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Forecasting, Forecasting[1]

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Abstract: Future improvements in the meteorological forecasts used in fire management will come from improvements in three areas: observational systems, forecast techniques, and postprocessing of forecasts and better integration of this information into the fire management process.

A look at the role that meteorology will play in fire management in the year 2000 is really a look at the science and art of fire management, and only in part at what the science and technology of the atmospheric sciences will be able to provide to meet those management needs. To discuss the atmospheric sciences and technologies for the year 2000, assume what fire management needs will be. Since I take on the dual task of forecasting fire management needs as well as the supporting science and technologies of the atmospheric sciences, I will begin by describing the forecast process itself.

The first step in forecasting is accurately assessing the current situation. In the atmospheric sciences, this involves comprehensive observation and analysis of the current weather. I will assume here that a full understanding of current fire management is also required to forecast the future; for example, how priorities are established in dispatching crews and equipment when resources are limited. In the atmospheric sciences, physics dictate an orderly, albeit sometimes rapid, change to a new situation. This physical memory of the past has, I believe, an analog in management.

The second step in forecasting is identifying and quantifying those forces that will produce change. For example, how rapidly will tropical moisture move northward into the Rocky Mountains and produce lightning-started fires? Or, when will the upper air trough move onshore, and when will the Santa Ana wind decrease? Again, I believe that there is a predictable, parallel process in fire management in which a given starting point and a rate of change can be used to predict the future. In this case, they are not based on Newton's laws, but are of equal importance in producing change.

I identify here only three of the possible forces of change in fire management. First, economic use of crews, equipment, etc., on a national scale is a strong force. Pre-positioning of shared resources, i.e., crews and equipment, based on weather forecasts is one example. Fire intelligence will need potential fire severity forecasts on a national scale from a range of 1 week to 1 month. Second is the need for emergency response when life and property are immediately threatened by wildfire. The urban-wildland interfaces--such as the Los Angeles Basin, suburban Hobart and Mount Wellington, the Wasatch Front of Utah. the Dandenongs of Melbourne, and the front range of Colorado--have rapidly been urbanized. There, traditional wildfire fuels combine with high value structures and, frequently, with limited transportation systems. Rapid deployment and dispatch of fire crews and equipment may need to

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be supported by short-range forecasts or emergency response meteorological support activity. The third management force is in continued support of fire danger on the short-time scales. Forecasts of specific manning and action levels of preparedness will probably not change.

The third step in forecasting is adding or subtracting the accumulated change to or from the initial assessment of the situation. If the initial assessment was correct, and the quantitative evaluation of change was correct, then the initial value plus the change should produce a perfect forecast. The initial assessments of both meteorology and management, however, are imperfect. Also, imperfect are the assessments of change.

Given this imperfect initial state and imperfect forecast of change, what is the value or information contained in the forecast? Given a perfect analysis of the current or initial state, the ability to forecast change decreases rapidly as the forecast period increases. Also, the spatial resolution of those weather forecasts tend to contain only information for large areas as the forecast period increases. At what uncertainty in the forecast, either in time or in spatial resolution, does the forecast contain no useful information? When does a fire manager decide to bet on climatology rather than the forecast?

Using this summary of the forecast process, the initial state, the forces of change, the final state, and the value of information, I will state the three assumptions I have imposed on fire management:

1. Economics will dictate sharing of resources between geographic areas--a national fire intelligence system will be using meteorology more effectively.

2. Fire emergency response centers will integrate meteorology into the decision process.

3. Information content and quality of forecasts will be integrated into the decision process; i.e., probability forecasts.

Given these three assumptions and the forecast process described above, I will address the topics of observations, forecasting, and use of weather information.

Under the Observational System. I address the probable state-of-the-art in assessing the current situation; under Weather Forecasting, the tools that will exist or will be needed to provide an assessment of the future; and under Using Weather Information, how one might use these forecasts in fire management.

