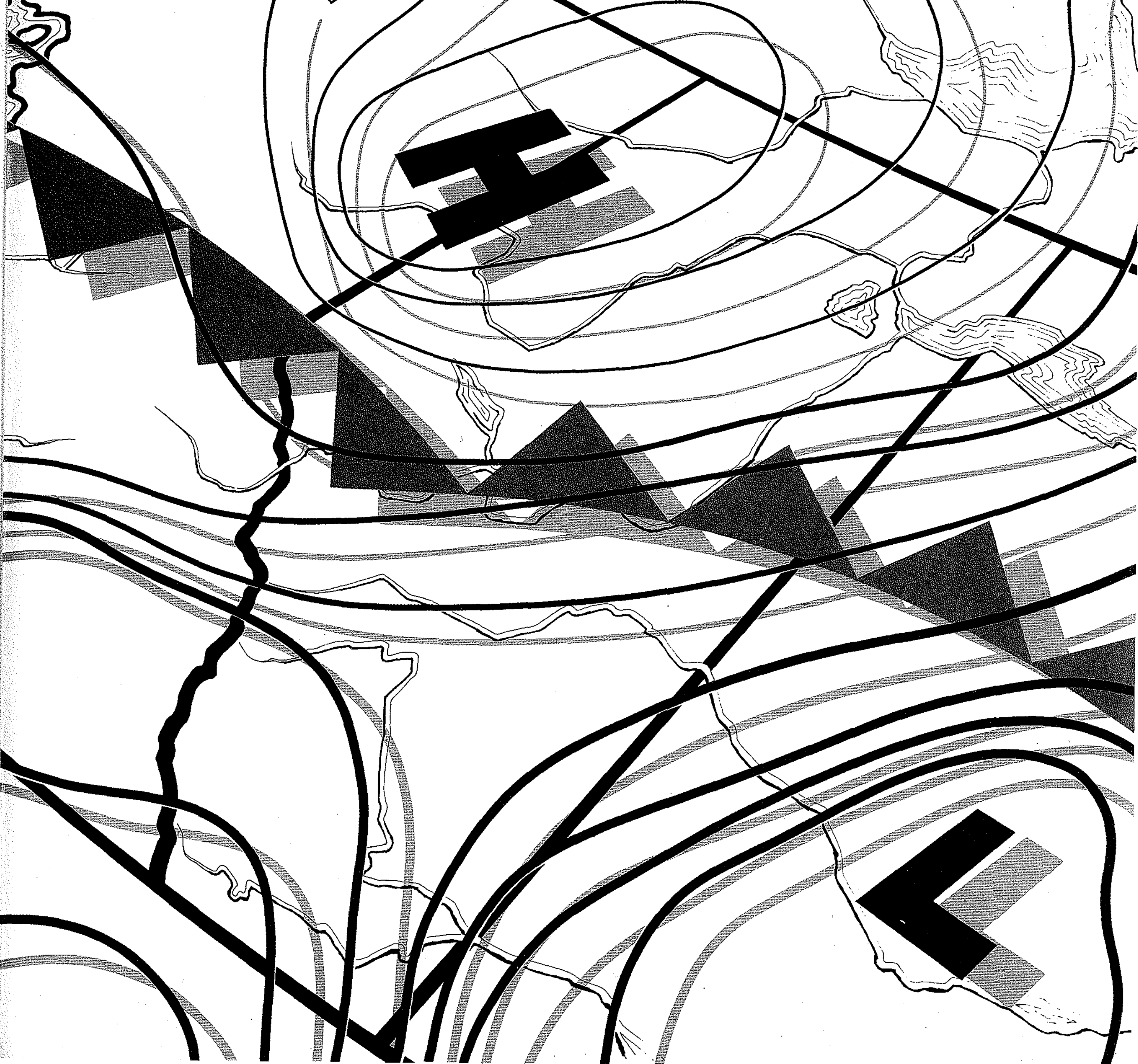

CURRENT APPLIED CLIMATOLOGICAL RESEARCH IN ALBERTA

Proceedings of the Workshop and 11th Annual
Meeting of the Alberta Climatological Association,
February 24, 1987, in Edmonton, Alberta

T. Singh, compiler

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ABSTRACT

The theme of the 1987 meeting of the Alberta Climatological Association was current applied climatological research in Alberta. The workshop consisted of a tutorial on methods for estimating evapotranspiration and a technical session on climatological research. In the annual meeting, 14 agencies and institutions presented reports on diverse topics that are currently being investigated in Alberta.

RESUME

Le congrès de 1987 de l'Alberta Climatological Association portait sur la recherche en climatologie appliquée en cours à l'heure actuelle en Alberta. L'atelier de travail comportait des travaux dirigés sur les méthodes d'estimation de l'evapotranspiration et une séance spécialisée sur la recherche en climatologie. Au cours de la réunion annuelle, 14 organismes et agences ont présenté des rapports sur divers sujets faisant l'objet d'études à l'heure actuelle en Alberta.

FOREWORD

The Alberta Climatological Association (ACA) provides for the exchange of scientific and technical information on climate activities in Alberta. Individuals and agencies from both the private and public sectors are encouraged to share their climatological experiences and concerns. The theme of climate activities has brought together a very interesting and diverse selection of technical papers for the 11th Annual General Meeting of the ACA.

The future direction of climate studies and research in Alberta is addressed by the keynote speaker. Emphasis is placed on climate change and how impacts might be addressed in long-term planning for more-efficient use of renewable resources. A tutorial session on evapotranspiration marks the first time this type of seminar has been included in the program. It is hoped that a topic of interest can be addressed each year in a similar fashion. The remainder of the program covers subjects from climate activities in Saskatchewan to microwave attenuation by rainfall.

The members of the executive extend their appreciation on behalf of the ACA to A.D. Kiil, Director, Northern Forestry Centre, and his staff for hosting the 11th Annual General Meeting and publishing the proceedings. Also, the assistance of the executive, the speakers, and all of the participants was greatly appreciated.

Bruce Thomson
Chairman

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CLIMATE RESEARCH IN ALBERTA: IDEAS FOR THE FUTURE

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INTRODUCTION

In 1985 I agreed to provide the Alberta Climate Advisory Committee with a few ideas about climatology research in Alberta. At first I developed a list of topics that fell under the general heading of applied climatology. This list, however, did not stir my imagination or enthusiasm, and it did not relate to the hot topic then and now of climate change. I realized that we in Alberta were not in the best position to do work on Global Circulation Models (GCM), since that type of work was in the good hands of the Atmospheric Environment Service and more recently McGill University. What was not obvious to me was how these large-scale models could relate to problems on a regional scale. Also, being somewhat cynical I felt that no one outside of Alberta would really look at climate change scenarios on a regional scale within Alberta. So, somewhat naively I suggested that the community of climatologists in Alberta should consider a regional climate model.

At the invitation of your chairman I am pleased to be able to explain my thoughts on this subject and to offer a few additional ideas. There is no expectation that the members of the Alberta Climatological Association will now receive true enlightenment, but one thing with being a keynote speaker is that I feel no compunction in bringing forth the odd wild idea, since this could cause someone more sensible to see a problem in a new light.

CLIMATOLOGY, CLIMATE CHANGE, AND ALBERTA

Climate is "the synthesis of the weather" (C.S. Durst), the long-term manifestations of weather, however they may be expressed. More rigorously, the climate of a specified area is represented by the statistical collective of its weather conditions during a specified interval of time (usually several decades). Climatology, as we all know, is the scientific study of climate. For many of us the most common activity is climatography, the presentation of climatic data. Another common activity (and the theme of this meeting) is applied climatology, the application of climatic data to the solution of specific design or operational problems.

Heretofore, the expression of climate has been largely by means of numerical tables and charts of average and extreme values of climatic elements. The manipulation of these elements into various significant indices and coefficients has been a fairly recent trend in climatology, along with the introduction of statistical frequencies, deviation, correlations, and the like.

Alberta Environment's Research Management Division report 82/12, *An assessment of collection and handling of climate data by Alberta government agencies*, has shown that most of the climatology research within Alberta is related to applied climatology or to climatography.

At one time we would have been content to understand the natural variation of climate due to changes in the inclination of the planet or its orbit or the output of the sun; however, other influences (such as volcanoes and, more recently, man) add extra complexity to the problem. Concern over changes in global climate caused by rising atmospheric concentrations of carbon dioxide and other trace gases has increased in recent years as our understanding of atmospheric dynamics and global climate systems has improved. Yet despite a better understanding of climatic processes, many of the effects of human-induced climatic changes are still poorly understood (Gleick 1986). Attempts have been made to translate these changes in climatic variables--such as temperature and precipitation--into environmental and societal impacts. Such assessments have focused primarily on agricultural productivity. Climate change is not always a source of problems but could provide new opportunities in agriculture, forestry, or tourism.

An important aspect of the study of climate change and impacts is the identification and evaluation of the likely impacts of such climatic changes in order to begin developing appropriate public policy responses in areas such as agriculture, water-resource management, and energy. Perhaps the greatest limitation of this research is our inability to evaluate the nature of the most-important local and regional climatic impacts. (The only people who really care about local and regional impacts are those living in the area; hence we must be responsible for understanding what could happen in Alberta.) The U.S. National Academy of Sciences concluded in 1979 that "At present, we cannot simulate accurately the details of regional climate and thus cannot predict the locations and intensities of regional climate changes with confidence."

As the theoretical understanding of the global climate system improves, there is growing confidence that the "greenhouse effect" from the additional carbon dioxide generated by burning fossil fuel will cause a gradual warming of the Earth. If a warming trend does persist, there will be complex changes in regional climates virtually everywhere. Since the warming is expected to be greater at the poles than in the equatorial zone, the resulting decrease of the temperature gradient will cause changes in the large-scale atmospheric circulation patterns, and this will most likely lead to changes in precipitation patterns and soil moisture as well as temperature. The shifts in precipitation and soil moisture will generally be more important than temperatures in determining where things can grow on a warmer Earth, and that in turn will have political and societal implications.

Evaluations of global climate change are based almost entirely on results from general circulation models. These models solve prognostic equations representing physical and dynamic climatic processes, including equations of motion, thermodynamics, and mass and water vapor continuity in three dimensions. Some models include nine or more vertical layers with spatial resolutions around 250 to 750 km. Such models are used primarily to evaluate carbon-dioxide-induced changes in climatic variables such as temperature, precipitation, changes in soil moisture, and runoff. The complexity and spatial scale of these models, along with the significant computing power and time required to evaluate details of climatic changes, significantly limits their usefulness to researchers interested in regional impacts.

Kellogg (1985) suggests that a first step in climatic impact studies should be to develop climate scenarios, which are fairly detailed descriptions of what could occur to the climate regionally and which should include estimates of changes of seasonal precipitation and soil moisture as well as interannual variability. These would not be actual predictions, but self-consistent pictures of likely patterns of change. According to Kellogg (1985) "there have been remarkably few attempts to develop such surprise-free climate scenarios and to apply them to agricultural crop production or economic models, and there have even been pronouncements apparently intended to discourage such efforts."

Climate models are still incomplete in several respects, and when used to reveal the regional patterns of climate change accompanying a global warming they may not have sufficient spatial resolution or may not respond in the same way as the real system. There are, however, approaches that can be used to develop climate scenarios, and these include:

1) use of global circulation models,

2) comparison to the Altithermal Period, 4500 to 8000 years ago, and

3) comparison to anomalously warm or cold periods in this century.

Despite the known limitations, general circulation models offer detailed information on potential large-scale climatic changes that may result from increasing atmospheric concentrations of radiatively active gases. Some results from GCMs suggest that plausible changes in certain critical hydrologic variables--especially precipitation and evapotranspiration--may lead to major regional water-supply problems, including changes in runoff and soil moisture patterns (Gleick 1986).

Major changes in water availability caused by alterations in temperature and precipitation patterns may be even more important to society. Such hydrologic changes will affect nearly every aspect of human well-being, from agriculture productivity and energy use to flood control, municipal and industrial water supply, and fish and wildlife management. This sensitivity was witnessed in southern Alberta when there was a lack of moisture in 1985 and too much moisture at harvest in 1986.

Soil-moisture changes are anticipated in some of the most productive agricultural areas of the world. Recently there have been a number of attempts to evaluate the regional hydrologic implications of climate changes. The results provide the first tentative evidence that relatively small changes in regional precipitation and evaporation patterns might result in significant changes in regional water availability. For example, Nemec and Schaake (1982) show that a climate change of +1°C and ±10% in precipitation results in a ±50% change in average annual runoff.

Schwarz (1977) concluded that certain characteristics of water supplies, particularly the variability of streamflow, are very sensitive to changes in climate. He also concluded that a full understanding of the relationships between climatic changes and water supply, not yet achieved, is a desirable goal and that a range of likely climate-change scenarios should be available to water-resource planners.

GCMs do not yet provide sufficient detail on regional impacts to be used for purposes of prediction, but they do provide an internally consistent description of plausible patterns of climatic change. One approach has been to combine the strengths of global climate models with the strengths of regional hydrologic models. Water balance models coupled with the results of GCMs were investigated by Gleick (1986) with promising results. Once a region has been characterized by water balances, the effects of climatic changes can be evaluated in several ways:

1) After verifying model accuracy using historical data it is possible to use that historical data to evaluate the effects of past fluctuations in precipitation and temperature on historical runoff and soil moisture.

2) By determining the sensitivity of runoff and soil moisture to theoretical changes in the magnitude and temporal distribution of precipitation and temperature, it is possible to assess a wide range of hypothetical climate changes in order to evaluate the hydrologic sensitivity of a watershed.

3) By incorporating even rough regionally disaggregated changes in temperature and precipitation predicted by GCMs, a first estimate can be made of the impacts of future predicted climatic change on regional hydrology.

AGRICULTURE AND IMPACT ON CLIMATE

In addition to "natural" climate changes and those induced by burning fossil fuels, man can alter the regional climate in profound ways. Consequently, it may be wise to look into this potential problem.

Consider the Indus river region of eastern Pakistan and northwestern India that now contains the Rajputana desert. Two thousand five hundred years before Christ the area contained an early agricultural civilization that lasted about 1000 years. There was a rapid decline about 1700 B.C., with changing climate a contributing factor. People helped make it a dust bowl and the lakes became salty, indicating less recharge with fresh water; however, this region has now remained dry despite several subsequent global climatic changes.

The air over the Rajputana has been and continues to be moist. Summer monsoon winds from the Arabian Sea moving over the desert contain four times the water vapor of air over most deserts and 80 percent of that over tropical rain forests (Bryson and Murray 1977). These are therefore monsoon winds of the rainy season, but rain does not fall. In the Rajputana the air, instead of rising and causing rain, is sinking, absorbing moisture, creating the conditions similar to the subtropical anticyclones--a desert region.

Climatologists at the University of Wisconsin-Madison found that dust, which man may have started and contributes to today, may be an important reason. Over 5 tons of dust is suspended over each square mile. The desert thus sustains itself by supplying the dust. Civilization may have created the original dust bowl conditions by overworking the land during dry periods and hence creating more dust. Now, when grass and vegetation try to reestablish, cattle, sheep, and goats graze it because of food pressures and kill off the vegetation again. The result is that today the desert is growing about one-half a mile per year, advancing into arable lands.

We assure each other that such conditions could never arise in Alberta. In India the pressure to use and hence abuse the land is economic. In Alberta keeping the land is as much an emotional issue as it is economic. If the government through its economic support policies keeps land in use that should not be cultivated, is it contributing to a process in which continued land use during poor climatic conditions leads to further decline of an agricultural region?

CLIMATE MONITORING

Satellite instrumentation now allows for monitoring reflected solar and emitted earth radiation. These data are the basis of the heat budget and the global vegetative index product (Gray and Tapley 1985). Gray and Tapley reported that

1) the global vegetative index product augments the heat balance data by providing early detection of atypical vegetation changes, suggesting changes in synoptic climatology, and

2) the global vegetative index time series depicts the botanical response to accumulated weather effects, thereby being a real integrator of weather into climatology.

Discussion at a recent workshop in Toronto on land modeling looked at the effects of climate change on terrestrial ecosystem complexes. The premise, which is similar to that of Gray and Tapley, is that vegetation is a major characteristic of a climate zone. The vegetation distribution under different climates indicates aspects of the sensitivity of the earth system to climate change. The analysis of large-scale vegetation changes can help define requirements for regional climate impact studies. One study reported at the workshop looked at identifying sensitive regions based on the biotemperature (BT = 0 if $\leq$C), precipitation, and potential evapotranspiration.

The Canadian Climate Program recognizes that plants, insects, and other organisms are extremely sensitive to climatic variables. It is well documented that extensions or reductions in their distributions represent one of the most convincing and cost-effective ways of measuring the impacts of climate change. One could ask if it would be a worthwhile exercise to develop a monitoring network of climatic indicators of pests, plants, and diseases.

SYNOPTIC/MESOSCALE LINK

An important question is how can one handle a sparse surface network of climate stations when trying to carry out a regional climate analysis. One way perhaps is to correlate surface observations with synoptic diagnosis above the ground. For example, Kline and Klein (1986) assessed the synoptic climatology of monthly mean temperature at 109 surface stations in the U.S. relative to 700-millibar heights at 133 grid points.

STATISTICS

Another use of long-term climate data is in the development of probabilities of various climate scenarios. For example, based on past information what is the probability of a wet harvest, given a set of antecedent conditions (that is, we want a conditional probability)? In soil erosion studies a question that has come up is, in a given period of time, say 5 years, how much soil could be eroded? This of course depends on the type of weather conditions, such as snowmelt, that are conducive to erosion. One way to handle this question may be to develop data sets that show the probability of certain types of weather phenomena, given certain conditions. One could then use a Monte Carlo technique to simulate the 5-year weather for many trials, calculating soil movement for each trial, and hence develop a probability curve for the amount of soil that could be eroded in the 5-year period.

Other types of probability analysis have been carried out to determine whether another heavy precipitation event in the vicinity of the Great Salt Lake can be expected within certain time periods, such as 50 years or 100 years (Karl and Young 1986). Statistical techniques are being tested by the Atmospheric Environment Service for climate predictions, and such methods could be useful in Alberta for regional impact assessments.

GEOGRAPHIC INFORMATION SYSTEMS

Combining climate information and change scenarios with other data such as soil types and groundwater conditions into a geographic information system (GIS) offers an exciting potential for evaluating the use of our land resources.

Geographic information systems are the hot topic in land use. They are similar to nongeographic information systems in that they share the ability to accept, process, and present data, to update and modify data, and to combine data from different sources. Specifically, a GIS provides

1) information support for government operations (property ownership, land value, tax assessment),

2) information support to improve services to users (transportation, health, education), and

3) the ability to integrate data from all sectors to provide for decision making and planning activities.

Geographic information systems are unique in that locational identifiers are attached to the data that form the computerized maps. These maps can then be analyzed by a variety of techniques to yield information that is valuable in resource and cartographic concerns.

There are two generic classes of information associated with GIS: spatial data and thematic data. Spatial (locational) data describes the location of map features using a coordinate referencing system. Thematic (nonlocational) data describes the actual phenomena or characteristics, such as the variable, its classification, and value name (attribute information). Data management is very important in a GIS, which is basically a technology that handles graphic and tabular geographic data. At the Alberta Research Council, GIS development is directed toward land issues, but there is a requirement for climate information so that land-use decisions can include all factors.

Combining different types of data sets can improve our ability to understand more complex problems of regional climate and to carry out better and more complete analyses. This could be one justification for a regional climate center.

CLIMATE SERVICE CENTERS

Alberta Environment has conducted a study into the feasibility of a climate service center. The results of this study have not been released, but it is interesting to consider the concept. One could imagine such a center providing the capability for multidisciplinary teams consisting of climatologists plus other types of experts devoting their attention to the investigation of regional climate, changes, trends, and impacts.

Combining data bases is feasible only if agencies now using climate data fully support the concept. Perhaps contributing agencies should provide a level of funding in addition to data, but I do not believe there is a desire yet to do so in this province. It is doubtful that contract funding could support a climate service center without some form of subsidy. The planned Prairie Climate Workshop (Fall 1987) could be a valuable forum in which to determine the private sector interest in climate, which in turn may help support the concept of a climate service center.

