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CRITERIA FOR WEATHER MODIFICATION OPERATIONS AND EFFECTIVE EVALUATION

by

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Introduction

One goal in the research on operational seeding and evaluation techniques (OSET) has been to consider the design of future operational projects in weather modification so as to allow meaningful evaluation for both the user and the scientific community. Major emphasis has been placed on the development of statistical-physical evaluation procedures that are most appropriate in defining the efficacy of operational seeding projects, and, at the same time, provide useful information relating to the physical processes involved in weather modification. Our studies of evaluation methodologies revealed that effective utilization of statistical-physical methods in evaluating the results of weather modification operations is strongly dependent upon careful attention to four basic tasks involved in carrying out cloud seeding activities. These include (1) design of the seeding operations, (2) determination of seeding criteria, (3) the conduct of each seeding mission, and (4) the collection and recording of data for use in subsequent evaluation of the project results. Credibility of weather modification evaluations can only be established through careful attention to all phases of the operational procedures. Reliable evaluation of many past seeding operations has been impossible because of deficiencies in operational procedures, particularly in the collection and recording of pertinent data. This report is aimed at presenting our findings about operational criteria that affect evaluation.

Our view is that skilled evaluation of on-going operational projects during the next 10 to 20 years can be a major source of scientific information to compliment pure experimental efforts of the scientific community. However, this will require future operational projects to become more experimental in nature (and credible) through requirements concerning mode of operation, project instrumentation, data collection, record keeping, and reporting procedures. To be operationally feasible, these requirements must be established within a realistic framework, and this has been one of the objectives of OSET. Thus, in specifying selection of seeding situations through the application of meteorological concepts, such as precipitation prediction variables, it is realistic to require the operator, or project designer (WMAB, 1978) to make use of all available information on the meteorology and climatology of the seeding area. On the other hand, one cannot require the operator to carry out an extensive study of precipitation prediction in the target area prior to initiating operations where a need and demand for weather modification exists. Such studies should be a part of a national scientific effort. Therefore, OSET efforts have been concentrated on establishment of operational criteria that will benefit science without interfering with operational projects conducted when adverse weather has created a need and demand for weather modification. However, it is likely that future state and/or federal regulations will require at least a short, focused study of the meteorological conditions relevant to precipitation forecasting in the operational area (WMAB, 1978).

This part of the Final Report is concerned with our recommendations for effective accomplishment of the four tasks listed earlier. In so doing, we have classified operations into two general types, and have discussed needs and recommendations under each type. The types are (1) the common commercial operation in which all weather situations satisfying the seeding criteria are treated, and (2) the more scientific piggyback operation, or piggybacking of science, in which some randomization is applied. The piggyback operation has been further subdivided into two classes. The first is a limited operation with some randomization and should include a good measure of the treatment variable (hail, rain, snow). This could be satisfied by the inclusion of a 5-cm or 10-cm radar system with routine scope photography, RHI capability, and gain reduction for defining precipitation intensity within the storm echoes. The second piggyback operational approach is one we call the "sky unlimited" type. In it some randomization of seeding days occurs and the amount of supporting instrumentation and measurements are limited only by funds and personnel available for the project. Thus, additions to the limited piggyback operation might include such measurement devices as dense networks of precipitation gages, cloud physics aircraft, upper air stations to supplement the NWS network, Doppler radar, additional satellite data (more frequent and greater resolution than normally transmitted), and surface mesoscale networks to measure various meteorological parameters (wind, temperature, humidity, etc.).

With respect to randomization, the Weather Modification Advisory Board (WMAB) recommends that 1/3 of the qualifying seed days remain untreated in future piggyback operations (WMAB, 1978). Another suggestion has been to carry out the randomization between operations; that is, during periods when weather conditions are identical but when seeding is not needed to modify the natural precipitation. For example, in the Midwest seeding to increase corn and soybean yields with additional rainfall is normally effective only during July and August (Huff and Changnon, 1972). Possibly, randomization requirements could be met in similar June and September rains.

Table 1. Basic Design Steps for Weather Modification Operations.

