ATMOSPHERIC RESEARCH FOR THE NATION'S ENERGY PROGRAM

A REPORT TO NSF OF A WORKSHOP HELD AT NCAR

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ATMOSPHERIC RESEARCH
FOR THE NATION'S ENERGY PROGRAM

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EXECUTIVE SUMMARY

Energy production, distribution and use will need to be continuously "managed" into the indefinite future. Part of this management will involve an understanding of how our future energy uses will affect the global environment and how the global environment will affect our energy uses.

The atmospheric system is intimately linked to energy production and to environmental impact. Of special importance is the extreme variability of weather and climate and their pervasive nature in almost all phases of human activities. The atmosphere may have been too lightly regarded for its energy relationships in recent decades.

The Dixie Lee Ray Report The Nation's Energy Future recommended increased basic research in those areas of the social and physical sciences related to energy systems and their uses. The atmospheric sciences can contribute substantially to research in this area.

The present report identifies those parts of various energy systems which are especially sensitive to weather variability. The report focuses attention on those aspects of the atmospheric sciences which could contribute substantially to improved utilization, efficiency, and conservation of future energy systems and resources.

From the text of the report we select and recommend a significant increase in basic research in the following areas of the atmospheric sciences:

- Short-range and long-range specification and prediction of weather variables directly related to energy system operations.

- Atmospheric dispersion and chemical transformations of pollutants, particularly in the planetary boundary layer.
- The control of radiation and temperature through cloud modification.
- Micrometeorological and microclimatic effects on agricultural productivity and efficiency.

In addition, we recommend any energy-oriented basic research program in the atmospheric sciences participate in the emerging redirection of the nation's global atmospheric research program (GARP) to assure relevance of climatic information to energy problems.

We recognize the probability of success may be small in the areas of extended-range forecasting and certain aspects of weather modification. However, these probabilities are not zero, and almost any measure of success could have a great impact on energy systems.

INTRODUCTION: SCOPE OF THE REPORT

This report results from a workshop held at the National Center for Atmospheric Research (NCAR) September 30 - October 3, 1974, with the objective of relating meteorological research "to the proposed national energy research and development program." The group, in fact, met to respond to the Dixie Lee Ray Report The Nation's Energy Future.

Participants in the workshop included meteorological scientists and meteorologists involved in the commercial application of the science, together with experts in the engineering and economics of the electrical and petroleum industries. The workshop was supported by the National Science Foundation (NSF) through the office of Energy Related General Research and the Atmospheric Sciences Section.

There are existing research programs in virtually all aspects of meteorology. Recent developments in computer modeling and observational capability will enable many programs to move ahead significantly. This report determined where different approaches are justified by the new emphasis on energy, drawing support from the new meteorological capabilities. The goal of such research is long-term benefit, consistent with the time scale for benefits from basic studies.

This report seeks to identify the areas where improved weather science and technology offer potentials for a particularly large benefit to the national energy picture, and assesses our capabilities for achieving these potentials. The report recommends research priorities and a framework to help stimulate the efforts of the atmopsheric science community.

The report is divided into three sections:

1. A section which delineates the relationship of meteorological and climatological phenomena as related to energy;
2. A section on measuring and forecasting meteorological and climatological phenomena; and
3. A summary of findings and recommendations.

I. ENERGY PROBLEMS AND ISSUES RELATED TO WEATHER AND CLIMATE

Carefully prepared quantitative estimates of the value of improved forecasts to various sectors of the United States economy are simply not available at this time.

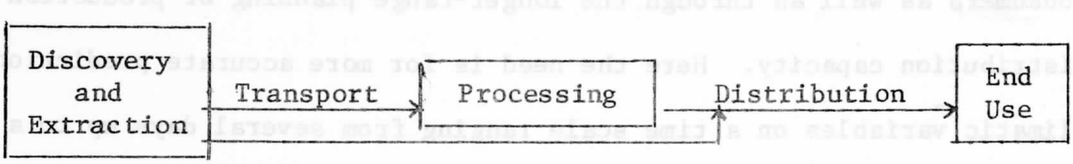
The few existing studies[1] do not specifically address the use of weather information by the nation's energy systems.

For this reason, the following discussions on energy problems and issues are couched in qualitative terms. We recommend a thorough and systematic assessment be undertaken at an early date on the use and value of forecast information by energy systems. The results of this analysis can help channel the research effort to improve forecasts in those directions promising the greatest social payoff.

A. Weather and Energy Systems

Weather influences all energy delivery systems. Better weather information can increase the efficiency of energy systems. In general, energy systems share the functional components shown in Figure 1.

Figure 1. Basic Components of Energy Systems



As the figure shows, some basic energy commodities are usable for direct consumption after extraction. But most energy goods go through several components of the energy system.

[1] J. A. Russo examined the impact of adverse weather on the construction industry in a report published in 1965 by the Travelers Research Center of Hartford, Connecticut. J. C. Thompson produced a quantitative overview of the potential benefits of improved forecasting in a report published in 1972 by California State University at San Jose. The World Meteorological Organization has sponsored a small number of studies evaluating the benefits of national weather services.

