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Development of Mountain Climate Generator and Snowpack model for Erosion Predictions in the Western United States Using WEPP, Progress Report No. 1

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Development of Mountain Climate Generator and Snowpack Model for Erosion Predictions in the Western United States using WEPP

Progress Report No. 1

November 1, 1989 – June 30, 1990

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Intermountain Research Station
U.S. Department of Agriculture
Forest Service
1221 South Main Street
Moscow, Idaho 83843

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EXECUTIVE SUMMARY

This report summarizes work conducted during the initial funding period (November 1, 1989 through June 30, 1990) of a Cooperative Agreement between the United States Forest Service (USFS) and the Utah Water Research Laboratory (UWRL), Utah State University. The purpose of the agreement is to develop a procedure for incorporating western mountain climate into the existing Climate Generator (CLIGEN), which is part of the Water Erosion Prediction Project (WEPP) procedure.

In the Western U.S., few meteorological observations exist in high elevation areas where Forest Service properties are located. Therefore, a procedure for estimating climatological variables in mountainous areas is needed to apply WEPP in these regions. A physically-based approach, an expanded and improved orographic precipitation model, is proposed in this report. It will use radiosonde data and also lightning data to simulate convective storms. Climatological sequences thus estimated at un-gaged locations will be represented using stochastic models, similar to the approach used in the existing CLIGEN, and their parameters will be available to users through maps. By using these stochastic models, WEPP users can synthesize climate sequences for input to WEPP.

Several alternative approaches to developing the Mountain Climate Generator (MCLIGEN) have been formulated and evaluated. These options vary in their spatial resolution. Some will provide synthetic climate inputs whereas others will provide synthetic sequences of water delivery to the ground surface or overland flow delivery. The latter will reduce the user's responsibility for judging adequate snowpack or hydrological simulations, but will enormously increase the effort required for parameterization during the developmental phase. Based on our evaluation, we recommend that Option 2 for generating fine scale climate sequences be adopted. This option appears to satisfy the WEPP spatial resolution requirements of the USFS and requires a reasonable level of developmental effort. We also recommend that Option 3 be available to the users. We recommend that under this option snowpack initial conditions at a specified date be available based on a return period or exceedance probability. Under this option discontinuous simulation periods could be considered.

The data, models, and parameters needed to implement the recommended approach can be divided into three parts: 1) climatological process models, 2) a snowpack simulation model, and 3) stochastic models of climatological variables and parameter regionalization. A chapter of the report is devoted to each of these three parts. Each chapter includes a literature review and a description of the proposed methodology and work plan for its development.

We further recommend that a comprehensive plan for data collection for validation of the entire WEPP methodology applied to the mountainous Western U. S. be developed. Also, we propose that UWRL take the lead in setting up a user group for orographic precipitation modelers.

CHAPTER 1

Introduction

1.1 Objective

The overall objective of the work that UWRL is conducting under a Cooperative Agreement with the USFS is “to develop a procedure for incorporating western mountain climate into CLIGEN, which is part of the WEPP procedure”. As a secondary objective we are also proposing to develop a western U.S. snowpack simulation model for inclusion in WEPP.

This work is part of a large USFS research and development effort, and as such must provide a usable product within the project schedules established by them. The MCLIGEN which will be developed by UWRL will furnish climate inputs to WEPP with the goal that acceptably accurate erosion predictions are provided for design and planning purposes. Existing procedures for nonorographic areas in CLIGEN will be evaluated and may be modified if necessary to achieve acceptable levels of accuracy. The representation of climate in mountainous areas will be a major challenge because climatological data are scarce, and meaningful interpolation of climate variables is more difficult in orographic areas. The project will identify existing techniques which provide adequate climate inputs, adapt existing procedures where appropriate, and develop new procedures within the constraints of available existing data and project resources.

1.2 User Requirements

The MCLIGEN should be capable of providing three climate “event types” as input to WEPP:

- *Initial snowpack water equivalent on a specified date.*
- *Melt period climate* – precipitation, temperature, and solar radiation characteristics.
- *Winter and summer storms* – duration, intensity, and amount.

The WEPP user will need these “event types” accessible in three “event forms”:

- *Design events* associated with various occurrence frequencies or return periods.
- *Continuous simulation* of climate for up to 20 year periods using stochastic methods. This will be particularly useful in assessing the erosion potential from timber harvest areas, and it could include the capability for estimating a probability distribution of erosion potential, average potentials, or perhaps high or low extreme climate cases. High cases could be useful for design of sediment control measures, such as detention basins.
- *Selected representative historical events or sequences* (e.g., average, dry, and wet). This capability would enable users to make erosion estimates for climate sequences based upon historical events (appropriately adjusted when transferred from one location to another), and it would be an alternative to the sequences generated using stochastic methods. The user could select a recorded event or sequence of data from a station or stations which the user considers best represents the conditions at the site which is under evaluation. This type of climate input would also be useful when a user desires to simulate past events as opposed to hypothetical future events.

Users will be able to choose the form of climate input which they can use. The generator will have the capability of providing climate inputs based on locational information (such as latitude, longitude, elevation, slope, and aspect).

1.3 Project Status

Three developmental phases were defined in the work plan submitted to the USFS on September 8, 1989 (Appendix A):

Phase I: Climate data evaluation and generator design

Phase II: MCLIGEN coding and evaluation at representative sites

Phase III: Generalization to entire Western U.S.

Work undertaken during the first funding period, beginning November 1, 1989, and ending June 30, 1990, has been part of Phase I. Specifically, we have conducted a literature review, key issues identification, and have begun design of the MCLIGEN. These activities were listed as Tasks 1, 2 and 5 in our September 8, 1989 work plan (see Table 1-1). Considerable effort has been invested building the USU project team. This has been necessary due to the complexity of the project and the need for close coordination between the hydrology and meteorology disciplines.

This report contains our proposed approach to developing MCLIGEN. In the next funding period climate generator design will be undertaken including preliminary data analyses in selected representative regions.

1.4 Outline of Report

The report is divided into six chapters and an Executive Summary. In Chapter 2 the existing CLIGEN for WEPP is summarized and alternatives for a Western U. S. MCLIGEN are presented. Chapters 3, 4, and 5 address the three major types of models to be used in the proposed work: climatological process models, the snowpack simulation model, and stochastic models and parameter regionalization. Each chapter includes a literature review, discussion of the proposed methodology, and description of work plan. Chapter 6 contains a summary of recommendations based on work conducted during the funding period ending June 30, 1990. Appendices B and C contain summaries of available climate data sources for use in the project and digital geographic data, respectively.

Table 1-1. Phases and tasks from September 8, 1989 work plan.

Phase I – Weather Data Evaluation and Generator Design

- Task 1 – Literature review
- Task 2 – Key issues identification
- Task 3 – Review of USFS field program
- Task 4 – Data evaluation
- Task 5 – Design mountain weather generator

Phase II – Mountain Weather Generator Coding and Evaluation at Representative Sites

- Task 6 – Coding
- Task 7 – Evaluation based on weather characteristics
- Task 8 – Evaluation based on erosion prediction

Phase III – Generalization to entire Western U.S.

- Task 9 – Generalization
 - Task 10 – Documentation
-

CHAPTER 2

Proposed Mountain Climate Generator (MCLIGEN)

2.1 Existing WEPP Model

2.1.1 CLIGEN and WEPP Model Design and Operation

The United States Department of Agriculture (USDA) WEPP is developing a "process-oriented erosion prediction technology based on hydrologic and erosion science" (Rawls et al. 1987). WEPP will include three basic versions: "a representative landscape profile version, a watershed version, and a grid version that covers" an entire field (Rawls et al. 1987) (see Figure 2-1). The major modules in WEPP are climate generation, snow accumulation, snowmelt, infiltration, runoff, channel routing, soil temperature, erosion, soil moisture, crop growth, plant residue, and tillage. Our project focuses on the first three modules and their modification for use in Western mountain conditions.

The developers of the WEPP model chose to operate the model in a two-stage process. First, a climate file is generated, and then the erosion model can be run for many different management practices under constant climate conditions. The WEPP developers chose to provide the capability to operate the model from a stochastically generated sequence. When a historical sequence is to be used, it must first be converted to the CLIGEN output format. The model operation sequence and the variables generated by CLIGEN are shown in Table 2-1.

The developers of WEPP used operational criteria in setting the resolution and complexity of the simulations. In the operation of the erosion portion of the model, they selected a rapidly running, "indication" type model as opposed to a detailed simulation. Their criteria are shown in Table 2-2.

WEPP was designed to be used in local offices where computational capability is not great. It was also recognized that a farmer or operator would probably not wait a long time to run the model. Furthermore, a detailed model rapidly becomes site-specific and then is only as good as its input data. In many conditions, the available input data do not justify the operation of a detailed model.

The WEPP model requires the input files shown in Table 2-3. The climate file is generated by converting historical sequences to stochastic model parameters. Random variability introduced by the stochastic model is all that is needed to change the generated climate sequence.

CLIGEN will eventually be available in forms that will operate from three types of input data. These data types could be a long-term climate sequence, a specific storm history, or a specific design storm. We understand that at present, stochastic model parameters for only long-term historical sequences are available for WEPP operation.

Existing WEPP model climate options are described by A. Nicks (memo dated May 5, 1989), as follows:

1. Average annual soil loss
2. Continuous simulation
3. Design storm

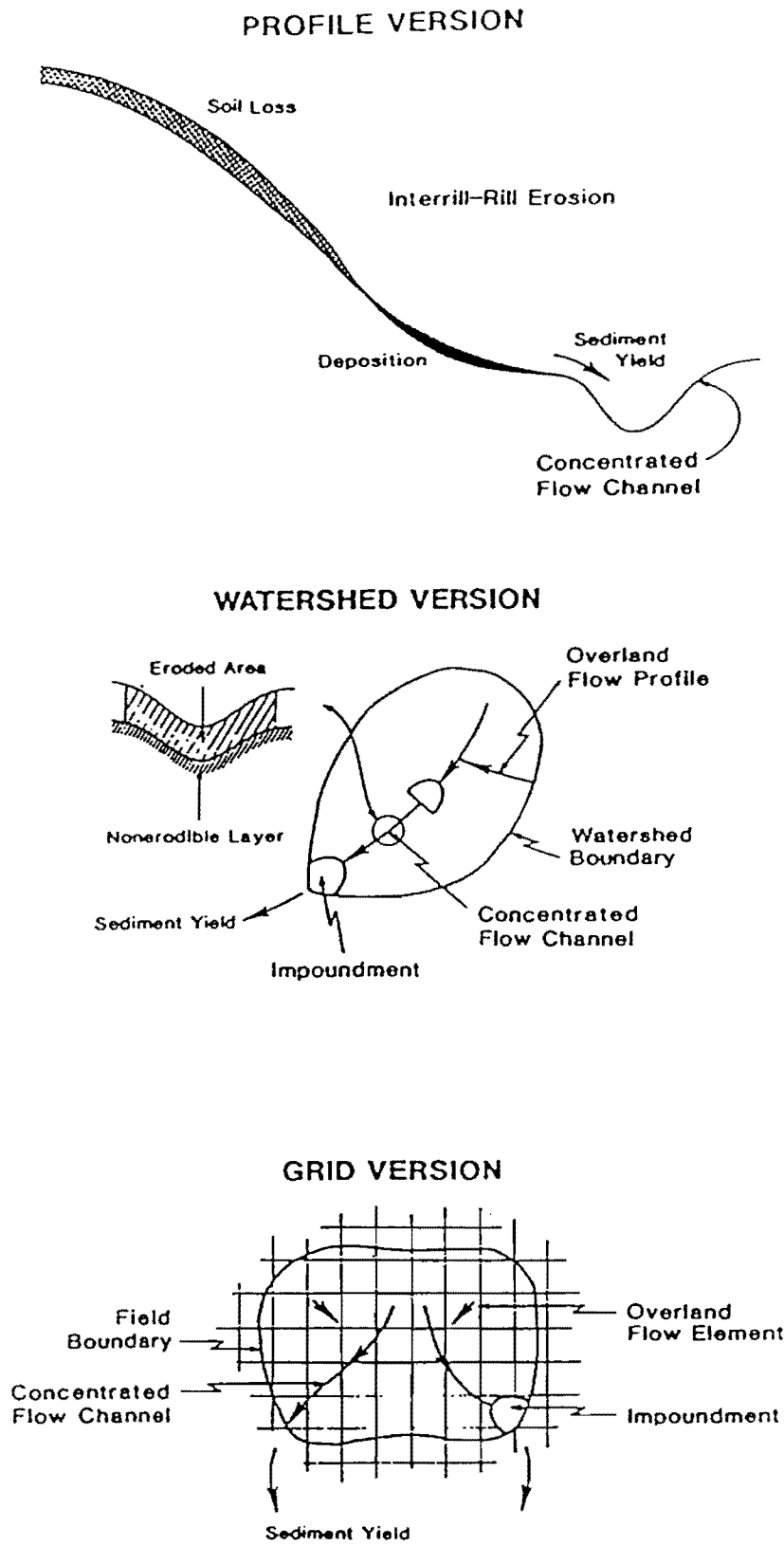


Figure 2-1. Model structure (after Rawls et al. 1987).

Table 2-1. The WEPP model operation strategy and the climate variables generated by CLIGEN.

| <i>WEPP Model Operation</i> | | | |
|-----------------------------|---------------------|------|---|
| First | RUN CLIGEN | then | RUN WEPP |
| | Amount | 1. | Disaggregates Precipitation. |
| | Duration | 2. | Time/Intensity Format Conv. |
| | Maximum Intensity | 3. | Calculates Infiltration, Water Balance, Deep Percolation, Evapotranspiration. |
| | Time to Peak | | |
| | Maximum Temperature | 4. | Calculates Crop Growth and Erosion. |
| | Minimum Temperature | | |
| | Solar Radiation | | |

Table 2-2. The criteria set for developing the CLIGEN and WEPP codes.

| <i>WEPP Operational Criteria</i> | |
|----------------------------------|--|
| 1. | Each management practice simulation will require less than one minute per simulation run on IBM-PC. |
| 2. | If an internal simplification of the model causes less than a 10% change in the output - that change will be judged to be appropriate. |

Table 2-3. The Input data files required to run the WEPP model.

| <i>WEPP Model Input Requirements</i> | |
|--------------------------------------|---|
| 1. | Climate file -- generated by CLIGEN model |
| 2. | Slope file -- generated by user - simple |
| 3. | Soil file -- generated by user - simple |
| 4. | Management file -- generated by user |

4. Select a specific type of year (dry, wet, etc.)
5. Select a specific frequency storm in a specific month
6. Run a series of design storms

7. Run a specific period of record
8. Run a specific period of record from historical data

Existing parameter and data requirements for WEPP CLIGEN are presented in Table 2-4 (A. Nicks memo dated May 5, 1989).

2.1.2 Design Goals for a Mountain Version of CLIGEN

In our review of WEPP and its associated submodel, CLIGEN, we have concluded that it is possible to develop a mountain version of CLIGEN. The design requirements of our effort are shown in Table 2-5.

Table 2-4. Climate data generation using CLIGEN.¹

| <i>Parameter and Data Attributes</i> | |
|--------------------------------------|-----------|
| 1. Station | |
| Number (state, station) | |
| Name | |
| 2. Station Location | |
| Latitude | |
| Longitude | |
| Elevation | |
| 3. Rainfall Frequency | |
| .5 hr. 10 yr. | |
| 6 hr. 10 yr. | |
| 24 hr. 10 yr. | |
| 4. Rainfall Parameters | |
| Mean daily | 12 values |
| Std. dev. daily | 12 values |
| Skew coef. daily | 12 values |
| Probability wet/wet | 12 values |
| Probability dry/dry | 12 values |
| Mean max .5 hr. | 12 values |
| | (72) |
| 5. Temperature Parameters | |
| Mean max. air temp. | 12 values |
| Mean min. air temp. | 12 values |
| Std. dev. max temp. | 12 values |
| Std. dev. min temp. | 12 values |
| | (48) |
| 6. Solar Radiation | |
| Mean daily solar rad. | 12 values |
| | (12) |
| 7. Wind | |
| Ave. wind speed | 12 values |
| Direction | 12 values |
| Percent time | 12 values |
| | (36) |
| 8. Dew Point Temperature | |
| Mean daily | 12 values |
| | (12) |

¹ A. Nicks dated May 5, 1989.

Table 2-5. The design requirements of the UWRL Mountain CLIGEN (MCLIGEN).

| MCLIGEN Model Input Design Strategy | | | | | |
|--|--|----|---|----|--|
| 1. | Maintain capability to operate from historical sequences. | | | | |
| 2. | Maintain capability to input design storm sequence. | | | | |
| 3. | Provide the capability to generate stochastic sequences for any Western location. <ol style="list-style-type: none"><tr><td>a.</td><td>Develop maps of stochastic model parameters to allow operation of MCLIGEN for any given area.</td></tr><tr><td>b.</td><td>Parameter fields will be developed from the use of gage and radiosonde data combined with sophisticated model studies.</td></tr> | a. | Develop maps of stochastic model parameters to allow operation of MCLIGEN for any given area. | b. | Parameter fields will be developed from the use of gage and radiosonde data combined with sophisticated model studies. |
| a. | Develop maps of stochastic model parameters to allow operation of MCLIGEN for any given area. | | | | |
| b. | Parameter fields will be developed from the use of gage and radiosonde data combined with sophisticated model studies. | | | | |
| 4. | MCLIGEN will "look, feel and operate" like CLIGEN. | | | | |

2.2 Overview of Proposed MCLIGEN

It can be expected that almost all applications of WEPP will be at sites where climate data are not readily available. Therefore, the development of MCLIGEN for WEPP must provide a means for using observed climate data and transferring them to ungaged sites. Also MCLIGEN must have the capability of representing climate sequences in a compact form using stochastic models. Since snowmelt is a significant source of runoff in the Western U.S., MCLIGEN also will be required to provide the climatological inputs necessary for estimating snow runoff.

Several options have been evaluated by UWRL for generation of the climate inputs to WEPP when it is applied to mountain sites in the Western U.S. These options are discussed in Section 2.3.

Figure 2-2 represents the data, models, and parameters needed for each of the five options considered for MCLIGEN. This figure is divided into four columns: data, physical process models, stochastic models, and stochastic model parameters. The key to the vertical organization of Figure 2-2 is the series of physical process models in the second column. This series is precipitation (and other climatological variables), wind, snowpack, hydrology, and erosion. The first three models are to be developed by UWRL and the latter two are being developed by the USFS.

The data, models, and parameters assigned to UWRL can be divided into three parts: 1) climatological process models (Models A and B), 2) a snowpack simulation model (Model C), and 3) stochastic models of climatological and snowpack variables including parameter regionalization by mapping or geographical information system (GIS) (Models E, F, G, and H). Part 1 would be used only in the developmental phase under all options. Part 2 would be needed for the developmental phase under all options and would be incorporated into the operational MCLIGEN under Options 1, 2, and 3. Stochastic models and parameter regionalizations would be developed for application in MCLIGEN under all options.

2.3 Optional Forms of MCLIGEN

Five optional forms of MCLIGEN have been evaluated. The components of each option are represented in adaptations of Figure 2-2 (see Figures 2-3 through 2-7, respectively). The combination of component models needed for development and application of each option are listed in Table 2-6. In Figures 2-3 through 2-7 models needed for development purposes are represented by boxes with thick boundary lines. Models that would be operated by the WEPP user are represented by shaded boxes connected by thick dashed lines and arrows.

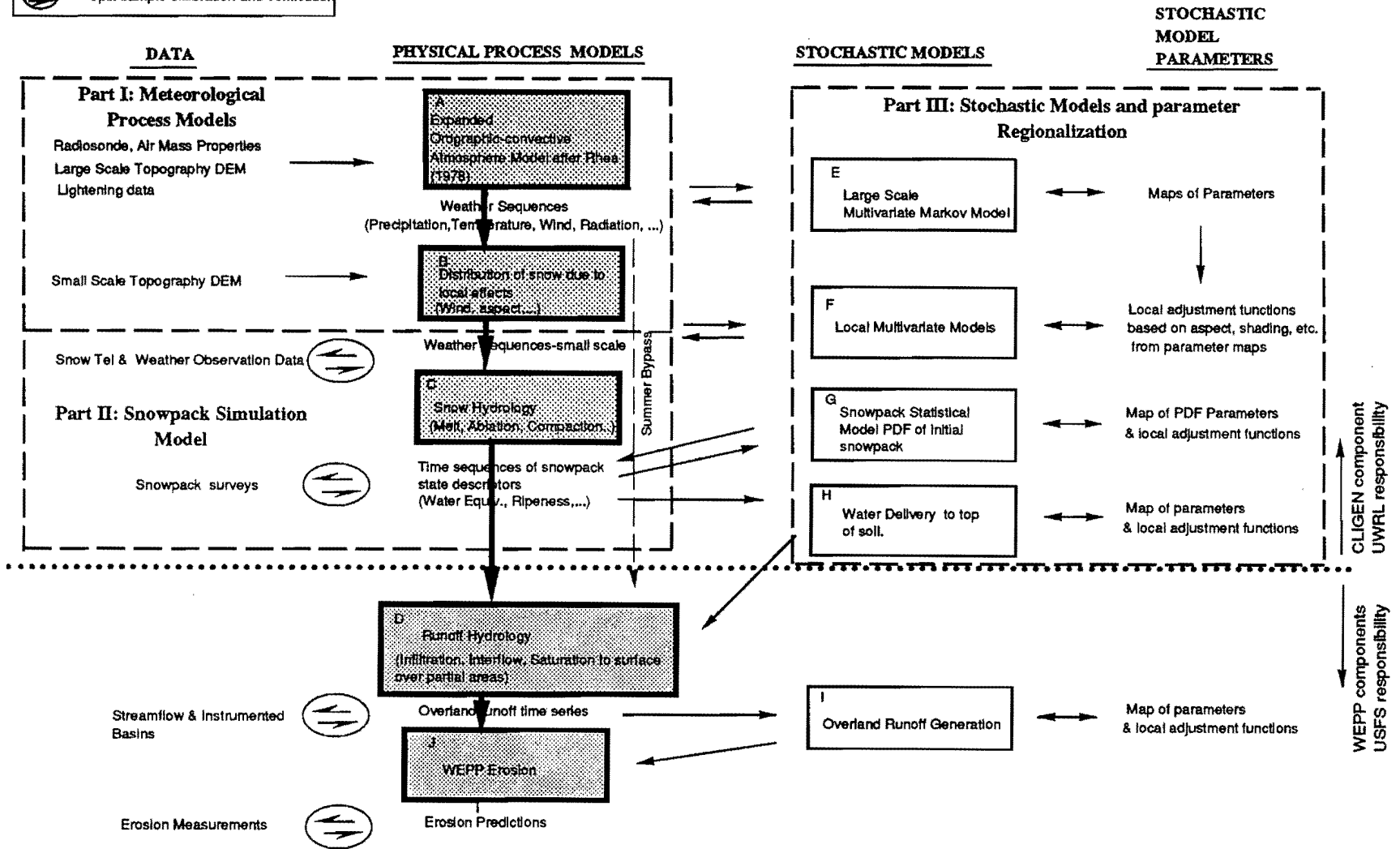
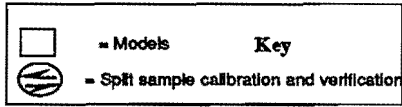


Figure 2-2. Relationship of mountain climate generator to WEPP.

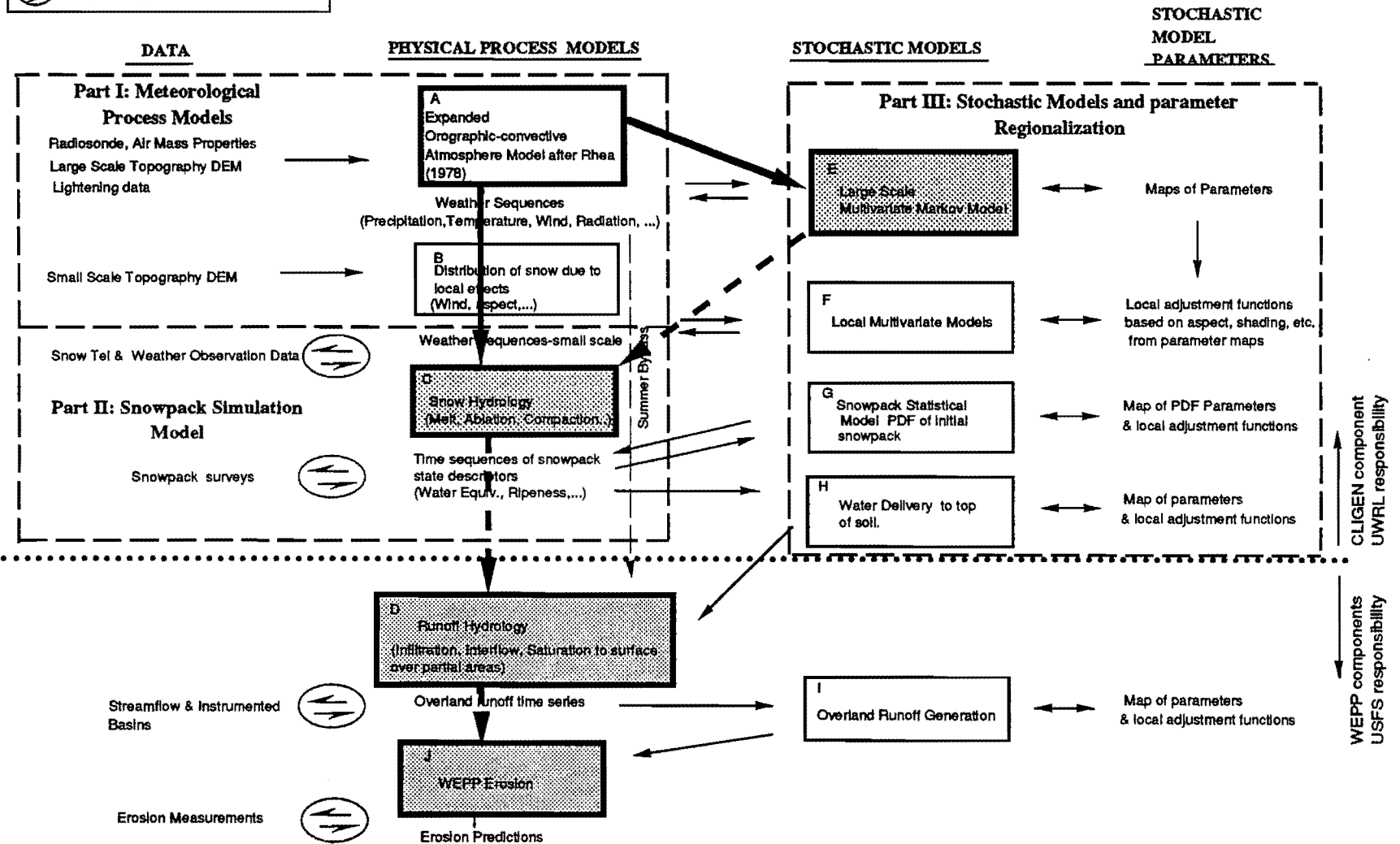
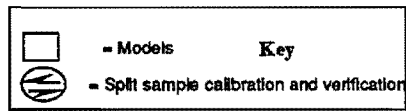


Figure 2-3. Option 1: Coarse scale climate sequences.

