UNIVERSITY OF ALBERTA

SOIL MOISTURE IN ALBERTA:
A COMPARISON OF GLOBAL CLIMATE MODELS AND OBSERVATIONS

by

Michael TAUTCHIN

A THESIS

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SOIL MOISTURE IN ALBERTA:

A COMPARISON OF GLOBAL CLIMATE MODELS AND OBSERVATIONS

submitted by

Michael TAUTCHIN

in partial fulfillment of the requirements for the degree of Master of Science

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To Kim and Lowell

ABSTRACT

Global soil moisture data from seven global climate models (AES, GISS, GFDL, OSU, UI, NCAR and UKMO) were obtained from the models' developers, and Alberta soil moisture values were extracted. For each model, the $1XCO_2$ and $2XCO_2$ simulation runs were compared. The models were also compared with each other. Observed Alberta spring and fall stubble soil moisture measurements were obtained from Alberta Agriculture and converted to model units. Observed soil moisture means and standard deviations were calculated for each model's Alberta grid, for each spring and fall that observed soil moisture values were available. The observed means were compared with the values of model $1XCO_2$ simulations.

The results showed that all the models (except NCAR) had similar annual variations in both the $1XCO_2$ and $2XCO_2$ runs. They exhibited an increase in soil moisture during spring, a decrease in late summer and a fairly constant soil moisture during winter. The UI model displays the closest $1XCO_2$ simulation match to the observed spring and fall means. The AES model runs an order of magnitude wetter than the other GCMs. The UKMO model shows an incorrect surface type for some areas of the province. All the models (except AES) showed an increase in winter $2XCO_2$ soil moisture compared to $1XCO_2$ simulations and a decrease in summer $2XCO_2$ soil moisture compared with $1XCO_2$.

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Soil Moisture in Alberta:

A Comparison of Global Climate Models and Observations

PAGE

List of Figures

List of Tables

Chapter 1

1.1 Introduction

Worldwide monitoring gives concrete evidence that the composition of our atmosphere is changing (Ramanathan et al., 1985). The increasing concentration of CO_2, water vapour, and some 30 additional radiatively-active trace gases in the atmosphere is resulting in a change in the radiation budget and thus a general warming at the surface of the earth. This global warming, commonly referred to as the "greenhouse effect", has potentially far-reaching impacts on global ecosystems, agriculture and water resources in the near term (Bach, 1988).

Climate impact studies assess the consequences for society of climate variability caused by anthropogenic sources (Bach et al., 1985). There are two major assessment approaches. Using climate modeling (e.g. general circulation models) to contruct climate scenarios to quantitatively assess regional and seasonal patterns of climate change induced largely by CO_2 is the "physical" method of assessment (Bach et al., 1985). The second main approach to assess climate change is the "analogue" method (Lough et al., 1983). This method uses regional and seasonal climate patterns based on instrumental data to build analogues for global warming scenarios. Bach (1988) discussed the advantages and disadvantages of both methods.

The physical method, considered in this thesis, has the advantage of describing past and present climates in a physically consistent manner, as well as showing climate response to a change in some external forcing, such as through CO_2. Bach emphasized that both the analogue and physical methods, and the interpretation of the results derived from them must be approached with caution, since they are beset with many difficulties.

Climate impact researchers use global climate model (GCM) results in their scenarios of a warmer future climate and its effects on regional agriculture, forestry, recreation and the economy. However, if the model's simulation of 20th century climate is not accurate, one cannot put much confidence in the forecasts made by the model. According to Walker (1991), a number of independent critical studies have tried to validate the regional output of climate models and all have concluded that the models fail to adequately simulate the present climate. Walker did not reference which studies these were or for which regions. Moreover, he suggested that the climate change impact studies "throw all the uncertainties out the window".

The objective of this thesis is to examine Alberta soil moisture in seven of the most referenced global climate models (AES, GFDL, GISS, OSU, UI, NCAR and UKMO), comparing them with one another and with observed Alberta soil moisture. The global climate models had been run both with current CO_2 concentrations ($1XCO_2$) as well as with double the present CO_2 concentrations ($2XCO_2$). The output from these model runs has not heretofore been examined with a view to soil moisture in Alberta. Consequently, this study provides a unique opportunity to show which models predict a decrease or an increase in soil moisture amounts with future climate warming, at what time of year they predict this, and for which areas of the province. By comparing the $1XCO_2$ model results with observed Alberta soil moisture, it is also possible to obtain some measure of validation of the models.

An examination of soil moisture was undertaken because it is more important than temperature and precipitation in determining where things grow (Kellogg and Zhao, 1988) yet is virtually ignored in GCM studies in favor of temperature and precipitation results. Alberta was chosen as the area of study because of its importance as an agricultural province and because no research has been conducted in this field for this region. Seven GCMs were selected for the study because regional comparisons between no more than two GCMs had been found in a study of the related literature (though, in some cases, comparisons between multiple versions of the same model were made). The seven particular models used in this paper were chosen because they appear to have the greatest profile, documentation and use. In theory, this should facilitate the acquisition of model data. Unfortunately, experience contradicted this naive assumption.

1.2 Literature Review

A complete review of GCM modelling could take thousands of pages, so this literature review is limited to studies of GCM results for Canadian prairie provinces and existing comparisons amongst GCM soil moisture simulations.

The concern over global climate change projected by GCMs has resulted in numerous Canadian impact studies: estimating effects of climate change on agriculture in the prairie provinces (Arthur, 1988), implications of climatic change for agriculture in Ontario (Smit, 1987), the effects of a sea level rise at St. John, New Brunswick (Martec, 1987), and at Charlottetown, Prince Edward Island (Lane, 1988), implications of climate change for downhill skiing in Quebec (Lamothe and Periard, 1988), economic perspectives on the impact of climate variability and change (Timmerman and Grima, 1988), implications of climatic change for tourism and recreation in Ontario (Wall, 1985), estimating effects of climate change on agriculture in Saskatchewan (Stewart et al., 1987), climatic trends and the effects of weather variability on wheat yields on the Canadian Prairies (Stewart, 1987), a socio-economic assessment of the physical and ecological impacts of climate change on the marine environment of the Atlantic region of Canada (Stokoe, 1987), climate variability and the immediate concern for prairie agriculture (Shaykewich and Dunlop, 1987), and an overview of the effects of climatic change and climatic variability on forest vegetation in Western Canada (Singh and Higginbotham, 1987). The Canadian Climate Centre of Environment Canada has sponsored these studies and others as part of its Canadian Climate Impacts Program (Environment Canada, 1987). Arthur (1988) reported that the prairie regions would not suffer substantial crop losses and that with minor adjustments to crop management the losses to all crops could be attenuated or avoided entirely. Arthur based her study on temperature and precipitation changes using the GISS and GFDL models. She stated that in Alberta the GFDL crop losses associated with the $2XCO_2$ scenario could be attenuated by shifting cropping patterns. Smit (1987) also used the GISS and GFDL models for his study of the implications of climate change for agriculture in Ontario. He expected that a $2XCO_2$ climate change could have "profound" effects on Ontario's agri-food sector, with production diminishing for many common crops. Smit used mean daytime temperature, potential evapotranspiration and precipitation output from the two GCMs.

In estimating the effects of climate change on agriculture in Saskatchewan, Stewart et al. (1987) used the GISS $2XCO_2$ temperature and precipitation predictions and compared them with 30-year normals for the province. They wrote that the $1XCO_2$ model climate did not resemble the actual Saskatchewan climate, and consequently they replaced it for comparison purposes with the 1951 to 1980 normals.

Stuart (1991) studied climate and climate change in the

Mackenzie Basin using the surface air temperature and precipitation output of the GISS, GFDL and OSU models for that region. Stuart mentioned that because of the poor horizontal resolution of the models, the Basin failed to show up in any model's surface topography. The variability (standard deviation) in the mean of the monthly temperature and precipitation amounts was so large for each model that the differences may not be statistically significant.

These impact assessments are well intentioned, but typically they use data from only one or two GCMs (usually the GISS and GFDL models), without knowing which model does a better job of simulating the present climate. The assessments evaluate the impacts of only one or two of the climate variables modelled by the GCMs (usually temperature and precipitation). Soil moisture is often completely ignored. In a U.S. EPA-sponsored report on the impacts of climate warming on water availability and hydrology in the U.S., prepared by the NASA Goddard Space Flight Center (Rind and Lebedeff 1985), a consideration of soil moisture is partially absent from the assessment. In addition, although the authors are mindful of the shortcomings of GCMs, they base their impact assessment of the large field of water resources on only one GCM, their own GISS model.

An investigation of the annual variation of temperature and precipitation in three GCMs (GISS, GFDL and OSU) was recently made for Alberta (Wong et al., 1988). The models' projections of the changes in the Alberta temperature and precipitation fields due to a doubled atmospheric carbon dioxide concentration were also studied. However, soil moisture was again not considered. Their comparison of the models' predicted monthly mean temperatures with those observed showed the models' temperatures differing by up to 3°C from the observed temperatures at grid points averaged over the province (predicted often being warmer than observed). There also exists a lag time of about 1 month between the models' annual temperature time series and the observed series. The OSU model most closely simulated the observed data. The GISS model's temperature profiles closely resemble the shape of the observed temperature profiles but show a greater lag and a higher summer temperature than the OSU model. The GFDL model consistently exhibits higher peak temperatures than do OSU and GISS (by 1 to 3°C). OSU had the highest index of agreement for southern Alberta (0.87), northern Alberta (0.87) and all of Alberta (0.88), followed by GISS and GFDL (see Table 1). The index of agreement (d) is a measure of the degree to which a model's predictions are error free (Willmott, 1981). It varies between 0.0--indicating one of a variety of complete disagreements--and 1.0, which indicates perfect agreement between the observed and predicted observations.

index of agreement, $$d = 1 - \frac{\sum_{i=1}^{N} (P_i - O_i)^2}{\sum_{i=1}^{N} [|P'_i| + |O'_i|]^2} \quad 1.2.1$$

where P = predicted variates, O = observed variates, $P'_i = P_i - \bar{O}$ and $O'_i = O_i - \bar{O}$ (where $\bar{O}$ is the observed mean)

The agreement between the observed and predicted precipitation in Alberta was far poorer than the temperature agreement. All of the models produced more precipitation than observed throughout the year. The exception is OSU which produced less precipitation than observed during summer and winter. The GFDL model exhibited the best index of agreement for precipitation in southern Alberta (0.34), northern Alberta (0.37) and all of Alberta (0.40), followed by GISS and OSU. For the index of agreement, the sums are done with monthly means.

Table 1

Comparisons of GCM Results With

Observations of Normal Climate for Alberta

(Based on Wong et al., 1989)

GCM TEMPERATURE COMPARISONS

	ALL ALBERTA			NORTH ALBERTA			SOUTH ALBERTA		
	GISS	GFDL	OSU	GISS	GFDL	OSU	GISS	GFDL	OSU
CORRELATION	0.99	0.94	0.97	0.99	0.93	0.97	0.97	0.93	0.96
INDEX OF AGREEMENT	0.83	0.81	0.88	0.86	0.83	0.87	0.88	0.82	0.87

GCM PRECIPITATION COMPARISONS

	ALL ALBERTA			NORTH ALBERTA			SOUTH ALBERTA		
	GISS	GFDL	OSU	GISS	GFDL	OSU	GISS	GFDL	OSU
CORRELATION	0.92	0.67	0.35	0.90	0.51	0.34	0.83	0.80	0.24
INDEX OF AGREEMENT	0.37	0.40	0.28	0.36	0.37	0.27	0.30	0.34	0.33

The report of Wong et al. is extremely useful in that it intercompares GCMs, compares their output with observed climate variables, and does this for Alberta. Soil moisture, however, considered the most important parameter in determining where things can grow (Kellogg and Zhao 1988), was not assessed. This was an unfortunate oversight, considering Alberta's agricultural requirements, and one which this thesis proposes to redress.

Why is soil moisture rarely examined in impact assessments? First, it is more difficult to acquire and assemble soil moisture data from model archives. Soil moisture is obtained from secondary model calculations. The temperature and precipitation variables are primary rather than secondary variables (generated from the primary variables). Secondary model parameters are calculated by GCMs but they are not always included in the data archives. It is also less time consuming to acquire these data for only a few GCMs rather than for the seven considered in this thesis, although this is not a problem specific to the soil moisture parameter. Finally, some researchers, such as the authors of the Goddard-EPA report, make the mistake of assuming that temperature and precipitation are the most important variables to consider in impact assessments. Some previous considerations of soil moisture in the GCM models appeared, for example, in a paper describing the sensitivity of soil moisture in North America and Asia to the doubling of CO_2 (Kellogg and Zhao, 1988). The authors considered the NCAR, GFDL, GISS, UKMO and OSU models, but on a continental scale rather than a regional scale. The AES and UI model results, not available at the time, were not included. Part I of the paper dealt with soil moisture changes over North America due to CO_2 doubling. The paper provides low-resolution maps of soil moisture changes on a continental scale and does not examine soil moisture data for individual grid points or for Alberta. Kellogg and Zhao (1988) also considered the sources of observed soil moisture data and mentioned the desirability of comparing a model's $1XCO_2$ soil moisture distribution with the real distribution. They recognize a serious problem in knowing what the real distribution is, since it is rarely measured directly and must be deduced indirectly. Kellogg and Zhao discussed the general characteristics of the five GCMs and their soil moisture algorithms. They came to the following general conclusions about the sensitivity of soil moisture in the models based on monthly mean GCM data. First, the $1XCO_2$ models do not perform well in simulating the seasonal changes of observed soil moisture. They found modest agreement in the large-scale regional increases that occur in winter, but relatively poorer agreement with the summer changes. Kellogg and Zhao also concluded that the modellers' high degree of confidence in their own individual soil moisture climates was not justified in an absolute sense when soil moisture predictions are compared with real data. They found, however, that there was some useful information in the results. For example, evidence pointed towards a CO_2-induced increase in soil moisture in winter in the middle and high latitudes of North America, including Alberta. Results of the comparison for summer tended to show a decrease in soil moisture for the prairies. Soil moisture is the result of a near-balance between precipitation and evaporation. Evaporation is largely dependent on surface temperature. Kellogg and Zhao suggest the drier summer results are consistent with the mean temperature increase at higher latitudes.

Meehl and Washington (1988) of NCAR compared the soil moisture sensitivity of two GCMs (NCAR and GFDL). In this paper, the authors used soil moisture-cloud-precipitation feedback mechanisms to explain the models' results and differences. The authors mentioned that the two models reach soil moisture saturation at different times in the control ($1XCO_2$) runs (GFDL earlier than NCAR). According to them, the extent of summer dryness with increased CO_2 is determined by how close the control runs are to saturation in the spring. The closer the NCAR model is to saturation in late winter and spring in the control run, the greater the summer dryness with increased CO_2! This paradox is difficult to explain because the NCAR and GFDL models use different field capacities, and this changes the time at which soil becomes saturated in the models, making soil moisture intercomparisons difficult.

Meehl and Washington also mentioned that adjustments made to the surface drag coefficient and land albedo can affect soil moisture amount. Evaporation affects soil moisture, and adjustments of the surface drag coefficient could increase or decrease evaporation, which could lead to an increase or decrease in soil moisture. The NCAR GCM uses a non-zero surface wind constraint for evaporation. In low-wind situations, this increases the evaporation and results in lower soil moisture. A higher land albedo results in a decrease of absorbed solar radiation at the surface and a corresponding decrease of surface temperature. The authors associate these changes with increases in precipitation, low cloud, and soil moisture. The adjustments are made when the model's control run does not accurately simulate the observed climate. Different GCMs use different values for these parameters. They point out that global soil moisture in the NCAR model are significantly less than that in the GFDL model in spring. Also, the increase in soil moisture in the NCAR model in winter and spring is much greater than that in the GFDL model. This is somewhat misleading. It does not mean that the NCAR model receives more precipitation in winter and spring. The GFDL model is already close to saturation in winter and spring, hence any additional precipitation due to CO_2 warming results in runoff. The confusion is caused by Meehl and Washington's loose usage of the term "deficit". To a hydrologist, a soil moisture deficit occurs when cumulative evaporation is greater than cumulative precipitation, resulting in a reduction of soil moisture storage below some long-term average. Meehl and Washington, however, appear to think of a soil moisture deficit as occurring if the modelled $2XCO_2$ soil moisture drops below that simulated in the control run. In other words, they use the term "deficit" to refer to what should rather be described as a negative soil moisture anomaly.

Manabe and Wetherald (1987) also investigated the large-scale (North American) changes in soil moisture induced by an increase in atmospheric carbon dioxide. The investigation was based on two versions of a GDFL general circulation model of the atmosphere with a static mixed ocean layer. The first version of the model specifies the distribution of cloud cover. The second version computes cloud cover and incorporates the interactions among cloud cover, radiative transfer and the atmospheric circulation. Results from both models showed that, in response to a doubling (or quadrupling) of atmospheric CO_2, soil moisture is reduced in summer (June, July and August) over extensive midcontinental regions of North America. Over northern Canada, the CO_2-induced reduction of soil moisture results from an earlier occurrence of snowmelt, followed by a period of intense evaporation. During the GCM winter (December, January and February) their simulations showed increasing soil moisture with increasing carbon dioxide over most of North America poleward of 30 °N. Their results differ from those of Washington and Meehl (1984), whose NCAR model suggested a CO_2-induced increase of zonal mean soil moisture throughout the year in the middle latitudes of the Northern Hemisphere. The magnitude of the NCAR models's increase in summer, though, was considerably less than its increase in winter. Both models use the so-called "bucket" (15-cm field capacity) soil moisture method. The GFDL model simulates more snowmelt in winter and early spring and less in late spring in $2XCO_2$ runs compared with $1XCO_2$ runs. Both models also predict more runoff in early spring and less in late spring. In comparing the $2XCO_2$ and $1XCO_2$ runs, however, significant differences exist between the two models (Washington and Meehl, 1988). The GFDL model indicates winter and spring soil moisture close to saturation (15 cm). The increased winter and spring precipitation with increased CO_2 therefore goes mostly to runoff. The NCAR model predicts soil moisture much less than saturation, so that similar CO_2-induced increases in precipitation are retained in the NCAR "bucket" at most gridpoints, with less runoff than in GFDL. Both models predict similar increases in springtime evaporation. Washington and Meehl mentioned the lack of appropriate observed data as one critical factor prohibiting the verification and calibration of the soil moisture parameterization in the models. Other factors include the highly parameterized hydrology in the models and the complexity of hydrological processes in the real world. They suggest that the NCAR model underestimates and that the GFDL model overestimates summer soil dryness due to increased CO_2.

Chapter 2

DESCRIPTION OF GLOBAL CLIMATE MODELS

2.1 Introduction

So far, GCMs are considered to be the most appropriate and most sophisticated means to analyse whether and how climate may change when some climatic variables do. Specifically, the variable of greatest concern in recent years is the increase in the concentration of atmospheric carbon dioxide. These models which are used by climate impact assessors, have been reviewed in Chapter 1. Unfortunately, a high degree of sophistication does not necessarily imply results with corresponding validity. Climate impact assessors will sometimes use GCM results without fully understanding how these results were obtained, how they differ from model to model, and whether the GCM variables being examined are the best ones for the researchers' purposes. Impact assessors may tend to trust the relative sophistication of three-dimensional, dynamic GCM models (compared, for example, with simple heat balance climate models or models with only one or two dimensions). They also have a tendency to take the results of a single GCM model at face value and incorporate them into an impact forecast. In some instances they may use the results of the perturbed GCM run (GCM experiments using double or quadruple CO_2 concentrations) without first verifying how well the control run ($1XCO_2$) results simulate current climate.

Although the researcher may have neither the time nor the endurance to assemble and compare the results, variables, requirements and characteristics of the various GCM models, this really should be done if the model predictions are to be used for climate impact assessment.

One GCM variable rarely considered in comparisons of the models is soil moisture. This is strange in view of the fact that soil moisture is considerably more important than temperature in determining where things can grow (Kellogg and Zhao, 1988). Even though the temperature range may be within plant growth tolerance, growth will not occur if there is insufficient soil moisture available to the plants. It is necessary for this reason for climate impact assessors to assign more importance to the role of soil moisture than to the more commonly considered variables of temperature and precipitation in their studies. It is also prudent that they be made aware of the strengths, shortcomings and differences in the way in which soil moisture is treated by the various GCMs. The present thesis represents a first step towards this goal.

2.2 Global Climate Models Defined

Comparisons will be made between seven Global Climate Models (see Table 2) selected for being the most comprehensive, evolving and well known models. Other two-and three-dimensional models exist, but they appear to be used far less in climate impact studies than the seven models shown in Table 2.

Table 2

The Global Climate Models Compared in This Thesis

Model; Researcher(s); Laboratory Location; Version Year

1) AES; Boer, McFarlane, Laprise, Henderson, Blanchet; Atmospheric Environment Service, Canadian Climate Centre, Downsview, Ontario; 1990
2) GFDL; Manabe, Wetherald; Geophysical Fluid Dynamics Laboratory of NOAA, Princeton; 1986
3) GISS; Hansen, Russell, Rind, Stone, Lacis, Lebedeff, Ruedy, Travis; NASA's Goddard Institute of Space Studies New York; 1983
4) OSU; Schlesinger, Han, Gates; Oregon State University, Corvallis, Oregon; 1985
5) UI; Schlesinger; University of Illinois, Champaign; 1988
6) NCAR; Washington, Meehl; National Center for Atmospheric Research, Boulder, Colorado; 1984
7) UKMO; Mitchell; United Kingdom Meteorological Office, Bracknell; 1987

A Global Climate Model (GCM), also referred to as an Atmospheric General Circulation Model (AGCM) is a set of computer programs based on the equations of motion which,

> "retain sufficient resolution to represent atmospheric structure at synoptic and planetary scales and include explicit representations of the main physical processes that determine the atmospheric circulation on seasonal and longer time-scales" (Boer et al. 1984).

The models consider thermodynamic physical processes such as long and shortwave radiation, condensation, evaporation, freezing and melting, etc. They also simulate ocean-atmosphere interactions, with varying degrees of oceanic complexity.

GCMs are similar to numerical weather prediction (NWP) models, and in some cases derived from them. Although their resolution is lower than that for NWP models (about 500 km compared with about 100 to 200 km for NWP models) they predict the same details as NWP models. These models should correctly handle the climatic effects of variables such as clouds and radiation, atmospheric moisture, precipitation, ocean fluxes (currents) and land surface processes. They attempt to correctly simulate feedbacks among these variables. Then in a numerical experiment, if one parameter (say, the amount of CO_2 in the atmosphere) is changed, the model can be used to determine what the response of the earth's climate will be. According to Chahine (1992), GCMs are the basic tools for studying these exchanges, and are valuable for forecasting weather up to 10 days. He mentions that GCM use for climate forecasting, though, is not as developed. The models do not yet account for the full hydrological cycle and its interaction with the atmosphere, oceans and land.

In a GCM, the fundamental dynamical equations describing large-scale atmospheric motion are coupled with boundary conditions (land and ocean albedo, surface drag coefficient, surface elevation, sea surface temperature and sea ice) and other input such as solar radiation at the top of the atmosphere.

2.3 GCM Characteristics

Once the parameters and initial conditions have been set, the time variation of the input conditions is determined numerically over a global network of gridcells. The gridcells contain a gridpoint at the centre of each cell. The input values at a gridpoint do not indicate the condition at that discrete point, but rather they represent the mean of the data over the cell for which that gridpoint serves as centre. Figures 1 to 7 show the gridpoint spacing (horizontal resolution) of each model over western Canada. Within Alberta boundaries, this resolution results in 7 gridpoints for AES, 5 for GFDL, 3 gridpoints for the GISS model, 7 for OSU and UI, 3 for NCAR and 2 for UKMO. The global horizontal resolution for the models appears in Table

3a. The calculations are then run until a statistical equilibrium is achieved (the model's time-averaged statistics are no longer changing significantly). When we speak of averaging times for the models to reach a kind of equilibrium we are speaking of model time. Most of the GCMs settle down to a steady state after 10 to 15 years, and the climate statistics are developed after that, as the model is run for 20 to 50 years or more. Some models (not the ones compared in this thesis) have been run for several centuries, but this is at a sacrifice of model complexity and requires a lot of computer time. According to Kellogg (in correspondence), this procedure had to be followed for both the control run ($1XCO_2$) and the perturbed run ($2XCO_2$), and the model response was then the difference. The model provides the global spatial distribution of various climate variables, and these can be compared with the present observed climate (usually a 30 year period e.g. 1951-80) to determine the accuracy of the model's simulation. These control runs can be changed to perturbed runs by altering one or more parameters and determining how the variables have changed once the model has again reached equilibrium. This may be done by altering the parameter either instantaneously (e.g. doubling the concentration of carbon dioxide at the beginning of the run) or gradually throughout the run, giving more realistic transient runs. From correspondence with Kellogg, the former experiments are referred to as "equilibrium experiments" as distinct from the latter, "dynamic experiments" run by more modern GCMs.

This thesis will consider how well the seven GCMs simulate the observed soil moisture variable in control runs (1 X CO_2) for Alberta and their projections of soil moisture in Alberta for perturbed runs (2 X CO_2). The GCM simulation results were obtained from several sources, mostly the modelling labs. Section 5.2 discusses the sources of the data.

Table 3a:
General Characteristics of the Seven Global Climate Models Considered*

Model	Horizontal domain; coordinates	Vertical domain; coordinates	Horizontal resolution (degrees)	Vertical resolution (layers)
AES	global; latitude-longitude	surface to 0 mb; σ**	3.75 lat by 3.75 long	10
GFDL	global; latitude-longitude	surface to 0 mb; σ**	4.5 lat by 7.5 long	9
GISS	global; latitude-longitude	surface to 10 mb; σ**	8 lat by 10 long	9
OSU	global; latitude-longitude	surface to 200 mb; σ**	4 lat by 5 long	2
UI	global; latitude-longitude	surface to 200 mb; σ**	4 lat by 5 long	2
NCAR	global; latitude-longitude	surface to 0 mb; σ**	4.5 lat by 7.5 long	9
UKMO	global; latitude-longitude	surface to tropopause; σ**	5 lat by 7.5 long	11

*Characteristics for GCMs except AES and UI based on Kellogg and Zhao (1988)

** $\sigma = (p-p_t)/(p_s-p_t)$ where p is pressure, p_t is the pressure at the top of the model, and p_s is the surface pressure.

Table 3b: General Characteristics of the Seven Global Climate Models Considered*

Model	Cloud distribution in troposphere; influence on radiation	Insolation	Land/ocean distribution	Topography
AES	clouds are allowed to form in each layer; they affect albedo and IR radiative transfer	seasonal and diurnal cycles	realistic	realistic
GFDL	clouds are allowed to form in each layer; they affect albedo and IR radiative transfer	seasonal cycle	realistic	realistic
GISS	clouds are allowed to form in each layer; they affect albedo and IR radiative transfer	seasonal and diurnal cycles	realistic	realistic
OSU	clouds are allowed to form in each layer; they affect albedo and IR radiative transfer	seasonal cycle	realistic	realistic
UI	clouds are allowed to form in each layer; they affect albedo and IR radiative transfer	seasonal cycle	realistic	realistic
NCAR	clouds are allowed to form in each layer; they affect albedo and IR radiative transfer	seasonal cycle	realistic	realistic
UKMO	clouds are allowed to form in each layer; they affect albedo and IR radiative transfer	seasonal and diurnal cycles	realistic	realistic

*Characteristics for GCMs except AES and UI based on Kellogg and Zhao (1988)
See Section 2.3 for meaning of "realistic" land/ocean distribution and topography

Table 3c: General Characteristics of the Seven Global Climate Models Considered*

Model	Ocean	Climate Averaging time for 1 X CO2 and 2 X CO2 results
AES	mixed layer 50 m deep; prescribed seasonal heat flux convergence correction is applied (see Sec. 2.3)	The monthly averages are calculated over the last 10 years of each run
OSU	mixed layer 60 m deep	last 10 yrs. of simulation
UI	mixed layer 60 m deep	last 10 yrs. of simulation
GFDL	mixed layer 50 m deep	last 10 yrs. of simulation
GISS	mixed layer with seasonally varying depth is prescribed from climatology but with a maximum allowed depth of 65 m; prescribed seasonal ocean heat flux convergence	last 10 yrs. of simulation
NCAR	mixed layer 50 m deep	last 3 yrs. of simulation, but last 7 yrs. for calculation of significance
UKMO	mixed layer 50 m deep; prescribed seasonal ocean heat flux convergence	last 8 yrs. of simulation for 1 X CO_2, last 5 yrs. for 2 X CO_2

*Based on Kellogg and Zhao (1988)

Figure 1:
Distribution of AES GCM Gridpoints in Alberta
and Within 2 Degrees Lat. and 4 Degrees Long. of Alberta

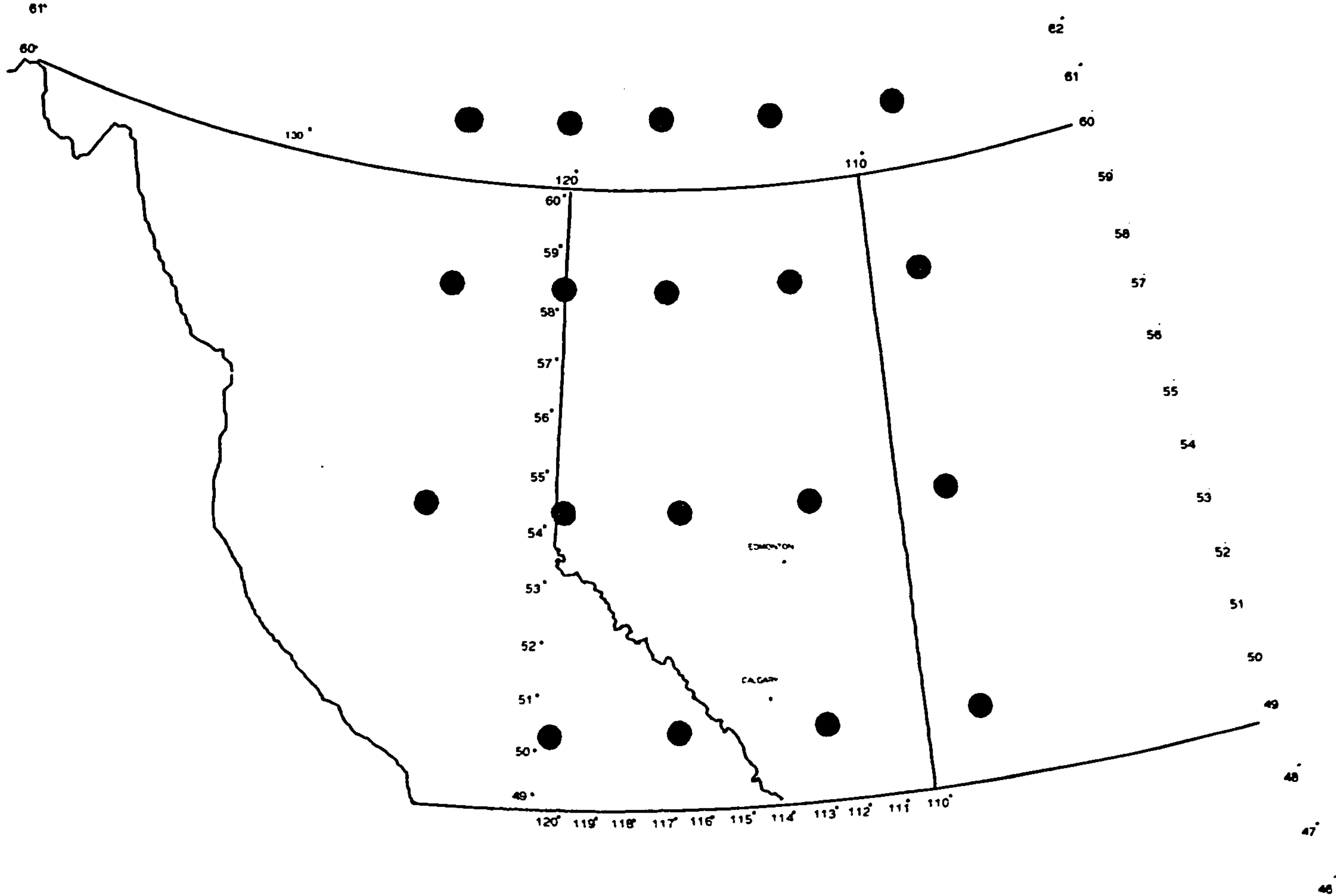


Figure 2·
Distribution of NCAR GCM Gridpoints in Alberta
and Within 2 Degrees Lat. and 4 Degrees Long. of Alberta

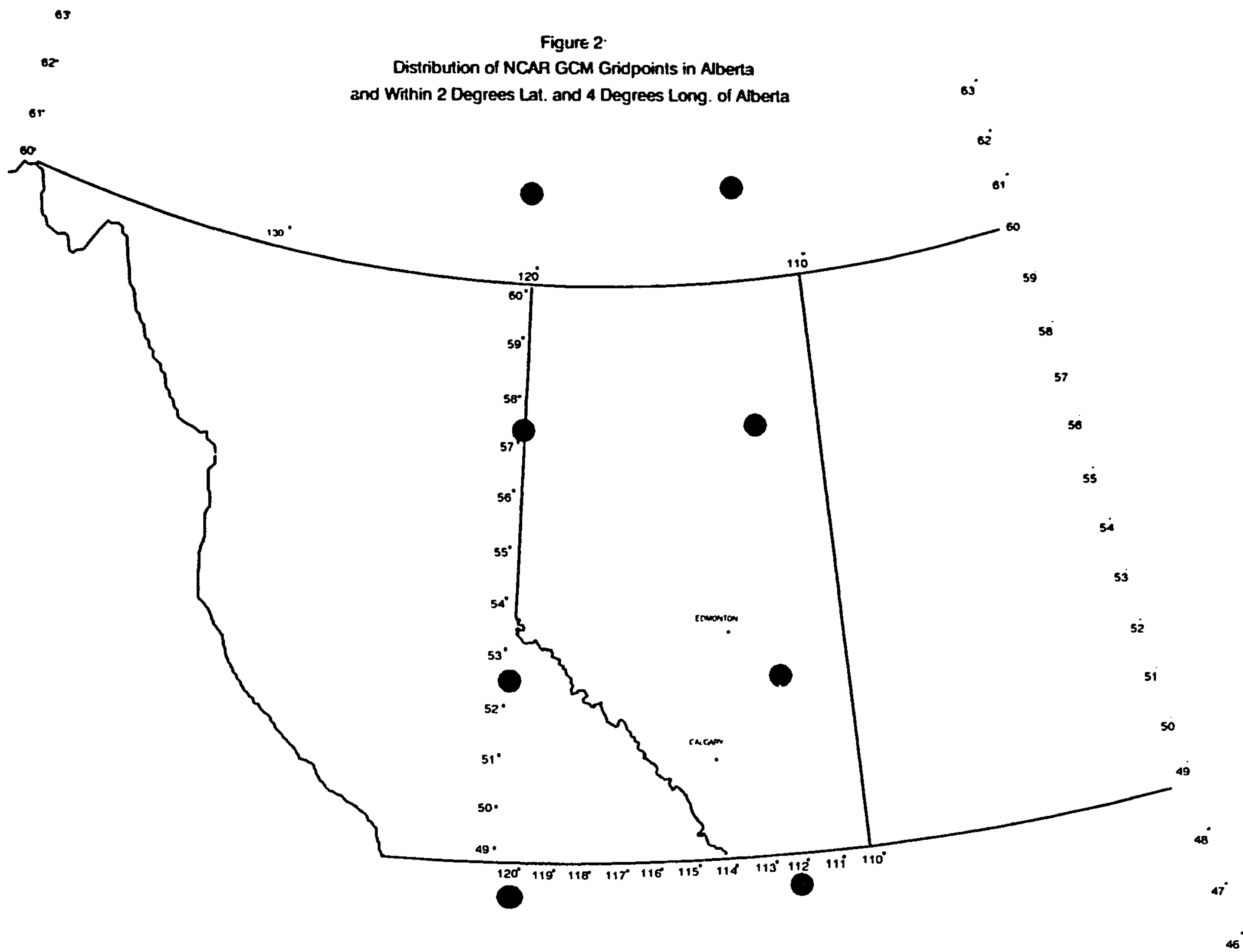


Figure 3:
Distribution of GFDL GCM Gridpoints in Alberta
and Within 2 Degrees Lat. and 4 Degrees Long. of Alberta

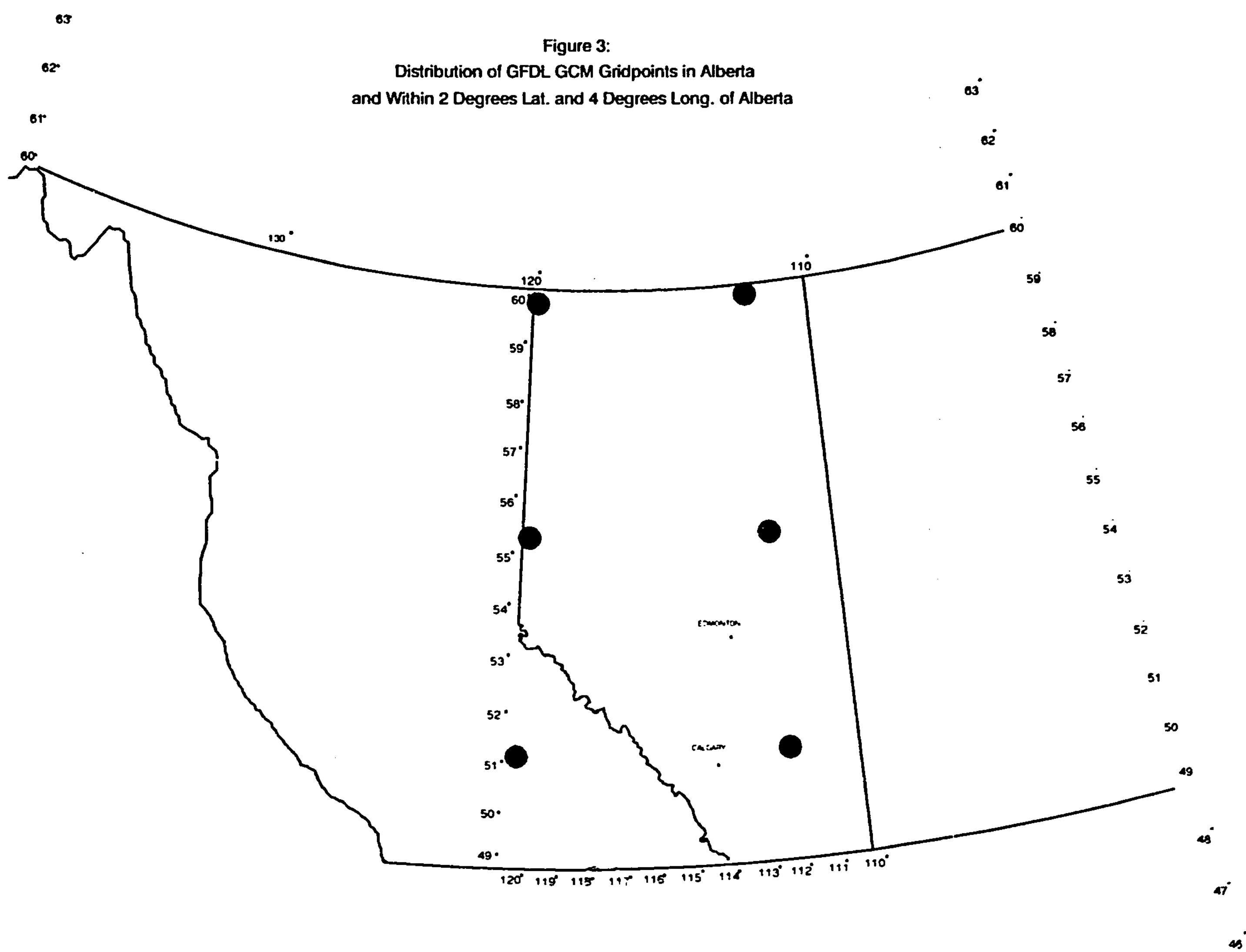


Figure 4:
Distribution of GISS GCM Gridpoints in Alberta
and Within 2 Degrees Lat. and 4 Degrees Long. of Alberta

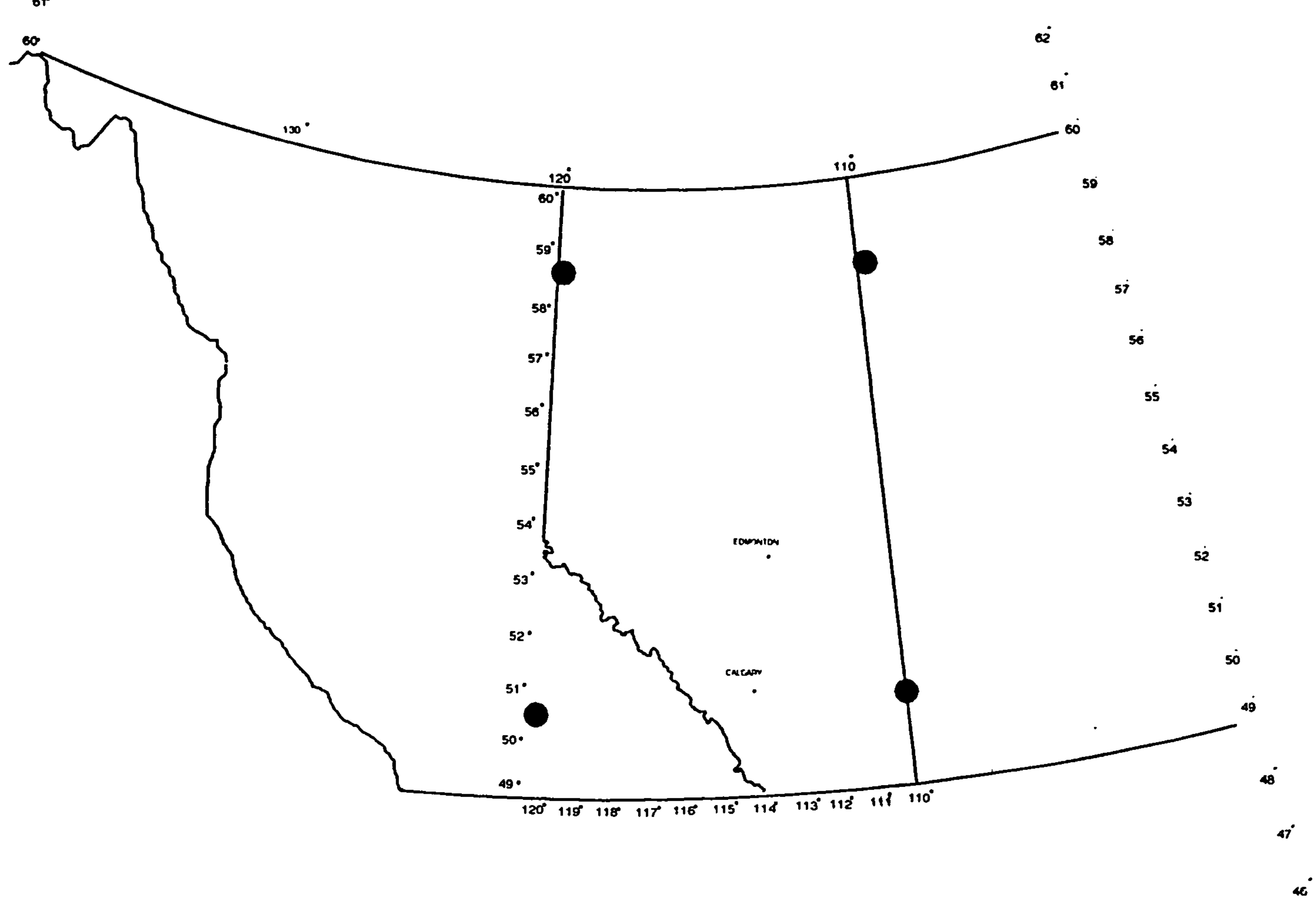


Figure 5:
Distribution of OSU GCM Gridpoints in Alberta
and Within 2 Degrees Lat. and 4 Degrees Long. of Alberta

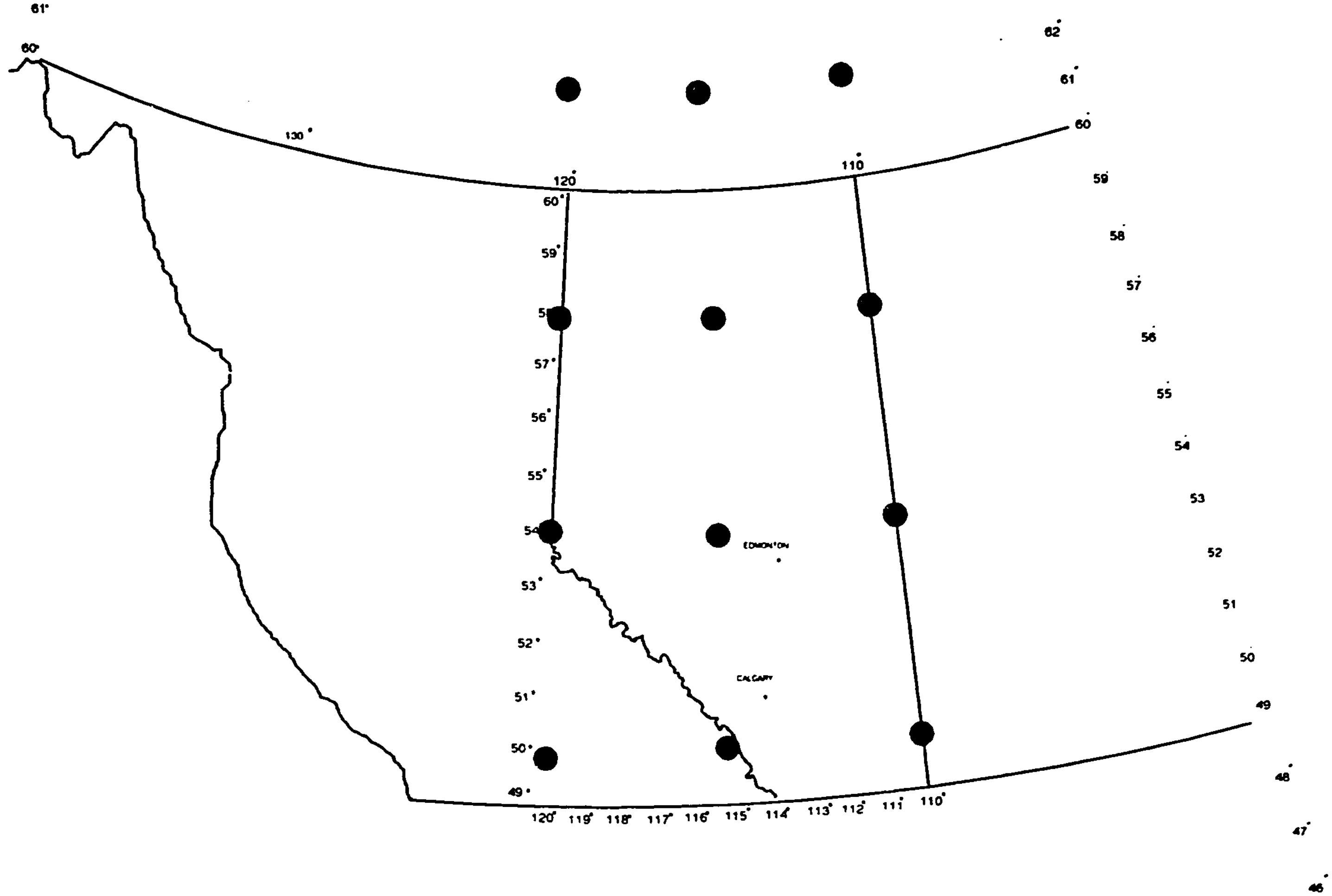


Figure 6:
Distribution of UI GCM Gridpoints in Alberta
and Within 2 Degrees Lat. and 4 Degrees Long. of Alberta

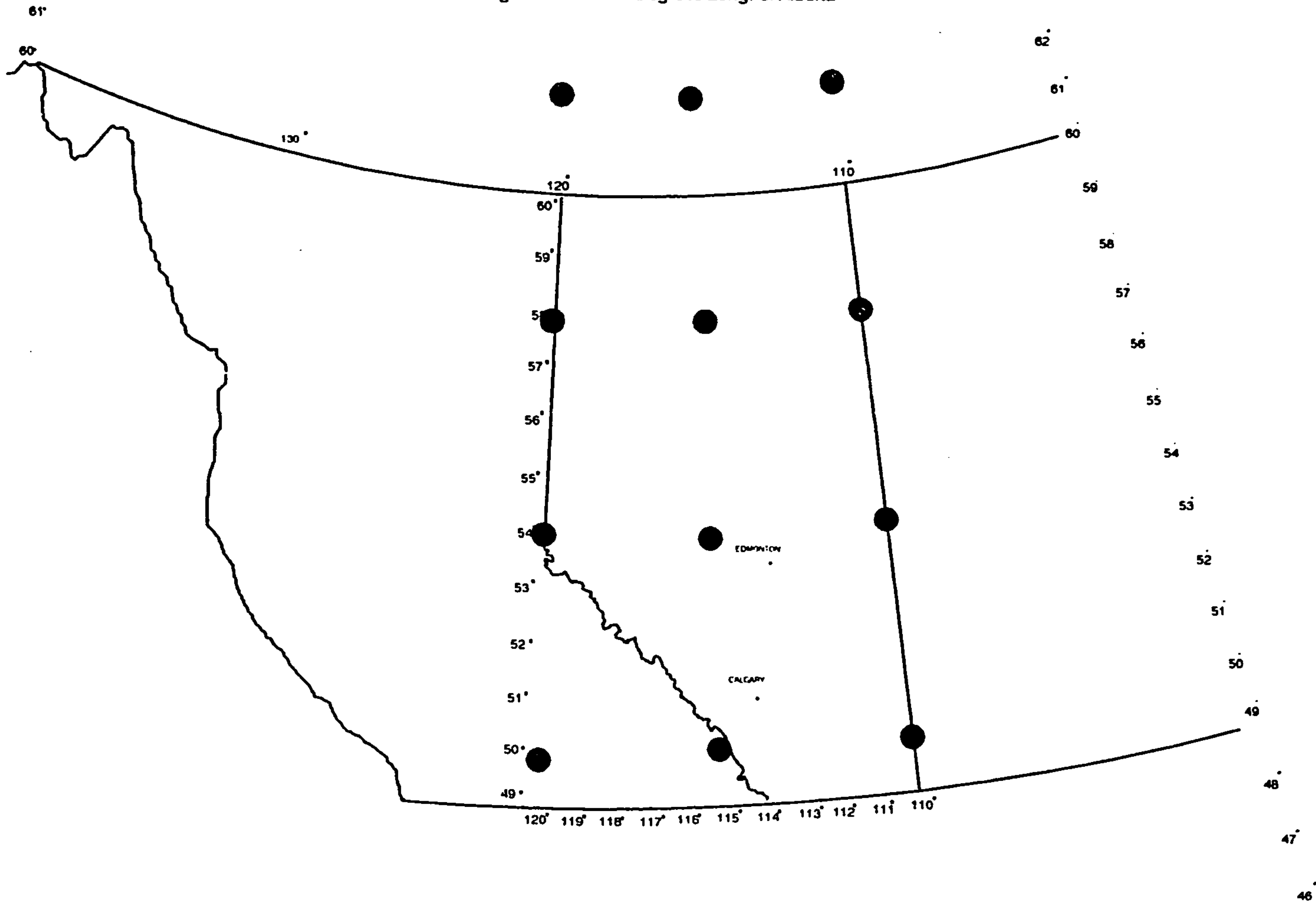
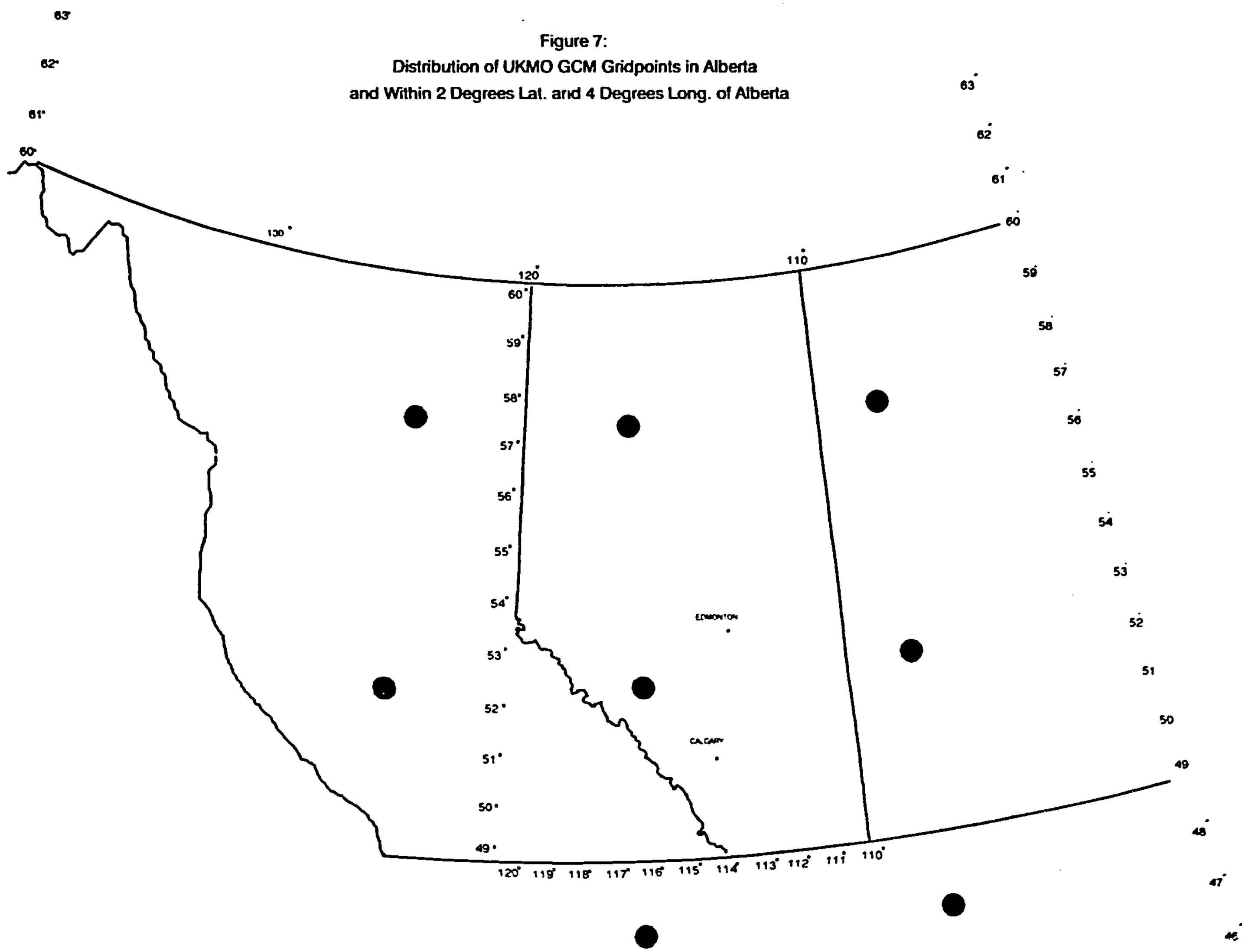


Figure 7:
Distribution of UKMO GCM Gridpoints in Alberta
and Within 2 Degrees Lat. and 4 Degrees Long. of Alberta



2.4 Model Surface Types

The five GCMs that were studied by Kellogg and Zhao (1988) and are compared with two additional GCMs in this thesis, involved rather low horizontal resolution (see Table 3a); nevertheless, the outlines of the continents and positions of major mountain ranges were specified. From correspondence with Kellogg, this is why the term 'realistic' is used to describe how the models introduced topography. Some earlier models used highly idealized topography, for example, just one continent. There are some minor differences in the topographic data used, but these differences are small compared to the problem of low resolution. At the time GCM data were obtained for this thesis, results from the current generation of GCMs with better resolution were not available.