Effective management of such systems requires planning immediate operations and formulating long-range projections associated with changes in capacity to produce energy. Thus, both short- and long-range weather and climate should be explicitly incorporated into the decision models to optimize planning.

This is necessary since different components of the energy system are subject to weather losses of two types:

1. Sensitivity of the components to physical damage from severe weather events, and
2. Sensitivity to weather fluctuations, creating variations in energy demand.

With sufficiently accurate warnings of the impending event, system losses of the first kind can often be reduced by appropriate protective measures, with minimum response times of a few hours to a day.

System losses of the second kind are less visible but no less real. Losses can be substantially reduced through the timely adjustment of inventory levels and flows of supplies from primary producer to ultimate consumers as well as through the longer-range planning of production and distribution capacity. Here the need is for more accurate prediction of climatic variables on a time scale ranging from several days up to a few years.

(1) Short-Term Impact on Energy Delivery Systems

"Short-term" forecasts relate to periods from one hour up to one week. This could be further subdivided into periods from one to twelve hours and from one day to one week. It will be clear from the context when one of these subperiods is especially appropriate.

The significant and increasing sensitivity of regional and hourly load patterns of electric utilities to weather conditions must be considered by utility management in solving problems arising in the design and operation of large interconnected electric power systems. Unlike other energy forms, electric energy cannot be stored or held to meet future demands. It must be produced to satisfy the immediate demand of consumers. Service reliability is an objective of the industry. Each production system must be able to (1) meet the present needs of its customers, and (2) plan for the future needs of its service area. To do this, industry planners prepare both short-term and long-term forecasts of electric energy demand.

To meet the demands of its customers on an hour-to-hour and day-to-day operational basis, an electric utility must "load" the most efficient generating facilities located closest to the load centers before less efficient units are brought into service. In addition, to provide reliability of service, the system must have "spinning reserve" capacity[2] to meet the load requirements if any of the loaded generating units malfunction.

If the system operator knows the level and location of system loads during the next several hours, he can then optimize system performance in terms of lowest cost of generation and most efficient transmission of energy. The system's hourly loads are affected by diurnal variation in temperature, isolation, and other weather variables. Thus, increased precision of short-term mesoscale forecasts of these variables could result in more efficient dispatch and control of the system.

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[2] "Spinning reserve" is composed of units which are operating, but carrying no load, and immediately available if required. It represents only a portion of a utility's reserve capacity and varies with the load on the system.

Weather forecasts for one to seven days would provide management with advanced warning of severe local weather conditions. For example, advanced knowledge of the severe icing conditions in the Northeast in December 1973 would have enabled utility management to take preparatory actions reducing the level and duration of the electric outage. Moreover such forecasts could increase efficiency in the utilization of electric energy by providing residential, commercial and industrial users with reliable weather information on which to base actions related to their use and conservation of energy.

(2) Medium- to Long-Term Impact on Energy Delivery Systems

More accurate 15 to 45 day weather forecasts could mean more efficient resource allocation by private firms and a consequent reduction in the relative cost of energy to consumers. Accurately forecasting protracted periods of unusually high or low mean temperatures or premature seasonal changes would generate information with a high marginal value of all components of the energy systems.

Improved weather forecasts can lower energy costs by allowing time for more efficient adjustments of fuel production, inventory levels, and plant maintenance. Spot shortages of petroleum products and coal experienced in the United States during the 1972-73 and 1973-74 winter seasons could have been partially averted by improved weather forecasting. Unexpected curtailments in the supply of natural gas can be caused by an early, severe winter. In the absence of advance weather prediction, firms will plan for the normal curtailment period, which may begin in early October. Being caught short in September by an unanticipated onset of winter conditions will increase costs of production to the affected firms and, if substitutes are not immediately available, productive facilities must be shut down. Indeed, improved weather forecasting will have even greater value as the gas crisis worsens and the Federal Energy Administration becomes more involved in planning fuel allocation. Extended-range forecasting is of even greater utility to the suppliers of fossil fuels. They could improve planning of inventory levels, mine output and refinery yield patterns. From 1% to 3% of total petroleum inventories are actually available as deliverable supply. The electrical industry has effectively zero inventory. Because energy systems operate at low inventory levels, unexpected weather changes often result in market distortions and high costs to consumers. Improved weather forecasting will permit better planning of import requirements worldwide if sufficient advance notice is available.

Long-term planners of energy systems must consider meteorological events and climatological data in planning facilities both for production and for distribution. Again, the large interconnected electric utility systems provide a good example. This industry is extremely capital intensive, requiring an average investment of $142,000 per employee.[3] A high percentage of this is invested in base load production facilities which have a planning-construction lead time of approximately ten years. This long lead time presents an acute problem because electric utility loads are becoming increasingly sensitive to weather as our society tends to utilize greater numbers of electrically powered devices such as

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[3] *Fortune*, July 1974, pp. 124-125.

air-conditioners and electric heating systems whose use varies with weather changes.[4] Weather variables such as temperature, humidity, wind speed and precipitation significantly affect these responses and their values must be estimated. Long-term forecasts of the extreme value distribution of these variables would be of great value to the industry in planning future facilities.[5]

B. <u>Boundary Layer Phenomena and Energy Policy</u>

Almost all of the impact of the weather and climate on man's activities, including his energy systems, is focused in the planetary boundary layer, i.e., that part of the atmosphere mixed and stirred by its frictional relation to the earth surface.