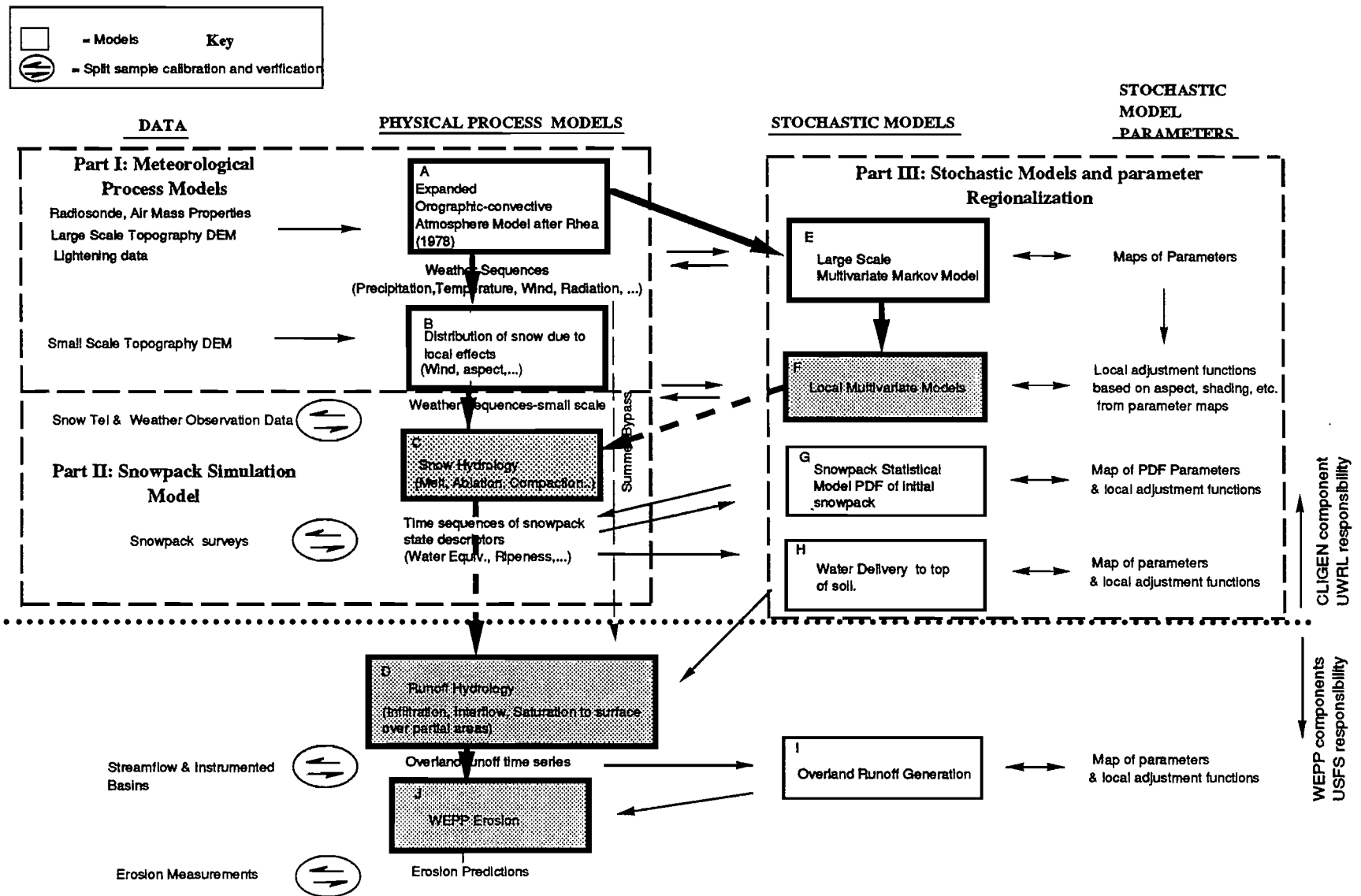


Figure 2-4. Option 2: Fine scale climate sequences.

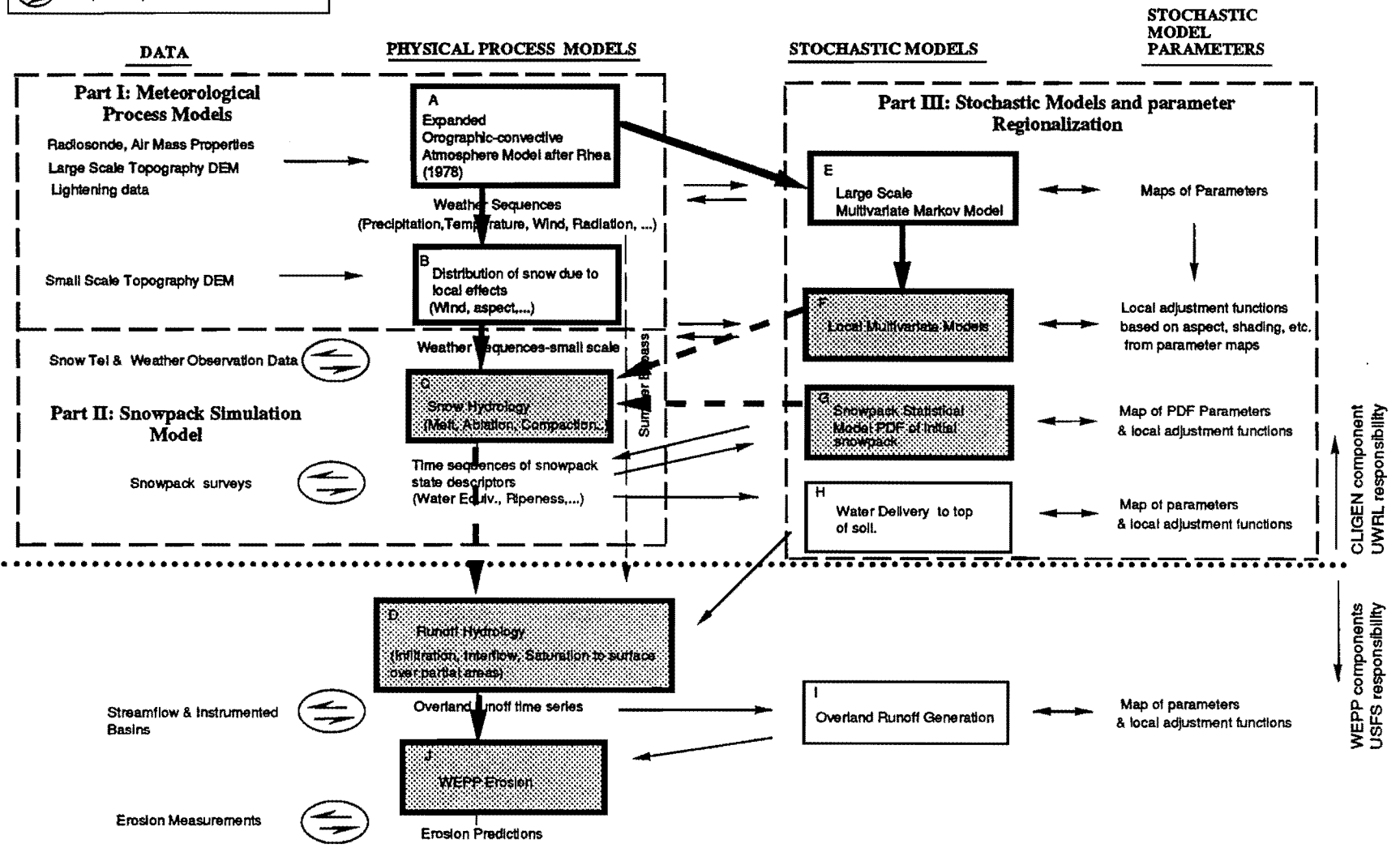
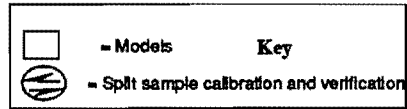


Figure 2-5. Option 3: Snowpack initial conditions on a specified date.

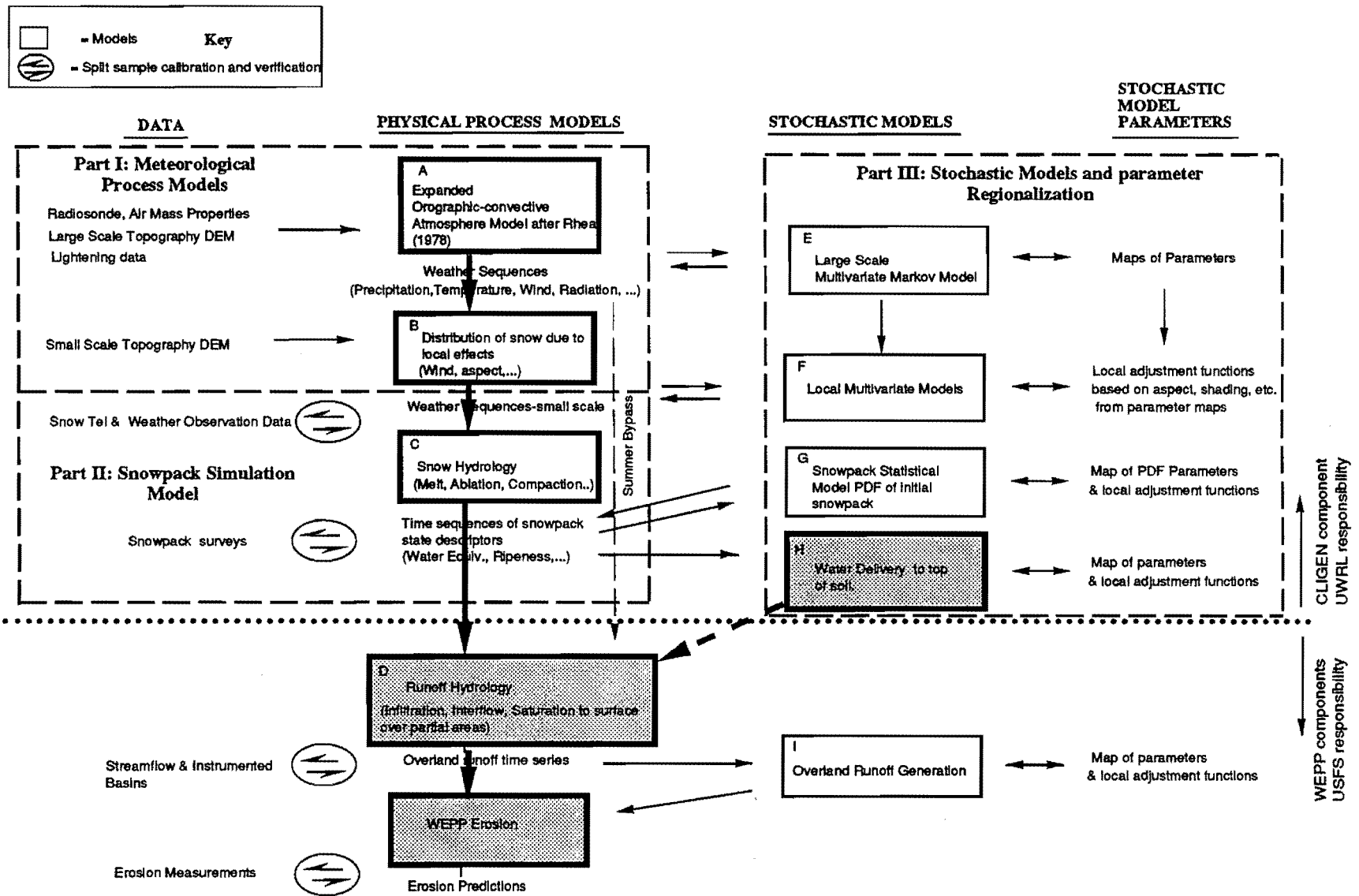


Figure 2-6. Option 4: Water delivery sequences.

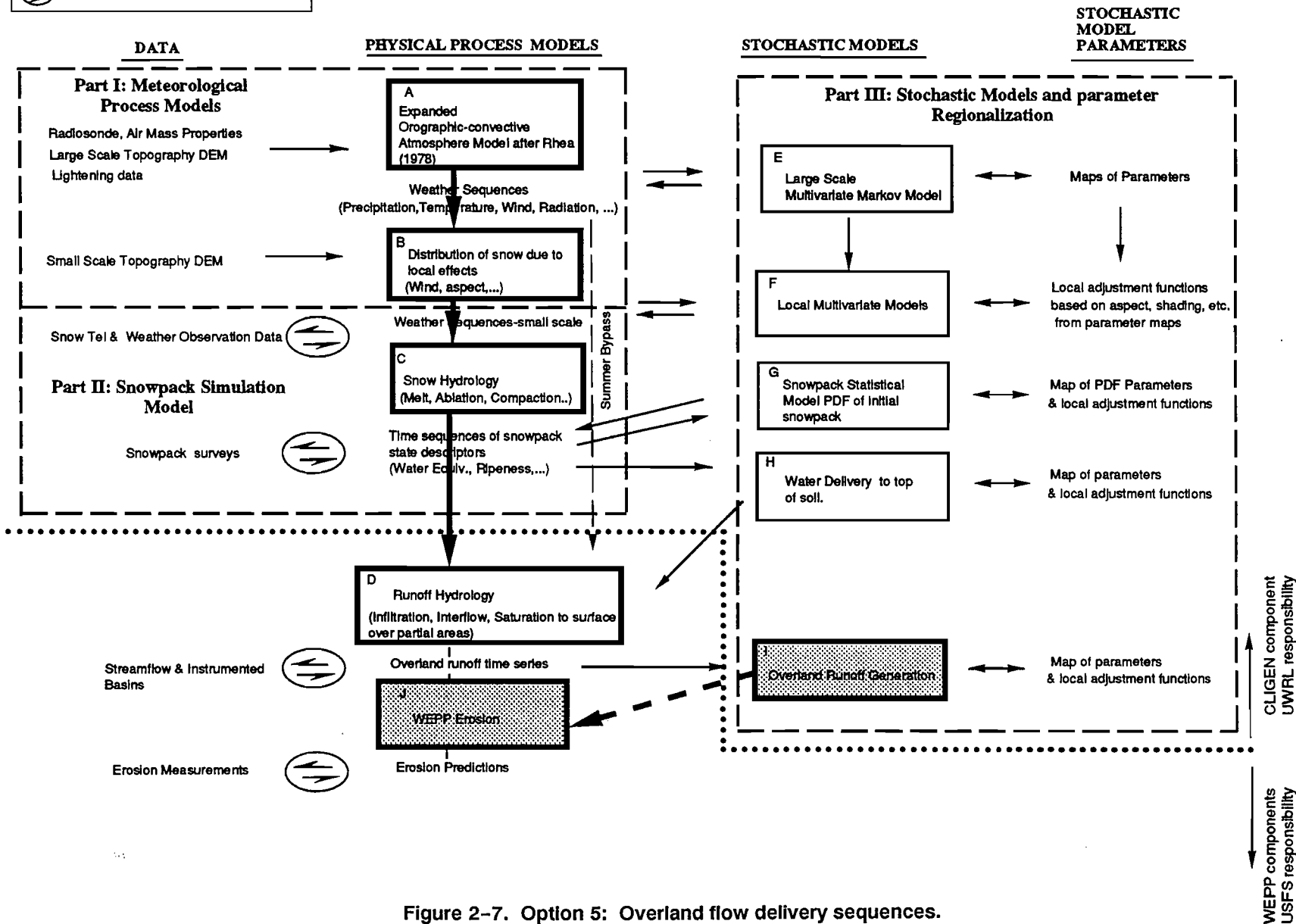
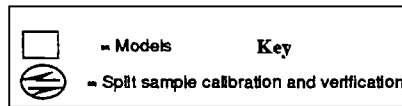


Figure 2-7. Option 5: Overland flow delivery sequences.

Table 2-6. Options.

| | | |
|--|-----------------------------------|-----------------------------------|
| 1. Coarse scale climate sequences | <u>Development</u> A C D* J* | <u>Application</u> E C D* J* |
| 2. Fine scale climate sequences | <u>Development</u> A B C D* J* | <u>Application</u> F C D* J* |
| 3. Snowpack initial conditions at a specified date | <u>Development</u> A B C D* J* | <u>Application</u> F C G D* J* |
| 4. Water delivery sequences | <u>Development</u> A B C D* J* | <u>Application</u> H D* J* |
| 5. Overland runoff delivery sequences | <u>Development</u> A B C D* J* | <u>Application</u> I J* |

*USFS to develop this component

Under *Option 1* (see Figure 2-3) MCLIGEN would provide the user with coarse-scale climate sequences from stochastic models (Model E). However, these would not take into account the distribution of snow by wind, and after local effects of orography and vegetation. Wind also influences snowmelt, evapotranspiration, and the timing and rate of runoff in mountain regions. Because of these effects and because the USFS is interested in evaluating erosion from relatively small sites, this option is not recommended.

Option 2 (see Figure 2-4) would provide the WEPP user with fine-scale climate sequences. These would be obtained from using the physically-based approach of Model B. The stochastic model (Model F) is similar to Model E but with parameters adjusted for local conditions (slope, aspect, vegetation, shading, etc). This option is intended to satisfy the scale requirements of the USFS. It would require that WEPP include a snowpack model (Model C) to simulate the accumulation and ablation of snow. A disadvantage of including the snowpack model in WEPP is that the user may not be qualified to identify problems with a snowpack simulation. Therefore, this option should include precautions to minimize the chance of unrealistic snowpack simulations.

Option 3 (see Figure 2-5) was suggested by the USFS. It would require the specification of snowpack initial conditions at a specified date. These would be used to initialize the snowpack model (Model C). This option would then proceed in the same way as Option 2, using fine scale climate sequences. It differs from Option 3 in that the accumulation of the snowpack would not be simulated. Since it uses the snowpack model through the snowmelt period it would have the same disadvantage that Option 3 has. The user would be given the choice of specifying the snowpack initial conditions or obtaining them from a joint probability distribution (Model G).

Option 4 (see Figure 2-6) is significantly different from Options 1, 2, and 3. Rather than provide the WEPP user with climate sequences, it would provide the user with sequences of water delivery to the top of the soil. Water delivery sequences would be stochastically generated (Model H) from sequences of snowmelt output by the snowpack model (Model C) or by precipitation models (Models A

and B). By so doing the user would not be responsible for achieving an adequate snowpack simulation. The user would select parameters for simulation of coarse scale water delivery sequences and adjustment procedures to obtain fine scale sequences based on the site topography and vegetative conditions, including temporal changes in vegetative conditions due to regrowth after logging. This two-step approach, beginning with coarse scale sequences and adjusting them for local effects, is analogous to that proposed in Models E and F for climate sequences. However, it would be complicated by the need to change the timing as well as the magnitude of the variables. An example of this problem is the delayed occurrence of snowmelt on north facing slopes compared with south facing slopes. Option 4 has the advantage of reducing the chance of unrealistic snowpack simulations by a user who is not familiar with snowpack modeling. However, this advantage could only be achieved at the expense of additional effort to obtain snowmelt sequences for stochastic modeling at coarse and fine scales during the developmental phase. Also, consistent temperature or solar radiation sequences may be needed for use in the "crop growth" module of WEPP.

Option 5 (see Figure 2-7) takes Option 4 one step further. Instead of providing the WEPP user with water delivery sequences, the user would be given overland flow delivery sequences. These would be generated from a two-step approach in a similar manner to the water delivery sequences in Option 4. It has a similar, but stronger (since they include hydrology and snowpack considerations) advantage and disadvantage to Option 4 (snowpack considerations only).

On the basis of our evaluation of the options described above we recommend Option 2. If Option 3 is of interest to the USFS, we propose that it also be included. Option 1 does not appear to meet the resolution requirements of the USFS. Options 4 and 5, while offering some important advantages to the user over Option 2, appear to require unrealistically high developmental effort to provide adequate parameterization.

2.4 Summary of Development of MCLIGEN – Options 2 and 3

For Model A we propose to use the Rhea-type (Rhea 1978) model of orographic precipitation, modified to include convective precipitation in mountainous regions. This will provide a physically-based approach for estimation of precipitation at ungaged mountain sites using data from gaged sites and also radiosonde data. The Rhea-type model will be supplemented with the capability for simulation of other climatological variables (e.g. solar radiation, maximum and minimum air temperature, and dew point temperature). When precipitation is in the form of snow its spatial distribution on the ground will be determined using Model B, which will take into account the effects of wind and local topography on snow delivery. Model A will be adapted to include the capability for simulating precipitation from convective storms. For this purpose lightning data sets will be used.

At times of the year when snowpack is present, climate inputs will be used to drive a snowpack simulation model (Model C). The principal purpose of this model will be to provide estimates of water delivery to the top of the soil. These estimates will be input to the hydrology model (Model D) when snowpack is present. When snowpack is absent the snowpack simulation model will be bypassed and climatological inputs will be transferred directly to the hydrology model. The hydrology model will drive the WEPP erosion model (Model J).

During the development phase (under Options 2 and 3) the sequence of Models A, B, C, D, and J will be applied to gaged sites in selected regions. If sufficient data are not available to calibrate and validate the hydrology and erosion models, only Models A, B, and C will be applied. The scale of resolution for Model A will be coarse, which for this purpose is defined to be of the order of a 2 to 10 km grid.

Model B will provide for a much finer scale of resolution, perhaps 60 to 90 m, depending on the availability of topography from a Digital Terrain Model (DTM) or topographical maps.

Once a satisfactory performance of Models A and B is achieved in the selected study regions, they will be used to synthesize climate sequences over a coarse grid of ungaged sites. Model A will provide sequences at the coarse-scale of resolution, whereas Model B will synthesize sequences at the fine-scale of resolution.

Climate sequences from Model A will be modeled using stochastic techniques (Model E) and stochastic model parameters will be mapped. Adjustment procedures will be developed for obtaining (fine-scale) Model B output from stochastically generated sequences of (coarse-scale) Model A output. Similar adjustments have been applied by Hungerford et al. (1989) in mountain regions. They should be designed to take into account the effects of local topography and shading. Also, the capability for representing the effects of regrowth after logging should be included.

2.5 Summary of User Capabilities of MCLIGEN – Options 2 and 3

Under Option 2 the user will need to specify a latitude and longitude for the site to be evaluated. The necessary topographical inputs will be specified by the user or obtained from a digital elevation model (DEM) (see Appendix C). Also, the user will specify shading conditions at the site and any changes in vegetation conditions to be considered over the simulation period.

MCLIGEN will use the site location information to obtain parameters for the coarse-scale stochastic models (Model E) of the climate variables. Topographical and vegetative information will be used to obtain local adjustment factors (Model F) for converting the coarse-scale sequences to fine-scale sequences. These climate sequences would then be input to the hydrology model (Model D) and other WEPP modules. During the winter period the snowpack model (Model C) will be used to obtain a snow-melt sequence. The output from the snowpack model will be input to the hydrology model.

Option 3 would proceed similar to Option 2 from the user perspective. The principal difference being that the snow accumulation period prior to the initial date would not be simulated when Option 3 is selected. Under this option the user must either specify the snowpack conditions on a particular date close to the time of the occurrence of the maximum snowpack water equivalent or obtain them for a specified date and return period from a joint probability distribution.

CHAPTER 3

The Development of a Climate Generator for Mountainous Terrain

3.1 Purpose

This chapter details a strategy developed by the UWRL to develop a MCLIGEN model that can be used with the USDA WEPP model in mountainous terrain. This is difficult because of the lack of detailed climate data and the large changes in elevation associated with small changes in distance. In developing this strategy, we have attempted to maintain the development objectives of the original climate generation model. The outlined strategy uses the available data and the latest models to develop a climate generation model that maintains the “look and feel” of the original CLIGEN model. MCLIGEN is proposed to operate from contour maps of the model parameters.

3.2 Literature Review

Researchers have experienced little success in attempting to extrapolate climate data (precipitation, temperature, dewpoint, etc.) in mountainous terrain using scattered gaged data and statistical techniques. A significant improvement to these attempts would be a procedure which incorporates the physical relationships that exist between such sites and other data sets. These relationships are often expressed in the form of computer models. Detailed precipitation models, which also must deal with temperature and humidity, are sufficiently mature that they have become the subject of books and reviews. A wide range of models have been applied to precipitation modeling. Pielke's (1984) book summarizes the art, although it is becoming dated. More recently, Foufoula-Georgiou and Georgakakos (1988) have reviewed the status of current efforts in space-time precipitation modeling and forecasting.

Most precipitation models fall into two classes: 1) stochastic (Woolhiser and Roldan, 1982) which tend to contain little physics and 2) full hydrodynamic codes (Pielke 1982; and Georgakakos and Lee, 1987). The hydrodynamic codes tend to be fully descriptive and as a result require significant computer time and input data. The primary motivation for the dynamic models is real time precipitation forecasting and where data have been available they have achieved significant success. These codes, which must accurately predict amount, location, and timing are not well behaved in complex terrain.

Rhea (1978) developed an orographic precipitation model which has been quite successful in predicting snow accumulation and runoff from the Colorado mountains. This model type is much simpler in its physics and is typical of a third type of code (Tesche and Yocke, 1978; and Tesche 1988). Although these models do not attempt to handle the details of complex convective storms that are common in the high sun period, they do summarize important details that describe snowfall. These models have been used extensively in Colorado (Judson 1976; and Williams 1980) and in the Pacific Northwest (Hayes 1986).

3.3 MCLIGEN – The Approach

Our approach to MCLIGEN is two-stage. First, we will generate synthetic climate data sequences at a relatively coarse-scale grid points (2 – 10 km) in the area to be simulated. These sequences will

be generated using a modified orographic precipitation model which will use radiosonde data for inputs. Then a fine-scale distribution model will be used to represent the distribution of the snow and the local variations of temperature at the study site. Grid spacing at the fine scale will be on the order of 50 m. Once the data sequences have been generated, standard WEPP stochastic sequences and run procedures can be used. The stochastic model parameters will be spatially displayed on GIS contour maps which can be easily utilized in the field.

3.3.1 Rationale

Meteorological models of precipitation and temperature in mountainous terrain have had little success. There is, however, a significant difference in expectations of meteorological and climate models. To be of value, meteorological models must not only simulate the proper precipitation and temperature, they must also accurately represent the timing of events. In a climate model, the exact details can be ignored as long as the averages are correct. Climate models have been much more successful in mountainous terrain.

Table 3-1 shows the scale of the climate model that will be required to generate the synthetic climate sequence required for WEPP operations in mountainous terrain.

Table 3-1. Typical correlation distances for some important MCLIGEN variables between locations in mountainous terrain.

| <i>Mountain CLIGEN Variable Correlation Assumptions</i> | | | |
|---|-------------|-----------------|---------------|
| <i>Variable</i> | <i>Area</i> | <i>Altitude</i> | <i>Aspect</i> |
| Wet/Dry Day | Long | Long | Long |
| Intensity | Moderate | Moderate | Long/Mod |
| Duration | Long | Moderate | Moderate |
| Time-Peak | Long | Mod/Long | Long |
| Max. Temp. | Long | Short | Moderate |
| Min. Temp. | Long | Short | Moderate |
| Solar Rad. | Long | Long | Short |

As Table 3-1 shows, few of the variables have short correlation distances when considered in a time-averaged sense. We expect that a resolution of 2 to 10 km will be sufficient for potential precipitation, temperature, and radiation calculations. A separate model, operating on a finer scale will be necessary to develop local precipitation accumulation, temperatures, and radiation levels for the specific erosion study areas. This model will be especially important in accounting for wind effects on frozen precipitation around fine-resolution terrain features.