CONCLUSION

Often our activities are carried out in spite of the weather. Much of our economy (forestry and agriculture) is sensitive to climate patterns, changes, and trends. In Alberta we should be placing a greater emphasis on climate impacts. I encourage the development of a "regional climate model" for Alberta and the development of innovative techniques for climate research.

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METHODS OF MEASURING OR ESTIMATING EVAPOTRANSPIRATION FROM NATURAL SURFACES

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ABSTRACT

Methods of direct micrometeorological measurement of the vertical water vapor flux (i.e., evaporative flux) will be explained, with emphasis on underlying assumptions. Also, methods of estimating evapotranspiration from related observations (weather-station type observations) will be introduced.

INTRODUCTION

This brief paper is by no means a comprehensive review of evapotranspiration. The aim is simply to give an introduction to some of the underlying notions of evaporation at a very basic level, emphasizing key variables and underlying assumptions.

It is hoped that this will serve as a point of reference for people who are interested in evapotranspiration (ET), have not been trained in agrometeorology, and might erroneously think that "pan evaporation" is the whole story (if pan evaporation happened to equal the actual evaporation from a natural surface this would be an accident)--or that the wealth of empirical relationships between ET and variables such as mean daily temperature and daily sunshine hours represent the essence of our knowledge.

It is convenient to categorize knowledge of ET as:

1) **Forecast.** At present we have no great skill in forecasting the weather beyond about 5 days; therefore, we cannot forecast ET. We can, however, make a climatological type of forecast of ET based on climatologically-expected weather, i.e., expected radiation, wind, and temperatures.

2) **Diagnostic/historical.** Here we are concerned with past and present ET rates (and perhaps thence cumulative water loss) in terms of

   i) direct measurement of ET over a short period at a specific location, and

   ii) indirect determination of ET from related measurements over a short period at a specific location.

Clearly there are other possible subdivisions of the historical knowledge category (including the popular subdivision of indirect determination from poorly related measurements over a long period of time and over large areas). Here the concern is not with what is practical, but with what is known and what might be done with sufficient resources.

METHODS OF DIRECT MEASUREMENT OF EVAPOTRANSPIRATION

There are only two possibilities: measure what water the soil loses, or measure what the atmosphere gains.

Change in Soil Storage

Water loss (and hence ET) from the soil may be measured by

1) Lysimetry (weighing of an isolated soil sample). The weighed sample must match its surroundings in all respects (including soil moisture profile, perhaps the hardest aspect, since the core cannot recharge naturally), necessitating large installations (ideally). Expensive, not portable, cannot resolve ET over very short periods.

2) Changes in soil moisture profile.

Clearly these methods determine ET from a specific location, and extrapolation to a larger area involves an assumption of symmetry.

Micrometeorological Methods

The general procedure is to mount instruments at some height z (see Table 1 for symbol definitions) above the ground and determine the vertical vapor flux $\bar{E}(z)$ at that height averaged over some period of time, typically about 30 minutes (subsequent 30-minute averages of course being added to get the cumulative loss).

Micrometeorological methods ALWAYS involve an assumption of symmetry (Fig. 1). Applying a simple intuitive notion of mass conservation to the (imaginary) box drawn, and assuming (as is usually very reasonable) that one may neglect any change of storage of water in the box, one may readily conclude that the measured flux $\bar{E}(z)$ is only equal (even ideally, let alone allowing for instrument errors) to the surface flux, that is to say, the rate of loss from the ground, $\bar{E}_o$, provided the lateral vapor flux is independent of position.

Hence only at a spatially-uniform site may one use a micromet technique to measure ET. Micromet techniques do have a major advantage in being fairly portable and not terribly expensive.

What IS the vertical vapor flux?

A slab of air (Fig. 2) of cross-section A and depth $\Delta z = w\Delta t$ is considered to be the air that in a short time interval Δt has moved (with vertical velocity w) across the horizontal plane z through area A. The volume of air crossing z through A in time Δt is $w\Delta t\ A$, and the corresponding mass of water vapor crossing z through A in time Δt is $\rho_v\ w\Delta t\ A$. The RATE of passage of water vapor across plane z per unit area is simply

$$E = \frac{\rho_v\ w\Delta t\ A}{\Delta t\ A} = w\rho_v$$

(having dimensions, of course, of kg $m^{-2}\ s^{-1}$; i.e., mass of water per unit area per unit time). This is the instantaneous rate of water vapor movement across the plane at z. The atmosphere is turbulent, so that w and ρ_v fluctuate drastically in time. We therefore AVERAGE N consecutive measurements of the instantaneous vapor flux over a period of time of the order of 30 minutes to obtain the AVERAGE vertical vapor flux

$$\bar{E}(z) = \frac{1}{N}\sum_{i=1}^{N} w_i\ \rho_{v_i}$$

Table 1. Definition of symbols[a]

e	vapor pressure (Nm^{-2})
$e*(T)$	saturation vapor pressure at temperature T
c_p	specific heat of air at constant pressure ($J\ kg^{-1}\ {}^{\circ}K^{-1}$)
r	turbulent transfer resistance ($s\ m^{-1}$)
r_v, r_H	values of r for heat, vapor
s	slope of the curve of $e_*(T)$ versus T ($Nm^{-2}\ {}^{\circ}K^{-1}$)
w	vertical velocity of the air ($m\ s^{-1}$)
z	height above ground (m)
B	Bowen ratio
E	water vapor flux density ($kg\ m^{-2}\ s^{-1}$)
E_o	surface value of E, i.e., rate of evapotranspiration
E^P	value of $\bar{E}$ from Penman's combination equation
L	latent heat of vaporization/sublimation ($J\ kg^{-1}$)
$Q*$	net radiation ($W\ m^{-2}$)
Q_H	sensible heat flux density ($W\ m^{-2}$); the flux of heat to/from the atmosphere
Q_E	latent heat flux density ($W\ m^{-2}$); the energy equivalent of the vapor flux density
Q_G	soil heat flux density ($W\ m^{-2}$)
T	temperature
ρ	air density ($kg\ m^{-3}$)
ρ_v	vapor density ≡ absolute humidity ($kg\ m^{-3}$)
γ =	$\rho\ c_p/0.622\ L$ psychrometric "constant" ($Nm^{-2}\ {}^{\circ}K^{-1}$)

[a] An overbar denotes a time average value.

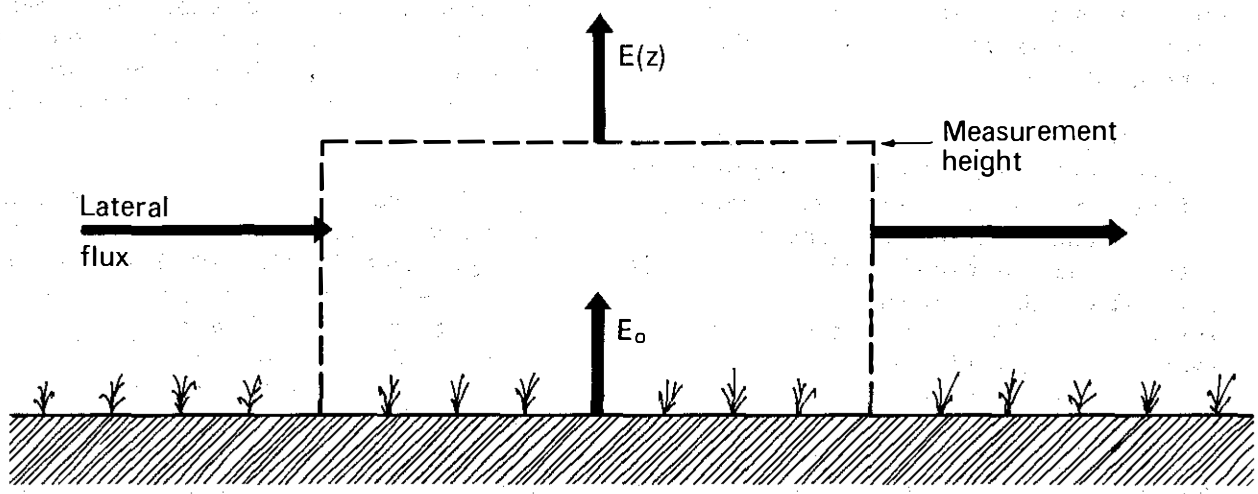

Figure 1. The measured vapor flux at height z will differ from the surface evapotranspiration rate, unless the rate of horizontal vapor movement is independent of position (i.e., unless there is horizontal uniformity).

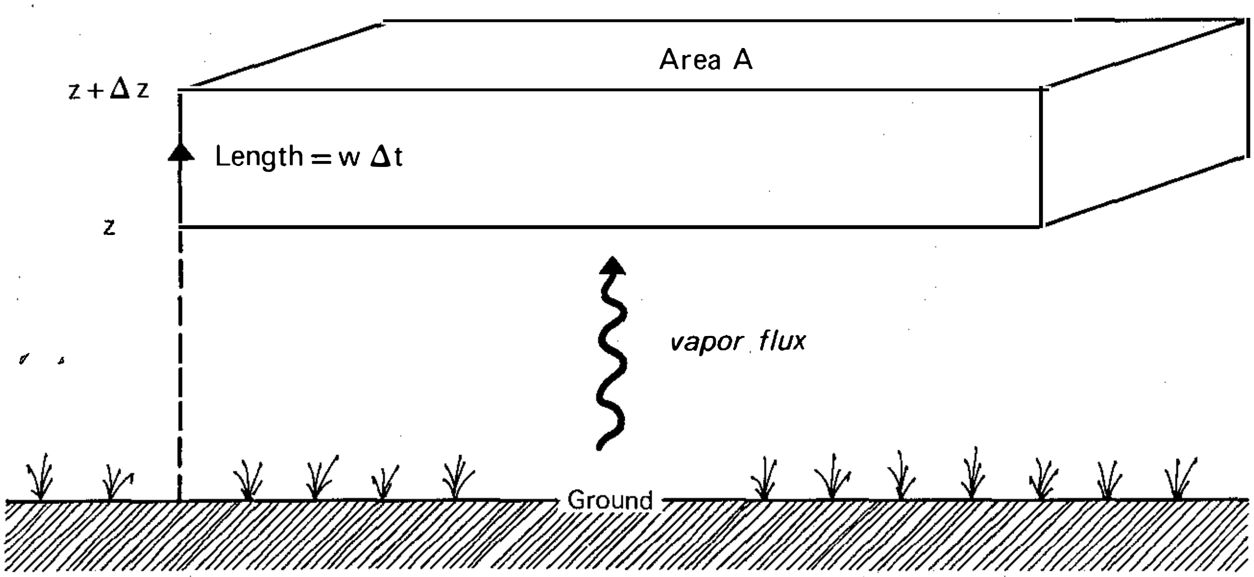

Figure 2. The slab of moist air drawn is the volume that in time Δt has crossed the plane at z with velocity w through area A.

and provided we have a horizontally uniform site, this is equal to the surface evaporation rate for the same period of time.

This type of measurement is called eddy correlation, because in effect we are measuring the correlation between two fluctuating variables, the vertical velocity w and the absolute humidity ρ_v. The variables ARE correlated because, generally, upward-moving air has come from regions close to the ground where the humidity is largest, while downward-moving air brings our instrument the relatively dry air remote from the ground.

We may say that the time average vertical vapor flux is DEFINED by, or is,

$$\bar{E}(z) = \overline{w\rho_v} = \frac{1}{N} \sum_{i=1}^{N} w_i \rho_{v_i} \qquad [1]$$

and the eddy correlation technique measures ET directly.

Eddy correlation became technologically feasible only fairly recently. There is an older micromet technique falling in the category of "direct measurement of ET over a short period at a specific location" called the Bowen ratio method, but it is crucial to note that this method involves assumptions that may not always be reasonable--these will be pointed out in the following development.

Figure 3 illustrates that over a uniform surface the net radiant energy flux density Q^*($J\ m^{-2}\ s^{-1}$) is balanced by a combination of heating/cooling of air Q_H, evaporation/condensation at the surface (consuming/releasing energy at a rate $Q_E = L\bar{E}$), and heating/cooling of the soil Q_G. Here, Q_G Q_H, and Q_E are all energy flux densities like Q^*, having dimensions $J\ m^{-2}\ s^{-1}$, i.e., energy loss/gain per unit area of surface per unit time. The energy balance is

$$Q^* = Q_H + Q_E + Q_G \qquad [2]$$

with the sign convention being

$Q^* > 0$ radiant energy gain at surface

$Q_H > 0$ heat flow from surface to air

$Q_E > 0$ vapor flow from surface to air

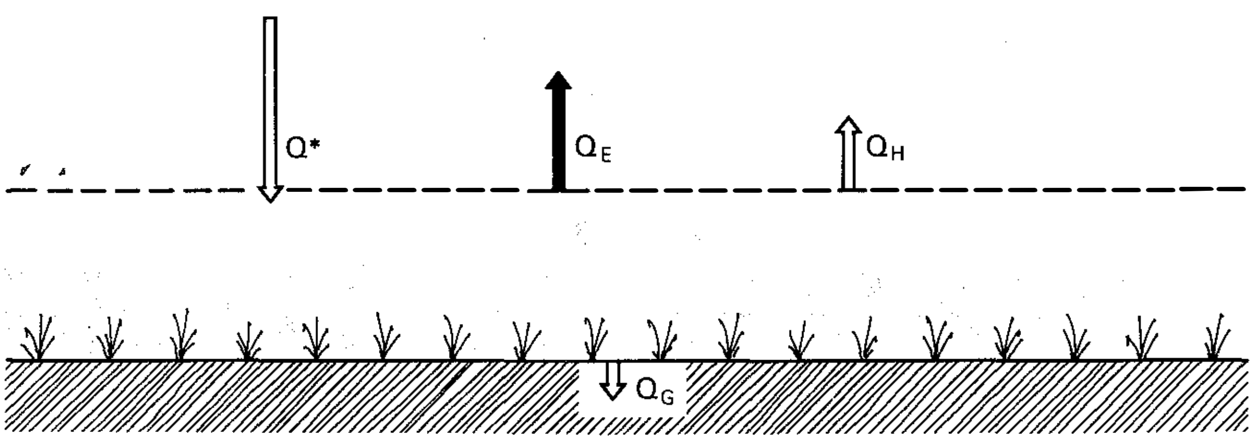

Figure 3. The energy fluxes to and from the surface (assuming horizontal uniformity). The fluxes must add together in such a way as to conserve energy.

$Q_G > 0$ heat flow into the soil

Defining the Bowen ratio, $B = Q_H/Q_E$, we may write

$$Q_E = \frac{Q^* - Q_G}{1 - B} = L\bar{E}. \quad [3]$$

Q_G will usually be small relative to Q^*, so that to a large extent, $\bar{E}$, the evaporation rate, is controlled by Q^* and B.

But how would we determine B? At this point the assumptions enter.

Figure 4 conveys the simple hypothesis that turbulent mixing causes heat (vapor) to flow from point z_1 to point z_2 in response to the time average temperature (vapor pressure) difference at a rate controlled only by a transfer resistance whose size depends on the degree of mixing. Mathematically this concept is expressed by the aerodynamic equations (which may be expressed in a host of different but equivalent forms).

$$Q_H = \rho c_p \frac{\bar{T}_1 - \bar{T}_2}{r_H} \quad [4a]$$

$$Q_E = \frac{\rho c_p}{\gamma} \frac{\bar{e}_1 - \bar{e}_2}{r_v} \quad [4b]$$

where r_v, r_H have the same units ($s\ m^{-1}$), get smaller as wind speed increases, and are certainly similar in magnitude.

Let us adopt these equations to express Q_H and Q_E. Then, further assuming $r_v \equiv r_H$ (which is fairly well above short crops but very risky close above tall crops, which have complex and perhaps not coincident height distributions of the vapor and heat sources)

$$B = \gamma\, \Delta\bar{T}/\Delta\bar{e}.$$

The Bowen ratio method consists of measuring $\Delta\bar{T}$ and $\Delta\bar{e}$ over a small height interval $z_2 - z_1 \sim 1$ m above the surface (averaging for ~30 minutes), simultaneously measuring Q^*

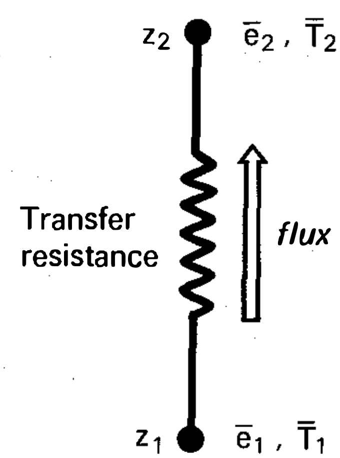

Figure 4. In the Ohm's-Law analogy for turbulent transport of heat and water vapor between separate points z_1 and z_2, the flux is assumed to be proportional to the driving difference and inversely proportional to a transfer resistance.

and Q_G, and combining to obtain $\bar{E}$ from equation (3).

The measurements of $\Delta\bar{e}$ and $\Delta\bar{T}$ are very demanding--one must measure, accurately, tiny differences in temperature, perhaps only of the order of 0.05°C. Once a suitable system has been designed and built (this is not expensive, but it requires care and knowledge) one has a portable system to measure ET. Again, note the assumptions, most critically horizontal uniformity, and $r_V = r_H$.

We have covered the two direct micromet techniques for determining ET; we will now turn to indirect determination.

INDIRECT DETERMINATION OF EVAPOTRANSPIRATION

I will go back only as far as Penman (1948). Like others before him, Penman wished to deduce ET from weather station data. Earlier efforts had been based only on aerodynamic theory such as that outlined earlier to evaluate Q_H and Q_E. Penman's vital step was to combine both aerodynamic theory and the concept of the surface energy balance, and his equation is called Penman's Combination Equation. This is the foundation for modern methods of estimation of ET from weather station data.

Penman's equation can be applied to all kinds of geometries (evaporation from wet blotting paper to airstream), but here I will consider evaporation from a horizontal surface against which the vapor pressure and temperature are e_o and T_o. Let us assume there is a Stevenson screen above, where we measure e_a and T_a. All atmospheric variables will now be assumed to be time averages--I will drop the overbar. Penman combined

$$Q_H = \rho c_p \frac{T_o - T_a}{r}$$

$$Q_E = \frac{\rho c_p}{\gamma} \frac{e_o - e_a}{r}$$

$$Q^* = Q_E + Q_H + Q_G$$

$$e = E_*(T_o).$$

Note the last equation: THE AIR ADJACENT TO THE EVAPORATING SURFACE IS ASSUMED TO BE SATURATED. Penman's combination equation gives the evaporation from thoroughly wet surfaces.

Some fairly simple manipulation yields

$$Q_E = \underbrace{\frac{s}{s+\gamma}(Q^* - Q_G)}_{A} + \underbrace{\frac{\rho c_p(e_*(T_a) - e_a)/r}{s+\gamma}}_{B} . \qquad [5]$$

Here s, γ, ρ, and c_p are simple functions of the gross temperature and pressure. Hence the actual rate of evaporation from a wet surface is determined primarily by

1) $Q^* - Q_G$, with Q_G often negligible,

2) vapor pressure deficit VPD = $e_*(T_a) - e_a$, and

3) to a lesser extent wind speed, which affects r (actually $r \propto 1 / \sqrt{\text{wind speed}}$).

The first of the two terms, A (the equilibrium term), is often much larger than B, the vapor pressure deficit term. Note that for a saturated atmosphere above a wet surface

$$Q_E = \frac{s}{s+\gamma}(Q^* - Q_G).$$

Provided energy is supplied (open system--radiant energy delivery), evaporation can continue into a saturated atmosphere. This equilibrium rate is relevant to, for example, conditions far out over the ocean (where Q_G would be a convective transfer term in the water).

Conversely, if $Q^* - Q_G = 0$, then

$$Q_E = \frac{\rho c_p(e_*(T_a) - e_a)/r}{s+\gamma}.$$

Evaporation may continue, provided the air is not saturated. How? The ground becomes cooler than the air at screen height, and Q_H (the heat flux) is directed downward, providing energy to drive Q_E, i.e.,

$$Q_H + Q_E = 0 \quad \text{with} \quad Q_H < 0.$$

The assumption of a wet surface is a problem--how does this help us for the more common case of an unsaturated surface, a dry canopy transpiring, or a wet soil overlain by dry soil?