There are real conflicts between the objectives of adequate energy production and a livable atmospheric environmental quality. Meteorological research must lead to effective and enduring coexistence between these dual and conflicting objectives.

Two major problem areas badly need definitive research:

1. The specification and prediction of atmospheric diffusion and dispersion over time scales of one to twenty-four hours and distance scales of zero to 100 miles; and

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[4]This trend is likely to continue. Air-conditioning is becoming more popular in the northern areas and electric heating may be chosen by more homeowners in view of the impending critical shortage of natural gas and the supply problems of the oil industry.

[5]Given that a typical 1000 MW base load nuclear generating facility will cost approximately $600 million and that carrying charges approximate 15%, there could be a significant potential cost to society of bringing such a unit to the operational stage before it is required.

2. Fundamental studies of chemical reactions among trace gases in a turbulent and often nonhomogeneously mixed atmosphere.

Human diseases and the accelerated destruction of structures and artifacts are associated with periodic exposures to unusually high concentrations of man-made pollutants. This has given rise to regulatory controls which limit the use of the atmosphere for waste disposal. In the United States, these regulatory systems are still in an evolutionary state, but they have already had a major impact on energy production. They pose constraints on fuels which can be used and they require pollution abatement systems which add appreciably to the costs of energy production or conversion. Restrictions on the sulfur content of fuels used in power production have increased the use of low sulfur fuels, which have become a scarce resource. These restrictions have also led to substantial investments in pre- or post-combustion sulfur compound removal and storage. Similarly, concerns for the environmental impact of radionuclides which might be released from nuclear power and fuel processing facilities have tended to retard the expanded use of nuclear power plants.

In addition, secondary pollutants are formed by chemical reactions in the atmosphere. Adequate understanding is not yet available on the formation of irritants and plant damaging compounds (loosely termed photochemical smog) out of relatively innocuous oxides of nitrogen, hydrocarbons, and water vapor. A further concern is the health effects of sulfates, which are formed in complex reaction systems involving SO_2, NH_3 metallic ions, water vapor, sunlight, and, possibly, the oxides of nitrogen. Our present knowledge of cause and effect associated with multiple pollutants and numerous reactions involving them is incomplete.

More examples of this sort will emerge and call for regulation of associated primary pollutants in the future. The impact of such constraints on energy production is likely to become increasingly severe.

Information on atmospheric boundary layer phenomena would help in the allocation of various types and qualities of fossil fuel in combustion facilities under the constraints embodied in air pollution standards or goals.

Pollution exposures are determined by the planetary boundary layer processes of pollutant transport, mixing, transformation, and removal. More and better information on boundary layer phenomena will facilitate both short-term (e.g., fuel switching) and long-term (e.g., plant location) planning for energy systems. These allocation decisions will have significant consequences for the major fossil fuel burning industries, including electrical generation, basic metal, pulp and paper, and the petrochemical group.

Atmospheric diffusion, dispersion, and chemical reaction rates are highly variable, both in time and geographic location. Damaging air pollution episodes are determined by these atmospheric variabilities and the combination of pollutant sources in a given area. Quite literally, atmospheric variabilities are a valuable waste disposal resource. High dispersion rates and low reaction rates (the two tend to go together) allow permissible pollutant emission rates to be at least 1000 times greater than when dispersion is minimal and reaction rates are high. If time-variable emission controls for large sources (such as energy production plants) can be devised, the use of variable atmospheric dispersion and reaction rates could make it possible to minimize the use of scarce or expensive fuels while maintaining desirable levels of air quality.

C. Meteorology and Energy in Agriculture

The lowest few meters of the atmosphere--the biolayer--abound in opportunities for basic atmospheric science. Fluxes of energy, momentum, gases, particulates, and events across interfaces can be treated quantitatively to explain and refine relationships vital to man's well being, particularly concerning agriculture.

Crop production involves a large consumption of energy. Energy consumption per unit of crop output is steadily increasing while total worldwide consumption is increasing at an even greater rate.

The proportion of total United States energy output used by agriculture ranges from approximately 6% to 13%, depending on whether the processing and distribution of food is included in the calculation.

The energy is consumed locally to cultivate crops, and consumed remotely to provide water, fertilizer, and other inputs. Even small improvements in productive efficiency offer disproportionate energy savings, due to the relative importance of these activities. Large gains in efficiency are possible, with atmospheric science providing a key link.