3.3.2 Course Scale Data Generation Strategy

Our strategy in the development of MCLIGEN is to modify an orographic precipitation model to provide the climate data sequences. Inputs to the orographic model are the radiosonde data taken twice

daily at NOAA Class A weather stations. The expanded orographic model will provide the climate sequences for each model node. Existing historical data sets will be used to validate the synthetic climate data sequences. Generation of the stochastic model parameters becomes very similar to generating the parameters for a flatland historical sequence. By generating the climate sequences first, we can verify the accuracy of the climate models independently of the stochastic models. The end user-operator will generate intensity-based sequences for each location using procedures that are similar to those of the current WEPP model. However, because of the steepness of the terrain and the presence of extensive snow cover, a local distribution model will be operated after the climate sequence for the site has been computed. Water inputs to the erosion model will come from both precipitation events directly and from snowmelt.

Many attempts to model precipitation for hydrological uses ignore two major data sets. These are the radiosonde and lightning data collected by the National Weather Service. The national radiosonde data set, combined with a good orographic model, can provide the wet/dry state and amount sequences needed for the stochastic model. Most precipitation events in the Mountain West during the low-sun seasons are orographic in nature. Good models exist for distributing precipitation under orographic conditions. Our choice for the orographic model is one developed by Rhea (1978) and improved by many others. However, during the high-sun seasons, we will need to improve the convective treatment included in the Rhea model.

Over the past decade significant improvements have been made in our understanding of convective precipitation and its modeling. Real time convective models require far too much input data and computation time and do not work well in mountainous terrain. However, in a climate model we only have to predict the precipitation amount and distribution. Thus, our approach to the convective model will be to use the orographic model to calculate an instability index for each node in the lifted airmass. A vertical wind field will be generated by combining surface heating and mechanically induced forces. The vertical wind fields will then be added to the lifted airmass to determine the locations and percentage of the airmass which becomes conditionally unstable. Next, a one-dimensional convective model will be used to generate cells in these areas, and precipitation patterns and intensity will be calculated by the one-dimensional model and the horizontal wind field. The lightning data set will be used in conjunction with the few measurements that exist to develop durations, intensities, and areal distribution functions.

The combination of an orographically-based model of precipitation and the snow telemetry (SNOTEL) data set provide an excellent combination for the wet/dry state and amount sequences required for MCLIGEN. Because they use two separate data sets, the SNOTEL data can be used to calibrate and validate the precipitation model. The precipitation model will generate wet/dry state and amount sequences for each node. The sequences are physically-based, taking into account the latest available data on variation in altitude and aspect. We do not know much about the variation of stochastic model parameters in complex terrain. However, we do have a great deal of information on climatic variability. Our two step approach, the generation of a location specific climate data sequence followed by the conversion of the sequence to stochastic model parameters, uses both our scientific understanding of physical mechanisms and empirical evidence based on observed data. The model and data application sequence are shown in Table 3-2.

Most of the models needed to develop MCLIGEN model parameters exist, and we have experience with each of them. There are a couple of models and model components that are yet to be developed. Additionally, none of the models have been applied in the exact fashion proposed here. The status of each of the models to be used in the project is detailed in Table 3-3.

Table 3–2. The model sequence to be used in developing MCLIGEN coefficients from data and synthetic data sequences.

| <i>MCLIGEN</i> | | | |
|---|----------------------|----|--|
| <i>Types of Models Required to Develop Climate Sequence</i> | | | |
| 1. | Wet/Dry State | | |
| | Gaged Stations | -- | Markov Chain Type Model |
| | Ungaged Location | -- | Radiosonde Data --> Orographic Model or Orographic/Convective Model --> Synthetic Data Sequence Sequence --> Stochastic Parameters |
| 2. | Solar Radiation | | |
| | All Areas | -- | Radiosonde Data --> Orographic Model Saturation --> Clouds Clouds --> Walters (1987) Model Walters Model --> Radiation |
| 3. | Duration, Intensity | | |
| | Gaged | -- | Mixed Exponential |
| | Ungaged | -- | Linear Extrapolation of Radiosonde --> Orographic/Convective Model --> Precipitable Water + Cell Size Prob. --> Stochastic Distribution of Rain/Snow --> Local Precipitation Pattern |
| 4. | Time to Peak | | |
| | Gaged | -- | Direct From Data |
| | Ungaged | -- | Cell Size and Horizontal Wind |
| 5. | Temperature, Maximum | | |
| | Gaged | -- | Direct From Gage |
| | Ungaged | -- | Radiosonde --> Air Mass Temperature Amount + Orographic Model --> Lifted Temperature Lifted Temperature + Local Heating Model --> Maximum Temperature |
| 6. | Temperature, Minimum | | |
| | Gaged | -- | Direct From Gauge |
| | Ungaged | -- | Radiosonde --> Air Mass Temperature Amount + Orographic Model --> Lifted Temperature Lifted Temperature + Long Wave Radiation Model --> Minimum Temperature |

3.3.3 Fine Scale Distribution Strategy

The local distribution model (Model B) that we propose to implement is based on the following assumptions:

1. Precipitation potential is constant over coarse-scale grid square.
2. Temperature varies adiabatically over coarse-scale grid square.

Table 3-3. The status of the models that we propose to use in developing MCLIGEN.

| <i>MCLIGEN</i> <i>Status of Models Required to Develop Climate Sequence</i> | | |
|--|-----------------------|---|
| 1. | Markov Chain | -- Established procedures. Several variations. |
| 2. | Orographic | -- Rhea (1978). Orographic precipitation model has been shown to have good success in predicting stratus and weakly convective storms. Needs modification for use in MCLIGEN. |
| 3. | Orographic/Convective | -- Not yet developed. Expect to add a simple 1D convective precipitation model to the Rhea model. Critical components are vertical wind and precipitable water. Needed to estimate cell size and intensity. |
| 4. | Time to Peak | -- Not yet developed. Simple relationship developed from cloud size (stratus) or cell size (convective). |
| 5. | Solar | -- Rhea (modified) to get cloud field. Walters to calculate solar intensity at elevation through clouds. |
| 6. | Temperature | -- Rhea (modified) + Walters (1988) + LHM (local heating model, not yet defined). Use Rhea model to develop air mass temperature at altitude. Solar intensity at altitude. LHM - radiation + wind + pressure --> local temperature profile. |

3. Vapor pressure varies hydrostatically over coarse-scale grid square.
4. Potential radiation balance is constant over coarse-scale grid square.
5. Free stream wind constant over coarse-grid square.
6. Skipped when precipitation is rain.

The major problem with the fine-resolution model is how to handle the terrain in a fashion which is consistent with the goals of the WEPP. Because the USFS has not yet selected a GIS or DTM and because exact calculations of wind blown snow and other distribution variables would likely be very time consuming, we have evaluated the following alternatives:

Alternative A—Three Dimensional Terrain - Rigorous Solution

1. Requires terrain model and an extensive link to the coarse-scale model.
2. This solution is extremely computer intensive, both in handling the details of terrain and in the flow simulations that would be expected to be used to justify the terrain data input effort.
3. Exact boundary conditions would be required for each of the variable inputs. Many of the boundary conditions may not be known to sufficient accuracy by the field user.
4. Prospects for success - low.

Alternative B—Two Dimensional – Simplified Terrain

1. The erosion study area would be broken up into smaller regions that could be approximated by preprogrammed terrain descriptions. The size of the region could be input, along with aspect, slope, and elevation.
2. Graphical techniques would be used to add important clutter objects. These objects would be features such as major rock outcrops or trees and vegetation that significantly affect snowmelt and runoff. The objects could be chosen from clip art and oriented using a mouse or cursor keys.
3. Simplified rule-oriented solutions would be used to distribute snow, calculate temperature differences from the air mass, and calculate radiation and evaporation loads.
4. Moderately simple boundary conditions would be used in the calculations.
5. Prospects for success – high.

Alternative C—One Dimensional – Linear Terrain

1. This option is the simplest terrain alternative and would use the current WEPP terrain model. Terrain elements would be divided similar to Alternative B but would be summarized by a single dimensional slope.
2. This makes clutter difficult to handle. Local drift development calculations, for instance, are not possible.
3. This alternative presents the simplest of boundary conditions.
4. It would also use the same rule-orientated solutions described in Alternative B.
5. It is computationally simple.
6. Prospects for success – moderate.

We recommend that Alternative B be chosen. This requires that the computer running the model have a graphical capability. By the time this development effort is completed it is reasonable to expect that computers in Forest Service field offices will include the necessary graphical capabilities.

3.4 Work Plan

The MCLIGEN development effort will be divided into three coordinated parts as described in Section 2.2. The climate modeling effort (Part I) will follow the overall development plan of the project. The development of models, data comparisons, and the development of user software will occur over a three year period. Each year's work plan is summarized below.

FY 90/91

Task 1—Model development: The Rhea-type orographic model will be expanded to provide temperatures, percent cloud cover, precipitation potential, and dewpoints. Additional routines will be added to improve summer precipitation predictions.

Task 2—Data development: Test areas for the model will be identified and data requirements specified. Digital terrain data, radiosonde information, and ground truth information for each test area will be prepared. A research watershed will also be identified that can provide the detailed climate and snow information necessary to develop and test the local distribution model.

Task 3—Model - Data comparison: Initial model applications will take place in two 50 x 50 km sections of Utah. These sections will be in the Wasatch and Uinta mountains, thus providing verification in both north-south and east-west terrain features.

Task 4—Cooperative Effort Development: Significant capability and interest exists in orographic precipitation models and in furthering the development of WEPP. During this year we will establish cooperative relationships with those involved in both systems.

FY 91/92

Task 1—Model Development: Effort will continue in the development of the summer precipitation model. Refinements to the winter precipitation model may be necessary as it is compared with the wide range of climates that exist across the Western U.S. In addition, coding of the local distribution model will begin. Models to convert from daily to intensity format data will be developed.

Task 2—Data Development: Test areas will be identified in five locations across the Western U.S. Each of these areas will be chosen for its specific climatic conditions. A location having high resolution climate data will be identified in each to allow the local distribution model to be developed and tested. Lightning data sets for Utah and the other four test areas will be collected for use in the summer precipitation model.

Task 3—Model - Data comparisons: The summer-time precipitation model will be compared to the data sets developed in Utah. Winter-time synthetic data sequences will be generated for the four non-Utah areas and compared to actual data sequences. Day-step-to-WEPP required input sequences will be generated and compared.

FY 92/93

Task 1—Model Development: This year will be devoted to the optimization of the user software model and the stochastic climate sequences for each coarse grid location and its interface to the local distribution software. Some refinement of the summer precipitation software is also expected.

Task 2—Data Development: Continued effort is expected in collecting data for the fine distribution model validation and development.

Task 3—Model - Data Comparisons. Data for each of the five target sites will be compared to the sequences developed by the stochastic weather sequences for these sites. Local distribution functions will be tested for each of the fine-resolution locations. Some user testing is expected at this stage of the development.

CHAPTER 4

Snowpack Simulation Model

4.1 Purpose

The objective of the snowpack simulation model is to model the evolution of snowpack as a spatially distributed process subject to inputs or forcing by the climate. The input will be sequences of climate variables from a physical or stochastic model. Physical inputs, either measured or from the orographic precipitation (climate) model, will be used in the development phase for model calibration and verification. For operational use, input will be from the stochastic model described in Chapter 5 which is designed to reproduce selected statistical characteristics of climate sequences. These sequences should consist of the following:

- Precipitation (amount and form – rain or snow)
- Temperature (obviously related to the form of precipitation)
- Incoming radiation (solar and long wave, estimated from cloud cover and solar angles)
- Wind
- Atmospheric moisture content (relative humidity or dewpoint)

The current WEPP CLIGEN simulates each of these sequences for non-mountainous regions (Nicks et al. 1987). MCLIGEN will be regarded as a point model, that is, for application at a site small enough ($< 10^5 \text{ m}^2$) to be characterized as uniform with respect to the following site variables:

- Slope
- Aspect
- Vegetation (for shading, roughness, interception, and albedo)
- Elevation

We expect to obtain the site variables from a GIS. Distributed parameter capabilities will be provided through separate application of the model to distributed sites. This is also the philosophy used by Leavesley et al. (1987). Output will consist of meltwater available for infiltration or runoff at the base of the snowpack. Additionally, variables to keep account of the state of the snowpack will be maintained and could be output if desired. These could include state variables such as water equivalent, energy content, density and liquid water content, as well as sublimation and evaporation.

4.2 Literature Review

Our basic understanding of snow hydrology has evolved over the past 35 years, starting with the report *Snow Hydrology* (U.S. Army Corps of Engineers 1956) and is now described in most introductory hydrology texts (Bras 1990; Linsley et al. 1975; and Viessman et al. 1977). A good reference work is the *Handbook of Snow* (Gray and Male, 1981). Leavesley (1989) summarizes some remaining problems in-

volved in snowmelt runoff modeling. The processes involved in snowmelt are highly complex, involving mass and energy balances as well as heat and mass transfers. The major state variables which characterize snowpack are water equivalent, depth, vertical temperature and density profiles, albedo, and liquid water content. Many snowmelt models have been developed to describe the evolution of these variables. These include: the Stanford Watershed model snow components (Anderson and Crawford, 1964), National Weather Service River Forecast System (NWSRFS) – snow accumulation and ablation model (Anderson 1973), the USU simulation model (Riley et al. 1966), the Anderson point energy and mass balance model (Anderson 1976), snow components of the SHE model (Morris 1982), and the USGS Precipitation–Runoff Modeling System (PRMS) (Leavesley et al. 1983; and Leavesley et al. 1987).

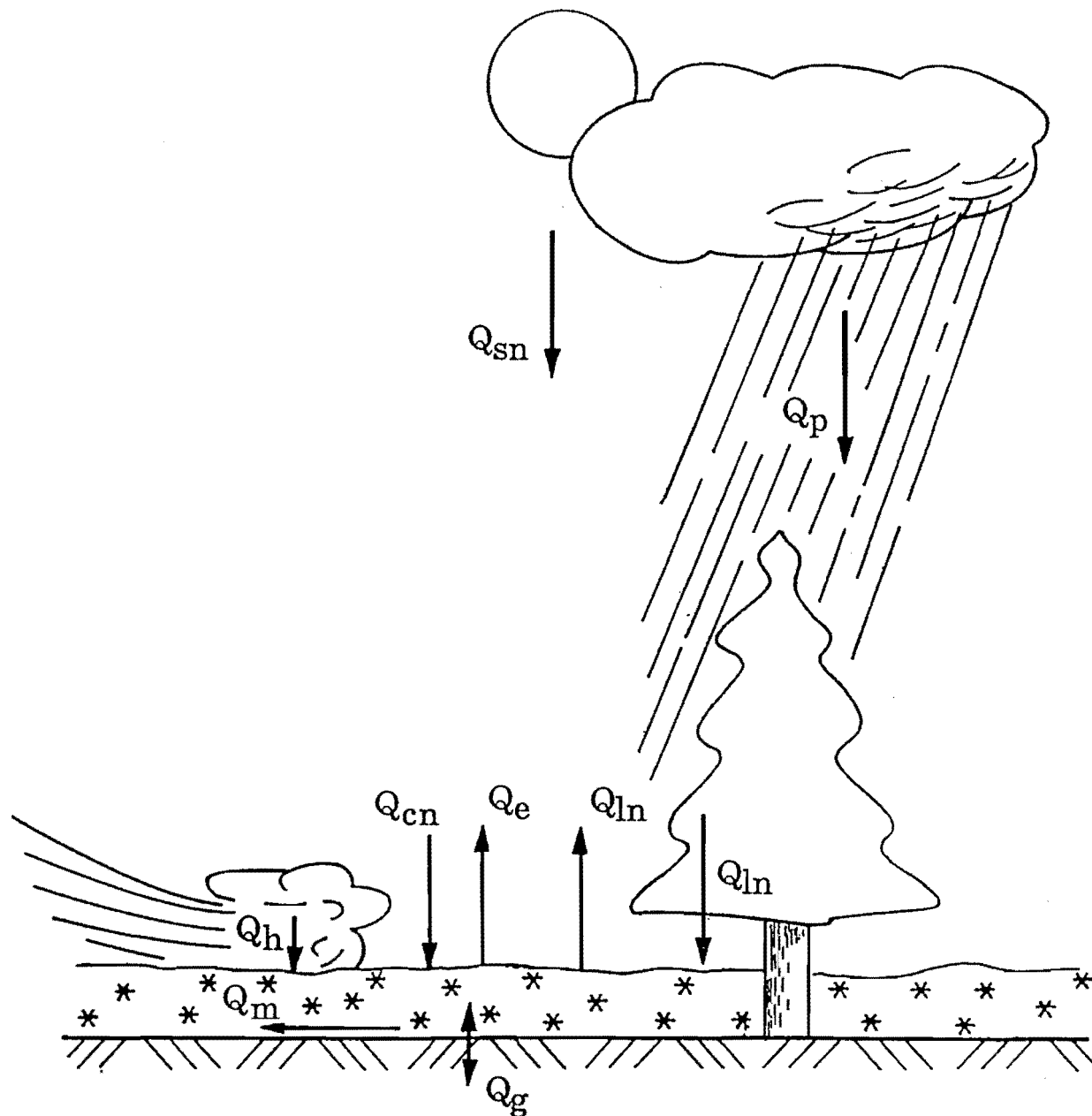
Levels of model implementation range from index related methods, through energy budget methods, and full solutions of the equations for flow of energy and mass. The SHE model (Morris 1982) has implementations at all these levels of detail, dependent upon the available information. The USU simulation model (Leu 1988; and Riley et al. 1966) appears to be a hybrid containing elements from all three levels. The Stanford Watershed Model uses a combination of energy budget and index methods (Anderson 1968). The NWSRFS model uses index related methods during dry melt periods and an energy budget approach for melt during rain. Anderson’s point energy balance model (Anderson 1976) is a detailed solution to the mass and energy flow equations using finite difference techniques. The PRMS snow component maintains energy and water balances assuming a two layer system (Leavesley et al. 1987). However, the level of sophistication in a model should be consistent with the input data. Charbonneau et al. (1981) tested different snowmelt runoff basins in an alpine basin in France and concluded that the choice of interpolation procedures for input data such as air temperature and precipitation is much more crucial than the level of sophistication of individual snowmelt models. This issue is addressed in Chapter 3 through the use of an orographic precipitation model, an approach that is gaining popularity (Day et al. 1989; Rhea 1978; and Tesche 1988).

Recently, the World Meteorological Organization (1986) compared 11 different snowmelt runoff models from several countries. Most of the models were at a basin–scale; therefore, they were on too large of a scale for use here, but their relevant conclusions were:

- Most models use a temperature index approach, with monthly melt factor.
- It is important to suppress melt during the ripening period to account for the cold content and liquid water storage.
- Subdivision of basins into elevation zones is important.
- Further work on lapse rates is necessary.
- The interception of snow is important, especially to forecast the effect of land use changes.

Before reviewing the details of the modeling approaches we describe some of the important processes involved in snowmelt and snowpack ablation (see Figure 4–1). The energy balance equation is fundamental (Male and Gray, 1981).

$$Q_m = Q_{sn} + Q_{ln} + Q_h + Q_e + Q_g + Q_p - dU/dt \quad (4.1)$$



- Q_{sn} - Solar Radiation
- Q_{ln} - Longwave Radiation
- Q_e - Latent Heat of Evaporation
- Q_{cn} - Latent Heat of Condensation
- Q_h - Sensible Heat
- Q_g - Ground Conduction
- Q_p - Heat brought with Precipitation
- Q_m - Heat Carried away by Melt

Figure 4-1

- Q_m = energy flux available for melt,
- Q_{sn} = net short-wave radiation flux absorbed by the snow,
- Q_{ln} = net long-wave radiation flux at the snow-air interface,
- Q_h = convective or sensible heat flux from the air at the snow-air interface,
- Q_e = flux of the latent heat (evaporation, sublimation, condensation) at the snow-air interface,
- Q_g = flux of heat from the snow-ground interface by conduction,
- Q_p = flux of heat from rain, and
- dU/dt = rate of change of internal (or stored) energy per unit area of snowcover.

Table 4-1 from (Male and Gray, 1981) gives typical magnitudes of the fluxes involved in the energy balance so that their relative importance can be assessed.

Note that the radiation fluxes are about an order of magnitude larger than sensible and latent heat fluxes which are in turn an order of magnitude larger than fluxes to the ground.

4.2.1 Radiative Heat Transfers

This consists of absorption and reflection of incoming solar (shortwave) radiation as well as absorption and emission of longwave radiation. It is the most important energy exchange mechanism for snow-melt (Male and Gray, 1981). Incoming solar radiation is a function of latitude, season, aspect, and radiative transmissivity of the atmosphere as well as weather conditions (e.g. clouds). Apart from the effect of clouds the other factors are predictable. In forested mountain regions, shading plays an important role in the amount of radiation reaching a given point. Dozier (1979) describes a complete solar radiation model which includes a shading function. The reflection of solar radiation is described in terms

Table 4-1. Selected daily energy flux transfer (kJ/m²)^a during the melt period in the absence of vegetation (Bad Lake, Saskatchewan).

| Date (Day/Mon/Yr) | Q_{sn} | Q_{ln} | Q_n^b | Q_h | Q_e | Q_g |
|----------------------|----------|----------|---------|-------|-------|-------|
| 11-4/75 | 8090 | -6320 | 1770 | 186 | -855 | -45 |
| 12-4/75 | 9620 | -8480 | 1140 | 782 | 26 | -22 |
| 14-4/75 | 12290 | -9430 | 2860 | 13 | -395 | -4 |
| 17-3/76 | 4630 | -4500 | 130 | 1830 | -555 | 64 |
| 27-3/76 | 7200 | -7720 | -520 | 1517 | -208 | -237 |
| 28-3/76 | 7790 | -7120 | 670 | 70 | -201 | -111 |
| 29-3/76 | 9070 | -7660 | 1410 | 532 | -60 | -180 |
| 30-3/76 | 9290 | -6040 | 3250 | 827 | 140 | -270 |

^apositive values indicate an energy gain by the snow.

^bthe daily net radiation flux transfer: $Q_n = Q_{sn} + Q_{ln}$.

of albedo which can vary considerably as a function of the condition and age of the snow surface. Given the magnitude of the solar radiation term in the energy balance, modest albedo changes are important to the snow surface energy balance. The assignment of some nominal value to snow albedo in climate models can lead to large errors (Dozier 1987).

Incoming longwave radiation is essentially black-body radiation from the atmosphere, and is often written as a function of surface air temperature. The most common form of this relationship is the one developed by Brunt (1952):

$$Q_{li} = \sigma T_a^4 (a + b \sqrt{e}) \quad (4.2)$$

where T_a is air temperature, e vapor pressure, and s the Stefan-Boltzmann constant. $a = 0.62$ and $b = 0.005 \text{ (Pa}^{-0.5}\text{)}$ are coefficients given by (Kuz'min 1961). Male and Gray (1981) report considerable scatter in this relationship and give some alternate forms. Price and Dunne (1976) considered a physical approach to calculation of radiation, but they concluded that the results were inaccurate due to problems associated with using near surface measurements to characterize the vertical distribution of air mass properties, so they opted for empirical expressions for the net radiation.

Outgoing longwave radiation is essentially described by:

$$Q_{le} = \epsilon \sigma T_s^4 \quad (4.3)$$

Here T_s is the temperature of the snow ($^{\circ}\text{K}$) and e the emissivity, usually between 0.97 and 1 (Anderson 1976; and Male and Gray, 1981). In areas of high relief the atmospheric radiation received at a point, e.g. in a valley, is reduced because part of the sky is obscured by the adjacent mountains. However the mountain side slopes radiate according to Equation 4.3. A thermal view factor is used to account for this effect (Male and Gray, 1981).

4.2.2 Latent Heat of Evaporation/Sublimation

Evaporation of liquid water and sublimation of ice will occur at the surface at a rate controlled by the vapor pressure gradient and turbulent diffusion in the overlying air (Bras 1990; and Male and Gray, 1981). As well as removing water, these processes can cool the snowpack considerably by removal of latent heat. One unit of evaporation can freeze 7.5 units of liquid water (Bras 1990). The turbulent diffusion is controlled by surface roughness and the log profile of wind velocity with height. The magnitude of these effects underscores the importance of wind and the difference between open and forested areas. Price and Dunne (1976) suggest adjustments to the neutral condition expressions that account for stable, stratified conditions common over a cold snowpack. This is still the subject of debate (Kuusisto 1986).

4.2.3 Sensible Heat Transfers

Sensible heat can be transferred between the snowpack and atmosphere and is dependent upon the temperature gradient and turbulent diffusion similar to latent heat. At the base of the snowpack there are energy exchanges with the soil and melt water percolation which forms infiltration or runoff depending on the underlying conditions of the soil. Energy exchanges with the soil are generally much smaller than the surface energy transfers (Bras 1990) and are frequently neglected over short time periods. However, their integrated effect over a season can be significant (Male and Gray, 1981).

Melt is generally considered to occur at or near the snow surface because that is where most of the energy is available for melt. Anderson (1968) reports that 80 percent of solar radiation is absorbed in the top 2–6 inches of a snowpack, dependent on density. The surface also receives any new snow or rain which can bring with it significant energy. Within the snowpack snow is subject to compaction as well as percolation and refreezing of melt or rain water. This leads to formation of ice crusts, layers, and lenses which affect transport processes in the snowpack. Fluxes of heat and liquid water are the most important with some transport occurring in the gas or vapor phase. Measures such as cold content and liquid–water holding capacity (Male and Gray, 1981) have been introduced to quantify some of these effects.

The effect of vegetation, especially forest cover on the distribution of snowpack, is an issue clearly of relevance to the Forest Service and this study. One of the conclusions of the World Meteorological Organization (1986) study was that the effect of vegetation on interception was important, especially when trying to forecast the effect of land–use changes. McKay and Gray (1981) discuss this issue in detail, noting the following factors that affect the distribution of snow at different scales:

- Macroscale ($10^4 - 10^5\text{m}$)—elevation, orography, meteorological effects such as standing waves, flow of wind around barriers, and lake effects.
- Mesoscale ($10^2 - 10^3\text{m}$)—redistribution due to wind and avalanches, and deposition and accumulation related to elevation, slope, aspect, vegetative cover height, and density.
- Microscale ($10 - 10^2\text{m}$)—primarily surface roughness and transport phenomena.

McKay and Gray (1981) quote results due to Kuz'min (1961) that relative to virgin soil, forests retain 1.3 to 1.4 times more snow. Forest cuttings of 100 to 200m radius and forest edges retain 3.2 to 3.4 times more snow. Troendle and Leaf (1980) published a graph that depicts maximum accumulation in an opening five times the tree height. For openings larger than 14 times the tree height, there is a decrease in the amount of snow when compared to adjacent forest. Toews and Guns (1988) report that this relationship may not be valid in southeastern British Columbia. There seems to be general agreement that trees, through their affect on boundary layer wind patterns, influence the accumulation of snow, but there are few quantitative results and little physical understanding that can be applied to quantify these affects. An empirical relationship (McKay and Gray, 1981) is often used to relate the snowcover water equivalent in a forest, WEP_f , and in a clearing, WEP_c , related to tree density p :

$$WEP_f = WEP_c(1 - 0.37p) \tag{4.4}$$

The affect of forest on albedo is also important.