Without going into a treatise on ocean models, four of the climate models used a simple mixed layer ocean model that had about the right heat capacity to simulate the SST (sea surface temperatures) changes between summer and winter. The ocean temperatures were determined by the heat flux at the surface, and there was no horizontal transport of heat by the oceans, i.e., no ocean currents. In the case of the GISS ocean model, another contraint was introduced, and that was to preserve the present SST gradients. This was an attempt to introduce the effects of ocean currents, even though there were no actual currents in the model. It should be added at this point, that the current generation of climate models by GFDL, GISS, NCAR and UKMO all have circulating oceans with various degrees of complexity. This is a very fundamental improvement and one of the reasons the new models should be compared once data are available.

The GISS model is the only one of the seven that allows more than one type of surface (land, water, ice) to exist at the same time within one grid box. The model allows for four surface categories in each cell:

-land, no permanent ice (a fixed fractional coverage)

-land ice (glaciers, fixed coverage)

-ocean or lake ice (coverage varies)

-open water (ocean or lake, coverage varies).

Although the topography of the models generally resembles the Earth's, the Earth's detailed elevation structure is smoothed out in each model. This is not a cause for concern in the relatively flat regions of Alberta, but it is a problem in the mountains. For example, the GISS model's highest elevations are about 1800 m in the Rockies, while the actual height of mountain ridgelines is more like 3400 m. Orographic precipitation can change rapidly near hills and mountains and with it the amount of soil moisture and runoff. The GCMs can reproduce the broader effects of orographic precipitation but the impact assessor should be aware that the soil moisture data at a gridpoint is an areal mean and that the topography is idealized. Small-scale topographic features that affect soil moisture, such as slope, aspect, peaks and valleys, are not resolved by the models.

2.5 Model Temperature Sensitivity

The temperature sensitivity of a GCM is often characterized by how much the equilibrium global mean surface temperature is increased when the concentration of CO_2 is doubled. It is important to recognize that the CO_2 increase does not directly cause the entire temperature increase. Various feedback mechanisms raise the temperature as well. For example, in the GISS model, the total global mean surface temperature change of 4.2°C, associated with a doubling of CO_2, has been broken down as follows (Jenne, 1989):

a. Temperature change at the surface due to the enhanced greenhouse effect of the CO_2 alone................ 1.6°C

b. Water vapor mass increased by 33% in the total atmospheric column and located at higher levels .. 1.6°C

c. A decrease of 1.7% in total cloud amount, with some increase in cirrus clouds. Cloud tops became somewhat higher................ 0.8°C

d. Changes in the surface albedo, mostly due to a reduction in sea ice........................... 0.4°C

Total 4.4°C

Actual surface temperature increase in the GISS GCM 4.2°C

The temperature sensitivity of the other models is qualitatively similar to the above. Table 4 gives global annual average differences in surface air temperature and precipitation for the GCMs considered in this thesis. Table 5 gives changes simulated for the globe, the land area and for the ice-free ocean for the AES model.

Table 4

Model Comparison of Global Results for 2xCO_2 Simulations Showing Global Annual Average Differences in Surface Air Temperature (T) and Precipitation (P) Simulated by GCMs

(Based on Env. Can., 1990)

Model	Change in T (°C)	Change in P (% 1xCO_2)
AES	3.5	8%
GISS	4.2	11%
GFDL	4.0	9%
OSU/UI	2.8	8%
NCAR	4.0	7%
UKMO	1.9 to 5.2	2 to 15%

Table 5
Mean Annual Changes Due to Double CO_2 for the AES Model

(Based on Env. Can., 1990)

Variable	Globe	Land	Ice Free Ocean
Percent of globe	100.0	29.0	63.5
Surface air temp. (°C)	3.5	4.4	2.7
Precipitation	3.8%	0.9%	4.3%
Evaporation	3.8%	3.8%	3.3%
Cloud cover	-2.2%	-1.9%	-3.3%
Soil moisture		-6.6%	
Sea ice mass	-66.0%		

The importance of clouds in the models can be seen in the GISS example breaking down the surface temperature increase into various feedback mechanisms. All models parameterize clouds and allow them to vary. The AES GCM has a complicated cloud model in which six types of clouds are considered, each with a typical liquid water content. In the AES model, the clouds may be fully overlapped, non-overlapped or randomly overlapped (Boer et al., 1984).

Clouds both transmit and scatter solar radiation. Low clouds generally reflect sunlight, thereby cooling the lower atmosphere. High clouds reflect solar radiation poorly but radiate at a much lower temperature than low clouds near the Earth's surface, causing a net warming compared with a cloud free atmosphere (Jenne, 1989). Consequently a detailed treatment of clouds is necessary for GCMs. AES's cloud model appears to be the most detailed of the six.

Chapter 3

A Brief Description of Soil Moisture Characteristics

3.1 Introduction

The most common definition of "soil moisture" according to Ward (1975) is simply all the subsurface water above the water table in the zone of aeration. The zone of aeration is the zone in which the pore spaces are filled with both water and air; capillary forces predominate. The zone of aeration comprises the layers of soil from the ground surface to the underground zone of saturation (see Fig. 8). Within the zone of saturation, pore spaces are completely filled with water and the pressure within the water is equal to or greater than the atmospheric pressure. While all water below the ground surface is commonly referred to as groundwater in lay terms, groundwater is more accurately the water within this saturated zone, and its characteristics will not be considered here.

3.2 Storage of Soil Moisture

Soil particles are never in perfect contact with other soil particles and this creates small pore spaces between them. The different structure of the soil will create different pore spaces (see Fig. 9). Water can be stored within these spaces but must be retained against the downward force of gravity. Soil water can be held between soil particles by the capillary force. Most water in coarse-grained, moist soil is retained by this force. Surface tension results from the fact that water molecules are more strongly attracted to other water molecules within the same body of liquid than to molecules of surrounding water vapour. This attraction holds the water in situ and must be overcome in order to create movement between the air and water interface. The capillary force varies inversely with the radius of curvature of the water surface. The force will decrease as the radius of the pore space increases.

Soil water can also be stored as a thin film around soil particles by the retention process of adsorption. Adsorption is an electrostatic process whereby polar water molecules are attracted to charged soil particles. The force is significant only over a small distance, accounting for a thin film of 3 to 7 molecules thickness (Low 1961). Within certain soils, however, the combined effect of the adsorption retention can result in large amounts of soil moisture storage. If the soil has a large area of adsorbed water film (as in the case of some clays), as much as 800 g/m^2 of water can be retained over the surface cross-section. Soils such as sands by contrast, with smaller specific surfaces (surfaces that can adsorb water), will retain less than 1 g/m^2 of water (Hillel 1971). Another soil moisture retention force is osmotic pressure. Kirkham

(1964) describes how dissolved salts in the presence of a semi-permeable membrane (a plant root, for example) increase the force with which water is held in the soil.

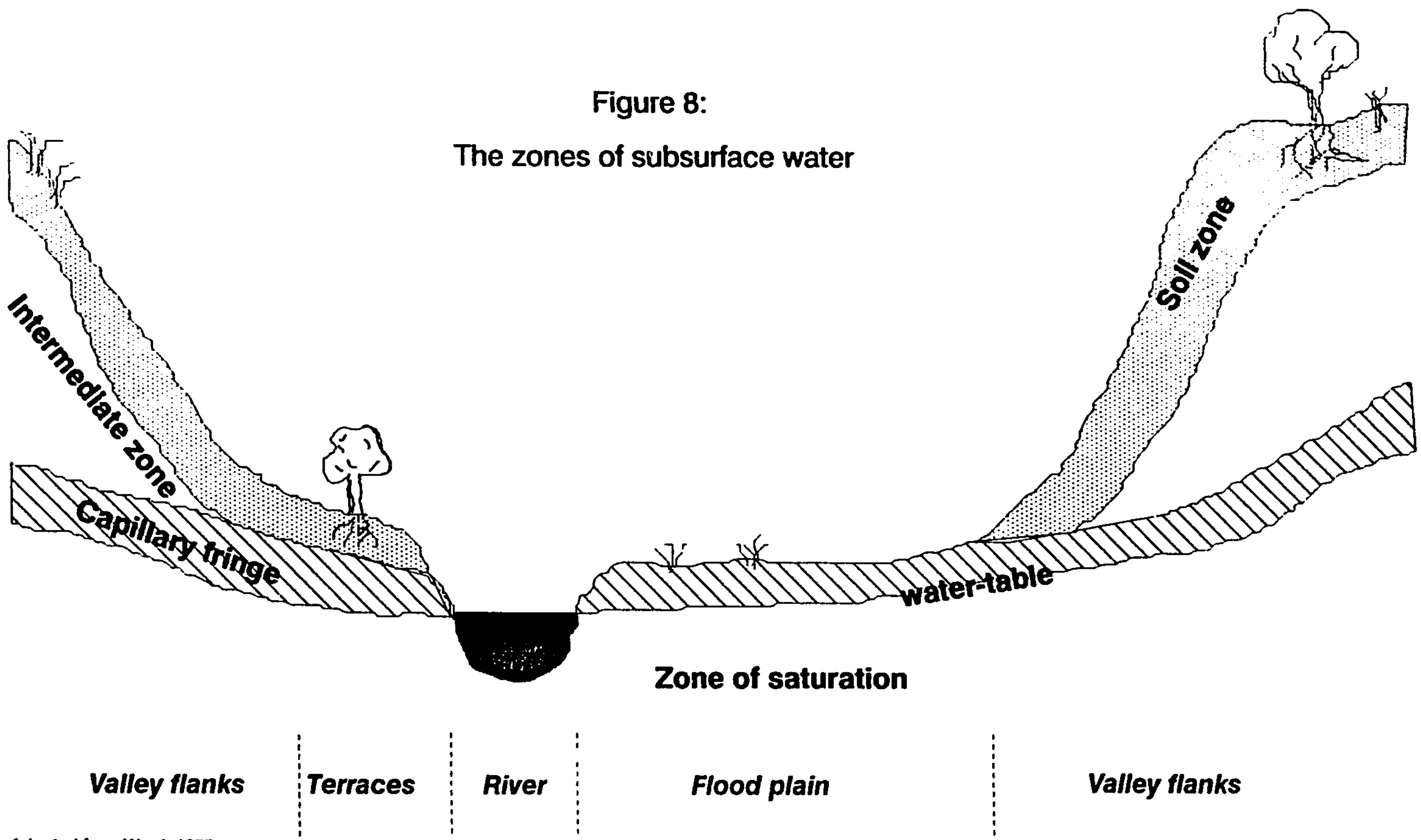
3.3 Field Capacity of Soils

GCMs calculate soil moisture using certain physical assumptions (see Section 5.2). The GCMs consider the amount of soil moisture in their control and perturbed runs either as a fraction of field capacity or as an absolute mass of water in a given volume of soil. Field capacity is defined by Veihmeyer and Edlefsen (1937) as "the amount of water held in soil after excess water has drained away and the rate of downward movement has materially decreased" (see Fig.9a). For the AES model, this "amount of water" has an extensive property, i.e. it depends on the region it considers, but is expressed as an intensive quantity (i.e. a mass of water per unit of cross-sectional area, e.g. a field capacity of 150 kg m^{-2}). It may also be expressed as an equivalent depth of bulk water, e.g. 15 cm. GCM scientists define important soil moisture terms differently than soil scientists do. Soil moisture is calculated for the GCMs in this thesis using the "bucket" method. In this method, one imagines a "bucket" of a certain depth (the field capacity) in the ground with its rim at the surface. The depth of the bucket differs, depending on the model (and, in the case of

AES, with the location). The amount of water in the bucket at any time is the accumulated precipitation minus evaporation, as in Thornthwaite's water balance model (Thornthwaite, 1948). When the bucket becomes full, the soil is saturated, field capacity has been reached, and any further precipitation results in runoff. Different bucket depths used in the GCMs mean different field capacities. Soil scientists, however, consider soil saturation and field capacity to be separate entities, functions of soil texture and porosity. To a soil scientist, saturation occurs when soil pores are filled with water. For medium textured soils, a porosity of 50% would approximate saturation. Field capacity occurs at approximately 35 to 40% by volume. The use of the bucket concept is not very realistic, but Ward (1975) states that, although untenable in theory, the subjective variable "field capacity" has proven valuable in practice. Van Bavel (1969) suggested that the idea of a retentive capacity is essential and useful in broad generalizations pertaining to watershed hydrology, drainage, and irrigation. The AES model uses a modified bucket approach. For the AES model, field capacity is set to various but unchanging values, that is, this field is specified for each gridpoint, and remains fixed throughout the model runs (Sargent, correspondence, 1993). This field is only available in a "specified fields" dataset, provided by Environment Canada. These "FCAP" values for Alberta appear in Table 8a (Chapter 5.2b). It is difficult to find details on how the other models handle field capacity or runoff. The GISS model has variable field capacities for different terrain types in its top and bottom soil layers (see section 5.1d). From available literature, it appears that field capacity for the five other GCMs does not vary from point to point, for soil type, or for season.

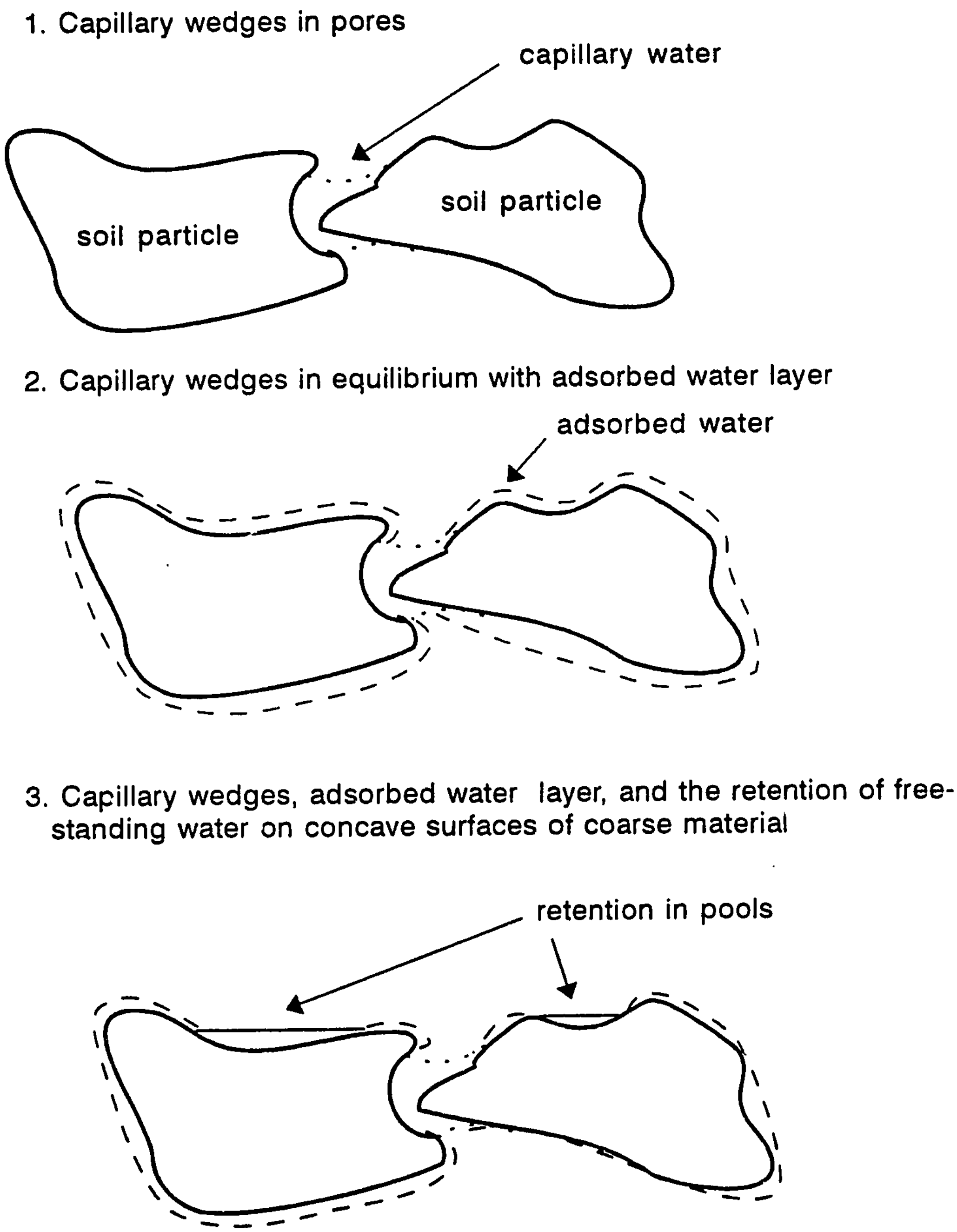
Figure 8:

The zones of subsurface water



Adapted from Ward, 1975

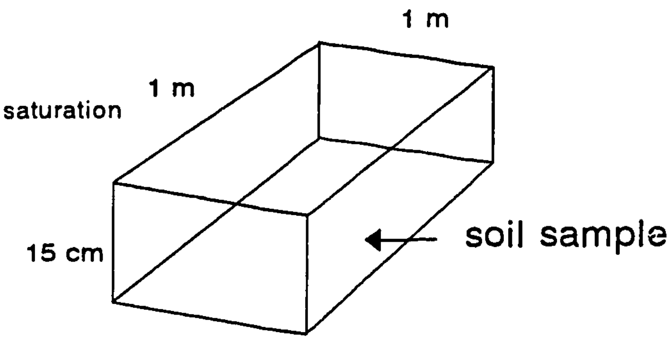
Figure 9: Types of Water Retension

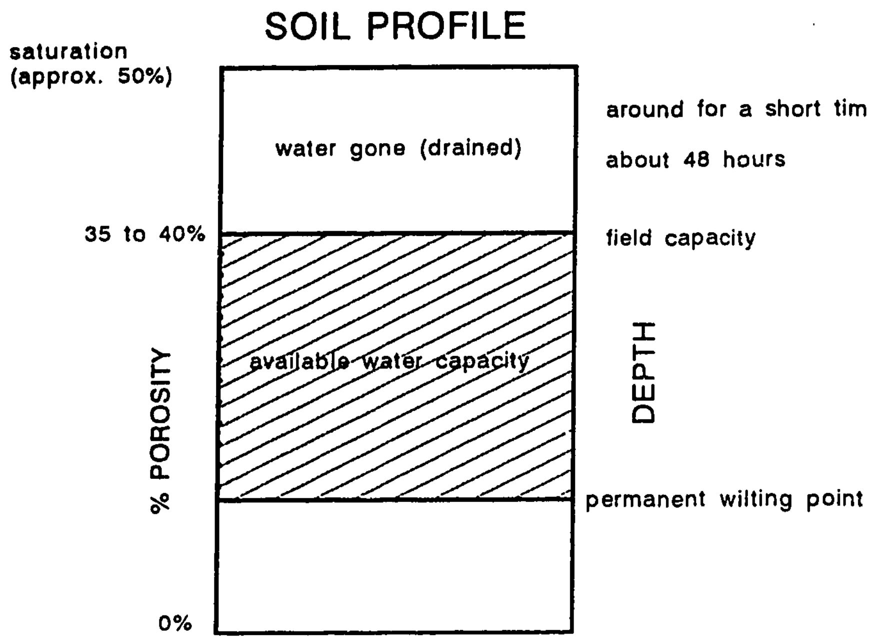


Adapted from Ward, 1975

Figure 9a: Soil Science vs. GCM Treatment of Soil Moisture

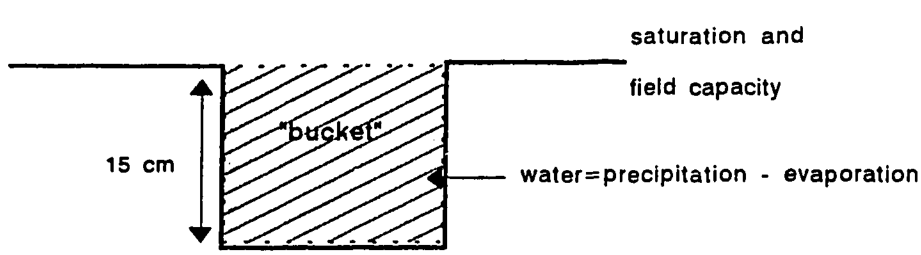
soil sample porosity = $\frac{m^3\ H_2O}{m^3\ soil}$ at saturation





In soil science, saturation and field capacity are a function of porosity. At saturation, all the pores are full of water and this amounts to about 50% of the total volume.

GCMs use the "bucket method" of measuring soil moisture. A "bucket", usually 15 cm deep does not take soil texture or porosity into consideration. The bucket has no soil in it. When the bucket is full, saturation occurs and field capacity is reached--a different definition of terms than above.



Chapter 4

Observed Soil Moisture

4.1 Methods of Measuring Soil Moisture

While many methods exist to measure soil moisture in the field, Wilson (1970) has described nine of the ones most frequently used. They are:

1. Gravimetric
2. Neutron scattering
3. Gamma-ray attenuation
4. Electrical resistance
5. Electrical capacitance
6. Archimedes principle
7. Chemical
8. Thermal conductivity
9. Ultrasonic

Wilson considered the first three methods to have gained the greatest acceptance because they are often the easiest to implement and the most accurate. The method used to measure the observed Alberta soil wetness for this thesis was not one of these nine. It is by Howard, Heywood and Michielsen (1992) and is explained later in this section.

The gravimetric method involves weighing a soil sample before and after it has been dried and attained a constant weight. The weight of the water in the wet sample is the difference between the weights of the wet and dry samples, and can be expressed as a percentage of the mass of the dry sample. The gravimetric method is labour intensive and time consuming, making a survey of soil moisture for a region the size of Alberta difficult. The neutron scattering method involves placing a high-energy neutron emitter into the soil where the neutrons are slowed by collisions with hydrogen nuclei present in soil water. An underground receiver counts the neutrons. The neutron count is a function of the soil moisture by volume, which must be determined by calibration. The neutron scattering method saves labour but requires a large initial investment. The gamma ray attenuation technique is based on the observation that the scattering and absorption of gamma rays are related to the density of water in the soil (Dmitriyev, 1966). A gamma ray emitter is placed underground and a receiver measures the amount of scattering and absorption of the gamma rays by the soil water. This technique also requires a large initial investment and while it has been used extensively in field studies in the U.S.S.R., in North America it is primarily used in the laboratory.

The Alberta soil moisture data in this thesis were provided by soil moisture specialist A.E. Howard of the Alberta Agriculture Conservation and Development Branch. Sites are selected where topography is level, and, when possible, where the soil is medium textured. Sites in southern areas usually are stubble fields (no fall tillage).

Sites in many central and northern regions are cultivated fields. The number of sample sites ranges from about 250 in the early 1980s maps to about 400 in the recent maps. Samples have been taken throughout October since 1982 to produce the "Stubble Soil Moisture for Fall" maps, and throughout April since 1988 to produce the "Stubble Soil Moisture for Spring" maps (see Appendix A). Soil is sampled using a 2-m king tube probe. The probe is pushed without turning into the soil. The depth of penetration is the depth of the moist soil, since the probe will penetrate moist soil but will be stopped by dry soil, rock, gravel, and frozen soil. A collector at the end of the tube provides a sample of soil (about 10 cc) at the spatial end of the penetration depth, after a clockwise twist of the probe. The soil is removed from the collector and inspected for degree of wetness, depth of moisture, and soil texture (Howard et al., 1992). The moisture category of the soil is determined by the depth to which moist soil was found. This determination is done with a simple visual, hand-held examination of the sample. Soils are considered to be moist if they remain in the shape of a ball after being pressed into that shape by the hand. The auger method has not been calibrated against one of the "standard" methods. The categories are shown in Table 6 and are estimated for a medium textured soil.

Table 6

Alberta Stubble Soil Moisture Categories for Medium Soil Textures (Compiled by Alberta Agrigulture)

Category	Soil Moisture Depth
High	Subsoil moist to beyond 75 cm below surface. No dry layers
Medium	Subsoil moist to 45-75 cm
Low	Subsoil moist to 15-45 cm
Very Low	Little or no available water below 15 cm

These categories apply to medium soil textures. Wherever possible, samples were taken from this type of soil. For coarse sandy soils, the penetration depth (soil moisture depth) is multiplied by 1.5 and then Table 6 applies, using this adjusted soil moisture depth. For fine clay soils, the penetration depth is multiplied by 0.7.

This method provides measurements of Alberta stubble soil moisture as an effective depth of moist soil, whereas in the GCMs soil moisture is considered to be the effective depth of liquid water in the soil. A conversion method or factor is required to translate the Alberta soil moisture measurements into GCM units of moisture if the two are to be compared. Mr. Howard and the Environment Canada Winnipeg Climate Centre are developing such a technique. As of 1992, a rough procedure has been developed, shown in Table 7. For the conversion of soil moisture to a water depth, 75 cm of wet soil translating to 11.25 cm of water is basically an assumption that the moist soil has a water content of 15 % by volume.

Table 7

Conversion of Alberta Agriculture

Stubble Soil Moisture Measurements into

Percentage of Field Capacity (F.C.)

Category	Soil Moisture Depth	% of F.C.*	cm moisture*
High	Subsoil moist to > 75 cm No dry layers	> 75	> 11.25
Medium	Subsoil moist to 45-75 cm	45 to 75	6.75 to 11.25
Low	Subsoil moist to 45 cm	15 to 45	2.25 to 11.25
Very Low	Little or no available water below 15 cm	< 15	< 2.25

* where Field Capacity = 15 cm

4.2 Observed Soil Moisture in Alberta

Kellogg and Zhao (1988) stated that it is useful to compare the monthly average distribution of soil moisture calculated for a GCM control run to the average for the real soil. Data on temperature, pressure, etc. are readily available for such a comparison, but this is not the case for soil moisture. Lawford (1992) mentioned that reliable soil moisture datasets for verifying GCM outputs are difficult to obtain. In Alberta, soil moisture measurements have been made using several of the methods described in Section 4.1, but only at small [illegible]ntal sites. For the province as a whole, however, t[illegible] extensive soil moisture measurements are the Alberta Agriculture Conservation and Development Branch "Soil Moisture Maps" (see Appendix A). The data, collected as described in Section 4.1, have been used to generate maps of Alberta stubble soil moisture for the spring (April) and fall (October) seasons (Howard et al., 1992). At the time of writing this thesis, Alberta spring soil moisture maps were available from 1988 to 1991. Alberta fall soil moisture maps were available from 1982 to 1991. The maps are based on about 400 single measurements made over the spring and fall periods. When comparing the GCMs to actual Alberta soil moisture, then, comparisons can only be made between the October and April monthly GCM soil moisture data and the October and April actual soil moisture. The NCAR model could not be compared with the observed April and October values since only winter and summer seasonal soil moisture data were provided by NCAR. The variation of $1XCO_2$ and $2XCO_2$ average soil moisture of the models for NCAR-type seasons appears in Appendix B, Tables 8a to 8g. In these tables, the monthly means (20-minute time steps averaged over each month, with the monthly values averaged over a climatological period of 10 model-years) for models other than NCAR were averaged over the winter and summer seasons. The maps generally show greater soil moisture in the spring, due to infiltration of snowmelt water, than in the fall, when soil moisture is evaporating or percolating deep into the soil, below the 100 cm level. Soil moisture remains generally low to very low in the southeastern region of the province in both seasons throughout the period of measurement. West-central Alberta tends to have consistently the greatest amount of soil moisture, and the Peace River and Grande Prairie regions tend to be slightly drier than central Alberta. These are general geographic regions and not well-defined agricultural regions.

Only four years of spring measurements and nine years of fall measurements make it difficult to derive a stable "normal" seasonal soil moisture amount over an area, using these data. It is not possible to tell whether any of the soil moisture seasons are particularly anomalous (abnormal) because they are all anomalous! An anomalously large amount of precipitation does not necessarily imply a corresponding soil moisture anomaly since a lot of evaporation in the same season may even bring about a soil moisture deficit. An average actual soil moisture for the seasons is calculated for the model gridpoints shown in Figures 1 to 7. The procedure for calculating the mean and standard deviation soil moisture values from the observed maps, and comparing them with the GCM data is described in Section 5.2a.

Chapter 5

Soil Moisture Sensitivity in the Models

5.1 Soil Moisture Parameterization in the Models

5.1a Introduction

Sensitivity analysis assesses the change in model output resulting from a change in inputs or model parameters. To begin with, it is important to see how the GCMs parameterize soil moisture.

More current versions of the models than those compared in this thesis may have upgraded soil moisture parameterizations, but details were not available to the author. Delage and Hogue (1992) discussed a more sophisticated treatment of soil moisture for the Canadian NWP model. Their plan was to incorporate the newly developed Canadian Land Surface Scheme, CLASS (Verseghy, 1991), which contains all of the important physical processes such as snowmelt, soil freezing/ thawing, and seasonal changes in vegetation characteristics. CLASS has three soil layers, capped by an explicit snow layer and one of five types of canopy. The changes in the NWP model will eventually be incorporated into the AES GCM.

5.1b AES Model

This model's treatment of soil moisture and hydrology is more realistic than the usual "bucket" treatment (see Section 3.3). Soil moisture and snow mass are prognostic variables in the model. Soil moisture, w, is expressed as:

$$w = W/W_c \qquad 5.1.1$$

where W is the total soil moisture mass in the surface soil layer (single layer model), and W_c is the field capacity (see Table 8a, Chapter 5.2b). This superscript parameter is idealized because in the natural situation, the field capacity varies widely according to the soil's characteristics. The field capacity in the AES model is expressed in kg/m^2 instead of a "bucket" depth in cm. Clearly, however, 200 kg m^2 is equivalent to a 20 cm bucket depth.

The soil moisture in this model is further subdivided into both liquid w_l and frozen w_f forms so that:

$$w = w_l + w_f \qquad 5.1.2$$

The prognostic equations for these two components of soil moisture and snow mass, S, are:

$$W_c \frac{dw_l}{dt} = P_l - E_l + M_f + M_s - R \qquad 5.1.3$$

$$W_c \frac{dw_f}{dt} = -E_f - M_f \qquad 5.1.4$$

$$\frac{dS}{dt} = P_s - E_s - M_s \qquad 5.1.5$$

where P_l, P_s are respectively rain and snow precipitation rates; E_l, E_f, E_s are respectively the liquid soil moisture, frozen soil moisture and snow evaporation/sublimation rates; M_s, M_f are the melting rates of snow and frozen soil moisture; and R is the runoff. Precipitation arriving at the surface is regarded as either rain or snow (no hail) according to whether the surface air temperature (T_s) is above or below the freezing point (T_f).

The evaporation rates in the prognostic equations must add up to the total evaporation rate:

$$E_l + E_f = E_w \qquad 5.1.6$$

$$E_w + E_s = E_{VTs} \qquad 5.1.7$$

where E_l is the liquid evaporation rate, E_f is the frozen sublimation rate, E_w is the total soil moisture evaporation/sublimation rate, E_s is the snow evaporation/sublimation rate and E_{VTs} is the turbulent vertical flux density of moisture at the surface. The contributions of E_l and E_f to E_w are assigned according to whether the surface temperature is above or below the freezing point, i.e.:

$$E_l = E_w, \quad E_f = 0 \quad \text{if} \quad T_s > T_f \qquad 5.1.8$$

$$E_l = 0, \quad E_f = E_w \quad \text{if} \quad T_s \leq T_f \qquad 5.1.9$$

Pack ice and glacial ice are also considered in the model but their parameterization is of no concern for Alberta soil moisture comparisons.

Runoff is not explicitly calculated. When the total soil moisture reaches a value in excess of the field capacity (w>1), the excess is assumed to run off, and w is set to unity.

5.1c The GFDL Model

The surface hydrology of this model is similar to that of the NCAR mod . Soil moisture is dete ined prognostically from a one-layer model with 15 cm field capacity.

The prognostic equations for soil moisture, over snow-free land are:

$$\text{if } W < W_{fc} \qquad \frac{dW}{dt} = P - E \tag{5.1.11}$$

$$\text{if } W = W_{fc} \text{ and } P > E \qquad \frac{dW}{dt} = 0 \text{ and } R = P - E \tag{5.1.12}$$

and over snowcover they are:

$$\text{if } W < W_{fc} \qquad \frac{dW}{dt} = S_m + P \tag{5.1.13}$$

$$\text{if } W = W_{fc} \qquad \frac{dW}{dt} = 0 \text{ and } R = S_m + P \tag{5.1.14}$$

where:
- W = soil moisture (cm)
- W_{fc} = field capacity (cm)
- E = potential evapotranspiration rate (cm/s)
- R = runoff rate (cm/s)
- P = rainfall rate (cm/s)
- S_m = snowfall rate (cm/s)

Runoff occurs only when the bucket is full.

5.1d The GISS Model

In this model, the soil moisture is determined prognostically from a two-layer model. The upper/lower layer field capacities in cm are prescribed as 1/1 for desert, 3/20 for tundra, 3/20 for grass, 3/30 for shrub, 3/30 for woodland, 3/45 for deciduous forest, 3/45 for evergreen forest and 20/45 for rainforest. When the ground is frozen, water cannot be taken out of the soil.

The prognostic equation for the upper layer is:

$$\frac{dW1}{dt} = \frac{(P - E - R)}{W_{fc1}} + \frac{(W2 - W1)}{T} \quad 5.1.15$$

The prognostic equation for the lower layer is:

$$\frac{dW2}{dt} = \frac{Wfc1}{Wfc2} \times \frac{(W2 - W1)}{T} \quad 5.1.16$$

where:

P = precipitation rate

E = evaporation rate

R = runoff rate

T = time constant for diffusion of moisture between layers

Wfc1 = field capacity in the upper soil layer

Wfc2 = field capacity in the lower soil layer

W1 = layer 1 soil moisture depth

W2 = layer 2 soil moisture depth

5.1e The OSU Model

In this model, soil moisture is determined prognostically from a one-layer model with a 15-cm field capacity. The prognostic equation is:

$$\frac{dW}{dt} = P + S_m - E - R \qquad 5.1.17$$

where W = soil moisture depth

P = precipitation rate

S_m = snowfall rate

E = evaporation rate

R = runoff rate

If W > 15 cm, W is set to 15 cm and excess ground water is taken as additional runoff.

5.1f The UI Model

This model is an updated version of the OSU model, but soil moisture is determined prognostically using the same equations as the OSU model.

5.1g The NCAR Model

Soil moisture is determined prognostically from a one-layer model (as with AES) but using a 15 cm field capacity.

The equation for soil moisture is:

$$\frac{dw}{dt} = P - E + S_m \qquad 5.1.18$$

where E is the rate of evaporation, S_m is the rate of snow melt and w is soil wetness. If the soil wetness in the bucket equals the field capacity and additional precipitation is added, runoff occurs. The evaporation rate is related to soil moisture amount such that the greater the soil moisture, the greater the evaporation rate. If the soil moisture amount exceeds a critical value (75% of the field capacity), the evaporation is that of a liquid surface. If soil moisture is less than the critical value, the evaporation rate is reduced linearly as a function of soil moisture amount.

5.1h The UKMO Model

Soil moisture is determined prognostically from a one-layer model with a 15-cm field capacity. The prognostic equations are the same as for GFDL.

5.2 Soil Moisture in Alberta for GCM Control Runs

5.2a Introduction

In this section, the annual soil moisture variations of control and perturbed GCM runs are compared with each other and with observed stubble soil moisture for different areas of Alberta. An exact spatial comparison of soil moisture values between models cannot be performed since model grid locations differ. Because of the grid locations differing from model to model, as well as the availability of only two months of observed mean soil moisture data, simple side-by-side comparisons are made rather than the objective univariate statistical tests proposed by Chervin (1981). None of the models' data included standard deviations of soil moisture.

The Alberta Agriculture "Alberta Stubble Soil Moisture Maps" provide data based on measured soil moisture for the province. The maps consist of polygons showing the different depths to which soil is moist in April and October throughout agricultural regions of the province. Comparisons can thus be made between the actual values and GCM values for two months of the year.

To begin the comparison, a conversion is made from depth of soil moisture on the maps to cm of soil moisture to match the units of model output (see Chapter 4). Transparent soil moisture maps (see Appendix A) for each year and season (spring and fall) are then overlaid on maps of the same scale showing each model's Alberta gridcells. A second transparency with dot matrix is then put over the two images. The dot resolution is about 40 km on the scale of the gridcell and moisture maps. By counting the number of cells in each observed soil moisture polygon for each GCM grid cell, one can calculate the spatial mean stubble soil moisture in each GCM grid cell for each April and October in the available years of data. The spatial standard deviation for each GCM grid cell is also calculated. A temporal mean of actual Alberta stubble soil moisture for both April and October is calculated as the mean of each year's spatial mean value. A temporal standard deviation is also calculated about this temporal mean. Unfortunately, the complete province could not be sampled using soil moisture maps. The northern regions and parts of the eastern slopes have no soil moisture data. Consequently, no comparison between model control run values and actual soil moisture values could be made in these areas. In other GCM grids, observed moisture values are available for only part of the grid. If observed values exist for less than 50 % of the grid area, a comparison is also not made, since the available observed values may not be representative of the whole grid's stubble soil moisture. This occurs for regions north and east of 56°N, 114°W, and for regions south and west of 55°N, 118°W.

5.2b AES 1XCO_2 Run

The AES Global Climate Model (1990) control and perturbed data were obtained from Dr. Neil Sargent at the Canadian Climate Centre in Downsview, Ontario. Five megabytes of condensed data containing several model parameters were received in ASCII format on 3.5 inch diskette. Liquid and frozen soil moisture data were extracted from this data set. A program was written to convert the data into Statistical Applications Software (SAS) format to allow for data analysis using SAS. A subset of gridpoints in and around Alberta (25 points) was then created, and soil moisture amounts for these points were converted into cm of field capacity to make the units of soil moisture comparable with those of the other models.

Figure 10 (A to T) shows the annual variation of AES 1XCO_2 soil moisture as well as the mean and standard deviation of the observed April and October Alberta stubble soil moisture (where data are available). Each figure presents the results for a single GCM grid cell in Alberta. Each cell is identified by its corresponding central point. The AES soil moisture values are a sum of model frozen soil moisture and liquid soil moisture. The most interesting feature is how much higher the soil moisture values are compared to the other GCMs. It is important to note that there is a different field capacity for each grid cell. These values are shown in Table 8a and should be consulted when viewing the AES figures. The values still seem impossibly high for some months, however. Dr. Neil Sargent (Canadian Climate Centre) mentioned in correspondence that the model "runs fairly wet". The AES "bucket size" of approximately 80 cm would require 5.4 m of soil at the 15 % volume value used in converting observed soil moisture to water depth. This depth of soil is, of course, unrealistic, which demonstrates that that AES soil moisture values are also unrealistic. Most AES grid points show soil moisture peaking in spring, (April or May), with a minimum during fall, between August and September. Soil moisture tends to increase from September to December and remains almost constant throughout the winter at all grid points in the province until the spring recharge and peak. The values increase toward the Eastern Slopes and the north and northwest parts of the province (with about 40 to 75 cm of soil moisture). The drier areas tend to exhibit more annual variability than the wetter areas. Unfortunately, since observed soil moisture values are only available for April and October, it is not possible to tell how accurately the model's annual variation simulates the actual soil moisture annual variation. All AES model values are at least double the observed stubble soil moisture values. Spatial differences in soil moisture show similar trends. The areas and months with low observed soil moisture are areas of low model soil moisture. The observed wetter regions of the province are also simulated by the AES model, but in both cases the model values are much larger.

Tablc 8

Annual Soil Moisture Means (cm) for the AES GCM

1XCO_2 Run as a Function of Lat. and Long.

for Gridpoints in and near Alberta (see Fig. 1)

	LONG °W				
LAT °N	123.75	120.00	116.25	112.50	108.75
61.22	56.2	21.8	21.6	58.1	73.7
57.51	55.3	57.0	57.9	29.0	65.0
53.80	62.5	70.1	71.3	36.7	37.5
50.09	48.3	58.0	49.3	35.3	26.9

Table 8a

AES GCM Field Capacity Values (cm) for

for Gridpoints in and near Alberta

	LONG °W				
LAT °N	123.75	120.00	116.25	112.50	108.75
61.22	64.1	52.1	60.1	72.1	80.1
57.51	56.2	59.9	64.9	45.6	80.1
53.80	64.1	72.1	74.9	42.0	48.0
50.09	56.2	64.1	56.2	45.0	48.0

5.2c GFDL 1XCO_2 Run

The GFDL (1986) control and perturbed data were obtained from Mr. Roy Jenne at the United States National Center for Atmospheric Research (NCAR) in Boulder, Colorado and were supplied in printed form. Monthly soil moisture climate data for North America were provided and a subset of gridpoints for the Alberta region was identified. These were keyed in manually. Soil moisture units were provided in mm and were converted to cm for comparison purposes. Figure 12 (A to F) shows that the GFDL model soil moisture values are far lower (about 8 to 12 cm) than those of the AES model. The GFDL spring and fall values compare well with the observed stubble soil moisture values at most gridpoints, and generally lie near or within one standard deviation of the observed mean.

While the soil moisture absolute amounts differ considerably between the AES and GFDL models, both models exhibit similar annual variations. The GFDL model exhibits the maximum soil wetness during April and the minimum in August or September, as does AES. Where there is a spatial increase or decrease in observed mean April or October soil moisture, there is a similar fluctuation in GFDL model values. South and central areas of the province are drier than north and west areas. GFDL soil moisture values do not exceed field capacity (15 cm) so there is no runoff in any of its Alberta grids.

Table 9

Annual Soil Moisture Means (cm) for the GFDL GCM $1XCO_2$ Run as a Function of Lat. and Long. for Gridpoints in and near Alberta (see Fig. 3)

	LONG °W	
LAT°N	**120.00**	**112.50**
59.99	12.7	8.8
55.55	13.4	8.1
51.11	12.4	10.1

5.2d GISS $1XCO_2$ Run

The GISS GCM (1985) control and perturbed data were also obtained from Mr. Roy Jenne at NCAR and were received in the same format as the GFDL data. Figure 11 (A to D) shows that the model's soil wetness for each Alberta gridpoint (about 8 to 20 cm) is substantially lower than the AES values but higher than those of GFDL. While closer to the observed mean than AES, the soil moisture does not compare as closely as GFDL. The model values fall outside one standard deviation of the observed mean except for October at 50.87 N, 110.00 W and at 50.87 N, 120.00 W. The annual cycle of GISS soil wetness is similar to that of AES and GFDL, where the minimum occurs in August or September and the maximum occurs in April or May. GISS soil moisture increases north and west in Alberta. The model soil moisture values exceed field capacity in some cases, so runoff occurs.

Table 10

Annual Soil Moisture Means (cm) for the GISS GCM $1XCO_2$ Run as a Function of Lat. and Long. for Gridpoints in and near Alberta (see Fig. 2)

	LONG °W	
LAT °N	120.00	110.00
58.70	19.2	16.9
50.87	15.6	10.6

5.2e OSU $1XCO_2$ Run

The OSU (1985) and UI (1988) control and perturbed data were provided by Drs. Michael Schlesinger and Hajo Smit of Champagne, Illinois, in both digital and hard-copy form. The data were multiplied by 15 cm (the field capacity) to obtain the soil moisture amount in cm. According to Dr. Schlesinger (personal communication), the OSU model is the "old" model and the UI model is the new one. The values never exceed field capacity (15 cm) so there is no runoff. The OSU model tends to show decreasing soil moisture amounts toward the north and western regions of Alberta. This is opposite to AES, GFDL and GISS. OSU moisture values vary from about 6 to 12 cm. They exhibit the closest fit to observed April and October mean values, being within one standard deviation of the observed October mean at all six gridpoints with available data, and one standard deviation of the observed April mean at two of the six gridpoints with available data.