For example, in comparison to subsistence farming, experimental plots can give 20 times as much plant product per kilogram of water used. To do research in the effect of a particular cultivation technique, such as the application of a fertilizer, requires a faster way of evaluating the result than weighing after harvest is completed and many weather factors have complicated the relation between cause and effect. Direct measurement of CO_2 eddy flux down onto the crop would show the photosynthesis rate and the plant growth rate. Such a measurement is feasible and, employed as part of a larger program probing the microclimate and heat and water fluxes of the growing crop, would be a worthwhile basic study.

Fertilizer is a major end product of the energy cycle. Petroleum based fertilizers account for approximately 5% of all crude oil used in the United States. Optimum use of fertilizers depends upon precipitation conditions (e.g., avoidance of intense rainfall and washout) as well as insolation, wind conditions, soil temperature and moisture conditions. Short-term forecasts (from 1 day to several days) of these parameters, combined with appropriate scheduling of planting and fertilizing,can permit major savings in the use of fertilizer.

In many farm areas, pumping for irrigation is the largest consumptive use of electric energy during the growing season. Electric energy demand can be reduced, and water resources conserved, by utilizing regional precipitation forecasts ranging over periods from one day to several days. For accurate projections of irrigation requirements these precipitation forecasts should include location, intensity, amount and anticipated duration.

The choice of crop mix (for example, the planting of 100-day corn instead of 120-day corn, if the planting time is expected to be delayed in the spring) can minimize the risk of major crop loss due to early frosts. Long-term predictions of air and soil temperature and of cloud cover and precipitation can improve decision making with respect to crop rotation because of the time required to acquire seed and prepare the soil for different crops.

The deposition of insecticide on plants is related to particle size, the natural micrometeorology of flow within the crop, and plant physiology -- with added aspects such as particle electrification, evaporation, and turbulence introduced by the dispersing method. Another issue is assessment of a particular soil treatment aimed at decreasing evaporative losses of valuable soil moisture. The total potential for energy saving in agriculture throughout the United States and the world is substantial while the benefits in delaying or avoiding the onset of major famines are even larger.

D. Weather Modification and Energy

(1) Advertent Modification

When Dr. Schaefer first dropped a few pounds of dry ice into a supercooled stratus cloud deck in 1946, the hole cut in the cloud had an effect not generally appreciated. An additional 1,000 megawatts of solar radiation reached the ground. This observation dramatizes the way in which man, intentionally or unintentionally, can strongly modify atmospheric energy with small inputs. All the energy aspects of weather are on occasion subject to man-caused modification. The challenge for the future is to develop basic understanding of the conditions under which weather modification can produce beneficial energy effects or avoid deleterious effects, and to develop the technology to recognize these conditions and act on them.

Weather modification has received considerable research impetus in the United States during the past two decades. But there has been relatively little intentional control or avoidance of harmful inadvertent effects. There still exists a large area of uncertainty about the consequences of intentional modification of the large, complex weather phenomena which constitute the important weather events. This is especially true of the downwind effects from large seeding programs. Further basic research will narrow the area of uncertainty and bring more portions of the weather modification field to the point where actions with favorable benefit/cost ratios may be conducted. The research will refine physical and numerical models which relate weather effects to the inputs controllable by man.

Man's main modification tools are:

1. Particles which locally control nucleation (freezing or condensation) of atmospheric water or which alter radiation;
2. Alteration of radiation properties of surfaces; and
3, Direct alteration of heat or moisture.

Weather phenomena and these tools can be linked for energy benefits in several ways. Some of these are already under active investigation or are employed operationally.

Increased precipitation from warm or cold clouds has already provided hydroelectric power, water for crops which would otherwise be unobtainable or would require an energy cost if provided by other means, and water to remove heat and waste products from fueled power plants.

Ice storms, tornados, hurricanes, hailstorms, blizzards, floods and any other extreme weather phenomena which interrupt transportation and communication and destroy lives and property all place special demands on energy systems. Research is presently under way in the modification of severe winter storms, hailstorms, and hurricanes, and any advances in treating these and other severe storms will be of great value. Influencing the intensity (or path) of severe storms conserves energy otherwise consumed in the reconstruction and repair of storm-caused damage.

An ability to effectively disperse warm fog would greatly reduce the quantities of jet fuel now burned by aircraft in holding patterns or being rerouted to alternative destinations.

The augmentation of winter snowpack, while somewhat better understood than many other aspects of deliberate modification, is an area with obvious benefits to the production of hydroelectric power, and in which there are still important unanswered questions, particularly with respect to downwind processes.

There presently is no specific effort aimed at modifying clouds to affect radiation and temperature at the ground. The creation of clouds can alter radiation and hence surface temperatures in ways desired for direct and indirect effects. Cirrus produced from seeded cumulus clouds can temporarily shield a city in summer and decrease the requirements for cooling of buildings. Cloud shadow will also inhibit the loss of water to the atmosphere by evaporation. A low stratus deck at night, generated by locally augmenting humidity by water spray or (in special cold situations) by seeding with freezing nuclei, could serve as a heat shield of long-wave radiation, thus keeping the ground warm. This decreases man's energy requirements on cold nights, sometimes can decrease crop freezing, and incidentally inhibits the creation of strong inversions which keep pollutants from being diluted by mixing. Cutting holes in fog and stratus clouds will let the ground surface get cooler at night (or even in the day at high latitudes) and warmer during the day if there are not higher clouds shielding the sun.