THE OBSERVATIONAL SYSTEM

Recent procedures in observing weather for fire management were based on manual techniques of reading dials and gauges, weighing fuel sticks, and categorically describing the sky. Of necessity, these weather observations were made only where and when personnel were available. As a result, the observations were seasonal--namely during the fire season--were limited to nominally once per day, and were occasionally not available when personnel had higher priorities. Observations of upper air winds and temperature (stability) to support smoke management decisions were usually at locations far removed from the sites of prescribed burns. Also, the variations of upper air winds and stability induced by complex terrain further reduced the information content of these weather observations. Lack of reliable upper air winds data and temperatures also prevented prediction of probabilities of crown fires or long-distance spotting. In essence, the limited weather observing system gave both fire managers and weather forecasters an imperfect assessment of the initial situation to which the forecast changes were to be applied. Simply stated, a perfect forecast of change applied to an imperfect knowledge of the current situation will lead to an imperfect forecast.

What currently in development or research stages will allow a more accurate assessment of the current state of weather? Four significant activities all noted here. First is the development and deployment of remote automatic weather stations (RAWS) (Wolfson 1987). These surface-based weather observing platforms do not require personnel and, therefore, may be placed where observations are most needed. RAWS transmit data through geostationary satellites to a central receiver at frequent intervals. A network of RAMS properly deployed provides frequent weather observations at critical locations and, therefore, improves assessment of the current situation. Second, is the development of the automated lightning detection system (Vance and Krider 1978). Like RAWS, the lightning detection system provides temporal and spatial weather information and is fully automated. A third type of system under development is designed to provide upper air winds. These systems, NEXTRAD (Next Generation of Radar) and Profile (Durham and Wilk 1987, Chadwick and Hassell 1987), are also automated and have data telemetry capabilities. These three fully automated data collection systems for surface weather, upper air winds, and lightning detection have real-time communication capabilities to both centralized and dispersed decision centers. These systems are the observation platforms of the future, which will provide a more accurate assessment of the current weather.

Unless these data collection systems are deployed correctly, however, we still may inaccurately assess the current situation. This leads to the fourth significant development and research activity in weather observations. That is, determine how many of these data collection platforms are needed and where to obtain the desired level of assessment of current weather? The first three activities described above are primarily engineering activities. This fourth development addresses data sampling procedures, information content, and acceptable margin of error (Fujioka 1986; Jacobson and Brucker 1985). In particular, I will describe a current research program to obtain optimal weather station deployment.

The first step in determining where to locate weather stations is to define those weather elements, or combination of elements, that are critical to the operational decision. An example of where these sampling techniques might be used are in designing air quality networks of sampling locations to determine total air pollution burden. Another example is in designing rainfall measuring networks for water yield or flood prediction. A third example, and the one that I will use to describe this process, is for fire danger and fire behavior assessment.

A common means of integrating weather into fire management in the United States is by assigning a manning or action preparedness level to a particular value of burning index. It is determined from the cumulative distribution of historical values of that index. In the United States, the burning index is a measure of fire behavior, in particular the Byram flame length (Byram 1959), and is composed of rate-of-spread of a fire (Rothermel 1972) and the energy output of that fire (Deeming and others 1972). Fire behavior and fire danger are dependent on the nature of fuels; however, my intent here is to determine the spatial variability of weather rather than fuels. The integrating variable for fire management then should take on the meteorological characteristics of the burning index, but exclude variations of that index produced by nonmeteorological factors, namely fuels. For this reason, the target variable is defined as the fire weather index (Fosberg 1978). The fire weather index maintains the appropriate weightings of humidity, windspeed, and temperature, while limiting the effects of fuels variability. Hence, it is an index of weather that is linearly related in windspeed and relative humidity response to the burning index and fire behavior, the target variable for fire management.

Because the spatial variability of weather as well as what the weather is at a specific point are concerns, I introduce the concept of field (spatial) variation. The new term, target field, describes the combination of the target variable and the spatial variation of that variable. In the following example, that target field is the fire weather index, which is composed of temperature, humidity, and windspeed. Procedures to develop a target field are better left to a paper on that specific topic. I will only outline the general procedure here.