Table 11

Annual Soil Moisture Means (cm) for the OSU GCM $1XCO_2$ Run as a Function of Lat. and Long. for Gridpoints in and near Alberta (see Fig. 4)

	LONG °W		
LAT°N	**120.00**	**115.00**	**110.00**
58.00	5.5	4.0	5.1
54.00	5.8	5.4	3.6
50.00	7.8	6.4	5.4

5.2f UI $1XCO_2$ Run

Figure 14 (A to I) shows the annual variation of UI $1XCO_2$ GCM soil moisture values versus the mean and standard deviation of actual stubble soil moisture (where available) for the UI gridpoints in Alberta. This model shows similar annual variation to AES, GFDL and GISS, with the maximum soil moisture in April or May and the minimum in August or September at each gridpoint. Unlike AES, GFDL and GISS, there is not a clear trend of increasing soil moisture toward the northwest region of Alberta. Five out of nine UI gridpoint April soil moisture values lie within one standard deviation of the observed mean. Four out of nine October soil moisture values lie within one standard deviation of the observed mean.

Table 12

Annual Soil Moisture Means (cm) for the UI GCM $1XCO_2$ Run as a Function of Lat. and Long. for Gridpoints in and near Alberta (see Fig. 5)

	LONG °W		
LAT°N	120.00	115.00	110.00
58.00	5.1	4.3	3.8
54.00	6.5	4.8	3.9
50.00	7.5	6.2	4.8

5.2g NCAR $1XCO_2$ Run

NCAR GCM (1984) data were obtained from Mr. Roy Jenne at NCAR, after consulting with Drs. Warren Washington and Gerald Meehl, also of NCAR. The data were downloaded from an NCAR file through a modem. A SAS program was written to read in the appropriate gridpoints and a conversion from metres to centimetres of soil moisture was made. Since NCAR model soil moisture values were provided for only winter (average of December, January and February) and summer (average of June, July and August) its annual variability cannot be plotted. In addition, a comparison cannot be made with the observed mean April and October soil moisture values. Table 4 shows the variation with season for NCAR $1XCO_2$ and $2XCO_2$ average soil moisture. Soil moisture values for this model never exceed field capacity within the Alberta grid, so there is no runoff. There is a sharp increase in winter soil moisture as one moves north and west toward the 61.90 N grid, and a decrease in summer soil moisture toward the northwest. NCAR soil moisture amounts are the lowest of all the six models for the agricultural regions of Alberta.

Table 13

Annual Soil Moisture Means (cm) for the NCAR GCM $1XCO_2$ Run as a Function of Lat. and Long. for Gridpoints in and near Alberta (see Fig. 6)

	LONG °W	
LAT°N	**120.00**	**112.50**
61.90	3.6	2.1
57.40	6.3	3.1
52.90	7.2	3.1
48.40	0.9	2.2

5.2h UKMO $1XCO_2$ Run

UMKO GCM (1987) data were obtained from Dr. Paul Norris at the British Meteorological Office, Bracknell, U.K. The data were global soil moisture values provided on a 3.5" diskette. A SAS program was written to read the data into

SAS format and a subset of Alberta values was created. Values greater than 99 indicate a non-land surface type (ice, sea, and sea ice). At first, most values for the province indicated a surface type corresponding to sea. Correspondence with Dr. Norris did not clear up the matter. Eventually, an error in the U.K. documentation was found by the author, Dr. Norris was notified of this, and the data were read in correctly. Some of the monthly data, however, still indicate a surface type equal to sea or ice.

Figure 15 (A to L) shows the annual variation of UKMO $1XCO_2$ GCM soil moisture values versus the mean and standard deviation of actual stubble soil moisture (where available) for the UKMO gridpoints in Alberta. This model shows similar annual variation to AES, GFDL and GISS, with the maximum soil moisture in April or May and the minimum in August or September at most gridpoints. Missing points for months in the graphs indicate values out of range (again, the bogus values of 100 or 10,000 cm).

Table 14

Annual Soil Moisture Means (cm) for the UKMO GCM $1XCO_2$ Run as a Function of Lat. and Long. for Gridpoints in and Near Alberta (see Fig. 7)

	LONG °W		
LAT°N	**123.70**	**116.20**	**108.70**
57.50	12.2	11.3	13.0
52.50	12.4	12.2	11.9
47.50	11.9	11.1	10.9

Table 14 is based on a sample where units greater than 99 cm (indicating surface type=sea or sea ice) have been removed.

5.2h Discussion

Based on the data made available by the AES, GFDL, GISS, OSU, UI, NCAR and UKMO GCM labs, as well as available Alberta stubble soil moisture data, the UI model most accurately simulates current Alberta soil moisture. The UI model also has one of the better model grid resolutions for Alberta (nine grids). The OSU model values also approximate several observed means. The AES model has good resolution but compares poorly with the observed means, lying further from the observed means than all the other GCMs in the comparison, except, in some cases, UKMO, where some months are not represented in the annual variation because of their incorrect surface type and accompanying values of greater than 99 cm of soil moisture.

5.3 GCM Perturbed Run Data for Soil Moisture in Alberta

5.3a Introduction

In this section, we compare each model's perturbed ($2XCO_2$) run with its control run. We also compare GCMs. Comparison is made between annual variation of the runs in timing and magnitude. Changes in soil moisture amounts with changes in location are also considered.

5.3b AES $2XCO_2$ Run

Figure 16 (A to T) shows the annual cycle of the AES $1XCO_2$ and $2XCO_2$ GCM soil wetness. The most striking feature is the large decrease in soil moisture for the perturbed run from November to March at 18 of the 20 gridpoints. These particular values now resemble the values of the other models' control runs. For 8 of 20 grids, April to November moisture amounts are 1 to 6 cm below control values. In the extreme northwest (61.22 N, 120.00 W) the $2XCO_2$ run shows a 10 cm increase from May to October. Small increases in $2XCO_2$ values over $1XCO_2$ values occur in south and central Alberta for October and November at 50.09 N, 116.25 W, at 53.80 N, 112.50 W and at 53.80 N, 116.25 W. The model simulates small increases of about 1 or 2 cm of soil moisture for June to November at 57.15 N, 108.75 W, for May and June at 57.51 N, 112.50 W, for May to September at 61.22 N, 116.25 W, for June to October at 61.22 N, 123.75 W, and a large increase of 10 cm for May to November at 61.22 N, 120.00 W.

5.3c GFDL $2XCO_2$ Run

Figure 18 (A to D) shows far less variation between GFDL control [illegible]turbed monthly soil moisture values than occurs in the [illegible]. The control and perturbed variations are similar. [illegible] the southeast region of the province (51.11 N, 112.50 W) there is an increase in the perturbed soil moisture values over the control values of about 2 to 4 cm during December to March. A decrease in the perturbed values occurs in this region from April to December (about 0.5 to 4 cm). The southwest region of the province (51.11 N, 120.00 W) shows perturbed values almost identical to control values from December to August. Decreases in soil moisture occur from August to mid-November, with the largest decreases of about 3 cm occuring around mid-September. GFDL east-central Alberta (55.55 N, 112.50 W) $2XCO_2$ soil moisture is greater than control values by about 1 to 3 cm from September to mid-March, but lower values occur during the summer (April to August). West-central (55.55 N, 120.00 W) perturbed values exhibit a similar pattern, as does the northern region of the province. GFDL perturbed soil moisture values never exceed field capacity.

5.3d GISS $2XCO_2$ Run

Figure 17 (A to I) shows that the GISS model's perturbed run soil moisture exceeds the control values for most months at all four gridpoints. The annual variations for both runs are similar. The greatest increases in $2XCO_2$ soil moisture (about 2 to 8 cm) compared to $1XCO_2$ occur during winter months and the smallest increases occur in August and September. Southeast Alberta (50.87 N, 110.00 W) sustains a slight decrease in soil moisture during September and October. The GISS $2XCO_2$ run shows a small decrease in July to September at 58.70 N, 120.00 W during June to October. GISS $1XCO_2$ and $2XCO_2$ soil moisture values at times exceed field capacity.

5.3e OSU $2XCO_2$ Run

Figure 19 (A to I) shows that a similar variation occurs at all nine grids, with $2XCO_2$ values increasing over $1XCO_2$ values in spring (March to May) and remaining below $1XCO_2$ values for most of the remaining months. The largest $2XCO_2$ decreases occur from July to September. OSU $2XCO_2$ soil moisture values do not exceed field capacity.

5.3f UI 2XCO$_2$ Run

Figure 20 (A to I) shows a similar annual variation for UI 1XCO$_2$ and 2XCO$_2$ soil moisture values, with increases in spring and decreases in summer. At all nine grids, perturbed soil moisture exceeds control soil moisture by about 2 cm from December to March. The peak values occur one month sooner (March) for the 2XCO$_2$ simulation. 2XCO$_2$ soil moisture is lower from mid-March to mid-July then again in September. However, for the driest month in each run, (August), the control and perturbed values are nearly equal. The UI 2XCO$_2$ soil moisture values do not exceed field capacity.

5.3g NCAR 2xCO$_2$ Run

NCAR soil moisture data were made available only for two seasons--winter (December, January and February) and summer (June, July and August). Table 2 was created to allow for comparisons to be made between the control and perturbed GCM runs for NCAR-type seasons. The NCAR model simulates an increase in perturbed soil moisture over control soil moisture during winter for all the Alberta gridpoints. NCAR simulates a decrease in summer soil moisture in the 2XCO$_2$ run for all Alberta gridpoints except in the far northern region of Alberta, where an increase occurs.

5.3h UKMO $2xCO_2$ Run

The UKMO perturbed run shows its greatest departure from the control run at southern and central Alberta latitudes. At high latitudes (57.5 N, 62.5 N) there is little departure, with the perturbed run showing slightly lower soil moisture compared with the control run. In general, the $2XCO_2$ simulation follows a similar annual variation to the $1XCO_2$ run (fairly constant mid-summer soil moisture, a decrease in late summer, and a recovery in fall to the mid-summer values), but is drier, especially from July to September. An exception occurs in March, when, in the low and central Alberta latitudes, the $1XCO_2$ run simulates a decrease in soil moisture while the $2XCO_2$ run simulates an increase.

5.3i Discussion

Based on the soil moisture data made available by the GCM labs as well as available observed Alberta stubble soil moisture data, the GFDL, GISS and UI model $2XCO_2$ runs closely simulate the annual variation of their $1XCO_2$ runs in monthly timing of increases and decreases. The AES model's perturbed run is not realistic with its huge departure from control run winter soil moisture values. For agricultural regions of Alberta, most of the models (AES, GFDL, OSU, UI, NCAR, UKMO) predict drier conditions during summer months and most models (GFDL, OSU, UI, NCAR) predict wetter soil moisture conditions during the winter. These wetter conditions disappear in the perturbed runs before the increases in $1XCO_2$ spring soil moisture peak, though, so the simulated wetter conditions do not continue into the planting season. The GISS model predicts more soil moisture year-round with its $2XCO_2$ simulation compared to its control run at two of its four grids (central and north-central Alberta).

It can be argued (Dr. David Halliwell, personal correspondence) that since some of the modellers do not use soil moisture as a diagnostic variable (to check the validity of the model), there is little importance to the actual number other than how it modifies the behaviour of the model (e.g. evaporation). One GCM may use a completely different range of numbers for soil moisture, yet get the same evaporation since soil moisture is used differently. From this viewpoint, changes in soil moisture may be more critical. Yet some GCM modellers use their GCM soil moisture values to help verify their model's accuracy (Boer et al., 1992, Kellogg and Zhao, 1988, Meehl and Washington, 1988), and climate change impact assessors will use the simulated soil moisture numbers.

The observed data can be used to show that one model or another has realistic values for soil moisture, but this is an independent question from whether or not the changes in soil moisture between control and perturbed simulations are realistic. The changes are what is interesting in the $2XCO_2$ scenario. In response to this, Appendix F shows the percent change in 2XCO2 soil moisture with respect to 1XCO2 soil moisture for the GCMs. The AES model shows a 70% to 90% decrease in soil moisture over winter (primarily February) and small (less than 10%) decreases in summer soil moisture for most grids. GISS shows 10% to 60% increases in winter soil moisture and a decrease in summer soil moisture only in the far northwest portion of the province. GFDL shows mostly 5% to 50% increases in winter soil moisture and approximately 20% to 40% decreases in summer soil moisture. The OSU and UI models also show winter increases and summer decreases in soil moisture, however the change in the timing and magnitude of the soil moisture variability is large. Increases and decreases of 70% to 140% occur at different locations in June-July and August-September for these two models. The UKMO model shows its largest soil moisture increases in March (40% to 80%) except in northern Alberta. Its largest soil moisture decreases occur in August-September (40% to 80%), though again not for northern Alberta. Differences in seasonal changes might be related to seasonal precipitation or evaporation.

Chapter 6

Discussion, Interpretation and Conclusions

The research documented in this thesis was undertaken to provide an original investigation into soil moisture in Alberta through a comparison of seven Global Climate Models and observations. It was found that climate change impact assessors frequently use only one or two GCMs in their assessments, neglect the assessment of soil moisture, and often do not go directly to the source for data, but consult "third-hand" reports for GCM simulation results. This thesis is a first step in remedying that situation.

Each of the seven GCM model developers were contacted to acquire first-hand soil moisture data. This was a frustrating experience in some cases. In theory, all GCM data can be accessed through NCAR digital archives in Colorado. NCAR, howe[illegible] [illegible]quested several thousand dollars to provide the necessary data. The data for some GCMs were not available in their archives, even though those model developers mentioned through correspondence that they had provided NCAR with such data. These data were then provided free of charge by the developers for use in this thesis.

The observed soil moisture data provided by Alberta Agriculture are the best source of measurements available for the province. They are, however, as yet insufficient both temporally and spatially to make good comparisons with the annual variability of the GCMs. Their units of measurement also differ from GCM units and this contributes to unreliability in the comparisons.

The differences between the GCMs' units of soil moisture measurement (especially in the case of AES), soil moisture field capacities and resolutions also adds to frustration in comparison attempts. The GCMs' use and definition of soil moisture terms is often different or incorrect compared to those in the field of soil science.

The lack of detail in GCM documentation of soil moisture processes is unfortunate considering the importance of soil moisture. Errors in GCM documentation and data significantly slow down the comparison procedure, but offer valuable reminders that researchers can contribute to building a false paradigm if they use third-hand data.

Despite the problems encountered while developing this thesis, they offered useful lessons in gathering and quality-controlling data. As stretched as the comparisons are (with adjustments for insufficient data, unit conversion, etc.), they nonetheless present a first look at soil moisture in Alberta through comparisons of GCMs and observations.

Considering the general characteristics of the GCMs compared in this thesis, the AES model has the best horizontal resolution (3.75 deg. lat. by 3.75 deg. long.) and the second best vertical resolution (10 layers). The UKMO model has the best vertical resolution (11 layers), but at 5 degrees latitude by 7.5 degrees longitude, its horizontal resolution is the second most coarse. The OSU and UI models have the closest comparison to observed soil moisture values, but they have the least vertical resolution (2 layers). The GISS model is the only one of the seven that allows more than one type of surface to exist at the same time within one grid box. Its more detailed treatment of surface type, though, is undermined by its low horizontal resolution. The UKMO model is wrong in some of its surface type designations for Alberta.

Considering the soil moisture parameterization of the models, each model is highly unrealistic in how it treats soil moisture storage, field capacity, saturation and runoff. The AES model makes the attempt to achieve some realism in soil moisture storage by not keeping the "bucket" depth constant for all regions. As described in section 5.2b, however, the model's field capacities are an order of magnitude greater than the other models. Another annoying feature of the AES model was to treat soil moisture as a different physical quantity (mass per volume) than the other models (depth). The GISS model appears to have the most detailed of the GCM soil moisture parameterizations with a two-layer model having upper and lower layer field capacities that differ according to a selection of eight canopies. The GFDL, NCAR, OSU and UI models are similar in their parameterizations of soil moisture.

The timing of the models' annual variability for $1XCO_2$ run soil moisture simulations is similar, though the magnitudes differ. The models generally show constant winter soil moisture, increases in spring soil moisture with snow melt and runoff, then decreases in late summer. The UI model most accurately simulates observed Alberta soil moisture for spring and autumn.

For the $2XCO_2$ runs, most of the models predict less soil moisture during summer months. Most models predict more soil moisture during the winter.

The main objective of this thesis was to bring together soil moisture values from seven GCMs and observed measurements for intercomparison. Some reasons for the differences in values for the models exist in their parameterization of soil moisture (Chapter 5). Other reasons can be found in feedback mechanisms that incorporate several other aspects of GCM behavior besides soil moisture. The great amount of time required for a thorough analysis of each model's behavior puts that study outside the realm of this thesis.

A conclusion of this thesis that needs to be stressed is the weakness with which soil moisture is treated by the GCMs. People are using the output for policy decisions. As mentioned by Dr. D. Halliwell and Dr. D. Chanasyk (personal correspondence), the modellers cannot respond to criticism by saying the models "were not set up to do realistic soil moisture simulations" if they are neglecting to tell people not to treat the numbers as if they are realistic! The modellers can't claim that soil moisture is only used in the models to adjust evaporation, and then use it as an indicator of future conditions.

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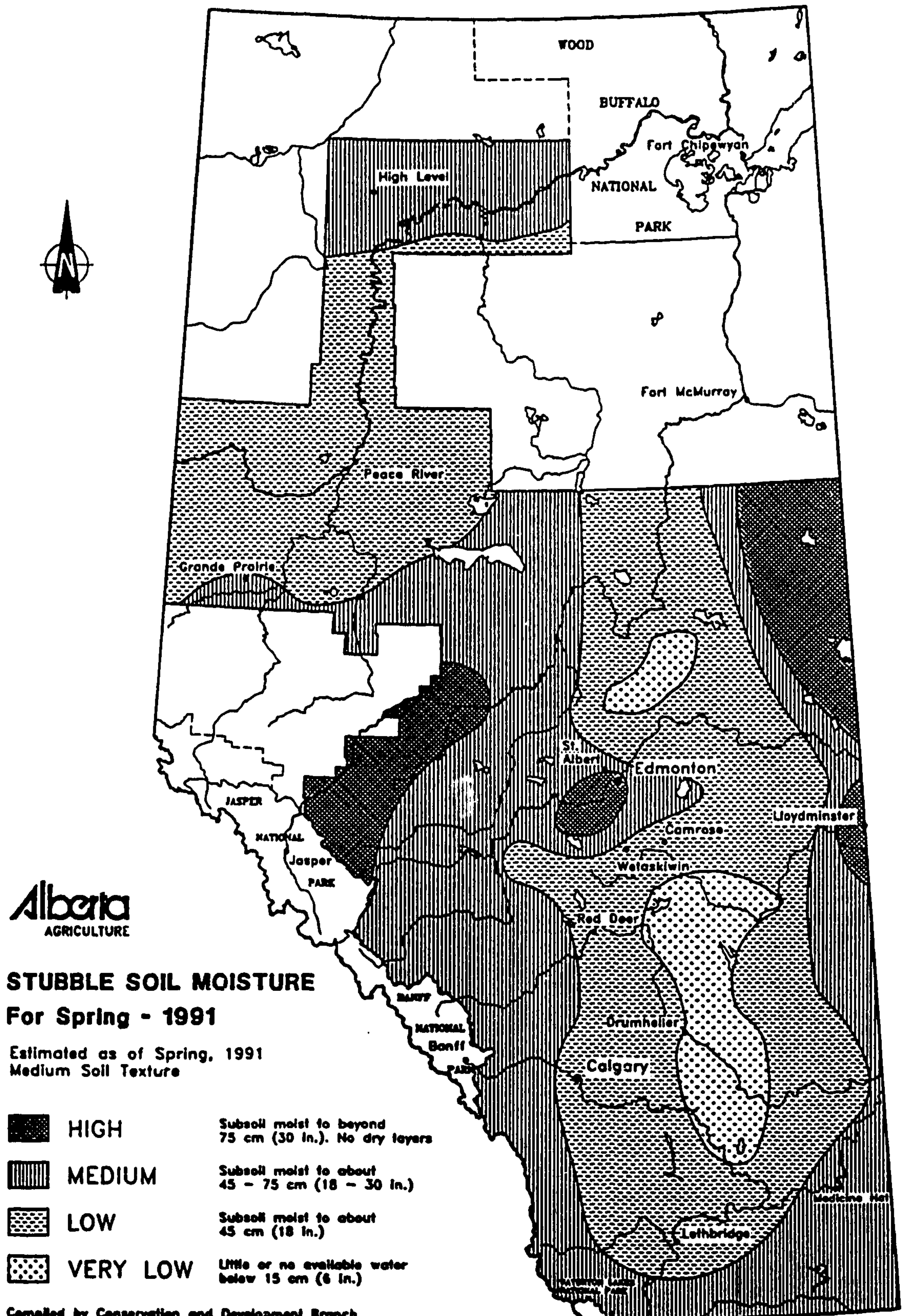
Appendix A:

Alberta Stubble Soil Moisture Maps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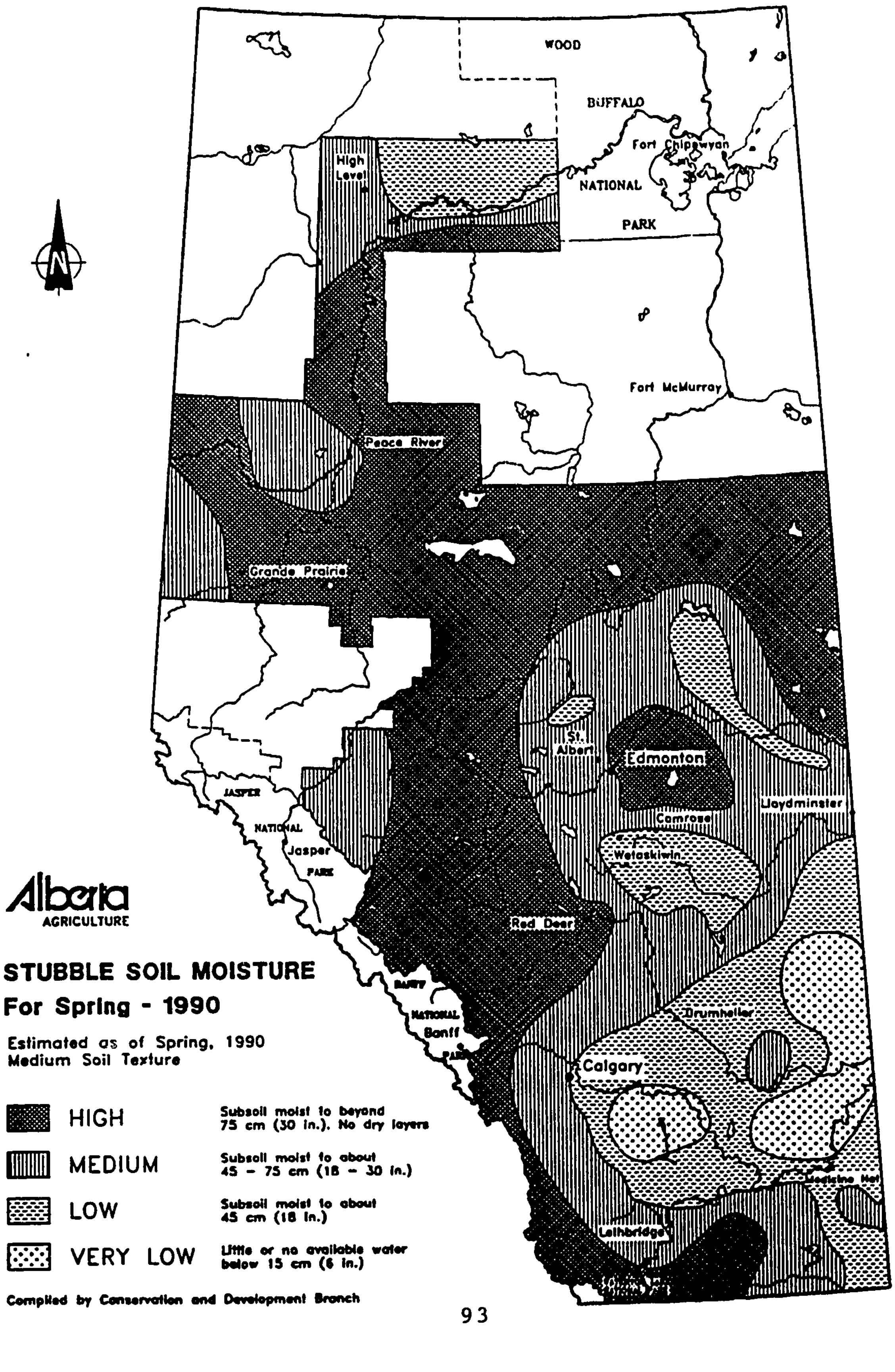
Camrose
Wetaskiwin
JASPER
NATIONAL
PARK
Jasper
Red Deer
Drumheller
BANFF
NATIONAL
PARK
Banff
Calgary
Medicine Hat
Lethbridge
Alberta
AGRICULTURE
STUBBLE SOIL MOISTURE
For Spring - 1991
Estimated as of Spring, 1991
Medium Soil Texture
HIGH
Subsoil moist to beyond 75 cm (30 in.). No dry layers
MEDIUM
Subsoil moist to about 45 - 75 cm (18 - 30 in.)
LOW
Subsoil moist to about 45 cm (18 in.)
VERY LOW
Little or no available water below 15 cm (6 in.)
Compiled by Conservation and Development Branch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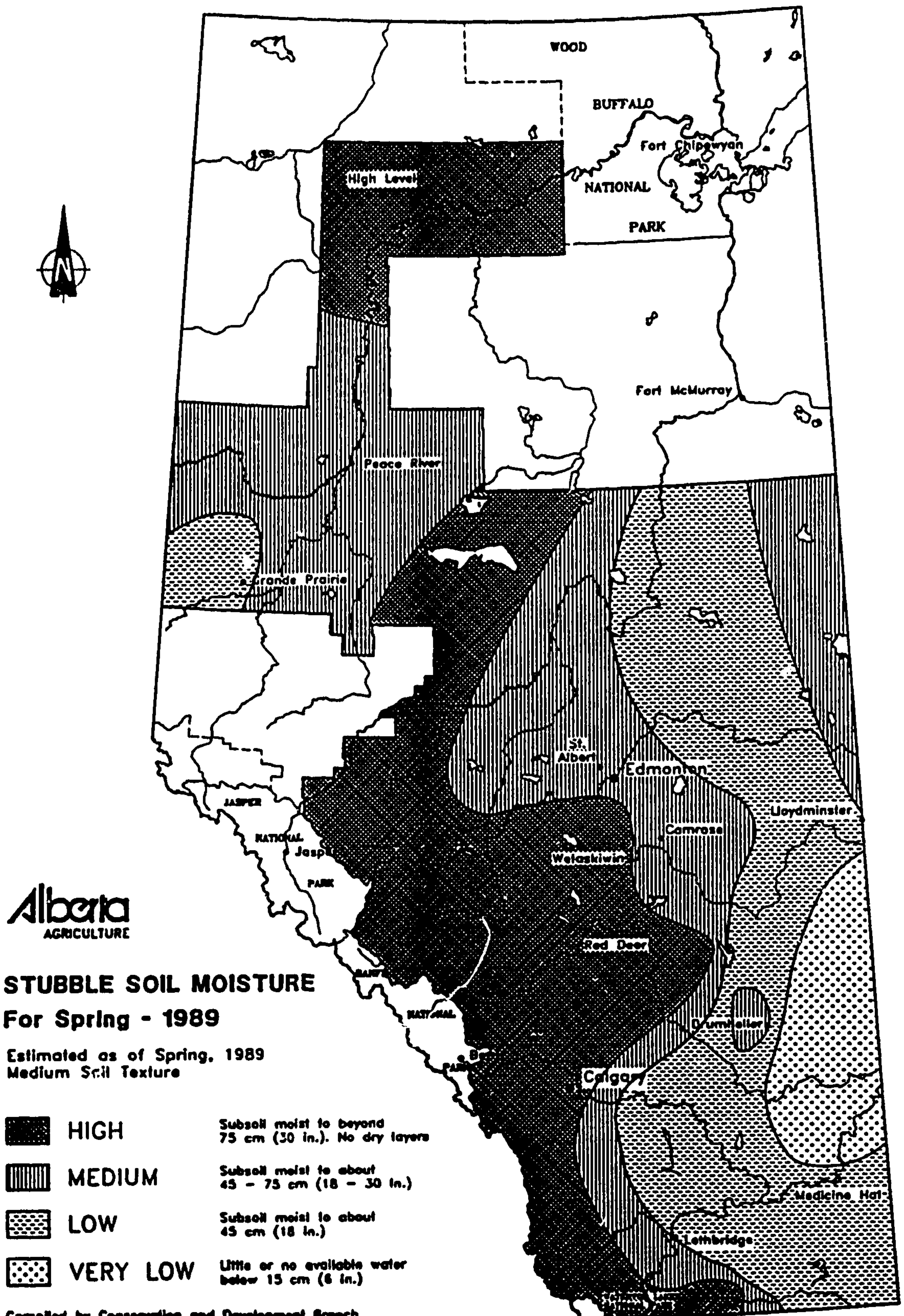
Wetaskiwin
JASPER
NATIONAL
Jasper
PARK
Red Deer
BANFF
NATIONAL
Banff
PARK
Drumheller
Calgary
Medicine Hat
Lethbridge
Alberta
AGRICULTURE
STUBBLE SOIL MOISTURE
For Spring - 1990
Estimated as of Spring, 1990
Medium Soil Texture
HIGH
Subsoil moist to beyond 75 cm (30 in.). No dry layers
MEDIUM
Subsoil moist to about 45 - 75 cm (18 - 30 in.)
LOW
Subsoil moist to about 45 cm (18 in.)
VERY LOW
Little or no available water below 15 cm (6 in.)
Compiled by Conservation and Development Branch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Fort McMurray
Peace River
Grande Prairie
JASPER
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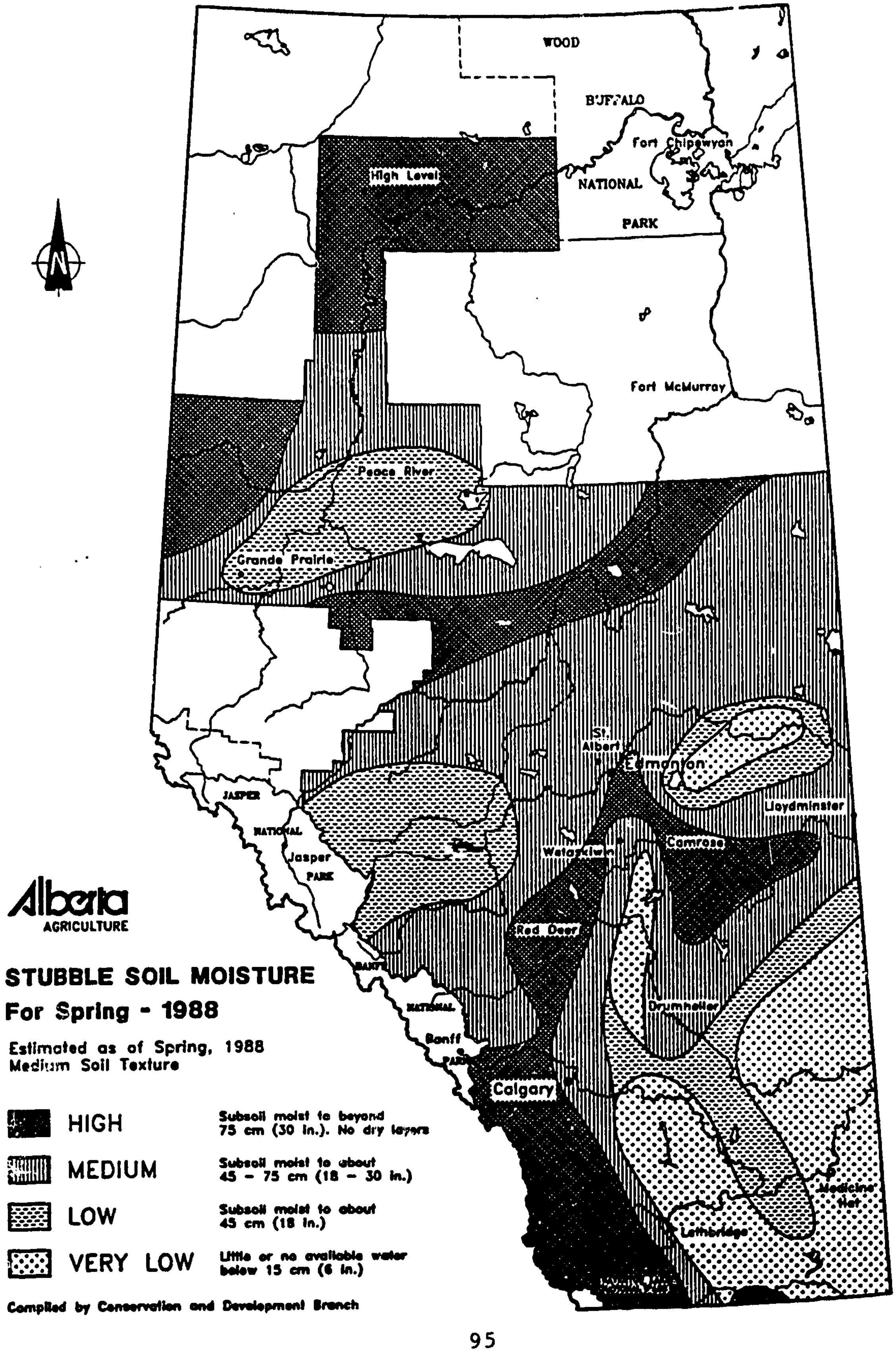
PARK
St. Albert
Edmonton
Lloydminster
Camrose
Wetaskiwin
Red Deer
Drumheller
Calgary
Medicine Hat
Lethbridge
Alberta
AGRICULTURE
STUBBLE SOIL MOISTURE
For Spring - 1989
Estimated as of Spring, 1989
Medium Soil Texture
HIGH
Subsoil moist to beyond 75 cm (30 in.). No dry layers
MEDIUM
Subsoil moist to about 45 - 75 cm (18 - 30 in.)
LOW
Subsoil moist to about 45 cm (18 in.)
VERY LOW
Little or no available water below 15 cm (6 in.)
Compiled by Conservation and Development Branch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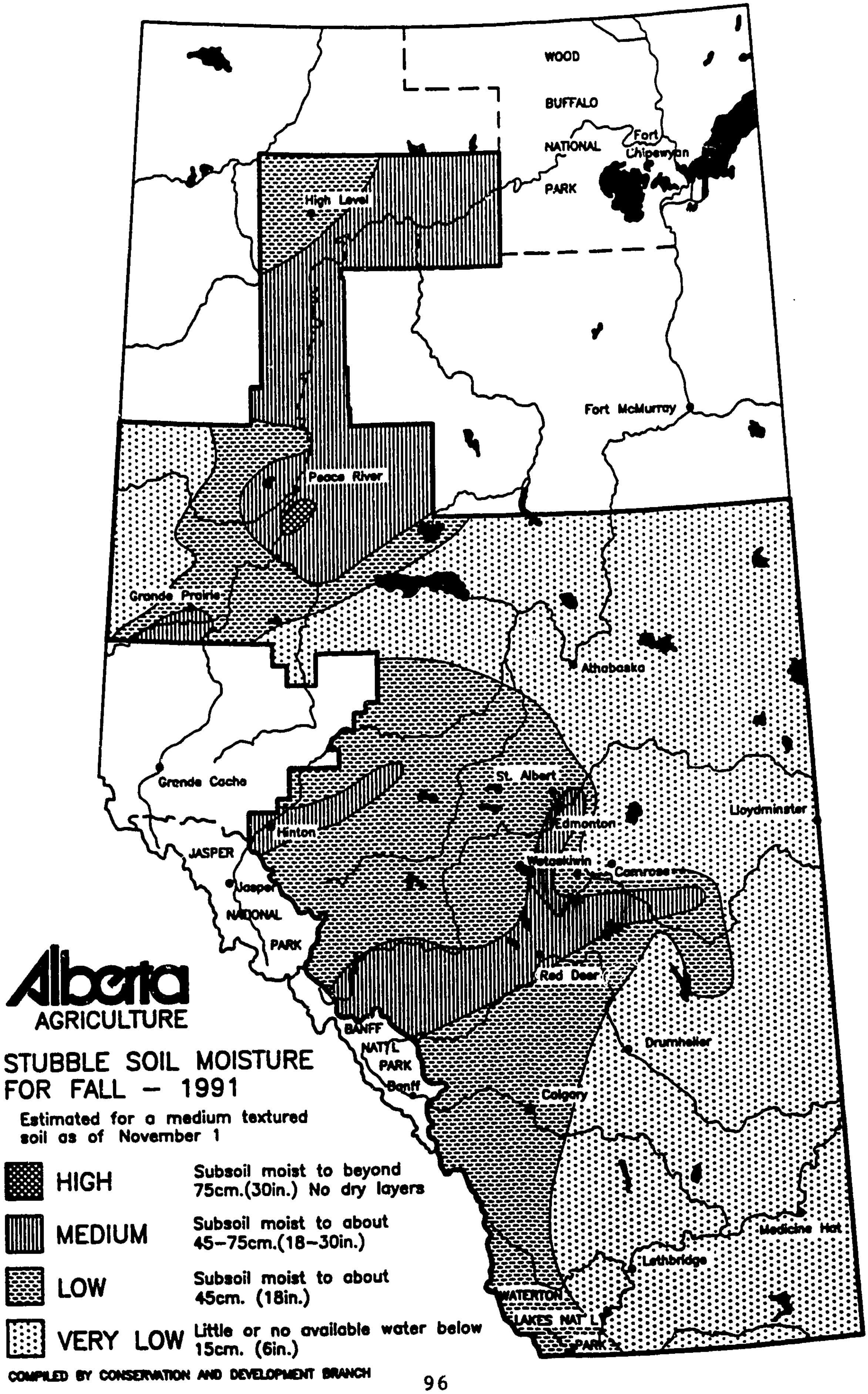
Lloydminster
Wetaskiwin
Camrose
Red Deer
Drumheller
BANFF
NATIONAL
Banff
PARK
Calgary
Medicine Hat
Lethbridge
Alberta
AGRICULTURE
STUBBLE SOIL MOISTURE
For Spring - 1988
Estimated as of Spring, 1988
Medium Soil Texture
HIGH
Subsoil moist to beyond 75 cm (30 in.). No dry layers
MEDIUM
Subsoil moist to about 45 - 75 cm (18 - 30 in.)
LOW
Subsoil moist to about 45 cm (18 in.)
VERY LOW
Little or no available water below 15 cm (6 in.)
Compiled by Conservation and Development Branch


Alberta
AGRICULTURE
STUBBLE SOIL MOISTURE
FOR FALL - 1991
Estimated for a medium textured soil as of November 1
HIGH
Subsoil moist to beyond 75cm.(30in.) No dry layers
MEDIUM
Subsoil moist to about 45-75cm.(18-30in.)
LOW
Subsoil moist to about 45cm. (18in.)
VERY LOW
Little or no available water below 15cm. (6in.)
COMPILED BY CONSERVATION AND DEVELOPMENT BRANCH
WOOD
BUFFALO
NATIONAL
PARK
Fort Chipewyan
High Level
Fort McMurray
Peace River
Grande Prairie
Athabasca
Grande Cache
St. Albert
Edmonton
Lloydminster
Hinton
JASPER
Jasper
NATIONAL
PARK
Wetaskiwin
Camrose
Red Deer
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Medicine Hat
Lethbridge
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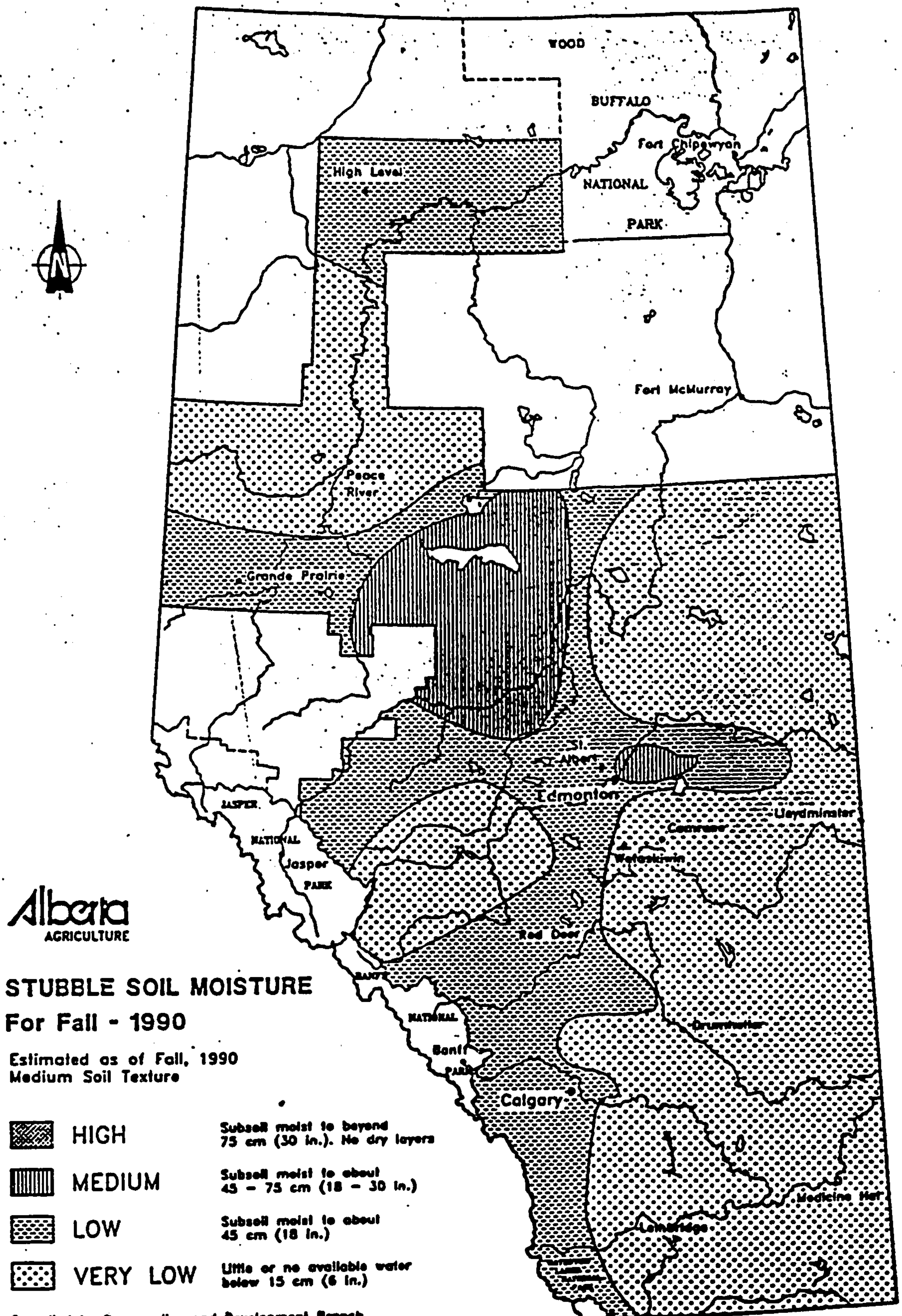
PARK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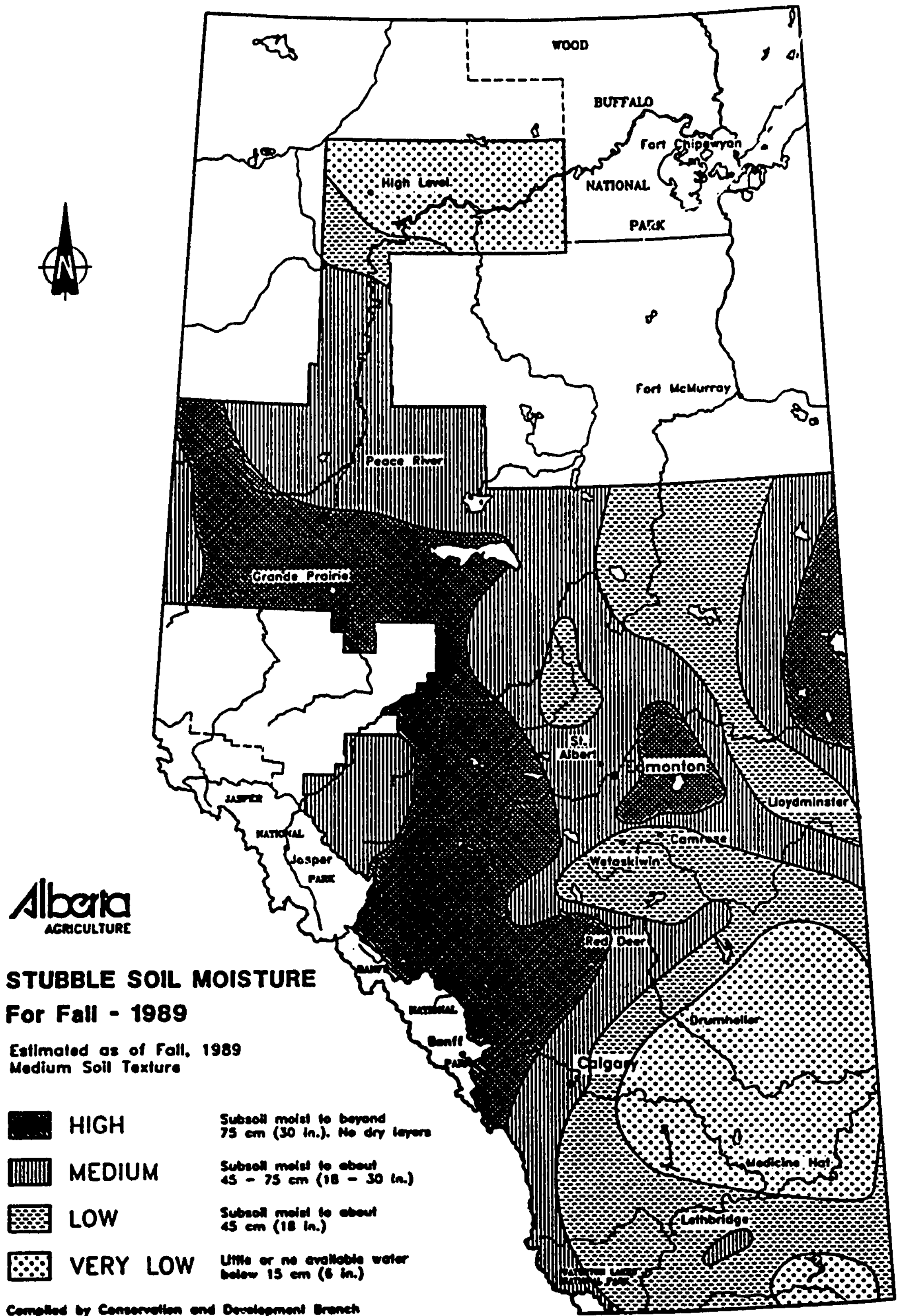
Red Deer
NATIONAL
Banff
PARK
Drumheller
Calgary
Medicine Hat
Lethbridge
Alberta
AGRICULTURE
STUBBLE SOIL MOISTURE
For Fall - 1990
Estimated as of Fall, 1990
Medium Soil Texture
HIGH
Subsoil moist to beyond 75 cm (30 in.). No dry layers
MEDIUM
Subsoil moist to about 45 - 75 cm (18 - 30 in.)
LOW
Subsoil moist to about 45 cm (18 in.)
VERY LOW
Little or no available water below 15 cm (6 in.)
Compiled by Conservation and Development Branch