Obviously, cloud reduction would be helpful for solar energy systems. With supercooled stratus clouds simple seeding produces large effects, which provides a practical and already well developed tool that could be used more extensively and more effectively. With warm stratus clouds, effective tools are not yet available. Effects have been produced by hygroscopic particles, electrification, carbon black and aircraft down-wash. The tailoring or engineering of such techniques deserves attention, as does the investigation of other approaches.

While solar heating and cooling systems are still a subject of intense research activity, the renewable energy resource represented by solar radiation will soon be tapped on a significant scale. The feasibility of systems designed to convert solar heat into useful energy will depend heavily on the extent to which extended periods of cloud cover can be avoided. If clouds can systematically be manipulated to alter radiation and thus surface temperatures, numerous opportunities will arise to increase the useful yield of solar conversion systems and reduce the demand for cooling caused by unwanted accumulations of waste heat.

In agriculture, significant savings in energy could be derived from an improved understanding and wider application of the processes involved in augmenting precipitation, including the intimately related techniques of hail suppression. Such energy savings would arise by reducing the requirements to pump groundwater and (in an even more substantial way) from the enhanced ability to produce any given level of farm output with smaller quantities of energy-intensive inputs through reductions in crop damage due to hail and drought.

(2) Inadvertent Modification

Many of man's inadvertent effects on weather are tied to energy sources. The gases and particulates emitted during the combustion of fossil fuels in electric generating plants, homes, factories and vehicles constitute such a large source as to clearly produce effects on the weather. The heat released in urban areas from energy consumption and from the different heat storage and radiation characteristics in comparison to natural areas constitutes a man-made perturbation of the atmosphere. On the global scale, the burning of fossil fuel results in increasing the concentration of carbon dioxide in our atmosphere which affects the global radiation balance.

As the weather consequences of the emission of heat or material become better known the real impact of a particular energy strategy can be assessed. There are current studies researching inadvertent weather modification and local heat effects of "power parks" and urban concentrations, but the importance of the subject and the difficulties of handling it dictate greater attention must be devoted to these problems. Specifically, improved mesoscale and boundary layer models now being developed should be used to assess these effects.

Not enough is known about the regional and global effects of very large point sources of water vapor, particulates and waste heat, such as are represented by the newer power generation facilities of economically efficient size. The operation of these plants is critically affected by the sites selected for them, with interactions which cannot only affect the efficiency of their output, but also create conditions leading to increased use of energy in adjacent activities.

II. MEASURING AND FORECASTING METEOROLOGICAL AND CLIMATOLOGICAL PHENOMENA

A. Why New Observations Are Required

Progress in the atmospheric sciences depends on a balanced mix of theory and observation. Theory can specify what observations are important. Observations can give insight so improved theory can be synthesized and tested.

The very wide scales of atmospheric phenomena make the task of providing meaningful observations very challenging. But man's ability to observe the atmosphere has been greatly enhanced in the past decade by the wide variety of new platforms in space, in the atmosphere and in the sea, and from rapid progress in the techniques of remote and in situ sensing. We now need to couple these new sensing techniques to the specific observational requirements of the entire planetary boundary layer, the dynamics of cloud systems which are candidates for modification through seeding, and transport processes in the surface biolayer.

Experienced gained in developing the global observing system for the First GARP Global Experiment (FGGE) has already demonstrated the handsome payoff possible when the observing system closely matches requirements. Indeed, a close match between the needs of theory and what is being proposed can even be tested via simulation models before the entire system is commited. Thus a careful specification of what is needed can lead to a flurry of activity in instrument development directed toward meeting these specific needs. Engineering and technology will surely rise to the challenge if requirements are spelled out and resources made available in a timely manner.

B. Observations for Climate Physics: A Special Problem

Our climate determines a large component of man's energy needs and knowing man's future needs will assist wisely evaluation of energy resources. Progress in the ability to predict climate 10 years hence will be severely limited until some special observations are obtained. One of the most important of these relates to clouds. The global distribution of clouds at various heights, their radiative properties and the physics of the interactions of such characteristics are all a function of the large-scale atmospheric behavior.

Clouds are the shutters for the globe. They not only control the sunlight; they also control the heat loss from the earth to space. Few prediction models include clouds, and none at this time properly account for cloud control of radiation transfer. The models do not need to account for every cloud in the atmosphere, rather a limited volume average effect of the cloud. Therefore, a set of special observations is needed to learn how to model the effects of clouds.

This is one of several sets of observations necessary to understand important physical and/or chemical processes so they can be included in climate models. Others (noted at the recent Stockholm Conference on the Physical Basis of Climate Modelling) are:

- wind induced mixing and heat budget of the upper ocean layer,
- the heat budget of sea ice and snow covered land, and
- the storage of water in the soil.