Selection of weather events is particularly important in developing a target field. An assessment of weather events or situations in which management decisions are critical are used to determine the data base for the target field, i.e., the decisionmaker has an important role in this process. Examples of significant weather events include the southern California Santa Ana (McCutchan and Schroeder 1973) and the Hudson Bay High of the Lake States (Schroeder and others 1964). Once these critical events have been identified, a variety of objective and subjective analyses of the weather data lead to a quantitative spatial description of the target field. These analysis techniques involve computer simulations of physical processes. statistical analysis of climatological data, and subjective interpretation and adjustments of the target field. The target field is defined in a form consistent with Geographic Information Systems (GIS), in that spatial position of observations and interpolation of those data can be used in a number of analyses. We have chosen to convert the observed target field data to a high resolution Cartesian coordinate grid of north-south and east-west parallel lines, and this digitized data base is then treated as perfect. Nonlinear, optimal interpolation techniques (Fujioka 1986) are then used to find those locations that will minimize the error between the perfect data and the depiction of those points with an assumed number of sample points (weather stations). If 2000 data points are in the GIS and the problem is where to place 2000 weather stations, we would find those locations coinciding with the data base and containing no error. If, more realistically, the problem is where to place 50 or 100 weather stations in that array of spatially distributed data, we would find that the error is not zero. and is greater with 50 stations than with 100 weather stations. The total error in spatial estimates will decrease exponentially as the number of weather stations increases; however, these errors do not decrease uniformly over the geographic area.

Acknowledging error, and that the errors are not uniformly distributed in space, brings us back to management's role in the design of an observational network. The analytical techniques (Fujioka 1986; Jacobson and Brucker 1985) allow the fire manager to develop a number of scenarios. These scenarios are played against the total error and the localized pockets of persistent error. The fire manager can pose a series of scenarios:

1. Number of weather stations that will be installed.
2. External external weather data, for example, National Weather Service (NWS) and Federal Aviation Administration (FAA) observations that will be used.
3. Areas that will be excluded from observation (wilderness areas).
4. Areas where resource values are high and require observations.
5. Alternative sites to minimize impacts of localized error.

In all the scenarios, the fire manager has control of the weather station network design. A proposed 50-fire weather station network for southern California accounts for the NWS and FAA weather observation sites and excludes the Pacific Ocean (conditions 1, 2 and 3 above, fig. 1).