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NATIONAL
Jasper
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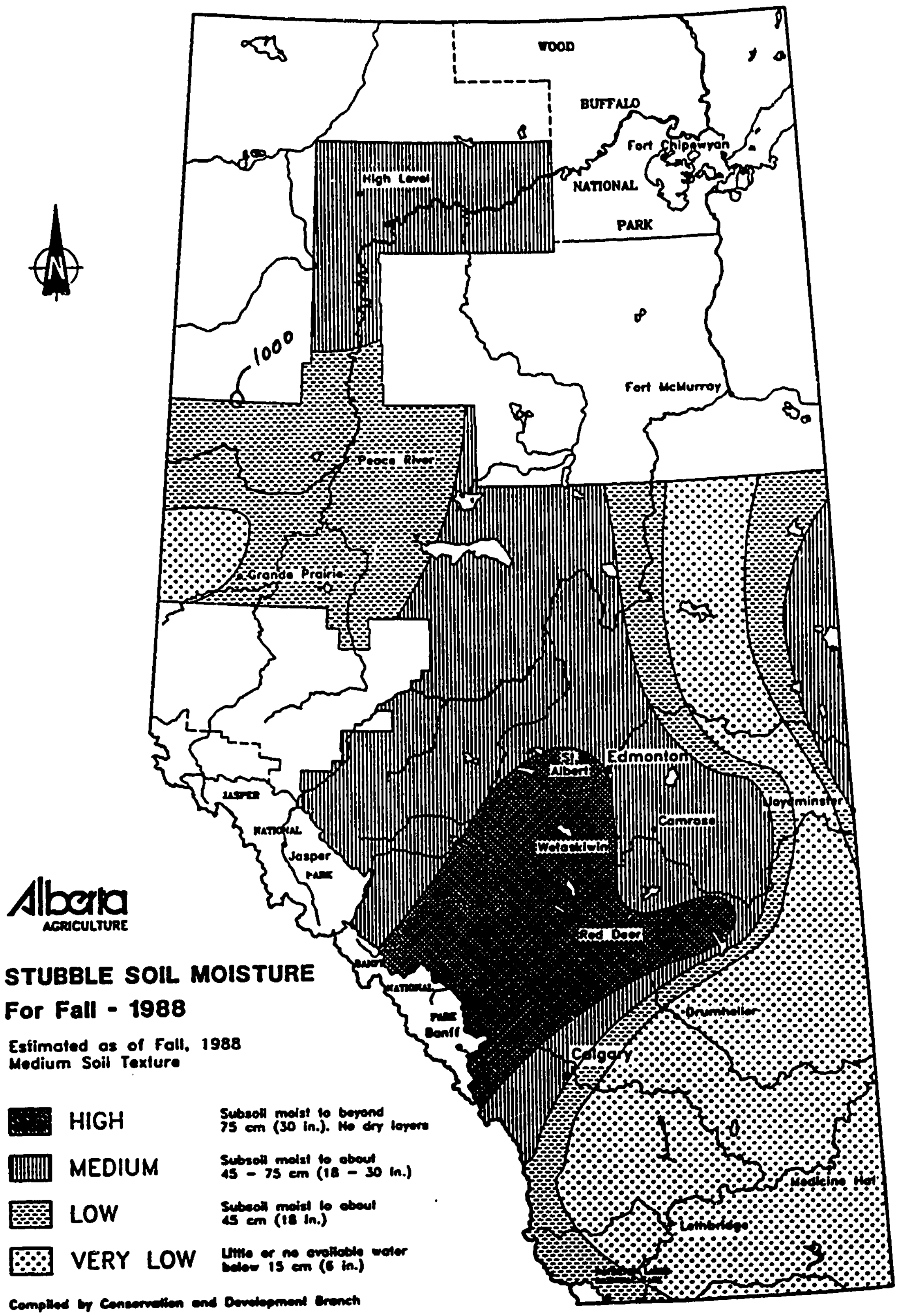
Red Deer
BANFF
NATIONAL
Banff
PARK
Drumheller
Calgary
Medicine Hat
Lethbridge
Alberta
AGRICULTURE
STUBBLE SOIL MOISTURE
For Fall - 1989
Estimated as of Fall, 1989
Medium Soil Texture
HIGH
Subsoil moist to beyond 75 cm (30 in.). No dry layers
MEDIUM
Subsoil moist to about 45 - 75 cm (18 - 30 in.)
LOW
Subsoil moist to about 45 cm (18 in.)
VERY LOW
Little or no available water below 15 cm (6 in.)
Compiled by Conservation and Development Branch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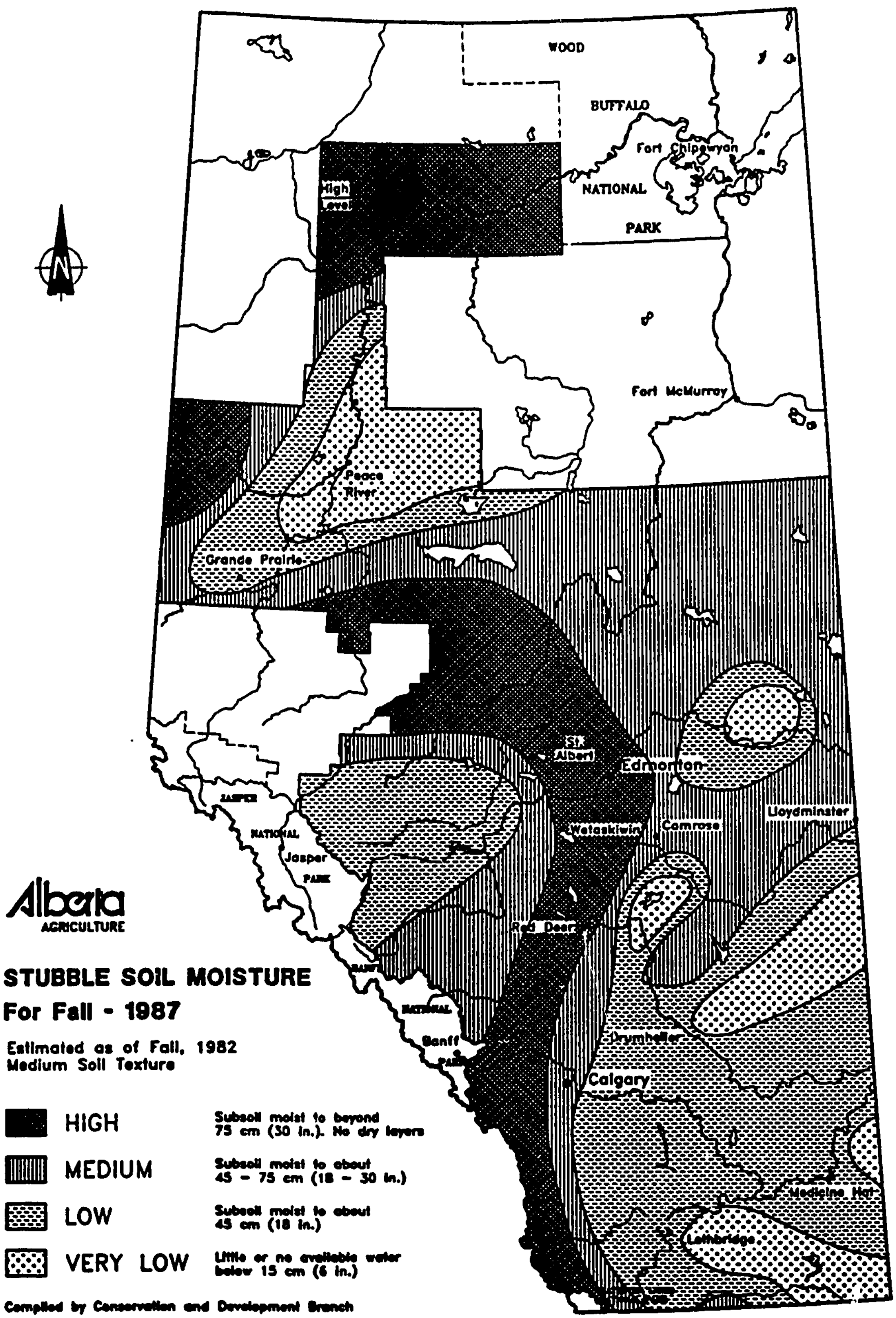
Calgary
Medicine Hat
Lethbridge
Alberta
AGRICULTURE
STUBBLE SOIL MOISTURE
For Fall - 1988
Estimated as of Fall, 1988
Medium Soil Texture
HIGH
Subsoil moist to beyond 75 cm (30 in.). No dry layers
MEDIUM
Subsoil moist to about 45 - 75 cm (18 - 30 in.)
LOW
Subsoil moist to about 45 cm (18 in.)
VERY LOW
Little or no available water below 15 cm (6 in.)
Compiled by Conservation and Development Branch


Alberta
AGRICULTURE
STUBBLE SOIL MOISTURE
For Fall - 1987
Estimated as of Fall, 1982
Medium Soil Texture
HIGH
Subsoil moist to beyond 75 cm (30 in.). No dry layers
MEDIUM
Subsoil moist to about 45 - 75 cm (18 - 30 in.)
LOW
Subsoil moist to about 45 cm (18 in.)
VERY LOW
Little or no available water below 15 cm (6 in.)
Compiled by Conservation and Development Branch
WOOD
BUFFALO
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Fort Chipewyan
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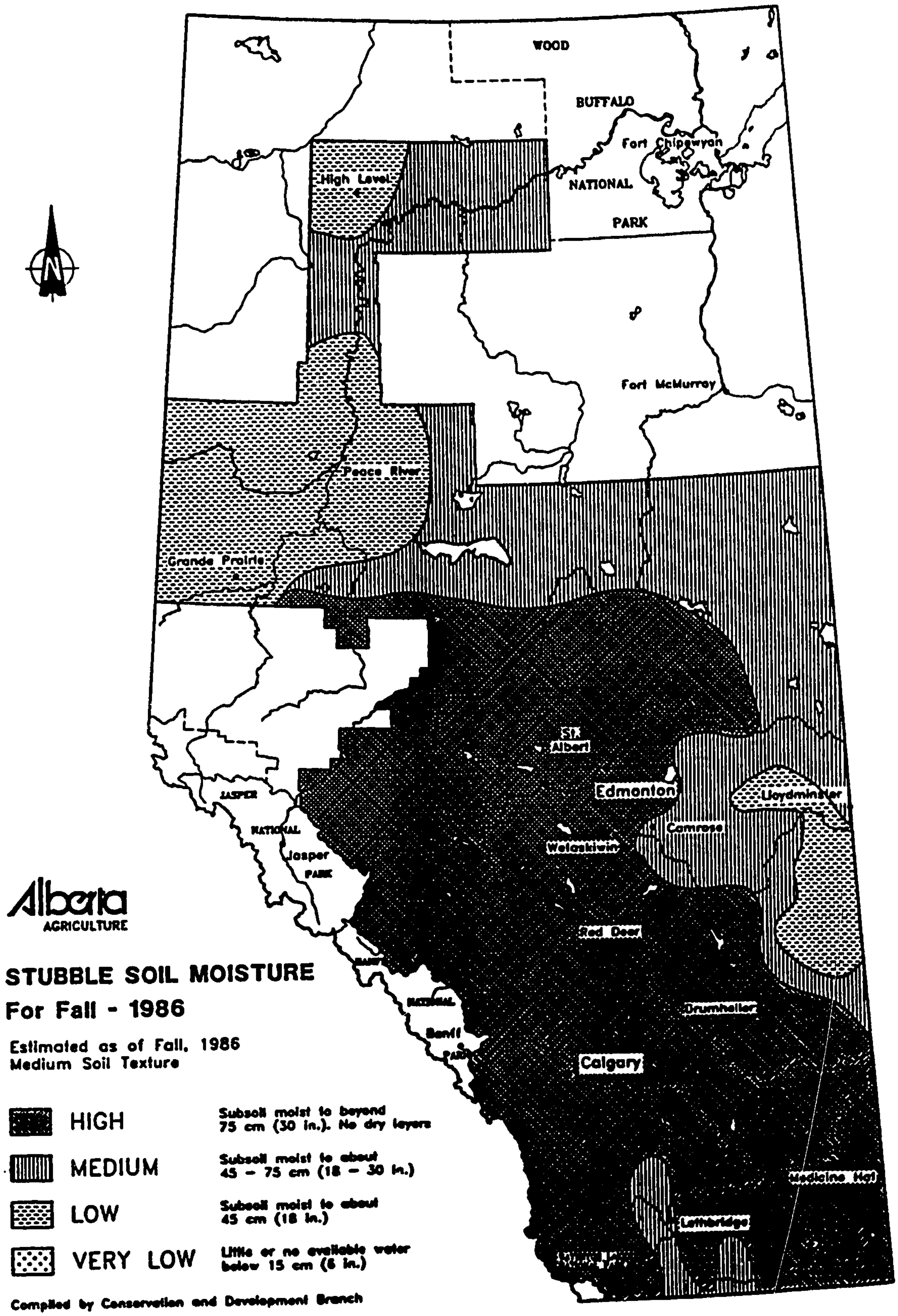
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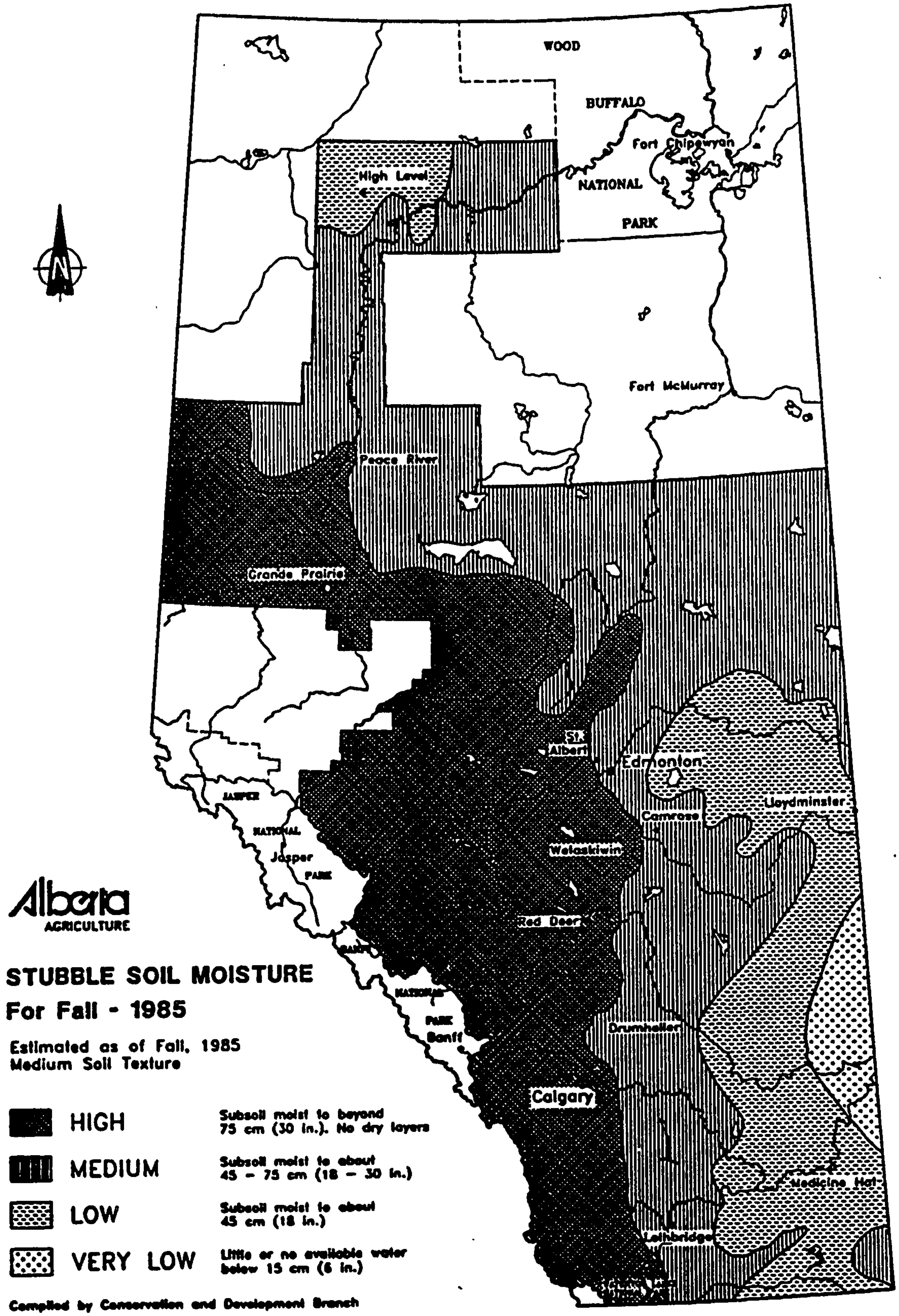
Lethbridge
Alberta
AGRICULTURE
STUBBLE SOIL MOISTURE
For Fall - 1986
Estimated as of Fall, 1986
Medium Soil Texture
HIGH
Subsoil moist to beyond 75 cm (30 in.). No dry layers
MEDIUM
Subsoil moist to about 45 - 75 cm (18 - 30 in.)
LOW
Subsoil moist to about 45 cm (18 in.)
VERY LOW
Little or no available water below 15 cm (6 in.)
Compiled by Conservation and Development Branch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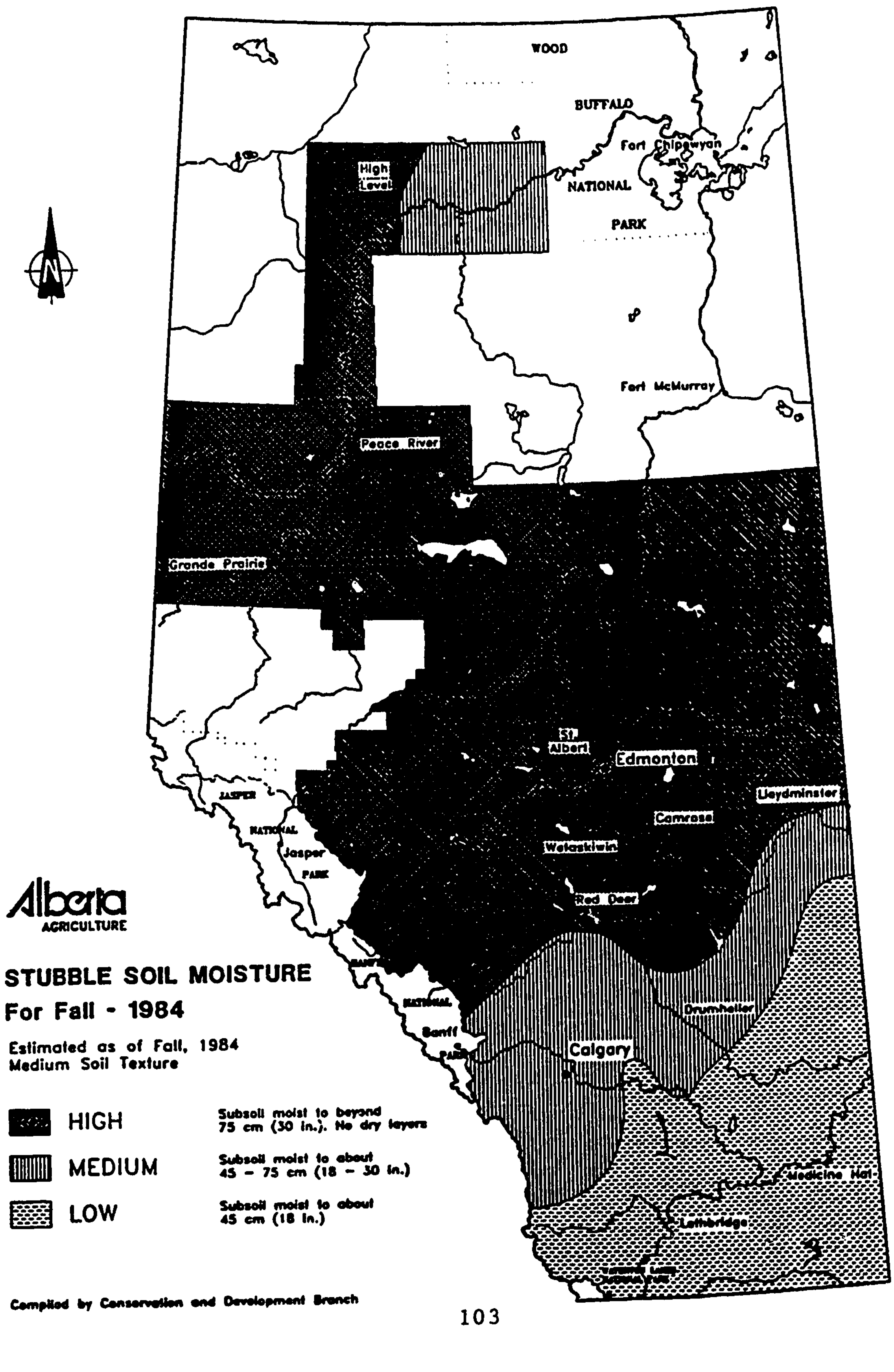
Alberta
AGRICULTURE
STUBBLE SOIL MOISTURE
For Fall - 1985
Estimated as of Fall, 1985
Medium Soil Texture
HIGH
Subsoil moist to beyond 75 cm (30 in.). No dry layers
MEDIUM
Subsoil moist to about 45 - 75 cm (18 - 30 in.)
LOW
Subsoil moist to about 45 cm (18 in.)
VERY LOW
Little or no available water below 15 cm (6 in.)
Compiled by Conservation and Development Branch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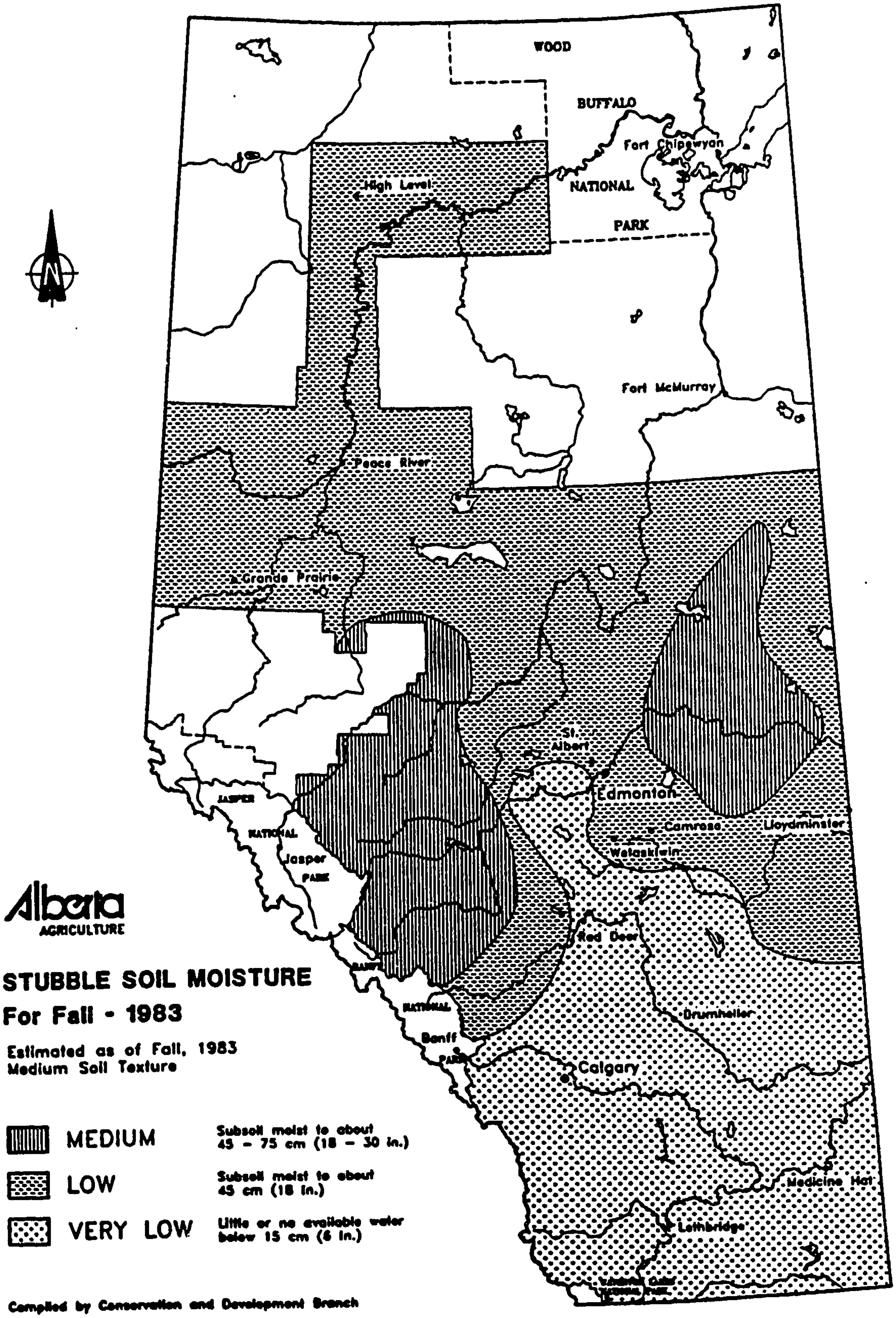
Medicine Hat
Lethbridge
Alberta
AGRICULTURE
STUBBLE SOIL MOISTURE
For Fall - 1984
Estimated as of Fall, 1984
Medium Soil Texture
HIGH
Subsoil moist to beyond 75 cm (30 in.). No dry layers
MEDIUM
Subsoil moist to about 45 - 75 cm (18 - 30 in.)
LOW
Subsoil moist to about 45 cm (18 in.)
Compiled by Conservation and Development Branch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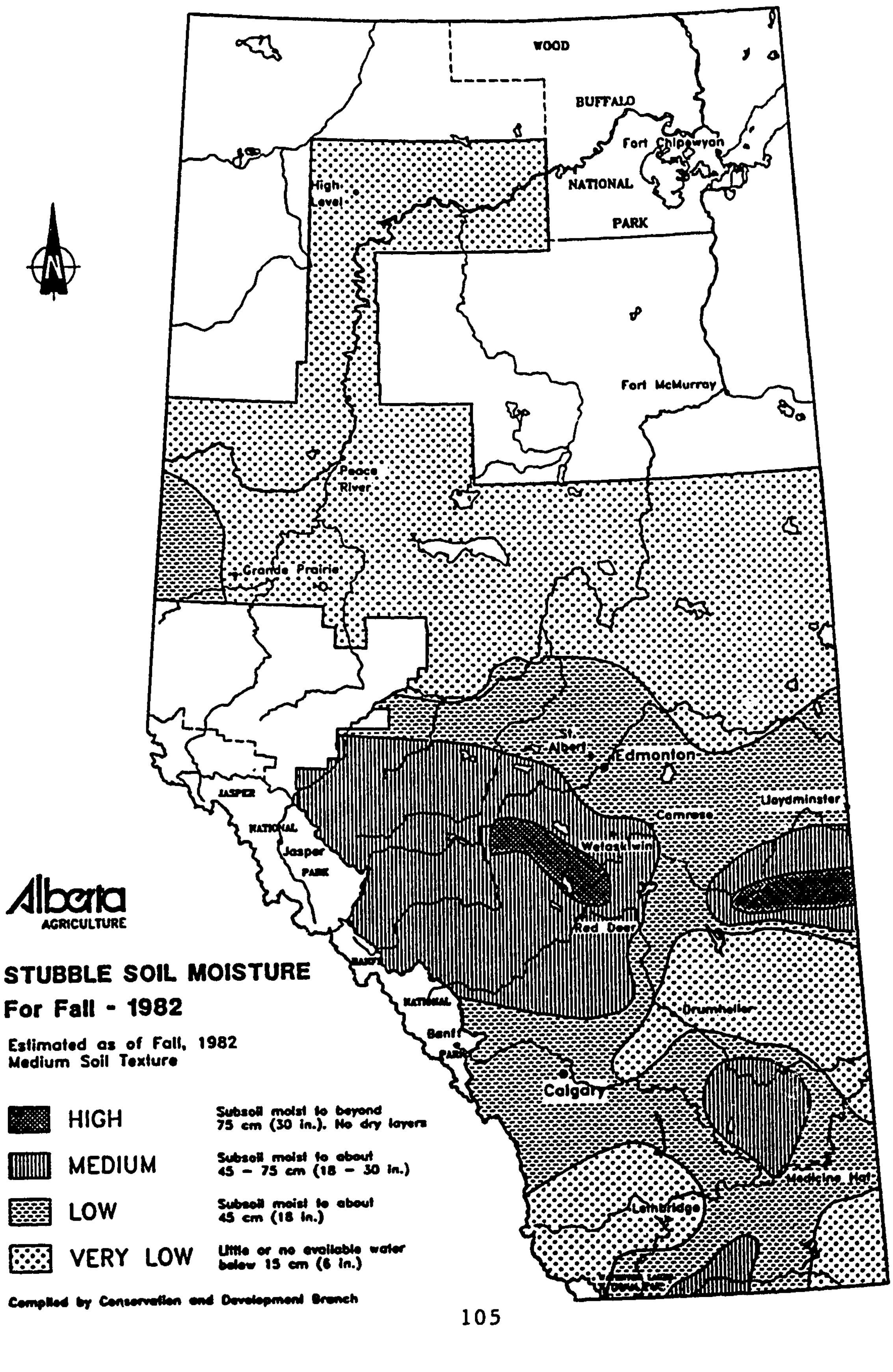
Medicine Hat
Lethbridge
Alberta
AGRICULTURE
STUBBLE SOIL MOISTURE
For Fall - 1983
Estimated as of Fall, 1983
Medium Soil Texture
MEDIUM
Subsoil moist to about
45 - 75 cm (18 - 30 in.)
LOW
Subsoil moist to about
45 cm (18 in.)
VERY LOW
Little or no available water
below 15 cm (6 in.)
Compiled by Conservation and Development Branch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Drumheller
Calgary
Medicine Hat
Lethbridge
Alberta
AGRICULTURE
STUBBLE SOIL MOISTURE
For Fall - 1982
Estimated as of Fall, 1982
Medium Soil Texture
HIGH
Subsoil moist to beyond 75 cm (30 in.). No dry layers
MEDIUM
Subsoil moist to about 45 - 75 cm (18 - 30 in.)
LOW
Subsoil moist to about 45 cm (18 in.)
VERY LOW
Little or no available water below 15 cm (6 in.)
Compiled by Conservation and Development Branch

Appendix B:

Variation of GCM 1XCO2 and 2XCO2 Average

Soil Moisture for NCAR-Type Seasons

APPENDIX B
Table 15a
Variation of AES 1XCO2 and 2XCO2 GCM Average Soil Moisture (cm)
for NCAR-type Seasons (Winter=Dec. to Feb., Summer=Jun. to Aug.)

LAT	LONG	MONTH	CONTROL	DOUBLE
50.09	108.75	WINTER	25.8	9.0
50.09	112.50	WINTER	37.3	16.6
50.09	116.25	WINTER	55.3	28.4
50.09	120.00	WINTER	63.8	56.6
50.09	123.75	WINTER	55.8	56.1
53.80	108.75	WINTER	36.7	10.1
53.80	112.50	WINTER	37.8	11.1
53.80	116.25	WINTER	72.6	18.4
53.80	120.00	WINTER	72.0	18.1
53.80	123.75	WINTER	64.0	37.6
57.51	108.75	WINTER	64.5	16.8
57.51	112.50	WINTER	29.4	6.0
57.51	116.25	WINTER	59.0	15.5
57.51	120.00	WINTER	59.0	13.7
57.51	123.75	WINTER	56.0	11.3
61.22	108.75	WINTER	75.2	9.9
61.22	112.50	WINTER	57.2	8.0
61.22	116.25	WINTER	20.7	2.9
61.22	120.00	WINTER	21.1	5.0
61.22	123.75	WINTER	56.6	10.3
50.09	108.75	SUMMER	28.8	23.4
50.09	112.50	SUMMER	33.9	31.2
50.09	116.25	SUMMER	44.4	43.9
50.09	120.00	SUMMER	52.1	47.8
50.09	123.75	SUMMER	41.4	35.1
53.80	108.75	SUMMER	38.8	36.4
53.80	112.50	SUMMER	35.8	35.1
53.80	116.25	SUMMER	70.0	69.1
53.80	120.00	SUMMER	67.8	65.0
53.80	123.75	SUMMER	60.0	57.4
57.51	108.75	SUMMER	63.6	67.3
57.51	112.50	SUMMER	26.6	27.2
57.51	116.25	SUMMER	55.4	51.5
57.51	120.00	SUMMER	54.3	51.4
57.51	123.75	SUMMER	54.0	52.4
61.22	108.75	SUMMER	71.0	69.2
61.22	112.50	SUMMER	56.7	53.7
61.22	116.25	SUMMER	19.3	20.0
61.22	120.00	SUMMER	19.8	32.0
61.22	123.75	SUMMER	54.4	55.7

CONTROL=1XCO2 run in cm, DOUBLE=2XCO2 run in cm
See Section 4.2 for averaging procedure

Table 15b
Variation of GISS 1XCO2 and 2XCO2 GCM Average Soil Moisture (cm) for NCAR-type Seasons (Winter=Dec. to Feb., Summer=Jun. to Aug.)

LAT	LONG	MONTH	CONTROL	DOUBLE
50.87	110.00	WINTER	4.1	5.8
50.87	120.00	WINTER	6.4	9.0
58.70	110.00	WINTER	6.1	7.9
58.70	120.00	WINTER	6.8	7.5
50.87	110.00	SUMMER	2.8	3.6
50.87	120.00	SUMMER	3.8	5.8
58.70	110.00	SUMMER	4.9	5.9
58.70	120.00	SUMMER	5.9	5.6

Table 15c
Variation of GFDL 1XCO2 and 2XCO2 GCM Average Soil Moisture (cm) for NCAR-type Seasons (Winter=Dec. to Feb., Summer=Jun. to Aug.)

LAT	LONG	MONTH	CONTROL	DOUBLE
51.11	112.50	WINTER	3.7	4.2
51.11	120.00	WINTER	5.0	4.9
55.55	112.50	WINTER	3.1	4.2
55.55	120.00	WINTER	4.7	4.9
59.99	112.50	WINTER	2.8	4.1
59.99	120.00	WINTER	4.3	4.7
51.11	112.50	SUMMER	2.9	2.4
51.11	120.00	SUMMER	3.3	3.2
55.55	112.50	SUMMER	2.0	1.5
55.55	120.00	SUMMER	4.2	3.3
59.99	112.50	SUMMER	2.6	2.0
59.99	120.00	SUMMER	3.8	2.9

Table 15d
Variation of UI 1XCO2 and 2XCO2 GCM Average Soil Moisture (cm) for NCAR-type Seasons (Winter=Dec. to Feb., Summer=Jun. to Aug.)

LAT	LONG	MONTH	CONTROL	DOUBLE
50.00	110.00	WINTER	2.1	3.2
50.00	115.00	WINTER	2.9	3.6
50.00	120.00	WINTER	3.8	3.9
54.00	110.00	WINTER	1.5	2.7
54.00	115.00	WINTER	1.9	2.8
54.00	120.00	WINTER	2.7	3.5
58.00	110.00	WINTER	1.3	2.2
58.00	115.00	WINTER	1.5	2.2
58.00	120.00	WINTER	1.8	2.3
50.00	110.00	SUMMER	0.4	0.5
50.00	115.00	SUMMER	0.5	0.4
50.00	120.00	SUMMER	0.6	0.4
54.00	110.00	SUMMER	0.3	0.3
54.00	115.00	SUMMER	0.5	0.4
54.00	120.00	SUMMER	0.8	0.5
58.00	110.00	SUMMER	0.4	0.4
58.00	115.00	SUMMER	0.5	0.4
58.00	120.00	SUMMER	0.8	0.5

CONTROL=1XCO2 run in cm, DOUBLE=2XCO2 run in cm
See Section 4.2 for averaging procedure

Table 15e
Variation of OSU 1XCO2 and 2XCO2 GCM Average Soil Moisture (cm)
for NCAR-type Seasons (Winter=Dec. to Feb., Summer=Jun. to Aug.)

LAT	LONG	MONTH	CONTROL	DOUBLE
50.00	110.00	WINTER	1.6	2.5
50.00	115.00	WINTER	2.7	3.2
50.00	120.00	WINTER	3.0	2.9
54.00	110.00	WINTER	1.1	1.9
54.00	115.00	WINTER	1.9	2.4
54.00	120.00	WINTER	2.0	2.2
58.00	110.00	WINTER	1.3	1.7
58.00	115.00	WINTER	1.2	1.7
58.00	120.00	WINTER	1.8	2.2
50.00	110.00	SUMMER	1.9	0.7
50.00	110.00	SUMMER	1.9	0.7
50.00	115.00	SUMMER	0.8	0.7
50.00	115.00	SUMMER	0.8	0.7
50.00	120.00	SUMMER	3.2	0.1
50.00	120.00	SUMMER	3.2	0.1
54.00	110.00	SUMMER	1.0	0.3
54.00	110.00	SUMMER	1.0	0.3
54.00	115.00	SUMMER	1.0	0.6
54.00	115.00	SUMMER	1.0	0.6
54.00	120.00	SUMMER	1.9	0.3
54.00	120.00	SUMMER	1.9	0.3
58.00	110.00	SUMMER	2.1	0.6
58.00	110.00	SUMMER	2.1	0.6
58.00	115.00	SUMMER	0.8	0.6
58.00	115.00	SUMMER	0.8	0.6
58.00	120.00	SUMMER	1.3	0.7
58.00	120.00	SUMMER	1.3	0.7

Table 15f
Variation of NCAR 1XCO2 and 2XCO2 GCM Average Soil Moisture (cm)
Seasons (Winter=Dec. to Feb., Summer=Jun. to Aug.)

LAT	LONG	MONTH	CONTROL	DOUBLE
48.40	112.50	WINTER	0.0	8.6
48.40	120.00	WINTER	0.0	14.2
52.90	112.50	WINTER	5.6	8.1
52.90	120.00	WINTER	13.0	14.2
57.40	112.50	WINTER	5.8	10.2
57.40	120.00	WINTER	12.0	13.7
61.90	112.50	WINTER	4.0	7.8
61.90	120.00	WINTER	6.9	11.3
48.40	112.50	SUMMER	4.5	2.3
48.40	120.00	SUMMER	1.9	2.5
52.90	112.50	SUMMER	0.7	1.7
52.90	120.00	SUMMER	1.4	4.6
57.40	112.50	SUMMER	0.3	0.7
57.40	120.00	SUMMER	0.6	2.2
61.90	112.50	SUMMER	0.3	0.6
61.90	120.00	SUMMER	0.3	1.7

CONTROL=1XCO2 run in cm, DOUBLE=2XCO2 run in cm
See Section 4.2 for averaging procedure

Table 15g
Variation of UKMO 1XCO2 and 2XCO2 GCM Average Soil Moisture (cm)
for NCAR-type Seasons (Winter=Dec. to Feb., Summer=Jun. to Aug.)

LAT	LONG	MONTH	CONTROL	DOUBLE
47.5	108.7	WINTER	13.9	14.1
47.5	108.7	WINTER	13.9	14.1
47.5	116.2	WINTER	14.1	13.6
47.5	116.2	WINTER	14.1	13.6
47.5	123.7	WINTER	14.4	14.2
47.5	123.7	WINTER	14.4	14.2
52.5	108.7	WINTER	14.1	14.1
52.5	108.7	WINTER	14.1	14.1
52.5	116.2	WINTER	13.8	13.9
52.5	116.2	WINTER	13.8	13.9
52.5	123.7	WINTER	14.2	14.0
52.5	123.7	WINTER	14.2	14.0
57.5	108.7	WINTER	14.4	14.3
57.5	108.7	WINTER	14.4	14.3
57.5	116.2	WINTER	14.0	13.9
57.5	116.2	WINTER	14.0	13.9
57.5	123.7	WINTER	13.8	14.0
57.5	123.7	WINTER	13.8	14.0
62.5	108.7	WINTER	111	12.9
62.5	108.7	WINTER	111	12.9
62.5	116.2	WINTER	103	12.8
62.5	116.2	WINTER	103	12.8
62.5	123.7	WINTER	89.2	13.5
62.5	123.7	WINTER	89.2	13.5
47.5	108.7	SUMMER	14.1	13.8
47.5	108.7	SUMMER	14.1	13.8
47.5	116.2	SUMMER	14.1	13.7
47.5	116.2	SUMMER	14.1	13.7
47.5	123.7	SUMMER	13.9	13.4
47.5	123.7	SUMMER	13.9	13.4
52.5	108.7	SUMMER	14.2	13.9
52.5	108.7	SUMMER	14.2	13.9
52.5	116.2	SUMMER	14.2	13.9
52.5	116.2	SUMMER	14.2	13.9
52.5	123.7	SUMMER	14.0	13.9
52.5	123.7	SUMMER	14.0	13.9
57.5	108.7	SUMMER	13.5	12.7
57.5	108.7	SUMMER	13.5	12.7
57.5	116.2	SUMMER	13.0	12.7
57.5	116.2	SUMMER	13.0	12.7
57.5	123.7	SUMMER	3.9	3.7
57.5	123.7	SUMMER	3.9	3.7
62.5	108.7	SUMMER	13.6	13.4
62.5	108.7	SUMMER	13.6	13.4
62.5	116.2	SUMMER	13.5	13.6
62.5	116.2	SUMMER	13.5	13.6
62.5	123.7	SUMMER	4.3	4.3
62.5	123.7	SUMMER	4.3	4.3

CONTROL=1XCO2 run in cm, DOUBLE=2XCO2 run in cm
See Section 4.2 for averaging procedure

Appendix C:

Spatial Mean and Standard Deviation of Measured Alberta Stubble Soil Moisture for Spring and Fall at GCM Gridpoints

APPENDIX C

Table 16a
Spatial Mean and Standard Deviation of Measured Alberta Stubble Soil Moisture for Spring and Fall (cm) for AES GCM Gridpoints

YEAR	MONTH	LAT	LONG	SPACMEAN	SPACSTD	MOISTURE
1988	4	50.09	112.50	5.67	4.62	43.14
1989	4	50.09	112.50	7.45	3.96	43.14
1990	4	50.09	112.50	6.86	3.96	43.14
1991	4	50.09	112.50	6.39	2.59	43.14
1988	4	50.09	116.25	14.10	2.10	55.93
1989	4	50.09	116.25	15.00	0.00	55.93
1990	4	50.09	116.25	12.30	2.87	55.93
1991	4	50.09	116.25	8.66	1.68	55.93
1988	4	53.80	112.50	9.45	3.93	40.59
1989	4	53.80	112.50	7.79	3.85	40.59
1990	4	53.80	112.50	9.90	4.00	40.59
1991	4	53.80	112.50	5.99	3.02	40.59
1988	4	53.80	116.25	8.93	3.36	74.40
1989	4	53.80	116.25	13.22	2.63	74.40
1990	4	53.80	116.25	13.89	2.34	74.40
1991	4	53.80	116.25	10.35	2.50	74.40
1988	4	57.51	116.25	10.99	4.14	64.61
1989	4	57.51	116.25	12.47	2.81	64.61
1990	4	57.51	116.25	11.94	4.06	64.61
1991	4	57.51	116.25	6.59	2.20	64.61
1982	10	50.09	112.50	4.61	2.34	25.98
1983	10	50.09	112.50	2.25	0.00	25.98
1984	10	50.09	112.50	5.77	1.80	25.98
1985	10	50.09	112.50	7.96	4.07	25.98
1986	10	50.09	112.50	14.40	1.74	25.98
1987	10	50.09	112.50	4.60	1.48	25.98
1988	10	50.09	112.50	2.90	2.02	25.98
1989	10	50.09	112.50	3.73	1.83	25.98
1990	10	50.09	112.50	2.36	0.53	25.98
1991	10	50.09	112.50	2.42	0.65	25.98
1982	10	50.09	116.25	4.22	1.16	39.65
1983	10	50.09	116.25	2.47	0.74	39.65
1984	10	50.09	116.25	8.40	1.90	39.65
1985	10	50.09	116.25	15.00	0.00	39.65
1986	10	50.09	116.25	15.00	0.00	39.65
1987	10	50.09	116.25	13.20	2.68	39.65
1988	10	50.09	116.25	9.05	4.34	39.65
1989	10	50.09	116.25	10.63	3.60	39.65
1990	10	50.09	116.25	4.67	0.73	39.65
1991	10	50.09	116.25	4.88	0.00	39.65
1982	10	53.80	112.50	4.96	3.47	32.32
1983	10	53.80	112.50	5.33	2.41	32.32
1984	10	53.80	112.50	13.58	2.96	32.32
1985	10	53.80	112.50	8.67	3.40	32.32
1986	10	53.80	112.50	11.10	3.46	32.32
1987	10	53.80	112.50	7.91	4.09	32.32
1988	10	53.80	112.50	7.16	4.28	32.32
1989	10	53.80	112.50	8.04	3.95	32.32
1990	10	53.80	112.50	2.86	1.34	32.32
1991	10	53.80	112.50	3.16	1.82	32.32

Table 16a con't.
Spatial Mean and Standard Deviation of Measured Alberta Stubble Soil Moisture for Spring and Fall (cm) for AES GCM Gridpoints

YEAR	MONTH	LAT	LONG	SPACMEAN	SPACSTD	MOISTURE
1982	10	53.80	116.25	6.09	3.60	68.45
1983	10	53.80	116.25	6.80	2.49	68.45
1984	10	53.80	116.25	14.86	0.88	68.45
1985	10	53.80	116.25	14.58	1.48	68.45
1986	10	53.80	116.25	14.08	2.44	68.45
1987	10	53.80	116.25	10.34	4.07	68.45
1988	10	53.80	116.25	10.72	3.38	68.45
1989	10	53.80	116.25	13.01	2.70	68.45
1990	10	53.80	116.25	5.77	2.75	68.45
1991	10	53.80	116.25	5.55	2.12	68.45
1982	10	57.51	116.25	2.25	0.00	53.16
1983	10	57.51	116.25	4.88	0.00	53.16
1984	10	57.51	116.25	13.83	2.30	53.16
1985	10	57.51	116.25	9.10	2.26	53.16
1986	10	57.51	116.25	7.26	2.26	53.16
1987	10	57.51	116.25	8.47	5.43	53.16
1988	10	57.51	116.25	7.63	2.21	53.16
1989	10	57.51	116.25	7.40	3.59	53.16
1990	10	57.51	116.25	4.17	2.10	53.16
1991	10	57.51	116.25	7.11	3.16	53.16

SPACMEAN = spatial mean for each year measured
SPACSTD = spatial standard deviation for each year measured
MOISTURE = Global Climate Model soil moisture value
See Section 5.2a for calculation procedure

Table 16b
Spatial Mean and Standard Deviation of Measured Alberta Stubble Soil Moisture for Spring and Fall (cm) for GISS GCM Gridpoints

YEAR	MONTH	LAT	LONG	SPACMEAN	SPACSTD	MOISTURE
1988	4	50.87	110.00	7.99	4.81	14.49
1989	4	50.87	110.00	8.18	4.53	14.49
1990	4	50.87	110.00	8.58	4.37	14.49
1991	4	50.87	110.00	7.09	3.19	14.49
1988	4	50.87	120.00	7.63	2.97	22.45
1989	4	50.87	120.00	14.44	1.70	22.45
1990	4	50.87	120.00	14.06	2.11	22.45
1991	4	50.87	120.00	11.12	2.62	22.45
1988	4	58.70	110.00	11.10	2.60	18.89
1989	4	58.70	110.00	7.60	3.11	18.89
1990	4	58.70	110.00	13.24	3.27	18.89
1991	4	58.70	110.00	9.12	4.34	18.89
1988	4	58.70	120.00	11.01	4.02	20.82
1989	4	58.70	120.00	11.08	3.26	20.82
1990	4	58.70	120.00	12.55	3.51	20.82
1991	4	58.70	120.00	6.38	2.13	20.82
1982	10	50.87	110.00	5.37	3.05	7.93
1983	10	50.87	110.00	3.79	2.22	7.93
1984	10	50.87	110.00	9.83	4.46	7.93
1985	10	50.87	110.00	8.73	4.26	7.93
1986	10	50.87	110.00	13.28	3.11	7.93
1987	10	50.87	110.00	7.28	4.36	7.93
1988	10	50.87	110.00	5.38	4.10	7.93
1989	10	50.87	110.00	6.81	4.13	7.93
1990	10	50.87	110.00	2.97	1.50	7.93
1991	10	50.87	110.00	3.44	1.92	7.93
1982	10	50.87	120.00	8.04	2.39	9.04
1983	10	50.87	120.00	8.33	2.24	9.04
1984	10	50.87	120.00	14.31	1.86	9.04
1985	10	50.87	120.00	15.00	0.00	9.04
1986	10	50.87	120.00	15.00	0.00	9.04
1987	10	50.87	120.00	8.35	3.82	9.04
1988	10	50.87	120.00	11.12	2.62	9.04
1989	10	50.87	120.00	13.74	2.36	9.04
1990	10	50.87	120.00	4.19	2.03	9.04
1991	10	50.87	120.00	6.22	2.07	9.04
1982	10	58.70	110.00	2.25	0.00	16.13
1983	10	58.70	110.00	5.56	1.63	16.13
1984	10	58.70	110.00	14.48	1.64	16.13
1985	10	58.70	110.00	10.02	1.79	16.13
1986	10	58.70	110.00	10.22	2.02	16.13
1987	10	58.70	110.00	10.08	2.14	16.13
1988	10	58.70	110.00	6.35	2.93	16.13
1989	10	58.70	110.00	7.68	3.73	16.13
1990	10	58.70	110.00	3.94	2.67	16.13
1991	10	58.70	110.00	3.02	2.03	16.13

Table 16b con't.
Spatial Mean and Standard Deviation of Measured Alberta Stubble Soil Moisture for Spring and Fall (cm) for GISS GCM Gridpoints

YEAR	MONTH	LAT	LONG	SPACMEAN	SPACSTD	MOISTURE
1982	10	58.70	120.00	2.49	0.75	18.05
1983	10	58.70	120.00	5.08	0.93	18.05
1984	10	58.70	120.00	14.43	1.70	18.05
1985	10	58.70	120.00	11.02	3.39	18.05
1986	10	58.70	120.00	6.99	2.93	18.05
1987	10	58.70	120.00	9.70	5.12	18.05
1988	10	58.70	120.00	6.29	2.35	18.05
1989	10	58.70	120.00	10.08	4.65	18.05
1990	10	58.70	120.00	4.46	2.44	18.05
1991	10	58.70	120.00	6.36	2.94	18.05

SPACMEAN = spatial mean for each year measured
SPACSTD = spatial standard deviation for each year measured
MOISTURE = Global Climate Model soil moisture value
See Section 5.2a for calculation procedure

Table 16c
Spatial Mean and Standard Deviation of Measured Alberta Stubble Soil Moisture for Spring and Fall (cm) for GFDL GCM Gridpoints