Climate models will not be successful unless they include some, if not all of, the processes listed above.

In order to test the fidelity of these climate models, other observations are required to determine if they are working properly. These include:

- three dimensional climatology of extended cloudiness,
- planetary radiative balance,
- extent of snow and sea ice,
- precipitation over the oceans, and
- depletion of soil moisture.

An extended series of these observations will be extremely helpful in devising simpler climate models, because they provide information on the variations in the parameters which control climate.

Finally, observations are needed of slowly varying elements of the ocean-atmosphere-cryosphere system that is our planet. These include:

- runoff from main river basins,
- thickness and extent of polar sheets, and
- deep ocean circulation,

and also of external factors such as:

- ozone and CO_2 content of the atmosphere,
- atmospheric aerosols, and
- integrated solar flux.

Many additional details are given in the document produced by the Stockholm Conference. It states what should be done. Man's future ability to determine climatic variations will depend on what is actually done to solve these key problems. As these climate physics observations become available, man's capacity to understand climate variations will be greatly enhanced.

C. Weather Forecasting and Prediction

(1) Introduction

Forecasting techniques and skill differ with forecast period. Maximum skill is found in the one to three day range using dynamical methods for numerical weather prediction. These methods are currently being extended to a week or more in the Global Atmospheric Research Program (GARP). Monthly and seasonal forecasts based largely on statistical methods presently exhibit marginal skill, but we can expect improvement from increased understanding of climate physics. For severe mesoscale disturbances up to 12 hours, special observational communication problems limiting forecast skill are being overcome. This section describes in more detail present forecast skill and research directions for improvement.

(2) Present Forecast Skill

(a) Short-range

Several techniques using dynamical and statistical methods can be used for objective forecasting of the large-scale motion of the atmosphere. The relative skill of a recent experimental set of these for winter forecasts of the 500 mb height field is shown in Figure 2. Note that forecasts without a statistical regression step approach, at late time, an error level greater by a factor $2^{1/2}$ than those with regression. The latter forecasts approach the climate mean forecast, since errors are filtered out.

The observed error growth arises in comparable degree from uncertainty in the determination of the initial state and inadequacies of the forecasting models. The first objective of the GARP is to extend the range of forecast skill by at least a factor of two through refinement of both observational and modelling capabilities.