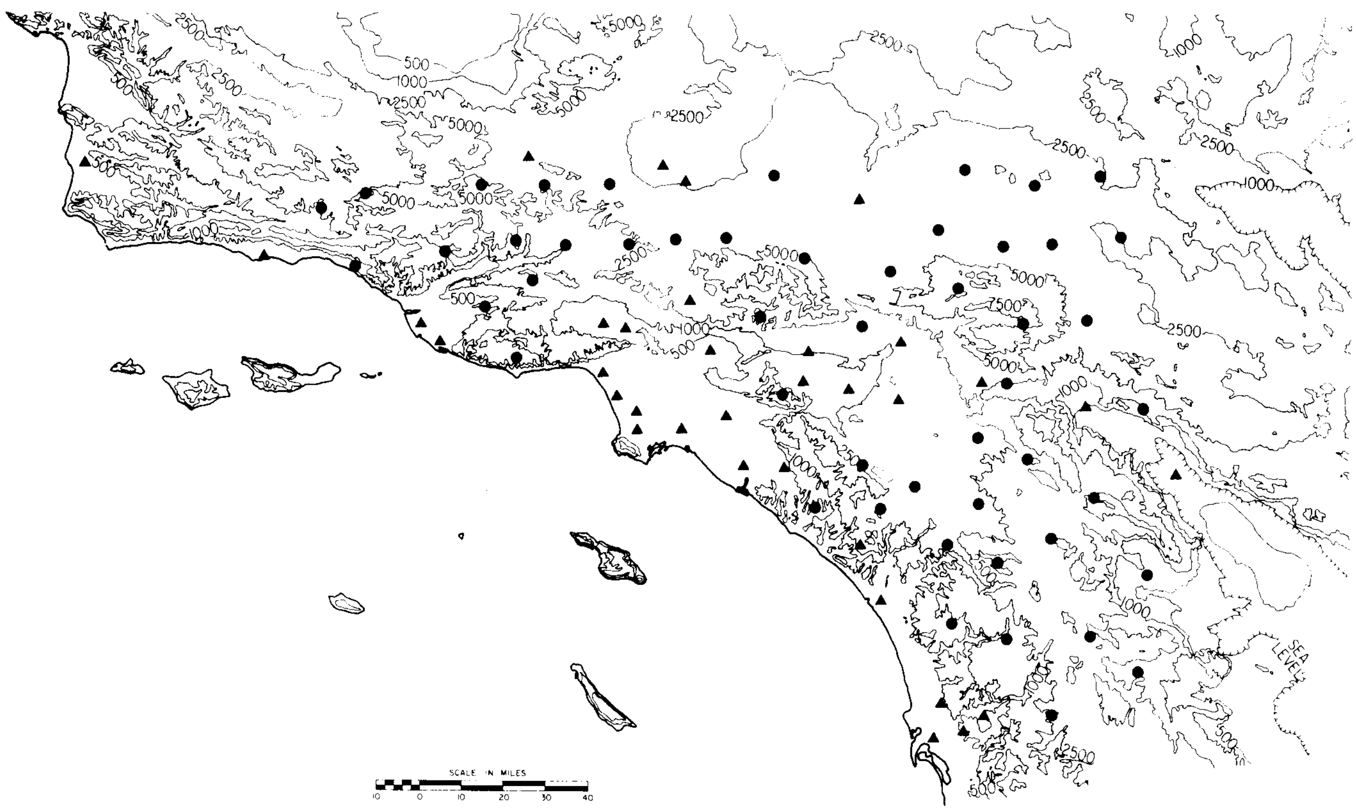

Figure 1--A proposed network of 50 fire weather stations for southern California. <u>Circles</u> represent the proposed network. <u>Triangles</u> represent National Weather Service and FAA observation sites. (after Fujioka 1986)

Siting upper air observational systems to support such activities as smoke management will require extension of existing technologies. One critical need is development of network design procedures that are based on a vector solution for optimizing networks. If a vector solution is considered as a multivariate orthogonal solution, then multiple resource needs can be considered.

WEATHER FORECASTING

The process of forecasting is based on an accurate assessment of current conditions. Research and development on observational systems, described in the previous section, will lead toward accurate assessment of current weather. This assessment is used to estimate the rate of change of each weather element. This rate of change is constant in neither time nor space. For example, near a cold weather front, temperatures and humidities will vary sharply over short distances. Movement of that weather front will result in abrupt temporal changes in weather.

Errors in Forecasting

The observational system improvements described above are not perfect. As a result, the initial assessment of the weather contains some error. Therefore, the forecast has errors due to both starting in the wrong place and going in the wrong direction. These forecast errors do not accumulate at the same rate everywhere. For example, our forecast for tomorrow may be extremely accurate in one location and be totally inaccurate in another. The specific forecast process is to use the initial estimate of the weather (the imperfect observational system), estimate the changes, and then establish a new estimate of the weather. Because of the high degree of nonlinearity in the physical description of the rate of change, this process of initial estimate, rate of change, and establishing a new estimate of the weather must be repeated numerous times to compensate for the nonlinearity of the rate of change, even for a 24-hour forecast. The result is that errors tend to be carried forward in forecasts and because the intermediate estimates of the weather contain errors, the error in the final forecast grows with the time interval of that forecast (Folland and Woodcock 1986; Gilchrist 1986).

If we examine that forecast error growth rate over time, two characteristics of the error are clearly dominant. For high spatial resolution of weather information (on, say, 10-km intervals), the error growth rate is such that no information or skill in forecasts exists beyond a few hours. At larger spatial scales, here information is averaged over a few hundred kilometers, forecasts are available to 3 days. At long, temporal intervals, the order of a 10- to 30-days, skill in forecasting is demonstrated only with both spatial and temporal averaging of the forecast. For example, a 5- to 10-day or 30-day forecast is valid for departures from the norm on a scale of 1000 km. Specifically, those medium- (out to 10 days) and extended-range (out to 30 days) forecasts are statistical departures from normal (i.e., climatology and confidence in that forecast departure). In essence, the information content of a forecast will show an exponential decrease of spatial resolution as the time period of the forecast increases. These limits give us the following: high spatial resolution forecasts are valid only on short time scales, and medium- and extended-range forecasts are valid on only 1000 km scales. Based on current technologies, predictions are not meaningful beyond 90-days prediction (Gilchrist 1986).