We may regard the actual rate from a wet surface as the potential rate or atmospheric demand from an unsaturated surface--Penman's value is the upper limit. There is a tricky conceptual point here: we cannot say that, having measured Q^*, T, etc. over a dry surface and calculated the corresponding E^P, if we now flood a large area the actual rate will be what we calculated--wetting the surface will have modified the atmosphere and invalidated the values Q^*, T, etc., that we plugged into the formula.

How is the actual rate from an unsaturated surface calculated? There are several approaches, and these will be mentioned but not pursued:

1) Penman's approach of $Q_E = f\, Q_E{}^P$, where $Q_E{}^P$ is the value obtained from his formula and f is an empirical function of soil moisture and other relevant properties;

2) the approach of Monteith (and others such as Tanner) is to allow the vapor resistance from the site of saturation (within stomates, or deep in soil) to differ from the heat transfer resistance (extra terms r_V/r_H appear in the equation and these are generally hard to estimate); and

3) over well-watered short crops various authors have suggested

$$Q_E = \alpha \frac{s}{s+\gamma}(Q^* - Q_G)$$

with $\alpha = 1$ or perhaps $\alpha \equiv 1.2$.

This summary does not do justice to the valuable efforts that have been made toward estimation of actual rate from nonsaturated surfaces. It is probably fair to say we can now construct physically-sound models of this process, but in doing so we invoke a complexity that renders the models impossible for use based on weather station data alone--we start needing details of the soil and canopy (leaf area profile and stomatal resistance, for example).

SUMMARY

The principles and processes controlling evapotranspiration are well understood, and methods are available with which we may measure evapotranspiration directly; these methods are portable and not terribly expensive but require care and attention to underlying restrictions on their validity. If we wish to estimate evapotranspiration from related measurements we have in general a very difficult problem--except for the case of a wet surface, for which Penman's equation is exact and fairly manageable. Considering the range of possible dry surfaces (bare dry soil, short crop, tall forest) it is not surprising that different adaptations of Penman's approach have had success over different surface types.

The many empirical formulae that estimate actual or potential evapotranspiration from basic and widely available data have not been mentioned but appear to be quite useful (see the following paper by Dr. Barry Grace).

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The following are presented only as a starting point for those who may wish to delve into the (vast) literature on evapotranspiration.

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In addition, Agricultural Water Management, a journal from The Netherlands, published the Proceedings of the International Workshop on Evapotranspiration as Volumes 8 and 9 in 1984 and 1985.

PRACTICAL APPLICATION OF EVAPORATION EQUATIONS IN ALBERTA

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ABSTRACT

Eight different, commonly used methods of calculating potential evapotranspiration (PE) were compared under different climatic conditions at the Agriculture Canada Research Station in Lethbridge, Alberta. Under conditions of low wind speed and moderate humidity the methods produced similar results; however, under dry, windy conditions estimates of PE differed widely. Equations that require the use of wind and humidity data as well as temperature and radiation data are recommended for use in computer simulation models in the Chinook-dominated, semiarid climate of southern Alberta.

INTRODUCTION

The use of computer models in agriculture to simulate field conditions is widespread. Most of the models currently used on an operational basis in southern Alberta for soil moisture evaluation, crop yield prediction, irrigation scheduling, etc., employ the widely accepted concept of potential evapotranspiration (PE) as the driving function for the calculation of field evaporation.

PE may be defined as evaporation from an extended surface of short, green crop that fully shades the ground, exerts little or negligible resistance to the flow of water, and is always well supplied with water. There are several methods of calculating PE, and the methods generally yield similar although not identical results. The more-common methods in use in western Canada include some adaptation of the Priestly-Taylor formula, Baier-Robertson formulae, and Jensen-Haise equation. Real evapotranspiration cannot exceed and is usually less than PE. Evaporation from a class A evaporation pan is always greater than PE. The reasons for these differences are best explained by reference to the conditions imposed by the definition of PE and an analysis of the reality of these conditions.

It is the intent of this paper to review and compare the most common methods of calculating PE currently in use in southern Alberta. The wide variety of models proposed for estimating PE are not reviewed in detail here. Doorenbos and Pruitt (1975), for example, identified 40 formulae for estimating potential and actual evapotranspiration for irrigated crops. No new methods or formulations for the calculation of PE are presented here.

PE MODELS

The problems associated with the concept of PE are related to the imprecise nature of the definition. Since the concept of PE is an abstraction, there is no reference standard to determine true PE values.

The lack of a suitable reference makes it difficult to test the various approaches to estimating PE. Nearly all formulations estimating PE are empirical and depend on the establishment of a known correlation between evapotranspiration and one or more climatic variables such as temperature, humidity, wind speed, and radiation. Some formulae relate evapotranspiration to direct observations from porous plate atmometers or pan evaporation. Almost all equations contain empirical coefficients that must be used to calibrate the models for local conditions. Each model for the estimation of PE has advantages and disadvantages.

Thornthwaite

Thornthwaite (1944, 1948) is credited with first proposing the concept of evapotranspiration. Indeed, the original concept was that PE would be equal to the consumptive use of water in irrigated agriculture. Thornthwaite, using the strong correlation between radiation and mean air temperature, proposed a model relating PE to air temperature:

$$PE = (d/360)1.6(10T/I)^a \qquad [1]$$

where T is the monthly mean air temperature, I is the heat index for the site (derived from long-term monthly air temperature), a is a function of I, and d is the day length.

Certain shortcomings are inherent in the method. Only day length and temperature are used as climatic input. Application of this method to short time periods leads to significant errors. For example, Pelton et al. (1960) found that PE estimations based on short-term mean temperatures by this method are unreliable because of the often excessive variation in mean temperatures. The failure of the Thornthwaite method over short time periods is attributed to the fact that short-term mean temperature is not a suitable measure of net radiation. Both PE and mean temperature are, however, correlated with net radiation over relatively long periods of time and, hence, the Thornthwaite model has success on a long-term basis (Rosenberg 1974). The use of the empirical method of Thornthwaite has declined in recent years as the availability of meteorological data required for more physically based methods (i.e., Penman and Priestly-Taylor) has increased. Certainly, for computer simulation models of soil moisture, irrigation scheduling, etc., which require PE estimations on a short-term basis, the Thornthwaite method is not recommended.

Pan Evaporation Model of Doorenbos and Pruitt[1]

Gay (1981) suggests that a possible standard for PE is the evaporation rate, which is measured directly with an evaporation pan (Epan). The basic model

$$PE = K_p(Epan) \qquad [2]$$

where K_p is a constant determined empirically, is a simple one. As PE rates differ from those of pan evaporation due to oasis and clothes-line effects, Doorenbos and Pruitt (1975) give guidelines for the appropriate reduction coefficients for a variety of climatic and site conditions.

[1] For appropriate coefficients and units of calculation for each of the described PE models, the original authors should be consulted.

Considering the accuracy, simplicity, and cost, Stanhill (1965) recommended class A pan evaporation as the best method of estimating PE. Usually crop water use is 60-90% of pan evaporation in regions where advection of sensible heat is unimportant (Rosenberg 1974). Thus, the relation between adjusted evaporation rates and PE from irrigated crops is quite good in temperate regions (Gay 1981). The ratio of real evapotranspiration to pan evaporation for class A pans over a range of sites is about 0.8 for grass to 1.0 for alfalfa (Pruitt 1966).

The Jensen-Haise Model

Jensen and Haise (1963) developed a model to predict PE by combining the effect of temperature on evaporation rate with that of solar radiation.

$$PE = C_t(T_d - T_x)K_s/L \qquad [3]$$

where T_d is the average daily temperature, T_x is a constant for a given location, K_s is daily solar radiation, L is latent heat of vaporization, and C_t is a temperature coefficient that is approximately equal to the reciprocal of the mean temperature. C_t can be estimated by

$$C_t = 1/(27 + 7.3C_h) \qquad [4]$$

with

$$C_h = 50 \text{ mb}/e_2 - e_1) \qquad [5]$$

where e_2 and e_1 are the saturation vapor pressures at the mean monthly maximum and minimum air temperatures for the warmest month. For actual calculations, refer to Jensen and Haise (1963). The coefficients for C_t and C_h vary with elevation and atmospheric moisture content, as well as with temperature. The adjustments are presented by Jensen (1966). The Jensen-Haise method produces good results when applied under conditions when advection is minor.

The Statistical Method of Baier-Robertson

In a statistical study of six Canadian sites, Baier and Robertson (1965) presented the results of a correlation of eight climatic variables (maximum temperature, temperature range, wind, duration of bright sunshine, vapor pressure deficit, solar energy at the top of the atmosphere, day length, and total sky and solar energy on a horizontal surface) with latent evaporation as measured with black, porous disk atmometers. Based on the equation of Holmes and Robertson (1958) for the conversion of latent evaporation to PE (equation 6), simple empirical estimates of PE are possible from readily available climatic data.

$$PE = 0.08636(LE) \qquad [6]$$

where LE is latent evaporation (Holmes and Robertson 1958).

Baier and Robertson (1965) provide eight different equations for the estimation of LE from different combinations of climatic parameters with the appropriate regression coefficients ranging from R = 0.68 for three meteorological variables (Baier-Robertson equation I) to R = 0.84 for six meteorological variables (Baier-Robertson equation VIII). Baier-Robertson I and VIII are presented here as equations 7 and 8.

$$LE = -87.02 + 0.928T_{max} + 0.933(T_{max} - T_{min}) + 0.0486K_a \qquad [7]$$

and

$$LE = -53.39 + 0.337T_{max} + 0.531(T_{max} - T_{min}) + 0.0107K_a + 0.0512K_s + 0.0977U + 1.77(e_a{*} - e_a) \qquad [8]$$

where LE is latent evaporation, T_{max} is maximum daily air temperature, T_{min} is daily minimum air temperature, K_s is the solar radiation measured at ground level, U is wind run, e_a* is the saturation vapor pressure, e_a is the vapor pressure, and K_a is the solar radiation at the top of the atmosphere as given in the Smithsonian Meteorological Tables (Baier and Robertson 1965).

The Penman Combination Equation

The model of Penman (1948) is probably the most widely known PE estimator. Penman's equation has a sound physical basis. In contrast to the pan observations and the empirical models, the Penman model is based on a simplified radiation budget. The formula requires observations of net radiation, wind, temperature, and humidity. In the manner of Doorenbos and Pruitt (1975), Penman's model may be written as

$$PE = S/(S + \gamma)[Q^* + f(u)(e_a^* - e_a)] \qquad [9]$$

where S is the slope of the saturation vapor pressure-temperature curve, γ is the psychrometric constant, e_a* is saturation vapor pressure of the air, Q^* is net radiation, and f(u) is a wind function that approximates the diffusivity of the atmosphere near the ground and is given by

$$f(u) = 0.27(1 + u/100) \qquad [10]$$

where u is the 24-hour wind run in kilometres (Doorenbos and Pruitt 1975). The weighting factor (S/S + γ) is the same as in the Priestly and Taylor formula (see below) and expresses the relative importance of the radiation and aerodynamic processes.

One of the major problems with the Penman model is the requirement for net radiation data. Unfortunately, net radiation data are not readily available for most locations. Net radiation has been measured at only six stations in the Canadian climatological network since 1965 (Selirio et al. 1971). For models that require estimates of net radiation--such as the Penman model or the Priestly-Taylor model (see below)--daily net radiation (Q*) can be calculated with equation 11 (Jensen et al. 1970) as adapted by Doorenbos and Pruitt (1975) and Jury and Tanner (1975).

$$Q^* = (1 - r)K_s - \sigma T_a^4 (0.34 - 0.44\, e_a^{1/4}) (1 + 0.9\, K_s)/K_a \qquad [11]$$

where K_s is solar radiation, T_a is absolute air temperature, e_a is the water vapor pressure of the air, σ is the Stefan-Boltzman constant, K_a is maximum possible solar radiation, and r is the albedo, assumed to be 0.25 for a crop surface and 0.1 for a bare soil surface (Doorenbos and Pruitt 1975). The actual vapor pressure e_a was calculated from the mean relative humidity and mean air temperature.

The Priestley-Taylor Correlation

The focus of the Priestly and Taylor (1972) model is the available energy (Q*) or net radiation, the primary factor controlling PE from well-watered crops in most regions. If measurements of net radiation are unavailable, estimates may be made using equation 11. An empirical constant (a) and a temperature-dependent weighting factor (S/S + γ) are also required.

$$PE = a(S/S + \gamma)Q^* \qquad [12]$$

where a is a constant that must be obtained by local calibration (Priestley and Taylor 1972).

The Selirio Adaptation of the Priestley-Taylor Correlation

Often measurements of global solar radiation are not available. Selirio et al. (1971) employed a regression equation utilizing solar radiation at the top of the atmosphere, duration of bright sunshine, and day length to provide an estimate of global solar radiation from which they calculate net radiation. Substituting this value in the Priestly-Taylor formula results in a functional equation:

$$PE = \frac{f(vp) * f(rdn)}{59} \quad [13]$$

where f(vp) and f(rdn) are the vapor pressure and radiation functions, respectively. Vapor pressure is expressed as the daytime mean temperature according to the following:

$$f(vp) = 0.516 + 0.02T_{dm} - 0.000152T_{dm}^2 \quad [14]$$

where T_{dm} is the daytime mean temperature. Radiation function is an estimate of net radiation based on the approximations of global solar radiation (Selirio et al. 1971) where

$$f(rdn) = 0.52(0.23 + 0.57n/N)Q_a + 7.3 \quad [15]$$

where N is day length, n is bright sunshine hours, and Q_a is solar radiation at the top of the atmosphere.

The Advection Modified Jury-Tanner Adaptation of the Priestley-Taylor Correlation

To account for the effects of high local advection on PE, Jury and Tanner (1975) proposed an advection-modified form of the Priestly-Taylor equation employing a vapor pressure deficit term and local calibration coefficient.

$$PE\ (1 + \frac{(a - 1)}{(e_e^* - e_a)}D_e)(S/S + \quad)Q^* \quad [16]$$

where D_z is the average vapor pressure deficit for the crop cycle. The quantities a and D_e must be obtained by local calibration (Jury and Tanner 1975; Shouse et al. 1980).

COMPARISON OF PE MODELS

Climatic data collected at the Lethbridge Research Station for 1983, 1984, and 1985 were used to calculate PE for each day of the growing season by eight different methods. The equations chosen for comparison included the methods of Penman, Jensen-Haise, Doorenbos-Pruitt, and Priestly-Taylor, the Selirio adaptation of the Priestly-Taylor equation, the Jury-Tanner adaptation of the Priestly-Taylor equation, and two Baier-Robertson equations (I and VIII). Climatic data from a 21-day period in June 1984 were arbitrarily selected for the comparison of PE methods.

Class A pan evaporation is the only measurement of evaporation made on a regular basis. Other parameters such as temperature, radiation, wind speed, and relative humidity all affect the magnitude of pan evaporation. Analysis of daily PE values from 1983, 1984, and 1985 indicated that formulae based on only radiation and temperature, i.e., Jensen-Haise, Selirio adaptation of the Priestly-Taylor formula, and Baier-Robertson I were the most poorly correlated to pan evaporation (R^2 of 0.43 to 0.67). These models also produced the lowest estimates of seasonal PE for 1983, 1984, and 1985 (Table 1). Equations that required humidity and/or wind

Table 1. Accumulated pan evaporation and potential evapotranspiration (mm) for the 1983, 1984, and 1985 growing seasons

	1983	1984	1985
Pan evaporation	1320	1334	1287
Doorenbos-Pruitt	964	937	896
Jury-Tanner adaptation	831	779	773
Priestly-Taylor	817	746	745
Baier-Robertson VIII	711	702	738
Penman	665	610	610
Baier-Robertson I	639	619	589
Selirio adaptation	600	549	548
Jensen-Haise	587	540	543

data were better correlated to pan evaporation, with R^2 values ranging from 0.67 for the Penman formula to 0.96 for the Doorenbos-Pruitt equation. These latter models tended to yield higher estimates of seasonal PE.

Daily values of PE for a 20-day June period (1984) at Lethbridge indicate the disparity of the estimates of PE for eight different methods of calculation (Fig. 1). Temperature, wind, humidity, radiation, and class A pan evaporation data for this period are displayed in Figure 2. Under conditions of low wind (<500 km wind run) and moderate relative humidities (45-85% RH), calculated values of PE ranged from 50 to 80% of pan evaporation. This is illustrated in Figure 1 for the time period of June 10 to June 20, 1984. Cool temperatures, high humidities, and precipitation (24.4 mm on June 21) had the effect of depressing pan evaporation and calculated PE values on the 20, 21, and 22 of June. Under conditions of high wind (>500 km wind run) and lower humidities (<40% RH), however, estimated values of PE varied widely, ranging from 15 to 60% of pan evaporation. For example, the dry (35% RH) and windy (1126 km wind run) conditions of June 30 resulted in calculated PE of 2.6 mm to 10.8 mm.

Employing the pan evaporation method of Doorenbos and Pruitt (1975), a reduction of 55-85% was applied to pan evaporation data for Lethbridge according to these guidelines. Under most conditions the highest estimates of PE were calculated using this method. Thus, seasonal totals (Table 1) are also the highest of the models examined.

The Jensen-Haise method for the estimation of PE consistently gave lower values than other methods tested and thus produced the lowest estimation of seasonal PE, with values ranging from 540 to 587 mm (Table 1).

The Baier-Robertson equations utilized were the most simple: Baier-Robertson I, with only three meteorological variables (equation 6); and Baier-Robertson VIII, the most complex, with six meteorological variables (equation 7). Equation I yields lower estimates of PE than does Baier-Robertson VIII. The discrepancies are most apparent under windy conditions where values of PE with equation I are often less than one-half those estimated with equation VIII. Under calm or low wind conditions Baier-Robertson I estimates of PE exceeded those of Baier-Robertson VIII. On a seasonal basis the simplest Baier-Robertson equation

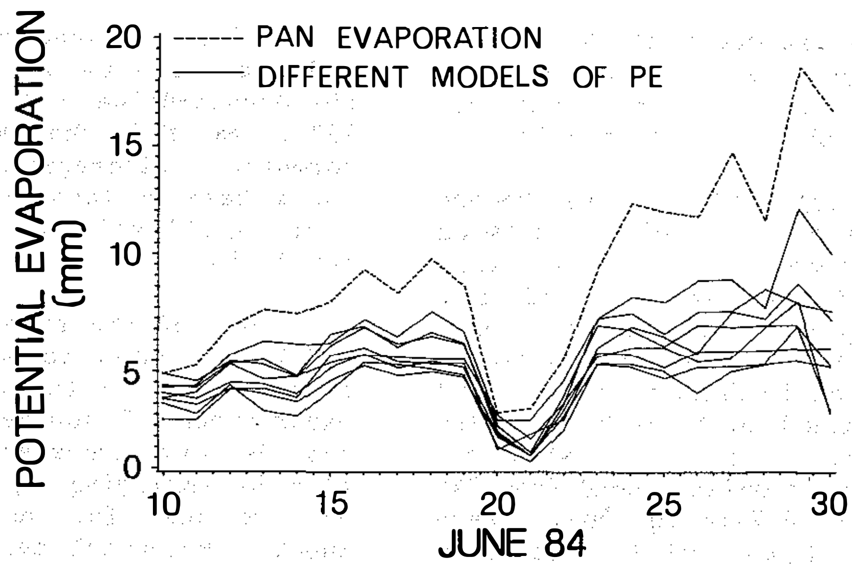

Figure 1. A comparison of class A pan evaporation and calculated values of potential evapotranspiration for June 10 to 30, 1984, for Lethbridge, Alberta.