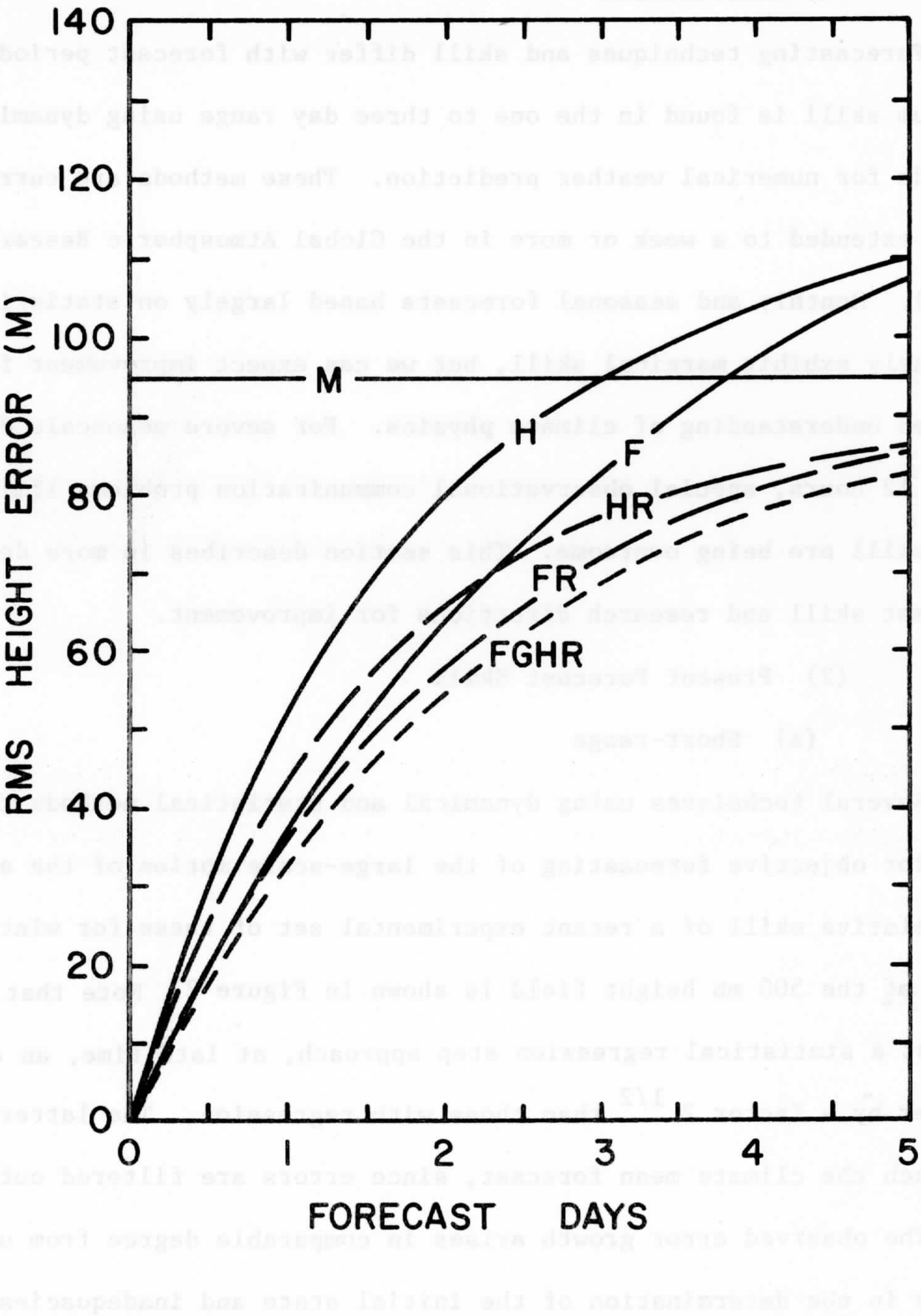

Fig. 2 Root mean square forecast height error vs. forecast period for various forecasting techniques. Climate mean (M), persistence of the initial height field (H), barotropic model (F), regression using the initial field (HR), regression using the barotropic forecast (FR), multiple regression using the barotropic forecast field, another barotropic forecast field starting 1/2 day earlier, and the initial height field (FGHR).

(b) Long-range

Forecasts of anomalies of 30-day averages have been issued every 15 days for many years by the National Weather Service (NWS). There is some tendency for anomalies to persist for a period of a month, thus a persistence forecast does have some slight skill. The NWS 30-day forecasts are significantly better than persistence forecasts for temperature and no worse for precipitation. However, these forecasts only shift the probabilities of various outcomes. Experience has shown, for example, the probability of a temperature being in a certain category called "much above average" is 11% with no forecast, 23% with a forecast of "much above average," and 2% with a forecast of "much below average." For other categories, the relative shifts in probability are smaller. As expected, analysis has shown most of the skill is found in the first half of the forecast period.

Seasonal forecasts, i.e., of anomalies of 90-day averages, have also been made by the NWS for many years but have been published only for about a year. There is no significant skill in either persistence or NWS forecasts for precipitation. For temperature, however, both persistence and NWS forecasts have slight, but equally significant skill. For example, the probability of "above average" temperature is 29% with no forecast, 38% with a forecast of "above average," and 23% with a forecast of "below average."

(3) Toward Improved Forecast Skill

As has been pointed out already, an improvement in short-range forecast skill is expected to come out of GARP efforts. A second objective of GARP is an improved understanding of the physical causes of climate change, and progress toward this will lead to improved long-range forecast skill. Current studies of the influence on the atmosphere of sea surface temperature anomalies and of ice and snow cover should indicate what component of monthly and seasonal average temperature and precipitation anomalies may be predictable as contrasted with the unpredictable change arising from the statistical fluctuations of random weather.

For longer-range forecasts, the inherently linear statistical methods may compete favorable with nonlinear dynamical methods. Thus by frequency-spectral and cross-spectral analysis guided by dynamical studies, it may be possible to find slowly changing predictors for regression prediction of perturbations in mean atmospheric properties. Even marginal improvements in long-range forecasting skill are important for improved energy utilization.

(4) Severe Storm Forecasts

There is also need for forecasts of the relatively small or mesoscale behavior causing severe weather and disruptive, violent storms. Mesoscale motions are inherently only predictable for short times, but even a few hours warning of severe weather can be of value.

Two general difficulties have slowed progress in developing mesoscale (12-hour forecasts). Many of the simplifying approximations valid for large-scale motions break down for these smaller scales. Moreover, observations are needed with an accuracy, resolution, and frequency far greater than can be easily handled by conventional observing and processing systems. Progress in the solution of theoretical difficulties is likely to involve not only the testing of mesoscale numerical dynamical models, but also the further development of methods. The NWS model output statistics methods based on observed statistical correlations between large-scale behavior and the development of violent storms are an example.

As for the observational problem, the situtation is changing rapidly. Recent development of remote sensing techniques, both earthbound and satellite-based, show much promise. For example, a new operational geostationary satellite, SMS-1, has been launched and is providing superb visible light images with 1/2-mile resolution during dalight, and infrared images with 4-mile resolution at 1/2-hour intervals both day and night. From these images quantitative information is available on wind, cloud growth, and boundary layer properties. The new AFOS communication system being developed by NOAA will lead to more rapid processing and transfer of such mesoscale information.

These statistical-dynamical models have not yet been fashioned into the needed short-range forecast tools, nor have the important delivery systems been completed for dissiminating the forecast information. Research and development in these areas could yield substantial benefit in terms of the ability to pinpoint severe weather systems ranging from tornados to hurricanes. This would lead to fewer disruptions to the energy system and, with an adequate delivery system, fewer disruptions to society with their attendant increased energy costs.