A. Review, Analysis, and evaluation of synoptic climato logical factors in the target and surrounding area (control).

B. Designation of cloud types that should be seeded (stratiform, isolated cumuliform, organized cumuli form, etc.).

C. Development of cloud seeding criteria.

D. Designation of cloud treatment techniques.

   1. Seeding agent(s) to be employed.
   2. Method of transfer to clouds (aircraft, ground generators, or others).
   3. Location of seeding in cloud (base, mid-level, top, other).
   4. Method of dispersal into cloud (AgI generator, flares, rockets, dry ice dispenser, etc.).
   5. Time(s) of day seeding is to be performed (if selective).
   6. Duration of seeding in each operation.

E. Requirements for facilities and equipment.

   1. Operational center.
   2. Meteorological equipment.
   3. Aircraft.
   4. Ground generators.
   5. Seeding devices.

F. Personnel.

   1. Meteorologist(s).
   2. Aircraft crew.
   3. Instrument technicians and observers.

G. Measurements to be made.

   1. Meteorological.
   2. Aircraft.
   3. Radar.
   4. Other.

Operational Design

The initial task in undertaking any weather modification project is the design of all phases of the operation. The design phase is *very* critical to both the successful operation of the project and to the evaluation of the results. In this initial task, the seeding criteria, facilities and equipment, personnel, operational techniques, and all other aspects of the operations are defined. Only those persons with considerable knowledge and experience in weather modification should be involved. As pointed out by the WMAB (1978), the design team should always consist of persons who are keeping up with the discoveries and innovations in the field of weather resources management. Atmospheric scientists skilled in synoptic meteorology and climatology and in cloud physics and dynamics are highly desirable as team members or as consultants in the design phase of the project.

Table 1 lists in sequence the basic design steps which we consider necessary after the location of a seeding project, the size of the target, starting time, and duration of the project have been established (largely or totally by sponsors). These basic steps should be followed for all weather modification operations, whether they are the regular commercial type (non-randomized), or piggyback (partially randomized).

As the first step in developing the project design, we recommend a review and evaluation of synoptic climatology in the target area for use as a design guide. This applies to both non-randomized and piggyback projects. For example, in an operational project to increase warm season (convective) rainfall, the means and annual variability in the number of thunderstorm days, the frequency of days with rainfall in various intensity categories, and the number of days with severe weather (hail, flash floods, severe thunderstorms) are useful in estimating the frequency of seeding opportunities, the potential for various amounts of seeding-induced rainfall, and the frequency of seeding missions that are likely to be aborted due to severe weather causes. Elliott (1967) has shown various applications of synoptic climatology in designing a cloud seeding program in the southern Sierras. Climatological data on the distribution of precipitation and other weather parameters can be found in summary form in various climatic publications. Three very useful publications are Hydrometeorological Report No. 5 (U.S. Weather Bureau, 1947), the Climatic Atlas of the United States (NOAA, 1977), and Climatology of Surface Fronts (Morgan et a!., 1977).

Before seeding criteria can be firmly established, the type of clouds which are to be treated during the project must be designated. The type(s) will depend upon the seeding purpose, climate of the project area, and time of year. For example, seeding to increase the natural rainfall during the growing season in the Midwest would require seeding primarily of convective clouds, possibly both isolated cumuliform and organized cumuliform, but, in any case, organized weather systems which are responsible for most of the Midwest precipitation during the warm season (Huff, 1969).

Seeding criteria applied in weather modification operations should be based upon acceptable meteorological concepts. These criteria should take advantage of the latest advances in seeding technology and apply useful information revealed by a review of the synoptic climatology of clouds, precipitation, storm systems, and other pertinent weather factors in the project area. Seeding criteria should be based on meteorological factors which are measureable and/or which can be calculated on a routine basis with sufficient frequency and accuracy to satisfy the seeding and evaluation requirements of the project.

The decisions required under cloud treatment techniques (Table 1) are dependent largely upon the preceding decisions regarding type of clouds to be seeded and the seeding criteria to be employed. Under facilities, all operational projects will require an operational center with space adequate for all personnel and equipment. The meteorological equipment will depend upon the type of project, that is commercial (non-randomized) or piggyback. The minimum requirement should be a weather radar set, preferably 5-cm or 10-cm, for real-time monitoring to help recognize seeding opportunities (or lack thereof), to help recognize severe weather events in sufficient time to avoid possible intensification by seeding, and to verify seeding activities over the target area. Needs with respect to aircraft, ground generators, and seeding devices will vary with the type, purpose, and location of the project. The same is true for the items listed under "F" and "G" in Table 1. For example, in "G", "other" in the case of piggyback operations might include additional measurement devices such as precipitation networks, cloud physics aircraft, and whatever the specific project could afford with additional funds supplied by federal or state government agencies.