4.3 Snowmelt Models

4.3.1 Index Related

These methods rely on the fact that variables such as temperature and radiation are highly correlated with snowmelt rate. The most commonly used approach is the degree–day approach based on temperature:

$$M = K(T_a - T_o) \tag{4.5}$$

M is melt rate, T_a an air temperature, T_o a reference temperature (usually 0 °C or 32 °F), and K a regression coefficient in the range 0.15 to 0.3 inches/(°F day) (Leu 1988). The air temperature T_a is usually some combination of daily maximum and average daily temperature. Another approach using net radiation (U.S. Army Corps of Engineers 1956) is:

$$M = 0.00238G + 0.0245(T - 77) \quad (4.6)$$

in which M is daily melt (inches), G net daily radiation (langleys), and T daily maximum temperature. This is sensitive to difficulties in the measurement of net radiation so it is not often used (Leu 1988).

Riley et al. (1966) and Male and Gray (1981) suggest modifying the degree-day approach to account for the effect of different radiation, dependent on aspect, slope, and albedo. This is:

$$M = K_m K_t \left(\frac{RI_s}{RI_h} \right) (T_a - T_o) (1 - A) \quad (4.7)$$

where K_m is the degree-day regression constant, K_t a vegetation transmission coefficient, RI_h the radiation index for a horizontal surface, RI_s the radiation index on a sloping surface dependant on aspect, and A the albedo. Albedo is frequently taken as an exponential function of age:

$$A = 0.4(1 + e^{-kt}) \quad (4.8)$$

which is designed to closely match the curves given by the U.S. Army Corps of Engineers (1956). This appears rather arbitrary, given the importance of radiative terms in the energy balance. Rather than the multiplicative approach to account for radiation, Bengtsson (1986) suggests adding a radiation term:

$$M = K(T_a - T_o) + (1 - A) R_s / L_f \quad (4.9)$$

where R_s is incoming solar radiation and L_f the latent heat of fusion. It is somewhat ironic that degree-day models, the most widely used because they are easy to apply, are more directly related to sensible heat transfers than the more important radiative transfers which dominate the energy budget and are only indirectly related to temperature.

Sugawara et al. (1984) in a tank model used for rainfall runoff in Japan used a degree-day approach with a linear tank component to account for liquid water stored in the snowpack.

The areal extent of snowcover is also well correlated with the area average water equivalent; these relationships have been provided by Leaf (1969). Therefore, periodic measurements of snowcover using remote sensing can be used to get an idea of snowpack buildup and snowmelt. The widely tested snowmelt runoff model of Martinec et al. (1983) and Martinec and Rango (1986) uses snow cover area coupled with a degree-day approach to model snowmelt runoff from fairly large basins. For our purposes we are mainly interested in properties at a point so this approach is not appropriate.

4.3.2 Energy Budget Methods

These methods are appropriate when full meteorological data are available but a complete solution of the energy and mass flow equations for the snowpack is either unwarranted or too expensive (Morris 1982). The energy balance Equation 4.1 can be written:

$$Q_{sn} + Q_{in} + Q_h + Q_e + Q_g + Q_p = ML_f + \rho C_s D \frac{\partial T}{\partial t} \quad (4.10)$$

where M is the rate of melt, L_f latent heat of fusion, ρ density, C_s specific temperature of ice, D snowpack depth, and T snowpack temperature. T and r are depth averaged quantities. The lefthand side is a sum of heat fluxes. The righthand side essentially represents the rate of change of cold content. The average temperature T is constrained to be less than or equal to freezing ($T \leq T_o$). It is assumed that melt only occurs when the snowpack is isothermal at $T = T_o$. In the SHE model (Morris 1982) data from an automatic weather station is assumed to provide net radiation, air temperature, humidity, wind speed, and precipitation. The log wind velocity profile and turbulent diffusion analogy with adjustments for stable or unstable conditions are then used to calculate Q_h and Q_e . Q_g is neglected and Q_p obtained assuming rain at the wet bulb temperature.

Rachner and Matthaues (1986) also use an energy budget approach but estimate the radiation from measurements of global radiation and an assumed albedo, held constant. Sensible and latent heat fluxes are assumed linearly related to air temperature with a proportionality coefficient which is a function of wind speed.

Vehvilainen (1986) suggests using an index method to estimate radiation from air temperature. This is basically equivalent to using the degree-day method to compute melt in an energy budget framework. The dependence of radiation on temperature is analogous to the modified degree day approach of Riley et al. (1966) and Male and Gray (1981).

4.3.3 Full 3D Solution

These models use conservation equations for the movement of energy and mass fluxes within the snowpack. Constitutive equations relating the permeability and thermal conductivity to the density of various components need to be written. Possibilities are endless and there is a lot of current research on this topic. Prominent early works in this area are Colbeck (1972) and Anderson (1976). The full distributed component to the SHE model is described by Morris (1982). Many recent works are included in Morris (1986), notably Kelly et al. (1986) and Motovilov (1986).

4.3.4 USU Model

This model was developed at USU (Riley et al. 1966; and Leu 1988). Basically it appears to be a codification of many of the procedures suggested in the report *Snow Hydrology* (U.S. Army Corps of Engineers 1956). The snowpack is described through six state-variables: depth D , water equivalent W , temperatures at 1/3 and 2/3 depths T_1 and T_2 , albedo A , and liquid or free water content F . It is a full 3D solution in one sense because it divides the snowpack into three layers and uses finite difference approximations to model the heat flow. However, free water content and density are depth averaged. Melt is generated from Equation 4.7, a modified degree-day approach, and is assumed to be generated at the top surface. Melt can occur regardless of the temperature of the snowpack (the snowpack temperature does not appear in Equation 4.7). However, water from melt or rain is not modeled as percolation through a layer unless its temperature has been raised to freezing point by the release of latent heat. Runoff occurs when the free water holding capacity, a function of density, is exceeded. Latent heat transfers at the surface and heat transfers to the ground are neglected. Other heat fluxes are all assumed to be accounted for by the generation of melt through Equation 4.7, except for sensible heat which is modeled as a diffusion process.

4.3.5 PRMS Model

This has been developed within the USGS (Leavesley et al. 1983; and Leavesley et al. 1987) with emphasis on data management and system-compatible file structures to take advantage of a variety of data sources. Modular design is emphasized so that alternative components can easily be developed, tested, and incorporated. The snow component (Leavesley et al. 1987) simulates accumulation and depletion within separate hydrologic response units. A water balance is computed daily and energy balance twice daily. The energy balance considers net radiation, approximations of convection and condensation, and the heat content of precipitation. A two layer snowpack is assumed, the surface layer the upper 3–5 cm and the lower layer the remaining snowpack. Surface layer melt and rainwater move into the lower layer and first satisfy the heat deficit by freezing. Then when the entire snowpack is isothermal at 0 °C, the liquid water holding capacity is filled before melt is generated. In this respect the PRMS and USU model are very similar.

4.4 Proposed Methodology

For the purposes of the current project, available data do not justify a model any more complex than an energy budget model. We believe the energy budget approach offers an advantage over a degree-day approach in that runoff is not predicted to occur when the temperature goes above freezing unless the liquid water holding capacity has been filled. For a deep snowpack this could have a significant impact on the timing and rate of runoff generation, factors that are important for erosion. The complexity of a three-dimensional model is probably not warranted; therefore, we propose an energy budget approach, using at least the following state variables to describe the snowpack:

- Water equivalent
- Temperature
- Liquid water content

These may be depth averaged (as in the SHE model) or defined over two (PRMS model) or three (USU model) layers. The additional variables: density (to determine liquid water holding capacity) and albedo (a function of snow surface age) may also be included.

Sites will be characterized using the following variables:

- Slope
- Aspect
- Vegetation
- Elevation

Precipitation inputs either measured or from the orographic atmosphere model will be used for model development and testing. For operational use, input will be stochastically generated. We will attempt to adjust the precipitation for site factors, such as vegetation, slope, and aspect, using equations similar to Equation 4.4. This will require coordination with procedures described in Chapter 3 and interaction with the climatological modelers who may have physical approaches to this issue.

Radiation inputs will be a function of the time of the year, site variables (aspect and shading), and cloud cover. For the model development phase, we hope to obtain cloud cover physically from the oro-

ographic-atmospheric model (Model A). For operational purposes radiation would have to come from a stochastic model and it may be better to parameterize it in terms of the temperature along the lines of equations 4.7 or 4.9. Albedo will probably be parameterized using Equation 4.8. This will probably be the weakest part of the model, and some effort directed towards a better understanding of changes in albedo may be warranted. Latent and sensible heat inputs will be parameterized as functions of air temperature, wind speed, and atmospheric moisture content. Heat inputs from the ground will either be ignored or taken as a constant rate over the season. We intend to evaluate the relative merits of one, two, or three layer models and use the degree of detail that seems to work best.

For evaluation of the models we will use SNOTEL and RAWS (remote automatic weather station) data (see Appendix B). The relevant daily SNOTEL data are:

- Snow water equivalent
- Precipitation
- Air temperature

The relevant RAWS data, measured hourly at 50 sites in Utah, are:

- Precipitation
- Wind speed and direction
- Air temperature
- Relative humidity

We hope to find a few RAWS sites near SNOTEL sites so that the models can be tested there. We also hope to obtain data from some experimental sites where radiation and snow temperatures have been measured so that these aspects of the model can be evaluated. At SNOTEL sites far from any weather station, the model will be run using input from the orographic precipitation model. This will provide a test of the orographic precipitation model as well as of the snow models.

4.5 Work Plan for Development of Snowmelt Generator

Development of the snowmelt generator consists of the following tasks:

1. Model development in standard modular format
2. Testing on hypothetical cases
3. Testing on easily available data
4. Initial evaluation and model revision
5. Identification of further data requirements
6. Acquisition of additional data
7. Testing with additional data
8. Testing with orographic-precipitation model input

9. Testing with stochastic model input

10. Final evaluation and revision with iteration over some steps above

The initial model will have standard data structures and interchangeable modules that are taken from the USU model, PRMS model, and SHE model. Hypothetical test cases will be used to initially test the model and highlight important aspects of the model capabilities. These test cases will include extreme, difficult to model cases, such as rain on snow, large changes in air temperature, and radiative inputs. The testing on easily available data will use data from SNOTEL and RAWS as well as data from past experimental work at USU. We anticipate that not all input data will be available so we will need to develop procedures to estimate reasonable default inputs. The hypothetical test cases will determine the sensitivity to these default estimates. Completion of the first three tasks will provide the information necessary for initial evaluation of the model (Task 4) and identification of further data requirements (Task 5). These tasks can be thought of as an initial phase of the snowmelt generator development. The procedure will be somewhat iterative because changes made under Task 4 will need to be retested using the hypothetical and easily available data. The test cases will be designed to highlight different approaches to the following parameterizations:

- Albedo variation with time
- Sensible and latent heating by air temperature and wind
- Radiation in terms of clouds or air temperature
- Vegetation canopy and effects of regrowth

Task 4 will consist of modifications to some of these parameterizations, guided by the testing of hypothetical cases and easily available data. However, we expect that the main outcome of the initial testing will be a need for additional data to pin down various aspects of the problem. Tasks 5 and 6 address this and require the identification of additional experimental sites. We hope to obtain at least some measurements from these sites in the winter 1990/91 so that we have more confidence in the model when we start using it with inputs from the precipitation model (Task 7) and stochastic inputs (Task 8).

The main variables used in comparisons will be model generated and actual measured snowpack depletion, in terms of water equivalent. We will compare to measured melt and runoff where possible to check the partition of depletion between evaporation/sublimation and melt. Where actual measurements are used to calibrate model parameters, we will use split-sample verification techniques (i.e., validation with data not used for parameter estimation).

CHAPTER 5

Stochastic Models and Parameter Regionalization

5.1 Purpose

CLIGEN uses gaged data to develop a stochastic representation of the “at-site” variability in daily precipitation, temperature, and solar radiation. A “physically based” climatic model is proposed (Chapter 2, Figure 2-2, Model A) to generate pseudo-historical climatic sequences at ungaged locations in mountain regions using radiosonde information. This model may operate at a coarse-grid scale of 2 to 10 km. A second model (Model B) may be used to adjust the results to finer grid spacings in conjunction with a DEM. Five options for MCLIGEN were presented in Chapter 2 and Options 2 and 3. Figure 5-1 illustrates the possible inter-relationships between Models A and B and the stochastic models that may be needed for Options 2 and 3.

The “physical” climatic model proposed for generating pseudo-historical climatic sequences at ungaged locations may or may not generate sequences that reproduce the statistical characteristics of observed sequences. A set of statistical measures that adequately characterize the desired properties of the climatic sequences of interest needs to be developed. Ideally, a strategy to ensure that the physical model is calibrated to match the statistical properties of observed sequences is needed. However, with variable record lengths and the lack of high elevation climate data, this may be somewhat difficult to achieve. Consequently, strategies for adjusting the properties of generated sequences may be needed.

A consideration of site characteristics (aspect, slope, etc.) may call for adjustment of the 2 to 10 km coarse resolution sequences generated by Model A. Such adjustments may be made using a subgrid scale physical model on a case by case basis or through some realistic adjustment factors. The latter is probably preferable. It is very unlikely that data will be directly available to develop such adjustments. Consequently, the use of a physical model may still be called for. In such a case a dimensionless representation of the mountain system may be developed and simulations conducted for various wind and climatic conditions. Two options are indicated for the development of an at-site stochastic model in Figure 5-1. The first option entails an adjustment of the stochastic model parameters fitted for Model A sequences. The second option entails an adjustment of the sequences generated by Model A prior to fitting a stochastic model. In either case, a review of the adequacy (in the context of the three input features and three types of analyses needed by the WEPP user) of the current CLIGEN procedures in the mountain climate situation is necessary. Some of the items of interest in this regard are listed in Figure 5-1. Another complication is that Model A operates at a 12-hour time step, and hence no synthetic data at the ungaged site at a higher resolution in time is available. Therefore, innovative procedures for disaggregating 12-hour climate data are needed.

Finally a strategy to present the model parameters to the end user is needed. Depending on the spatial resolution of interest, one or more of the strategies indicated in Figure 5-1 may be needed. Values of each stochastic model parameter may be encoded in a GIS format and incorporated into a GIS archive. Maps of parameter values may be prepared (these will inevitably be smoothed, lower resolution). In this case one could look into regression or functionalization of the parameter values in terms of site location and topographic characteristics. The generated and adjusted sequences from Models A and B for each region of interest could be directly made available on disk together with software for stochastic model parameter estimation.

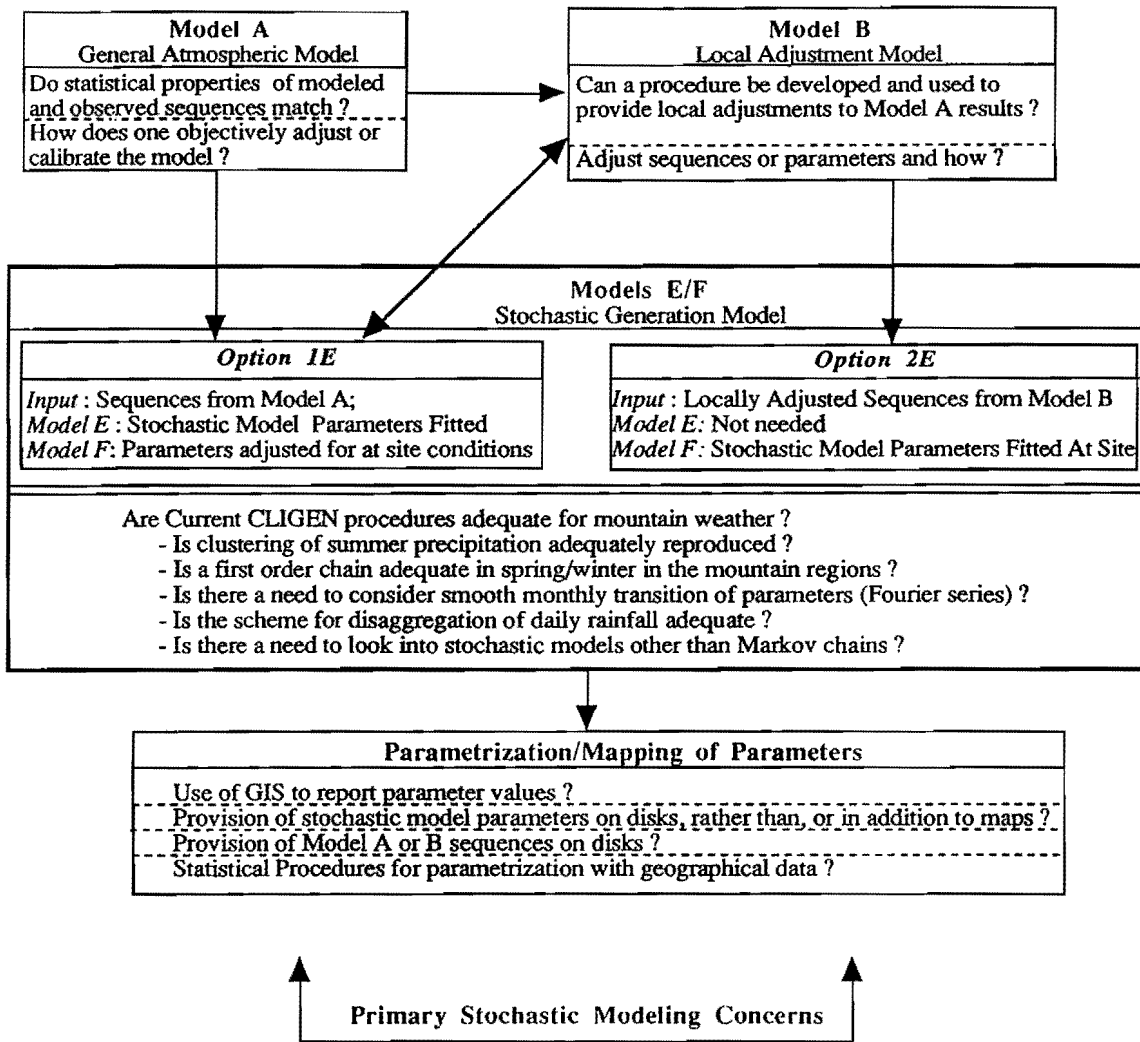


Figure 5-1. Primary stochastic models (Option 2).

5.2 Literature Review

The development of stochastic models for the description and simulation of precipitation, temperature, and solar radiation has been an active area of research. Some recent reviews of the literature are provided by Waymire and Gupta (1981), Georgakakos and Kavvas (1987), and Foufoula-Georgiou and Georgakakos (1988). The procedures used in CLIGEN build upon an approximately 25 year evolution of the use of Markov Chain models for describing the processes of interest. The basic structure of

CLIGEN is summarized first. Some alternate approaches discussed in the literature are subsequently reviewed. The intent of this review is to highlight possible modifications of CLIGEN that might be needed and the rationale advanced in the literature to necessitate such changes. A comprehensive review of all literature related to stochastic climate generation is not attempted here.

5.2.1 CLIGEN

This summary of CLIGEN is based on the Version 7, July '88 documentation of WEPP, Chapter 2. CLIGEN is based on climate generators that have been evolving in the Markov Chain framework for over 25 years. They have been extensively tested. The basic structure of the generator is summarized as Figure 5-2 below.

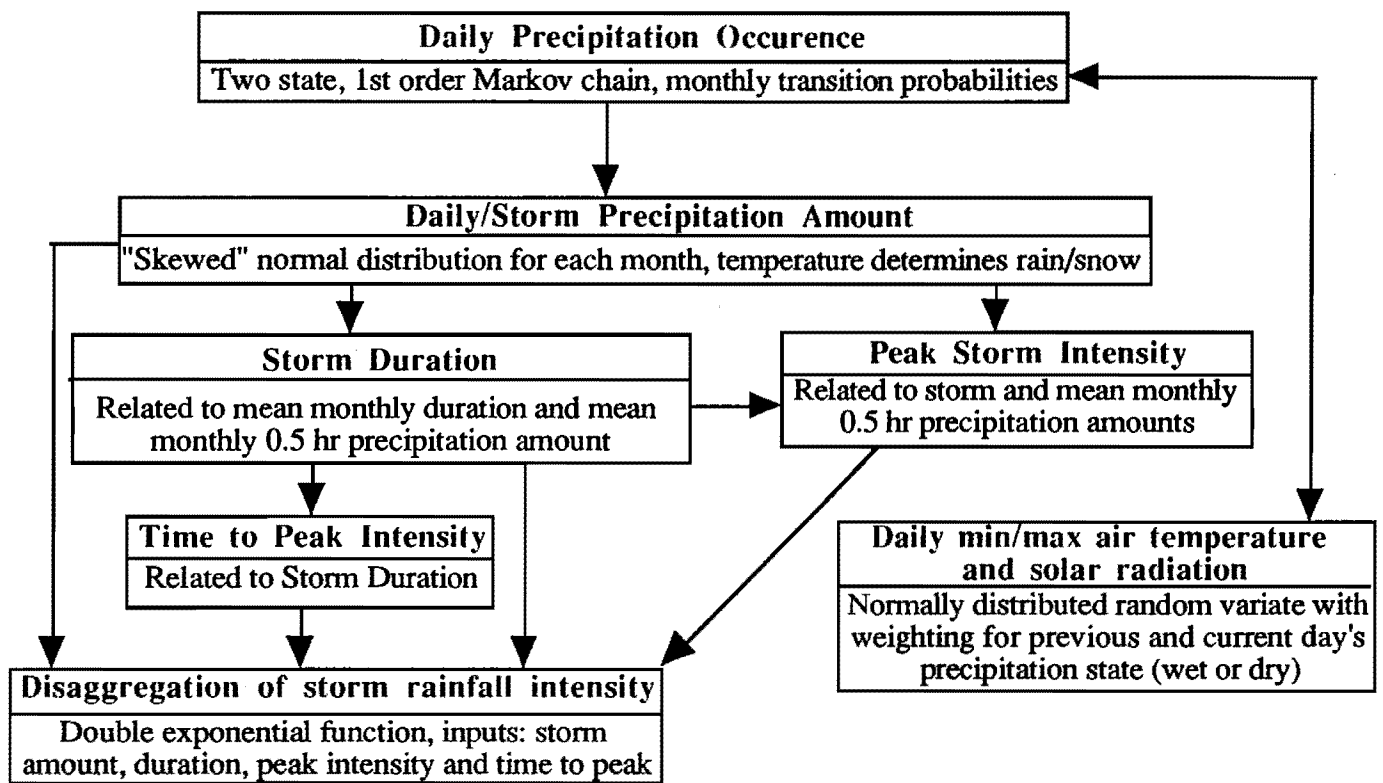


Figure 5-2. Summary of CLIGEN procedures.

Monthly transition probabilities between daily transitions from wet and dry states are computed to define the occurrence of precipitation through a first order Markov Chain. No smooth transition for the daily-state probabilities from one month to the next is considered. The transition probabilities are estimated from historical site data.

The daily precipitation amount is then computed using a skewed normal distribution. Historical data are used to compute the mean, standard deviation, and skew of daily precipitation. No more than

one storm event per day is allowed. If the average daily temperature generated is at or below 0 °C the precipitation is assumed to be snow rather than rain.

The storm duration is assumed to be exponentially related to the mean monthly duration of events and to the 0.5 hr. mean monthly average precipitation amount. The storm duration has an upper limit of 24 hrs. since one event/day is considered. The peak storm intensity and the time to peak intensity are related to the storm precipitation amount, the 0.5 hr. mean monthly average precipitation amount, and the storm duration.

The daily maximum and minimum air temperature and solar radiation are assumed to be normally distributed. The solar radiation is constrained between a maximum for the location for that day and 5 percent of the maximum daily value. An attempt is made to account for the possible dependence of daily temperature on the precipitation state (wet or dry) of the current day and the previous day. This dependence is built in by first estimating a weighing factor that appears to be a normalized ratio of the daily state transition probabilities. This weighing factor is then used to adjust the daily temperature through the random normal variate generated. Since solar radiation is modeled as a bounded process, using a bounded distribution (i.e. not normally distributed) to describe this process may be better than using a normal process and truncating the generated series.

While the basic structure (the Markov Chain model) of CLIGEN has a formal theoretical basis, most of the operational structure and procedures in CLIGEN are empirical. Consequently, applicability of the assumptions used in developing CLIGEN, and the functional representations used, need to be carefully reviewed in regions other than where it has been calibrated and found to work adequately. Some of the specific limitations of the CLIGEN type of model that have been identified and addressed by others in the literature are briefly summarized in this section.

1. Hopkins and Robillard (1964) state that the CLIGEN type of Markov Chain modeling oversimplifies the climatological situation. Trends in transition probability generating mechanisms must occur continuously rather than in discrete monthly steps. Feyerherm and Bark (1965) proposed the use of Fourier series to handle seasonal variation in transition probabilities. Woolhiser et al. (1988) consider the development of a first order, two state Markov Chain, where the daily transition probability is defined in terms of an annual average and m terms in a Fourier series, parameterized around the day. Richardson (1981) also considers a Fourier series representation for temperature and solar radiation. This approach, or another similar technique, is likely to be superior to the approach in CLIGEN and should be explored.
2. Hopkins and Robillard (1964) also suggest that spring and summer convective effects augment and supplement frontal precipitation to an extent varying progressively with the season, as the land surface warms, leading to a changing mix of transition probabilities. They argue that Markov Chain models may work during dry periods but that negative binomial compound Poisson models may be better during wet periods. (These models are a subset of the point process techniques referred to in the next section.)
3. Chin (1977) indicates that a second order Markov Chain is more appropriate in winter and a first order chain in summer; however, the order may vary by location. Feyerherm and Bark (1967) found that spring precipitation was better modeled with a second order than a first order chain, but they found that the properties of the generated sequences from the two models were quite similar. Tong (1975) uses the Akaike Information Criterion to select the order of a Markov Chain. Yakowitz (1976) provides some procedures for the estimation of the order of Markov

chains with hydrologic applications. Stern and Coe (1984) also provide procedures to estimate the order of a Markov Chain. We propose to first systematically (through split sample cross validation) evaluate the adequacy of a first order Markov Chain using mountain climatic data. Techniques for dealing with Markov chains with seasonally variable order and a smooth seasonal daily probability transition (or functional dependence structure) will also be looked into. Model parsimony (minimum number of parameters) will be a major criterion.

4. The choice of the mixed exponential distribution seems to be generally accepted in the literature for describing the precipitation intensity structure. Woolhiser et al. (1988) consider the development of a seasonally varying model with parameters of the precipitation amount model defined in terms of an annual average and m terms in a Fourier series, parameterized around the day. This is a "cleaner" representation than in CLIGEN, in the sense that model parameters vary smoothly with time instead of being "boxed into" monthly categories. However, Pickering et al. (1988) point out that extremes may be underestimated if the Fourier series representation is used as a consequence of the smoothing thus introduced. Yevjevich and Dyer (1983) conclude that using monthly means, as does CLIGEN, is enough to take care of the annual periodicity and is adequate.
5. The duration, peak intensity, and time to peak rules used in CLIGEN appear to be heuristics based on experience. The need to adjust and the type of adjustments to these heuristics will be assessed in the context of results from the physical climate interpolation model and observed data in mountain regions.
6. As for precipitation amount, Woolhiser et al. (1988) consider the development of a seasonally varying model with parameters of the temperature Autoregressive (AR) model defined in terms of an annual average and m terms in a Fourier series, parameterized around the day. The linkage between precipitation and temperature appears to be standard in the literature and to be deemed necessary by most investigators. If significant revisions to CLIGEN are undertaken, it will be important to recognize and maintain this interaction in an appropriate manner.
7. Pickering et al. (1988) also considered an AR(1) model for temperature, with the lag one autocorrelation conditioned on precipitation. They conclude that the consideration of the dependence of temperature on precipitation gives better results than models that do not consider this dependence. Their approach appears comparable to the CLIGEN approach, but is more consistent with standard Box and Jenkins types of model, and may be worth looking into. Richardson (1982) argues that temperature and solar radiation often have some persistence, are not randomly distributed, and argues for an approach based upon a seasonally varying lag one serial cross correlation with regional trends.
8. Larsen and Pense (1982) describe precipitation by a first order Markov Chain, precipitation amount by a two parameter gamma distribution (probably the same as CLIGEN), and model the temperature series as a bivariate normal (maximum and minimum temperatures), differenced from a sine wave fitted to the data (to remove periodicities), and with a lagged dependence considered between (maximum-maximum, minimum-minimum, maximum-minimum, minimum-maximum) temperatures and on precipitation state. Bruhn et al. (1980) present a similar model.