(5) Boundary Layer Research Requirements

Two major areas of fundamental meteorological research should be accelerated sharply to provide the necessary input of meteorological factors to the design and operation of time-variable pollutant emission systems and the setting of corresponding standards. First, better definition is required from both theory and experiment of the variability of atmospheric diffusion and dispersion in the planetary boundary layer, particularly in complex terrain. Significant advances in this area are now possible, thanks to much improved theoretical understanding provided by the work of Deardorff, Lumley and Tennekes, Donaldson, and others. This research should reduce present errors in concentration predictions from a factor of 2 to 10 (depending on the time of averaging) in ideal terrain conditions to a factor of less than two, and to produce reliable prediction systems for complex terrain situations in terms of large-scale atmospheric flow.

There are a number of classes of "complex terrain" situations which must be considered, since human habitation and activities occur in widely differing locations. Prominent among these in the environment-energy context, however, are land-sea locales, montain-valley complexes, and rolling lands with variable surface roughness, such as forests, croplands and urban structures. These variations in surface conditions have profound effects on air flow and atmospheric stability, in turn controlling atmospheric transport and diffusion. Some relatively simple terrain complexities can be treated theoretically; for the most part, however, both the theoretical models and the experimental data are inadequate. Research improving the specification of dispersion in complex terrain should be coupled with criteria defining an adequate level of knowledge and predictability.

The second research requirement calls for more reliable prediction systems of the combined effects of turbulent mixing, variable atmospheric temperatures and water vapor content, and multiple, non homogeneously mixed pollutants on important atmospheric chemical reactions. The conversion of SO_2 to SO_4 would be an excellent and timely problem for a new basic research thrust in this large and difficult field. More important, however, is the development of a fundamental understanding of the workings of the complex turbulent flow reactor which is the polluted atmospheric boundary layer.

Such knowledge will be useful beyond the consideration of energy production and utilization, but it may be critical to the resolution of the atmospheric environment/energy dilemma.

Recent theoretical developments have shown the processes of atmospheric diffusion and fast chemical reactions cannot be treated separately, i.e., in decoupled models.[6] The development and verification of coupled models, for energy-related air pollution systems, is badly needed. In addition, more accurate models of atmospheric dispersion and a better specification of chemical reaction systems, including rate constants, are also required.

The state-of-the-art in these areas has reached the point where some fundamental studies could produce useful results in one to three years. An early payoff, particularly in terms of the design of new energy production facilities, can be expected from such a research investment.

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[6] G.R. Hilst, 1974

III. FINDINGS AND RECOMMENDATIONS

Mostly, humanity must accept what nature gives or brings. Men and women are not as invulnerable to nature as they often vainly assume. We recommend a study of the ways in which energy systems now utilize forecast information and of possible improvements in their decision-making processes with respect to such information.

Weather and climate vary on short-term and long-term time scales. They vary enough to cause major impact on our needs, use, production and distribution of energy.

Timely warning on the progression of weather -- today, tomorrow, next week or next year -- will allow better response within the needs and boundaries of rational action.

There is under way a substantial effort to improve the understanding and ability to predict and control the atmosphere. This effort has not focused on energy issues. The omission seems surprising, at least from the perspective of 1975.

In this report we identify additional research areas that can contribute directly to the nations's energy program:

1. The nation's energy system is sensitive to weather and climate. Forecast information can reduce losses and interruptions. Improving the accuracy of forecasts on several time scales and the delivery system for this information will provide real benefits. We recommend efforts to improve both.
2. The production of energy requires dumping of combustion products and waste heat into the atmosphere and hydrosphere. Thus, man is faced with an environment energy dilemma. New theory and

new observational tools will enable man to resolve this dilemma rationally. We recommend research programs on the behavior of the boundary layer over simple and complex terrain so the location and use of facilities can be better planned.

3. Atmospheric sciences have already provided some ability to enhance or remove some types of clouds. More effective techniques will be particularly important in making maximum use of solar energy and reducing the energy consumed in hot weather cooling processes. We recommend studies directed toward determining the potential of these techniques over a variety of local climate situations.
4. Agriculture is a heavy user of energy, requiring the expenditure of up to 10 times the fuel energy produced in the form of food energy. We recommend research into methods of micrometeorological control of the biolayer aimed at reducing the energy demands of the food system.
5. The nation is planning a large effort to obtain a new set of climate physics observations. We recommend this program be accelerated and existing data collected by scientists be assembled into information on climate physics parameters with the view of more rapidly gaining insights into how the climate machine operates. Increased understanding here could have profound benefits.
6. All aspects of atmospheric science impact the energy system to some degree. We recommend reserving some support to accommodate truly innovative, albeit high risk, research efforts that may contribute to the nation's energy program.

Advances in all these directions will enhance the capability to deal with the most long-term task for the atmospheric sciences, which is to predict how humanity's future energy use will effect the global atmospheric environment and vice versa.

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