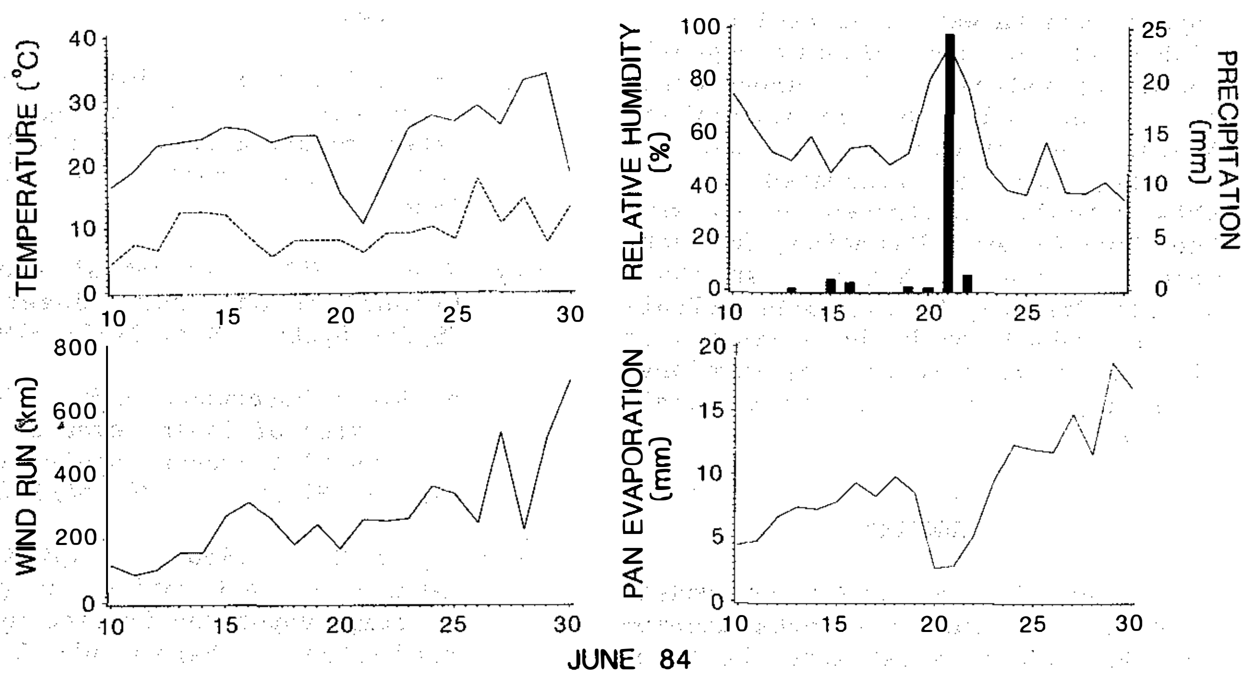

Figure 2. Maximum and minimum temperature, wind run, relative humidity, precipitation, and pan evaporation for June 10 to 30, 1984, for Lethbridge, Alberta.

yielded low estimates of PE similar to the other temperature-radiation based models of Jensen and Haise and the Selirio adaptation (Table 1).

The PE estimations by the Penman method tended to be midway between the low values of the Jensen-Haise and Selirio adaptation of the Priestly-Taylor model and the high values of the Jury-Tanner adaptation of the Priestly-Taylor formula and the Doorenbos-Pruitt method. The seasonal estimates of PE with the Priestly-Taylor model ranged from 745 mm in 1985 to 817 mm in 1983. These values were higher than the estimates from models that employed temperature and global radiation, i.e., Jensen-Haise and Baier-Robertson I. The Priestly-Taylor formula, however, does not react to changes in humidity and wind. For example, the increased wind and decreased humidity on June 29 and 30 (Fig. 2) do not affect the PE estimates for these days.

Values of PE estimated with the Selirio adaptation of the Priestly-Taylor formula were comparatively low (Table 1) and most closely approximated the values of the temperature-radiation model of Jensen-Haise. Again, the effects of wind and low humidity are not accounted for by this method. Estimates of PE with the Jury-Tanner adaptation, however, were consistently higher than those of the Priestly-Taylor model (Table 1) and indeed, with the exception of the Doorenbos-Pruitt estimations, were higher than the other models tested.

SUMMARY

Many of the simulation models currently in use in Alberta accumulate PE totals to estimate the total evaporation from a site during a given period of time. This information is then used to make management decisions. The accumulated PE for the 21 days examined here ranged from a low of 75.0 mm as calculated with the Jensen-Haise method to a high of 138.1 mm with the Doorenbos-Pruitt formula. Discrepancies this large could have serious consequences for such applications as irrigation scheduling.

Some of the computer simulation models currently in use on an operational basis in the semiarid, windy environment of southern Alberta may considerably underestimate evaporation by employing equations that do not account for advective energy input. Potential evapotranspiration equations that require humidity and wind data more correctly simulate real conditions in the Chinook-dominated climate of southern Alberta.

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THE HYDROMETEOROLOGICAL EVENTS OF THE JULY 16-18, 1986, STORM

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ABSTRACT

Over the 3-day period of July 16-18, 1986, heavy precipitation fell on the already moisture-laden soils of west-central Alberta. Extensive flooding followed. The hydrometeorological events surrounding the storm are discussed.

INTRODUCTION

After a dry June, July began wet across central portions of the province and continued wet through the middle of the month. This was especially true over the foothills of west-central Alberta, where at least scattered afternoon showers were recorded during each day of the first half of the month. A cloudy first half of the month and cool temperatures kept evaporation and evapotranspiration rates relatively low. Thus, by the 16th, foothills reservoirs were high, and soil moisture holding capacity had essentially been used. Over the period of July 16-18, a storm moved from southern British Columbia to central Saskatchewan. As it crossed central Alberta it dumped heavy precipitation over west-central watersheds. Very heavy snow fell at higher elevations; Grave Flats, at 2074 m, reported nearly 75 cm. Portions of the Banff-Jasper Highway were briefly closed due to snow accumulations. Heavy surface runoffs, augmented by snowmelt from higher mountain elevations, resulted in several rivers reaching one of the highest flood levels in many, many years. Extensive flooding was reported along the Athabasca, McLeod, Pembina, Paddle, North Saskatchewan, and Red Deer rivers.

DATA SOURCES

Precipitation measurements are made and recorded at several different times during the day, depending on the requirements of the agency collecting the data. Atmospheric Environment Service (AES) stations take precipitation readings every 6 hours, beginning at 1200 UTC (0600 MDT). Most climatological stations record measurements twice daily: at 0800 and 2000 MDT. Forestry lookout towers also report readings twice a day, but at 0800 and 1300 MDT. For climatological purposes, daily precipitation is measured in 24-hour periods. For AES stations in Alberta, the period is from midnight to midnight MDT. For forestry and climatological stations, the period runs from 0800 to 0800 MDT: precipitation collected overnight is ascribed to the previous day.

ANALYSIS

The largest precipitation amounts produced by the storm were over the foothills roughly half-way between Edmonton and Jasper and midway between Edson and Rocky Mountain House (Fig. 1). Two major axes of maximum amounts are evident: one from Obed (just east of Hinton) to

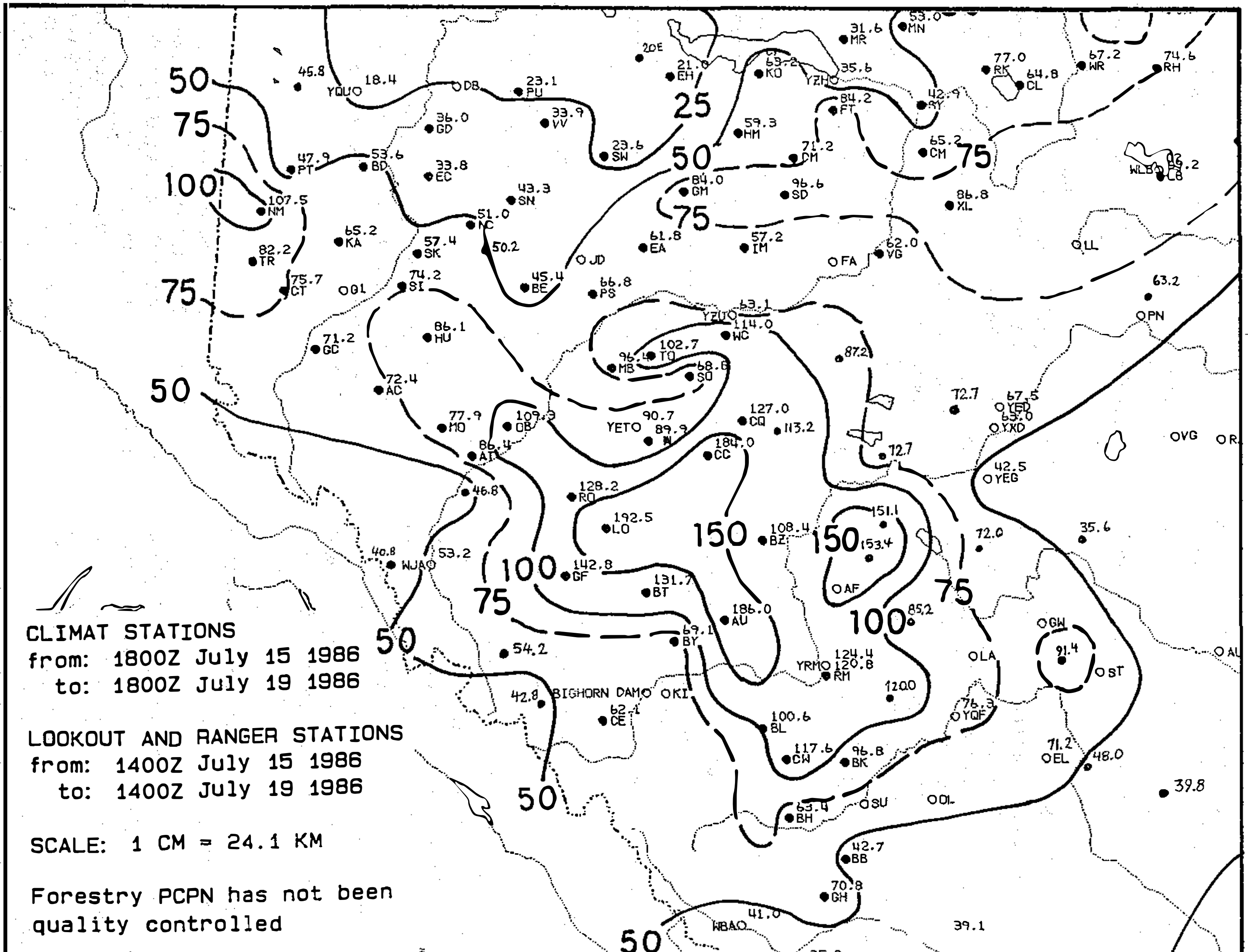

Figure 1. Precipitation amounts for west-central Alberta, July 15-19, 1986.

Clearwater (just northwest of Sundre) and one from Whitecourt to Eckville (just west of Red Deer). The precipitation amounts were not records except for the 24-hour rainfall amount of 104.5 mm at Carrot Creek (CC) on July 17, which was the greatest reported in 42 years (Table 1). Several higher elevation sites reported significant snowfalls (Table 2).

Considerable rain occurred over central Alberta during the first 2 weeks of July (Fig. 2), and this provided sufficient moisture to saturate soils in many areas in the foothills. Coincidentally, the largest 2-week accumulations were in the same areas that the July 18 storm would affect. The combination resulted in an extreme flood situation.

The July 16-18 storm was of a type commonly referred to as a 'cold low'. This feature is not uncommon for Alberta or, for that matter, North America. A great number of variables are involved, so that each cold low event is unique and there is considerable variation in precipitation type, amount, pattern, and areal extent for similar appearing storms.

At 1200 UTC (6 a.m. MDT) on July 16, a low was evident on the 50-kPa chart (500 mb or approximately 5580 m) over southern B.C. A trough extended from the low to near Edmonton then weakly toward Cold Lake (Fig. 3). At the surface, a weak trough reflected the upper air feature. Showers were reported along the north of the trough line, and there was some thunder shower activity over the foothills.

Over the next 48 hours (from 1200 UTC, July 16) the main upper atmospheric feature would spin northward in top-like fashion across southern B.C. and weaken (Fig. 4). At the same time, a weak trough would sweep across southern Washington and deepen and intensify into a low as it crossed the Rockies just north of Pincher Creek. This feature was the dominant one by the time it reached eastern Alberta (Fig. 5).

A surface low developed over eastern Montana by the evening of July 17 in response to the upper atmospheric activity over the mountains. This surface feature tracked north-northwest toward Edmonton, stalled just south of the city, and then swung eastward with the upper center. The moist air wrapped around the system contributed to a broad band of continuous precipitation that persisted to the west of the surface center (Fig. 6). The 70 kPa (700 mb) and 85 kPa (850 mb) charts for 0000 UTC July 18 are illustrated in Figures 7 and 8.

Relatively cold air accompanied the upper center (hence the term cold low). This increased the air mass instability associated with the system and also resulted in snow falling at high elevations along the foothills and throughout the mountains.

Figure 9 is an NOAA (National Oceanic and Atmospheric Administration) satellite picture taken at the height of the storm (i.e., 2054 UTC July 17, 1986).

As the upper and surface centers moved into Saskatchewan on July 18, the precipitation diminished to scattered showers.

SUMMARY

A major storm crossed Alberta in mid-July. It exhibited many classical meteorological characteristics in a fashion that was interesting from a meteorologist's viewpoint, but the storm was not otherwise spectacular. A widespread heavy rainfall did occur, but general precipitation accumulations remained well below

Table 1. The 24-hour precipitation amounts for July 17, 1986, and comparable 24-hour precipitation records

Station	July 17, 1986, 24-hour rainfall (mm)	Record 24-hour rainfall (mm)	Number of years of data
Banff	4.2	53.1	91
Brazeau	42.0	80.8	43
Carrot Creek	104.5	73.4	42
Clearwater	66.0	95.8	28
Edson (Airport)	37.6	68.6	63
Jasper	18.4	86.6	53
Lovett	63.0	94.2	41
Mayberne	61.6	79.8	39
Obed	43.6	67.8	26
Red Deer	16.4	85.3	47
Rocky Mountain House	72.0	76.7	37
Whitecourt	75.0	90.6	43

record levels. Unfortunately, the greatest rains fell on areas that had already been saturated by the events of the previous 2 weeks. Flooding followed.

ACKNOWLEDGMENTS

Thanks and appreciation are due the staff of Western Region Scientific Services Division, Atmospheric Environment Service, especially to Hilda Gutzmann for typing and to R.B. Thomson and M.N. Parker for data collection and some analyses.

Table 2. Snowfall amounts during the July 16-18 storm

Station	Total snowfall (cm)
Baldy	8.5
Burnt Timber	17.0
Cline	21.5
Grave Flats	74.8
Moose Mountain	17.0

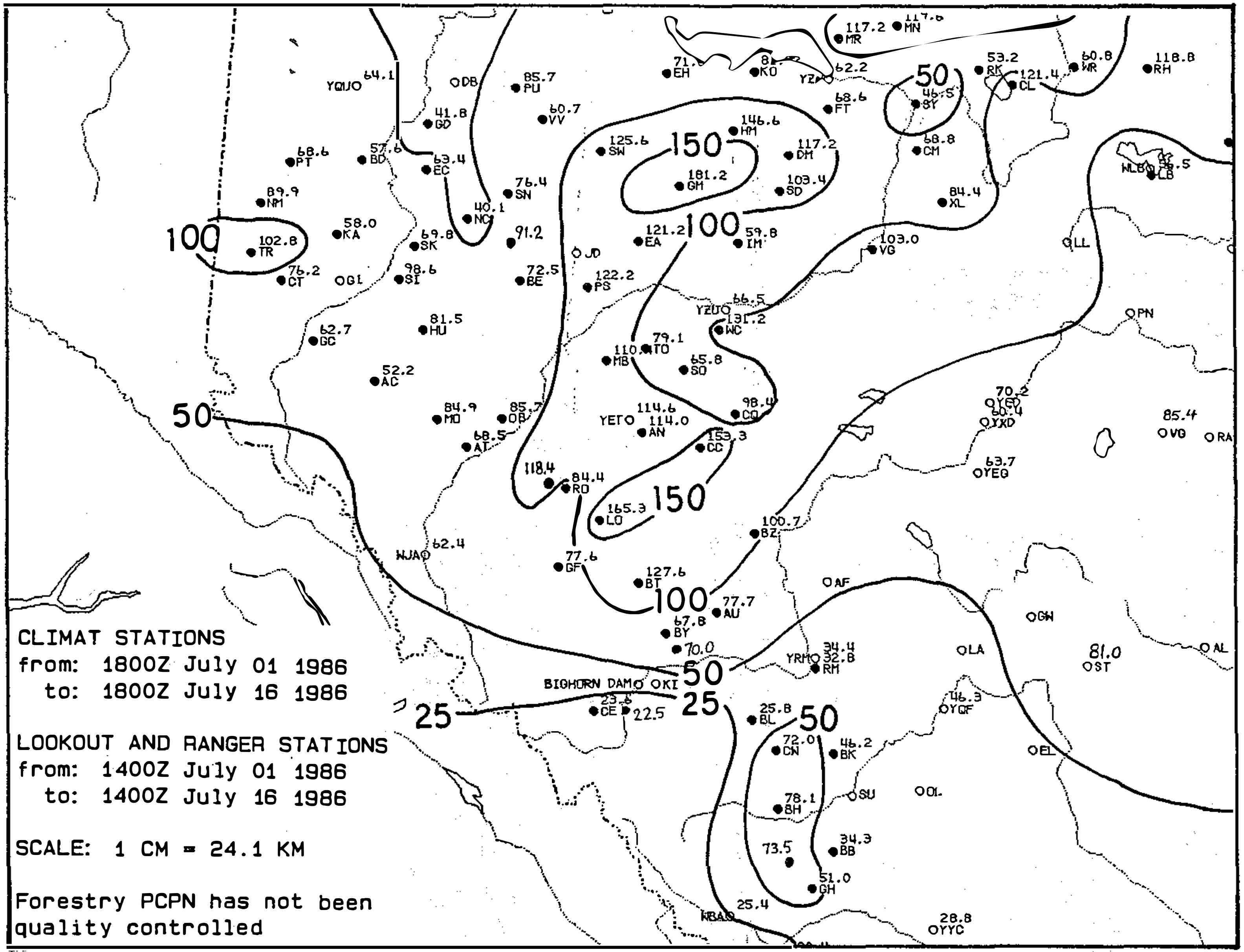

Figure 2. Precipitation amounts for west-central Alberta, July 1-16, 1986.

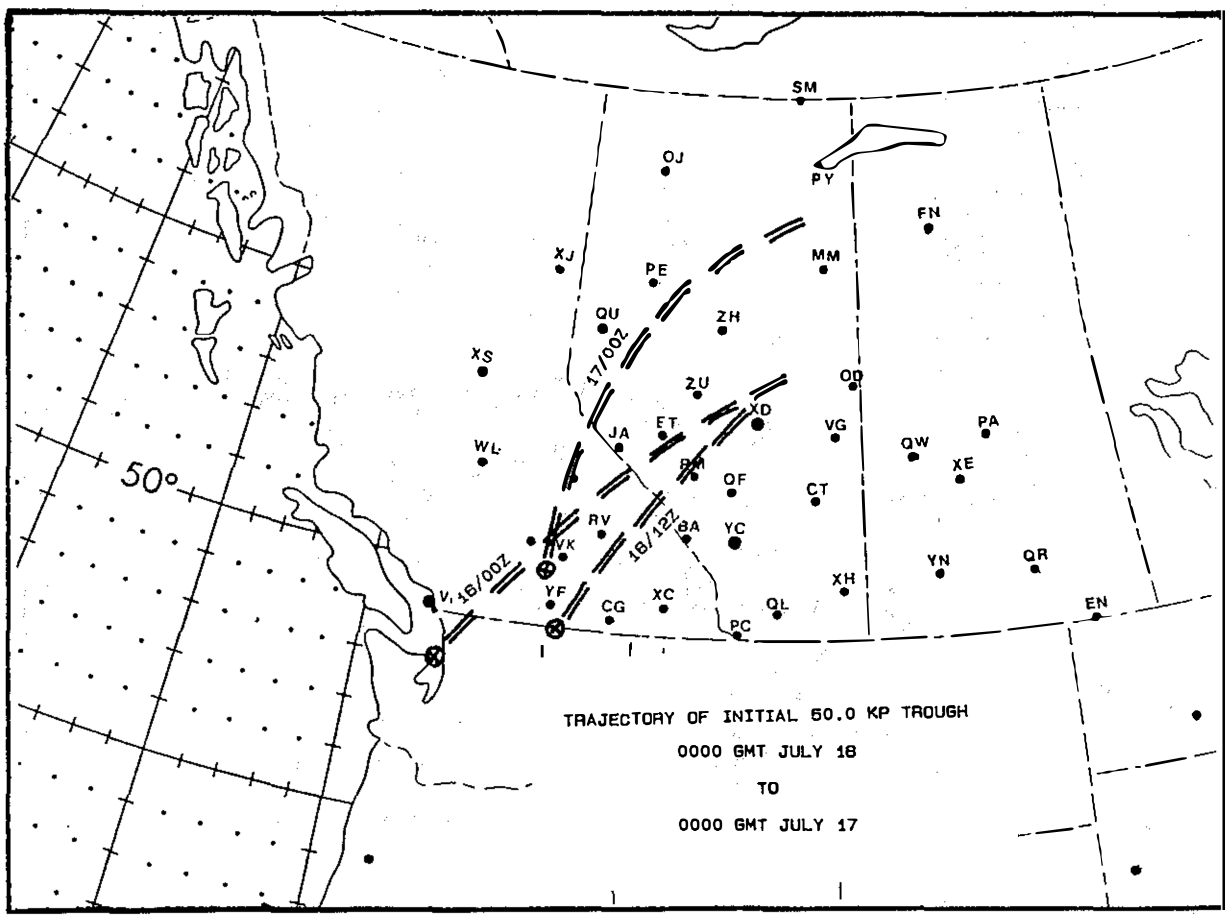

Figure 3. Trajectory of initial 50.0 kPa trough.