Determination of Seeding Criteria

Essential in evaluation of any modification operation is specific, well-documented information on the decision-making involved in the initiation of each seeding episode within the project period. The various methods and criteria to be used by the operator in selecting seeding situations should be specified in writing prior to each operational project.

The seeding criteria should be based upon acceptable meteorological concepts determined by meteorologists experienced in weather modification activities (research or operations). Since there may be several decision-making criteria utilized in an operational project, it is essential for later evaluation of treatment results that those used in each specific seeding operation are recorded at the time of the seeding decision. *Seeding criteria should be defined by the operator and the methods used to recognize cloud seeding opportunities clearly stated in the design document.*

Determining seeding potential (seedability) during operations is basically dependent upon synoptic weather forecasts (predictions) and meteorological observations. For prediction of seeding situations, several techniques are commonly used. These include general synoptic weather forecasts, such as issued by NWS, which indicate expectancies with respect to cloudiness, precipitation, temperature, dew point, winds, and other parameters derived from analysis of surface and upper air maps and charts developed from pibals, radiosondes, surface observations, radar observations, and satellite data. Seeding decisions (seedability) may then be based upon various factors, such as precipitable water, winds, type and extent of clouds expected, and natural precipitation expectances.

Cloud models are now frequently used in addition to standard synoptic analyses and forecasts to determine seedability. For convective cloud seeding, these models usually employ readily available morning and evening upper air data. The computer-generated cloud predictions then provide an objective method of determining seedability in a given weather situation.

Radar is now almost universally used on both experimental and commercial projects, since it serves multiple purposes. One of the important uses is as an observation tool to help determine seeding potential as the time for expected favorable seeding conditions approaches. That is, it serves to update and, possibly, modify the seeding decision made earlier from synoptic weather forecasts and/or computer model outputs.

Aircraft observations of various atmospheric parameters (ice nuclei, updraft speed and placement, CCN) are also used by some projects as an aid in determining seedability on any given day. Others may use simpler techniques for determining seedability. For example, in the Whitetop experiment during the early 1960's, the precipitable water from surface to 500 mb at key radiosonde stations and the wind direction at 4000 ft MSL over the target area were used in selecting seedable days (Braham, 1966).

Regardless of how seedability is determined, it is *essential* to have routine measurements of those meteorological factors from which seedability is determined available at a frequency that permits effective analysis and assessment of all weather situations during the operational period. This capability should be a basic requirement whether the weather modification operation is of the experimental, piggyback, or non-randomized commercial variety. For example, in a bare minimum type of commercial operation, the operator, using a ground-based seeding approach, might base his seeding decisions solely on synoptic forecasts derived from NWS charts and maps. In this case, the only requirement is that he have ready access to these, both routinely and expeditiously, whether by facsimile facilities at his operational headquarters, or other means. However, for projects involving on-site observations and control, use of radar and aircraft data are imperative to seedability decisions.

Daily determination of seed and no-seed situations requires certain facilities and equipment to obtain the information upon which to base the seedability decisions. As indicated above, the requirements would vary substantially, depending upon the type of project, funds available, and other factors. Below we have listed some of the considerations that may be inte-' grated into the decision-making, plus the type of facilities and equipment that would be helpful. Implementation of the entire list would occur in piggyback operations only, because of costs involved.

A. Potential Inputs for Determining Seedability.

1. Synoptic forecasts of clouds, precipitation, and other pertinent atmospheric characteristics.
2. Computer prediction of cloud properties from cloud models.
3. Natural precipitation predictions based partially on use of:
   a. Synoptic climatology models;
   b. Predictor variables derived from earlier synoptic studies.
4. Radar and satellite observations of conditions in and upwind of target.
5. Severe weather potential based on:
   a. NWS alerts and warnings;
   b. Radar monitoring;
   c. Updating of synoptic weather analyses.
6. Other.