Short-range forecasts, commonly called nowcasts (Browning 1982), cover a time interval out to approximately 6 hours. The information content is essentially that contained in the observations. As a result, nowcasting needs to be supported by an intensive observational network of weather stations, particularly in the mountainous West. Emergency response systems, such as those used in the vicinity of chemical or nuclear facilities, are an example of effective use of nowcast concepts. Here, high risk, accompanied with high value, combine to warrant the investment in the observational and intelligence systems used in nowcasting. Nowcasting requires substantial capital investment, in both an observational system and an intelligence center to utilize those observations for management decisions.

Highly accurate forecasts are currently available on a 1- to 3-day period. These forecasts are fully integrated into fire management decisions and little needs to be said here except that the current high level of skill demonstrated in these forecasts, both numerical (computer) and human interpretations, will continue to improve as the observational data base improves.

Forecasts in the medium-range (out to 10 days) and the extended-range (out to 30 days) are beginning to show useful skill in forecasting time and space averaged departures from normal. These forecasts, using both numerical and empirical methods, do not contain high time or space resolution of information. They contain information on the large scale atmospheric structure. The day-to-day variations in weather, which are the result of small (less than 1000 km) variations in the atmosphere are intentionally removed from the forecast process to reach further into the future. Thus, the information content of these forecasts differs greatly from that contained in traditional short-range (3 days or less) forecasts. In fact, the information is more useful when expressed as departure from normal for the medium- and extended-range forecast period. Further, these forecasts are not absolute values of departure, but are probability distributions of departure. While this is a somewhat different format for forecasts than what fire management normally receives, it is particularly appropriate for decisions on where to pre-position crews and equipment. The probabilities of fire severity and the confidence in those forecasts can be used effectively in the decisions. The rapid gains in medium- and extended-range forecast technology are in the quality of the time-space averaged forecasts of departure.

Increasing Spatial Resolution of Forecasts

In some areas, spatial variations of fire severity are relatively small. In the mountainous West, spatial variations of fire severity are large and occur over short distances. Forecasts of probable departures will need to incorporate at least the systematic spatial variations of fire severity into these forecasts. Techniques used to develop weather station networks, in fact, incorporate the systematic variability of weather in the optimization process. Research and development on increasing spatial resolution of weather information, and the rate that weather changes. both temporally and spatially at the mesoscale (100 km) are active topics. There are two general approaches to increase spatial resolution using coarse scale forecasts: (1) nested-grid modeling, and (2) a combination of statistical and objective analysis techniques that are dynamically contained.

Quality of forecasts and, in fact, secondary forecasts can be obtained by nested-grid modeling. This first procedure uses the coarse scale (medium- or extended-range forecast) to establish a local forecast of the large scale atmospheric condition. It then uses high resolution data on terrain variability of knowledge of small scale physical processes, such as the southern California Santa Ana to produce a high spatial resolution forecast. These techniques are currently in use in Europe (Dell'Osso 1984) for medium-range forecast periods. Use of these nested-grid procedures has not been attempted as yet beyond the 5- to 10-day period. Neither have these models been used with varying initial conditions to generate probabilistic forecasts. Instead, these nested-grid models are being used to forecast specific weather events.

The second approach to increase spatial resolution of forecasts uses techniques that combine the preservation of physical concepts with the efficiency of statistical (probability) forecasts without having to solve a large number of nonlinear differential equations on mainframe computers. For example, consider a pure statistical approach to develop high spatial resolution windspeeds and directions at a large number of locations. Unless these wind forecasts are in mass balance, an air quality forecast based on these winds could contain significant error. Here, I use an error trend to absurd levels, only to illustrate a point. Consider the case where mass balance is not conserved in the transport of smoke. Over time, the prediction could lead to smoke concentrations exceeding the density of mercury, or alternatively to a vacuum of air, depending on the direction of the systematic error contained in optimizing on local minimum error in the statistical analysis.