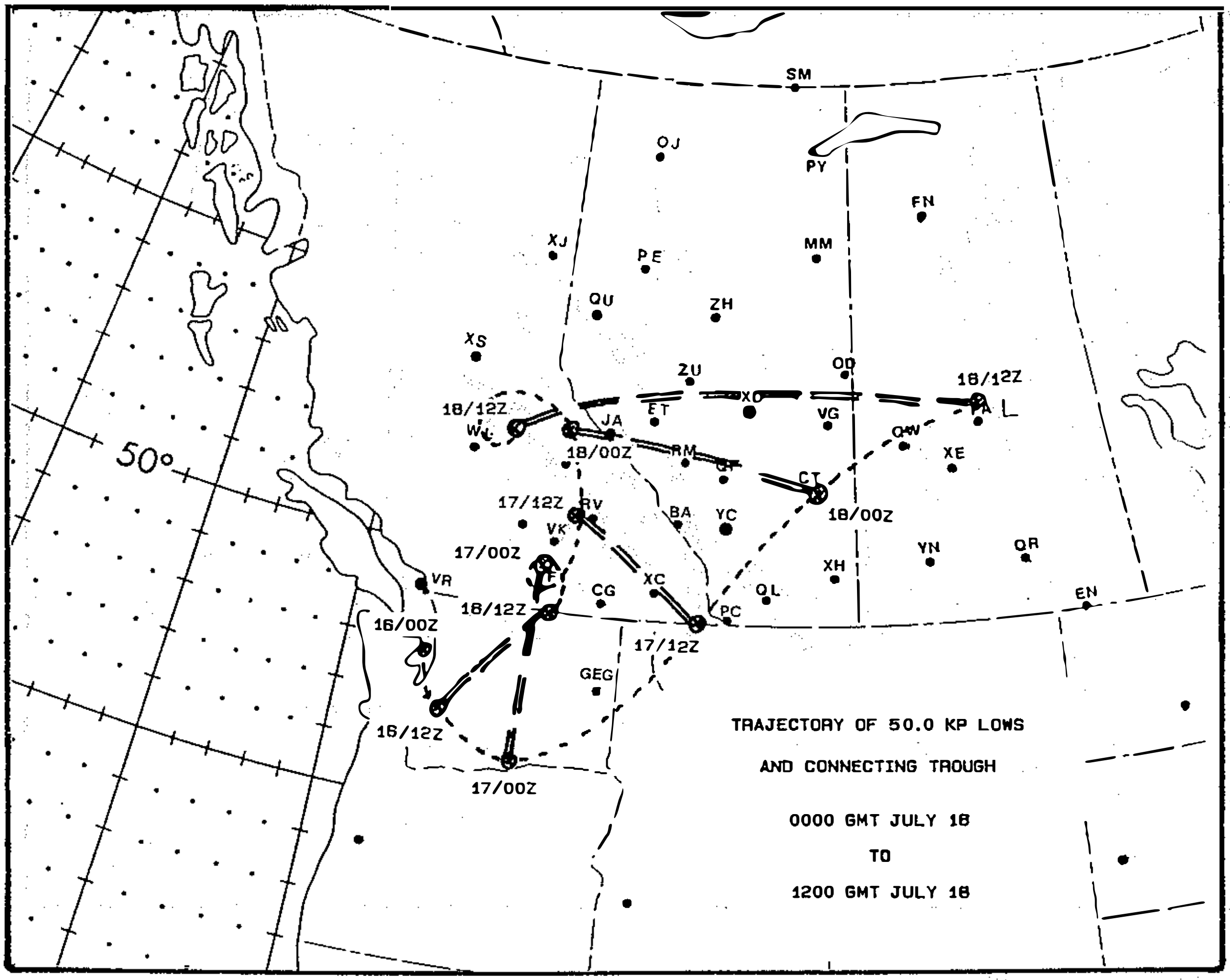

Figure 4. Trajectory of 50.0 kPa lows and connecting trough.

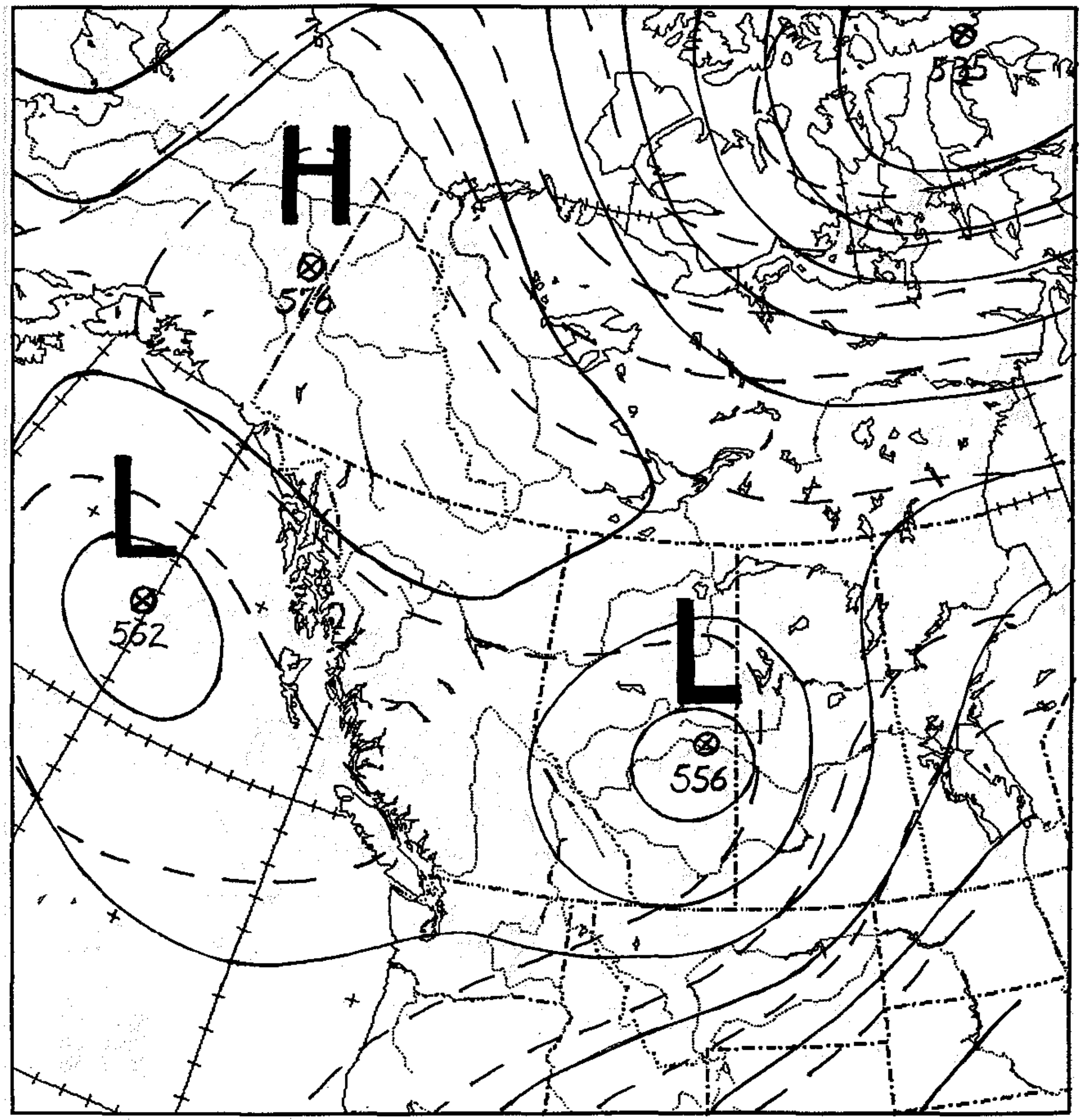

Figure 5. July 18, 1986, 500 mb analysis (heights and thickness) over Alberta.

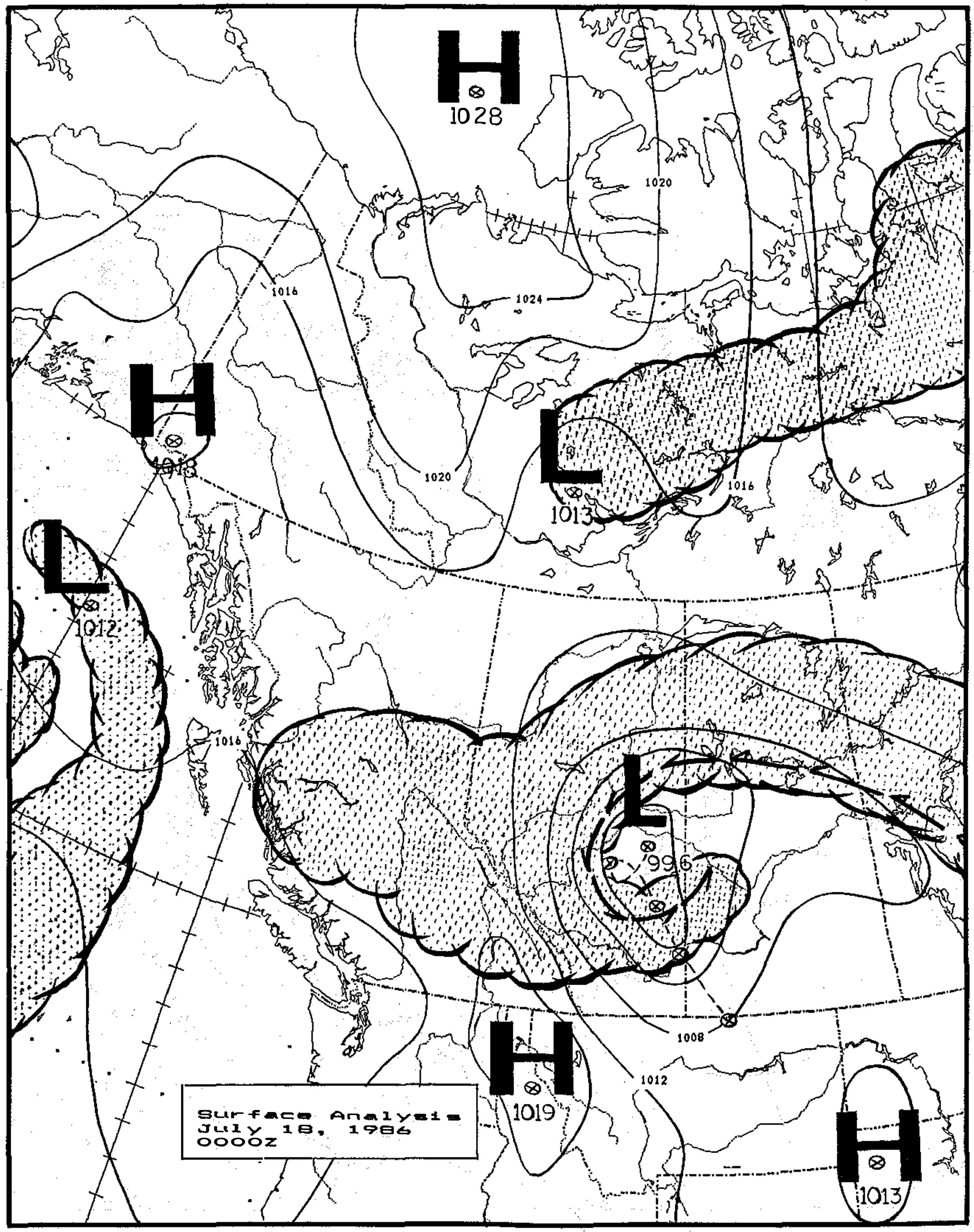

Figure 6. July 18, 1986, surface analysis of Alberta.

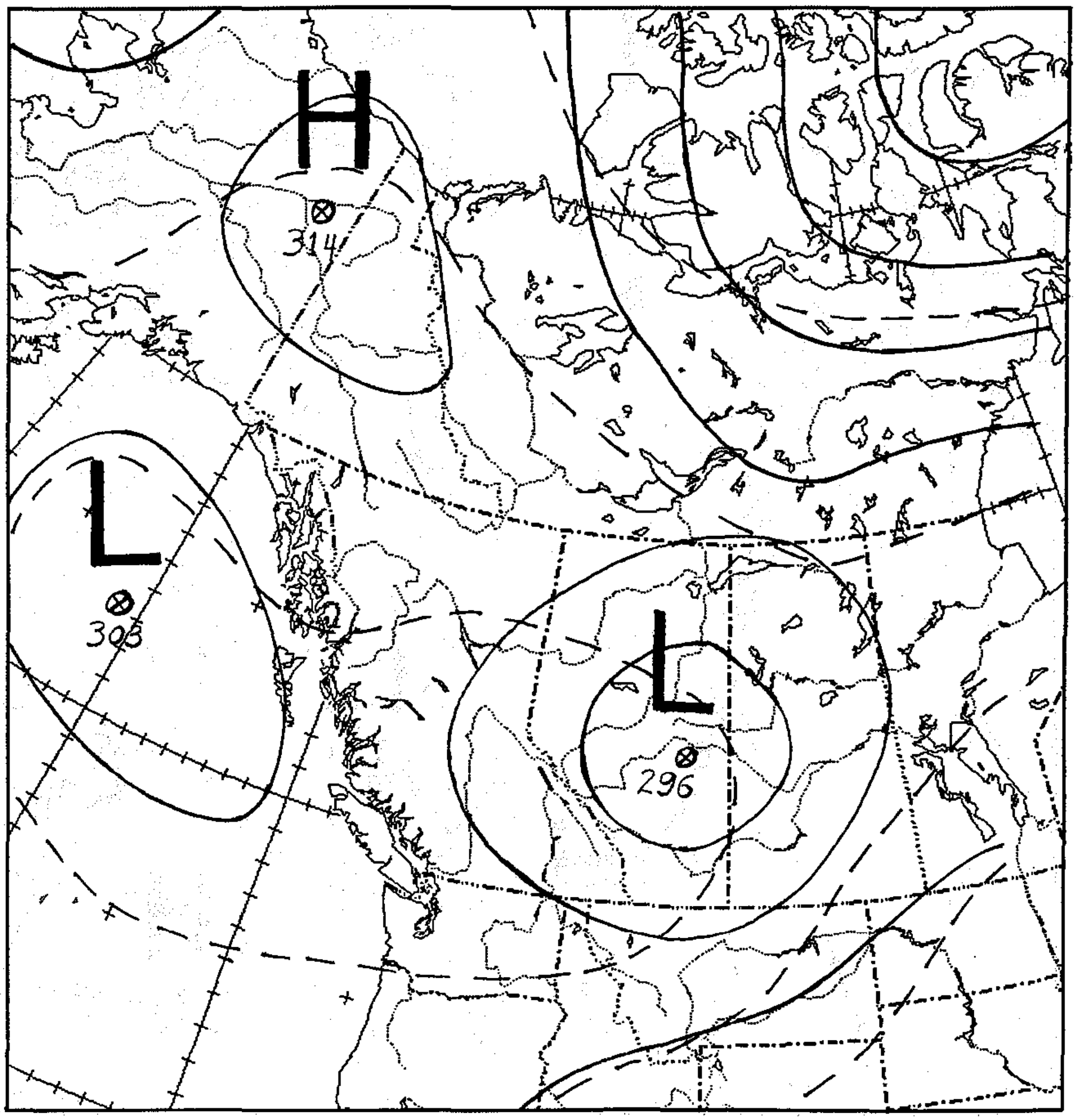

Figure 7. July 18, 1986, 700 mb analysis (heights and temperatures) over Alberta.

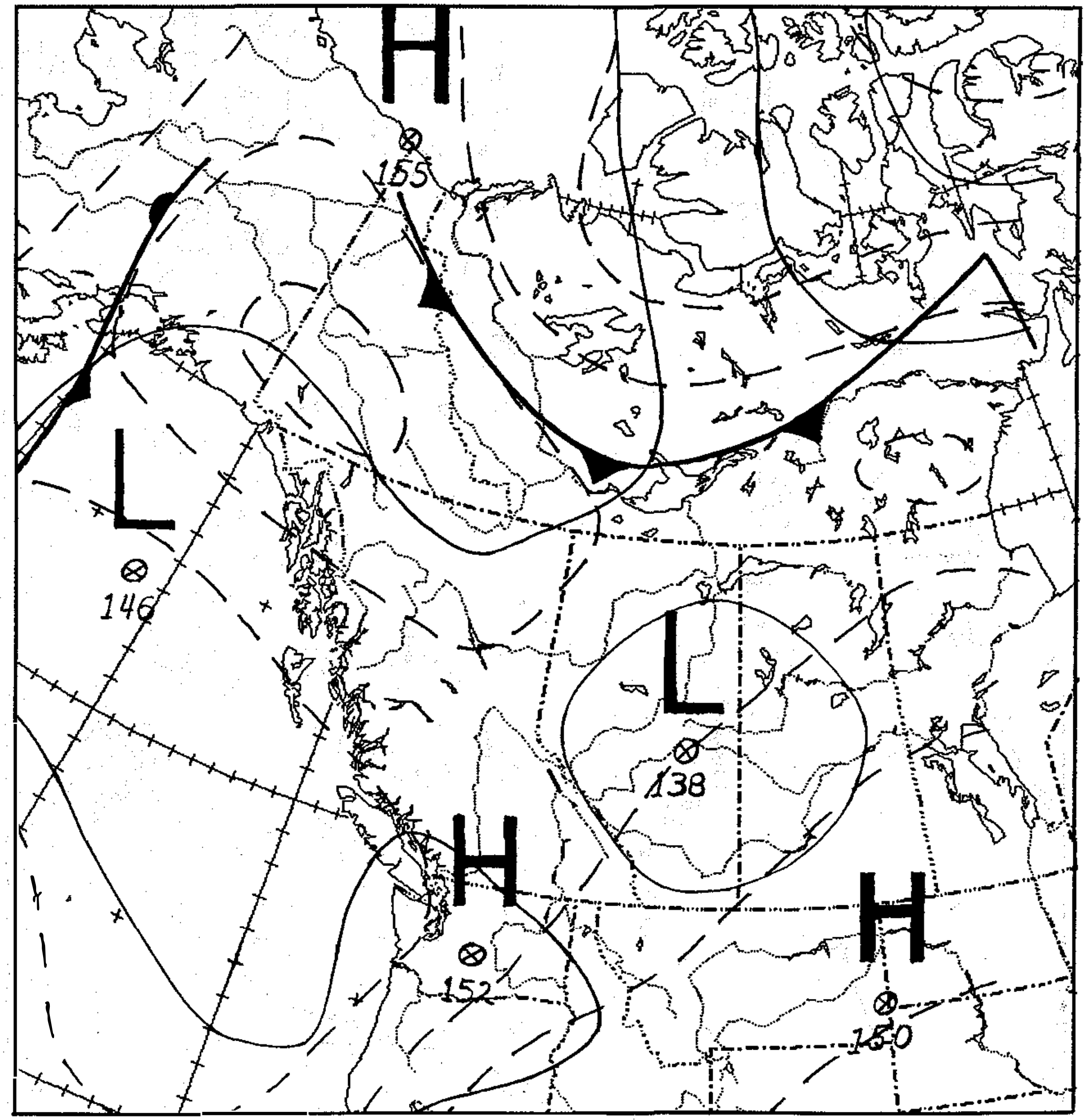

Figure 8. July 18, 1986, 850 mb analysis (heights and temperatures) over Alberta.