9. Foufoula-Georgiou and Georgakokas (1988) argue that Markov Chain models do not adequately reproduce long-term persistence and the effects of event clustering very readily. To address this situation Discrete Autoregressive Moving Average (DARMA) models were developed by Chang et al. (1984). Foufoula-Georgiou and Georgakokas (1988) indicate that these models lack a physical motivation and exhibit discontinuous memory. They also discuss various point process models and argue that problems with a class of point process models (Neyman Scott models) arise because they exhibit discontinuous memory and do not preserve extremes properly. They argue for the development of a discrete point process model for precipitation.
10. Srikanthan and McMahon (1983) compared the performance of a variety of models for precipitation, ranging from a two state Markov Chain to a seven state Markov Chain, to alternate renewal processes, and found that Allen and Haan's seven state Markov Chain model (states correspond to precipitation amounts) worked best. The multistate Markov Chain model is presented by Haan et al. (1976). The characteristics of the generated and historical series checked by them are of interest in our design of an experiment to verify the performance of CLIGEN with Western U.S. data. These items are: (a) average monthly and annual number of wet days; (b) mean, standard deviation, and skew of dry and wet spells per month; (c) maximum daily rainfall per month; (d) mean, standard deviation, and skew of rain depth on wet days per month; (e) correlation between rainfall depth and length of wet spells; (f) longest wet and dry spell per month; and (g) longest wet/dry spell in the record or replicate over a year.
11. Guzman and Torrez (1985) argue that daily transition probabilities may depend not only on whether the previous day was wet or dry. There may be feedback effects of rainfall amount on the next day's state. They define transition probabilities that are conditioned on prior rainfall state and amount. Smith and Schreiber (1974) argue that rainfall amounts should have a dependence on the previous day's rainfall amount. It may be worth looking into the importance of including such features in CLIGEN in selected areas in the Western U.S.
12. Hershenhorn and Woolhiser (1987) disaggregate daily rainfall into individual storms. They simulate the number of storms, storm amount and duration, and the starting time of each event, given the total rainfall for three successive days. Their approach considers a joint distribution of the number of events per day and the daily rainfall amount, uses the Weibull distribution to represent the marginal distribution of the daily rainfall amounts, and derives the conditional distribution of the number of events per day, given the daily amount using the negative binomial distribution with parameters dependent on the daily amount. This approach may be useful for summer thunderstorms, and is more rigorous than the CLIGEN procedure.

5.2.2 Alternate Approaches

Some approaches that have evinced a fair amount of interest recently are outlined below. We may pursue some exploratory work for representing the CLIGEN variables in the framework provided by the last two of these methodologies.

1. *Renewal models* consider wet/dry spells (durations) to be exponentially (or other) distributed and consider transitions alternately between W (wet) or D (dry). The Markov Chain models have been shown to be superior to these, since independence of storms (necessary for the alternate renewal process) is hard to justify at short time scales, leading to hard identification and fitting of distributions, and intensity-duration redistribution within the duration is not easily

done. Foufoula-Georgiou and Lettenmaier (1987) present a Markov renewal model for rainfall occurrence. These models admit clustering of events and are superior to Markov chains in that regard.

2. *DARMA* models follow by considering Y_n to be independently and identically distributed with Bernoulli distribution ($P(Y_n = 0) = p$, $P(Y_n = 1) = 1 - p$), and X_n to be formed through a probabilistic combination of the elements of Y_n such that the final model has p AR and q MA terms. They accommodate longer term persistence in an easier way than a higher order Markov Chain but exhibit discontinuous memory.
3. *Point Process* (PP) models consider a stochastic process that describes the occurrence of events in time (e.g. Poisson process – events occur randomly at times that are exponentially distributed, the number of events in an interval is independent, and time between events is independent). Foufoula-Georgiou and Lettenmaier (1987) consider discrete PP models where the sequence of times between events is formed through sampling from two geometric distributions according to a transition probability specified by a Markov Chain. This leads to a consideration of clustering such that the probability of having rain on a given day depends not only on whether the previous day was wet but also on the number of days since the last rain. Other similar models have recently appeared, and are worthy of investigation.
4. *Nonparametric Markov Processes*: There have been a number of recent advances (Yakowitz 1985, and Eubank 1989) in the nonparametric estimation of probability densities, regression, and prediction of Markov sequences. Essentially these methods use nearest-neighbor and kernel-density estimation techniques to make inferences about the structure of a generalized Markov process without assumptions as to linearity and form of the underlying distributions. Yakowitz and Karlsson (1987) have presented some applications to rainfall runoff prediction. These techniques are powerful as the size of the data set becomes large, and would be worthy of investigation for daily rainfall and temperature at a site. Noakes et al. (1989) present a systematic comparison of Yakowitz's nearest-neighbor based Markov process with Autoregressive Moving Average (ARMA), Autoregressive Integrated Moving Average (ARIMA), Fractional Gaussian Noise, Fractional ARMA for forecasting several geophysical time series, and report that the nearest neighbor method was tied with or superior to all the models considered according to a number of statistical criteria. We are currently working on a number of similar nonparametric estimators that are actually superior to the nearest-neighbor method tested by Noakes et al. (1989).

5.3 Proposed Methodology

The general structure of the proposed effort was reviewed in Section 5.1 and in Figure 5-1. In summary, for the primary stochastic models to be developed we wish to examine: (1) the significance of some of the current limitations of CLIGEN in the context of Western U.S. mountain climate, (2) procedures for statistically reproducing observed climatic sequences as part of the calibration of the physical model, (3) the need to alter the internal structure of CLIGEN, (4) procedures for disaggregation of daily rainfall, and (5) procedures for parameterization of model parameters. In addition it may be necessary to look at the development of probability distributions for other processes (e.g. snowpack initial conditions on a given date). Ten tasks (Figure 5-3) to address the above issues have been identified, and are outlined below.

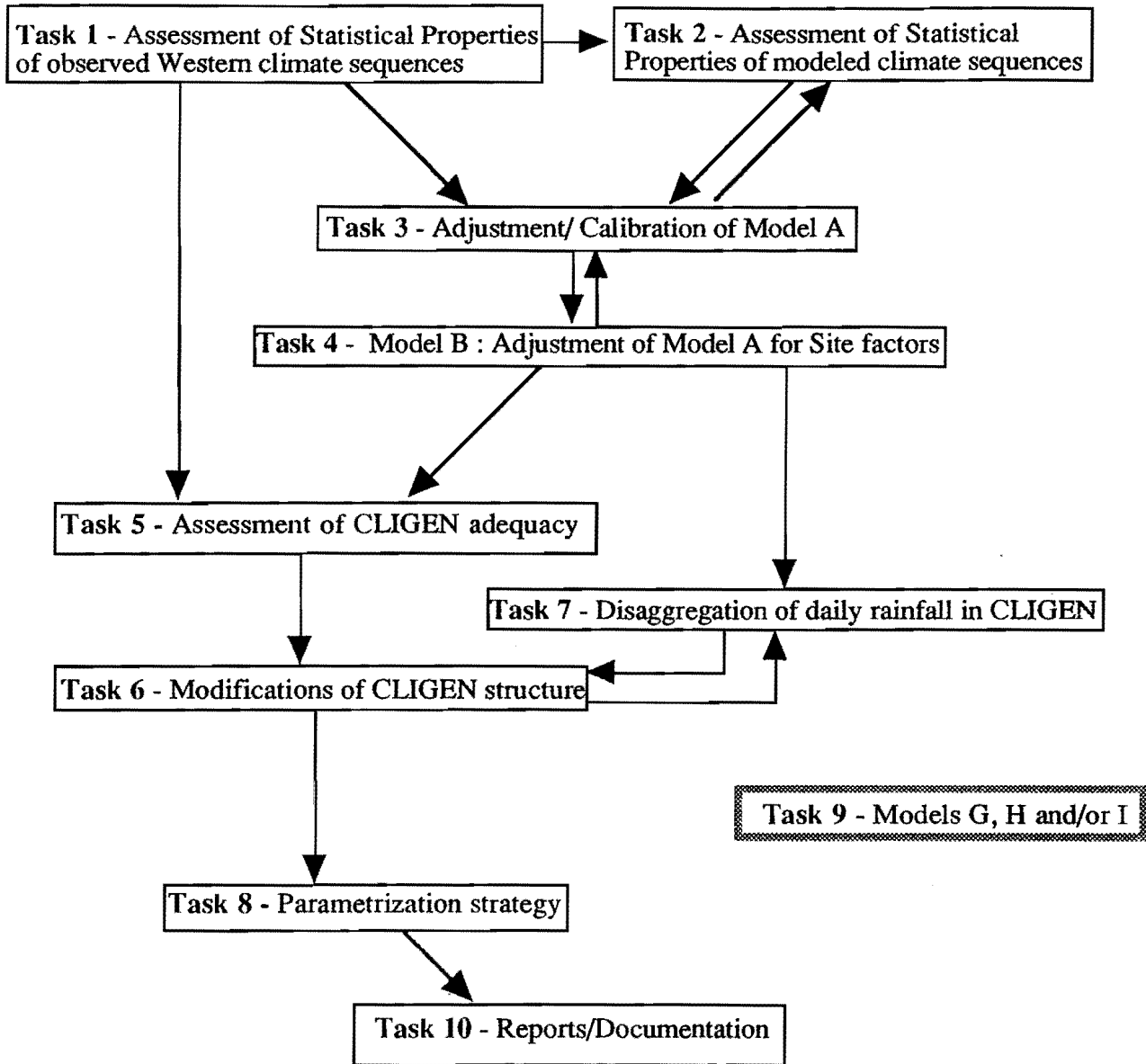


Figure 5-3. Research tasks.

5.4 Work Plan

5.4.1 Task 1 – Assessment of Statistical Properties of Observed Western Climate Sequences

To properly calibrate Model A and examine the adequacy of the current structure of CLIGEN to describe at-site rainfall, temperature, and solar radiation in mountain regions of the Western United States, it is imperative that available records, at least at selected representative sites, be examined to establish the characteristic statistical parameters and their variation over the region. A set of candidate instrumented sites and statistical measures, including those identified in the preceding section, will be

selected through discussion with USFS as to their likely importance to WEPP. Desired statistics for observed sequences at the sites of interest will be computed and their spatial variation examined graphically. These statistics could be distributions of snowpack properties on specified dates, interarrival times and amounts of rainfall events, or persistence in daily temperature and its dependence on prior precipitation. Any dominant characteristics of variation with topography or location will be noted and where possible related to likely physical and causative factors (e.g. predominant jet stream orientation). Seasonal variations as to these statistical properties will also be examined on a site-by-site basis to assess implications related to model features (e.g. significance of precipitation clustering or change in degree of persistence – order of Markov Chain).

We hope that in addition to its utility in calibrating the models to be developed and in assessing the adequacy of the CLIGEN procedures, this task will provide a quantitative understanding of the stochastic structure of relevant climatic variables in the Western U.S. The key here will be the proper selection of sites to be investigated to ensure adequate variety in and coverage of the field. This could be difficult since data at high elevations is very limited. We estimate that this task will take six months to complete.

5.4.2 Task 2 – Assessment of Statistical Properties of Generated Climate Sequences

We recognize that it will be impossible to reproduce exactly the climatic record at each gaged site using the proposed physical model (Model A). In addition to reproducing the average observed behavior of climate at the gaged sites, it will be desirable to reproduce the statistical properties of the observed sequences. The statistical measures adopted in Task 1 will be used with sequences generated by Model A. Additional measures will be necessary to define Model A's performance relative to the observed sequence. Items of interest are: (1) can confidence intervals (at-site) be developed for the observed sequences and compared with sequences from Model A, (2) can objective measures for robustness and consistency be developed (at-site, and across sites), and (3) can consistent global (formed by weighting at-site estimators) and local (at-site) performance measures (risk or loss functions) be developed and employed?

A first step in this process would be to compare the statistical properties for generated and observed series at each of a set of selected gaged sites. Given that approximately 20 years of radiosonde data are available at 12 hour intervals, an adequate data set exists for such a comparison, even at a seasonal level of disaggregation.

The second step would be to examine reasons for differences between generated and observed series, such as: (a) are corrections for local effects indicated, (b) what is the nature of these corrections, (c) do the differences stem from an inability of Model A to adequately reproduce the physical process, and (d) can and should process definitions be changed in the physical model to more faithfully reproduce observed behavior (e.g. persistence)?

The third step (Task 3) would be to develop and apply the necessary corrections so that at least basic statistical properties are well preserved.

We anticipate that this task will take two to four months; its timing is contingent on the progress made in developing Model A. Tasks 3 (calibration of Model A) and 4 (local adjustments) follow directly from the work done in this task, and may proceed concurrently.

5.4.3 Task 3 – Adjustment/Calibration of Model A

Objective methods of ensuring that Model A is calibrated are sought here. Calibration is defined through the optimal matching of the statistical properties of the observed and generated sequences.

Performance measures relative to each statistical measure, or class thereof, are to be developed in Task 2. This task uses such measures in a prioritized (priorities for each statistic to be matched selected in concert with USFS based on likely impact on the adequacy of erosion predictions, using WEPP) manner to calibrate Model A, or to adjust the sequences generated by it. Formal strategies for doing this are not readily apparent at this time. An iterative approach to establishing the sensitivity of the statistical measures to Model A parameters and the adjustment of these parameters will be pursued. Formal inverse problem solvers or optimization routines do not appear to be well suited for this situation. However, the “human” adjustment principles may follow the inherent search logic in formal stochastic optimization models.

Clearly Tasks 2–4 are highly interrelated because if significant adjustments from site considerations are needed the adjustments must be a part of the calibration and performance measurement processes. Consequently these tasks will have to be conducted in an iterative and piecewise fashion. Focusing on statistical properties of the sequences rather than upon the sequences themselves will be more robust. We expect this task to take two to four months.

5.4.4 Task 4 – Local Factors Adjustment – Model B

The generated sequences apply in an average sense to areas with a lateral extent of 25 to 10 km. In some locations and for some parameters (e.g. temperature with respect to aspect and shading and snowpack development because of local wind variability and convergence), site characteristics may decree the adjustment of these average quantities. Some parameters (e.g. occurrence of rain) may not change in the process of subgridding while others (e.g. amount of rain) may vary appreciably. Two possible strategies for dealing with this situation were outlined in Figure 5–1. The first strategy considered the fitting of a stochastic model to the larger grid sequence from Model A and then adjusting the parameters of this model for local effects. The second strategy considered an adjustment of the sequences from Model A prior to fitting a stochastic model. In either case a formal adjustment approach is needed. No high resolution (spatial) data is likely to be widely available. Consequently, a modeling approach is necessary. A basic requirement for this approach would have to be that the average quantities after adjusting for at-site effects in the 2x2 to 10x10 km grid area equal the generated sequences from Model A for the same area. This requirement makes it difficult to give general adjustments for local effects that are not coupled to both Model A results and site characteristics. The provision of a subgrid scale physical climate model that would have to be run every time site characteristics needed to be accounted for is neither practical nor desirable. Consequently, we propose that work be pursued to: (a) develop a dimensionless representation from kinematic and geometric considerations for subscale climate model applications, and (b) experiment with such a model with various aspects (with respect to wind and solar radiation) to develop adjustments for site effects to either sequences or parameters as appropriate. We anticipate that a limited suite of topographic features (e.g. one or two slopes and/or locations of vegetation) may be successfully parameterized in this manner. While adjusting the generated sequences in this manner is conceptually easier, adjusting the stochastic model or sequence statistical parameters is more practical and presentable to the user. However, it could be quite difficult to come up with such a representation, particularly in light of the complicated dependence structure between larger-scale and local-scale variables that is likely. We expect this task could take from four to six months of effort.

5.4.5 Task 5 – Tests of CLIGEN Structure

At this point it is reasonable to expect that most of the modifications needed to maintain CLIGEN’s applicability consistent with the eastern version will be relatively minor or procedural, or are consistent with recent developments of the same methodology by Woolhiser et al. (1988) and indicated by Nicks

(1988). We propose to assess the adequacy of the current set of assumptions in CLIGEN relative to the statistics computed in Task 1 and the goals of WEPP. For example, it may or may not be important to reproduce a higher order chain for winter precipitation, given the interest in specifying snowpack properties at a specified date. However, the order of the chain, particularly the interplay between temperature and precipitation, is very important in the spring melt period. Clustering of events for summer thunderstorms is not reproduced by the first order Markov Chain in CLIGEN. Its impact relative to WEPP might be significant since a long dry period followed by a clustered set of rainfall events may be significant in terms of soil loss. On a daily time-step for rainfall, event clustering may or may not be significant in the arid west. However, once disaggregation of daily rainfall into storm intensity and duration is considered, the structure of number of events and their spacing during a summer wet period may be quite significant. The work of Hershenhorn and Woolhiser (1987) addresses this issue in the Markov Chain context (without regard to clustering) and is potentially useful. We anticipate that this task will take three to four months.

5.4.6 Task 6 – CLIGEN Structure Modifications

This task follows directly from our observations in the previous task. At this point it is difficult to predict the nature and degree of effort that will be required. We anticipate that most modifications to be performed will be of the form reported in the literature of Markov Chain applications as reviewed in Section 5.2. However, if clustering effects are significant, it may be necessary to investigate an appropriate form of a discrete point process for the model. We anticipate this task may take one to four months.

5.4.7 Task 7 – CLIGEN Disaggregation of Daily Rainfall

Disaggregation of the 12-hour or daily rainfall values produced by Model A into storm event intensities and durations is likely to be a very challenging task since few data are recorded at shorter time scales. One idea to consider is to use a shorter time step for Model A with linear interpolation of the 12-hour radiosonde values. The uncertainty introduced by this method will be difficult to quantify. A second idea is to use the observed temporal rainfall structure of the closest upstream (wind direction) gaged station for disaggregation. This uses a real data structure for calibration. Changes in amounts or intensities of storm rainfall with altitude or location at the shorter time scales could be normalized with (or related to) the changes predicted for the 12-hour period. However, given the high degree of spatial variability in summer rainfall occurrence and amounts in the mountains, it is unclear at this point if this strategy will be particularly successful. Parameterization of short duration rainfall at base stations and procedures for spatial interpolation of these parameters in the neighborhood of base stations will also be investigated. We propose to at least explore these avenues in conjunction with other ideas presented in Chapter 3. Also, we are exploring the suitability of high elevation precipitation data in Canada for use in developing these procedures. We anticipate approximately four months of effort on this task.

5.4.8 Task 8 – Parameterization Strategy

Our current belief is that the most effective and simplest way to communicate the stochastic model parameters to the end user is through the use of a digital data base (GIS archive). This circumvents issues of smoothing out parameter values derived for variable topography and of information loss. However, this leads to a large data base that may have to be stored on a high capacity CD-ROM region by region. Software to perform local adjustments would also have to be provided. Some maps contouring the parameter values could also be produced for a visual grasp of large-scale spatial variability in the processes. However, there is no reason to believe that parameter values should contour uniformly and

smoothly in a physically meaningful manner on the map [e.g. Bulletin 17B flood skew map (USGS 1982)], and the maps may not be too useful for at-site predictions. We anticipate that this task will take between two to four months, depending on how many maps are needed and the spatial extent covered by the demonstration effort in Phase II.

5.4.9 Task 9 – Models G, H and/or I

At this point the development of stochastic representation for snowpack initial conditions for specified dates (Model G), for water delivery to the top of the soil (Model H), or for overland runoff generation (Model I) is not anticipated. These models would most likely have to be in a framework quite different from the current CLIGEN, Markov Chain models and may or may not need CLIGEN. Our current recommendation is to explore recent advances in nonparametric time series estimation (e.g. Yakowitz and Karlsson, 1987) for Models H and I. If pursued each of these models are likely to require nine months to a year of effort to develop.

5.4.10 Task 10 – Reports/Documentation

We propose that a report be submitted upon the completion of each major task (approximately every four to six months), and a comprehensive report and user documentation of the models developed be submitted at the end of two years of Phase II activity.

CHAPTER 6

Summary of Recommendations

We make the following recommendations for MCLIGEN:

1. That development of MCLIGEN proceed under Option 2, Fine Scale Climate Sequences, and Option 3, Snowpack Initial Conditions at an Initial Date (see Section 2.2). These options appear to satisfy the spatial resolution requirements of the USFS. (At our project progress meeting held on May 3, 1990 in Salt Lake City, the USFS accepted this recommendation.)
2. That the fine scale resolution climate model approach should be Option B – Two Dimensional – Simplified Terrain (see Section 3.3.3). This option will require a computer with graphics capability.
3. That development of a snowpack simulation model be included in the scope of work for future phases of this cooperative agreement. The close relationship between the data requirements for development and validation of MCLIGEN and a snowpack simulation model for the western version of WEPP provides a strong case for performing these two activities simultaneously under the same cooperative agreement.
4. That an overall strategy for obtaining data needed to adequately validate each of the parts of the entire WEPP erosion prediction methodology be developed. This strategy should be realistic in terms of potential funding, but must address the operational requirements for confidence and accuracy by WEPP users. It is proposed that the strategy be used by the various federal government agencies involved with WEPP for seeking and coordinating funding for data collection programs.
5. That the UWRL project team take the initiative to form an Orographic Precipitation Modeling Users Group (OPMUG). Such a group would provide a forum for sharing applications, experience, and ideas for improving orographic precipitation models. OPMUG may eventually associate with a professional organization, such as the American Geophysical Society, the American Meteorological Society, or the American Society of Civil Engineers.

APPENDIX A

PROJECT TASKS

Phase I - Weather data evaluation and generator design

Task 1 - Literature review

UWRL project personnel will thoroughly review the published literature in several areas: factors affecting Western U.S. weather - see key issues under Task 2, formulation of design (storm) events, stochastic models of weather and snowpack characteristics, spatial interpolation of weather and snowpack characteristics, available digital terrain (elevation) models and geographical information systems which could be used on this project, available weather records, and other areas identified during the project. Additionally, we will review WEPP project documentation (including, user requirements, the existing weather generator (CLIGEN), and the hydrologic model component). We will prepare the literature review in written form and submit it to the USFS by September 30, 1989. This review will form a basis for the development of weather model components, and it will be updated during the life of the project.

Task 2 - Key issues identification

To provide WEPP weather inputs at any location in the Western U.S., it will be necessary to use information from "gaged" sites to estimate weather at "ungaged" sites. Such spatial interpolations can be performed directly on weather characteristics, or indirectly on parameters in models of various characteristics. In either case it will be necessary to take into consideration regional moisture movements and orographical factors, such as aspect, elevation, slope, and rain shadow. We will identify these and other factors as key issues for special study in the literature review under Task 1. The Western U.S. regions will be defined according to these factors, thereby establishing subareas within which spatial interpolation can be performed. A digital terrain model may be very useful for this purpose. We understand that some structured synthetic testing of WEPP model components has already been performed to determine the components which are especially sensitive to weather inputs. We will review this work to determine the need for additional testing to support the development of the mountain weather generator.

Task 3 - Review of USFS field program

We will review current USFS WEPP field sites according to their representativeness with respect to the various key issues identified under Task 2. If serious gaps exist in the coverage of the subareas established under Task 2, these will be brought to USFS's attention so that additional representative field sites can be identified. These field sites will be used for evaluation of the mountain weather generator as outlined in Phase II, Tasks 7 and 8.

Task 4 - Data evaluation

We will perform data evaluation to provide event information for development of design storms, identification of representative historical events, and design of continuous simulation models. Additionally, we will analyze data from representative sites with respect to their serial and spatial correlation structure, including the factors identified under Task 2 such as the use of

principal components analysis. We will evaluate alternative interpolation methods at representative sites.

Task 5 - Design mountain weather generator

Based on the evaluation performed under Task 4 and information obtained from the literature review, we will propose alternative models for weather simulation. The overall weather model will be designed to meet the user requirements specified by USFS as far as possible. In January 1991, we will submit the proposed model, which will be described in a working document, to USFS for their review.

Phase II - Mountain weather generator coding and evaluation at representative sites

Task 6 - Coding

We will code the mountain weather generator, designed under Task 5, within the computer system requirements specified by the USFS, and we will thoroughly verify the coding.

Task 7 - Evaluation based on weather characteristics

Through a comprehensive program of independent tests performed at representative, Western U.S. gaged sites, we will evaluate the accuracy of the mountain weather generator outputs at ungaged sites. The independent tests used for this purpose will not have been used in the developmental work. Our evaluation will also include cross-validations. Additionally, we will compare the accuracy of alternative model components.

Task 8 - Evaluation based on erosion prediction

Through a series of WEPP runs at representative field sites, we will evaluate the influence of the mountain weather generator outputs on the accuracy of erosion predictions. We will also compare the accuracy of alternative model components. We will document the results of evaluations conducted under Tasks 8 and 9 and present this information to USFS. The schedule for this report has not yet been established.

Phase III - Generalization to entire Western U.S.

Task 9 - Generalization

Once the mountain weather generator has been adequately evaluated and improved to an acceptable level of accuracy, we will apply it to the entire Western U.S. In this step, we will achieve the capability for providing the user with weather inputs at any location in the Western U.S. by extending the methods which were developed and tested under previous project phases.

Task 10 - Documentation

During the developmental work in Phases I and II, we will write and update various working documents. Additionally, we will prepare a mountain weather generator user's manual for inclusion in the overall user's manual for the USFS-modified WEPP procedure. We anticipate that this documentation will include information on the expected accuracy of the generator in different regions, and also guidance on the selection (for example, design {storms} events, or the sequencing of historical events).

APPENDIX B

Summary of Climate Data Bases for the Western U.S.

Radiosonde Data Set

Data set begins in the mid 50's. Balloons are launched every 12 hours and provide profiles of temperature, dewpoint, pressure and wind. There are 20 active launch sites around the Western U.S.

RAWS – Remote Automated Weather Stations

Operated by the NFS and BLM, first order stations comprise a 75 mile grid network. Second order stations fill in between. Hourly measurements are precipitation, wind speed and direction, air temperature and humidity, soil and fuel (fire potential) moisture. Stations are generally located at mid to high elevations.

AFFIRMS and NFWDL (National Fire Weather Data Library)

Observations from nearly 1800 fire weather stations. One observation (usually early afternoon) per station per day and one forecast per fire zone per day are stored.

SNOTEL (Soil Conservation Service)

Snow course and snotel remote weather station data. Available data include monthly snow course, precipitation, streamflow and reservoir storage; daily snow water equivalent precipitation and temperature. This data set is the best resource for high elevation data.

ARS Water Data Base (Agriculture Research Service)

Research watersheds that have received research attention and been intensely instrumented. Length of records vary from 1 to 50 years and consist of rainfall and runoff data. Rain gage networks consist of 1 to more than 200 recording stations per watershed.

NWS First Order and Cooperative Weather Data Base

Available from Ashville, N.C. (all U.S.) or Reno, N.V. (Western U.S.) the digitized data base begins in 1948. A few select stations begin in 1928. Observations date back to near 1890 for some stations and a few to the early and mid 1800's. Observations include daily maximum and minimum temperature and precipitation. Some include dewpoint, humidity, sky conditions, evaporation, river gage height, or wind. There are efforts currently underway to digitize more of the historical data.