Implementation of A-1 above requires access to facsimile and/or teletype machines. This is viewed as a basic requirement for most, if not all, commercial and piggyback projects. Only if seedability is being determined strictly from other data, such as radar echoes and/or aircraft observations, could such data reception facilities be omitted. In these cases, however, constant surveillance would appear necessary.

A-2 requires access to an appropriate computer. A-3 would be a desirable product of the design phase that would help in the day-to-day decision making. The utility of radar and satellite observations is obvious. As pointed out earlier, radar provides an excellent check on how the predicted seedability conditions are developing as time progresses.

A-5 is particularly important in the scheduling of seeding operations. The WMAB (1978) has stated that all operational projects should have onsite, real-time monitoring to recognize seeding opportunities and to recognize severe weather events in sufficient time to avoid intensification of such events by seeding. *Radar is an excellent tool for these purposes, and must be part of the equipment in all weather modification operations aimed at increasing or decreasing precipitation (rain, hail, snow).*

A-6 is meant as a broad category for the Type II piggyback operations. That is, it could include input data supplied by telemetered precipitation networks, aircraft observations of cloud parameters, and other sources of data whose inclusion in the project would depend on available funds and personnel.

Cloud Seeding Operations (Missions)

Basic requirements for carrying out seeding missions will differ substantially, depending upon such factors as the type of operation (commercial, or piggyback), the seeding variable (rain, hail, snow), the climatic regime in which the target lies, and the time of the year the seeding is to be conducted. Requirements will also vary depending upon whether aircraft or ground generators are employed to transport the seeding material. Actually, the conduct of the missions is largely defined in the design phase where the type of clouds to be seeded, the seeding criteria, and the method of transport are established.

Except for orographic seeding to increase snowpack, most seeding is now carried out by aircraft in both experimental and commercial projects. A prime consideration in undertaking aircraft seeding is an adequate delivery system to carry out the seeding concept. For example, if the seeding is to be done at the mid-level of convective clouds, the aircraft would need to have an operational capability to fly at least to 20,000 ft. First, however, depending upon the size of the target area, the number of aircraft required to carry out seeding over the entire target must be determined. The aircraft should utilize approved weather modification apparatus for dispensing the seeding agent, whether it be by AgI smoke generators, flares, rockets, dry ice dispenser, or other technique. There must be adequate radio communication both with other aircraft and the ground operational center. In the piggyback operations especially, aircraft measurement of selected cloud parameters may be desirable for later evaluation of the results of the seeding. Also, in the piggyback operations, aircraft position must be recorded at short intervals. Where feasible, the aircraft position should be shown on the radar scope and photographed at intervals of 5 minutes or less. With ground generators, the exact location and seeding output should be known for each individual operation. In all cases, *the primary objective is to carry out cloud seeding through application of techniques dictated by the seeding criteria in use and satisfying other requirements of the project design.*

Components of a typical Type II piggyback operation are outlined below:

A. Aircraft System -- adequate delivery system to carry out seeding concept.

   1. Approved weather modification apparatus (AgI smoke generator, flares, rockets, dry ice dispenser, etc.).
   2. Communication with other aircraft and ground operational center (radio system).

3. Capability of operating at maximum seeding level whether base, mid-level, or cloud tops.
4. Visual observations and logging of these at frequent intervals.
5. Instrumentation for selected meteorological measurements to verify seeding criteria designated by the operator.

B. Radar System.

1. 5-cm or 10-cm wavelength with RHI capability and intensity measure.
2. Scope photographs at frequent intervals (10-min or less).
3. Logs showing any significant changes in operation and/or problems encountered.

C. Visual Observations.

1. Operational center.
2. Aircraft.

D. Precipitation Measurement Systems.

1. Network data (telemetered where feasible).
2. Procurement of NWS and other available precipitation data in and around target area for all operations. Hail insurance data should be included where applicable.

E. Cloud Cameras Upwind and Over Target Area (optional).

F. Others (depending upon funding).

A Type I piggyback operation should be required to use components A, B, and C. A commercial (non-randomized) operation could be limited to A-1 to A-3, plus a radar system. It is not realistic to demand any of the other components unless pertinent to making seedability decisions and/or verifying operational procedures.