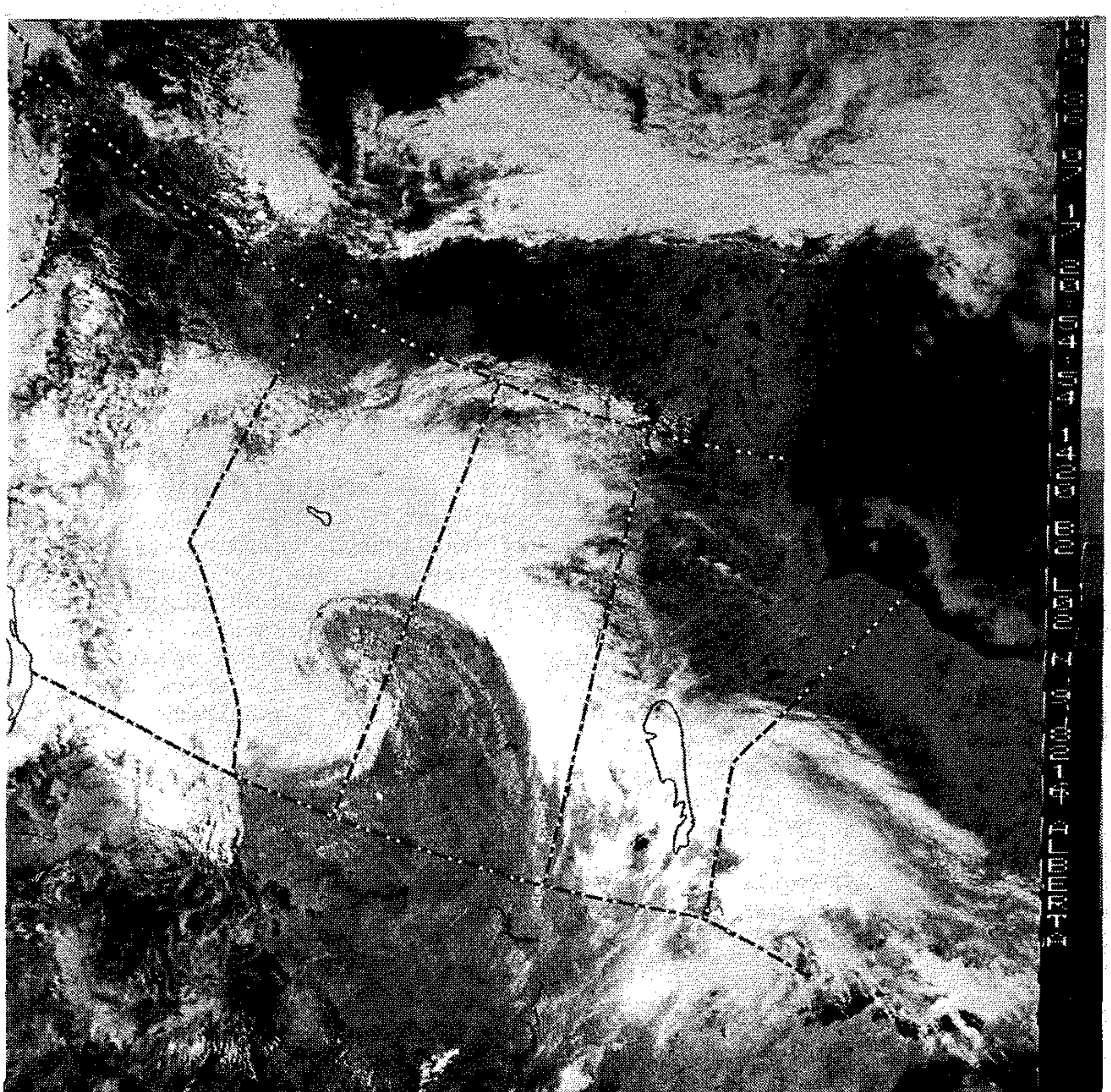

Figure 9. NOAA satellite picture taken at the height of the storm, July 17, 1986.

APPLICATIONS OF CLIMATOLOGY—THE CURRENT SASKATCHEWAN RESEARCH COUNCIL EXPERIENCE

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ABSTRACT

The applied climatological activities at the Saskatchewan Research Council (SRC) are concentrated in two main areas: 1) applications by meteorologists and climatologists and 2) advisory work to assist people of other fields in the applications. The work in the atmospheric program consists primarily of applications of climatology to the fields of agriculture, hydrology, engineering, and environmental impact assessment. The advisory work embraces a much greater variety of subjects, including crop science, engineering, law, veterinary science, biotechnology, archaeology, and recreation, for example. The SRC supplies data, provides advice on its use, and refers the user to other sources of information, if required; therefore, the SRC is involved in applied climatology of both a detailed and an advisory capacity and can provide a useful picture of activities in applied climatology.

INTRODUCTION

The Saskatchewan Research Council (SRC) has been undertaking applied climatological projects for many years now. Projects in this field continue today, and the purpose of this paper is to describe some of the more-recent projects of this long history.

The applied climatological activities at the SRC are concentrated in two main areas: 1) applications by meteorologists and climatologists and 2) advisory work to assist people of other fields in their applications.

The primary applications of climatology by meteorologists and climatologists at SRC are in the fields of agriculture, hydrology, engineering, and environmental impact assessment.

The advisory work embraces a much greater variety of subjects and disciplines, including agriculture, engineering, law, veterinary science, biotechnology, archaeology, and recreation, for example. We supply data, provide advice on its use and refer the user to other sources of information, if required.

INTENT

The purpose of this paper is to provide an overview of the recent SRC experience in the field of applied climatology. The more unique, useful, and/or interesting applications are emphasized whenever possible. This work has provided the author with many insights into the applications of climatology, several of which cannot be found in the textbooks or articles on the subject.

Thus, this information may also be of use to many other people.

APPLICATIONS BY SRC METEOROLOGISTS AND CLIMATOLOGISTS

As stated previously, the main applications are in the areas of agriculture, hydrology, engineering, and environmental impact assessment.

A common use of climate/weather data is for crop growth modeling. A joint study with the University of Saskatchewan simulated spring wheat yields for the Saskatoon crop district using the CERES wheat growth model (Fei and Ripley 1985; Ripley 1986) and daily weather data from the Saskatoon SRC Climatological Reference Station from 1960 to 1984. The comparison of the observed versus simulated wheat yields showed moderate success. The model's main weakness, overestimation in high-yield years and underestimation in low-yield years, appeared to be partly related to unsatisfactory root growth simulation.

Evaporation is a parameter that is of critical importance to plant growth. Another SRC study compared evaporation estimates based upon records from the several types of atmometers at the SRC Climatological Reference Station (Fei and Shewchuk 1986). The class A evaporation pan provided the most consistent data set from the 11 years of this study.

Another agricultural problem is that of herbicide spray drift. Herbicide spray drift trials have been conducted in joint studies with Agriculture Canada, the purpose of which was to evaluate and compare the performance of different types of sprayers. Also, a position paper on the dynamics of herbicides within the atmosphere has been prepared (Shewchuk 1987).

Considering that agriculture is quite susceptible to climatic change, the effects of climate warnings were explored. A publication with a chapter providing an estimation of the impacts of climatic change on agriculture in Saskatchewan is soon to be published (Williams et al. 1987). Impacts were estimated for climatic scenarios representing an extreme year and period of years from the instrumental record and a climate affected by doubled atmospheric carbon dioxide as simulated using global climatic model results (Goddard Institute for Space Studies Model). We believe that we have demonstrated that it is possible to make useful translations of climatic scenarios into estimates of likely effects on agricultural production, on the environment, and on the economy.

Wind erosion of soils has become an increasing concern in recent years. The 1980s have witnessed several of these black blizzards in the prairie provinces. This has led to a preliminary analysis of the temporal, spatial, and climatological aspects of dust storms in Saskatchewan (Wheaton 1985a; Wheaton and Chakravarti 1987). Dust storms have serious impacts, such as air pollution and the concurrent wind erosion of soil.

Regional and local climatic conditions influence the atmospheric dispersion of natural and anthropogenic emissions. Climatic factors such as wind speed and direction, atmospheric stability, mixing height, and frequency of ground-based inversions all contribute to the effective description of an area when air pollution processes are considered. The Saskatchewan Research Council works with government and industrial organizations to effectively develop long-term (monthly, seasonal, or annual) and short-term (hourly or daily) site-specific meteorological conditions that are considered important in the construction and operation of major industrial plants. Over the last several years SRC was a lead agency in the description of dispersion climatology for several significant projects in Saskatchewan. Much of this climatology served, in part, as input to air quality models that provide a systematic means of relating industrial source emissions to changes in ambient air quality.

Much work has concentrated on the atmospheric and climatological effects of such developments at thermoelectric and hydroelectric projects and different types of mines. The atmospheric and climatological considerations of such developments usually form one of the components in an environmental impact assessment of the project. The main topics of applied climatology coming into play here are air pollution climatology and industrial applications. One study, for example, considered the effects of a thermoelectric power plant on the atmosphere, soil, and crops in the vicinity of the plant (Shewchuk and Abouguendia 1986). Atmospheric, crop, and soil characteristics were measured during the summer for the past 4 years over an area of 10 000 km^2. This data would also be of use for other regional agrometeorological studies.

Climatology also can and should contribute to the design of structures such as dams and reservoirs (e.g., Wheaton and Whiting 1986; Whiting et al. 1986). An examination of the history of severe storms in the area provides a good basis for the sound design of a structure.

In summary, many of the climatological projects are in the field of applied climatology and often draw heavily on the relationships of climate to another sector.

ADVISORY WORK/USERS' WORK

Almost 1500 requests are fielded annually by the SRC in this area. There is a great variety in the nature of the requests, and almost any type of request can be expected. The highest frequencies of usage are by the SRC, closely followed by the 'other' category (that is, the public schools, libraries, and so on), then by the University of Saskatchewan, private business, and the federal government (Table 1).

The pool of climatic information that is used to supply the requestors with information and that is the basis of the climatic information system consists of two main portions (Fig. 1): 1) climatic records and statistics and 2) climatic studies and reports. Users initiate interaction by means of their requests to the SRC. The interaction then results in 1) satisfaction of their curiosity, 2) modification of their activities, e.g., matching of activities to the climate (as in planning for greater beer sales in a warmer area or time) and/or 3) planning of reports to be done by SRC or the requestor. The report may then become part of our climate library and may form the foundation for further work and fulfilling of more requests. This step, when undertaken, completes one of the feedback loops of the information system.

The nature of the requests range from the common to the highly unusual. The most common requests are for monthly, daily, and/or hourly temperature and precipitation information. Extremes of temperature and precipitation are also quite popular items. These requests are quite predictable, as well, occurring with high frequency at the times of extreme weather conditions.

Table 1. Types of climatic information users and their average annual frequencies, 1980 to 1984 (Wheaton 1985b)

Type of user	Average no. regular requests (on mail list)	Average no. nonregular requests	Total requests	Percentage of total
Federal government				
- Atmospheric Environment Service	26.0	24.2	50.2	3.5
- National Research Council	39.0	8.6	47.6	3.1
- Canadian Wildlife Service	13.0	0.6	13.6	1.0
- Prairie Farm Rehabilitation Administration	13.0	0.6	13.6	1.0
- Agriculture Canada	91.0	3.8	94.8	6.6
Provincial government	26.0	6.2	32.2	2.2
University of Saskatchewan	247.0	55.4	302.4	20.9
Media	13.0	11.2	24.2	1.6
Private business	221.0	12.2	233.2	16.2
Saskatchewan Research Council	294.0	31.0	325.2	22.5
Other (public, schools, libraries, foreign, etc.)	296.0	11.0	307.0	21.3
Total	1279.0	164.8	1443.8	100.0

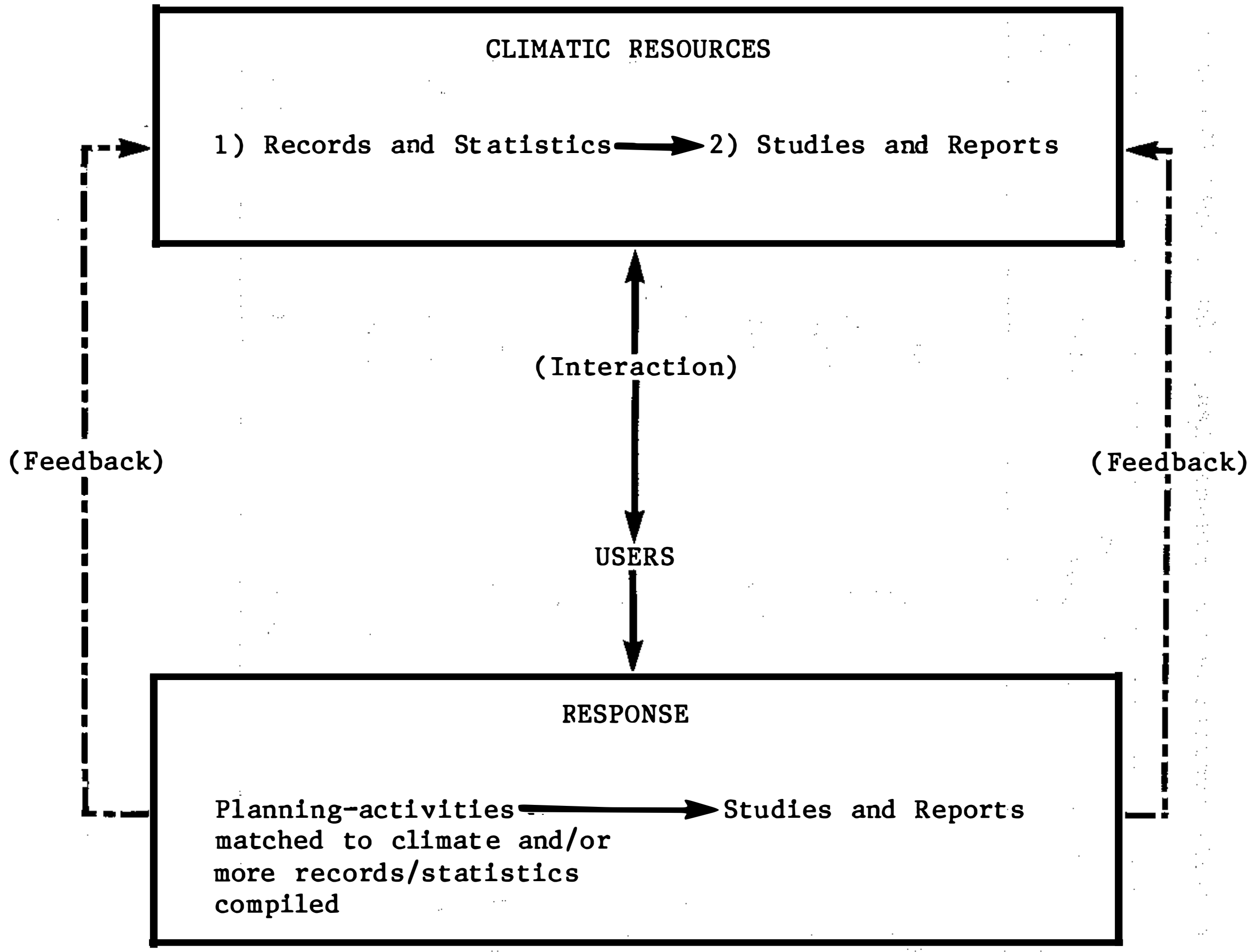

Figure 1. The Climatic Information System (Wheaton 1985b).

The requests can be grouped according to area of application: recreation, legal, education/media/conferences, engineering, wildlife, agriculture, environmental impacts, geology/geohydrology, veterinary sciences, horticulture, and miscellaneous. A few examples are provided for several fields of application in Table 2.

The more unique or interesting ones, depending on the perspective taken, are often the ones derived from simple curiosity. One request, for example, resulted in a description of the development and morphology of snow rollers. Another person was interested in the time of sunset at a small town in Saskatchewan several years ago, because he wanted to make sure the setting of one of the scenes in his novel was correct. Another unique request, to this author anyway, was for the climate of Saskatchewan in 1200 A.D. Saskatchewan Research Council archaeologists were looking for pieces in the puzzle of migration of the people living in northern Saskatchewan at that time. Another request that is possibly unique to the prairies is the use of weather and climate data to explore the causes of disease and damage to Saskatoon berries. Others that were new to this author were the use of cloudiness and bright sunshine data to explain bee's activities and the use of temperature data to help explain fish productivity. There

Table 2. Some examples of requests for climatic information

Discipline/field of application	Request	Purpose of request
Recreation	- wind speed and direction for a specific location	- to facilitate planning of a marina and breakwater
	- temperature and precipitation normals and variation	- information for a tourism booklet for locations in northern Saskatchewan
Law	- area, extent, and severity of a hailstorm	- evaluation of a hail insurance claim
	- rates of rainfall	- evaluation of flooding insurance claims
Education/media/ presentation	- tours of the climate reference station	- TV science shows, field information for class tours
	- frost season information	- winter wheat presentation at a conference
	- daily, monthly, and extremes of precipitation, temperatures, wind speed, relative humidity, and bright sunshine	- Star Phoenix readers
Engineering	- soil temperatures	- effects on pressure in gas lines and buried cables, pipeline stress calculations
	- global radiation	- for consideration of efficiency of low energy housing
	- heating degree days	- to compare with heating and ventilation costs, effectiveness of insulation
Wildlife biology	- mean annual air temperatures	- to evaluate fish productivity
	- air temperature	- to evaluate the caloric intake of falcons
Agriculture/ horticulture	- temperature extremes	- temperature tolerances of cacti in Saskatchewan
	- precipitation, growing degree days, and frost	- pasture productivity
	- daily temperature and precipitation	- relationship to cattle health problems
Geology/ geohydrology	- monthly precipitation	- to compare with groundwater levels
	- daily air temperature and wind information	- to explore the reasons for seismic traces and explosive noises

seems to be a new use of climate/ weather data every week.

CONCLUSION

Although many areas of applied climatology need further development to refine knowledge of the interrelationships, we have made some progress. It appears that users are becoming more knowledgeable about the potential use of climatology in their field of interest and will likely become increasingly sophisticated in their demands. More models do need to be developed and verified before the process can become fully operational, so we have much work to do. In conclusion, I hope to have triggered some interesting research ideas or operational areas of applied research. It was good to have the opportunity to share some of the unusual and intriguing applications of climatology with you.

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THE USE OF WEATHER RADAR TO PREDICT MICROWAVE ATTENUATION BY RAIN

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INTRODUCTION

The past few years have seen an emerging requirement to utilize microwave frequencies above 10 GHz for terrestrial radio-communication networks. Rainfall can cause significant attenuation in the received signal at these higher frequencies, and rain attenuation statistics influence system design. For a given value of the signal-fading margin with specified availability and performance objectives, limitations regarding the maximum spacing of repeater stations in a radio relay system are dictated by the rainfall climatology in the region.

Data collected by the Alberta Research Council's C-band (5-cm wavelength) weather radar at Red Deer were used in the summer of 1986 to simulate rain attenuation at an 18-GHz frequency along an 18-km microwave path operated by Alberta Government Telephones (AGT) in the Wetaskiwin area. Three tipping-bucket rain gauges were used in the vicinity of the microwave path to "ground truth" the radar-derived rainfall estimates. The relation developed by Marshall and Palmer (1948) was used to convert the radar reflectivity to rainfall intensity, and an empirical relation was chosen from the study by Zawadzki and Rogers (1972) to convert the rainfall intensity information to signal attenuation.