NWS Hourly Precipitation Data Base

Beginning in the mid 50's punch tape recording raingages were installed at some of the NWS weather stations (approx. 50 per state). This data base is the most widespread and long-term data base for precipitation observations on an interval more than one observation per day.

CAC (Climate Analysis Center) First Order and Cooperative

Observations, summaries, and forecasts for first order and cooperative stations. Best for current weather observations and forecasts.

Other Data Bases

A number of local data bases (not covering the entire Western U.S.) are also available. As an example the office of the Utah State Climatologist operates a state-wide network of agricultural weather stations that gather hourly weather data. Since the development of automated weather observing equipment a number of these type of networks have developed that enhance the coverage of the RAWS and SNOTEL networks. Many of these local networks cover the lower to mid elevations (populated and agricultural areas) while the RAWS and SNOTEL networks cover the mid to upper elevations (range and forest lands).

Other Potential Data Bases

Many other potential data bases are developing. One of particular interest is the potential of satellite image data bases. Many new techniques and new instruments are taking weather observations from space where coverage need not be limited to a specific location.

Radiosonde Data Set
Western Region Climate Center

Agency: Western Region Climate Center
Desert Research Institute
Reno, NV

Radiosonde Data Set - Upper Air

Air Temperature
Dew Point Temperature
Pressure
Wind

Data set begins in the mid 1950's. WRCC has the historical record for all stations located in the western eleven states and is current as of May, 1987. All other stations are obtainable from NCDC.

ACTIVE UPPER AIR DATA STATIONS FOR THE WORLD

| | | | | |
|---------|---|--------|--------|-----|
| 03131 | SAN DIEGO, CALIFORNIA | 012432 | 49N117 | 08W |
| X 03158 | SAN NICOLAS PMR, WS SITE 2, CALIFORNIA | 000933 | 16N119 | 33W |
| X 03160 | DESERT DOCK, NEVADA | 100736 | 37N116 | 01W |
| 03860 | HUNTINTON, WEST VIRGINIA | 024638 | 22N082 | 33W |
| 03879 | SALEM, ILLINOIS | 017538 | 39N088 | 58W |
| 03881 | CENTREVILLE, ALABAMA | 014032 | 54N087 | 15W |
| 03937 | LAKE CHARLES, LOUISIANA | 000530 | 07N093 | 13W |
| 03940 | JACKSON, MISSISSIPPI | 009132 | 19N090 | 05W |
| 03946 | MONETT, MISSOURI | 043836 | 53N093 | 54W |
| 03951 | LONGVIEW, TEXAS | 012432 | 21N094 | 39W |
| 10717 | BOGOTA, COLOMBIA | 254104 | 42N074 | 09W |
| 10809 | SAN JOSE.JUAN SANTA MARIA, COSTA RICA | 092010 | 00N084 | 13W |
| 11501 | CHRIST CHURCH, BARBADOS ISLAND, CARIBBEAN SEA | 004713 | 04N059 | 30W |
| 11629 | SANTO DOMINGO, DOMINICAN REPUBLIC | 001418 | 28N069 | 53W |
| 11634 | TRINIDAD, WEST INDIES | 001210 | 35N061 | 21W |
| 11641 | SAN JUAN (ISLA VERDE AIRPORT), PUERTO RICO | 000318 | 26N066 | 00W |
| 11643 | CURACAO, NETHERLANDS ANTILLES | 005412 | 12N068 | 58W |
| 11645 | SINT MAARTEN, NETHERLANDS ANTILLES | 000318 | 03N063 | 07W |
| 11647 | ANTIGUA, LESSER ANTILLES | 000417 | 07N061 | 47W |
| 11706 | GUANTANAMO BAY (NAS), CUBA | 003219 | 54N075 | 09W |
| 11715 | KINGSTON, JAMAICA | 000117 | 56N076 | 47W |
| 11807 | SWAN ISLAND, CARIBBEAN SEA | 001017 | 24N083 | 56W |
| 11813 | GRAND CAYMAN, CAYMAN ISLANDS | 000319 | 18N081 | 22W |
| 11814 | SAN ANDRES, COLOMBIA | 000212 | 35N081 | 42W |
| 11817 | TEGUCIGALPA, HONDURAS | 099914 | 02N087 | 15W |
| 11818 | BELIZE CITY, BELIZE | 000517 | 32N088 | 18W |
| 11901 | GUATEMALA CITY, GUATEMALA | 148914 | 35N090 | 31W |
| 11903 | MEXICO CITY, MEXICO | 223119 | 26N099 | 05W |
| 11904 | VERACRUZ, MEXICO | 001319 | 09N096 | 07W |
| 12714 | GRAND TURK, TURKS ISLANDS (BAHAMA ISLANDS) | 000921 | 27N071 | 09W |
| 12717 | NASSAU, NEW PROVIDENCE ISLAND, BAHAMA ISLANDS | 000225 | 03N077 | 28W |
| 12832 | APALACHICOLA, FLORIDA | 000729 | 44N085 | 02W |
| 12842 | TAMPA BAY, FLORIDA | 001327 | 42N082 | 24W |
| 12844 | WEST PALM BEACH, FLORIDA | 000726 | 41N080 | 07W |
| 12850 | KEY WEST, FLORIDA | 000324 | 33N081 | 45W |
| 12868 | CAPE KENNEDY, FLORIDA | 000528 | 28N080 | 33W |
| 12878 | MERIDA, MEXICO | 001120 | 57N089 | 40W |
| 12884 | BOOTHVILLE, LOUISIANA | 000129 | 20N089 | 24W |
| 12912 | VICTORIA, TEXAS | 003328 | 51N096 | 55W |
| 12919 | BROWNSVILLE, TEXAS | 000725 | 54N097 | 26W |
| 13601 | SAINT GEORGE (NAS), BERMUDA | 002532 | 22N064 | 41W |
| 13723 | GREENSBORO, NORTH CAROLINA | 027536 | 05N079 | 57W |
| 13840 | DAYTON, OHIO | 029839 | 52N084 | 07W |
| 13861 | WAYCROSS, GEORGIA | 004431 | 15N082 | 24W |
| 13873 | ATHENS, GEORGIA | 024633 | 57N083 | 19W |
| 13880 | CHARLESTON, SOUTH CAROLINA | 001332 | 54N080 | 02W |
| 13897 | NASHVILLE, TENNESSEE | 018036 | 15N086 | 34W |
| 13901 | STEPHENVILLE, TEXAS | 039932 | 13N098 | 11W |
| 13963 | NORTH LITTLE ROCK, ARKANSAS | 017234 | 50N092 | 15W |
| 13967 | OKLAHOMA CITY, OKLAHOMA | 039235 | 24N097 | 36W |
| 13985 | DODGE CITY, KANSAS | 079137 | 46N099 | 58W |
| 13996 | TOPEKA, KANSAS | 026839 | 04N095 | 38W |

| | | | | |
|---------|--------------------------------------|--------|--------|-----|
| 14607 | CARIBOU, MAINE | 019146 | 52N068 | 01W |
| 14684 | CHATHAM, MASSACHUSETTS | 001641 | 40N069 | 58W |
| 14733 | BUFFALO, NEW YORK | 021842 | 56N078 | 44W |
| 14735 | ALBANY, NEW YORK | 008642 | 45N073 | 48W |
| 14764 | PORTLAND, MAINE | 002043 | 39N070 | 19W |
| 14826 | FLINT, MICHIGAN | 023642 | 58N083 | 45W |
| 14842 | PEORIA, ILLINOIS | 020040 | 40N089 | 41W |
| 14847 | SAULT SAINT MARIE, MICHIGAN | 022146 | 28N084 | 22W |
| 14898 | GREEN BAY, WISCONSIN | 021044 | 29N088 | 08W |
| 14918 | INTERNATIONAL FALLS, MINNESOTA | 035948 | 34N093 | 23W |
| 14926 | SAINT CLOUD, MINNESOTA | 031545 | 33N094 | 04W |
| 14936 | HURON, SOUTH DAKOTA | 039244 | 23N098 | 13W |
| 16201 | KEFLAVIK (FWF), ICELAND | 004963 | 58N022 | 36W |
| 21001 | MANZANILLO, MEXICO | 000619 | 04N104 | 20W |
| 21101 | SOCORRO ISLAND, MEXICO | 003518 | 43N110 | 57W |
| 21504 | HILO, HAWAII | 001019 | 43N155 | 04W |
| 21603 | JOHNSTON ISLAND, NORTH PACIFIC OCEAN | 000316 | 44N169 | 31W |
| 22007 | CHIHUAHUA, MEXICO | 142928 | 42N106 | 04W |
| 22010 | DEL RIO, TEXAS | 031429 | 22N100 | 55W |
| 22013 | GUADALAJARA, MEXICO | 158920 | 41N103 | 23W |
| 22104 | EMPALME, MEXICO | 001227 | 57N110 | 48W |
| 22105 | GUADALUPE ISLAND, MEXICO | 000628 | 53N118 | 18W |
| 22536 | LIHUE, KAUAI, HAWAII | 003621 | 59N159 | 21W |
| 22548 | BARKING SANDS PMR (NS), HAWAII | 000522 | 02N159 | 47W |
| 22701 | MIDWAY ISLAND, NORTH PACIFIC OCEAN | 000628 | 13N177 | 21W |
| 23023 | MIDLAND, TEXAS | 087331 | 57N102 | 11W |
| 23044 | EL PASO, TEXAS | 119931 | 48N106 | 24W |
| X 23050 | ALBUQUERQUE, NEW MEXICO | 161935 | 03N106 | 37W |
| X 23062 | DENVER, COLORADO | 161139 | 45N104 | 52W |
| X 23066 | GRAND JUNCTION, COLORADO | 147239 | 07N108 | 32W |
| X 23154 | ELY, NEVADA | 190839 | 17N114 | 51W |
| X 23160 | TUCSON, ARIZONA | 078932 | 07N110 | 56W |
| X 23194 | WINSLOW, ARIZONA | 148735 | 01N110 | 44W |
| X 23230 | OAKLAND, CALIFORNIA | 000637 | 45N122 | 13W |
| 24011 | BISMARCK, NORTH DAKOTA | 050346 | 46N100 | 45W |
| X 24021 | LANDER, WYOMING | 169542 | 49N108 | 44W |
| 24023 | NORTH PLATTE, NEBRASKA | 084741 | 08N100 | 41W |
| 24090 | RAPID CITY, SOUTH DAKOTA | 096644 | 03N103 | 04W |
| X 24127 | SALT LAKE CITY, UTAH | 128840 | 46N111 | 58W |
| X 24128 | WINNEMUCCA, NEVADA | 131240 | 54N117 | 48W |
| X 24131 | BOISE, IDAHO | 087143 | 34N116 | 13W |
| X 24143 | GREAT FALLS, MONTANA | 111847 | 29N111 | 22W |
| X 24157 | SPOKANE, WASHINGTON | 072047 | 38N117 | 32W |
| X 24225 | MEDFORD, OREGON | 039742 | 22N122 | 52W |
| X 24232 | SALEN, OREGON | 006144 | 55N123 | 00W |
| 25308 | ANNETTE, ALASKA | 003755 | 02N131 | 34W |
| 25501 | KODIAK, ALASKA | 000457 | 45N152 | 30W |
| 25503 | KING SALMON, ALASKA | 001558 | 41N156 | 39W |
| 25624 | COLD BAY, ALASKA | 003055 | 12N162 | 43W |
| 25704 | ADAK, ALASKA | 000451 | 53N176 | 39W |
| 25713 | SAINT PAUL ISLAND, ALASKA | 001057 | 09N170 | 13W |
| 26411 | FAIRBANKS, ALASKA | 013564 | 49N147 | 52W |
| 26510 | MCGRATH, ALASKA | 010362 | 58N155 | 37W |
| 26615 | BETHEL, ALASKA | 003960 | 47N161 | 48W |
| 26616 | KOTZEBUE, ALASKA | 000566 | 52N162 | 38W |
| 26617 | NOME, ALASKA | 000564 | 30N165 | 26W |
| 27401 | BARTER ISLAND, ALASKA | 001570 | 08N143 | 38W |
| 27502 | BARROW, ALASKA | 001271 | 18N156 | 47W |

| | | | | |
|--------|--|--------|--------|-----|
| 40308 | YAP ISLAND, CAROLINE ISLANDS, NORTH PACIFIC OCEAN | 001409 | 29N138 | 05E |
| 40309 | KOROR ISLAND, CAROLINE ISLANDS, NO. PACIFIC OCEAN | 003007 | 20N134 | 29E |
| 40504 | PONAPE ISLAND, CAROLINE ISLANDS, NO. PACIFIC OCEAN | 003906 | 58N158 | 13E |
| 40505 | TRUK, CAROLINE ISLANDS, NORTH PACIFIC OCEAN | 000307 | 28N151 | 51E |
| 40710 | MAJURO, MARSHALL ISLANDS, NORTH PACIFIC OCEAN | 000307 | 05N171 | 23E |
| 41415 | TAGUAC, GUAM, MARIANA ISLANDS, NORTH PACIFIC OCEAN | 011113 | 33N144 | 50E |
| 41606 | WAKE ISLAND, NORTH PACIFIC OCEAN | 000519 | 17N166 | 39E |
| 50101 | ASCENSION ISLAND, SOUTH ATLANTIC OCEAN | 007907 | 58S014 | 24W |
| 51601 | LA PAZ (EL ALTO), BOLIVIA | 408016 | 30S068 | 11W |
| 51701 | LIMA, PERU | 013512 | 01S077 | 02W |
| 52502 | ASUNCION, PARAGUAY **** | 009225 | 15S057 | 31W |
| 52701 | ANTOFAGASTA, CHILE | 013723 | 25S070 | 28W |
| 52502 | ASUNCION, PARAGUAY **** | 002515 | 00S057 | 31W |
| 53701 | QUINTERO, CHILE | 000732 | 47S071 | 32W |
| 54702 | PUERTO MONTT, CHILE | 011041 | 26S073 | 07W |
| 55701 | PUNTA ARENAS, CHILE | 003853 | 02S070 | 51W |
| 61705 | PAGO PAGO, AMERICAN SAMOAN ISLS, S. PACIFIC OCEAN | 000514 | 20S170 | 43W |
| 62001 | EASTER ISLAND, CHILE | 004527 | 10S109 | 26W |
| 68201 | BYRD STATION, ANTARCTICA | 154380 | 01S119 | 31W |
| 70701 | DIEGO GARCIA ISLAND (NS) INDIAN OCEAN | 000207 | 18S072 | 24E |
| 87601 | MCMURDO, ANTARCTICA | 001877 | 53S166 | 44E |
| 87701 | HALLETT, ANTARCTICA | 000572 | 18S170 | 19E |
| 90001 | AMUNDSEN SCOTT, ANTARCTICA | 285490 | 00S | |
| ×93104 | CHINA LAKE (NAS), CALIFORNIA | 066635 | 47N117 | 47W |
| ×93111 | POINT MUGU PMR, WC, CALIFORNIA | 000234 | 07N119 | 07W |
| ×93116 | SAN NICOLAS PMR, WS SITE 1, CALIFORNIA | 017233 | 14N119 | 27W |
| ×93117 | SAN CLEMENTE, CALIFORNIA | 000733 | 01N118 | 35W |
| ×93214 | VANDENBERG AFB, CALIFORNIA | 010034 | 45N120 | 34W |
| ×93729 | CAPE HATTERAS, NORTH CAROLINA | 000435 | 16N075 | 33W |
| 93734 | WASHINGTON DULLES INT'L AIRPORT DIST OF COLUMBIA | 008538 | 59N077 | 28W |
| 93739 | WALLOPS ISLAND, VIRGINIA | 001337 | 56N075 | 29W |
| 93755 | ATLANTIC CITY, NEW JERSEY | 002239 | 27N074 | 34W |
| ×94008 | GLASGOW, MONTANA | 069648 | 13N106 | 37W |
| ×94240 | QUILLAYUTE, WASHINGTON | 005647 | 57N124 | 33W |
| 94789 | NEW YORK (FORT TOTTEN), NEW YORK | 000840 | 47N073 | 46W |
| 94823 | PITTSBURGH, PENNSYLVANIA | 035940 | 32N080 | 14W |
| 94918 | OMAHA, NEBRASKA | 040041 | 22N096 | 01W |

UPPER AIR DATA AIRZONA STATIONS

CATALOG OF NCDC DATA UADAZP01.NDC
 DATA FROM LOCAL SOURCE UADAZP01.NDC
 88/06/13 23:10:20

| | | | | | | | | | | |
|----------|------|---|-------|---|------|----|----|----|-------|----------------------------------|
| 00003124 | 9999 | 9 | 99999 | 9 | 1955 | 01 | 04 | 16 | | |
| 00003124 | 9999 | 9 | 99999 | 9 | 1971 | 07 | 30 | 12 | 6571 | FORT HUACHUCA |
| 00003125 | 9999 | 9 | 99999 | 9 | 1955 | 07 | 01 | 03 | | |
| 00003125 | 9999 | 9 | 99999 | 9 | 1971 | 07 | 27 | 12 | 7186 | YUMA/PROVING GROUND |
| 00003149 | 9999 | 9 | 99999 | 9 | 1963 | 08 | 13 | 20 | | |
| 00003149 | 9999 | 9 | 99999 | 9 | 1963 | 10 | 22 | 22 | 29 | PHOENIX/LITCHFIELD PARK |
| 00023109 | 9999 | 9 | 99999 | 9 | 1951 | 09 | 01 | 03 | | |
| 00023109 | 9999 | 9 | 99999 | 9 | 1956 | 02 | 29 | 21 | 5304 | DAVIS MONTHAN AIR FORCE BASE |
| 00023160 | 9999 | 9 | 99999 | 9 | 1956 | 03 | 01 | 04 | | |
| 00023160 | 9999 | 9 | 99999 | 9 | 1980 | 12 | 31 | 12 | 19327 | TUCSON/INTERNATIONAL AIRPORT |
| 00023160 | 3207 | N | 11056 | W | 1981 | 01 | 01 | 00 | | |
| 00023160 | 3207 | N | 11056 | W | 1987 | 12 | 31 | 12 | 5175 | TUCSON/INTERNATIONAL AIRPORT |
| 00023183 | 9999 | 9 | 99999 | 9 | 1948 | 01 | 01 | 03 | | |
| 00023183 | 9999 | 9 | 99999 | 9 | 1958 | 01 | 15 | 00 | 7219 | PHOENIX/SKY HARBOR INT'L AIRPORT |
| 00023194 | 9999 | 9 | 99999 | 9 | 1961 | 11 | 01 | 00 | | |
| 00023194 | 9999 | 9 | 99999 | 9 | 1980 | 12 | 31 | 12 | 13969 | WINSLOW/MUNICIPAL AIRPORT |
| 00023194 | 3501 | N | 11044 | W | 1981 | 01 | 01 | 00 | | |
| 00023194 | 3501 | N | 11044 | W | 1987 | 12 | 31 | 12 | 4941 | WINSLOW/MUNICIPAL AIRPORT |

CATALOG COMPLETE -
 STATIONS 9
 RECORDS 69721
 PRUS 8466
 BLOCKS 186067
 BYTES 95249052
 ERRORS 0

UPPER AIR DATA CALIFORNIA STATIONS

CATALOG OF NCDC DATA UADCAPO1.NDC
 DATA FROM LOCAL SOURCE UADCAPO1.NDC
 88/06/21 00:43:12

7-11-88

| | | | | | | | | | | |
|----------|------|---|-------|---|------|----|----|----|-------|----------------------------|
| 00003120 | 9999 | 9 | 99999 | 9 | 1947 | 07 | 09 | 17 | | |
| 00003120 | 9999 | 9 | 99999 | 9 | 1958 | 10 | 31 | 06 | 1879 | CHINA LAKE/G1 RANGE |
| 00003123 | 9999 | 9 | 99999 | 9 | 1954 | 07 | 21 | 15 | | |
| 00003123 | 9999 | 9 | 99999 | 9 | 1954 | 10 | 15 | 15 | 192 | CAMP PENDLETON |
| 00003131 | 9999 | 9 | 99999 | 9 | 1956 | 06 | 16 | 03 | | |
| 00003131 | 9999 | 9 | 99999 | 9 | 1980 | 12 | 31 | 12 | 17891 | SAN DIEGO/MONTGOMERY FIELD |
| 00003131 | 3249 | N | 11708 | W | 1981 | 01 | 01 | 00 | | |
| 00003131 | 3249 | N | 11708 | W | 1987 | 12 | 31 | 00 | 5085 | SAN DIEGO/MONTGOMERY FIELD |
| 00003134 | 9999 | 9 | 99999 | 9 | 1957 | 04 | 23 | 09 | | |
| 00003134 | 9999 | 9 | 99999 | 9 | 1957 | 09 | 28 | 12 | 562 | BAKER/TEAM 19 |
| 00003146 | 9999 | 9 | 99999 | 9 | 1962 | 02 | 28 | 18 | | |
| 00003146 | 9999 | 9 | 99999 | 9 | 1968 | 08 | 30 | 18 | 1710 | EL CENTRO/RANGE 1 |
| 00003158 | 9999 | 9 | 99999 | 9 | 1973 | 09 | 04 | 16 | | |
| 00003158 | 9999 | 9 | 99999 | 9 | 1980 | 12 | 30 | 19 | 1820 | SAN NICHOLAS/ISLAND SITE 2 |
| 00003158 | 3316 | N | 11933 | W | 1981 | 01 | 05 | 20 | | |
| 00003158 | 3316 | N | 11933 | W | 1983 | 01 | 07 | 19 | 133 | SAN NICHOLAS/ISLAND SITE 2 |
| 00023106 | 9999 | 9 | 99999 | 9 | 1955 | 02 | 08 | 15 | | |
| 00023106 | 9999 | 9 | 99999 | 9 | 1955 | 04 | 09 | 21 | 183 | HAMMER AIR FORCE BASE |
| 00023114 | 9999 | 9 | 99999 | 9 | 1951 | 03 | 01 | 17 | | |
| 00023114 | 9999 | 9 | 99999 | 9 | 1968 | 05 | 31 | 18 | 5788 | EDWARDS AIR FORCE BASE |
| 00023129 | 9999 | 9 | 99999 | 9 | 1948 | 12 | 01 | 03 | | |
| 00023129 | 9999 | 9 | 99999 | 9 | 1956 | 04 | 16 | 15 | 6837 | LONG BEACH/WSO AIRPORT |
| 00023174 | 9999 | 9 | 99999 | 9 | 1970 | 07 | 01 | 14 | | |
| 00023174 | 9999 | 9 | 99999 | 9 | 1971 | 04 | 30 | 14 | 416 | LOS ANGELES/INT'L AIRPORT |
| 00023201 | 9999 | 9 | 99999 | 9 | 1962 | 02 | 06 | 18 | | |
| 00023201 | 9999 | 9 | 99999 | 9 | 1971 | 03 | 26 | 18 | 1294 | CHICO/AIR FORCE BASE |
| 00023203 | 9999 | 9 | 99999 | 9 | 1952 | 11 | 15 | 03 | | |
| 00023203 | 9999 | 9 | 99999 | 9 | 1963 | 01 | 31 | 10 | 3332 | CASTLE/AIR FORCE BASE |
| 00023230 | 9999 | 9 | 99999 | 9 | 1948 | 01 | 01 | 03 | | |
| 00023230 | 9999 | 9 | 99999 | 9 | 1980 | 12 | 31 | 12 | 26225 | OAKLAND/WSO AIRPORT |
| 00023230 | 3745 | N | 12213 | W | 1981 | 01 | 01 | 00 | | |
| 00023230 | 3745 | N | 12213 | W | 1987 | 12 | 31 | 12 | 5101 | OAKLAND/WSO AIRPORT |
| 00023236 | 9999 | 9 | 99999 | 9 | 1948 | 01 | 01 | 03 | | |
| 00023236 | 9999 | 9 | 99999 | 9 | 1954 | 10 | 31 | 15 | 4983 | SANTA MARIA/PUBLIC AIRPORT |
| 00023273 | 9999 | 9 | 99999 | 9 | 1954 | 11 | 01 | 03 | | |
| 00023273 | 9999 | 9 | 99999 | 9 | 1959 | 06 | 30 | 12 | 3500 | SANTA MARIA/PUBLIC AIRPORT |

7-11-88

7-11-88

7-11-88

CATALOG COMPLETE -
 STATIONS 18 BLOCKS 239727
 RECORDS 86931 BYTES 122718276
 PRUS 10941 ERRORS 0

UPPER AIR DATA COLORADO STATIONS

CATALOG OF NCDC DATA UADCOPO1.NDC
DATA FROM LOCAL SOURCE UADCOPO1.NDC
88/06/16 05:51:44

Active
00023012 9999 9 99999 9 1948 10 16 03
00023012 9999 9 99999 9 1956 08 14 15 10595 DENVER/LOWRY AIR FORCE BASE

00023062 9999 9 99999 9 1956 08 15 04
00023062 9999 9 99999 9 1980 12 31 12 18816 DENVER/STAPLETON INT'L AIRPORT

00023062 3946 N 10453 W 1981 01 01 00
00023062 3946 N 10453 W 1987 12 31 12 5090 DENVER/STAPLETON INT'L AIRPORT

00023066 9999 9 99999 9 1948 01 01 03
00023066 9999 9 99999 9 1980 12 31 12 24058 GRAND JUNCTION/WALKER FIELD

Active
00023066 3907 N 10832 W 1981 01 01 00
00023066 3907 N 10832 W 1987 12 31 12 5035 GRAND JUNCTION/WALKER FIELD

CATALOG COMPLETE -
STATIONS 5
RECORDS 63594
PRUS 8310
BLOCKS 182030
BYTES 93182688
ERRORS 0

UPPER AIR DATA IDAHO STATIONS

CATALOG OF NCDC DATA UADIDP01.NDC
DATA FROM LOCAL SOURCE UADIDP01.NDC
88/06/14 20:48:06

43

00024131 9999 9 99999 9 1948 01 01 03
00024131 9999 9 99999 9 1980 12 31 12 24477 BOISE/AIR TERMINAL
00024131 4334 N 11613 W 1981 01 01 00
00024131 4334 N 11613 W 1987 12 31 12 5096 BOISE/AIR TERMINAL