YEAR	MONTH	LAT	LONG	SPACMEAN	SPACSTD	MOISTURE
1988	4	51.11	112.50	7.60	5.03	12.88
1989	4	51.11	112.50	8.54	4.95	12.88
1990	4	51.11	112.50	8.03	4.25	12.88
1991	4	51.11	112.50	6.75	2.89	12.88
1988	4	51.11	120.00	6.08	2.02	14.97
1989	4	51.11	120.00	15.00	0.00	14.97
1990	4	51.11	120.00	13.84	2.32	14.97
1991	4	51.11	120.00	13.84	2.32	14.97
1988	4	55.55	112.50	9.65	2.81	12.91
1989	4	55.55	112.50	7.74	2.80	12.91
1990	4	55.55	112.50	12.91	3.20	12.91
1991	4	55.55	112.50	10.72	3.41	12.91
1988	4	55.55	120.00	10.05	3.99	14.78
1989	4	55.55	120.00	10.67	3.25	14.78
1990	4	55.55	120.00	13.43	2.53	14.78
1991	4	55.55	120.00	6.93	3.35	14.78
1988	4	59.99	120.00	15.00	0.00	14.77
1989	4	59.99	120.00	15.00	0.00	14.77
1990	4	59.99	120.00	9.04	3.80	14.77
1991	4	59.99	120.00	8.03	2.10	14.77
1982	10	51.11	112.50	5.78	3.31	8.99
1983	10	51.11	112.50	2.82	1.08	8.99
1984	10	51.11	112.50	8.74	4.12	8.99
1985	10	51.11	112.50	9.29	4.47	8.99
1986	10	51.11	112.50	13.34	3.21	8.99
1987	10	51.11	112.50	13.53	3.07	8.99
1988	10	51.11	112.50	5.76	4.89	8.99
1989	10	51.11	112.50	5.94	4.06	8.99
1990	10	51.11	112.50	2.82	1.09	8.99
1991	10	51.11	112.50	3.40	2.08	8.99
1982	10	51.11	120.00	9.38	0.00	10.40
1983	10	51.11	120.00	9.07	1.16	10.40
1984	10	51.11	120.00	15.00	0.00	10.40
1985	10	51.11	120.00	15.00	0.00	10.40
1986	10	51.11	120.00	15.00	0.00	10.40
1987	10	51.11	120.00	15.00	0.00	10.40
1988	10	51.11	120.00	11.82	2.83	10.40
1989	10	51.11	120.00	13.84	2.32	10.40
1990	10	51.11	120.00	3.07	1.24	10.40
1991	10	51.11	120.00	6.28	2.12	10.40
1982	10	55.55	112.50	3.37	1.51	5.32
1983	10	55.55	112.50	5.88	1.95	5.32
1984	10	55.55	112.50	15.00	0.00	5.32
1985	10	55.55	112.50	9.72	3.02	5.32
1986	10	55.55	112.50	11.63	2.76	5.32
1987	10	55.55	112.50	11.66	2.77	5.32
1988	10	55.55	112.50	6.90	3.31	5.32
1989	10	55.55	112.50	8.92	3.45	5.32
1990	10	55.55	112.50	4.24	2.78	5.32
1991	10	55.55	112.50	2.66	1.13	5.32

Table 16c con't.
Spatial Mean and Standard Deviation of Measured Alberta Stubble Soil Moisture for Spring and Fall (cm) for GFDL GCM Gridpoints

YEAR	MONTH	LAT	LONG	SPACMEAN	SPACSTD	MOISTURE
1982	10	55.55	120.00	3.46	2.27	11.73
1983	10	55.55	120.00	5.64	1.70	11.73
1984	10	55.55	120.00	15.00	0.00	11.73
1985	10	55.55	120.00	13.24	2.62	11.73
1986	10	55.55	120.00	8.00	4.29	11.73
1987	10	55.55	120.00	7.87	4.23	11.73
1988	10	55.55	120.00	5.76	2.19	11.73
1989	10	55.55	120.00	12.27	2.82	11.73
1990	10	55.55	120.00	4.48	2.57	11.73
1991	10	55.55	120.00	5.51	2.83	11.73
1982	10	59.99	120.00	2.25	0.00	11.98
1983	10	59.99	120.00	4.88	0.00	11.98
1984	10	59.99	120.00	13.64	2.45	11.98
1985	10	59.99	120.00	7.30	2.29	11.98
1986	10	59.99	120.00	7.76	2.20	11.98
1987	10	59.99	120.00	8.14	2.05	11.98
1988	10	59.99	120.00	9.38	0.00	11.98
1989	10	59.99	120.00	4.44	2.85	11.98
1990	10	59.99	120.00	4.25	1.15	11.98
1991	10	59.99	120.00	8.03	2.10	11.98

SPACMEAN = spatial mean for each year measured
SPACSTD = spatial standard deviation for each year measured
MOISTURE = Global Climate Model soil moisture value
See Section 5.2a for calculation procedure

Table 16d
Spatial Mean and Standard Deviation of Measured Alberta Stubble Soil Moisture for Spring and Fall (cm) for UI GCM Gridpoints

YEAR	MONTH	LAT	LONG	SPACMEAN	SPACSTD	MOISTURE
1988	4	50.00	110.00	3.72	2.72	10.14
1989	4	50.00	110.00	4.34	2.06	10.14
1990	4	50.00	110.00	5.79	3.40	10.14
1991	4	50.00	110.00	6.78	2.81	10.14
1988	4	50.00	115.00	10.68	4.80	10.65
1989	4	50.00	115.00	12.45	3.80	10.65
1990	4	50.00	115.00	10.41	4.34	10.65
1991	4	50.00	115.00	6.77	2.43	10.65
1988	4	54.00	110.00	8.72	2.85	9.65
1989	4	54.00	110.00	5.95	2.25	9.65
1990	4	54.00	110.00	10.57	4.07	9.65
1991	4	54.00	110.00	9.41	4.70	9.65
1988	4	54.00	115.00	9.50	3.53	10.41
1989	4	54.00	115.00	12.11	3.49	10.41
1990	4	54.00	115.00	13.41	2.85	10.41
1991	4	54.00	115.00	8.21	3.17	10.41
1988	4	54.00	120.00	10.54	3.67	12.35
1989	4	54.00	120.00	9.05	3.01	12.35
1990	4	54.00	120.00	11.69	2.80	12.35
1991	4	54.00	120.00	6.52	3.51	12.35
1988	4	58.00	115.00	12.36	3.57	9.87
1989	4	58.00	115.00	12.94	2.74	9.87
1990	4	58.00	115.00	9.17	3.73	9.87
1991	4	58.00	115.00	6.99	2.27	9.87
1988	4	58.00	120.00	13.27	2.65	11.00
1989	4	58.00	120.00	11.11	2.65	11.00
1990	4	58.00	120.00	12.41	2.86	11.00
1991	4	58.00	120.00	5.88	1.91	11.00
1982	10	50.00	110.00	4.01	2.41	3.27
1983	10	50.00	110.00	2.25	0.00	3.27
1984	10	50.00	110.00	5.67	2.05	3.27
1985	10	50.00	110.00	5.73	2.48	3.27
1986	10	50.00	110.00	13.83	2.70	3.27
1987	10	50.00	110.00	4.03	1.49	3.27
1988	10	50.00	110.00	2.52	1.56	3.27
1989	10	50.00	110.00	3.09	1.49	3.27
1990	10	50.00	110.00	2.25	0.00	3.27
1991	10	50.00	110.00	2.25	0.00	3.27
1982	10	50.00	115.00	5.17	2.53	4.35
1983	10	50.00	115.00	2.80	1.64	4.35
1984	10	50.00	115.00	8.20	2.95	4.35
1985	10	50.00	115.00	13.28	2.60	4.35
1986	10	50.00	115.00	14.64	1.39	4.35
1987	10	50.00	115.00	8.84	4.21	4.35
1988	10	50.00	115.00	6.87	5.27	4.35
1989	10	50.00	115.00	8.18	4.52	4.35
1990	10	50.00	115.00	3.67	1.32	4.35
1991	10	50.00	115.00	4.01	1.24	4.35

Table 16d con't
Spatial Mean and Standard Deviation of Measured Alberta Stubble Soil Moisture for Spring and Fall (cm) for UI GCM Gridpoints

YEAR	MONTH	LAT	LONG	SPACMEAN	SPACSTD	MOISTURE
1982	10	54.00	110.00	4.95	3.72	2.55
1983	10	54.00	110.00	6.60	2.47	2.55
1984	10	54.00	110.00	13.68	2.81	2.55
1985	10	54.00	110.00	7.20	2.31	2.55
1986	10	54.00	110.00	9.48	2.75	2.55
1987	10	54.00	110.00	7.48	2.64	2.55
1988	10	54.00	110.00	5.56	3.01	2.55
1989	10	54.00	110.00	8.67	3.70	2.55
1990	10	54.00	110.00	2.49	0.77	2.55
1991	10	54.00	110.00	2.61	1.10	2.55
1982	10	54.00	115.00	6.16	3.49	2.92
1983	10	54.00	115.00	5.81	2.24	2.92
1984	10	54.00	115.00	15.00	0.00	2.92
1985	10	54.00	115.00	12.80	2.88	2.92
1986	10	54.00	115.00	13.20	3.09	2.92
1987	10	54.00	115.00	9.90	4.16	2.92
1988	10	54.00	115.00	9.42	3.19	2.92
1989	10	54.00	115.00	10.98	3.69	2.92
1990	10	54.00	115.00	4.95	2.71	2.92
1991	10	54.00	115.00	4.70	2.23	2.92
1982	10	54.00	120.00	3.91	2.42	4.55
1983	10	54.00	120.00	5.34	1.38	4.55
1984	10	54.00	120.00	15.00	0.00	4.55
1985	10	54.00	120.00	15.00	0.00	4.55
1986	10	54.00	120.00	5.51	2.35	4.55
1987	10	54.00	120.00	6.93	3.95	4.55
1988	10	54.00	120.00	4.85	2.07	4.55
1989	10	54.00	120.00	12.41	2.84	4.55
1990	10	54.00	120.00	3.67	1.33	4.55
1991	10	54.00	120.00	5.06	1.96	4.55
1982	10	58.00	115.00	2.25	0.00	2.91
1983	10	58.00	115.00	4.88	0.00	2.91
1984	10	58.00	115.00	12.82	2.77	2.91
1985	10	58.00	115.00	8.37	1.90	2.91
1986	10	58.00	115.00	7.64	2.22	2.91
1987	10	58.00	115.00	10.77	5.78	2.91
1988	10	58.00	115.00	8.28	1.96	2.91
1989	10	58.00	115.00	5.03	3.41	2.91
1990	10	58.00	115.00	3.81	1.31	2.91
1991	10	58.00	115.00	7.86	2.64	2.91
1982	10	58.00	120.00	2.25	0.00	3.44
1983	10	58.00	120.00	4.88	0.00	3.44
1984	10	58.00	120.00	15.00	0.00	3.44
1985	10	58.00	120.00	10.59	3.32	3.44
1986	10	58.00	120.00	5.92	1.93	3.44
1987	10	58.00	120.00	11.87	4.36	3.44
1988	10	58.00	120.00	6.90	2.28	3.44
1989	10	58.00	120.00	8.56	4.86	3.44
1990	10	58.00	120.00	2.76	1.06	3.44
1991	10	58.00	120.00	6.20	3.33	3.44

SPACMEAN = spatial mean for each year measured
SPACSTD = spatial standard deviation for each year measured
MOISTURE = Global Climate Model soil moisture value
See Section 5.2a for calculation procedure

Table 16e
Spatial Mean and Standard Deviation of Measured Alberta Stubble Soil Moisture for Spring and Fall (cm) for OSU GCM Grids

YEAR	MONTH	LAT	LONG	SPACMEAN	SPACSTD	MOISTURE
1988	4	50.00	110.00	3.72	2.72	10.34
1989	4	50.00	110.00	4.34	2.06	10.34
1990	4	50.00	110.00	5.79	3.40	10.34
1991	4	50.00	110.00	6.78	2.81	10.34
1988	4	50.00	115.00	10.68	4.80	12.27
1989	4	50.00	115.00	12.45	3.80	12.27
1990	4	50.00	115.00	10.41	4.34	12.27
1991	4	50.00	115.00	6.77	2.43	12.27
1988	4	54.00	110.00	8.72	2.85	8.32
1989	4	54.00	110.00	5.95	2.25	8.32
1990	4	54.00	110.00	10.57	4.07	8.32
1991	4	54.00	110.00	9.41	4.70	8.32
1988	4	54.00	115.00	9.50	3.53	10.65
1989	4	54.00	115.00	12.11	3.49	10.65
1990	4	54.00	115.00	13.41	2.85	10.65
1991	4	54.00	115.00	8.21	3.17	10.65
1988	4	54.00	120.00	10.54	3.67	10.69
1989	4	54.00	120.00	9.05	3.01	10.69
1990	4	54.00	120.00	11.69	2.80	10.69
1991	4	54.00	120.00	6.52	3.51	10.69
1988	4	58.00	115.00	12.36	3.57	8.29
1989	4	58.00	115.00	12.94	2.74	8.29
1990	4	58.00	115.00	9.17	3.73	8.29
1991	4	58.00	115.00	6.99	2.27	8.29
1988	4	58.00	120.00	13.27	2.65	8.91
1989	4	58.00	120.00	11.11	2.65	8.91
1990	4	58.00	120.00	12.41	2.86	8.91
1991	4	58.00	120.00	5.88	1.91	8.91
1982	10	50.00	110.00	4.01	2.41	2.38
1983	10	50.00	110.00	2.25	0.00	2.38
1984	10	50.00	110.00	5.67	2.05	2.38
1985	10	50.00	110.00	5.73	2.48	2.38
1986	10	50.00	110.00	13.83	2.70	2.38
1987	10	50.00	110.00	4.03	1.49	2.38
1988	10	50.00	110.00	2.52	1.56	2.38
1989	10	50.00	110.00	3.09	1.49	2.38
1990	10	50.00	110.00	2.25	0.00	2.38
1991	10	50.00	110.00	2.25	0.00	2.38
1982	10	50.00	115.00	5.17	2.53	4.26
1983	10	50.00	115.00	2.80	1.64	4.26
1984	10	50.00	115.00	8.20	2.95	4.26
1985	10	50.00	115.00	13.28	2.60	4.26
1986	10	50.00	115.00	14.64	1.39	4.26
1987	10	50.00	115.00	8.84	4.21	4.26
1988	10	50.00	115.00	6.87	5.27	4.26
1989	10	50.00	115.00	8.18	4.52	4.26
1990	10	50.00	115.00	3.67	1.32	4.26
1991	10	50.00	115.00	4.01	1.24	4.26

Table 16e con't
Spatial Mean and Standard Deviation of Measured Alberta Stubble Soil Moisture for Spring and Fall (cm) for OSU GCM Grids

YEAR	MONTH	LAT	LONG	SPACMEAN	SPACSTD	MOISTURE
1982	10	54.00	110.00	4.95	3.72	1.90
1983	10	54.00	110.00	6.60	2.47	1.90
1984	10	54.00	110.00	13.68	2.81	1.90
1985	10	54.00	110.00	7.20	2.31	1.90
1986	10	54.00	110.00	9.48	2.75	1.90
1987	10	54.00	110.00	7.48	2.64	1.90
1988	10	54.00	110.00	5.56	3.01	1.90
1989	10	54.00	110.00	8.67	3.70	1.90
1990	10	54.00	110.00	2.49	0.77	1.90
1991	10	54.00	110.00	2.61	1.10	1.90
1982	10	54.00	115.00	6.16	3.49	3.83
1983	10	54.00	115.00	5.81	2.24	3.83
1984	10	54.00	115.00	15.00	0.00	3.83
1985	10	54.00	115.00	12.80	2.88	3.83
1986	10	54.00	115.00	13.20	3.09	3.83
1987	10	54.00	115.00	9.90	4.16	3.83
1988	10	54.00	115.00	9.42	3.19	3.83
1989	10	54.00	115.00	10.98	3.69	3.83
1990	10	54.00	115.00	4.95	2.71	3.83
1991	10	54.00	115.00	4.70	2.23	3.83
1982	10	54.00	120.00	3.91	2.42	2.41
1983	10	54.00	120.00	5.34	1.38	2.41
1984	10	54.00	120.00	15.00	0.00	2.41
1985	10	54.00	120.00	15.00	0.00	2.41
1986	10	54.00	120.00	5.51	2.35	2.41
1987	10	54.00	120.00	6.93	3.95	2.41
1988	10	54.00	120.00	4.85	2.07	2.41
1989	10	54.00	120.00	12.41	2.84	2.41
1990	10	54.00	120.00	3.67	1.33	2.41
1991	10	54.00	120.00	5.06	1.96	2.41
1982	10	58.00	115.00	2.25	0.00	2.87
1983	10	58.00	115.00	4.88	0.00	2.87
1984	10	58.00	115.00	12.82	2.77	2.87
1985	10	58.00	115.00	8.37	1.90	2.87
1986	10	58.00	115.00	7.64	2.22	2.87
1987	10	58.00	115.00	10.77	5.78	2.87
1988	10	58.00	115.00	8.28	1.96	2.87
1989	10	58.00	115.00	5.03	3.41	2.87
1990	10	58.00	115.00	3.81	1.31	2.87
1991	10	58.00	115.00	7.86	2.64	2.87
1982	10	58.00	120.00	2.25	0.00	4.05
1983	10	58.00	120.00	4.88	0.00	4.05
1984	10	58.00	120.00	15.00	0.00	4.05
1985	10	58.00	120.00	10.59	3.32	4.05
1986	10	58.00	120.00	5.92	1.93	4.05
1987	10	58.00	120.00	11.87	4.36	4.05
1988	10	58.00	120.00	6.90	2.28	4.05
1989	10	58.00	120.00	8.56	4.86	4.05
1990	10	58.00	120.00	2.76	1.06	4.05
1991	10	58.00	120.00	6.20	3.33	4.05

SPACMEAN = spatial mean for each year measured
SPACSTD = spatial standard deviation for each year measured
MOISTURE = Global Climate Model soil moisture value
See Section 5.2a for calculation procedure

Table 16f
Spatial Mean and Standard Deviation of Measured Alberta Stubble Soil Moisture for Spring and Fall (cm) for UKMO GCM Grids

YEAR	MONTH	LAT	LONG	SPACMEAN	SPACSTD	MOISTURE
1988	4	52.5	108.0	6.54	4.11	14.48
1989	4	52.5	108.0	5.56	2.73	14.48
1990	4	52.5	108.0	7.66	3.73	14.48
1991	4	52.5	108.0	7.56	3.84	14.48
1988	4	52.5	116.2	9.47	4.06	14.19
1989	4	52.5	116.2	11.99	3.55	14.19
1990	4	52.5	116.2	11.57	3.91	14.19
1991	4	52.5	116.2	8.23	3.47	14.19
1988	4	57.5	116.2	11.04	3.92	100.00
1989	4	57.5	116.2	11.23	3.73	100.00
1990	4	57.5	116.2	12.69	3.50	100.00
1991	4	57.5	116.2	6.55	2.18	100.00
1982	10	52.5	108.0	5.09	3.58	6.63
1983	10	52.5	108.0	4.61	2.83	6.63
1984	10	52.5	108.0	10.81	4.53	6.63
1985	10	52.5	108.0	6.52	2.50	6.63
1986	10	52.5	108.0	12.02	3.56	6.63
1987	10	52.5	108.0	5.90	2.55	6.63
1988	10	52.5	108.0	4.26	3.21	6.63
1989	10	52.5	108.0	5.21	3.92	6.63
1990	10	52.5	108.0	2.43	0.66	6.63
1991	10	52.5	108.0	2.44	0.84	6.63
1982	10	52.5	116.2	6.45	3.10	100.00
1983	10	52.5	116.2	5.19	2.89	100.00
1984	10	52.5	116.2	13.47	2.84	100.00
1985	10	52.5	116.2	13.87	2.26	100.00
1986	10	52.5	116.2	14.89	0.78	100.00
1987	10	52.5	116.2	10.04	4.05	100.00
1988	10	52.5	116.2	10.15	3.85	100.00
1989	10	52.5	116.2	11.16	4.24	100.00
1990	10	52.5	116.2	4.55	2.20	100.00
1991	10	52.5	116.2	4.94	2.10	100.00
1982	10	57.5	116.2	2.47	0.72	100.00
1983	10	57.5	116.2	4.88	0.00	100.00
1984	10	57.5	116.2	14.29	1.87	100.00
1985	10	57.5	116.2	10.63	3.04	100.00
1986	10	57.5	116.2	7.54	2.22	100.00
1987	10	57.5	116.2	9.17	4.64	100.00
1988	10	57.5	116.2	6.69	2.42	100.00
1989	10	57.5	116.2	8.83	4.11	100.00
1990	10	57.5	116.2	4.29	2.62	100.00
1991	10	57.5	116.2	6.15	3.05	100.00

SPACMEAN = spatial mean for each year measured
SPACSTD = spatial standard deviation for each year measured
MOISTURE = Global Climate Model soil moisture value
A moisture value of 100 indicates a model surface type of 'SEA'
See Section 5.2a for calculation procedure

Appendix D:

Annual Variation of GCM Soil Moisture vs. Mean and Standard Deviation of Actual Alberta Stubble Soil Moisture

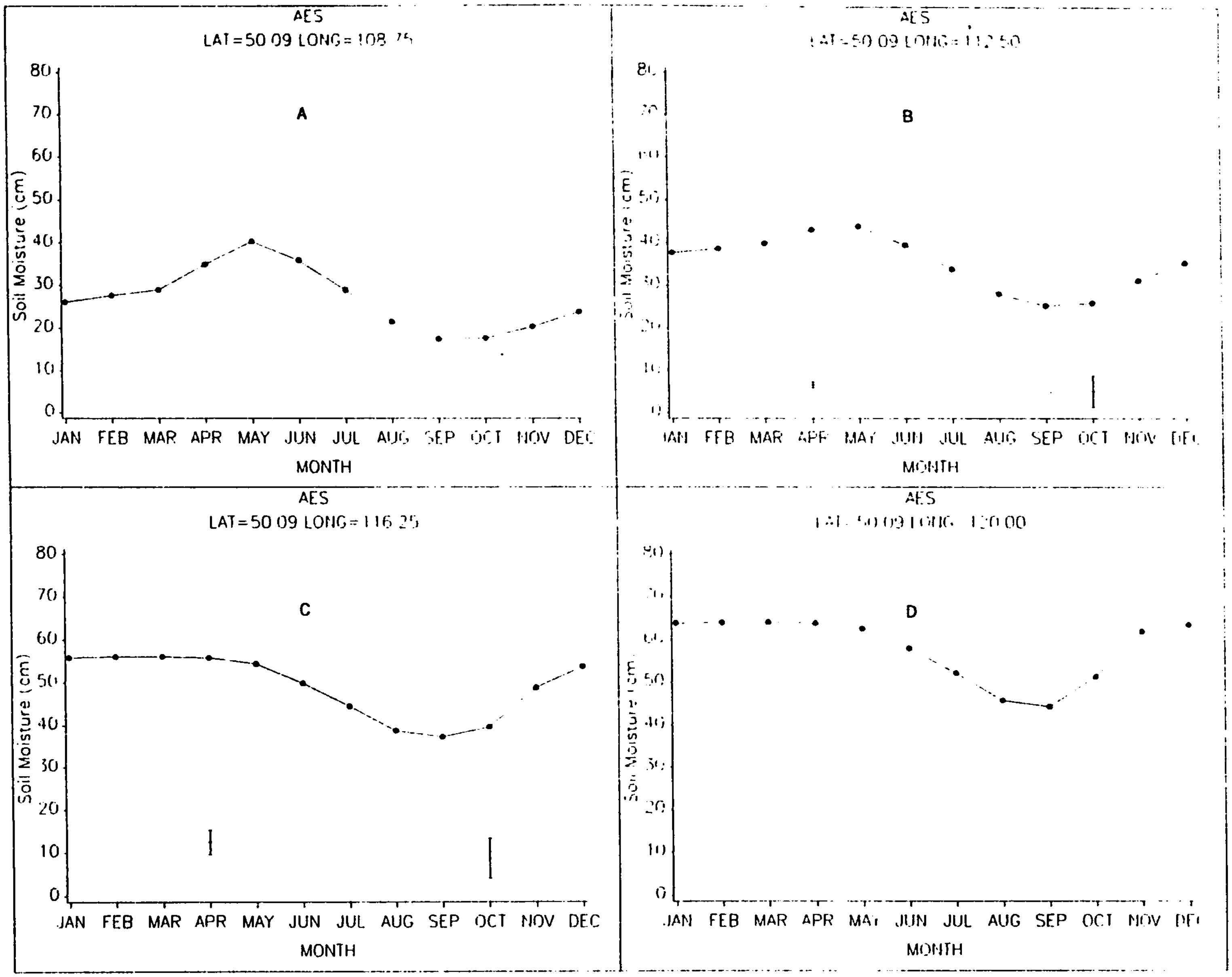

Figure 10 (A to D): Annual variation of AES 1XCO2 GCM soil moisture (points) vs. mean and standard deviation of actual Alberta stubble soil moisture (bars) where available for model gridpoints in and near Alberta

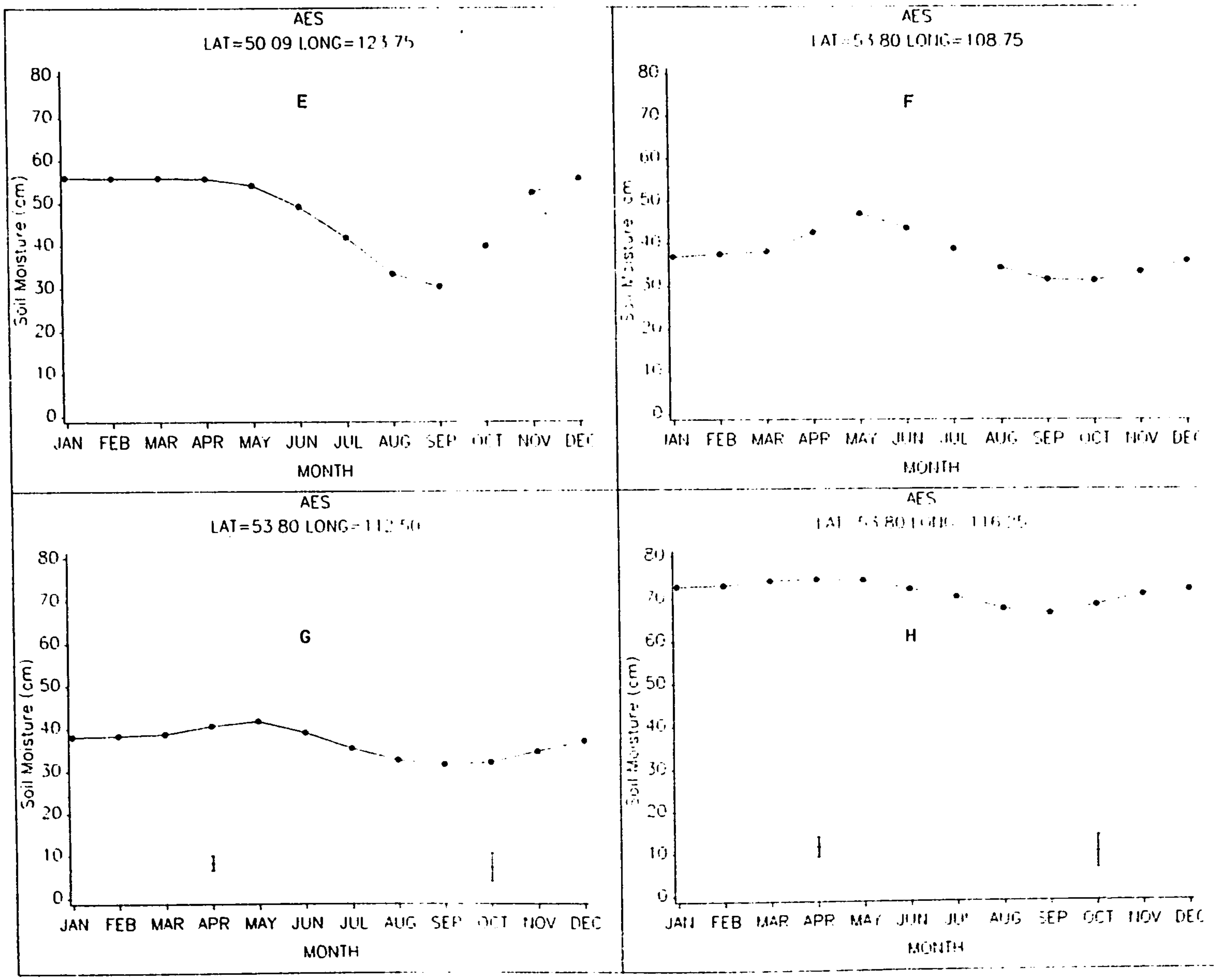

Figure 10 con't (E to H)

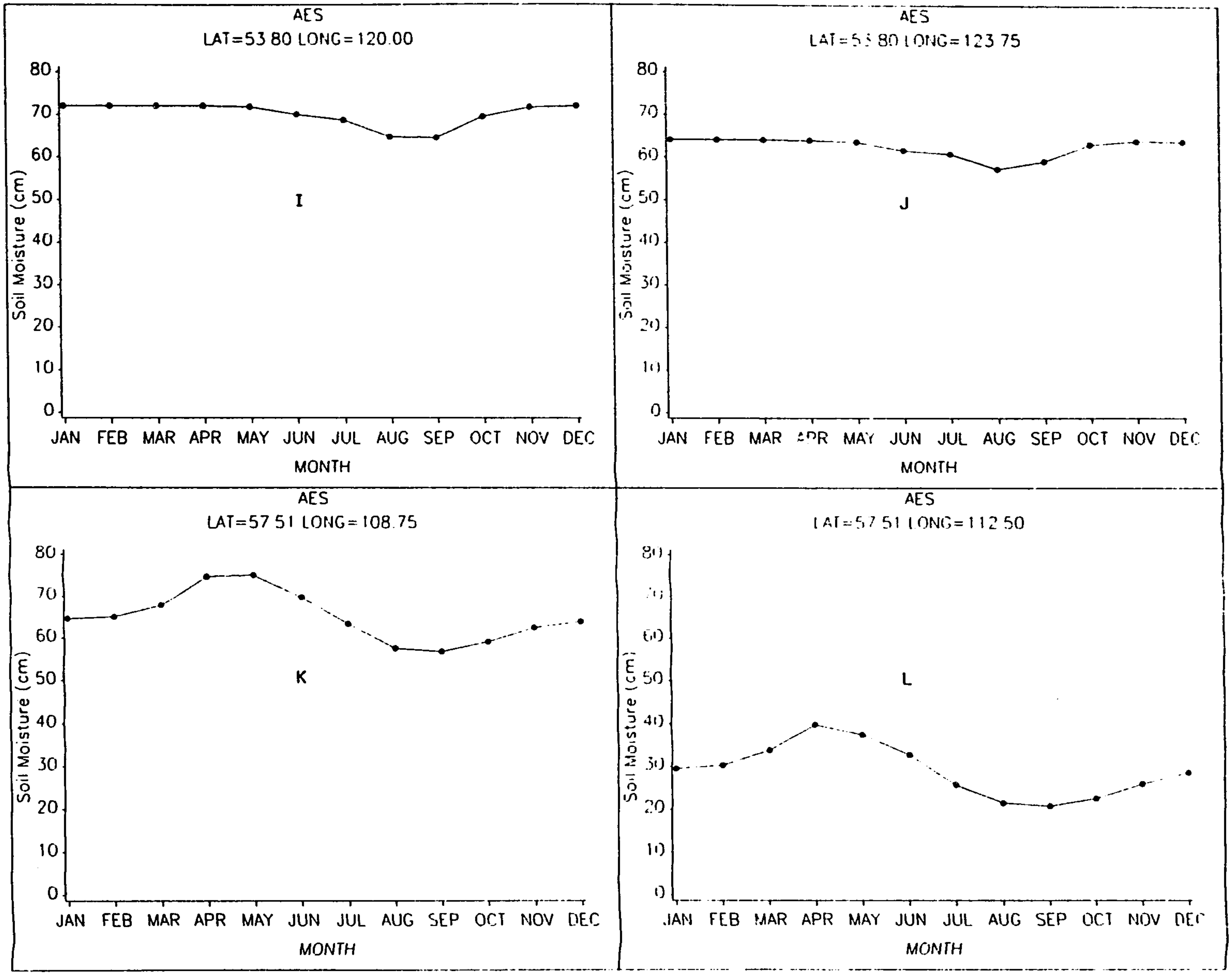

Figure 10 con't (I to L)

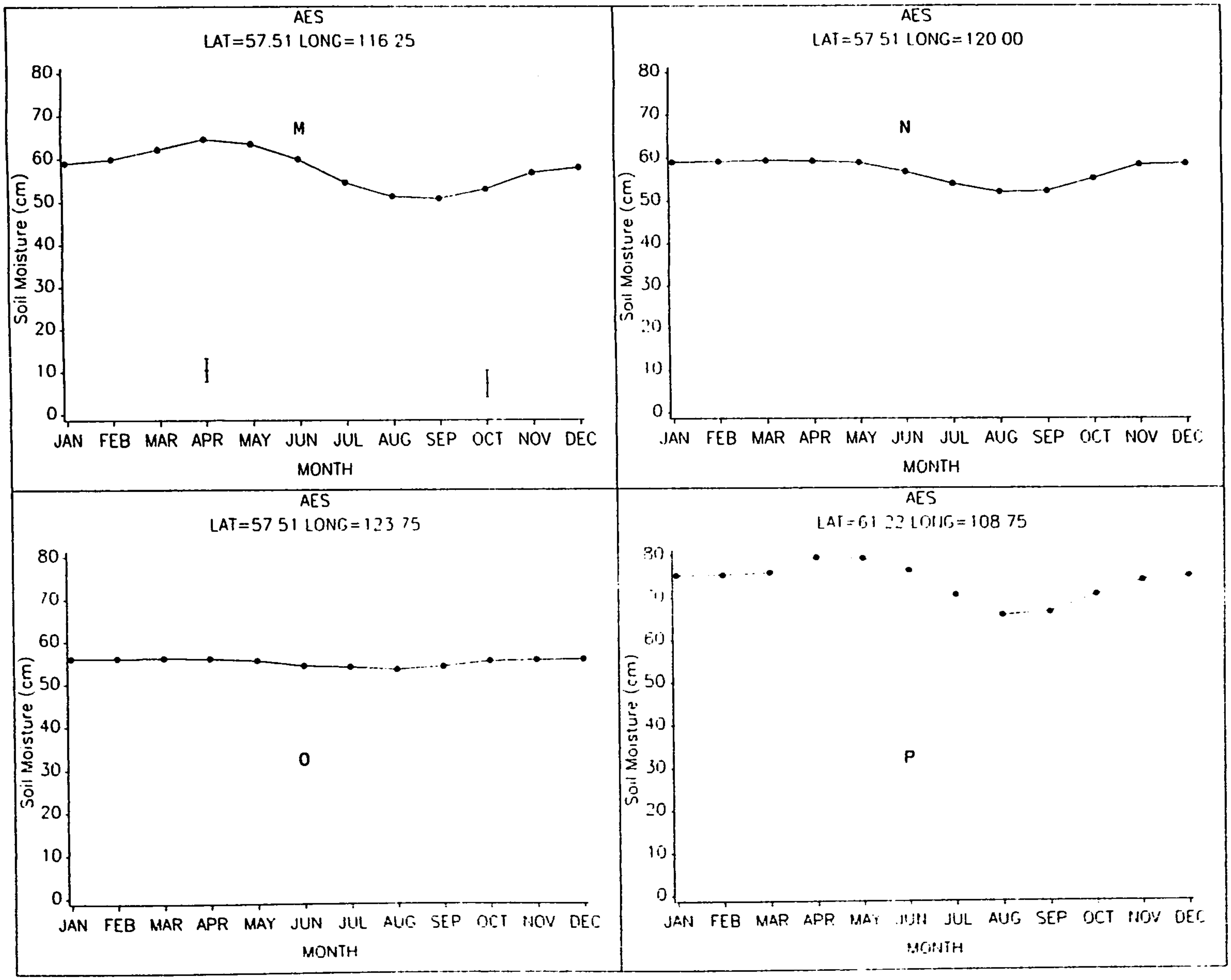

Figure 10 con't (M to P)

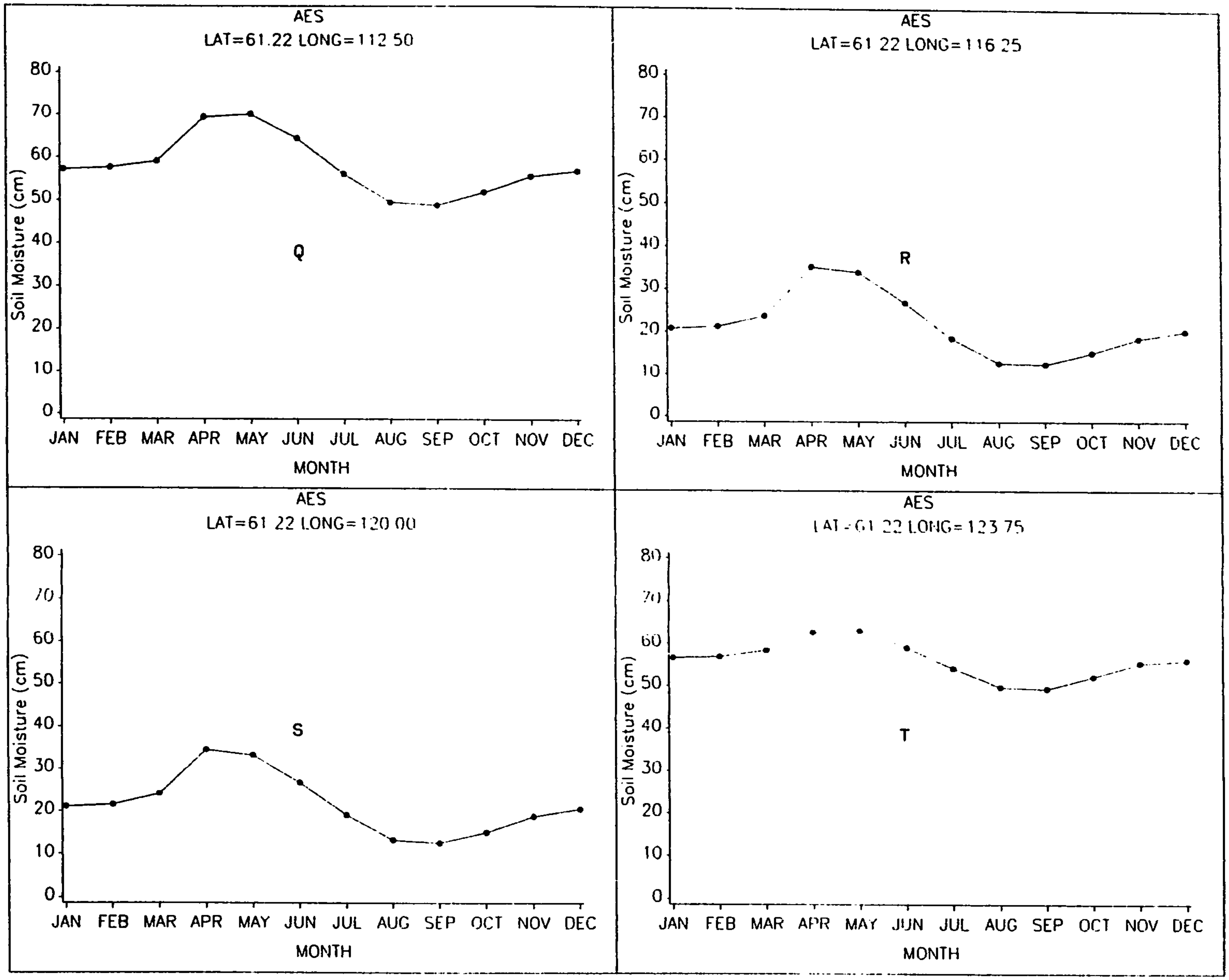

Figure 10 con't (Q to T)

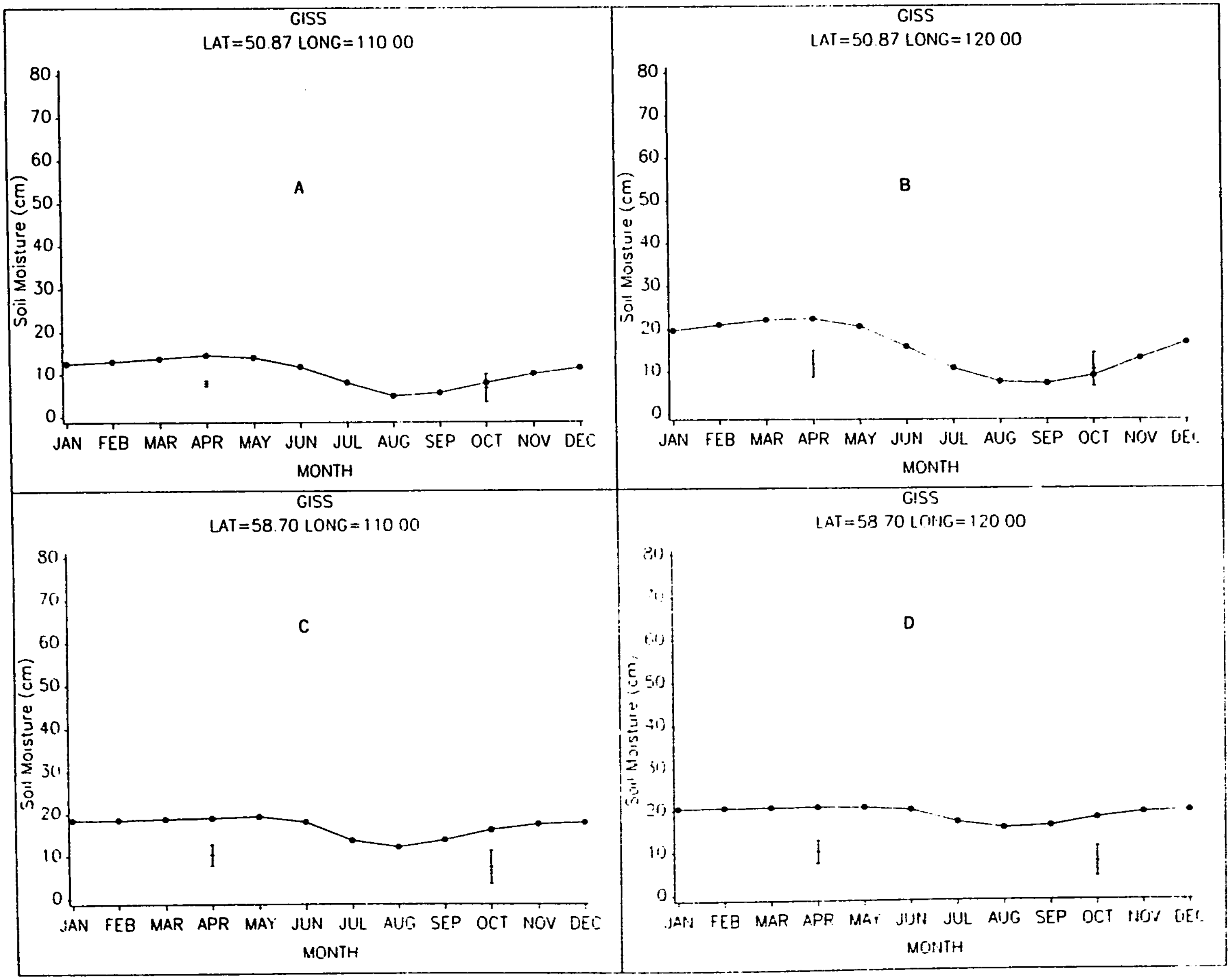

Figure 11 (A to D): Annual variation of GISS 1XCO2 GCM soil moisture (points) vs. mean and standard deviation of actual Alberta stubble soil moisture (bars) where available for model gridpoints in and near Alberta

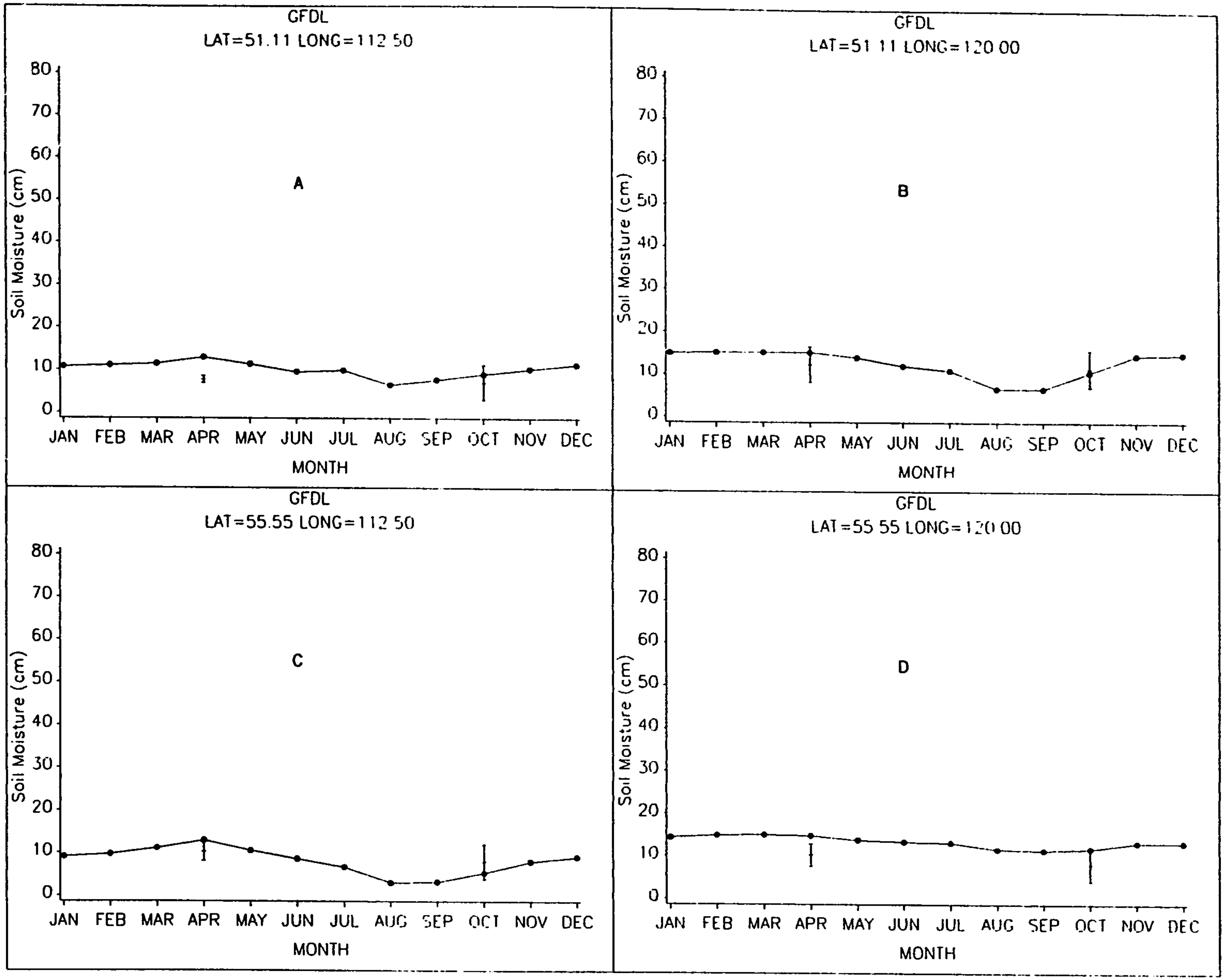

Figure 12 (A to D): Annual variation of GFDL GCM soil moisture (points) vs. mean and standard deviation of actual Alberta stubble soil moisture (bars) where available for model gridpoints in and near Alberta

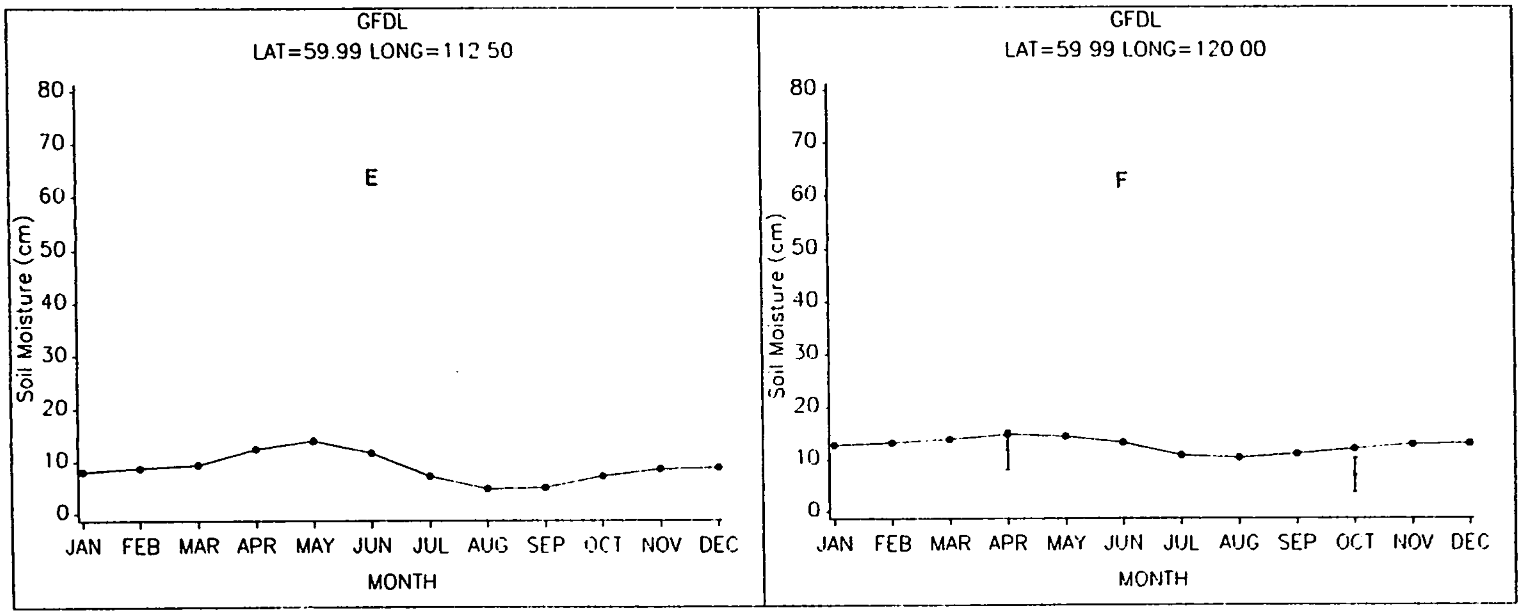

Figure 12 con't (E to ,)