The purpose of this paper is to demonstrate that weather radar can provide valuable rain climatological information at high spatial and temporal resolution on an area-wide or regional basis.

DATA AND METHOD OF ANALYSIS

Radar Data

The Alberta Research Council's C-band (5-cm wavelength) weather radar is located at the Red Deer municipal airport. The characteristics of the radar are: 5.635 GHz frequency; 478 s^{-1} pulse repetition frequency; 2 µs pulse duration; 200 kw typical peak power; linear horizontal polarization; 1.5 degree circular beam width; 40 dB antenna gain; 8 rpm maximum antenna azimuth rotation rate; and a step scan antenna elevation program going from 0 to 9 degrees elevation in 1.5 min or 0 to 21 degrees elevation in 3 min. The radar reflectivity is integrated over "bins" with dimensions of 1 km range and 1° azimuth, and the data for this study were recorded onto magnetic disk for the 1.5-degree elevation scan at approximately 3-min intervals.

The AGT microwave path was 18 km long between towers located at Kavanagh (radar coordinates: 012° azimuth and 109 km range) and Huard Lake (021°, 99 km) and operated at 18-GHz frequency. At 100-km range, the height of the radar beam center is approximately 3 km above ground level and the beam cross section is approximately 1.75 km. Unfortunately, the high beam altitude meant that the melting level (0°C temperature level) was usually intersected. The mixture of water, ice, and mixed phase hydrometeors increases the uncertainty in the reflectivity versus rain-rate relation.

Rain Data

Three tipping-bucket recording rain gauges were used in support of this study. One gauge (1 mm/hr resolution) was situated near the microwave tower base at Kavanagh, and two different gauges (1 mm/h and 0.1 mm/h resolution) were set up on the roof of the AGT office building in Wetaskiwin. The accumulated rainfall per minute for each gauge was recorded on magnetic tape cassettes using a 21X Micrologger system from Campbell Scientific Inc.

An interesting result was found upon comparison of the two rain gauges at the Wetaskiwin site. The low-resolution gauge consistently recorded approximately 20% more rain than the high-resolution gauge, even though both gauges had unobstructed exposure, were level, and were separated by only 2 m. The radar-estimated rain amounts taken from the radar bins directly above the rain gauges often differed by a factor of 2 from the gauge measurement; however, much of this uncertainty is likely associated with the drifting of precipitation from the illuminated volume above during the fall to the surface. The terminal fall velocity of a typical raindrop of 1- to 2-mm diameter is approximately 4 to 6 m/s. Raindrops can, therefore, easily drift a horizontal distance of 3 km or more during their fall time, given a mean wind velocity of 4 to 6 m/s (not uncommon) within the lower 3 km of the atmosphere. Summertime convective precipitation is characterized by great spatial and temporal variability, which makes it very difficult to make point predictions. Furthermore, because of turbulence, very exposed rain gauges may have catch deficiency errors up to 50% or more (Gray 1970); therefore, it is difficult to use the rain gauge measurements as an absolute ground truth. It is estimated that the area rain amounts estimated by the radar in this study are accurate to within approximately 20% error.

Radar-estimated Rain Intensity

The empirical relation developed by Marshall and Palmer (1948) was used to convert the radar reflectivity measurements to rainfall rate:

$$Z = 200\ R^{1.6} \qquad [1]$$

where Z is the equivalent radar reflectivity factor (mm^6m^{-3}) and R is the rain rate (mm/h). Although this relation was developed in eastern Canada for summer rainfall, the Marshall-Palmer relation has been found to be a reasonable approximation for steady rain at continental midlatitudes in general.

Estimation of Attenuation

An approximate relation for attenuation at 18-GHz frequency as a function of rain rate was obtained by interpolating the results from Zawadzki and Rogers (1972), who summarized the calculations and measurements of various authors. The relation used was

$$A(P,Q) = \int 0.055R^{1.15}dr \qquad [2]$$

where A is the attenuation between path points P and Q expressed in dB, R is the rain rate (mm/h), and dr is the differential range (km).

The integrated attenuation was estimated by selecting the radar bins that were situated directly above the microwave path between Kavanagh and Huard Lake and computing an average rain rate for each bin along the path, which included the radar bins on either side of the center line. This average rain rate per bin was used to allow for some drift of the precipitation from the volume aloft to the path near the ground. For this study, no wind information was recorded at the sites; however, some wind information regarding direction and speed can be inferred from the movement of the radar echoes in the vicinity, which can be used in the interpretation of the results.

CASE STUDY: JULY 9, 1986

A radar plan-position-indicator (PPI) plot showing the storm rain-intensity structure at 00:08 (all times are Mountain Daylight Time) on the morning of July 9, 1986, is shown in Figure 1. The microwave path was situated on the northeast side of the most intense portion of the storm at this time. The storm appeared to be a mesoscale convective complex comprised of three or four convective cells, as described by Byers and Braham (1949), each cell evolving over a time period of approximately 1 h. Regions with rain rates exceeding 25 mm/h were typically less than 10 km in diameter. Maximum rain rates exceeding 50 mm/h were confined to small regions, typically only one or two bins (1 to 3 km) in extent. The individual cells moved toward the northeast at a speed of approximately 9 m/s and passed directly over the microwave path.

The radar-estimated rain accumulation directly above Wetaskiwin totaled 5.8 mm for the time period from 00:01 to 00:56, with an average rainfall rate of 6.3 mm/h. The measured rain amounts from the two rain gauges were 0.6 mm and 1.0 mm for the period 00:36 to 00:50, corresponding to rain rates of 2.3 mm/h and 4.3 mm/h, respectively. The radar-estimated rainfall at Kavanagh was only 0.7 mm, whereas the gauge measurement was 5.0 mm over the period 00:21 to 00:28, which corresponds to a rain rate of 42.8 mm/h. A close inspection of the digital radar data recorded at 00:27 shows that rain rates of 41.7 and 46.1 mm/h were estimated for radar bins located within 3 km east of Kavanagh site. Since the storm cells were moving in a northeasterly direction one can assume that either the high rain rate region had passed directly over the Kavanagh site before the radar scan was recorded or that the rain drifted horizontally 2 to 3 km during its fall from the radar illuminated volume aloft. This case study illustrates some of the difficulties associated with comparing point surface observations with radar estimates for convective storms.

The predicted attenuation as a function of time for this case study is shown in Figure 2. The maximum estimated attenuation of 22.78 dB and the trend and response of the estimated attenuation curve with time agreed reasonably well with the attenuation measured by AGT. The maximum attenuation measured by AGT was approximately 28 dB.

DISCUSSION AND CONCLUSIONS

This brief study, in many regards, was a feasibility study. The use of an approximated empirical relation to estimate the attenuation at 18-GHz frequency gave encouraging results. Maximum estimated attenuations were usually within a few decibels of the measured values when maximum rain rates along or near the path were used. Measured attenuation was generally greater than the estimated value. The relationship between specific attenuation at a given frequency and rainfall intensity depends on the microstructure of the rainfall. The rain drop number concentration, size distribution, shape, and terminal velocity as well as the temperature and pressure are all variables in determining the specific attenuation. The relations used in this study are approximations of the more complicated situation that exists in nature.

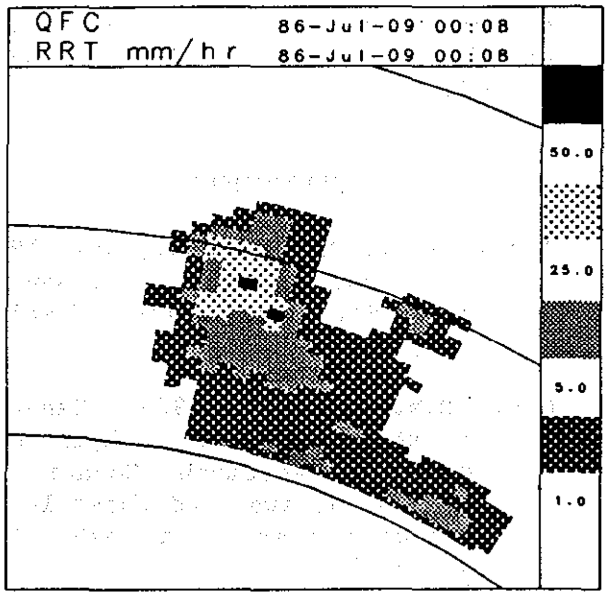

Figure 1. A map of radar-derived rainfall intensity (RRT given in mm/h) for the storm on July 9, 1986, (Case Study Number One) at 00:08 MDT near Wetaskiwin. The range ring spacing is 20 km.

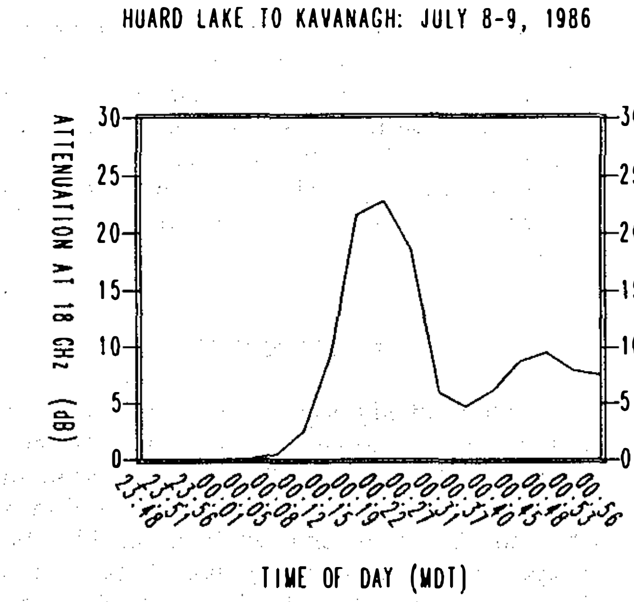

Figure 2. A plot of estimated attenuation as a function of time for Case Study Number One computed using the empirical relation given in equation 2.

Based on the analysis of four storm case studies, some preliminary conclusions can be drawn. Rainfall rates >50 mm/h are required over path lengths of approximately 5 km before significant attenuation (>20 dB fade) occurs at 18-GHz frequency. Summertime convective showers are generally the only meteorological phenomena in Alberta that produce such high rain intensities. Regions with rain rates >50 mm/h are often confined to areas less than 5 km wide; however, rainfall rates >100 mm/h in regions 1 to 5 km wide are often associated with hailstorms and severe thunderstorms. Since most summertime convective cells travel at speeds between 5 and 15 m/s, periods of significant attenuation generally pass within 5 to 15 min.

Future studies should attempt to use the Alberta Research Council's S-band (10-cm wavelength) radar, which has a 1° beam width, which illuminates a smaller volume and is able to scan closer to the ground. The S-band radar also has negligible attenuation and should provide more-accurate rain rates. Wind information would also be useful to improve the estimate of the precipitation that actually fell at a specific point on the ground.

The cumulative distribution of rain attenuation for an "average" year is needed to design a terrestrial radio-communication system. Many prediction methods are based on point rainfall intensity cumulative distributions. Variability in the point cumulative distribution from year to year is generally extremely high. In many models, the microstructure of the rainfall is assumed, on average, to be the same in every region. Radar can provide valuable information regarding the spatial and temporal structure of rainfall intensity to produce cumulative distributions of rain attenuation in much shorter time periods than can be achieved by using point ground measurements.

ACKNOWLEDGMENTS

This study was funded by Alberta Government Telephones and the Alberta Research Council. The author wishes to thank a number of key individuals at the Alberta Research Council who helped make this study possible: Bob Morris, Gary Cardinal, and Richard Anderson for maintaining the radar and recording system; Jim Mason and Rick Barlow for their efforts in collecting the rain gauge data; and Mark Johnson, Reinhard Drobig, Andrizej Krol, and Lorne Duncan for their computing support. The original organizational efforts of Dr. R.G. Humphries, Leslie Phillips, and Chris Ewing are recognized and appreciated. Finally, the discussions and contributions of Ed Reid, Les Abbott, and Craig Dobson of AGT are appreciated.

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MICROMETEOROLOGICAL RESEARCH
J.D. Wilson and J. Argete

Measurements of mean wind speed and turbulence were carried out behind two sections of 50% porous fence differing only in the vertical distribution of their porosity. One section of the fence was uniformly porous, and the other was relatively dense near the ground and open aloft. Slightly greater mean speed reduction was observed near the ground in the near lee of the section that was dense at ground level without any detrimental increase in the turbulence. This advantage was offset by less effective protection in the far lee. The numerical model, which uses a second-order turbulence closure scheme, simulates shelter flow by parameterizing the fence as a localized momentum sink.

Experiments on the modification of climate (wind, temperature, and humidity) within omnidirectional windbreaks (with a square, enclosed plot) will continue until the effects of a wide range of governing factors such as plot size versus fence height, ratio of fence height to surface roughness length, and atmospheric stability, have been examined.

OROGRAPHIC ENHANCEMENT OF SNOWFALL
C. Schneider and J.D. Wilson

A simple model that has been claimed to give useful predictions for snowfall in the Colorado Rockies is being implemented for testing in the Alberta Rockies. The model predicts mountain snowfall rate on the basis of readily available input data.

ATMOSPHERIC ICING RESEARCH
E.P. Lozowski, K.J. Finstad, K. Szilder, W.P. Zakrzewski, A. Nowak, W.W. Jiang, Y. Zhuang, R. Blackmore, and K. Johnson

E.P. Lozowski is completing a review and synthesis of atmospheric icing models. K. Finstad has developed an operational time-icing model for cylinders and airfoils. K. Szilder has designed a new, time-dependent model for cylinder icing that takes into account the effects of internal heat conduction. He is also investigating the overall heat transfer coefficient of rough cylinders. W.P. Zakrzewski is investigating the accretion of ice on fishing vessels by modeling the splashing effects of wave-generated, freezing spray.

A. Nowak has completed experiments in marine ice accretion using a small outdoor wind tunnel. It appears that icicle formation and sponginess may be the reasons for enhanced growth when brine sprays are used in place of fresh water. In view of this result, K. Johnson is carrying out modeling and experimental investigations of icicle growth, and R. Blackmore is making calorimetric studies of sponginess in accreted ice. Y. Zhuang is applying Monte Carlo methods to a modeling study of the diffusion of spray droplets in the marine boundary layer, with the aim of predicting the variation of the liquid content with height. Ms. W. Jiang is taking many of these results and incorporating them into a model of ice accretion on offshore drilling platforms.

SYNOPTIC AND MESOSCALE METEOROLOGY

G. Strong, E. Chan, D. Ball, C. Doyle, C. Nguyen, C. Sackiw, and E.R. Reinelt

G. Strong has completed a dissertation on the synoptic-mesoscale interaction and dynamics of severe convection storms. E. Chan is investigating the effects of the sea-surface temperatures of the 1981-82 El Nino, which have been simulated in the Atmosphere Environment Service's General Circulation Model.

D. Ball is studying the distribution and frequency of cloud patterns associated with fronts and cyclonic systems. Using digitized satellite images, he is deriving histograms pertinent to the climatology of cloud cover in western Canada.

C. Doyle is investigating various aspects of the hydrometeorology of ice jams in northern rivers. In particular, he has obtained interesting data sets for the Athabasca, Peace, and Hay rivers.

C. Nguyen is analyzing the causes of a heavy spring snowstorm in Calgary and the evolution of the weather patterns responsible for the extensive flooding in the Edmonton district in July. He has compiled comprehensive data sets by integrating and correlating satellite, radar, and surface observations.

C. Sackiw has completed a study on the cohesiveness of upper-air soundings in space and time. The results of this study will help in the design of an upper-air network capable of detecting and tracking atmospheric systems on a scale of a few kilometres.

E. Reinelt worked on synoptic climatology of upper-air parameters relevant to the incidence and control of forest fires. A catalogue of vertical wind and temperature profiles is being compiled for specific sites within the boreal forests of northwestern Canada.

ENVIRONMENTAL STUDIES AND RADAR METEOROLOGY

R.B. Charlton, F. Hopper, K. Al-Jumily, and D. Yiu

R. Charlton has written a textbook, currently in the form of 285 photocopied pages, that is being used by 75 students in Meteorology 307, an introductory course at the University of Alberta.

F. Hopper has completed an interesting study on the composition of Arctic haze. Hopper's related work on urban visibilities at low temperatures was recently published in *Atmospheric Environment*.

Working with the Weather Radar group, K. Al-Jumily has found that the correlation between two circularly polarized components of the radar echo is a better indicator of the presence of hail than previously believed.

D. Yiu is studying the relationship between in-cloud measurements of raindrop and ice-particle size distributions and simultaneously received radar echoes. This work concentrates on the differences between showers and continuous precipitation.

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Climatological research at the University of Calgary is conducted primarily in the departments of Geography and Physics. Some scientists in the Faculty of Environmental Design also engage in studies with a fair amount of climatological content. What follows is a partial list of persons involved in climatological research and their interest.

Dr. Mario Giovinetto (Geography): Short-term research is on atmospheric water vapor transport in the southern hemisphere. In the long term, he is involved in research on air-ocean interaction and Antarctic ice-sheet mass balance.

Dr. S.A. Harris (Geography): Dr. Harris is a geomorphologist with a wide ranging interest in applied climatology. He is investigating the distribution of permafrost in Alberta, the Yukon, and British Columbia. He is also working on thermal regimes and origins of various permafrost landforms in the western Canadian Rockies.

Dr. A.W. Harrison (Physics): Atmospheric radiation is his main interest. He is attempting to operationalize the use of radiometers for detecting and estimating cloud cover. Dr. Harrison maintains a continuing interest in atmospheric pollution and haze. Dr. C.A. Coombes (Physics) is also involved in radiation research.

Mr. Robert Hudson (Geography): He developed a model for the estimation of groundwater contribution to storm runoff in the Marmot Creek basin. He is also interested in modeling of storm flow.

Ms. Pamela MacQuarrie (Geography): Ms. MacQuarrie's research is on the soil moisture budget in irrigated wheat fields in Brooks. She is primarily concerned with the adequacy of moisture supplied through irrigation for optimal crop development.

Dr. Titus Mathews (Physics): He studies mesoscale features of Chinooks including gravity and hydrostatic waves. Dr. Mathews' research team includes Peter Lester and R.B. Hicks.

Dr. Lawrence C. Nkemdirim (Geography): Urban effects on climate continues to be the major focus. He is currently investigating micrometeorological processes near the ground during a Chinook.

The Institute of Humanities is holding a 3-day international symposium entitled "Civilization and Rapid Climate Change," on August 21-24, 1987. Dr. Harold Coward is organizing the conference.

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SCIENTIFIC SERVICES DIVISION

The following special reports, climatological studies, and activities were undertaken by Scientific Services personnel in the Western Region:

86-2 The effect of arctic haze on northern climate
86-3 Climate networks in the Territories: Policy and standards
86-4 Spring snowstorm: May 13-15, 1986
86-5 Foothills rainstorm: September 12, 1985
87-1 Ice thickness climatology for northern Canada
87-2 Rainfall extremes analysis
87-3 Breakup of Beaufort sea landfast ice (draft)

Climate of Wood Buffalo Park - completed
Winter Olympic Corridor climatology - completed
Climate of Calgary - in press
Climate of Yukon - in press
Station Climate Digest - under preparation for the following cities: Grande Prairie, Lethbridge, Medicine Hat, Fort McMurray, and Whitehorse

CO-OPERATIVE PROJECTS

The Alberta Agrometeorology Advisory Committee has completed a 2-year study to develop a new climate rating system for arable land in Alberta. A draft report was prepared.

A study of the frequency, dynamics, and impacts of Chinooks in southern Alberta is underway. This project is headed by the University of Calgary in cooperation with AES, San Jose State College, and the Alberta Research Council.

The Alberta Climate Advisory Committee will be holding a climate change workshop in September 1987. The dynamics and impact of climate change will be examined.

OTHER ACTIVITIES BY AES PERSONNEL

- Olympic data-logger data processed and stored in nonstandard hourly data format in AS/9.

- Automatic weather stations established at Pelly Island, Herschel Island, Cape Bathurst, and Sachs Harbour.

- Canadian Air and Precipitation-Monitoring Network (CAPMoN) station commissioned and put into operation at Esther, Alberta.