Optimizing on minimum error at each location for which a statistical solution has been obtained, however, may not be the best solution. Using the air quality example above, the optimal solution would be the best point prediction of wind direction and speed that did not violate the physical law conserving mass rather than the minimum error of each point. Such dynamically constrained objective analysis models are rapidly moving into a variety of applications (Fosberg 1984. 1985) in both nowcast and short-range forecasts. These techniques use statistical methods to assimilate data and constrain the spatial and temporal variations by the laws of physics. The nested-grid modeling technique uses statistical methods to organize data and then adjusts the resultant spatial depiction for physical consistency. An alternate method is using the physical principles in a direct solution of the governing equations to develop the high spatial resolution variations, then applying the statistical methods of the model generated data. This approach contains considerably more physics, but most of these models have received only limited validation with real data. Nevertheless, these models are conceptually similar to the global models and, therefore, the uncertainties and confidence in the forecasts should be easier to track through the system.

One type of mesoscale model that can be used in postprocessing to obtain high spatial resolution is dynamically constrained objective analysis. This group of models has been extensively tested with real data (fig. 2) and is being used in emergency response systems and other selected applications. These models, however, require an extensive amount of data to accurately depict small-scale spatial features, and contain no information on rate of change. Considerable effort is being expended to improve the depiction of the physical processes in these models and thereby reduce the data requirements, while retaining computational efficiency (Fosberg 1984; McGinley 1986, Ross and Smith 1985). These improvements in dynamically constrained objective analyses have the potential to be nested spatially within the computationally efficient large-scale models to provide greater spatial depiction at frequent time intervals.

Statistical models, such as those described for weather station network design in the section on The Observational System, can also be used to enhance the spatial information content.

An untested but promising method of increasing the spatial resolution of forecasts through postprocessing is that of a hybrid model combining the statistical covariance matrix techniques with the physically based objective analysis models or the mesoscale numerical simulation models. The physically based models would constrain the statistical spatial variations to physical consistency, i.e., the statistical representation of wind would assure mass consistency and, therefore, could be used