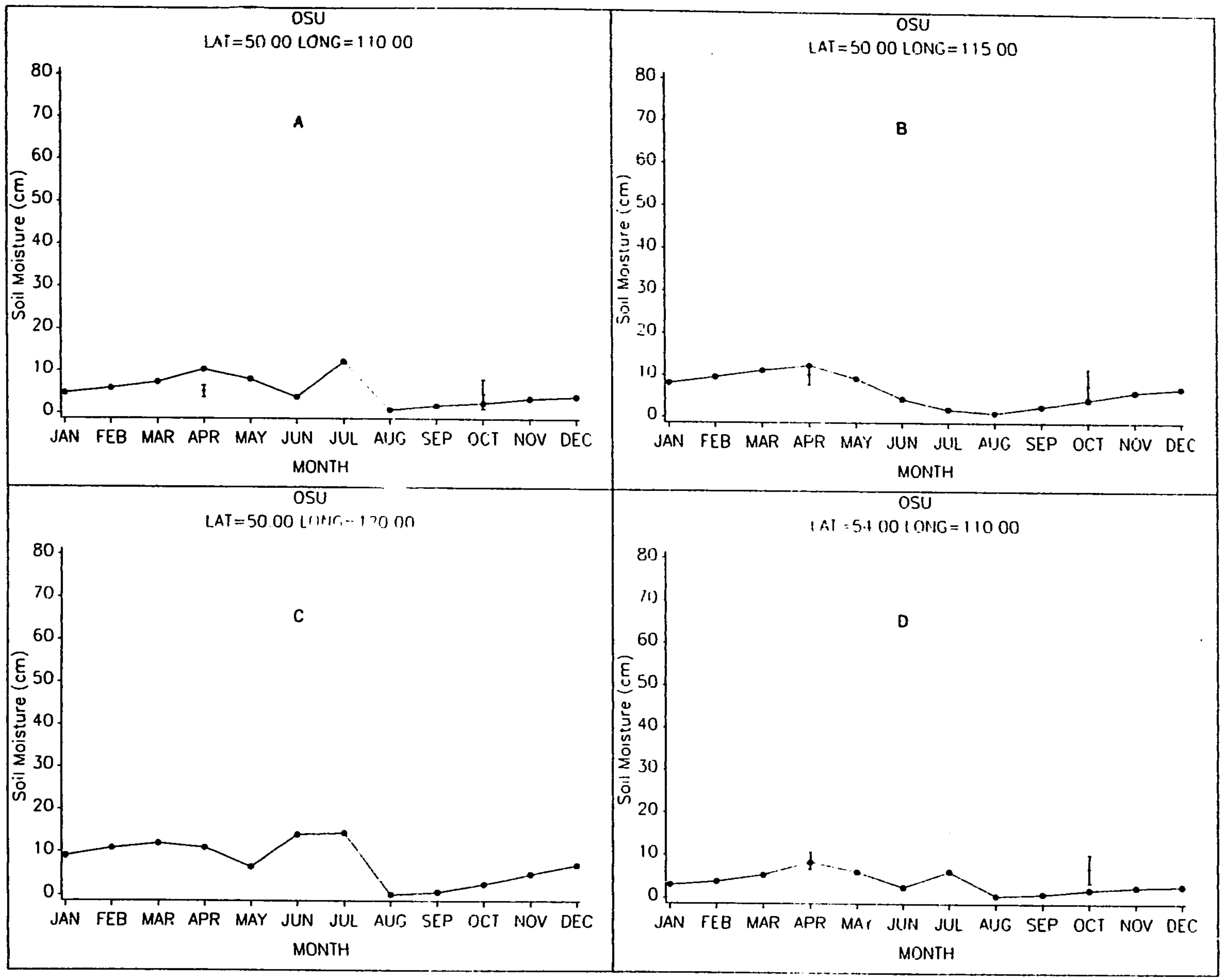

Figure 13 (A to D): Annual variation of OSU 1XCO2 GCM soil moisture (points) vs. mean and standard deviation of actual Alberta stubble soil moisture (bars) where available for model gridpoints in and near Alberta

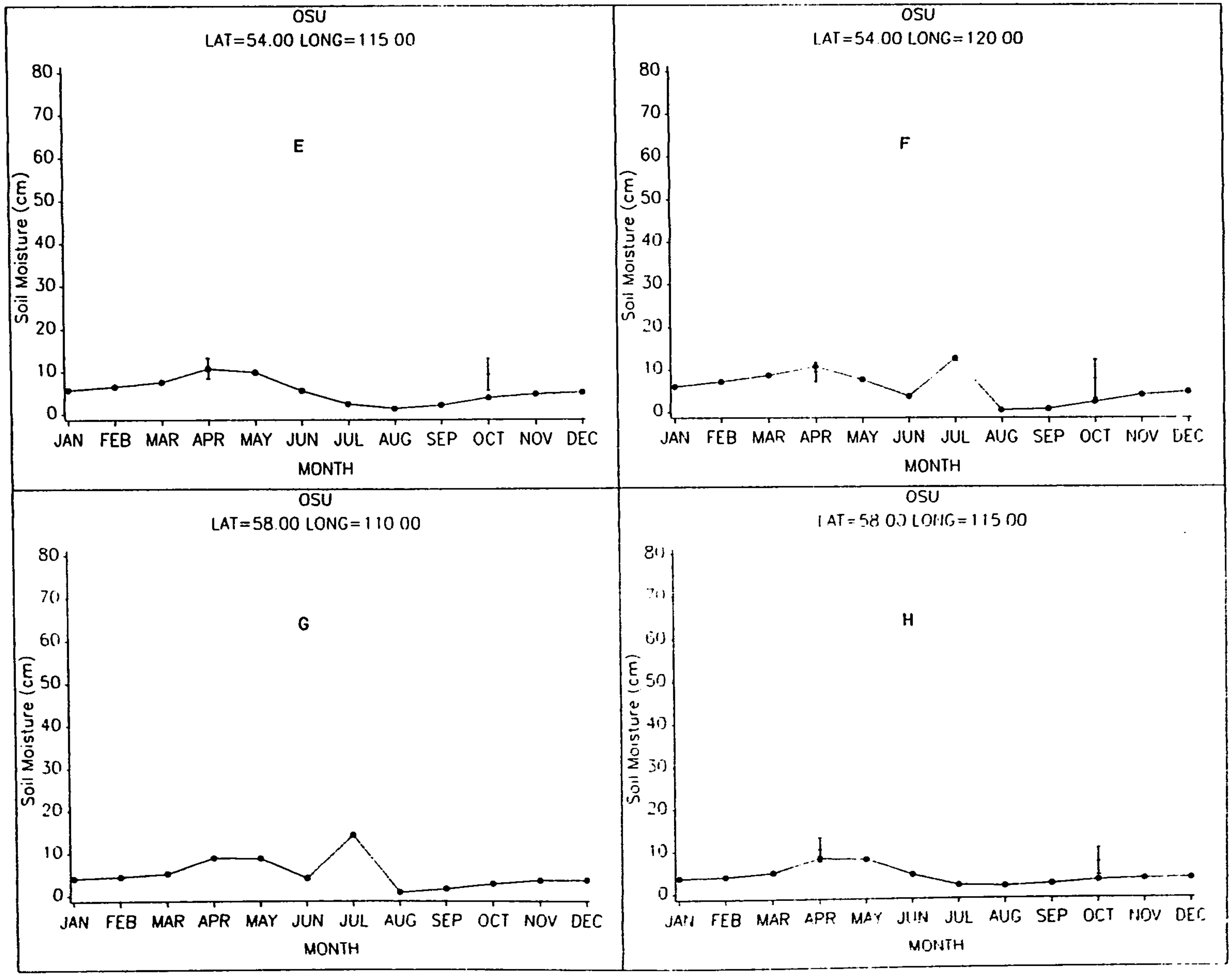

Figure 13 cont (E to H)

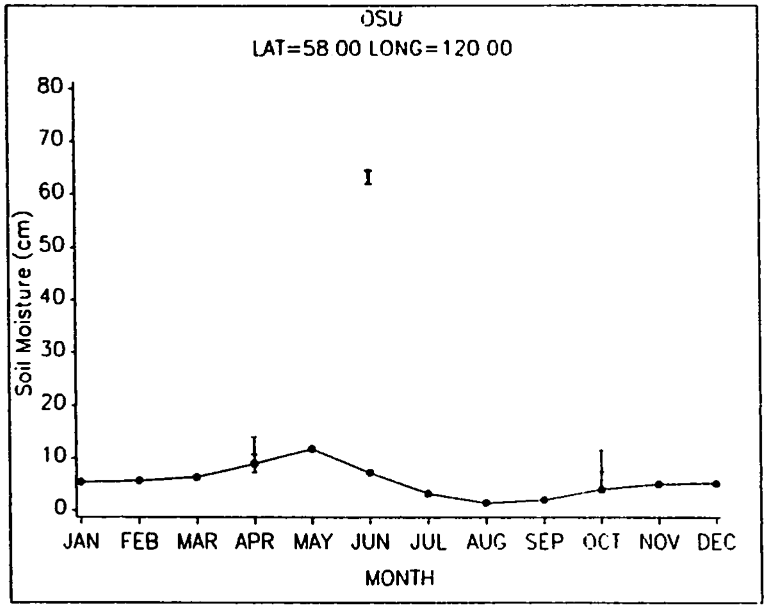

Figure 13 con't (I)

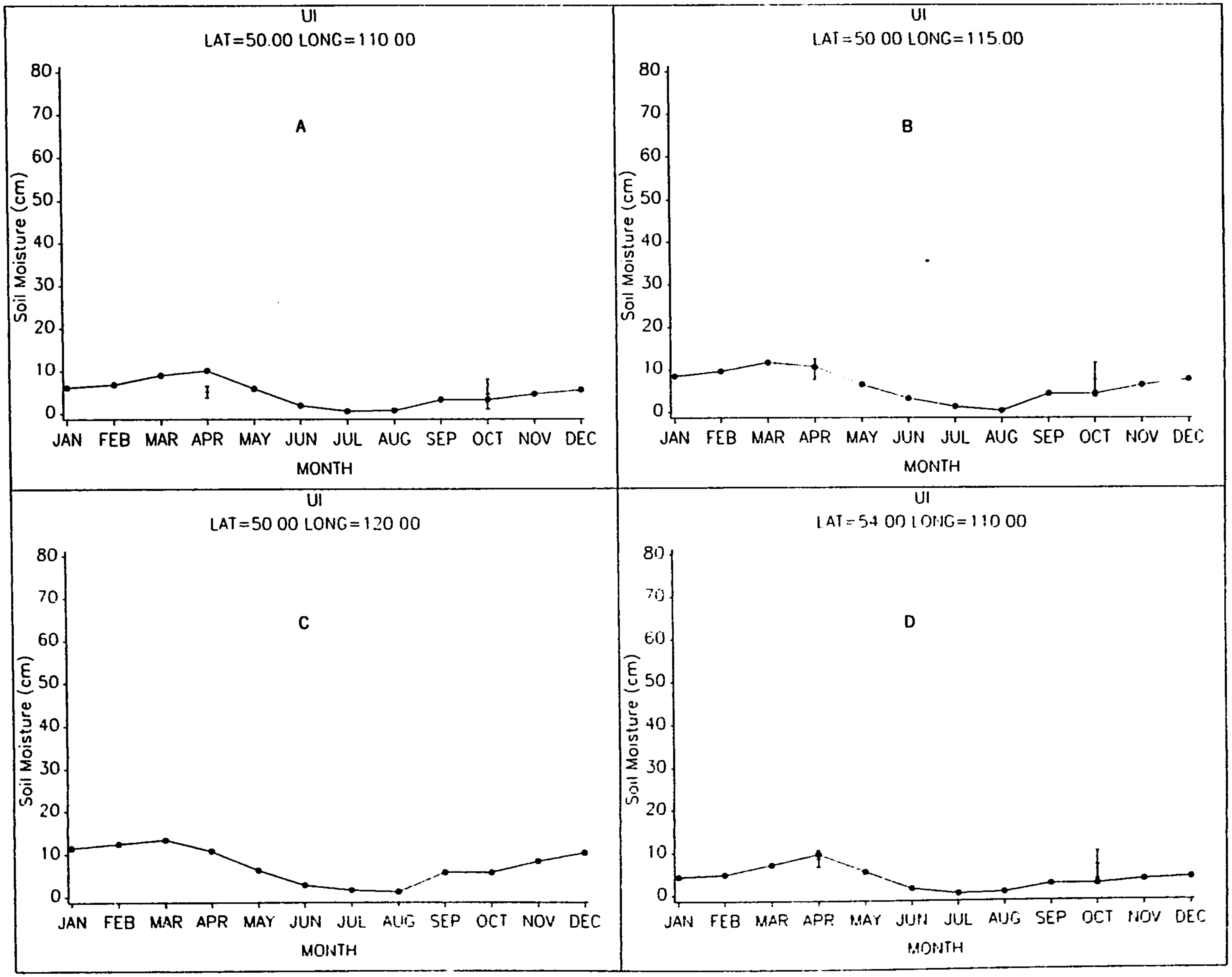

Figure 14 (A to D): Annual variation of UI 1XCO2 GCM soil moisture (points) vs. mean and standard devaiation of actual Alberta stubble soil moisture (bars) where available for model gridpoints in and near ALberta

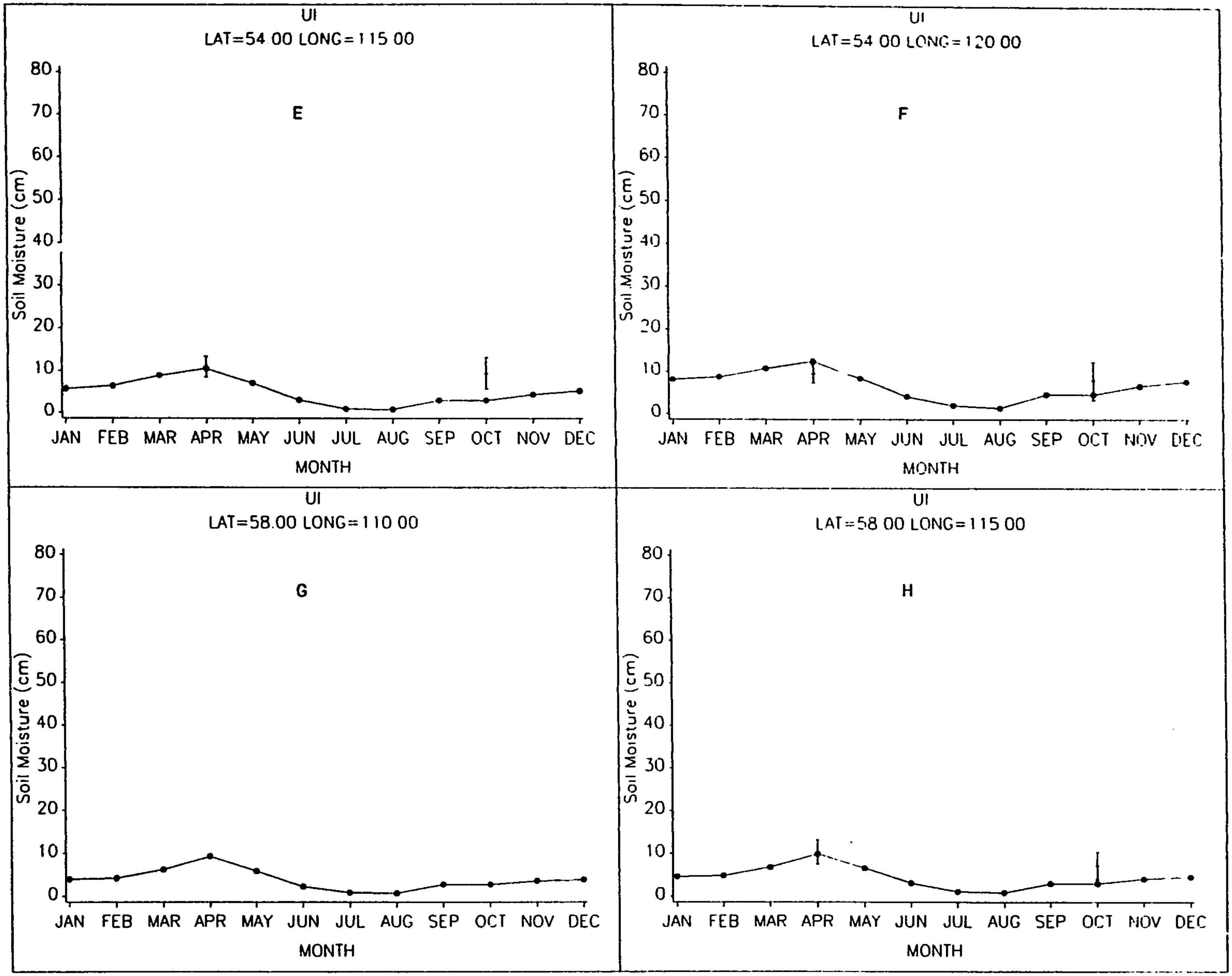

Figure 14 con't (E to H)

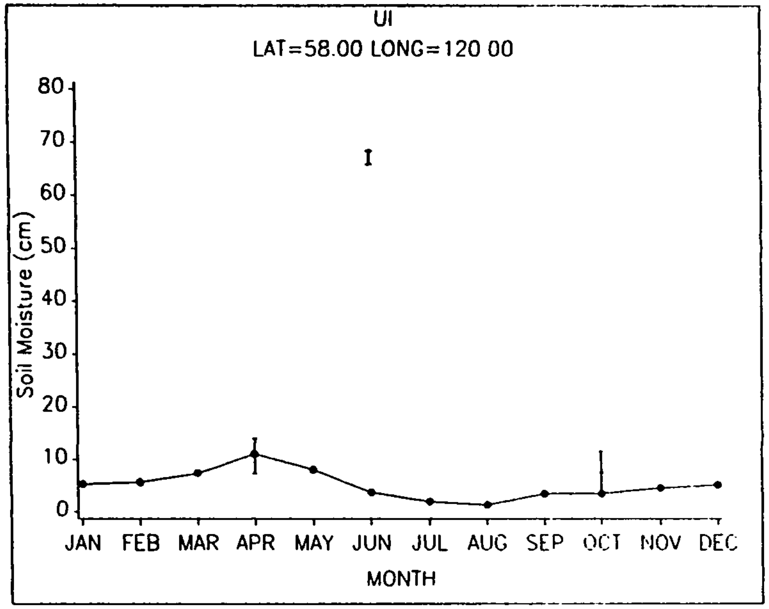

Figure 14 con't (I)

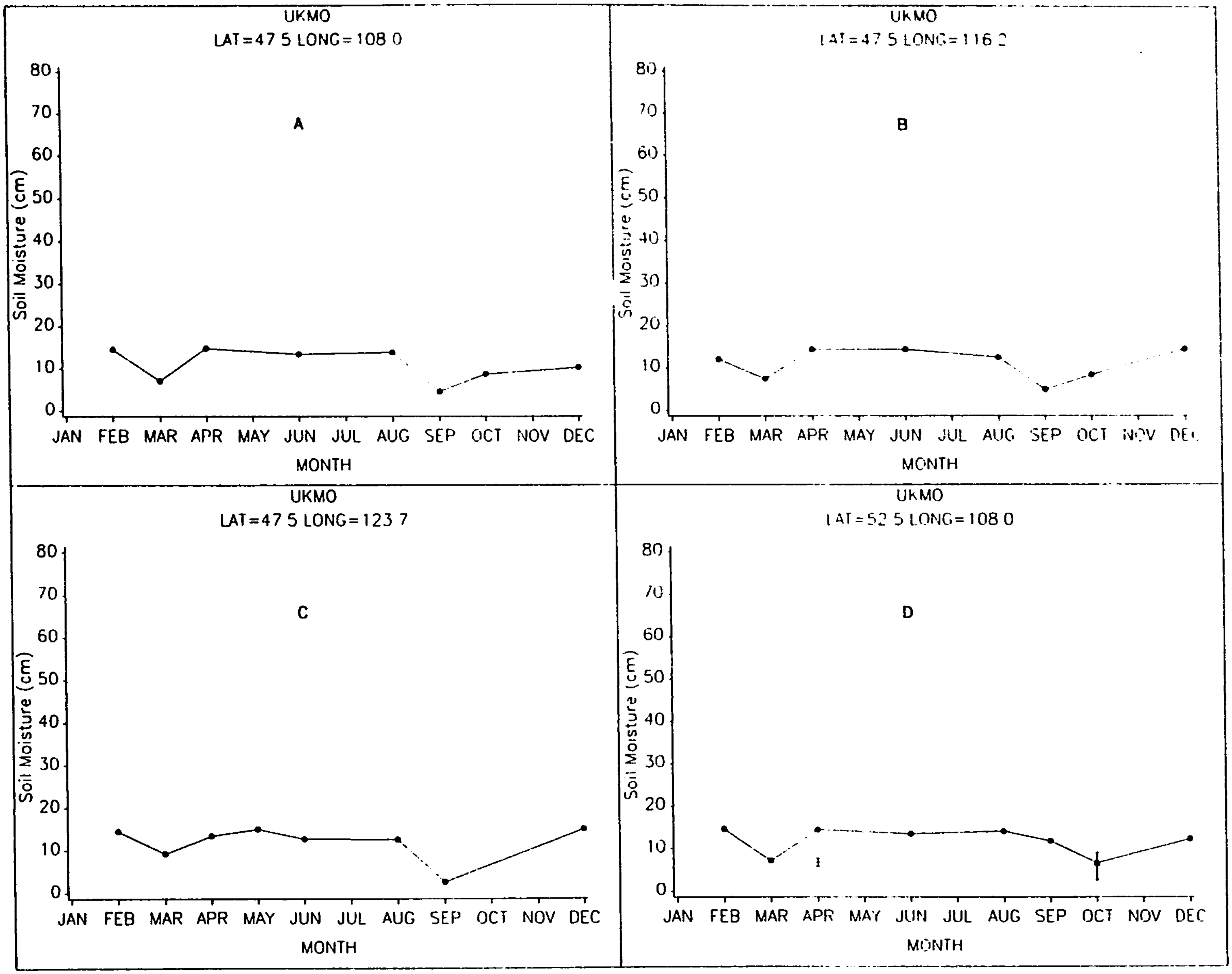

Figure 15 (A to D): Annual variation of UKMO 1XCO2 GCM soil moisture (points) vs. mean and standard deviation of actual Alberta stubble soil moisture (bars) where available for model gridpoints in and near Alberta

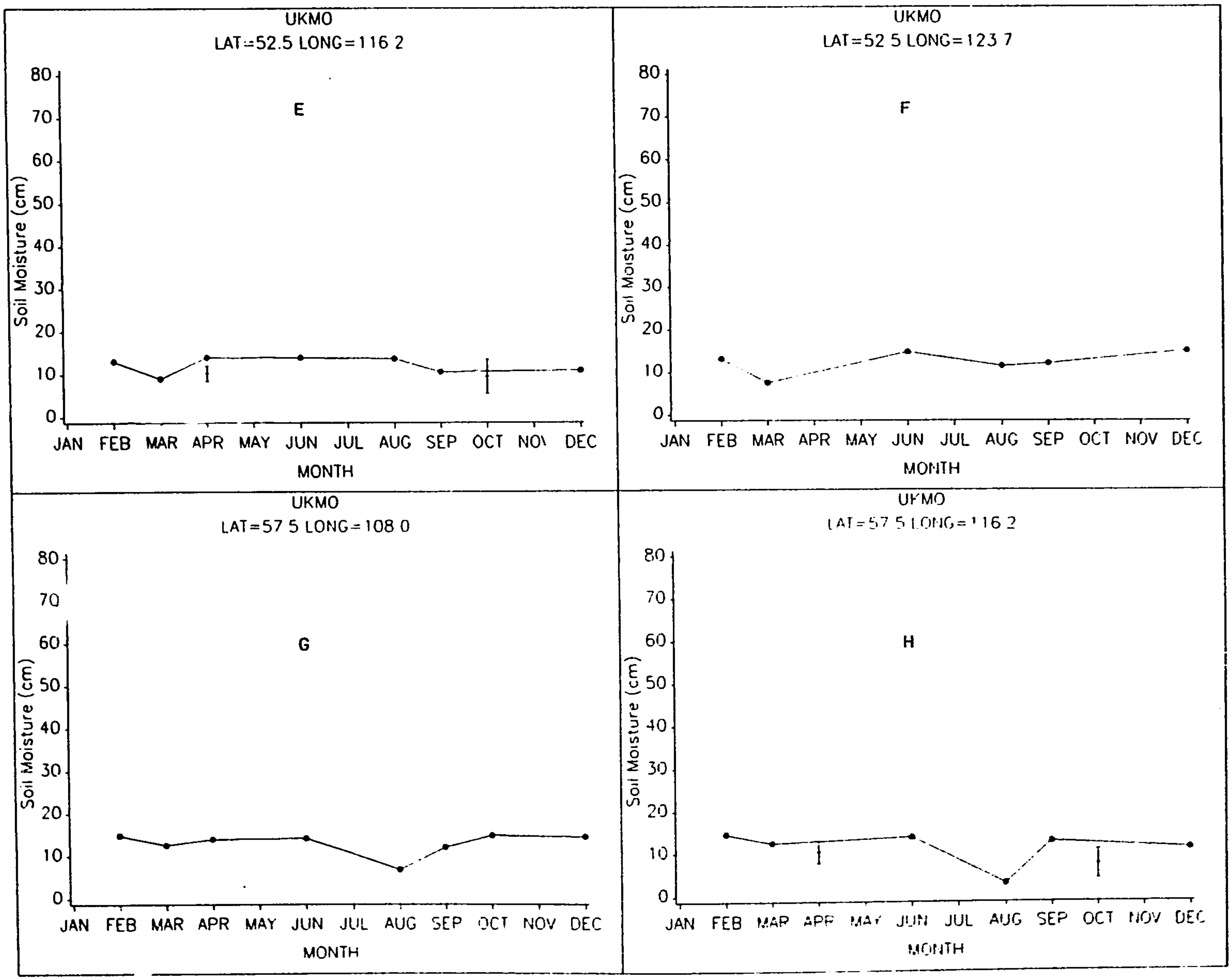

Figure 15 con't (E to H)

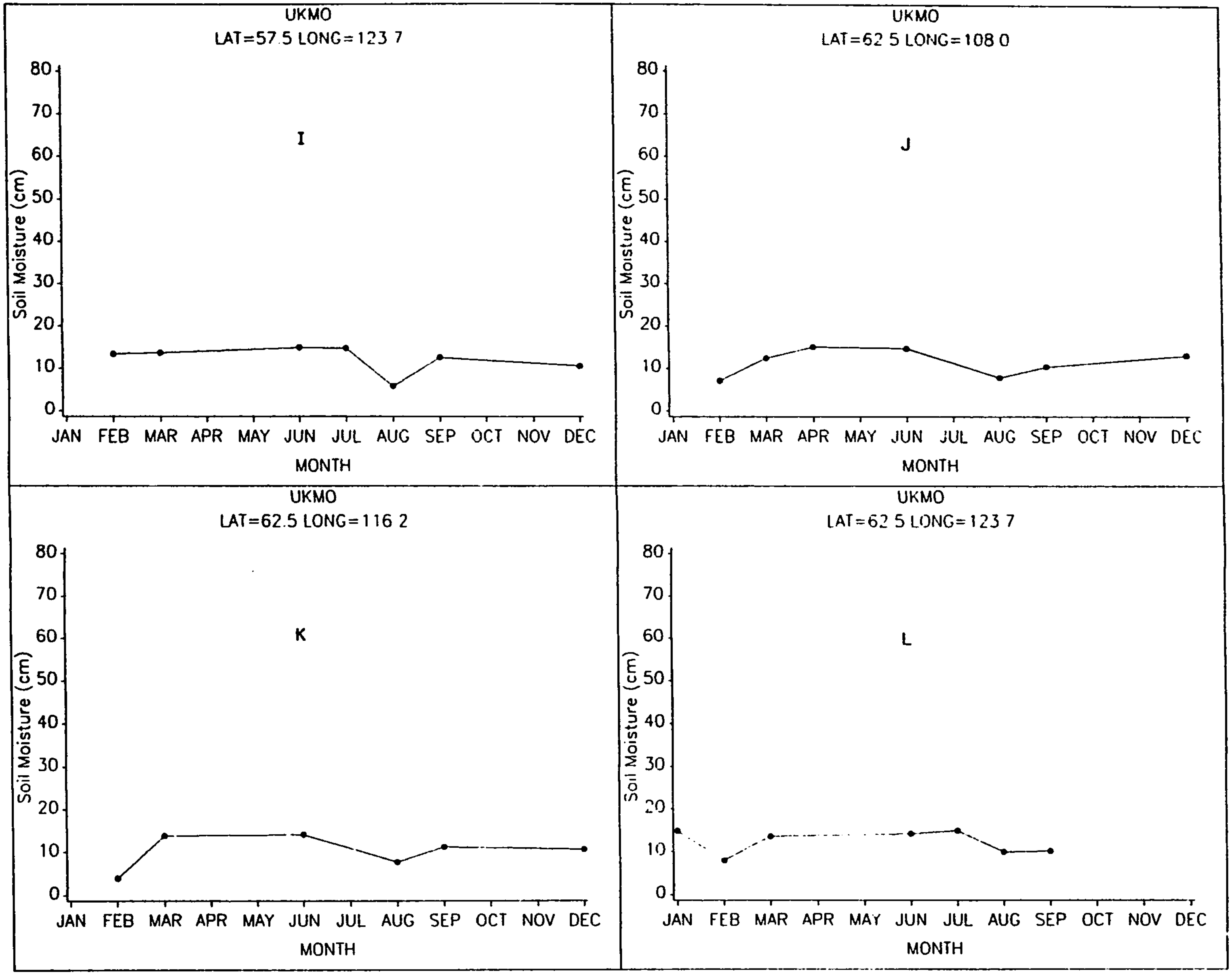

Figure 15 con't (I to L)

Appendix E:

Annual Variation of GCM $1XCO_2$ and $2XCO_2$ Soil Moisture for Model Gridpoints in and Near Alberta

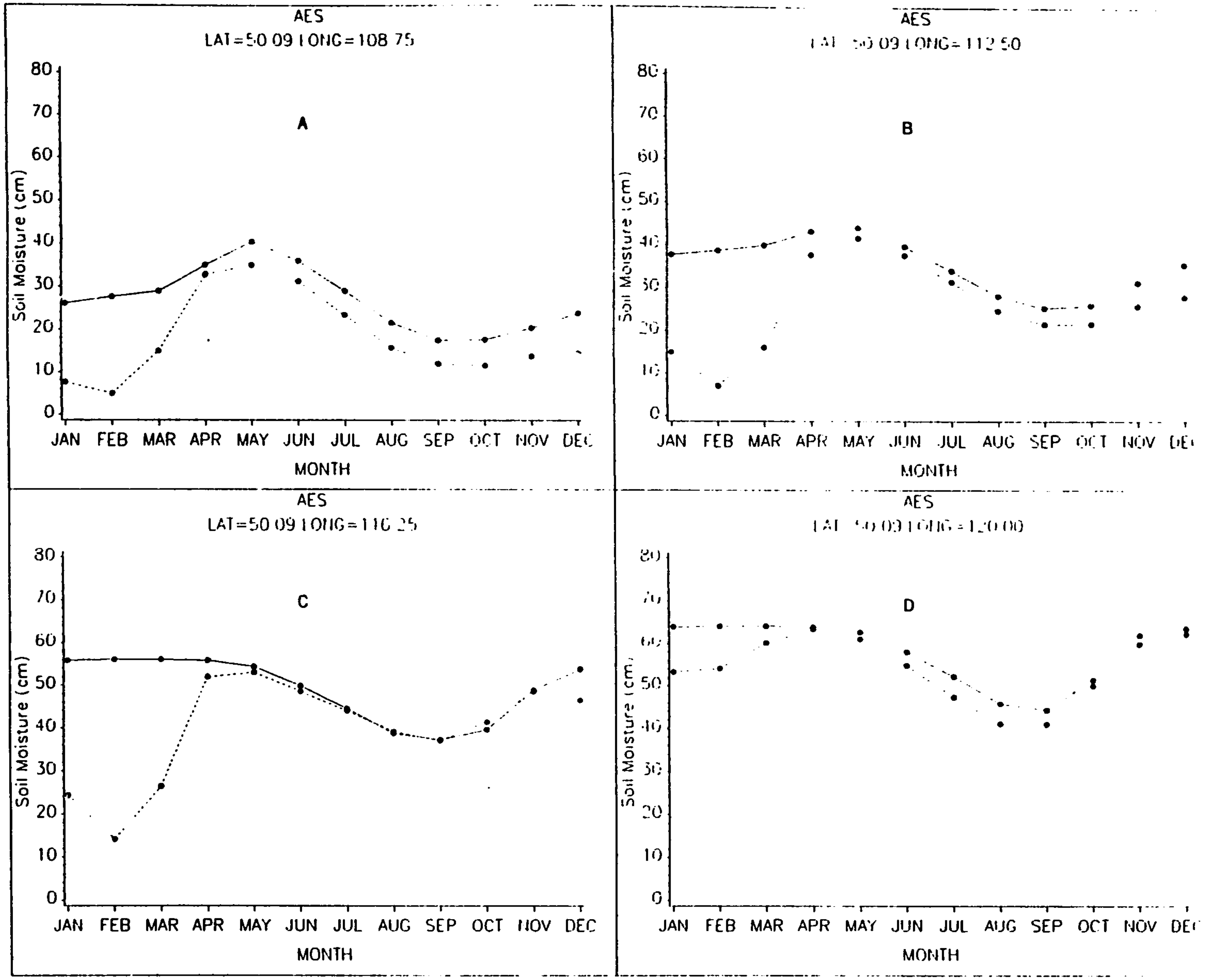

Figure 16 (A to D): Annual variation of AES 1XCO2 (solid line) and 2XCO2 (dashed line) soil moisture for model gridpoints in and near Alberta

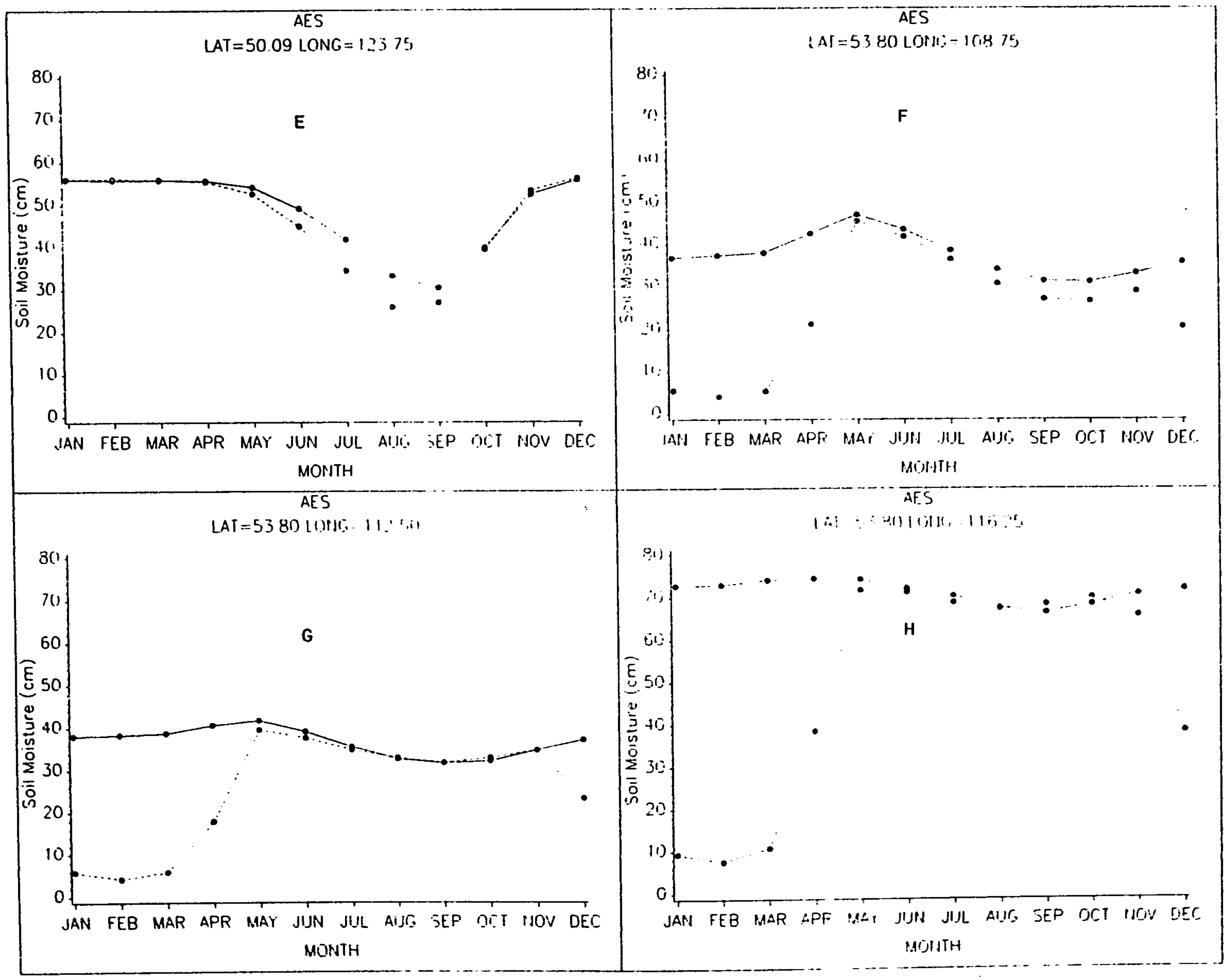

Figure 16 con't (E to H)

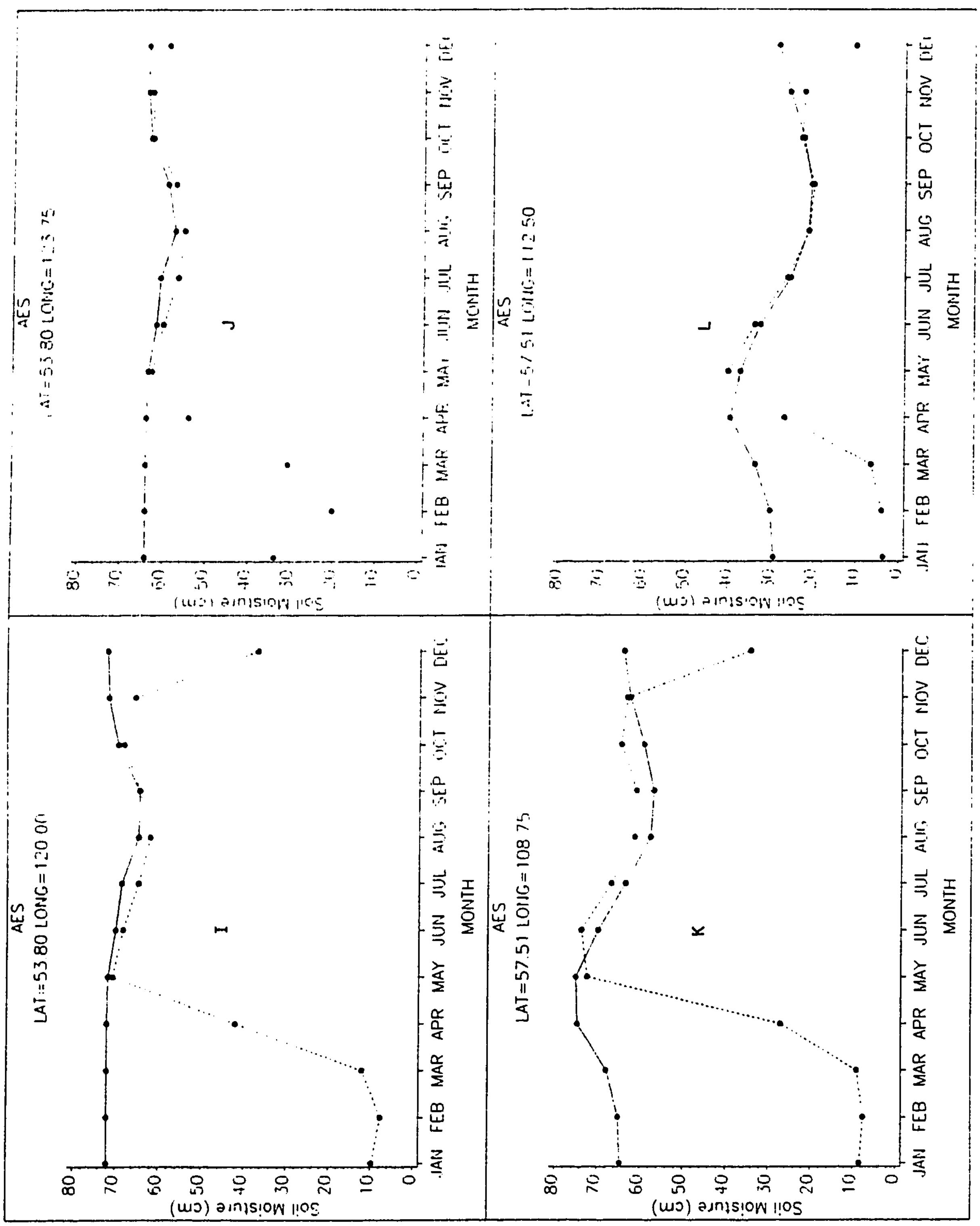

Figure 16 con't (I to L)

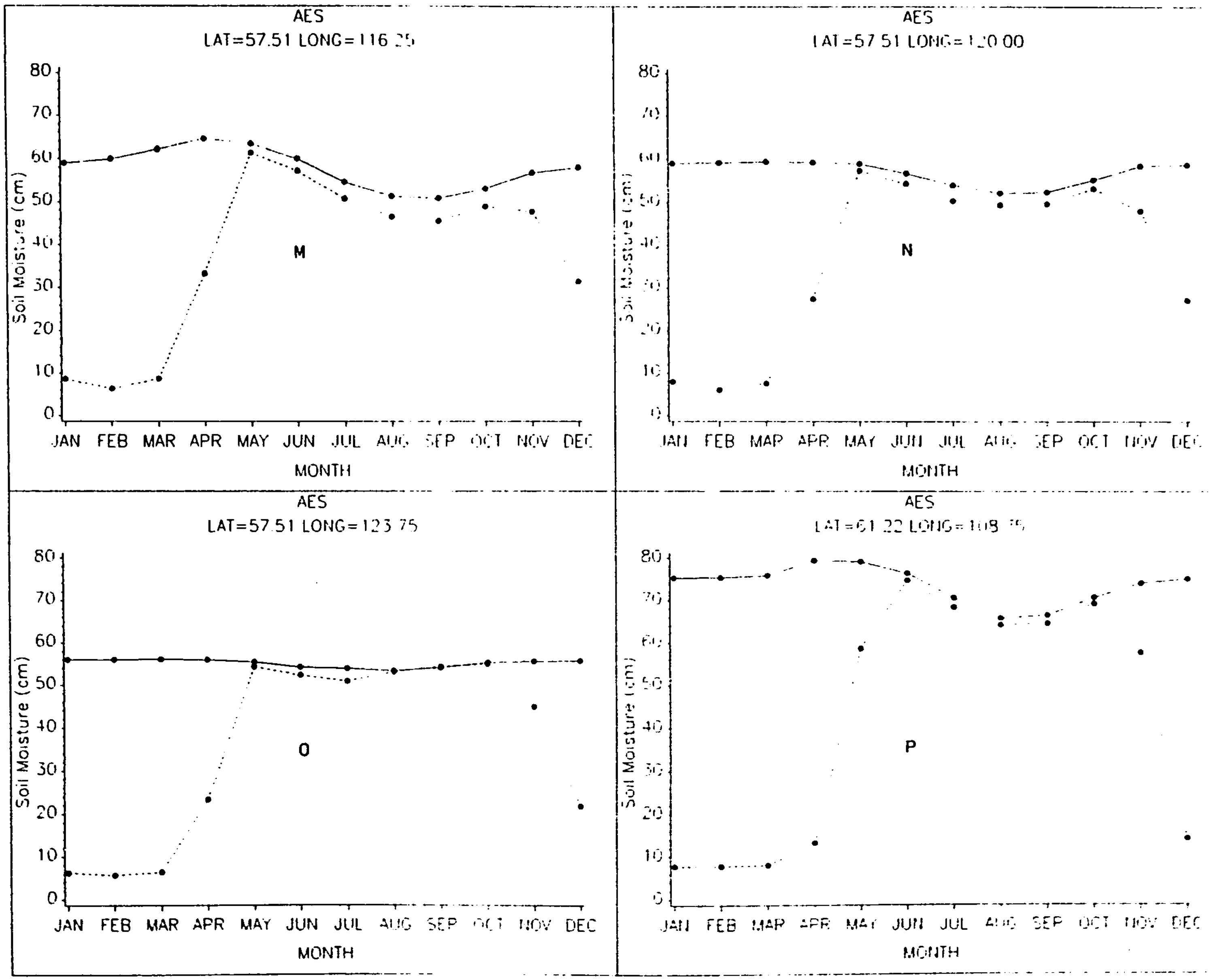

Figure 16 con't (M to P)

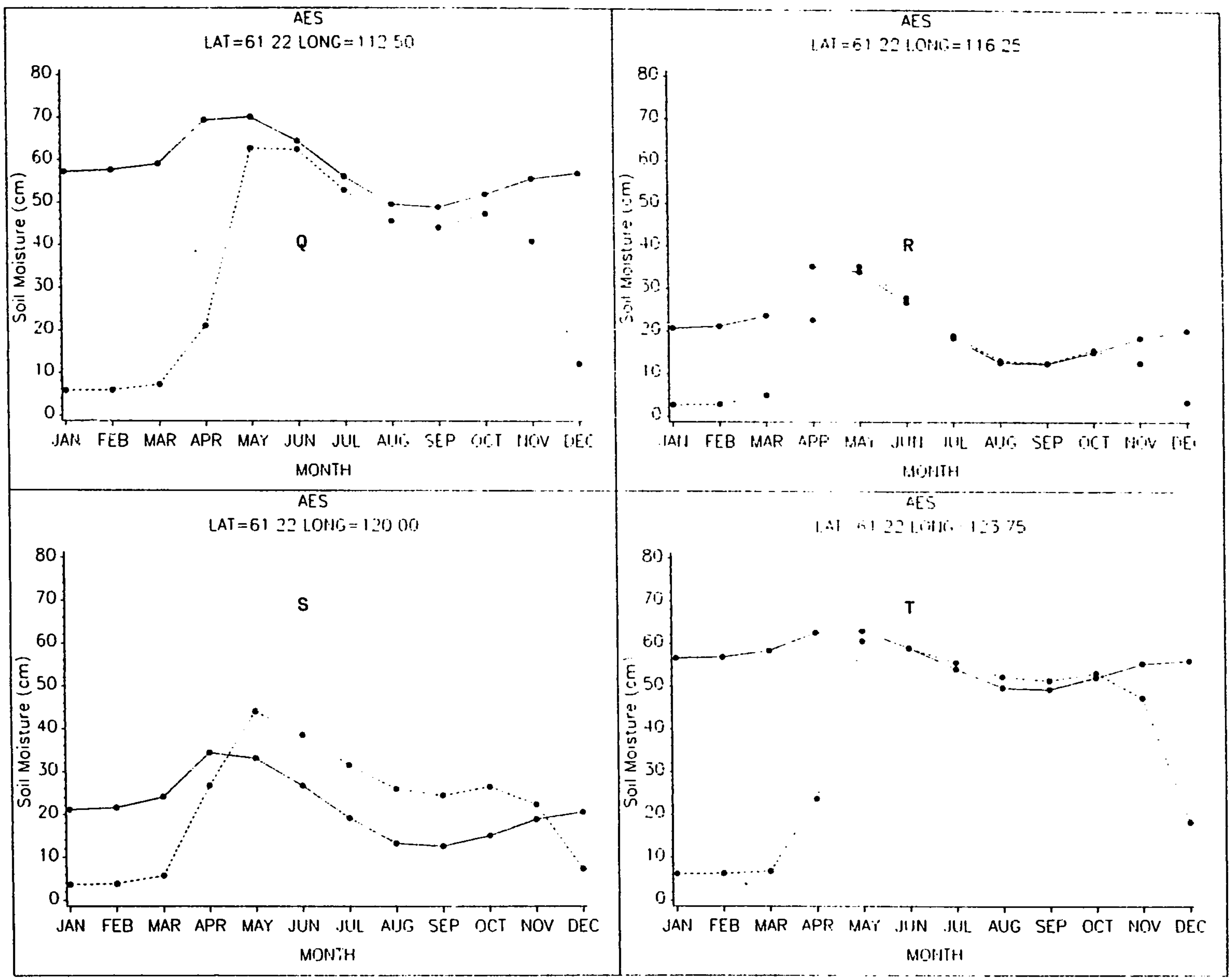

Figure 16 con't (Q to T)