- Unpublished report prepared for Emergency Preparedness Canada on the flooding of mid-July 1986.

Atmospheric Environment Service Climatological Network additions, deletions, and program changes during 1986.

Stations	Latitude	Longitude	Date	Program[a]
New				
Cameron Coulee	50°39'	114°02'	86/06/11	P
Maisie Mae	63°17'	138°47'	86/05/01	TP
Florann	49°16'	111°24'	86/07/08	P
Pennance Tower	58°23'	113°09'	86/06/01	TP
Whitesand Tower	59°40'	115°12'	86/06/01	TP
Sunnydale	64°03'	139°28'	86/07/29	TP
Rancheria[b]	60°07'	130°41'	86/06/24	P
Athabasca 1	54°43'	113°17'	86/07/24	P
Ellscott	54°29'	112°57'	86/07/24	TP
Miette Hot Springs	53°08'	117°46'	86/08/12	TP
McQuesten	63°31'	137°26'	86/10/13	TP
U of A Metabolic Center	53°31'	113°32'	86/10/22	TP
Closed				
Bragg Creek West	50°58'	114°37'	86/05/22	P
Program changes				
Ricinus	52°05'	115°00'	86/05/28	P to TP
Kananaski Pocaterra	50°42'	115°07'	86/05/22	TPW to TP
Florann	49°16'	111°24'	86/10/09	P to TP
Cameron Coulee	50°39'	114°02'	86/10/09	P to TP

[a] P = precipitation; T = temperature; W = wind.
[b] Storage gauge.

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The Water Resources Branch is made up of two divisions: the Water Survey of Canada (WSC) and the Hydrology Division. The WSC is the agency responsible for collecting, archiving, and distributing water quantity data from a nationwide network of more than 3000 gauging sites. This data consists primarily of river and stream discharge but also includes flow velocities, widths, depths, water level fluctuation in rivers and lakes, sediment transport, and less consistently more general data such as water temperature and ice thickness. The Hydrology Division conducts analytical and interpretive studies designed to complement the basic data collection activities of the WSC.

Current work in progress by the Hydrology Division within Alberta includes the following:

a) McLeod River Basin Modeling by application of the Tank Model,

b) an investigation of Alberta lake level fluctuations,

c) peak discharge determinations by indirect means,

d) computation of natural flow data for regulated streams such as the Milk River, and

e) N-day low flow duration and frequency analyses for selected streams in Alberta.

Water Survey of Canada data is available free upon request and may be obtained by contacting any of the regional offices in Vancouver, Calgary, Regina, Winnipeg, Guelph, Longueuil, Dartmouth, or Yellowknife.

Teja Singh
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Climate research activities at the Northern Forestry Centre focused on three projects during the year: climate of wetlands and the boreal forest, forest hydrology and microclimate, and research related to fire weather and environment.

RESEARCH ON CLIMATE OF WETLANDS AND THE BOREAL FOREST

Wetlands are widely distributed across the prairie provinces and other parts of Canada. The study of peatland dynamics and environment were continued during the year. A map of the wetlands regions of Canada has been published. A map and report on the ecoclimatic regions of Canada has been finalized and submitted for publication to Lands Directorate. A publication on improving Canada's wetlands for forestry will be published this summer. A symposium on the wetlands of Canada will be held in Edmonton, August 24-28, 1987.

As a major timber source, the boreal forest and its climate are of considerable importance to Canada. The effects of microclimate on the growth of trees and of climatic extremes on regeneration in harvested areas are of particular significance. A journal paper on climatic trends in the three major subregions of the boreal forest in western Canada was published in *Climatic Change*. Microclimatic data collected by the Canadian Forestry Service near Hinton, Alberta, were analyzed, and a paper is being prepared for publication in *Forestry Chronicle*. Work is also starting on a contract from the Canadian Climate Centre, entitled "Assessment of the implications of climatic change for boreal forests and the forest industry in the prairie provinces and Northwest Territories," in cooperation with the Saskatchewan Research Council and University of Saskatchewan.

The three experimental areas (Goose River, McLennan, and Wolf Creek) established during 1985 for wetland drainage research provided data on ground and air temperatures during the year. The ground temperature readings were at the soil-air interface and at depths of 7.5, 15, 30, 45, and 100 cm. Approximately half of each area is drained, and the remainder serves as a control. A weather station consisting of one Belfort recording hygrothermograph, for measuring air temperature, and one Belfort universal recording precipitation gauge were operative in each experimental area during 1986.

MICROCLIMATE RESEARCH RELATED TO FOREST HYDROLOGY

A study was conducted during the winter of 1986-87 to characterize aerodynamic properties of a juvenile stand of lodgepole pine. The aim of this research was to determine the time required for aerodynamic closure of a clear-cut through regrowth of planted lodgepole pine. This study has relevance to areas of the Alberta foothills where dry air and strong winter winds can evaporate significant amounts of snow.

In the field study, measurements were taken on wind speed, air temperature, relative humidity, and evaporation from snow pans in the open field and within the experimental stand. The study indicated that the snow evaporation in the stand was one-half to one-fifth of that in the open field. Detailed analysis of data is expected to provide an aerodynamic resistance parameter that could be related to stand height and density values. Further research will be needed to apply the results obtained from the artificial stand to natural stands.

FOREST FIRE RESEARCH

The joint CFS-AFS experimental burning project in the lowland black spruce fuel type of north-central Alberta was continued during the 1986 fire season. Three experimental fires were successfully conducted and documented in spite of the above normal precipitation in July. The proceedings of two fire weather seminars held in 1986 were produced. A paper coauthored by the AFS weather section on the 1980 and 1981 fire seasons in northern Alberta was published. A paper dealing with the adaptation of the Canadian Forest Fire Danger Rating System in Alberta was prepared for an international conference.

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In 1986, the Alberta Regional Division of the Prairie Farm Rehabilitation Administration (PFRA) continued with its long-range effort to improve its drought forecasting capabilities based on the extant scientific knowledge of solar radiation cycles, the El Nino phenomenon, and other probable contributing factors.

In the 1985 Alberta Water Sourcing Study (Phase I) report, PFRA recommended that hydrologists, water resource managers, agronomists, and climate scientists work together to determine how to effectively use the knowledge being accumulated on droughts to formulate and implement water resources strategies that will make our prairie agriculture less vulnerable to recurring drought. To achieve this objective, PFRA has encouraged the Hydrology Institute in Saskatoon to undertake appropriate prairie drought research. Also, PFRA staff involved in various hydrologic and design studies were briefed on the implications of climate change as it relates to water resources and soil conservation on the Canadian prairies.

Draft terms of reference have been prepared for a proposed study to assess the impact of climate change on PFRA water development programs.

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INTRODUCTION

In 1986, the main activity of the Atmospheric Sciences Department was the completion of the 5-year weather modification research project final report. The objectives of the 5-year research project were to develop weather management capabilities in hail suppression and precipitation augmentation to assist in the economic development of the province. In addition to the weather modification work, research activities through contract work were conducted in weather satellite applications, hydrometeorology, air pollution, crop yield modeling, and artificial intelligence forecast systems development.

The results of the program have been summarized in a final report to Alberta Agriculture submitted in early November of 1986, and the report is available from the Alberta Research Council. Some of the results from the study are as follows:

1. Research based on analysis of crop damage suggests a decrease of about 20% in the loss-to-risk ratio; however, this decrease cannot be statistically shown to be attributable to cloud seeding only.

2. Research also indicates that towering cumulus clouds can be made to rain by seeding, even when such clouds would not rain naturally. This is significant because towering cumulus clouds are just as prevalent in drought periods as they are in periods of normal rainfall. It was estimated that in southeastern Alberta, the rainfall in the growing season could be increased by 10% by seeding towering cumulus clouds.

3. Limited observations of snow clouds over the Rocky Mountains in southern Alberta indicated that a potential exists for increasing mountain snowpack for water supply augmentation.

4. Economic benefit-cost analysis has indicated that the capital and operating costs of a cloud seeding program in Alberta would be recovered if annual crop losses were reduced by about 5%. Given experimental evidence to date, this is a realistic goal.

In November 1986, the weather modification research program was canceled by Alberta Agriculture. This cancellation has had impacts on the Atmospheric Sciences Department and has resulted in further reductions in staff. About a dozen people of the previous department's staff will remain, and the department will still maintain some capabilities in a majority of the disciplines involved in weather modification research. In April 1987, it is anticipated that two departments (Atmospheric Sciences and Civil Engineering) of the Natural Resources Division of the Alberta Research Council will combine to form a new department, the name of which has not yet been finalized. The direction and goals of this new department are in the process of being developed.

ACTIVITIES

Field Project and Precipitation Network

A substantially reduced departmental budget for 1986-87 resulted in a reduction of staff and the elimination of field work during the summer period, including operational seeding. The network of about 700 volunteer precipitation stations, maintained since 1975, continued because of the minimal cost of its operations. The radars were not operated except for limited contract case studies.

Brown Haze

A preliminary project of urban aerosol effects on visibility and the design of a monitoring protocol for the Calgary area was completed for Alberta Environment.

Radar Studies and Computing Facilities

A pilot project on accessing and processing radar data from the AES Carvel and Vulcan radar sites was completed for Alberta Environment. In addition, a study to provide Alberta Government Telephones with radar-derived rainfall rates along a telecommunications path was completed. Development continues into the means of predicting damaging lightning flashes using radar information.

Mesoscale Forecasting Studies

Studies of the mesoscale reactions of the atmosphere to approaching synoptic weather systems has confirmed the existence of preferred regions for convective storm development induced by the larger scale weather systems. Studies are continuing to improve convective weather forecasting.

Greek Weather Modification Program

A number of Atmospheric Sciences Department staff assisted Intera Technologies Ltd. of Calgary in the weather modification program in Greece.

New Research Initiatives

Proposals for studies of wind shear, microburst, and other aviation hazards are under development. A project for the U.S. Federal Aviation Administration for provision of aircraft icing parameters has been initiated. A joint proposal with MacDonald Dettwiler Associates for development of an artificial intelligence forecasting system is expected to be approved for funding by AES. A test project for monitoring Arctic haze has been initiated with the Government of the Northwest Territories.

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P. Dzikowski
Conservation and Development Branch
Alberta Agriculture
Edmonton, Alberta

The Agricultural Weather Resource Specialist position in the Conservation and Development Branch was filled in September 1986, by Peter Dzikowski.

The climate-related activities of Alberta Agriculture are service oriented and are intended to provide a wider distribution of available information and climatic data analysis for agricultural applications.

The Brooks Horticultural Research Centre is the only provincial agricultural agency operating a full-time climate station. Weather data collection by Alberta Agriculture is typically short-term and project specific. There is growing interest and awareness of the requirement for weather monitoring at agricultural trials and research projects. The department is a user, not a supplier, of weather and climate data.

Alberta Agriculture continues the following projects with a weather or climate component.

a) Farm Weather Line is a cooperative project with AES that provides farmers with direct access to up-to-date recorded agricultural weather forecasts at four locations: Lethbridge, Calgary, Edmonton, and Grande Prairie.

b) Land Capability Classification for Alberta Agriculture is a project nearing completion that has a significant climate component.

c) An agriculture weather summary is issued regularly throughout the growing season.

d) A map of estimated soil moisture reserves on medium textured soils with stubble is issued in the fall.

e) There is ongoing evaluation of snow-trapping techniques to enhance soil moisture reserves.

f) There are a variety of projects related to irrigation that include on-farm irrigation scheduling, an irrigation district model for determining water supply requirements, and the evaluation of wind mills for pumping water.

David R. Graham
River Forecast Centre
Alberta Environment
Edmonton, Alberta

No new climatological stations were added to Alberta Environment's real-time meteorological network in 1986.

Because of budgetary considerations, Alberta Environment will no longer be compiling precipitation and temperature data from Alberta Environment's real-time meteorological network in the standard AES format. It will therefore no longer be sent to Downsview for public access; however, the Fisher and Porter 15-minute punch tapes are still being processed and published at AES in Downsview.

Cost-cutting measures have also led the River Forecast Centre to discontinue their involvement in the Penhold Radar Project. On a positive note, the snow cover area project, which uses NOAA (National Oceanic and Atmospheric Administration) satellite imagery to compute the percent snow cover for the upper Bow River watershed will continue for the 1987 season.

PUBLICATIONS

Water Supply Review and Snow Survey Summary, 1985-86. River Forecast Centre, Alberta Environ., Edmonton, Alberta.

B. Janz
Forest Protection Branch
Alberta Forest Service
Edmonton, Alberta

The Forest Protection Branch continues to gather weather data for real-time fire danger evaluation. A spin-off is the climatological data base that these observations provide.

In addition to the regular climatological elements observed as shown in Table 1 (max/min/precip), all of our stations measure relative humidity and wind (twice daily at lookouts (LOs) and once daily at other stations). We have the capability of hourly weather observations at all RAWS and FTS stations.

Anticipated Changes for 1987:

- a number of LOs may close or operate only during high fire-danger periods.

- no change in the number of RS stations is anticipated.

- RAWS--there will be no change, but one is being relocated.

- FTS telemetry type stations--we hope to have 10 operating by the end of the fire season.

FUTURE OUTLOOK

A detection study is currently underway to evaluate the detection efficiency of the forestry lookouts. As a result, some LO stations may be closed, others may be relocated, and others may operate only during high fire-danger periods. The impact on the climatological data base will be negative in that the continuity of climatological data may be interrupted or stations will be closed permanently.

There is some reorganization taking place that may affect some of

Table 1. Alberta Forest Service summary of climatological information, 1986

Type of station[a]	Number	Period of observation	Elements observed	AES archiving
LO	133	Fire season[b]	Max/min/precip	Yes
RS	14[c]	All year	Max/min/precip	Yes
RS	26	Fire season	Max/min/precip	Yes
RAWS (telemetry)	5	Fire season	Max/min/precip	No
FTS (telemetry)	1	Fire season	Max/min/precip	No

[a] LO = Lookout; RS = Ranger station; FTS = Forest technology system; RAWS = Remote automatic weather station.
[b] Fire season is normally April 1 to October 31. Lookout stations normally operate for 4-5 months during this period.
[c] Winter observations jointly funded by AES and AFS.

the ranger districts. This may result in stations being closed or the continuity of observations broken.

THE LIGHTNING, LOCATION, AND PROTECTION (LLP) SYSTEM

Our lightning data are being analyzed by Transalta Utilities to produce annual lightning maps for the province. These maps do not have a great deal of significance on a yearly basis. The first few years will also suffer from weaknesses in lightning detection efficiency and location of direction finders; however, once we have 5 years of data to generate a cumulative map we will have a product that is meaningful in terms of the lightning climatology of the province.

Two new direction finders are being added this year: one by AES and one by Transalta Utilities.

INVESTIGATIONS RELATING TO CLIMATOLOGY

1. At our RAWS station we measure both the 10 and 1 minute wind means. We have found very little difference between these measurements. In general, the errors due to anemometer exposure are greater than the errors introduced by taking the 1 minute mean rather than the 10 minute mean.

2. In cooperation with the University of Alberta we compared the performance of Stevenson screens with the traditional double asbestos roof, and we compared a screen of the same dimensions with a double crezon plywood roof. Our conclusion was that the error introduced by the crezon plywood was less than the error in reading the maximum or minimum thermometer. Our screens will be constructed with a crezon plywood roof in the future.

Allen Nip
Forest Research Branch
Alberta Forest Service
Spruce Grove, Alberta

TRI-CREEKS EXPERIMENTAL WATERSHED PROJECT

The Forest Research Branch completed its collection of climatic data on December 30, 1986. Precipitation, air temperature, and relative humidity data have been collected for the past 20 years. A report entitled *Climate of Tri-Creeks experimental watershed* is in the final stage of preparation.

An additional study involves the determination of snow accumulated in the cut block as compared to the adjacent forest. A report of the results of this study will be available in the summer of 1987.

The precipitation gauges in Tri-Creeks will no longer be monitored except those operated by AES (Fisher-Porter precipitation gauge) and by the Fire Protection Branch of AFS (maximum of 2 sacramento gauges). All other instrumentation (hygrothermographs and wind and solar radiation sensors) have been removed from the basin.

I.S. Selirio
Alberta Hail and Crop Insurance Corporation
Lacombe, Alberta

FORAGE RESEARCH UPDATE

In 1986, a research project to quantify the effect of soil moisture on growth and development of forage crops continued, following essentially the same treatments and procedures carried out in 1985. Weekly harvest of all the plots to determine growth were made together with weekly determination of soil moisture. In 1987, we expect to continue final trials at Brooks on plots seeded in 1984 and in Lacombe on plots seeded in 1984 and 1985. After the 1987 season, data from all the trials over the years will be analyzed.

LIVESTOCK FEED SECURITY PROGRAM (HAY AND PASTURE CROPS)

The weather-based insurance program for hay crops was modified in 1986 to allow producers to insure either their hay crops or their livestock feed requirements. The program covered all areas south of and including the Municipal District of Clearwater and the counties of Wetaskiwin, Camrose, Beaver, Minburn, and Vermilion River.

In 1986, 4842 producers participated in the program and reported daily rainfall records during the period May 1 to August 31. Also, AES provided official records of rainfall, temperature, and hours of sunshine from 171 stations.

To support the program, actual soil moisture observations in the spring were conducted on over 250 sites, and actual hay-bale measurements were taken of over 500 hayfields throughout the program area.

Drought in south-central and east-central Alberta resulted in another heavy payout for the third successive year under the Canada-Alberta Livestock Feed Security Program. Payments amounted to $18.4 million, for an average loss of $1.16 for every $1.00 in total premium or $2.32 for every $1.00 in premium paid by producers.

GRAIN CROPS

Total grain production in 1986 may have been a record, but for many farmers the year did not turn out nearly as well as expected nor as it appeared likely to do in early summer. Early drought, unseasonably early frosts, an extremely wet harvest season, grasshoppers, aphids, hail, and other hazards all contributed to a drastic reduction in crop yields and a serious loss of quality of grain over wide areas of the province. Fortunately, damage from hail was below normal.

Crop insurance payments exceeded the $100 million mark for the third successive year, although losses were well short of the record levels of the previous 2 years.

ALBERTA CLIMATOLOGICAL ASSOCIATION

Annual Meeting Minutes
February 24, 1987

Patti Papirnik

1. Meeting was brought to order at 10:20 a.m. by the chairman of the ACA, Bruce Thomson.

2. A brief introduction was given, which included an announcement of a tour of the facilities of the Northern Forestry Centre and an announcement of the upcoming symposium of climate change to be held in September 1987. The executive of the ACA was then introduced.

3. Adoption of agenda: Rick Barlow moved to accept the agenda as written. Elliot Kerr seconded the motion.

4. Election of officers: Two positions are up for reelection this year. S. Dupuis was thanked for his years of service to the executive. Patti Papirnik's term has expired. Two nominees were put forward by the chairman. These were P. Papirnik and L. Wojtiw. No other nominees were suggested from the floor. B. Hume moved and S. Selirio seconded the motion that nominations cease. Accordingly, P. Papirnik was reelected for a second term and L. Wojtiw was elected for his first term.

5. Treasurer's report: D. Graham read his treasurer's report for the period of February 1986 to February 1987. The bank balance now stands at $184.20. In response to a question from the floor, it was stated that the Northern Forestry Centre will cover the costs of the 1987 proceedings.

6. Public information and communications: B. Thomson gave some background to the issue of how to address the question of public information. He stated that the Alberta Climate Advisory Committee requested the ACA to examine this issue. The chairman stated that if pursued this would be a new direction and activity for the ACA. The members present were asked to comment and give the executive their recommendations.

   In the following discussion it was mentioned that as climatologists we have topical information that should be communicated. This could be done through press releases, newsletters, or by disseminating our keynote address.

   P. Dzikowski moved that the executive investigate this issue of public relations and communication of climate activities to the media and that the executive report back to the members at the next annual meeting. This was seconded by B. Hume.

   The motion was amended by P. Dzikowski following a question by R. Barlow that the executive come back to the members with their recommendations before the next meeting as the executive sees fit to do so. This amended motion was seconded by P. Mills and was carried.

7. R. Barlow moved that the business meeting be closed at 10:45 a.m.; this was seconded by P. Mills.

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