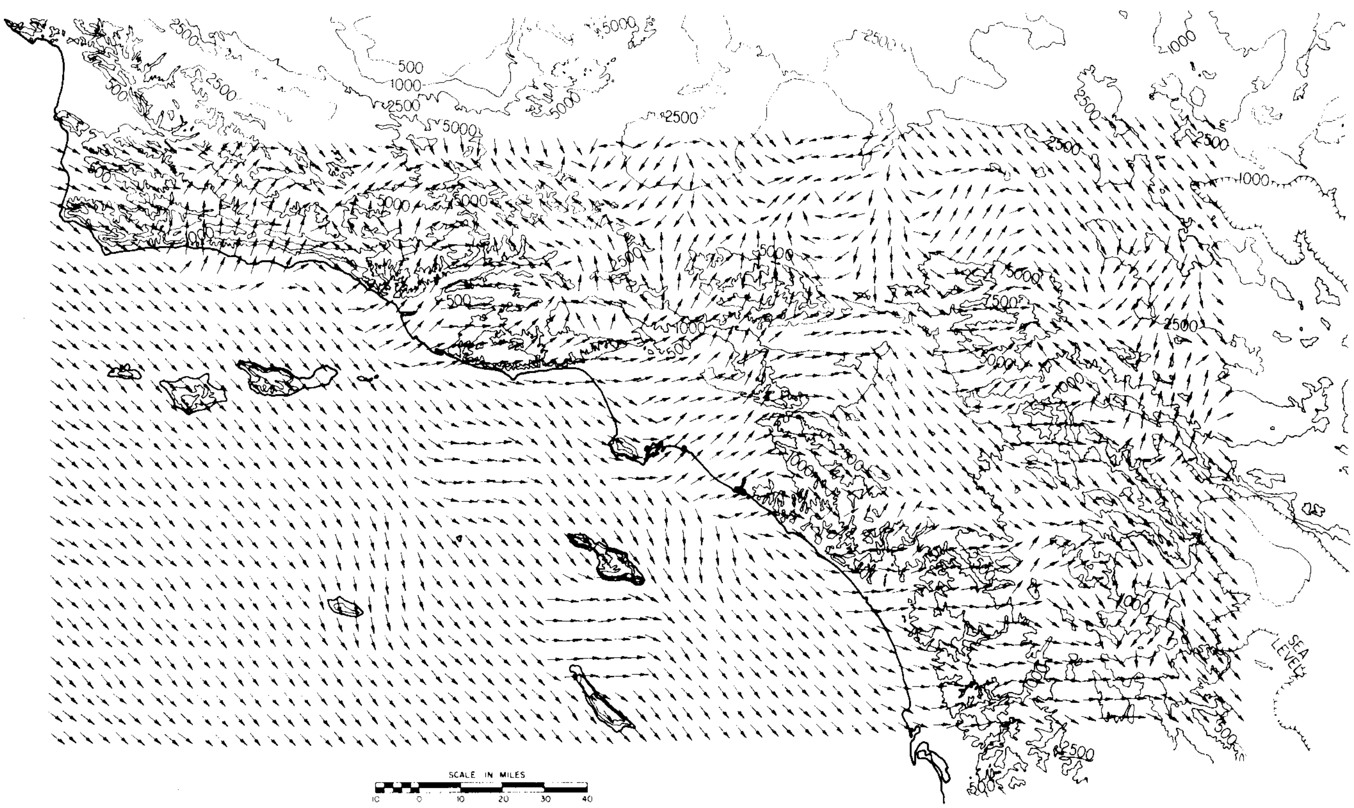

Figure 2--Modeled mesoscale windfield for southern California (after Fosberg, McElroy and Wakimoto 1987).

in smoke management or other air quality applications.

The techniques used to design weather station networks, in fact, contain the statistics of spatial variability of weather. Given this hybrid method of quantiying the spatial variations, one can use the spatially coarse forecasts and add the systematic fine scale spatial variability to those forecasts by the above two approaches (Fosberg and Fujioka 1987).

Postprocessing of Forecasts

Postprocessing is numerical analysis of the quantitative forecasts and takes place in two forms. One form is further meteorological interpretation of the forecasts, a common example being use of nested-grid objective analysis and prediction models. The intent of these postprocessing models is to enhance the spatial resolution of the forecast products. A second form of postprocessing is nonmeteorological: a common example is forecast fire danger.

The meteorological postprocessing most useful to fire management uses mesoscale models. They are designed to depict small-scale atmospheric features (on the order of a few tens of kilometers) and to cover areas a few hundreds of kilometers on a side. Mesoscale models range from statistical representations of the systematic spatial and temporal variations of weather to numerical simulation of detailed physical processes. This postprocessing of forecasts was described in the previous section.

Computer generated forecasts of weather tend to show bias or systematic error as the forecast period increases. These errors arise from several sources and are usually beyond control or correction by users such as fire managers. Two approaches are used to minimize these errors: Perfect Prognosis techniques (PPT) and Model Output statistics (MOS) (Klein 1978). Both are based on establishing regression relations between the forecast output and the observed weather. Perfect Prognosis Techniques are designed to correct statistically the differences between the observed behavior of the atmosphere and the forecastable behavior; that is, this approach removes bias from the incomplete physics in the forecast models. Model Output Statistics, on the other hand, are more general in that the statistical relation is established between the model output and the desired forecast variable. In the case of MOS, the desired forecast variable--such as a measure of fire danger--can be estimated without calculating intermediate meteorological variables. If the forecast model is modified, however, then MOS must be redeveloped because the bias correction is no longer appropriate. The current practice is developing PPT to establish the prediction of the meteorological variables, or fire-danger indicies, and using MOS to correct the model bias. Both PPT and MOS are applicable to empirical and numerical forecast procedures.