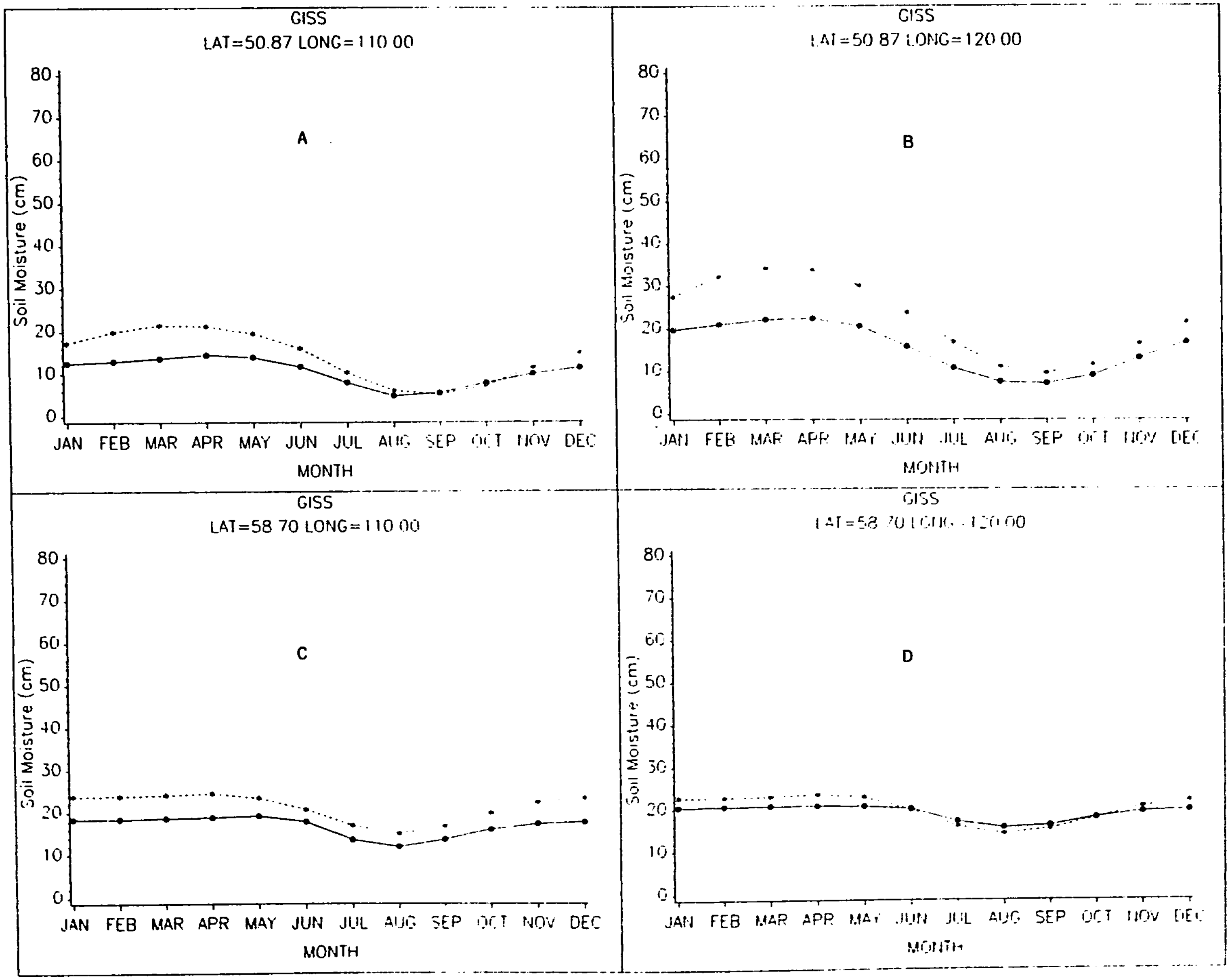

Figure 17 (A to D): Annual variation of GISS 1XCO2 (solid line) and 2XCO2 (dashed line) soil moisture for model gridpoints in and near Alberta

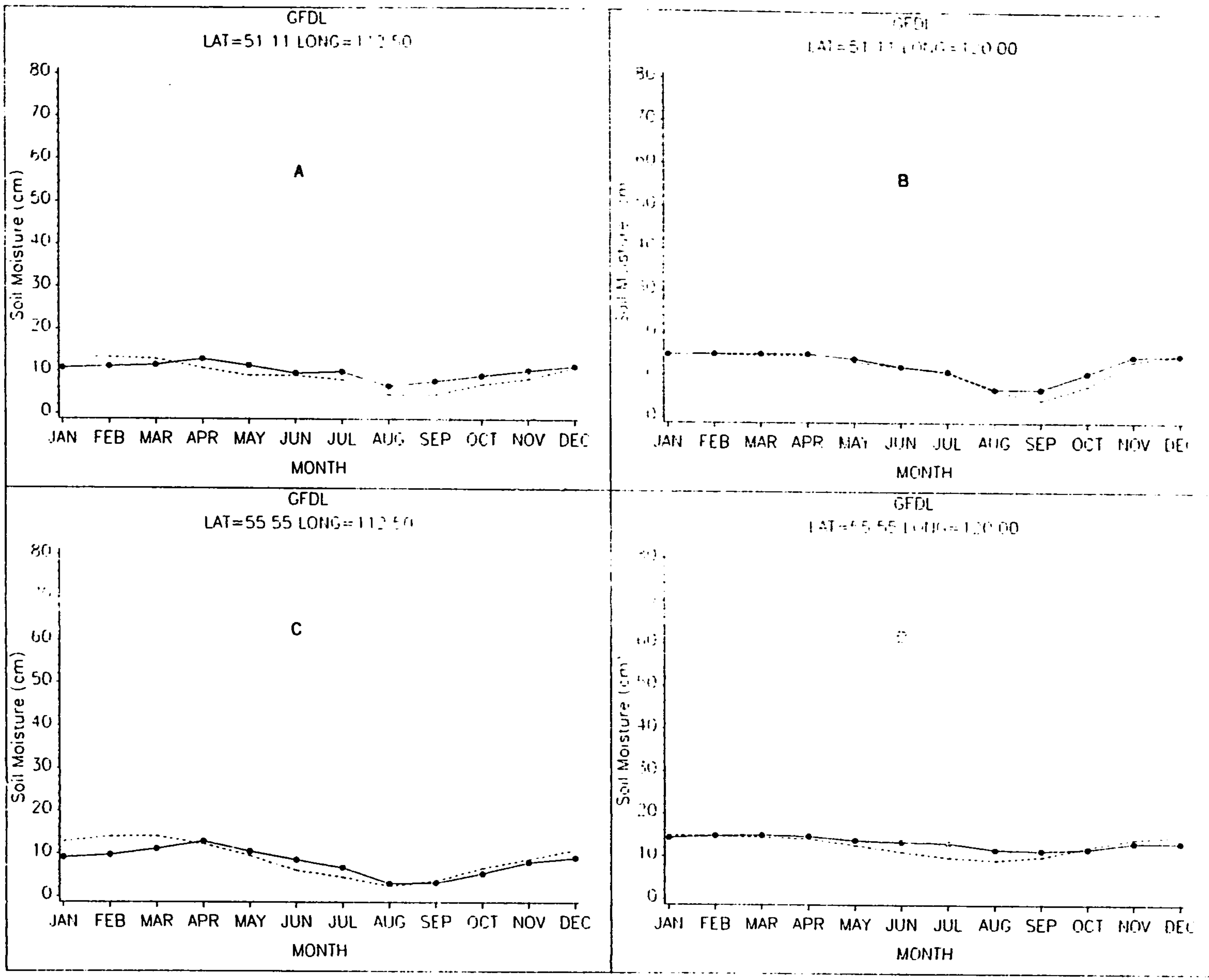

Figure 18 (A to D): Annual variation of GFDL 1XCO2 (solid line) and 2XCO2 (dashed line) soil moisture for model gridpoints in and near Alberta

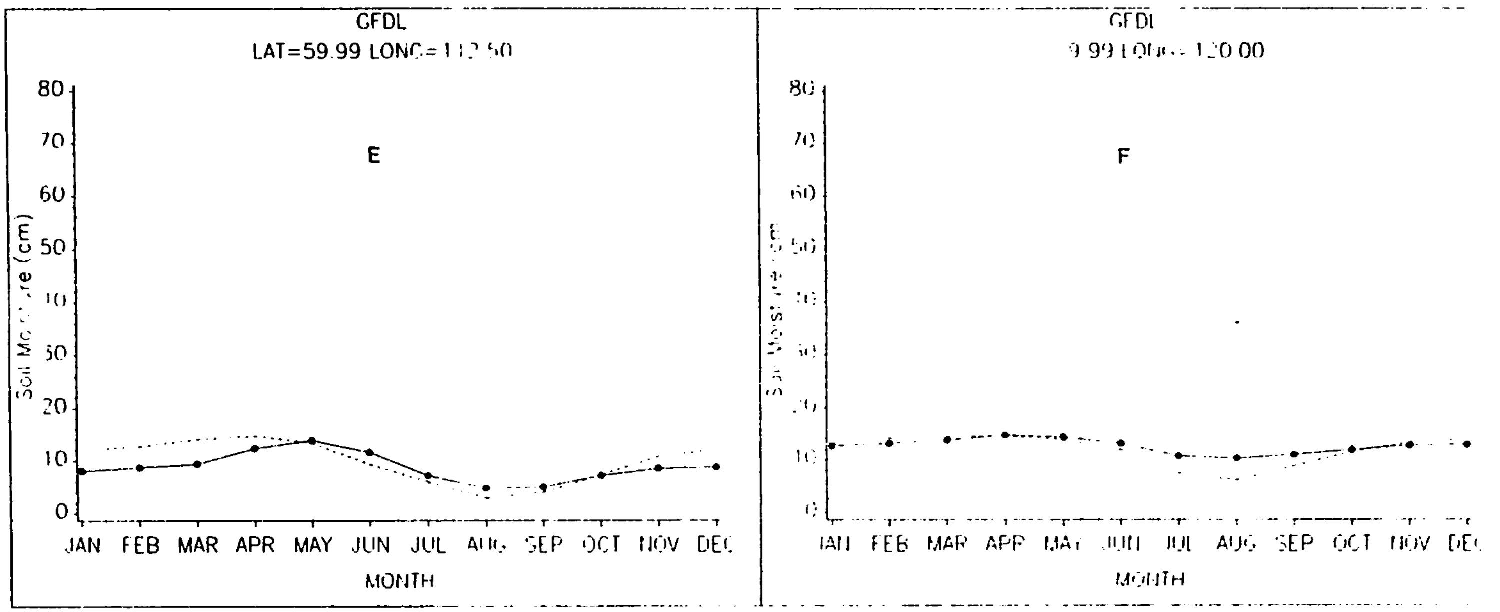

Figure 18 con't (E fo F)

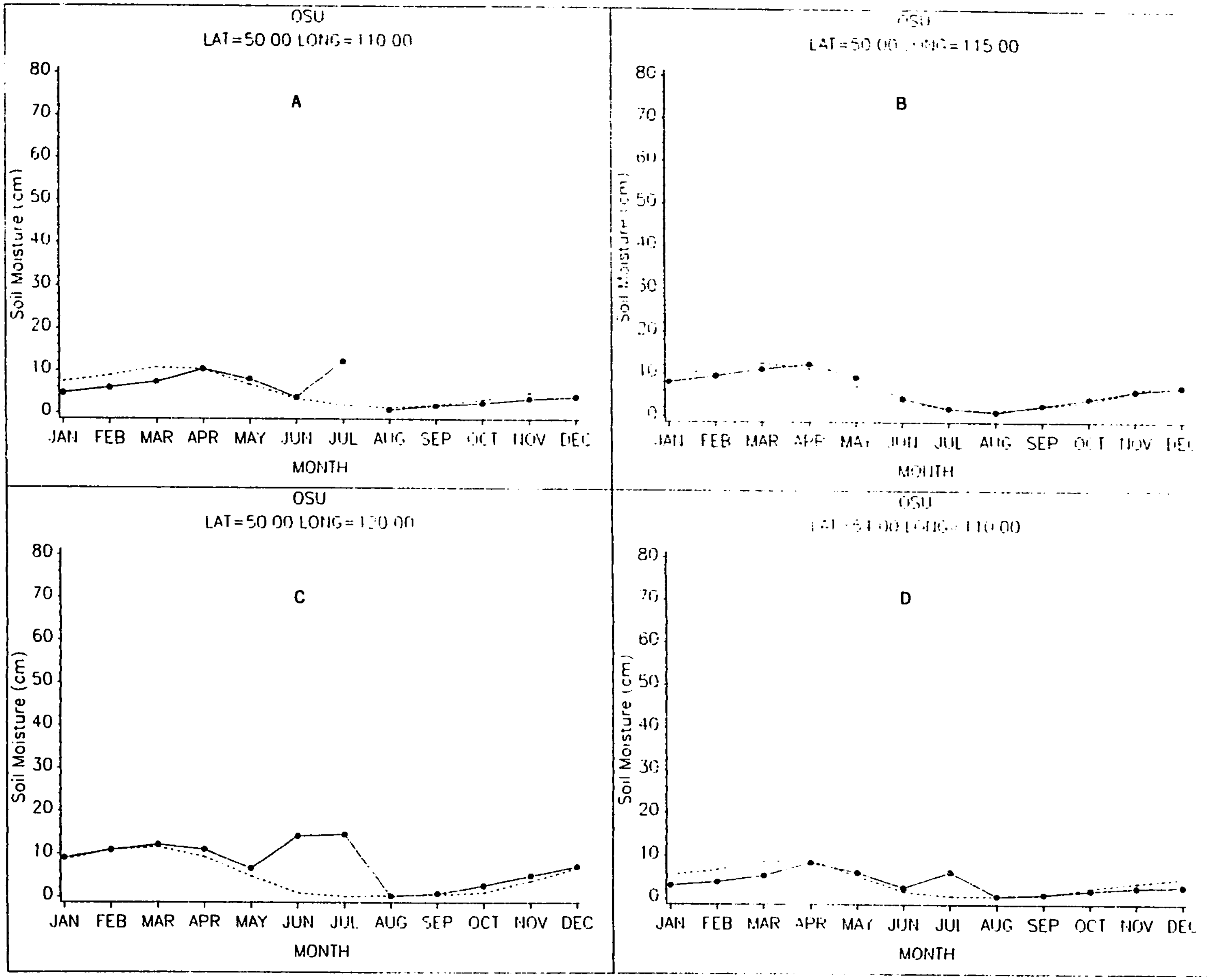

Figure 19 (A to D): Annual variation of OSU 1XCO2 (solid line) and 2XCO2 (dashed line) soil moisture for model gridpoints in and near Alberta

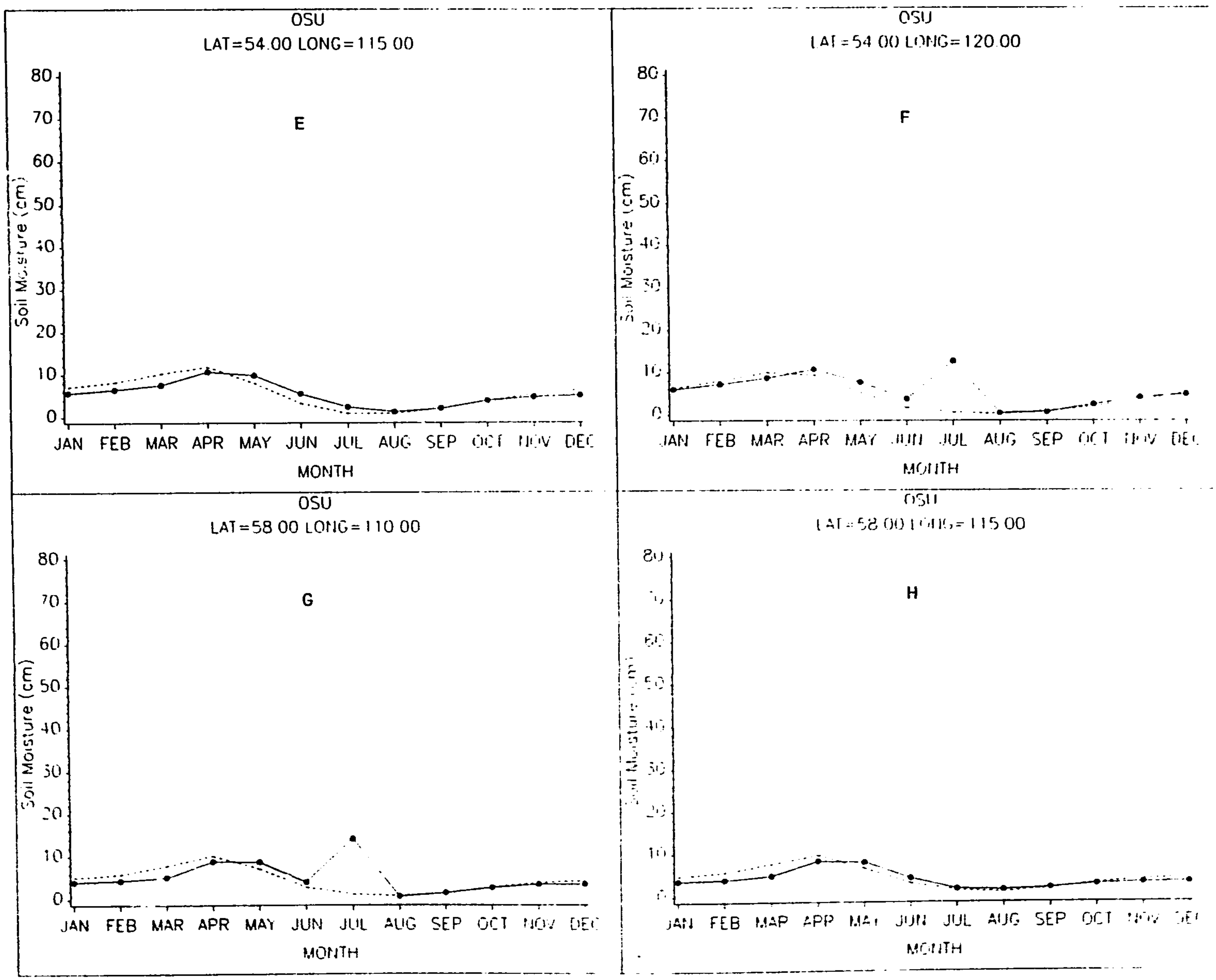

Figure 19 con't (E to H)

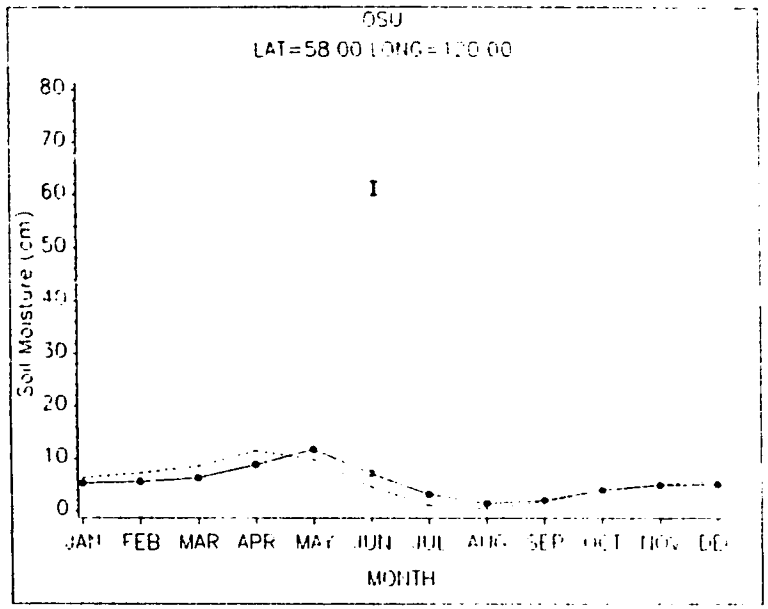

Figure 19 con't (I)

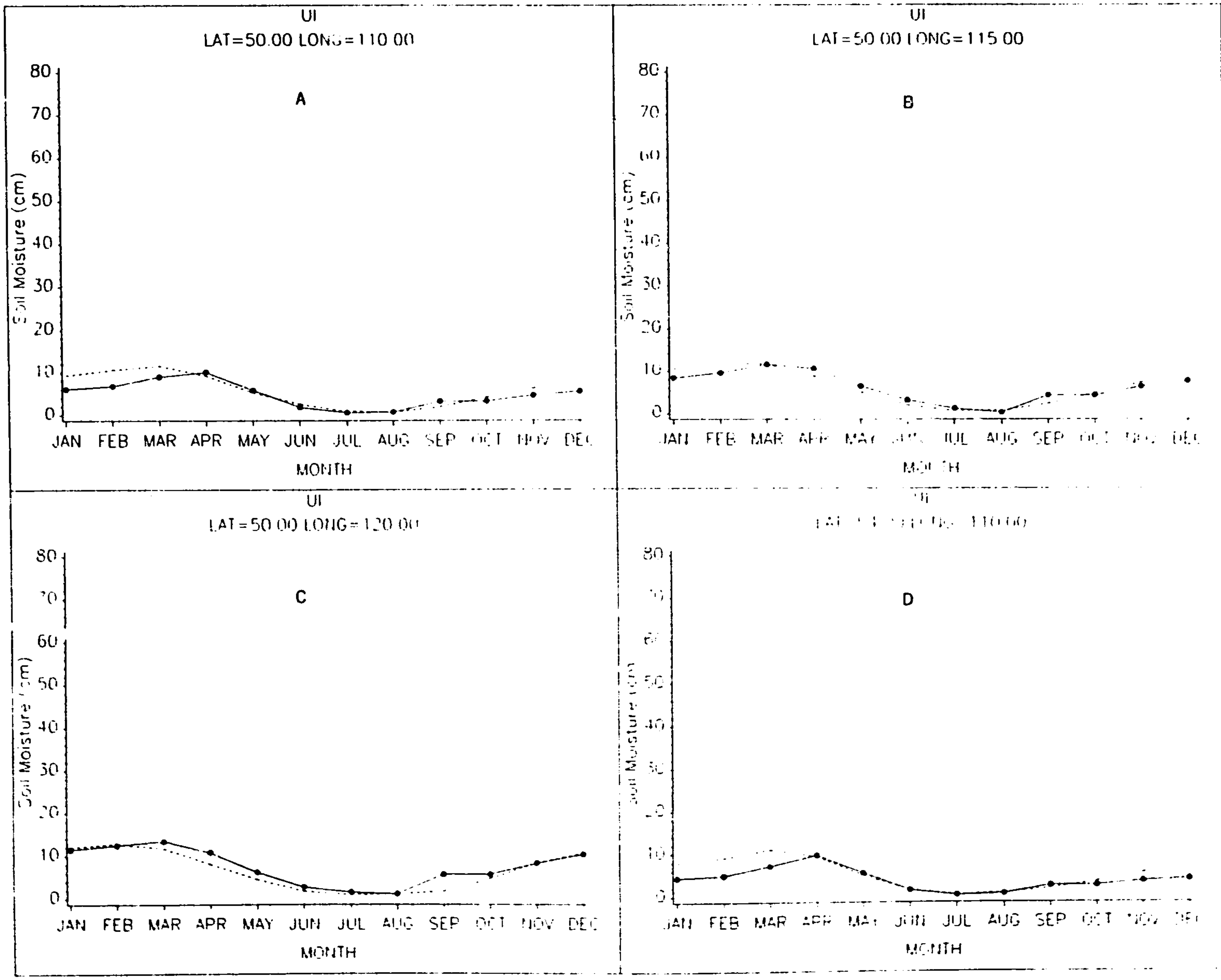

Figure 20 (A to D): Annual variation of UI 1XCO2 (solid line) and 2XCO2 (dashed line) soil moisture for model gridpoints in and near Alberta

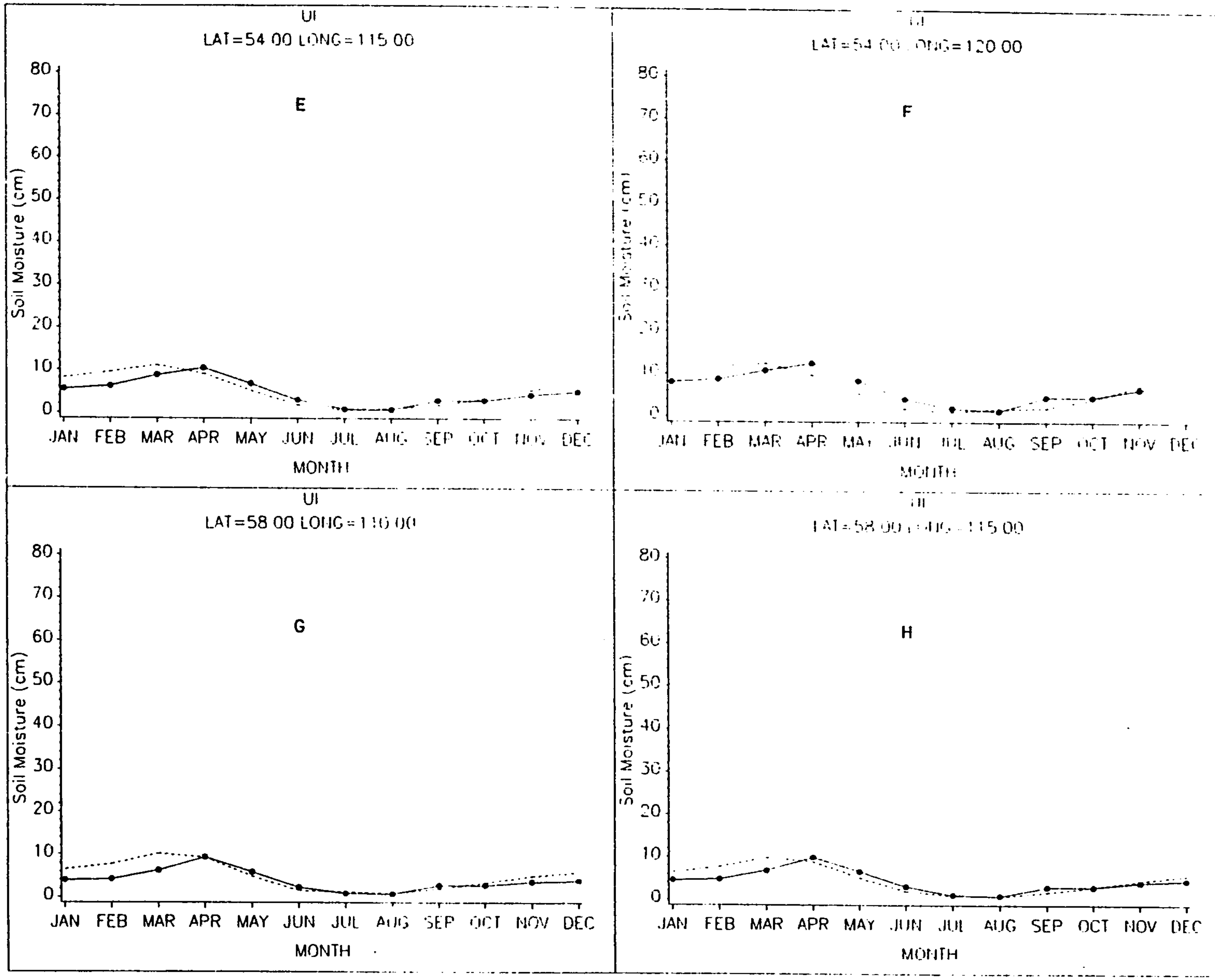

Figure 20 con't (E to H)

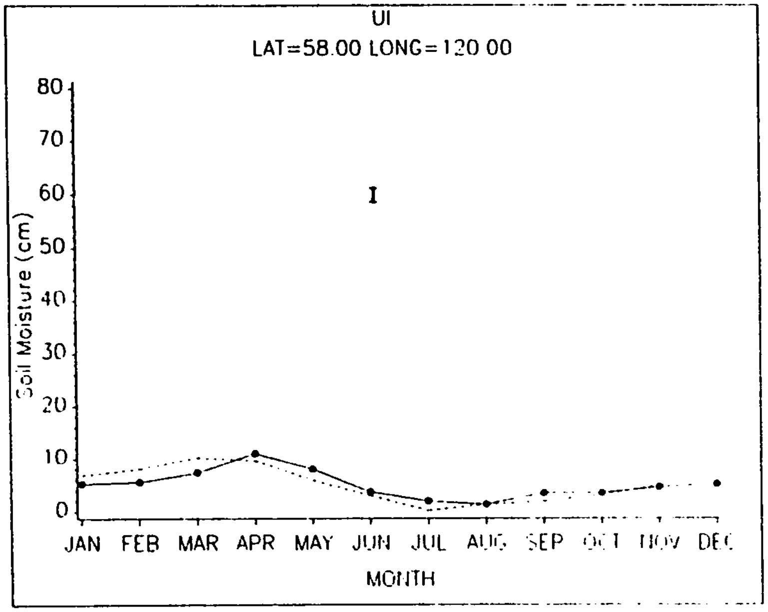

Figure 20 con't (I)

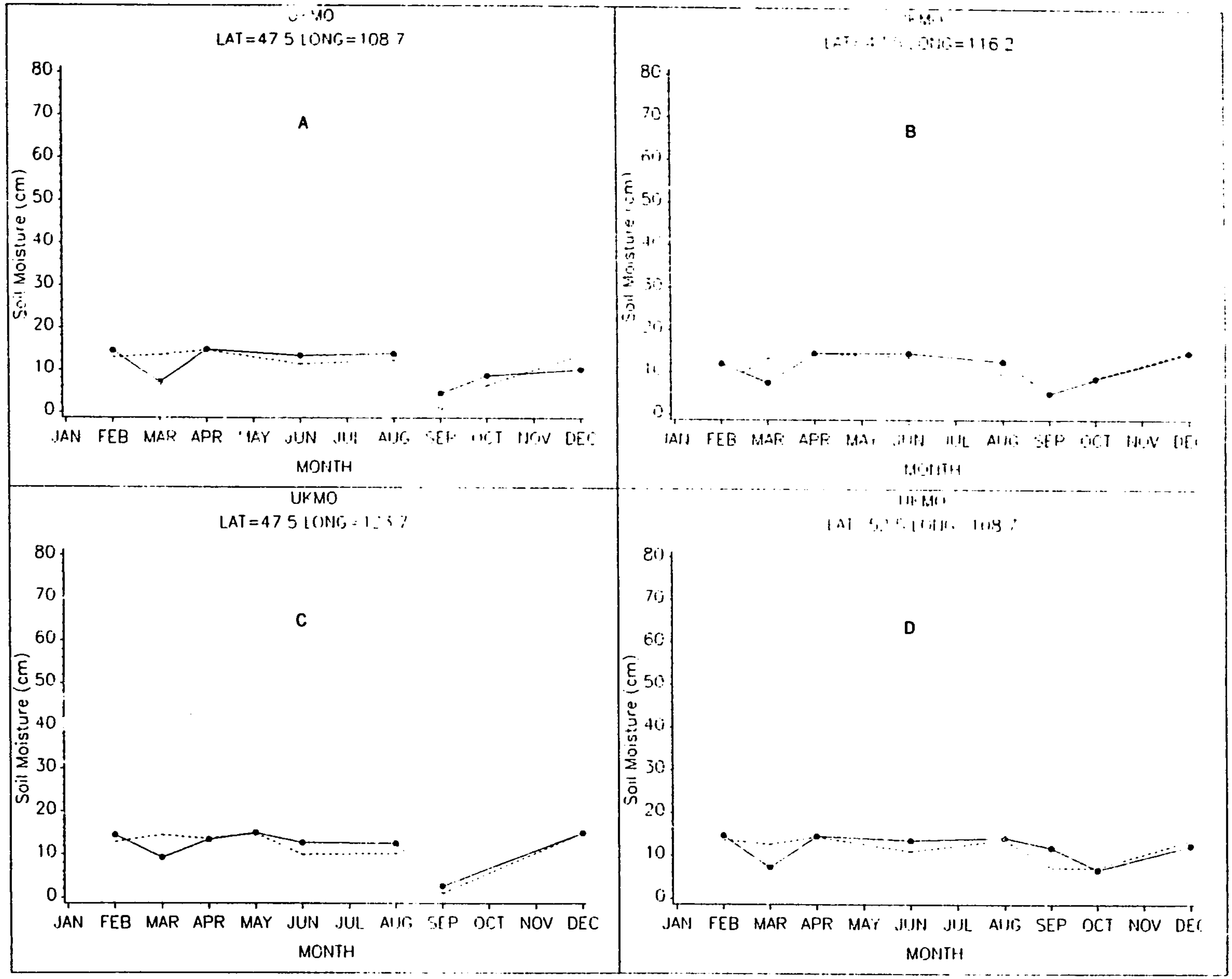

Figure 21 (A to D): Annual variation of UKMO 1XCO2 (solid line) and 2XCO2 (dashed line) soil moisture for model gridpoints in and near Alberta

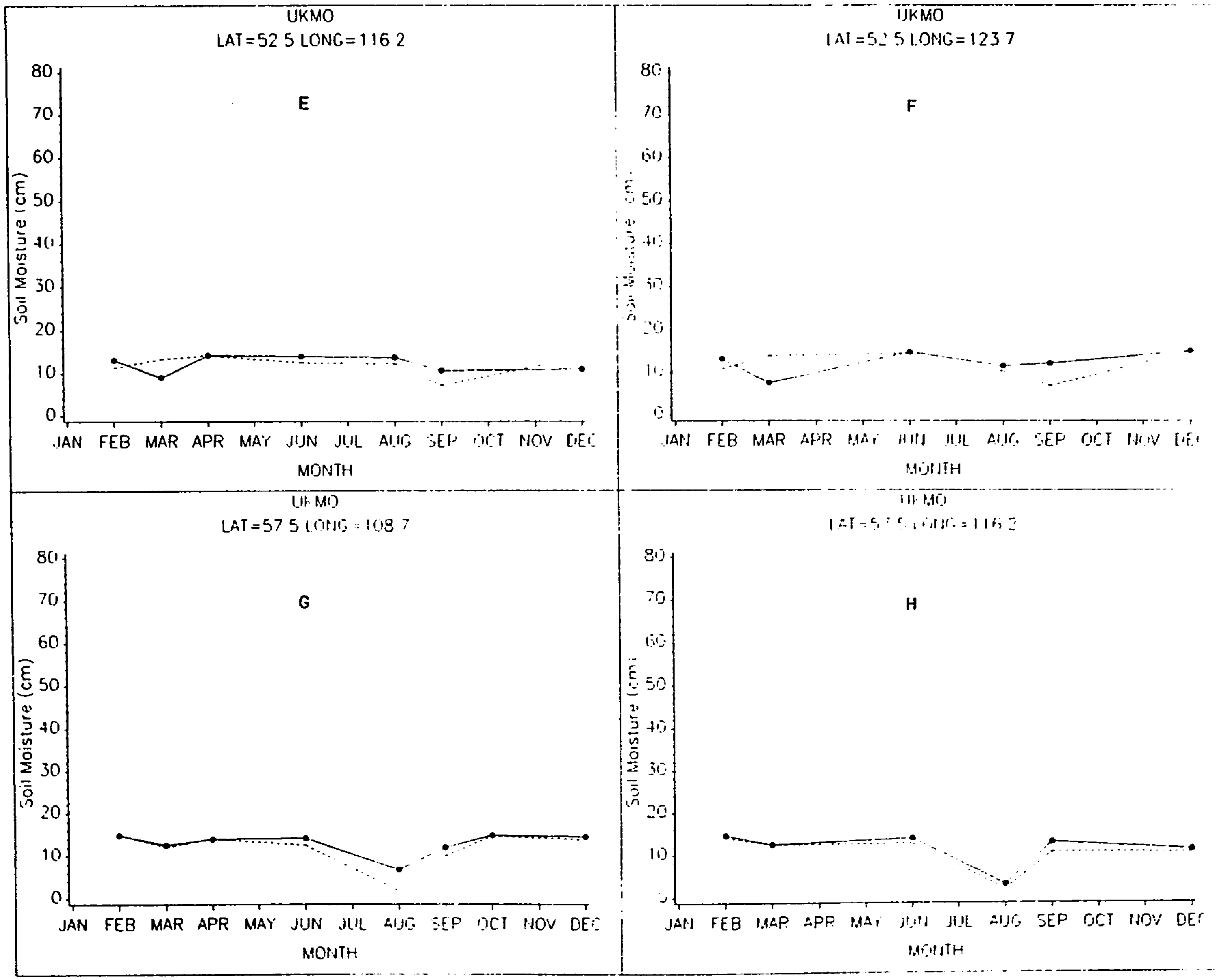

Figure 21 con't (E to H)

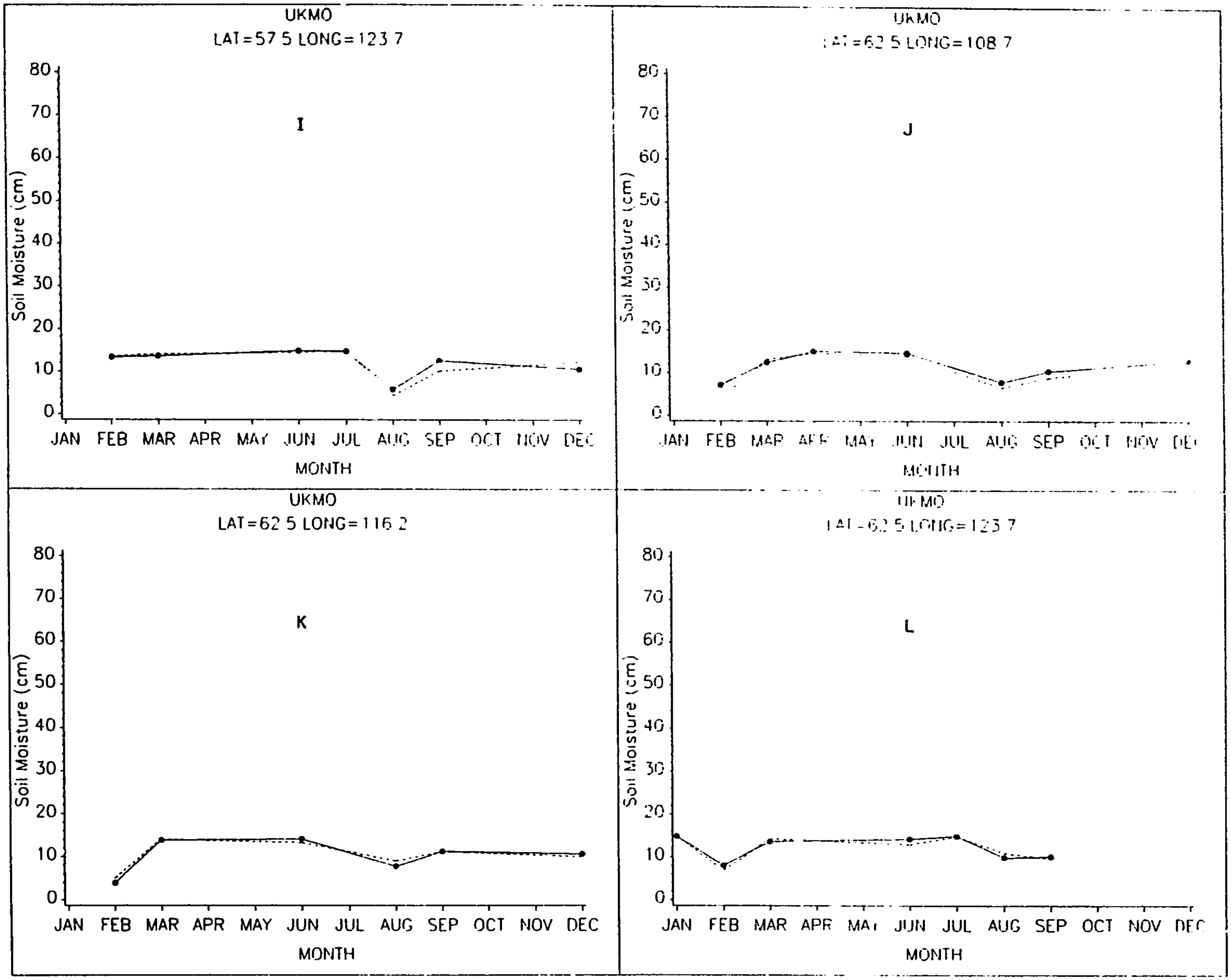

Figure 21 con't (I to L)

Appendix F:

Percent Change in GCM 1XCO_2 Soil Moisture Compared to 2XCO_2 Soil Moisture for Model Gridpoints in and Near Alberta

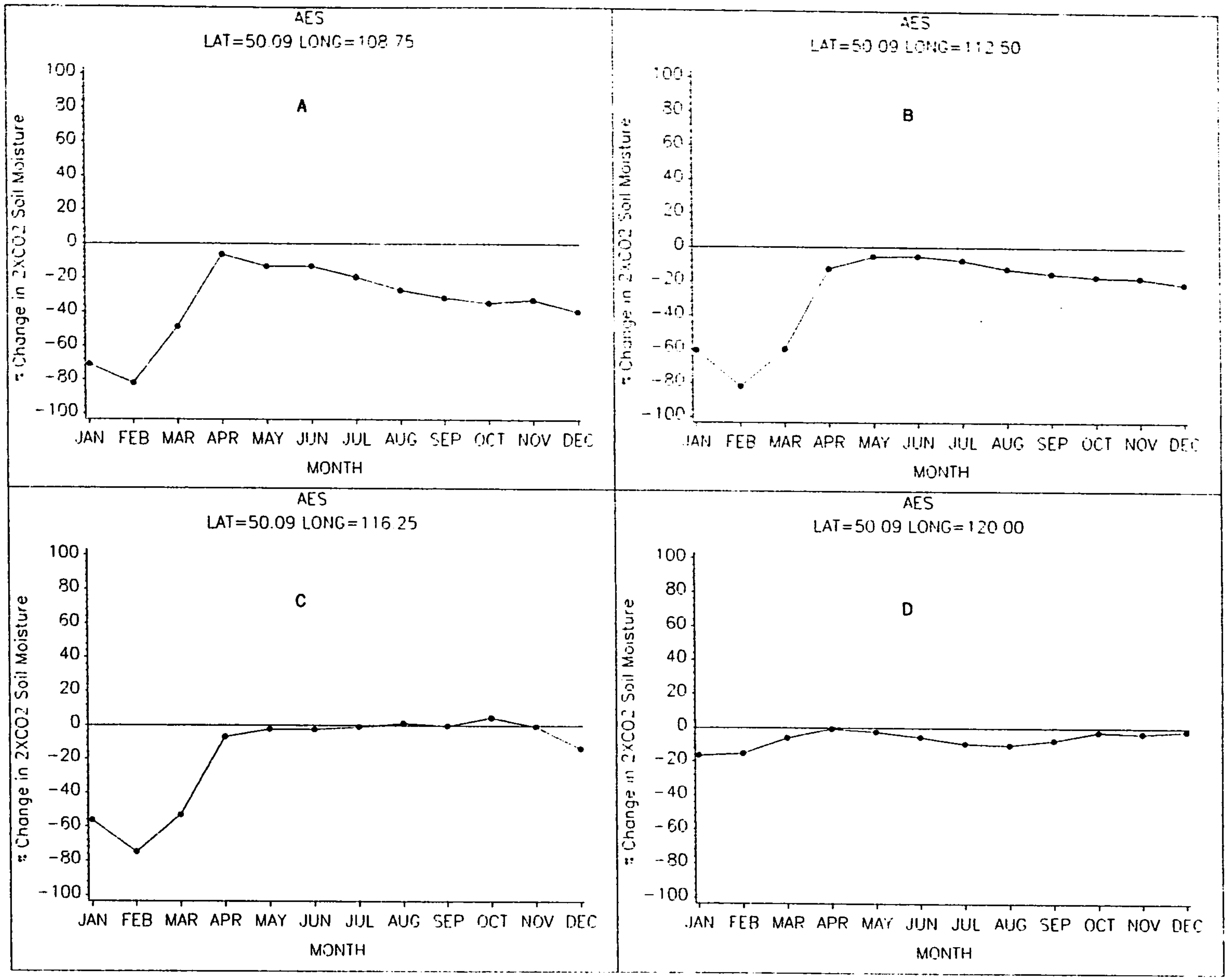

Figure 22 (A to D): Percent change of AES 2XCO2 soil moisture with respect to AES 1XCO2 soil moisture

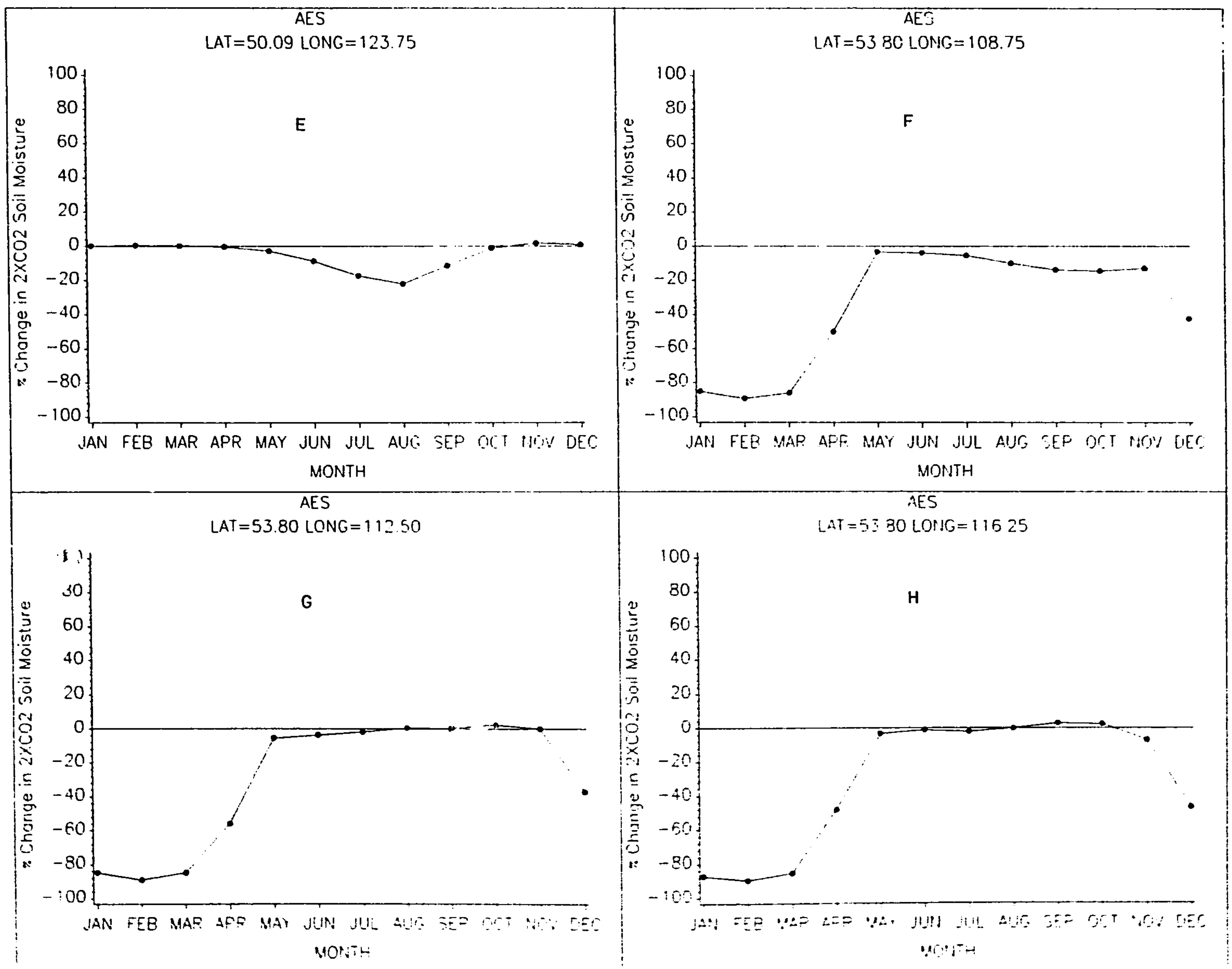

Figure 22 con't (E to H)