Data Collection and Recording

As part of OSET, we have also considered data collection and data handling criteria for operational projects. This includes instrumentation for making the necessary meteorological measurements, types of data to be collected, and the recording and filing of the collected data in the proper forms to facilitate various types of analyses for evaluating the operational results. *Detailed documentation of data is very essential to seeding evaluation and establishment of credibility in the results.*

Instrument requirements should be established through consideration of evaluation needs, but must be kept within realistic limits for operational usage. Optimum instrumentation is not likely to be achieved in the near future.

The WMAB Report (1978) states that "data compilation and archiving from the real-time measurements should be done in a manner that will permit independent analysts to assess the validity of the design and operation. For example, this would include recording the time and placement of each seeding activity; collecting photographic records or radar echoes routinely and with a frequency that permits recognition of the pertinent storm parameters and changes occurring in these parameters; and recording other data about altered weather, such as insurance records of hail claims, streamflow data, and precipitation data recorded in the project area." We consider these requirements reasonable and applicable to all types of piggyback operations. However, the requirement that the operator procure and record all available data in the project area that might be useful in future independent evaluation of the operational results is questionable for the relatively small-scale commercial projects having no governmental support, and usually undertaken on short notice to meet emergency needs for increased precipitation.

For the basic commercial type of operation (non-randomized) with no government financial support (such as is perceived for the piggyback types), it is our opinion that the operator should only be required to provide whatever instrumentation is necessary to determine his seeding criteria and to verify seeding activities over the target. *We consider radar essential to verification and, therefore, view it as a basic requirement for all precipitation modification operations.* More extensive instrumentation will be required in the piggyback operations, the types depending upon the amount of governmental financial support for these modified operational projects. It is our opinion that the installation and operation of precipitation networks for improving the measurement accuracy of the treatment variable (rain, hail, snowpack) should have top priority in the Type II piggyback operations. Depending upon funding, the next priority should be aircraft for measuring key atmospheric variables essential to evaluation of the seeding effects and helpful in solving the causation problem. Additional instrumentation should be optional, and priorities left to the judgment of the project leader. Needs can vary depending upon the location of project, project design, seeding criteria, seeding variable(s), and other factors.

Records must be kept of all pertinent information concerning various results.

Records for the commercial, non-randomized type include:

1. Date of each weather modification activity.
2. Description of type of seeding agent used.
3. Method of disseminating seeding agent (aircraft or ground-based generators).
4. Start and end times of each seeding activity.
5. Duration of each seeding activity in hours and minutes.

6. Amount and rate of dispersal of the seeding agent for each seeding activity.
7. Type of clouds seeded (stratiform, isolated cumuliform, organized cumuliform, or other types).
8. With aircraft seeding —
    a. description of aircraft flight track during each seeding mission;
    b. where clouds were seeded (base, mid-level, top, etc.);
    c. number of clouds or convective entities seeded.
9. Exact location of ground generators (if used).
10. Photographic records or tracings of radar scope at frequent intervals.
11. Description of how seeding decision (seeding criteria) was made for each mission and why seeding missions were not conducted on no-seed days.
12. Description of any operational problems during each seeding operation relating to equipment, personnel, weather conditions, etc.

With *Type II piggyback operations,* recording of additional data, such as that listed below, could be required as part of each mission depending upon its availability.

A. Aircraft — logs showing details of position with time, plus other observations deemed important.
B. Radar scope photographs showing both weather conditions and aircraft locations.
C. Radar logs showing all significant changes in operations during seeding mission.
D. Precipitation data -- special network(s) plus NWS and other sources in area of interest.
E. Visual observations by ground and aircraft personnel, if part of seeding criteria.
F. Cloud camera film, if part of seeding criteria and/or verification.
G. Other -- depending upon project funding -- could include one or more of the following:
    1. aircraft cloud measurements;
    2. Doppler radar data;
    3. special upper air soundings;
    4. special satellite data (increased frequency and resolution).

Requirements for data collection and recording are essentially the same for the non-randomized commercial and Type I piggyback projects, with two exceptions. With Type I piggyback operations, radar scope photography is a basic requirement (tracings unacceptable), and available precipitation records (NWS and other sources) should be included. Also, maps, charts, cloud model outputs or other information used in reaching the seeding decisions should be archived. It is anticipated also that designated seeding criteria are likely to involve more data analysis than many of the relatively small-scale commercial projects, so that the amount of data collected and stored will be somewhat greater on the Type I piggyback projects. *In general, all data used in any way in the planning and execution of precipitation modification projects should be archived in the most expeditious manner.* With the Type II piggyback projects, the data collection and record keeping will be substantially expanded. These projects should have precipitation network data in addition to that archived in the Type I operations, and in some cases, aircraft observations, upper air data, and other project measurements will be available for assistance in evaluation of seeding success and associated research.