Before one can look at meteorological or meteorologically driven fire related products from postprocessed forecasts, the characteristics of the forecast need to be defined. Short-range forecasts. nowcasting and out to 3 days are expressed in terms of absolute values; for example, expected temperatures rather than trends or departures from normal. Similarly, winds, humidity, and precipitation are quantitatively expressed, albeit as a range of each variable, and for specific locations. Forecasts for the 6 to 10 day period or out to 30 days, however, are expressed as trends or change on the 10-day period, and are expressed as probable (with probability bounds) departures from normal for 30-day forecast periods. Postprocessing of forecasts for periods of 6 to 10 days and out to 30 days will be expressed as statistical descriptors.

Fire-danger rating is an example of nonmeteorological postprocessing. Weather forecasts are used to calculate forecast fire danger indicies and to establish forecast manning and action class levels for the next day. Medium-range forecasts also have demonstrated postprocessing use. For example, air pollution episodes are forecast routinely for Western Europe, and forecasts of ice pack movements are used to pre-position icebreakers in the Baltic Sea. There has been limited success in using extended-range forecasts to pre-position fire crews and equipment in the United States. Current research activities focus on both improving these extended-range forecast applications and in improving the spatial resolution of medium-range forecasts. The goal is to provide information for decision analysis procedures in pre-positioning crews and equipment for both wildfire and prescribed fire opportunities.

Information content of forecasts as used here is in two parts. First is the technically or statistically significant content of information exceeding that contained in climatology. Skill scores have been designed to measure the accuracy of forecasts. Medium- and extended-range forecasts show meteorological skill in that information is contained in the forecast. How useful is that information? Does the forecast contain sufficient information to influence a fire manager's decision? A second measure of information content is the economic value of information (Brown and Murphy 1987). Specifically, can weather or fire severity forecasts actually show both skill and economic value?

Quantitative analysis of the forecasts through modeling of the decision process for pre-positioning crews and equipment for wildfire and even for prescribed fire is likely to be a major postprocessing activity in the future.

FUTURE USE OF WEATHER INFORMATION

Having assessed the current state of observations, forecasting, and postprocessing of weather, and having estimated the changes taking place, I have covered the first two steps in forecasting. Now I will apply these changes to the described initial state and forecast weather forecasting.

Techniques to design specialized weather station networks will be available and will be able to address multiple resource needs, e.g., fire, air quality, and water. We will see significant improvement in the weather observations at the surface. A corresponding upper air wind observation network, particularly in the mountainous West, will be deployed much more slowly. As a result, the assessment of the initial state of the weather will still be imperfect. The cost of implementing a high spatial and temporal resolution observational system will limit use of the technology.

Weather forecasting on the nowcast of high spatial resolution and short-time scales will become operational in only geographic areas with very high fire risk and potential damage, such as the urban/wildland interface. Use of this technology still will be limited to nuclear and chemical facilities with only minor efforts in fire management of the urban-wildland interface. Again, economics will dictate the rate of implementation of these technologies.

Short-range (out to 3 days) forecasting will continue to show steady, albeit slow, improvements in accuracy. The notable exception here will be in spot forecasts, which are based on the covariance matrices of spatial and temporal variability. These forecasts will provide more accurate information to fire management for initial attack. Medium-range forecasts have achieved operational acceptability and extended-range forecasts will soon reach that level for management decisions. These forecasts are and will be presented in a probability format. Fire management use of these forecasts will depend to a large extent on management capabilities to accept probability distributions as the forecast rather than a single value.

These probability distribution forecasts are actually better forecasts for decisions based on medium- and extended-ranges. Uncertainty in timing of a particular weather event, or the spatial position and distribution of that event are better expressed as probability distributions. These probability distributions will be the weather forecasts of the future.

Finally, I turn to postprocessing of weather forecasts. This is where fire management will see the greatest gain in meteorological support. Medium- and extended-range forecasts will be processed with a variety of fire danger and drought measures to forecast fire severity. These forecasts will be used to pre-position crews and equipment on both national and regional scales.

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