CATALOG COMPLETE -
STATIONS 2
RECORDS 29573
PRUS 3841
BLOCKS 84102
BYTES 43052112
ERRORS 0

UPPER AIR DATA MONTANA STATIONS

CATALOG OF NCDC DATA UADMTP01.NDC
DATA FROM LOCAL SOURCE UADMTP01.NDC
88/06/15 00:13:00

00024034 9999 9 99999 9 1948 01 01 03
00024034 9999 9 99999 9 1955 10 26 03 5709 GLASGOW/WB CITY

Active
00024143 9999 9 99999 9 1948 01 01 03
00024143 9999 9 99999 9 1980 12 31 12 24036 GREAT FALLS/INT'L AIRPORT

00024143 4729 N 11121 W 1981 01 01 00
00024143 4729 N 11121 W 1987 12 31 12 5060 GREAT FALLS/INT'L AIRPORT

Active
00094008 4813 N 10637 W 1985 01 01 00
00094008 4813 N 10637 W 1987 12 31 12 2274 GLASGOW/INT'S AIRPORT

CATALOG COMPLETE -
STATIONS 4
RECORDS 37079
PRUS 4921
BLOCKS 107384
BYTES 54970632
ERRORS 0

UPPER AIR DATA NEVADA STATIONS

CATALOG OF NCDC DATA UADNVP01.NDC
 DATA FROM LOCAL SOURCE UADNVP01.NDC
 88/06/18 01:26:04

| | | | | | | | | | | |
|----------|------|---|--------|---|------|----|----|----|-------|----------------------------------|
| 00003109 | 9999 | 9 | 999999 | 9 | 1951 | 08 | 11 | 06 | | |
| 00003109 | 9999 | 9 | 999999 | 9 | 1955 | 11 | 05 | 20 | 1831 | CAMP MERCURY |
| 00003132 | 9999 | 9 | 999999 | 9 | 1956 | 09 | 20 | 00 | | |
| 00003132 | 9999 | 9 | 999999 | 9 | 1958 | 10 | 31 | 12 | 1164 | TONOPAH |
| 00003133 | 9999 | 9 | 999999 | 9 | 1956 | 09 | 16 | 16 | | |
| 00003133 | 9999 | 9 | 999999 | 9 | 1979 | 05 | 14 | 00 | 12619 | YUCCA FLATS/TEST S TM21 |
| 00003143 | 9999 | 9 | 999999 | 9 | 1959 | 04 | 29 | 12 | | |
| 00003143 | 9999 | 9 | 999999 | 9 | 1967 | 12 | 19 | 00 | 542 | JACKASS FLATS |
| 00003160 | 9999 | 9 | 999999 | 9 | 1978 | 05 | 16 | 00 | | |
| 00003160 | 9999 | 9 | 999999 | 9 | 1980 | 12 | 31 | 12 | 1917 | DESERT ROCK |
| 00003160 | 3637 | N | 11601 | W | 1981 | 01 | 01 | 00 | | |
| 00003160 | 3637 | N | 11601 | W | 1987 | 12 | 31 | 12 | 5093 | DESERT ROCK |
| 00023118 | 9999 | 9 | 999999 | 9 | 1953 | 10 | 15 | 03 | | |
| 00023118 | 9999 | 9 | 999999 | 9 | 1957 | 09 | 23 | 18 | 982 | STEAD/AIR FORCE BASE |
| 00023128 | 9999 | 9 | 999999 | 9 | 1953 | 03 | 10 | 15 | | |
| 00023128 | 9999 | 9 | 999999 | 9 | 1955 | 05 | 15 | 15 | 562 | TONOPAH/AAF |
| 00023154 | 9999 | 9 | 999999 | 9 | 1948 | 01 | 01 | 03 | | |
| 00023154 | 9999 | 9 | 999999 | 9 | 1980 | 12 | 31 | 12 | 24168 | ELY/YELLAND FIELD |
| 00023154 | 3917 | N | 11451 | W | 1981 | 01 | 01 | 00 | | |
| 00023154 | 3917 | N | 11451 | W | 1987 | 12 | 31 | 12 | 5016 | ELY/YELLAND FIELD |
| 00023169 | 9999 | 9 | 999999 | 9 | 1949 | 01 | 01 | 03 | | |
| 00023169 | 9999 | 9 | 999999 | 9 | 1966 | 10 | 09 | 12 | 11187 | LAS VEGAS/MCCARRAN INT'L AIRPORT |
| 00023173 | 9999 | 9 | 999999 | 9 | 1948 | 01 | 01 | 03 | | |
| 00023173 | 9999 | 9 | 999999 | 9 | 1952 | 07 | 31 | 15 | 2648 | LAS VEGAS/WB AIRPORT |
| 00024128 | 9999 | 9 | 999999 | 9 | 1956 | 05 | 01 | 03 | | |
| 00024128 | 9999 | 9 | 999999 | 9 | 1980 | 12 | 31 | 12 | 17961 | WINNEMUCCA/WSO AIRPORT |
| 00024128 | 4054 | N | 11748 | W | 1981 | 01 | 01 | 00 | | |
| 00024128 | 4054 | N | 11748 | W | 1987 | 12 | 31 | 12 | 5036 | WINNEMUCCA/WSO AIRPORT |

Active

Active

Active

CATALOG COMPLETE -
 STATIONS 14
 RECORDS 90726
 PRUS 11743
 BLOCKS 257597
 BYTES 131866020
 ERRORS 0

UPPER AIR DATA NEW MEXICO STATIONS

CATALOG OF NCDC DATA UADNMP01.NDC
DATA FROM LOCAL SOURCE UADNMP01.NDC
88/06/15 04:14:39

00023002 9999 9 99999 9 1949 10 01 03
00023002 9999 9 99999 9 1961 01 31 09 5403 HALLOMAN/AIR FORCE BASE

00023039 9999 9 99999 9 1949 08 01 09
00023039 9999 9 99999 9 1961 01 26 22 4983 LAS CRUCES

00023050 9999 9 99999 9 1912 01 01 00
00023050 9999 9 99999 9 1980 12 31 12 24046 ALBUQUERQUE/INT'L AIRPORT

00023050 3503 N 10637 W 1981 01 01 00
00023050 3503 N 10637 W 1987 12 31 12 5088 ALBUQUERQUE/INT'L AIRPORT

Active

CATALOG COMPLETE -
STATIONS 4
RECORDS 39520
PRUS 4777
BLOCKS 104927
BYTES 53712576
ERRORS 0

UPPER AIR DATA ORGEON STATIONS

CATALOG OF NCDC DATA UADORP01.NDC
DATA FROM LOCAL SOURCE UADORP01.NDC
88/06/17 04:59:44

00024211 9999 9 99999 9 1946 01 02 16
00024211 9999 9 99999 9 1956 05 31 15 4787 PORTLAND

00024225 9999 9 99999 9 1948 01 01 04
00024225 9999 9 99999 9 1980 12 31 12 24168 MEDFORD/JACKSON COUNTY AIRPORT

00024225 4222 N 12252 W 1981 01 01 00
00024225 4222 N 12252 W 1987 12 31 12 5183 MEDFORD/JACKSON COUNTY AIRPORT

00024232 9999 9 99999 9 1956 06 01 04
00024232 9999 9 99999 9 1980 12 31 12 18909 SALEM/MCNARY FIELD

00024232 4455 N 12301 W 1981 01 01 00
00024232 4455 N 12301 W 1987 12 31 12 5118 SALEM/MCNARY FIELD

Actual

CATALOG COMPLETE -
STATIONS 5
RECORDS 58165
PRUS 7866
BLOCKS 171891
BYTES 87992352
ERRORS 0

CATALOG OF NCDC DATA UADUTP01.NDC
 DATA FROM LOCAL SOURCE UADUTP01.NDC
 88/06/16 15:36:39

| | | | | | | | | | | |
|----------|------|---|-------|---|------|----|----|----|-------|------------------------------|
| 00003121 | 9999 | 9 | 99999 | 9 | 1957 | 04 | 18 | 21 | | |
| 00003121 | 9999 | 9 | 99999 | 9 | 1957 | 09 | 28 | 12 | 591 | ST. GEORGE/TEAM 22 |
| 00024101 | 9999 | 9 | 99999 | 9 | 1950 | 02 | 01 | 03 | | |
| 00024101 | 9999 | 9 | 99999 | 9 | 1956 | 08 | 07 | 15 | 6186 | OGDEN/HILL AIR FORCE BASE |
| 00024103 | 9999 | 9 | 99999 | 9 | 1951 | 11 | 01 | 03 | | |
| 00024103 | 9999 | 9 | 99999 | 9 | 1957 | 07 | 31 | 12 | 1403 | DUGWAY/PROVING GROUND |
| 00024126 | 9999 | 9 | 99999 | 9 | 1948 | 01 | 01 | 03 | | |
| 00024126 | 9999 | 9 | 99999 | 9 | 1948 | 08 | 31 | 15 | 487 | OGDEN |
| 00024127 | 9999 | 9 | 99999 | 9 | 1956 | 08 | 07 | 23 | | |
| 00024127 | 9999 | 9 | 99999 | 9 | 1980 | 12 | 31 | 12 | 19144 | SALT LAKE CITY/INT'L AIRPORT |
| 00024127 | 4046 | N | 11158 | W | 1981 | 01 | 01 | 00 | | |
| 00024127 | 4046 | N | 11158 | W | 1987 | 12 | 31 | 12 | 5076 | SALT LAKE CITY/INT'L AIRPORT |

Active

CATALOG COMPLETE -
 STATIONS 6
 RECORDS 32887
 PRUS 4134
 BLOCKS 90702
 BYTES 46431072
 ERRORS 0

CATALOG OF NCDC DATA UADWAP01.NDC
 DATA FROM LOCAL SOURCE UADWAP01.NDC
 88/06/17 01:13:21

Active

| | | | | | | | | | | |
|----------|------|---|--------|---|------|----|----|----|-------|------------------------------|
| 00024157 | 9999 | 9 | 999999 | 9 | 1948 | 01 | 01 | 03 | | |
| 00024157 | 9999 | 9 | 999999 | 9 | 1980 | 12 | 31 | 12 | 25296 | SPOKANE/INT'L AIRPORT |
| 00024157 | 4738 | N | 11732 | W | 1981 | 01 | 01 | 00 | | |
| 00024157 | 4738 | N | 11732 | W | 1987 | 12 | 31 | 12 | 5070 | SPOKANE/INT'L AIRPORT |
| 00024227 | 9999 | 9 | 999999 | 9 | 1962 | 06 | 01 | 00 | | |
| 00024227 | 9999 | 9 | 999999 | 9 | 1964 | 01 | 31 | 00 | 1217 | OLYMPIA/AIRPORT |
| 00024233 | 9999 | 9 | 999999 | 9 | 1956 | 06 | 29 | 03 | | |
| 00024233 | 9999 | 9 | 999999 | 9 | 1962 | 05 | 31 | 12 | 5235 | SEATTLE/SEATTLE-TACOMA INT'L |
| 00024240 | 9999 | 9 | 999999 | 9 | 1948 | 01 | 01 | 03 | | |
| 00024240 | 9999 | 9 | 999999 | 9 | 1966 | 08 | 01 | 12 | 13447 | TATOOSH ISLAND |
| 00024244 | 9999 | 9 | 999999 | 9 | 1946 | 01 | 02 | 03 | | |
| 00024244 | 9999 | 9 | 999999 | 9 | 1956 | 06 | 28 | 21 | 8229 | SEATTLE/NAS |
| 00094240 | 9999 | 9 | 999999 | 9 | 1966 | 08 | 02 | 00 | | |
| 00094240 | 9999 | 9 | 999999 | 9 | 1980 | 12 | 31 | 12 | 10490 | QUILLAYUTE/WSO AIRPORT |
| 00094240 | 4757 | N | 12433 | W | 1981 | 01 | 01 | 00 | | |
| 00094240 | 4757 | N | 12433 | W | 1987 | 12 | 31 | 12 | 5066 | QUILLAYUTE/WSO AIRPORT |

Active

CATALOG COMPLETE -
 STATIONS 8
 RECORDS 74050
 PRUS 9353
 BLOCKS 204786
 BYTES 104831316
 ERRORS 0

UADWYP01.NDC
CATALOG OF NCDC DATA UADWYP01.NDC
DATA FROM LOCAL SOURCE UADWYP01.NDC
88/06/14 22:25:19

00024021 9999 9 99999 9 1948 01 01 03
00024021 9999 9 99999 9 1980 12 31 12 24069 LANDER/HUNT FIELD
00024021 4249 N 10844 W 1981 01 01 00
00024021 4249 N 10844 W 1987 12 31 12 4997 LANDER/HUNT FIELD

CATALOG COMPLETE -
STATIONS 2
RECORDS 29066
PRUS 3645
BLOCKS 80153
BYTES 41030604
ERRORS 0



Upper Air Data Sites

RAWS DATA
WESTERN REGIONAL CLIMATE CENTER

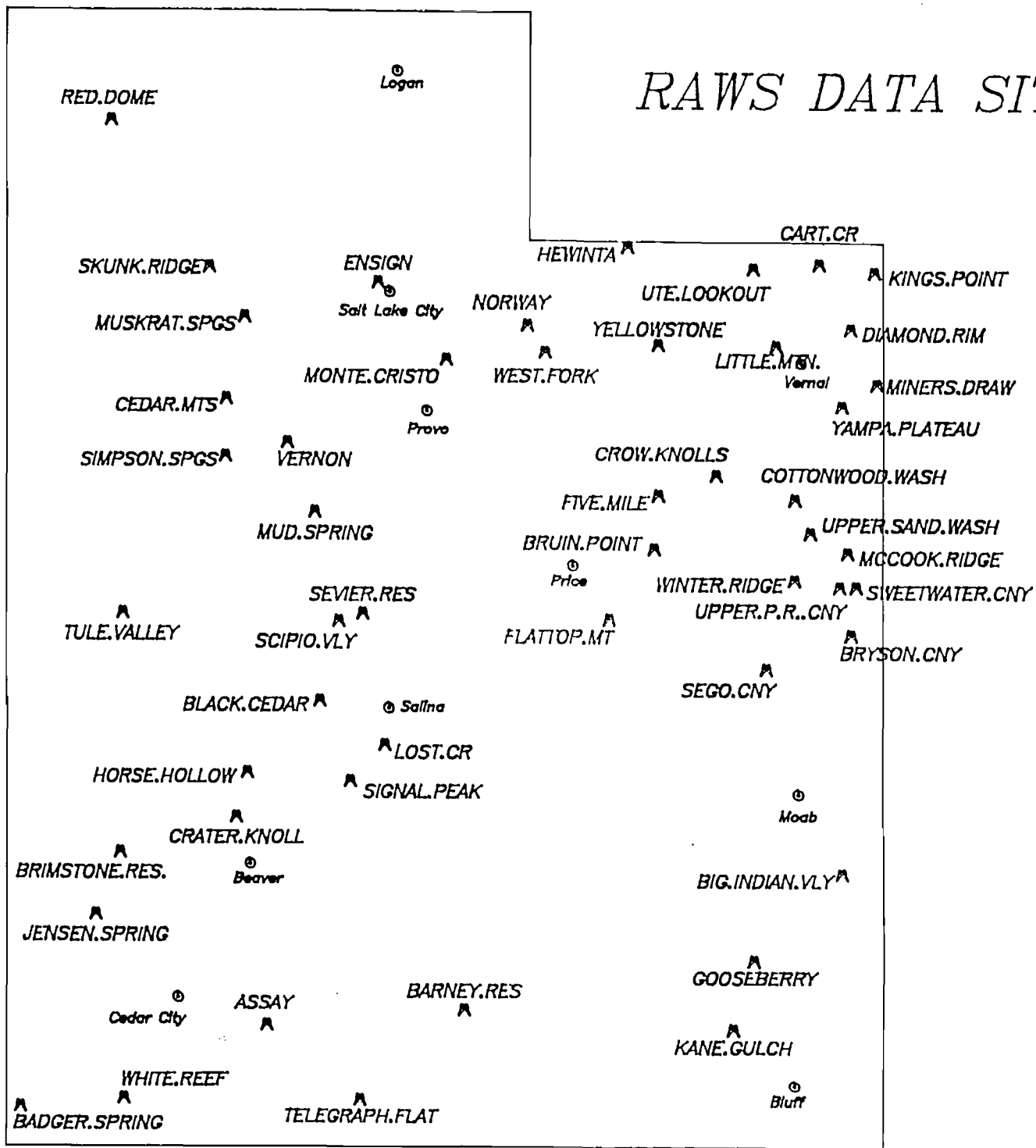
Agency: Western Region Climate Center
Desert Research Institute
Reno, NV

RAWS DATA SET

Precipitation
Mean Wind Speed
Mean Wind Direction
Average Air Temperature
Average Fuel Moisture
Average Relative Humidity
Maximum Wind Speed
Direction of Maximum Wind
Soil Moisture

The platforms are operated by BLM and NFS. Hourly data are transmitted via the GOES system to BIFC in Boise, Idaho.

RAWS DATA SITES - UTAH



75 Miles

50 Sites 9-89

Data Bases Maintained by the U.S. Department of Agriculture,
Forest Service (continued)

SYSTEM NAME: National Fire Weather Data Library (NFWDL)

BRIEF DESCRIPTION: A collection of fire weather observations and forecasts. Observations are from nearly 1800 special fire weather stations in the U.S. The periods of record for each station vary but the earliest beginning dates are about 1960. Only one observation (usually taken early in the afternoon) per station per day and one forecast per fire zone per day are stored.

CONTACT PERSON: Mr. Roger Bradshaw
Aviation and Fire Management
USDA/FS
Boise Interagency Fire Center (BIFC)
3905 Vista Avenue
Boise, ID 83705
FTS 554-2603 or (208) 334-2603

ACCESS POLICY: The data are available to government agencies either by direct access through USDA Ft. Collins Computer Center (FCCC) or indirectly by mail from the contact person, both for computer costs. Access to the FCCC is generally not granted to non-government requestors but copies of the data are available through the contact person. Fees are based on the quantity of work the request generates.

ACCESS LIMITATIONS: None

FORMAT: Government users can access this climatological data directly by computer using either interactive or batch modes or they can obtain the data in hardcopy or tape mediums from the contact person. Non-government users can only obtain the data in hardcopy or tape mediums.

COMMUNICATIONS: Half duplex asynchronous 300 and 1200 BAUD and up to 4800 BAUD synchronous dial-up capabilities are available. TELENET X.25 protocol is available. No error checking available.

SYSTEM DOCUMENTATION: Furman, R.W. and G.E. Brink, 1975. The National Fire Weather Data Library: What It Is and How To Use It. USDA/FS General Technical Report RM-19. Available from Publications Distributions, Rocky Mountain Forest & Range Experiment Station, Ft. Collins, Colorado.

Data Bases Maintained by the U.S. Department of Agriculture,
Forest Service

SYSTEM NAME: Administrative Forest Fire Information & Retrieval
Management System (AFFIRMS)

BRIEF DESCRIPTION: An interactive computer program designed to: 1) manage simultaneous entry of weather observations and forecasts from up to 100 users, 2) make those data (most recent 24 hourly observations and last forecasts) interactively available to other users, 3) automatically send input weather data to a set of National Fire Danger Rating System models and receive back NFDRS indices for system display, and 4) create a magnetic tape on which are stored daily weather observations and forecasts (climatological data available from National Fire Weather Data Library (NFWDL). Data from almost 1400 stations managed by AFFIRMS.

CONTACT PERSON: Mr. Roger Bradshaw
Aviation and Fire Management
USDA/FS
Boise Interagency Fire Center (BIFC)
3905 Vista Avenue
Boise, ID 83705

FTS 554-2603 or (208) 334-2603

ACCESS POLICY: The system is available to the general public for a fee. Contact person has details.

ACCESS LIMITATIONS: Generally, no limitations, except during principle U.S. fire seasons when access may be restricted to fire weather use only.

FORMAT: Real time (last 24 hours) data available only interactively. Climatological data available in hard copy and on tape from NFWDL.

COMMUNICATIONS: Full duplex asynchronous 300 and 1200 baud WATS lines used principally. Access to TELENET, etc., allows up to 9600 baud.

SYSTEM DOCUMENTATION: Helfman, R.S., R.L. Straub and J.E. Deeming, 1980. Users Guide to AFFIRMS: Time Sharing Computerized Processing for Fire Danger Rating. USDA/FS General Technical Report INT-82. Available from Publications Distribution, Rocky Mountain Forest & Range Experiment Station, Ft. Collins, CO.

SITE DOCUMENTATION: Location of weather observation sites available from contact person.

Snow Survey Hydrological Data Bases
USDA /Soil Conservation Service (SCS)

Agency: Data Analysis Group Leader
Soil Conservation Service
511 N.W. Broadway, Rm. 547
Portland, OR 97209

Contact: Kenneth C. Jones (503) 221-2843

System(s): Snow Telemetry (SNOTEL)
(current water year data)

Centralized Forecasting System (CFS)
(current and historical data)

Fort Collins Computer Center (FCCC)
(archived data)

Access Policy: Access to operational and real time data bases available to the general public without charge. Archived data bases can only be accessed by SCS personnel. A fee is charged on a cost recovery basis for major data retrievals from archived files.

Access Limitations: A simple cooperative agreement is required to access SNOTEL and CFS. Archived data requests will be processed by SCS agency contact.

Format: SNOTEL and CFS support interactive access. Hard copy and magnetic tape output is available.

Communications: SNOTEL and CFS support full duplex asynchronous communication at 300 or 1200 BPS. No error checking protocol is presently enabled. Synchronous communication is available on CFS for limited use.

Site Biographies: Site location information including site name, latitude, longitude, elevation, state, and hydrologic unit is available.

Data Stored: Monthly snow course, precipitation, streamflow, and reservoir storage data. Daily SNOTEL data consisting of snow water equivalent, precipitation, and temperature.

DATA BASE INFORMATION

USDA/AGRICULTURE RESEARCH SERVICE(ARS)

The ARS Water Data Base is a national resource of hydrologic data used by research scientists and engineers interested in water-related problems. The REPHLEX system was developed to provide current technologies to the data users of the data base. These procedures still do not always provide information in the form that a user may eventually need. Therefore the system is being modified and moved to new storage media to provide the best possible service to our user community. The basic philosophy of the system will continue to be one which provides the capability to look at the contents of the ARS Water Data Base and to extract portions of that data base for manipulation by the user.

ARS is collecting continuous data from various types of recording equipment. In all cases the data includes variable time-intensity readings known as breakpoint data (Brakensiek, et al, 1979). These data are sufficient to recreate storm hydrographs and rainfall hyetographs. To be of use to scientists in ARS, instantaneous readings need to be retained. The WDC stores rainfall and runoff data with some commonly derived information such as runoff rates in CFS and IN/HR as well as the original gage heights. One accumulation value, calculated on an annual basis, is also stored. An effort was made to eliminate all but these most fundamental data elements because of the number of records involved in storing time-series data from breakpoint readings.

The ARS Water Data Base consists of rainfall and runoff data stored by station year. 'Station year' is used here to signify a calendar year of data for one recording station. In addition to the original data captured by the recording device and the derived information mentioned earlier, the data stored in the ARS Water Data Base has some identifying information and various codes added to each record. Each breakpoint reading is stored as a separate record in the data base. Each station year of data is stored as a separate cataloged data set on magnetic tape. There are, as of June 1, 1988, over 13,000 such data sets, 8,300 and 5,000 station years of precipitation and runoff data, respectively. These data represent information from 305 different study areas varying in size from .2 hectare (0.5 acre) to 536 square kilometers (207 square miles). Rain gage networks have from 1 to more than 200 recording stations per watershed. Length of records for individual stations varies from 1 to 50 years.

Water Data Center
USDA-ARS Hydrology Laboratory
Rm. 139, Bldg. 007, BARC-West
Beltsville, Md. 20705

CONTACT: JANE THURMAN
(301) 344-4411

Tom Thurman

Workshop Data Base Inventory

Agency: Climate Analysis Center, NWS/NOAA

Contact: Jim Laver, (301) 763-8071

Contents: National Climate Assessment Data Base, NCADB

Spacial Domain: U.S. - Cooperative and first order stations. 24-hour rainfall amounts as reported in real time only--not historical/complete.

Time Period: Daily 24-hour precipitation amounts for each of last 40 days (on-line) for each of about 6-10,000 U.S. locations. (note - many stations are "criteria" reporters, i.e. report after first 1/2" is received. Most don't report "0" when no rain has fallen.

Parameters: 24-hour precipitation amount when reported.

Workshop Data Base Inventory

Agency: Climate Analysis Center, NWS/NOAA

Contact: Jim Laver, (301) 763-8071

Contents: Climate Assessment Data Base, CADB

Spacial Domain: Global 6,000 first order stations. (including 2400 U.S. synoptic and airways)

Time Period: Real time. Daily summary information and 3 or 6 hourly reported weather types. About 1,000 individual days (most recent) on-line locally. Archive will soon be available for ~ 10 years.

Parameters: Temperature (max, min, mean)
Precipitation (24-hour total)
R.H. (max, min)
Weather type reported (e.g. RW, SW, TRW)
Miscellaneous others



U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL WEATHER SERVICE

National Meteorological Center
Climate Analysis Center(CAC)
5200 Auth Rd. Room 811
Washington, DC 20233
October 1988

Information on the CAC Climate Dial Up Service (CDUS)

The CDUS provides public, near real-time access to weekly, monthly, and quarterly summaries of current weather and climate data, forecasts, and other data gathered and produced by the National Meteorological Center. You must have a remote terminal, e.g. a personal computer with monitor and keyboard, and a modem in order to use this service.

The CDUS system is menu driven, and accessible by use of your private password code that we issue to you. There is no connection charge for using this system, the only costs are your long distance telephone calling and a graded annual user fee of \$48-\$600, depending on intensity of use. Details and a sample User Agreement are appended.

A sample CDUS Menu and interpretation of the menu codes is attached. The menu contains special data sets of particular interest to those concerned with agriculture and energy, as well as standard sets of weather data. Data in the set you select from the menu is transmitted over telephone lines to the screen of your personal computer in your home or office. It is usually a simple matter for you to have the data go instead directly to your printer or as a new file on your computer's hard or floppy disk.

If you are interested in using this system, please contact Mr. Vernon Patterson, Mr. George Fullwood or Ms. Joanna Dionne at (301)763-8071.