Key Issues and Recommendations

Weather modification operations include two general types. These are (1) the common commercial operation in which all weather situations satisfying the seeding criteria are treated, and (2) the more scientific piggyback operation in which instrumentation is more comprehensive and some randomization is applied. Basic requirements for the two types of operations will differ substantially, but both can employ operational criteria that will benefit science without interfering with operations conducted when adverse weather has created a need and demand for weather modification.

Successful weather modification operations and credibility in subsequent evaluation of the results requires careful attention to four basic tasks. These include the (1) design of the operation; (2) determination of seeding criteria; (3) conduct of each seeding mission; and (4) collection and recording of all data pertinent to evaluation.

Design

- A key to evaluation, and a meaningful project, is attention to project design. The basic design steps are specified in Table 1, and it is important that these be specified in writing before project operations begin.
- Atmospheric scientists skilled in synoptic meteorology and climatology and in cloud physics and dynamics are highly desirable as members or consultants to the design team for weather modification operations of all types.

Seeding Criteria

- Seeding criteria should be based on acceptable meteorological concepts, take advantage of the latest advances in seeding technology, and apply useful information revealed by a review of the synoptic climatology of clouds, precipitation, storm systems, and other pertinent weather factors in the project area.
- Seeding criteria should be defined in detail by the operator and the methods used to recognize cloud seeding opportunities clearly stated in the design document.
- It is essential to have routine measurements of those meteorological factors from which seedability is determined made at a frequency that permits effective

analysis and assessment of all weather situations during the operational period. This should be a basic requirement for all types of weather modification operations.

Seeding Missions

- Basic requirements for carrying out seeding missions will differ substantially depending upon such factors as the type of operation (commercial or piggyback), the seeding variable (rain, hail, snow), the climatic region in which the target lies, the time of the year, and whether aircraft or ground generators are used to transport the seeding material. In all types of seeding missions, however, the primary objective must be to carry out the cloud treatment by applying those techniques dictated by the seeding criteria in use and satisfying any other requirements of the project design.
- Radar is viewed as a basic requirement for all precipitation modification operations. It is an excellent tool for real-time monitoring to recognize seeding opportunities, to reassess seedability predictions, and to recognize severe weather events in sufficient time to abort seeding missions. Furthermore, radar is essential to verification of seeding activities over the target area.
- In Type II piggyback operations, it is our opinion that installation and operation of precipitation networks for improving the measurement accuracy of the treatment variable (rain, hail, snowpack) should have top priority. Second priority should be aircraft for measuring key atmospheric variables that are essential to evaluation of seeding effects and helpful in addressing the causation problem. Additional instrumentation should be optional and left to the judgment of the project leader.

Recording of Data

- Detailed documentation of data is essential to seeding evaluation and establishment of credibility in the results. In general, all data used in any way in the planning and execution of precipitation modification projects should be archived in the most expeditious manner. This could best be achieved by a state or federal depository for the essential records. For example, the Illinois law requires submission of certain records at specified intervals during and following completion of operations (Illinois Rules and Regulations, 1979).

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Sources of Specific Weather Data by Date of Occurrence

Climatological Data. Daily, monthly, and annual data on precipitation and temperature at all stations operated by the Environmental Data and Information Service, NOAA. Summarized by State on monthly and annual basis. Available from National Climatic Center, Asheville, N.C.

Local Climatological Data. More detailed information on precipitation and temperature than provided by the State Climatological Data, and includes data on wind and other climatological factors. Available only for selected stations (mostly first-order stations). Published by the Environmental Data and Information Service, NOAA, Available from National Climatic Center, Asheville, N.C.

Hourly Precipitation Data. Hourly data for recording raingage stations operated by NOAA, Crops of Engineers, and other cooperating agencies. Monthly summaries published by Environmental Data and Information Service, NOAA. Available from National Climatic Center, Asheville, N.C.