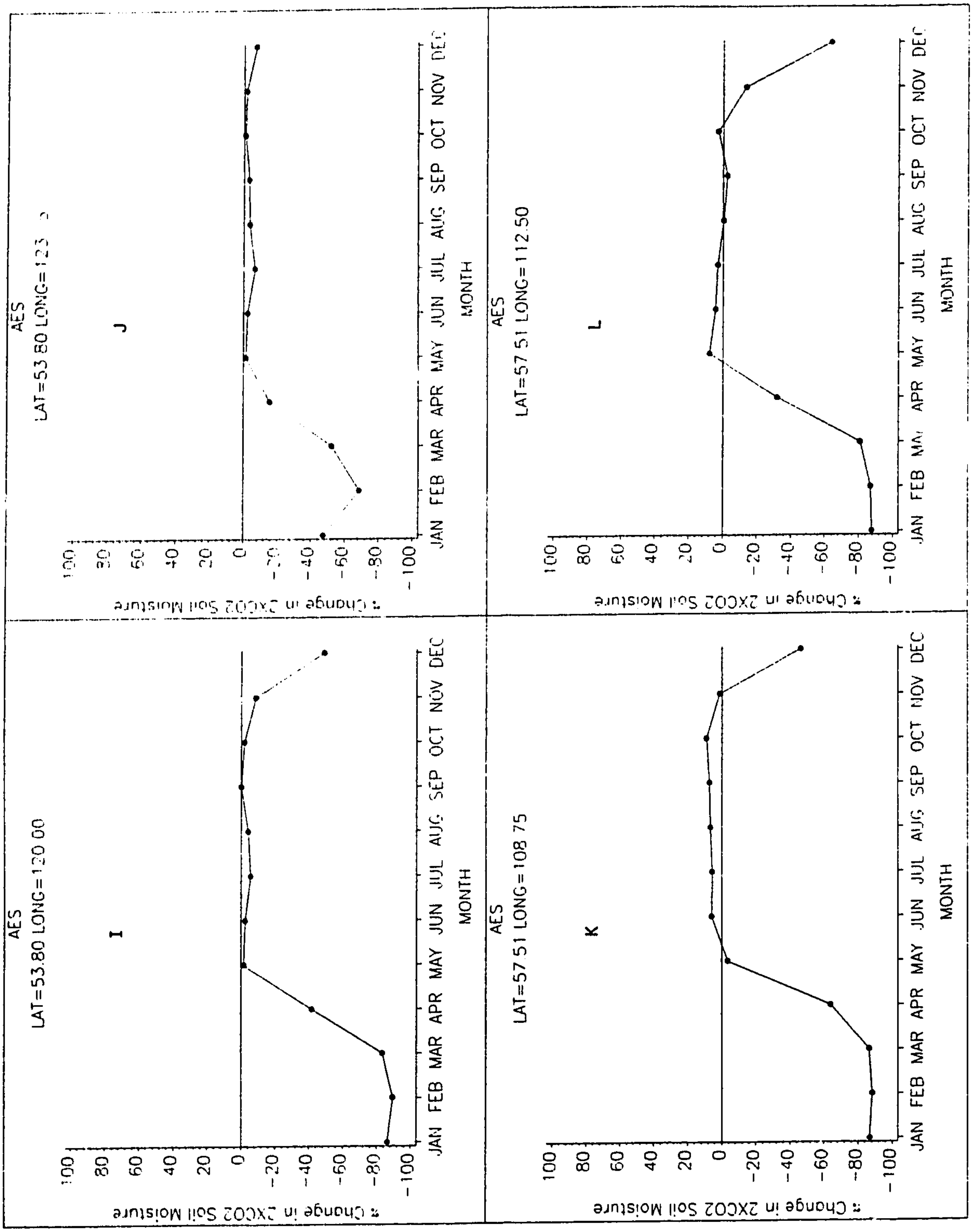

Figure 22 con't (I to L)

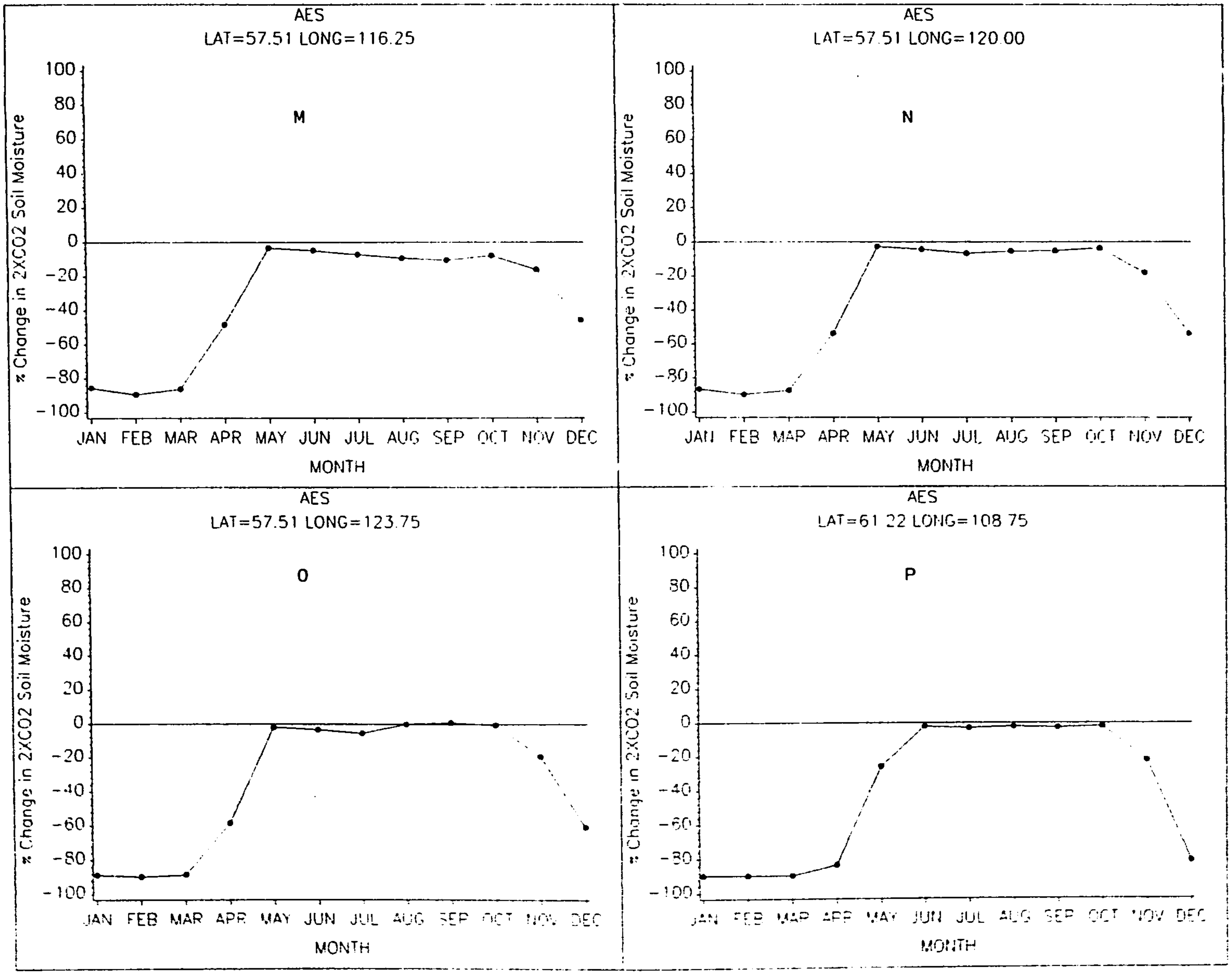

Figure 22 con't (M to P)

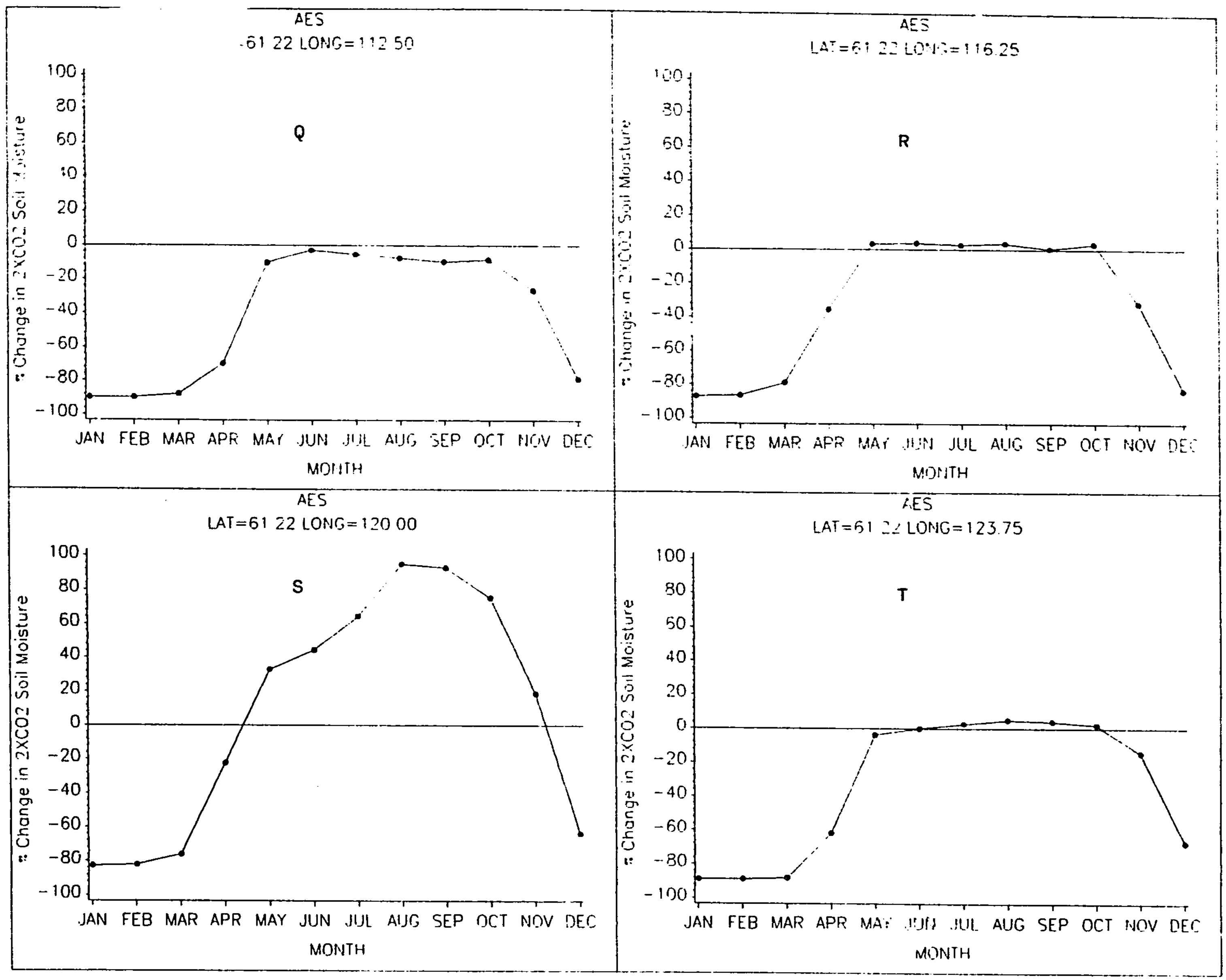

Figure 22 con't (Q to T)

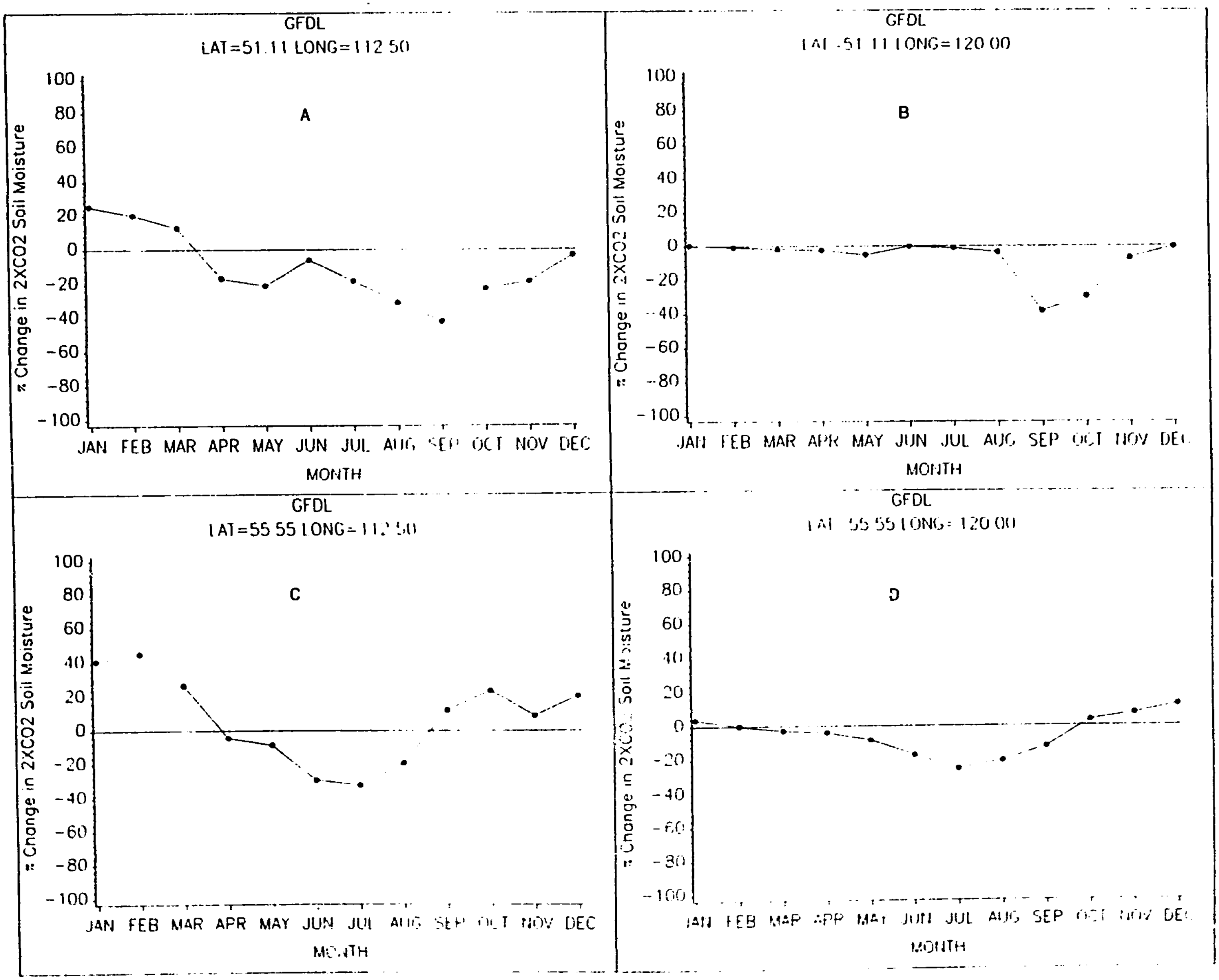

Figure 23 (A to D): Percent change of GFDL 2XCO2 soil moisture with respect to GFDL 1XCO2 soil moisture

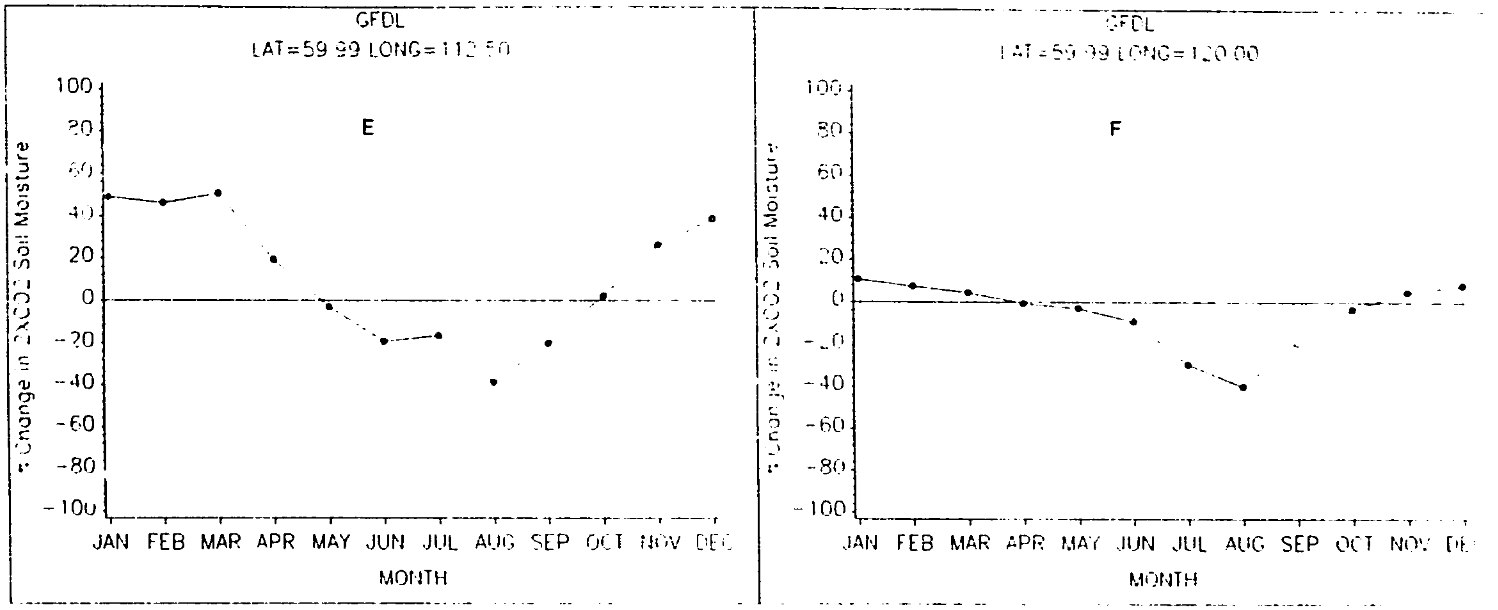

Figure 23 con't (E to F)

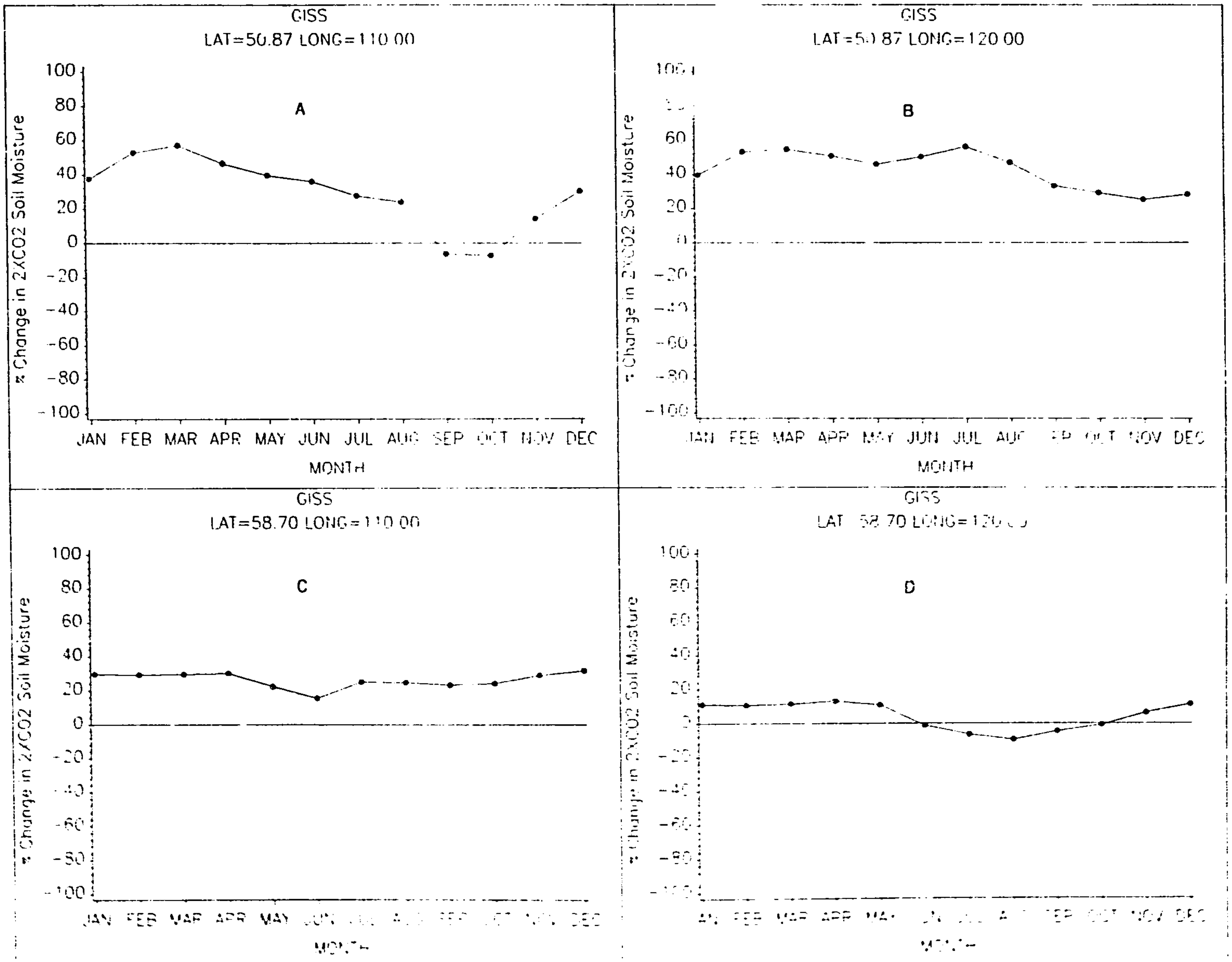

Figure 24 (A to D): Percent change of GISS 2XCO2 soil moisture with respect to GISS 1XCO2 soil moisture

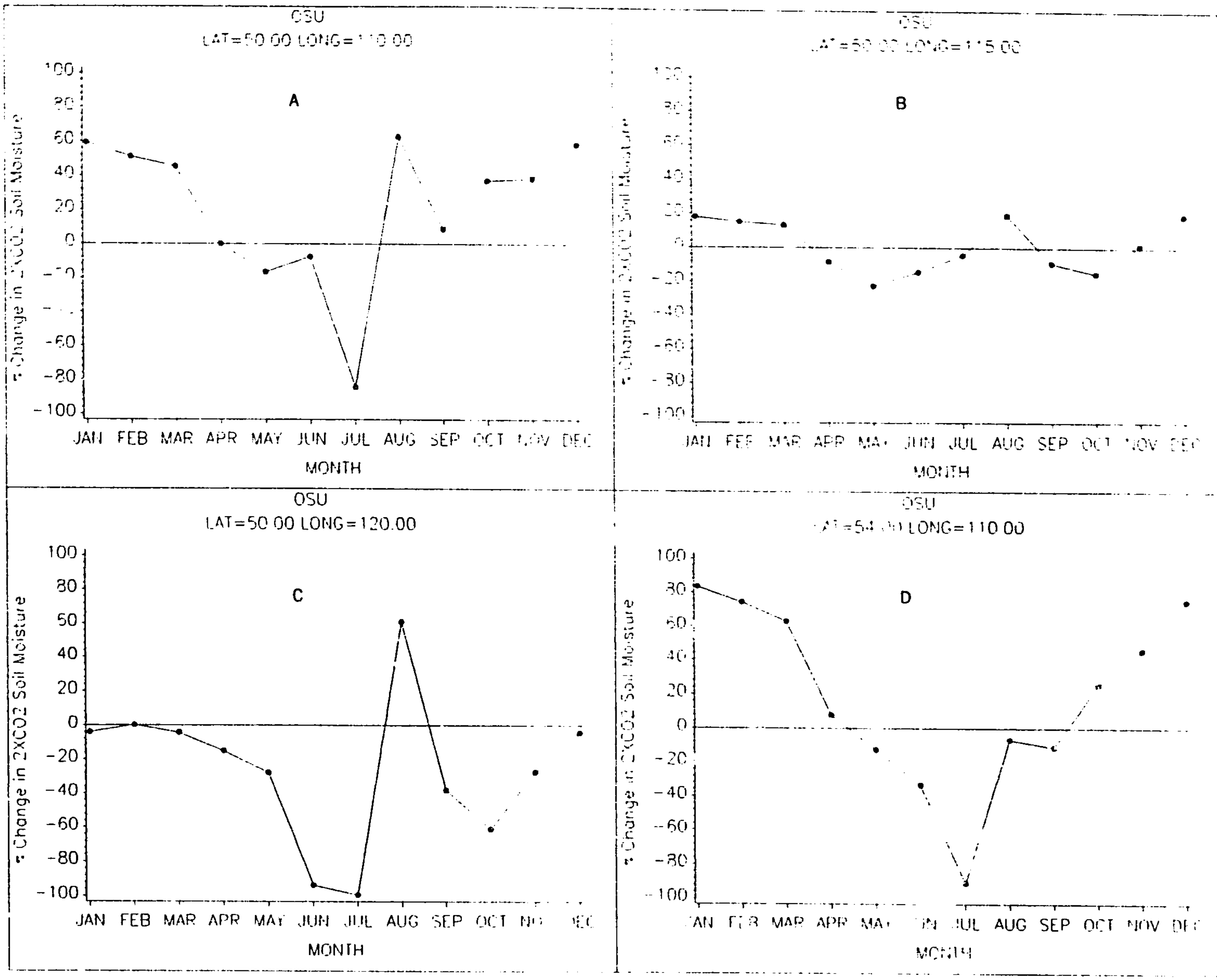

Figure 25 (A to D): Percent change of OSU 2XCO2 soil moisture with respect to OSU 1XCO2 soil moisture

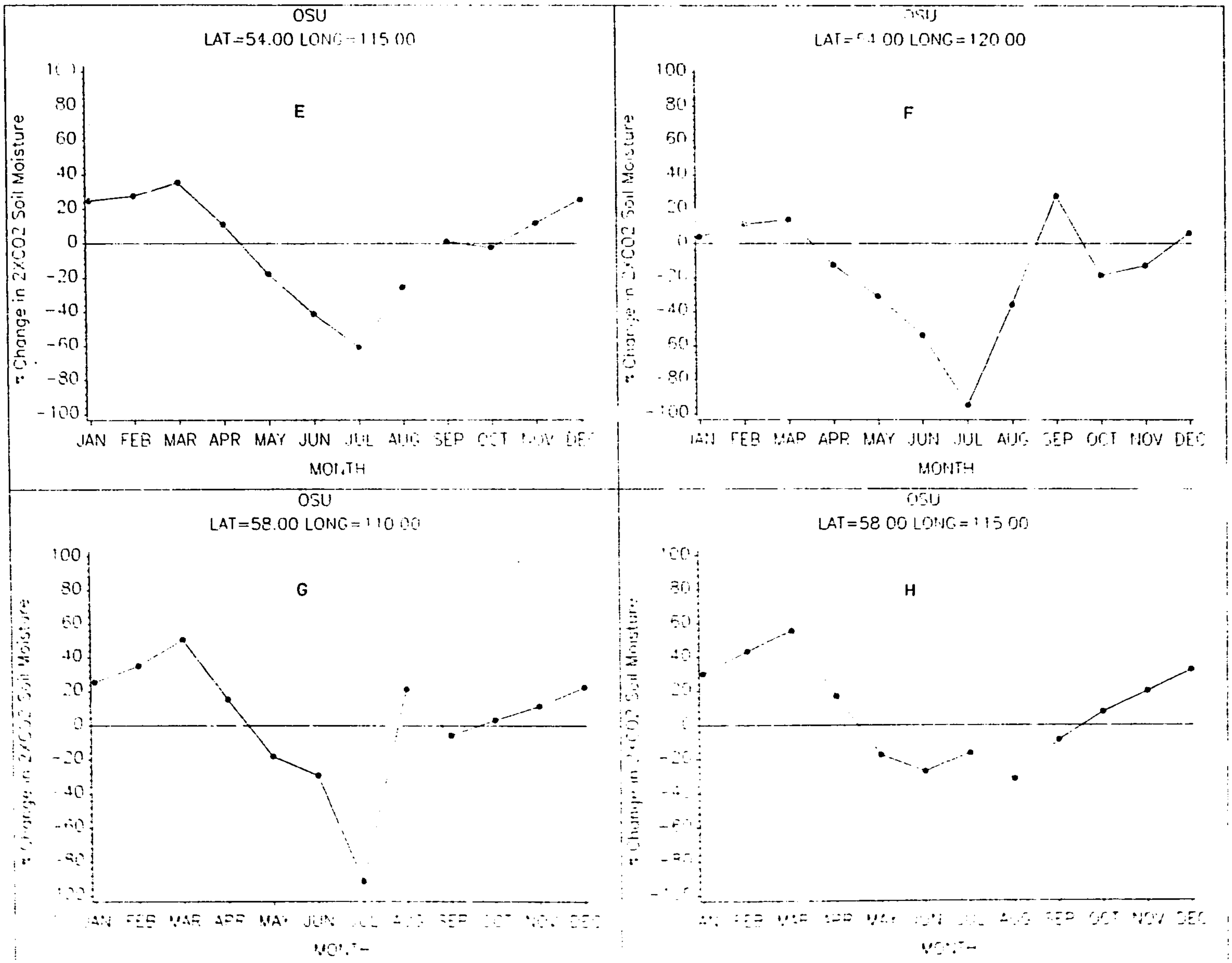

Figure 25 con't (E to H)

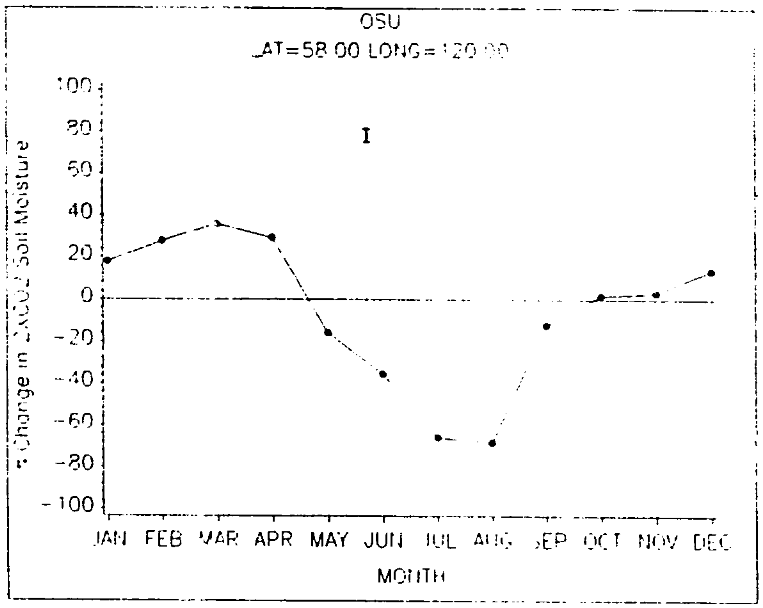

Figure 25 con't (I)

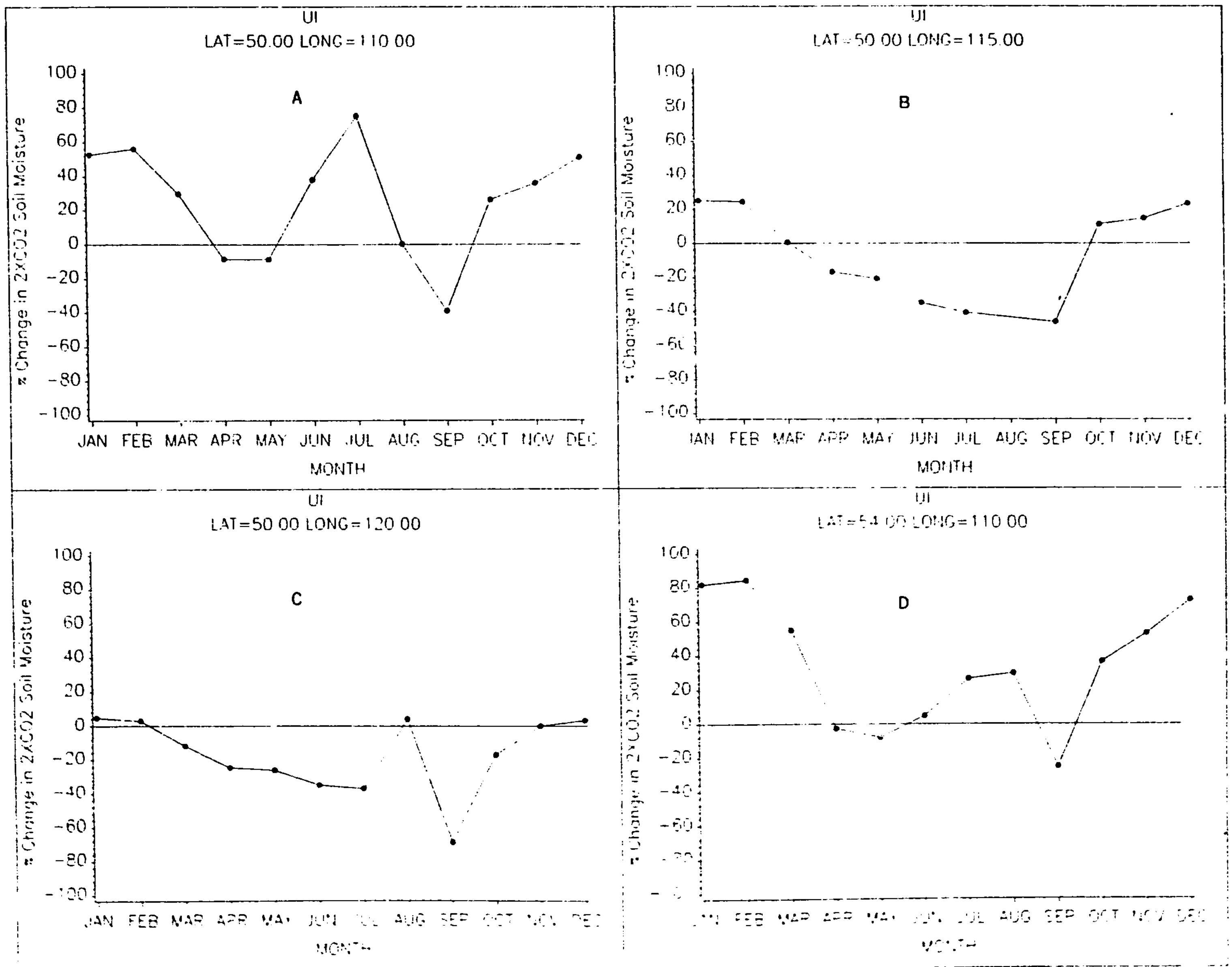

Figure 26 (A to D): Percent cnange of UI 2XCO2 soil moisture with respect to UI 1XCO2 soil moisture

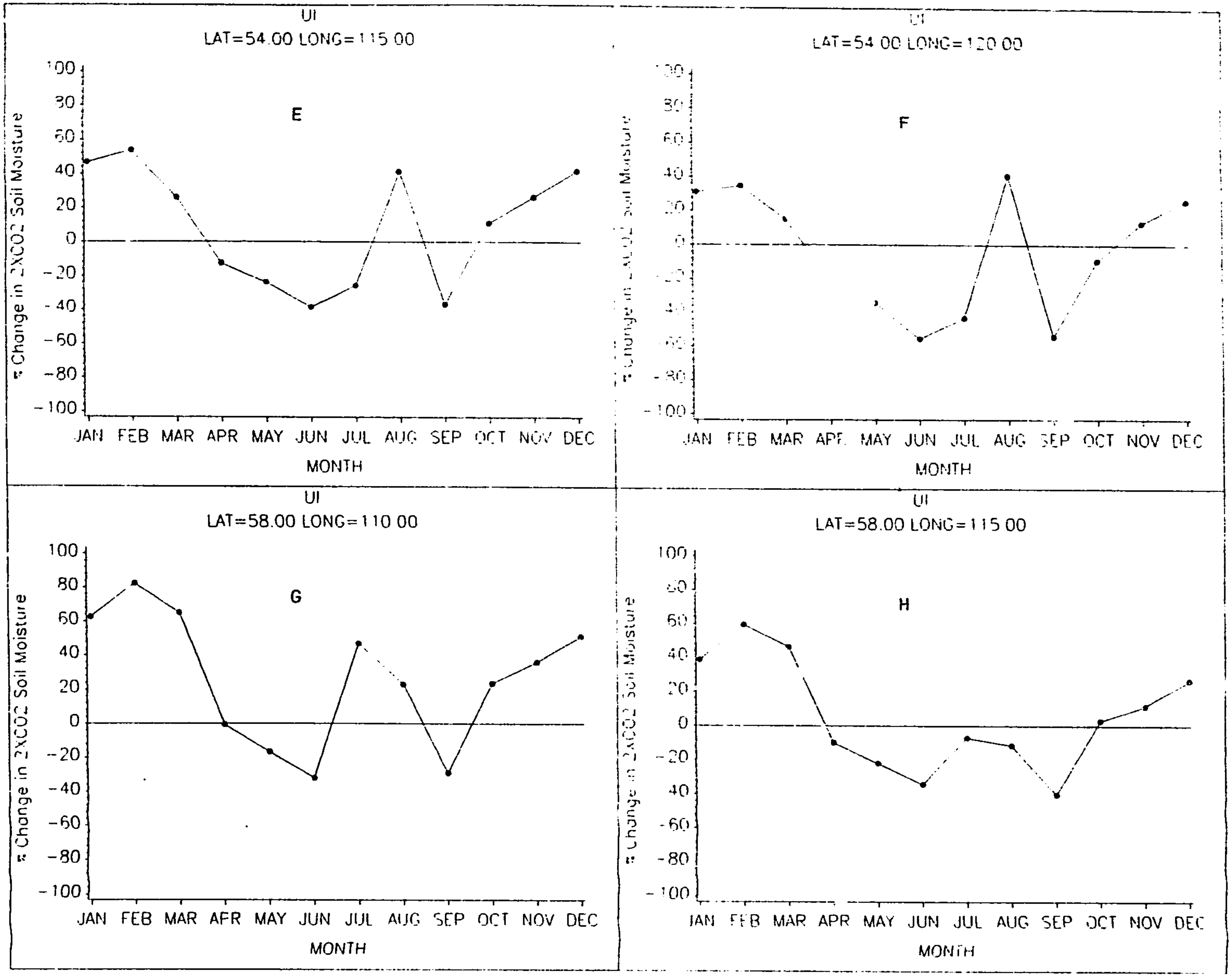

Figure 26 con't (E to H)

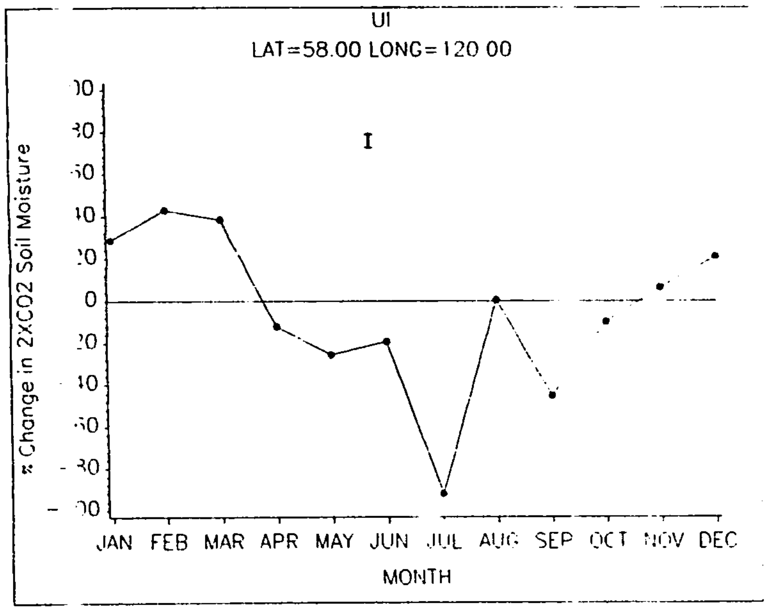

Figure 26 con't (I)

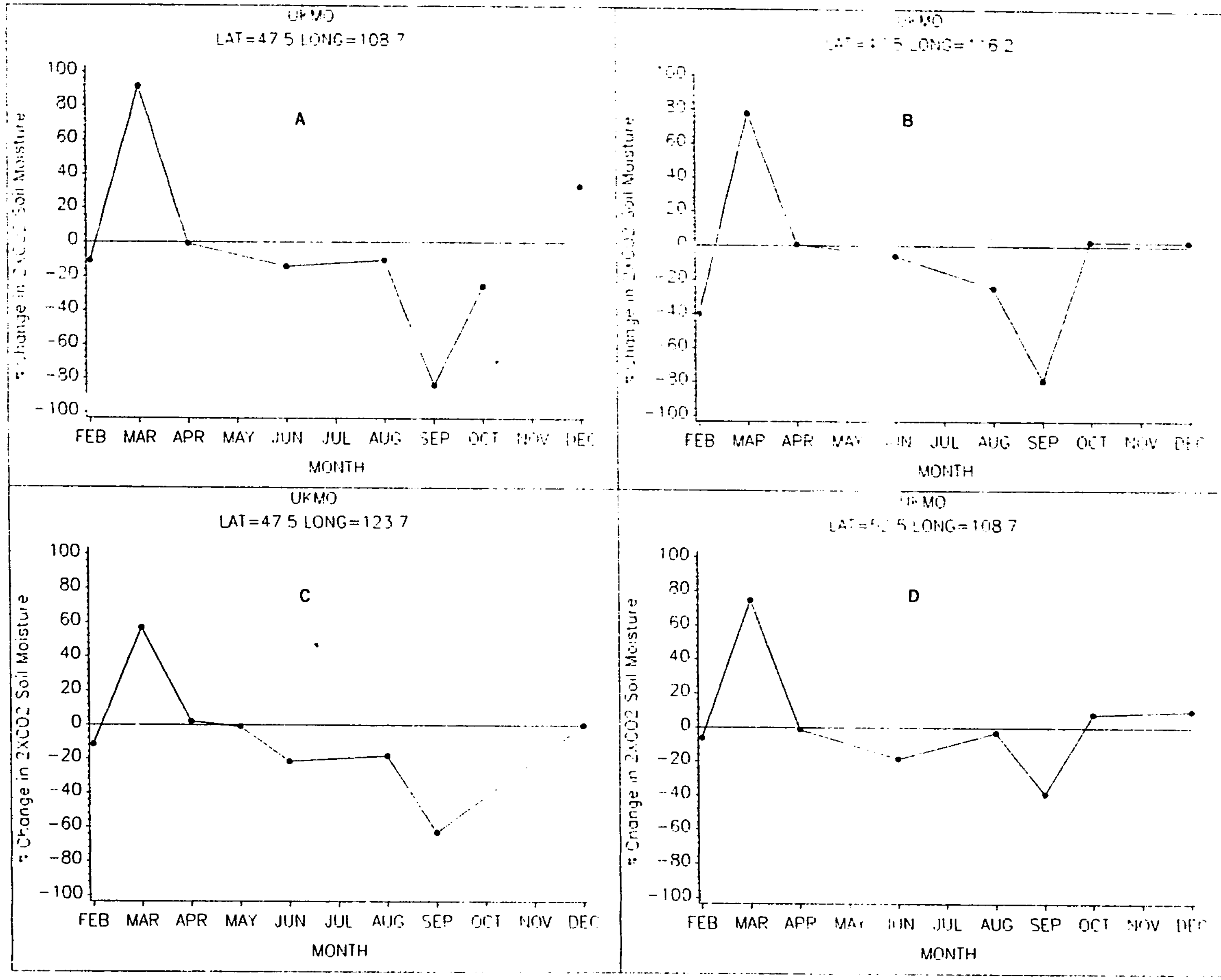

Figure 27 (A to D): Percent change of UKMO 2XCO2 soil moisture with respect to UKMO 1XCO2 soil moisture

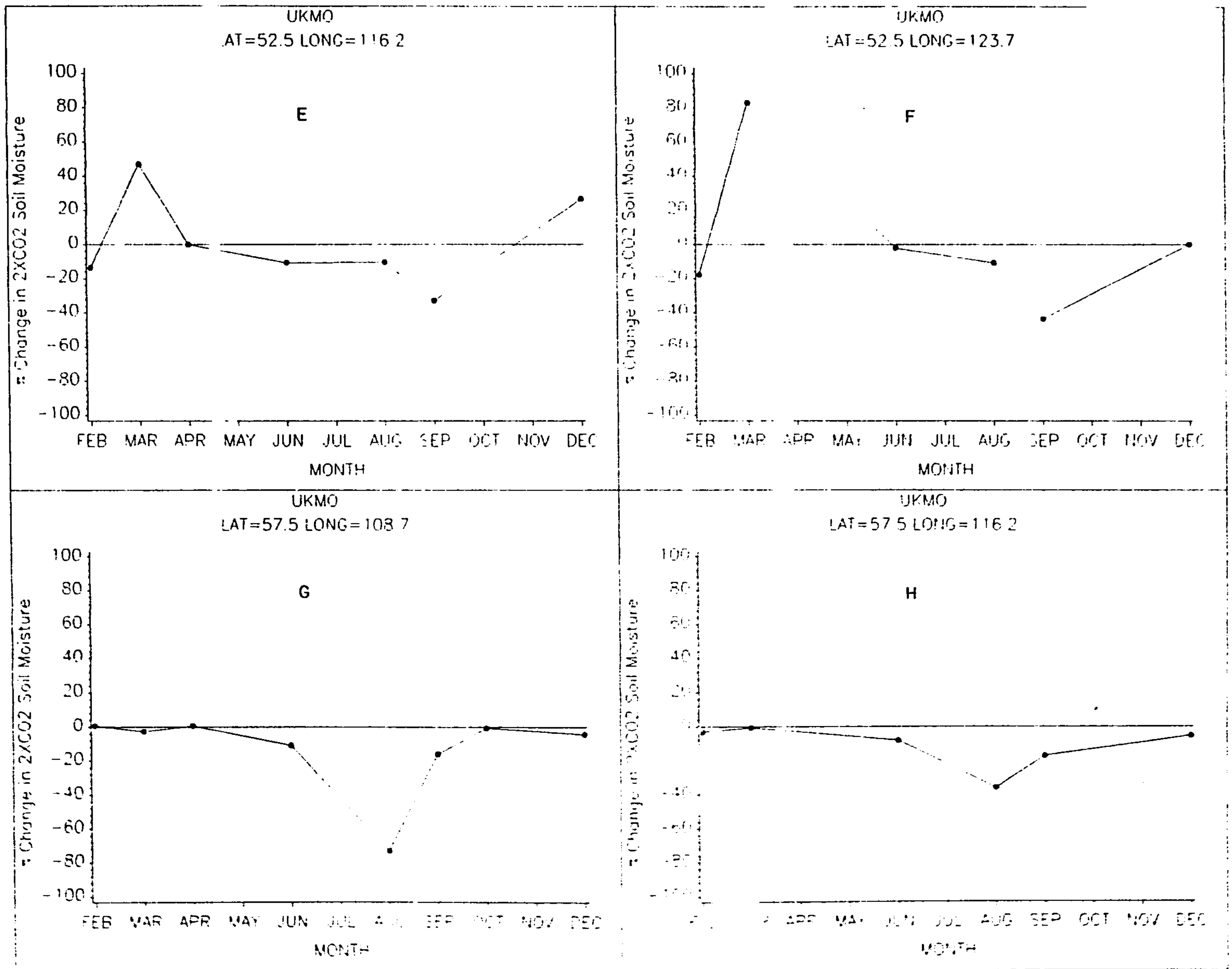

Figure 27 con't (E to H)

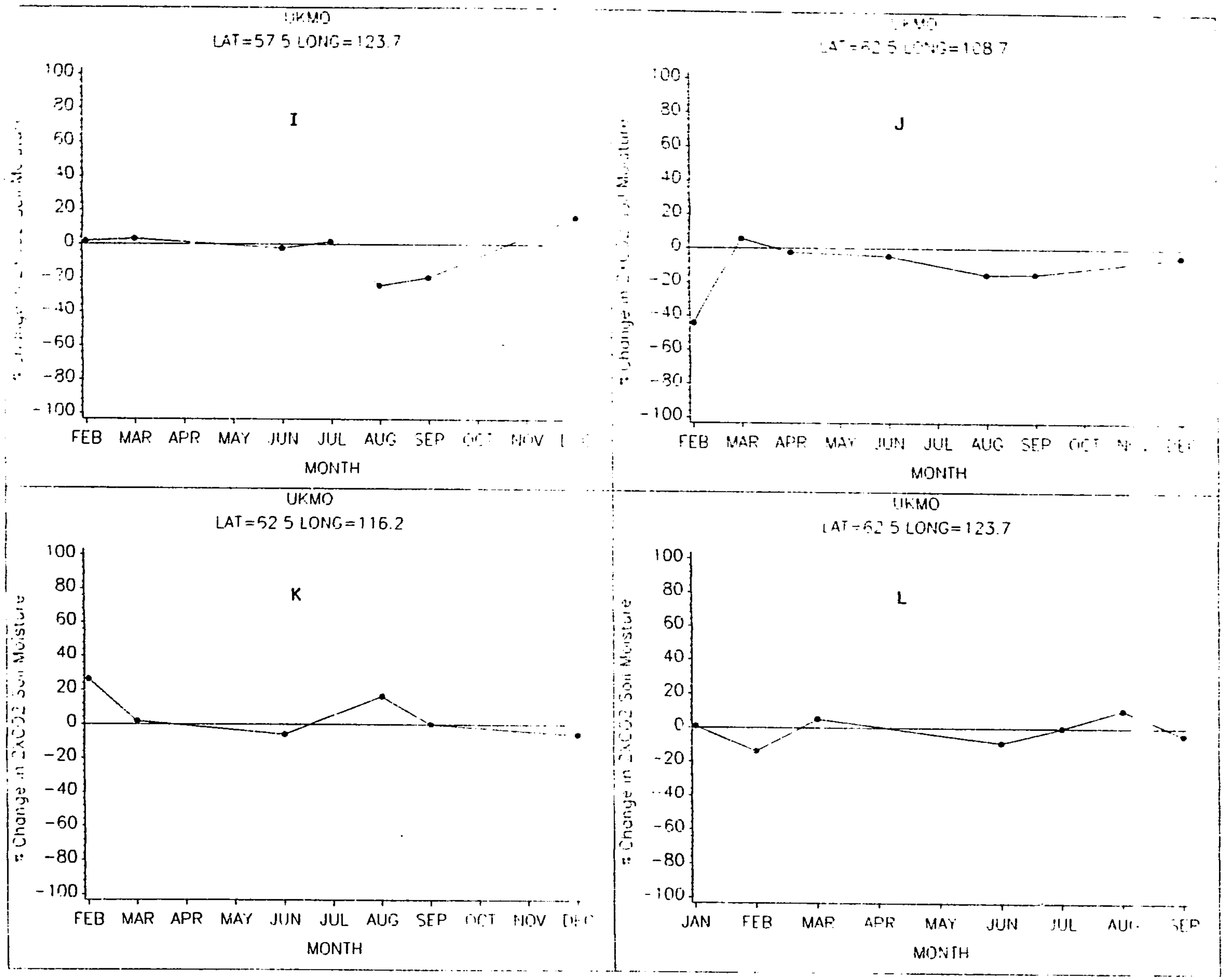

Figure 27 con't (I to L)