Attachments



DATA SETS CURRENTLY AVAILABLE ON THE CAC DIAL UP SERVICE:

| | |
|------------|---|
| CLIMRANK | MONTHLY AND SEASONAL CLIMATE RANKINGS BY AREAS. |
| DDAYEXP | EXPLANATION OF DEGREE DAY PRODUCTS. |
| → FORECAST | FIVE DAY, SIX-TO-TEN DAY, SEVEN DAY MAXIMUM AND MINIMUM, AND MONTHLY AND SEASONAL OUTLOOKS FOR TEMPERATURE AND PRECIPITATION. WEEKLY HEATING AND COOLING DEGREE DAY FORECASTS. MONTHLY HEATING OR COOLING DEGREE DAY FORECASTS. |
| → GLOBAL | DAILY, WEEKLY AND MONTHLY SUMMARIES OF TEMPERATURE AND PRECIPITATION DATA FOR MORE THAN 6000 LOCATIONS THROUGHOUT THE WORLD. |
| GRODGREE | CUMULATIVE WEEKLY GROWING DEGREE DAYS FOR CORN. |
| HIDYPRCP | HIGH DENSITY PRECIPITATION FOR THE PAST 8 WEEKS WHICH MAY BE ACCESSED BY STATE. |
| MAPS | MAPS OF THE WEEKLY TEMPERATURE PRECIPITATION AND THEIR DEPARTURES FROM NORMAL; MAPS OF THE SIX-TO-TEN DAY FORECAST BY CATEGORY. |
| MFOREIGN | MONTHLY TEMPERATURE AND PRECIPITATION DATA FOR ABOUT 175 FOREIGN CITIES. |
| → MCTYCDDY | MONTHLY COOLING DEGREE DAYS FOR 200 U.S. CITIES. |
| → MCTYHDDY | MONTHLY HEATING DEGREE DAYS FOR 200 U.S. CITIES. |
| MCTYPRCP | MONTHLY PRECIPITATION DATA FOR MORE THAN 200 U.S. CITIES. |
| MCTYTEMP | MONTHLY TEMPERATURE DATA FOR MORE THAN 200 U.S. CITIES. |
| MRECPRCP | COMPARISON OF CURRENT MONTHS PRECIPITATION TO RECORD |
| MRECTEMP | COMPARISON OF CURRENT MONTHS TEMPERATURE TO RECORD |
| MSACDDY | MONTHLY WEIGHTED STATE AVERAGE COOLING DEGREE DAYS. |
| MSAHDDY | MONTHLY WEIGHTED STATE AVERAGE HEATING DEGREE DAYS. |
| PASTDATA | DATA FOR THE PRECEDING THREE WEEKS AND THREE MONTHS SELECTIVELY. |
| PPDNOTE | EXPLANATION OF PROJECTED PALMER DROUGHT INDEX. |
| PPDCENTR | PROJECTED PALMER INDEX CENTRAL U.S. |
| PPDEAST | PROJECTED PALMER INDEX EASTERN U.S. |
| PPDSOUTH | PROJECTED PALMER INDEX SOUTHERN U.S. |
| PPDWEST | PROJECTED PALMER INDEX WESTERN U.S. |
| → SELECT | ALLOWS THE USER TO ACCESS DATA BY STATE. TEMPERATURE AND PRECIPITATION DATA FOR SEVERAL HUNDRED SUPPLEMENTARY STATIONS ARE ACCESSIBLE WITH THIS OPTION. DATA SUBJECTED TO LESS RIGOROUS QUALITY CONTROL THAN PRIMARY STATIONS. |
| WAPTDAT | APPARENT TEMPERATURES AND WIND CHILL FOR THE U.S. |
| WAPTOC | EXPLANATION OF APPARENT TEMPERATURES AND WIND CHILL. |
| → WCTYDDAY | WEEKLY DEGREE DAYS FOR MORE THAN 200 U.S. CITIES. |
| WCTYPRCP | WEEKLY PRECIPITATION DATA FOR MORE THAN 200 U.S. CITIES. |
| → WCTYTEMP | WEEKLY TEMPERATURE DATA FOR MORE THAN 200 U.S. CITIES. |
| WFOREIGN | WEEKLY TEMPERATURE AND PRECIPITATION DATA FOR ABOUT 175 FOREIGN CITIES. |
| WPDNOTE | EXPLANATION OF WEEKLY PALMER DROUGHT INDEX. |
| WPDCENTR | WEEKLY PALMER DROUGHT INDEX FOR THE CENTRAL U.S. |
| WPDEAST | WEEKLY PALMER DROUGHT INDEX FOR THE EASTERN U.S. |
| WPDSOUTH | WEEKLY PALMER DROUGHT INDEX FOR THE SOUTHERN U.S. |
| WPDWEST | WEEKLY PALMER DROUGHT INDEX FOR THE WESTERN U.S. |
| WSACDDY | WEEKLY POPULATION-WEIGHTED STATE AVERAGE COOLING DEGREE DAYS. |
| WSAHDDY | WEEKLY POPULATION-WEIGHTED STATE AVERAGE HEATING DEGREE DAYS. |

WXCLSMYI WEEKLY SUMMARY OF INTERNATIONALLY SIGNIFICANT CLIMATE
 EVENTS.
 WXCLSMYM MONTHLY SUMMARY OF U.S. SIGNIFICANT CLIMATE EVENTS.
 WXCLSMYS SEASONAL SUMMARY OF U.S. SIGNIFICANT CLIMATE EVENTS INCLUDING
 AN ANNUAL SUMMARY WHEN APPROPRIATE.
 WXCLSMYU WEEKLY SUMMARY OF U.S. SIGNIFICANT CLIMATE EVENTS.
 WXCPSMYH INTERNATIONAL WEATHER AND CROP HIGHLIGHTS.
 WXCPSMYI INTERNATIONAL WEATHER AND CROP SUMMARY.
 XTRMES THE EXTREME MAX AND MIN TEMPERATURE AND THE
 TOTAL PRECIPITATION FOR THE PAST 7 DAYS THAT
 WAS FOUND IN OUR DATA BASE.

DATA SETS ARE NORMALLY UPDATED AS FOLLOWS.

CLIMRANK UPDATED EARLY EACH MONTH
 5DAY FCST UPDATED MONDAY THROUGH FRIDAY MORNINGS
 MAX-MIN T THE 7 DAY MAX MIN TEMPERATURE FORECAST IS UPDATED
 DAILY MONDAY THRU FRIDAY MORNINGS.
 6-10DY FC UPDATED MONDAY WEDNESDAY AND FRIDAY LATE AFTERNOON
 DDAY FC THE WEEKLY DEGREE DAY FORECASTS ARE UPDATED BY MONDAY.
 THE MONTHLY DEGREE DAY FORECASTS ARE UPDATED BY THE 3RD.
 HIDYPRCP UPDATE BY MONDAY AFTERNOON.
 OUTLOOKS MONTHLY OUTLOOKS ARE UPDATED ABOUT THE FIRST
 AND 15TH OF THE MONTH. SEASONAL OUTLOOKS ARE
 UPDATED MONTHLY ABOUT THE FIRST OF THE MONTH.
 GLOBAL DAILY DATA UPDATED DAILY, DATA MAY BE UP TO 2 DAYS OLD
 WEEKLY DATA UPDATED MONDAY MORNING
 MONTHLY DATA UPDATED BY THE MORNING OF THE 3RD.
 GRODGREE WEEKLY DATA UPDATED BY MONDAY MORNING.
 MAPS UPDATED WHEN THE TABLES ARE AVAILABLE
 MCTYXXXX UPDATED MONTHLY BY THE MORNING OF THE 3RD
 MFOREIGN UPDATED MONTHLY BY THE MORNING OF THE 3RD
 MRECXXXX UPDATED MONTHLY BY THE 7TH OF THE MONTH
 MSAXXXX UPDATED MONTHLY BY THE MORNING OF THE 3RD
 PASTDATA UPDATED WEEKLY AND MONTHLY
 PPDXXXX UPDATED MONTHLY SOMETIME BETWEEN THE 3RD AND THE 10TH
 WCTYXXXX UPDATED WEEKLY BY MONDAY MORNING
 WFOREIGN UPDATED WEEKLY BY MONDAY MORNING
 WPDXXXXX UPDATED WEEKLY BY TUESDAY MORNING
 WSAXDAY UPDATED WEEKLY BY MONDAY MORNING
 WAPTDAT UPDATED WEEKLY BY MONDAY MORNING
 WXCLSMYI UPDATED WEEKLY TUESDAY AFTERNOON
 WXCLSMYM UPDATED MONTHLY BY THE 7TH
 WXCLSMYS UPDATED EVERY 3 MONTHS BY EARLY MARCH, JUNE, SEPT, & DEC
 WXCLSMYU UPDATED WEEKLY TUESDAY AFTERNOON
 WXCPSMYH UPDATED WEEKLY TUESDAY AFTERNOON
 WXCPSMYI UPDATED WEEKLY WEDNESDAY MORNING
 XTRMES UPDATED MONDAY THROUGH FRIDAY EXCEPT HOLIDAYS.

Data Bases in the Office of Utah State Climatologist

1. Hourly data from remote (RAWS-type) stations located largely in major cultivated agricultural areas. (We have a few in Utah's west desert where there are no NWS stations.)

Data bases are an hourly data base and a daily base.

Daily

- Total solar radiation
- Total precipitation
- Average, Maximum, and minimum temperature
- Average wind speed
- Maximum and minimum relative humidity
- Average, maximum, and minimum soil temperature at 4"

Hourly

- Average radiation intensity
- Average temperature
- Average wind speed
- Vector magnitude wind speed
- Vector direction of wind
- Standard deviation of wind direction
- Total hourly precipitation
- Average relative humidity
- Average soil temperature at 4"

Elements are sampled every two seconds. Averages and vector utilize the 1800 observations each hour.

Number

- 14 started in 1986
- 11 started in 1987
- 13 started in 1988

38 stations

2. Summary of the day which is the National Climatic Data Centers data from Co-op stations. Data base is daily. Maximum temperature, Minimum temperature, precipitation. A few (3 percent) have only precipitation.

Evaporation, wind (daily run at 18"), water temperature (max and min) (once each day humidity). Evaporation data are taken at only about 3 percent of the stations.

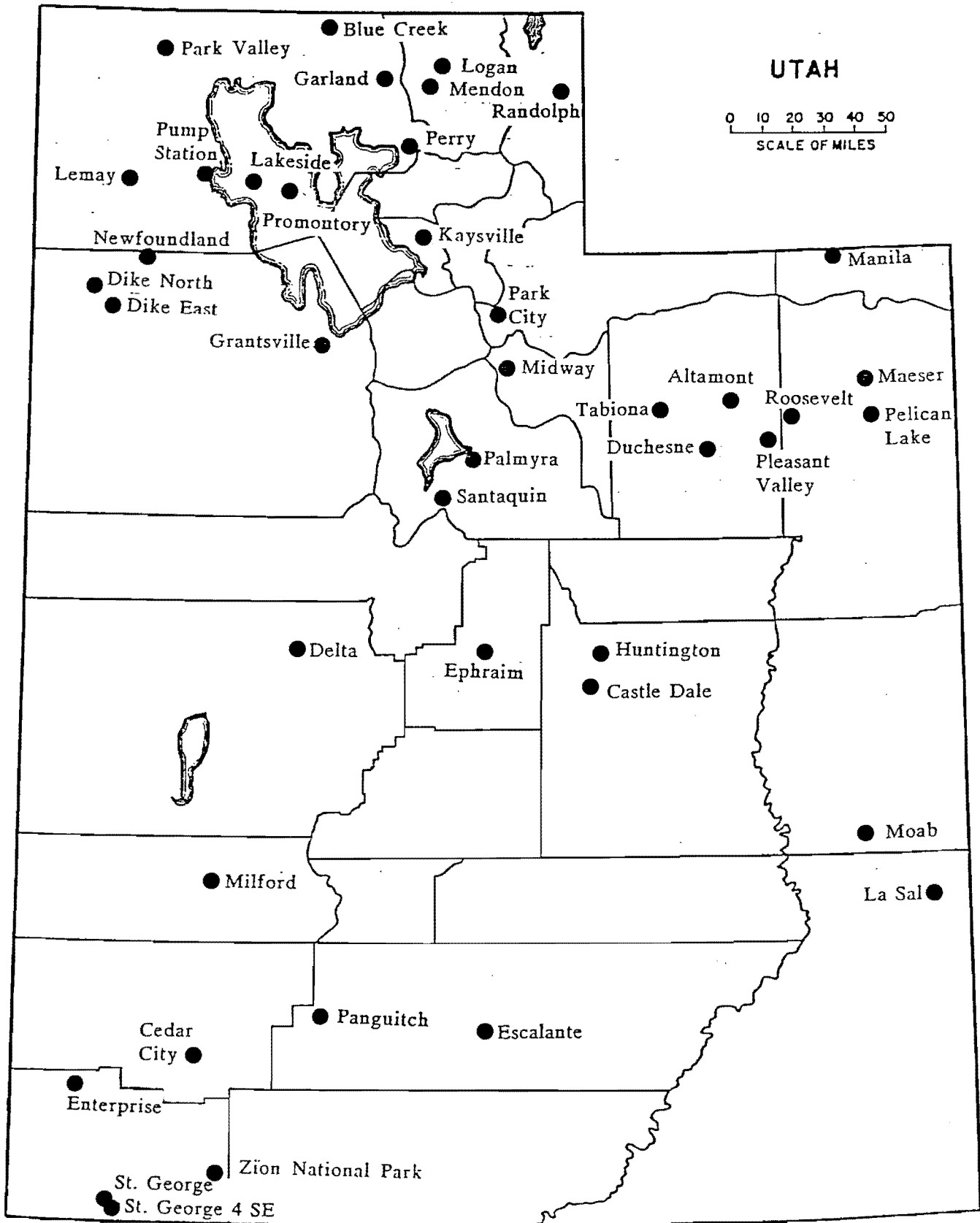
- Soil temperature (max and min at 4")
- Soil temperature (max and min at 8")
- Soil temperature (max and min at 20")
- Soil temperature (max and min at 40")

1 percent of all depths, 1 percent at only 4"

Elements read once daily (usually at morning, evening, or midnight)

Number

680 (approximately) with some period of data between 1948 and the present.
(Electronic media records began in 1948 but 56 stations were taken back to 1930
and 2 stations are for the period of record, late 1800's)



10 20 STATUTE MILES

42 - UTAH

42.0

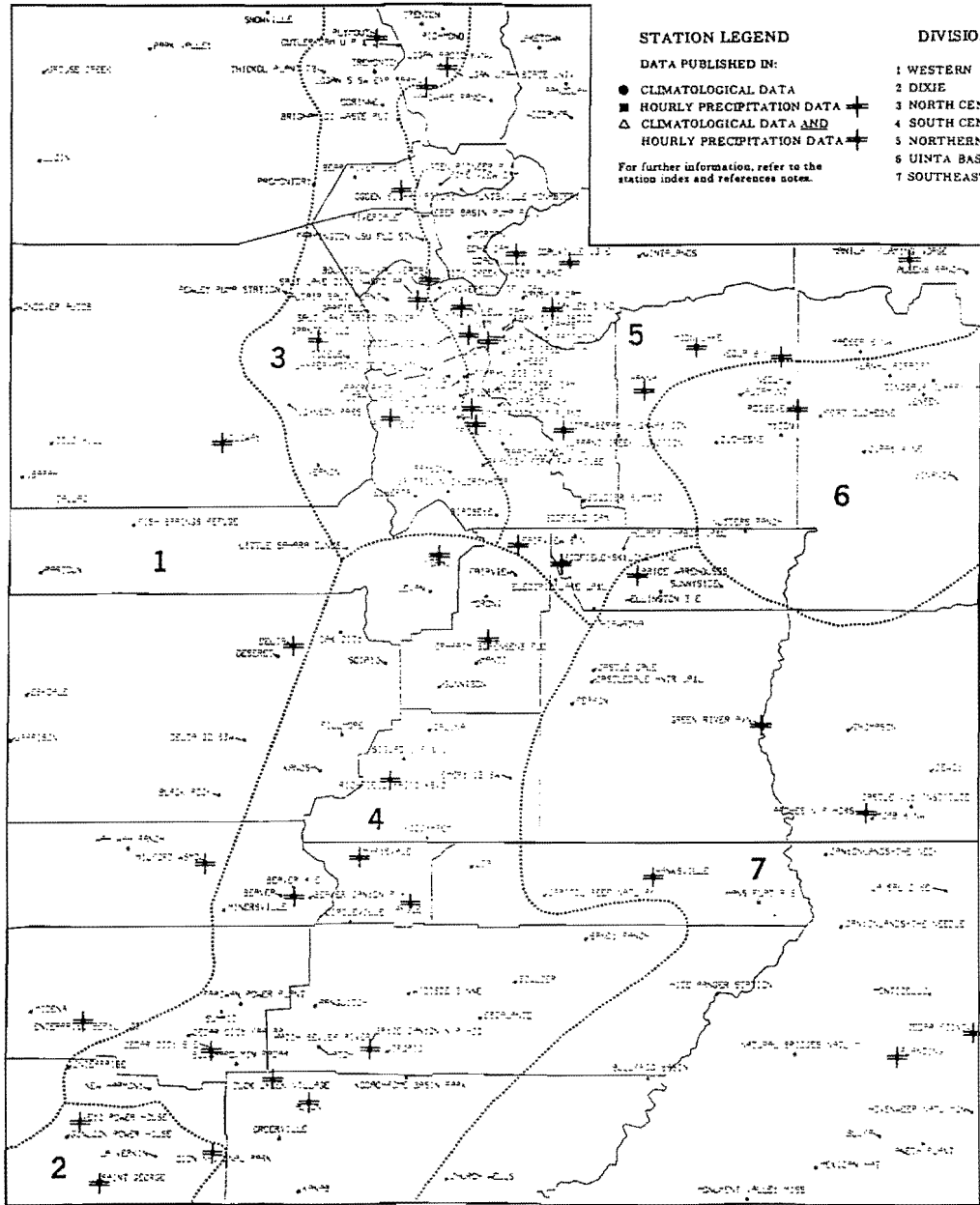
42.0

40.0

40.0

38.0

38.0



STATION LEGEND

DATA PUBLISHED IN:

- CLIMATOLOGICAL DATA
- HOURLY PRECIPITATION DATA
- △ CLIMATOLOGICAL DATA AND HOURLY PRECIPITATION DATA

For further information, refer to the station index and references notes.

DIVISIONS

- 1 WESTERN
- 2 DIXIE
- 3 NORTH CENTRAL
- 4 SOUTH CENTRAL
- 5 NORTHERN MOUNTAINS
- 6 UINTA BASIN
- 7 SOUTHEAST

-114.0

-112.0

-110.0

APPENDIX C

Digital Geographic Data

The purpose of this appendix is to summarize the digital geographic data available for use in this project. Some of this data may be incorporated in a GIS for use in the final product, while some data will only be used in model development. We also give some background information on DEM data and GIS.

Digital Elevation Models

Accurate parameterization of the earth's surface is critical to any modeling study in the meteorologic or hydrologic sciences. In climate studies, accurate surface representation is essential for cyclogenetic and energy budget calculations, and is the critical element for determining the location of precipitation areas in regions of complex terrain (Bourke 1988). In hydrology, accurate surface description is a major consideration for a diversity of studies from watershed modeling to groundwater quality analysis. The recent, widespread application of computer-assisted cartographic methods — in particular digital elevation models — has proven to be a boon to such modeling studies, surpassing manual cartographic methods in terms of both accuracy and efficiency.

Digital Elevation Models

A DEM can be thought of simply as an array of elevation values meant to represent surface features. Elevation values for the models are taken from a variety of sources, including terrestrial surveys, photogrammetric studies, and scanning of existing contour maps.

The formats for a particular DEM are nearly as numerous as the sources from which it is derived, but can be broken down into two basic types. One is the regular grid format, elevation values being entered at a series of regularly spaced points. These may appear as regularly spaced squares, triangles, or hexagons. While regularly spaced hexagons have the greatest information carrying capacity (Burrough 1986) and regularly spaced triangles appear to be the most consistent format in terms of information capacity and minimal redundancy (Peucker 1980a), it is the regularly-spaced square which is the most commonly used format. This format provides aesthetically-pleasing graphics, and has an implicit topology which is an advantage for data storage. Only the elevation need be stored as location is implicit. There is also the advantage of ease of manipulation of the data, although this notion may be overemphasized (Peucker 1980a). The major disadvantages of the regular grid format are the redundancy of data in flat terrain, and a north-south, east-west directionality for the regular square which may be undesirable for certain studies (Peucker 1980b).

The second type of DEM format involves coding elevation values at a number of irregularly spaced points. This format eliminates the data redundancy problem, but loses the implicit topological structure of the regular grid. The irregular grid has the great advantage of retaining more information in areas of complex relief (Burrough 1986), and, as such, is an excellent tool for describing ridge lines and drainage networks. Both the regular and irregular grid formats have deficiencies in adapting to regions of complex terrain. For the regular grid system, the grid mesh must be made very fine, leading to the data redundancy problem previously described, while the irregular system often retains unappealing visual evidence of its formulation (i.e. triangular structures appear in areas of complex relief).

Digital elevation models have seen widespread use, including applications by the U.S. Census Bureau and the U.S. Public Land Survey (Jannace and Ogrosky, 1987). Likewise, the USFS has a long history of DEM use (Gossard 1978; and Martin 1985). Other applications of DEMs, pertinent to this study, are outlined below.

Geographic Information Systems

A GIS is a collection of computer programs in a given hardware environment which operate on a geographic data base to analyze and synthesize data base elements (Robinoue 1986). A geographic data base is a collection of data referenced to spatial location typically stored in a digital form. This spatial data is usually composed of a series of data planes which may be raw data or the result of previous processing.

Geographic information systems include the hardware and software necessary for storage, retrieval, and manipulation of digital elevation data. It allows for easy, rapid updating of records and provides the means necessary to combine different data to create new data structures. The GIS is also the vehicle which provides for the pre-processing of elevation data which is sometimes necessary. Techniques included here involve data editing, format conversion, and coordinate system transformation (see Doyle 1978).

The Use of DEMS in Climate Modeling Studies

Research by Dickinson et al. (1989) serves to illustrate the importance of accurate parameterization of surface features for use within a climate model.

In their paper Dickinson and his colleagues present the results of two different model runs simulating January precipitation values for the Western U. S. In the first run, the researchers used the simulated topography of the coarse resolution Community Climate Model of the National Center for Atmospheric Research (NCAR/CCM). The orographic representation within the NCAR/CCM makes no allowance for the Sierra Nevada or Cascade Ranges, thus leading to unrealistically high precipitation values for the Great Basin. By contrast, the second model run employed the topography of a mesoscale model running within the larger NCAR/CCM (the mesoscale model was the NCAR/Pennsylvania State University Mesoscale Model Version 4, or more simply, the MM4). In the MM4 simulation, there is adequate representation of both Sierra Nevada and Cascade Ranges, and as a result, Great Basin precipitation values fall closer to climatological norms.

Use of DEMS in Hydrologic Studies

In contrast to the paucity of studies dealing explicitly with topography and climate, there exists an abundance of research relating elevation modeling to hydrology. Berich (1985) shows how GIS and DEM have been applied to studies of watershed modeling, groundwater analysis, and reservoir site selection. Similarly, Grayman (1985) notes how the Environmental Protection Agency is using DEMs for floodplain analysis. Drainage networks (Klein 1982; and Yuan and Vanderpool, 1986) and channel slope determination (Gardiner 1982) have also received significant attention.

DEMs have also been used to calculate basin characteristics. In a 1986 paper Wiltshire et al. show that characteristics such as drainage density and stream slopes can be calculated more easily using DEMs than from manual methods. Moreover, new basin characteristics, heretofore unavailable by manual methods, can be developed quickly and efficiently from DEMs. Wiltshire et al. argue that the bur-

geoning computer cartographic technologies will allow better predictive capabilities for the effects of land use change on hydrologic variables.

Mark (1984) provides a review of the basics of drainage network simulation. Several approaches to the automated detection of drainage networks are offered, as well as algorithms for determining the locations of ridge lines and channel networks. Mark makes a case for the inadequacy of digital line graphs in drainage network studies. Digital line graphs derived from existing contour maps often neglect intermittent or seemingly insignificant drainage channels. To remedy these oversights, Mark recommends the use of DEMs with their more complete representation of the drainage network under consideration.

Craig (1980) and Vanderpool (1982) applied computer cartographic methods to the problem of landform erosion. Unlike previous studies that dealt with erosion on only a single slope, the models of Craig and Vanderpool attempt to simulate erosion processes on regional scales. Vanderpool used her ERODE model to study drainage basin development over a 260 km² area near Moab, Utah, while Craig provides an example encompassing approximately 5000 km² in the central Appalachian Mountains. Both authors make the point that research of this sort is possible only through use of digital elevation information.

Excellent summary papers concerning digital elevation models and their applications are available in Douglas (1986) and Wadge (1988). Douglas presents a rather complete review of how channels and ridges are determined using DEMs. Particular attention is focused on the triangular irregular network which has proven so useful in modeling drainage networks. Wadge (1988) reviews various types of gravity flows and the usefulness of GIS and DEM systems in modeling such flows. Wadge notes the critical importance of such systems in assessing the hazards associated with gravity flows and slope instabilities.

Accuracy of Digital Elevation Models

Since it is not possible to completely describe the continuous surface of the earth using DEMs, it is necessary to comment on the accuracy of DEMs. Wadge (1988) notes that a large error entering at a single pixel may manifest itself at other points in the model study. In the case of dynamic flow, this error may eventually lead to the flow proceeding down an incorrect path.

The accuracy of a DEM will ultimately depend on the data source from which the elevation values are derived. For example, the U.S. Geological Survey's (USGS) 1:250,000-scale DEM is derived from digitizing existing 1:250,000-scale contour maps. The accuracy of such a model is approximately 50 feet in flat terrain, 100 feet in moderate terrain, and 200 feet in steep terrain. These values are consistent with the accuracy of the contours on the original map (Elassal and Caruso, USGS Circular 895-B). By contrast, the USGS 7.5-minute DEM developed from aerial photographs can have a vertical accuracy to less than 7 meters vertical RMSE (Elassal and Caruso, USGS Circular 895-B).

To a very real extent, the accuracy of DEM application to a model study will depend also on the logic of the particular GIS employed and the amount of pre-processing performed on the model (Yoeli 1983).

Potential DEM/GIS Application in WEPP

In this project a GIS would probably include the following raw data planes:

- Digital elevation data

- Digital line graph data (roads, rivers, etc.)
- Land cover and land use

The following processed information may be included as additional data planes:

- Model parameters for stochastic generation of precipitation
- Snowmelt model parameters

DEM data may be used for the following aspects of this study:

- Determination of slope, aspect, and horizon angles for the snowmelt modeling.
- Specification of coarse-scale topography for the orographic precipitation modeling.
- Determination of topographic setting for snow accumulation and redistribution. Interaction with land cover data planes may be required here.

Table C-1 lists the digital geographic data that may be of use in this study. Most of the data listed are available from the USGS, National Cartographic Information Center (NCIC) at a very reasonable price (\$90 per order plus \$7 per data set unit of coverage). The USGS 7.5 minute DEM data is available for about one-third of the topographic quadrangles in the U.S. Coverage of the Western U.S. is fairly good with about 50 percent of quadrangles mapped. This number is increasing. The Defense Mapping Agency (DMA) DEM data is available (from the USGS) for the whole country in 1° x 1° units. Twenty-three 1° x 1° units are required to cover Utah. About 400 1° x 1° units are required to cover the Western U.S. The National Oceanic and Atmospheric Administration (NOAA) continental DEM data set is in fact abstracted from the DMA data by taking every 10th data point and profile.

The 7.5 minute and 15 minute planimetric digital data is in digital line graph, or vector format. Coverage is fairly limited with about one-sixth of the quadrangles in the U.S. mapped with at least one of the five categories (boundaries, transportation, hydrography, public land survey, and hypsography). Quadrangles with all five categories mapped are very sparse. The 1:100000 digital planimetric data, also in digital line graph format, is available for the whole U.S.

Table C-1. Digital mapping datasets.

| <i>Name</i> | <i>Supplies</i> | <i>Resolution</i> | <i>Unit of Coverage</i> |
|-------------------------------------|-----------------|-----------------------------|-------------------------|
| 7.5 minute DEC Data | USGS/NCIC | 30m | 7.5 minute gradangles |
| Defense Mapping Agency DEM Data | USGS/NCIC | 3 cm sec (\approx 90m) | 1° quadrangle |
| Continental DEM Data | NOAA | 30 cm sec (\approx 900m) | 4 regions in U.S. |
| 7.5 minute Planimetric Digital Data | USGS/NCIC | (\equiv 1:24000) | 7.5 min quadrangle |
| 15 minute Planimetric Digital Data | USGS/NCIC | (\equiv 1:62500) | 15 min quadrangle |
| 1:100000 Digital Planimetric Data | USGS/NCIC | (\equiv 1:100000) | 30 min quadrangle |

We suggest that the continental DEM data be used for the large scale atmospheric modeling. Storage requirements prohibit use of the DMA data set for the large scale modeling. The local redistribution

and snowmelt models need higher resolution of local topography so we suggest using the DMA DEM data set. Incomplete coverage of the 7.5 minute USGS DEM data set is the reason for not recommending its use. We suggest that the user version of MCLIGEN should be able to access (via a G15) the DMA DEM for the local region so that parameters involved in the stochastic generation and snowmelt modeling can be automatically computed. Data planes containing the 1:100000 digital planimetric data should also be available to facilitate location of the site considered. This could be done by using roads, rivers, contours, etc., displayed on a screen to locate and "click on" the site of interest, rather than having to compute and key in site coordinates. Of course, the user should also have the capability to specify site parameters independent of the GIS.

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