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IMPROVED MODELS FOR INCREASING WIND PENETRATION, ECONOMICS AND OPERATING RELIABILITY

Final Report

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April 1984

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FINAL REPORT

April, 1984

Report Prepared by the

Division of Engineering Research
Michigan State University
East Lansing, Michigan 48824

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NASA Lewis Research Center
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FORWARD

This report was prepared by the Division of Engineering Research at Michigan State University under Contract NAG3-399 from the Wind Projects Office at NASA Lewis Research Center. Project managers for this contract were Dr. Len Gilbert and Mr. Richard Putoff.

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ABSTRACT

The need for wind power prediction in order to enable larger wind power penetrations and improve the economics and reliability of power system operation is discussed. Methods for estimating turbulence and prediction of diurnal wind power prediction are reviewed from the literature. A method is then presented to predict meteorological event induced wind power variation from measurements of wind speed at reference meteorological towers that encircle all wind turbine clusters and from sites within the wind turbine clusters. The methodology uses a recursive least squares model and requires (a) detection of event propagation direction, and (b) determination of delays between groups of measurements at reference meteorological towers and those measurements at towers in the array. Proper filtering of the data and methods for switching reference sites and delays for the transition from one frontal system to another is also discussed. The methodology is thoroughly tested on data from the SESAME array of meteorological towers in Oklahoma and at the Goodnoe Hills MOD-2 wind turbine cluster in Washington. The performance of the prediction methodology on data sets from both sites was quite good and indicates one or more hour ahead prediction of wind power for meteorological events is feasible.

SUMMARY

The large rapid changes in wind power for utilities with large wind generation penetration can cause serious reductions in operating economy and reliability. Prediction of wind power variation can allow a utility to schedule the connection and disconnection of wind and non-wind generation based on predicted load and predicted wind generation variation. The additional reserve generation capacity required to maintain operating reliability when wind power variation cannot be accurately predicted could be eliminated. Wind power prediction allows more effective control of generation so that large mismatches between total generation and load that violate NERC guidelines for reliable utility operation will not occur. Prediction also allows coordination of the various generation control options.

Section 2 of the report discusses the solutions to this unit commitment and generation control problem that do not require wind power prediction. A modified unit commitment and generation control that requires prediction of diurnal wind power variation, turbulence induced wind power variation, and meteorological event wind power variation is also discussed. The modified unit commitment is composed of a 24 hour, quarter hour, and minute update of the unit commitment. The 24 hour ahead unit commitment requires a 24 hour ahead forecast of slow trend and diurnal wind power variations that can be accurately predicted on a daily basis. The quarter hour updated unit commitment requires one or more hour ahead prediction of the large rapid wind power changes observed in meteorological events. The magnitude, time of arrival, and time of departure meteorological event induced changes cannot be forecasted but must be predicted based on measurements at meteorological towers that encircle the wind turbine clusters. The minute updated unit commitment requires fifteen minute ahead prediction of the evolutionary changes in the meteorological event and possible formation of storms or thunderstorms, which cannot be predicted one or more hours ahead.

The modified generation control is composed of the automatic generation control of steam turbine units; feedforward control of fast responding diesels, gas turbine, and hydro units not normally under automatic generation control; and feedback control of each wind turbine's blade pitch control of wind power output. Prediction not only helps generation controls by anticipation of the wind power variation but also in coordination of these three control options.

Measures of spinning reserve, unloadable generation, and load following requirements are developed based on the predicted diurnal and meteorological event based trend and the turbulence based cyclic wind power variation. These measures are needed within the unit commitment and modified generation control.

Section 3 of this report reviews the existing methods for predicting diurnal and turbulence wind power variation. A discussion of methods of incorporating these predictions within the modified unit commitment and generation is also given. A recursive least squares predictive model for meteorological event induced wind power variation is proposed. This recursive least squares predictor is based on measurements of wind speed and direction at meteorological towers that would encircle the wind turbine clusters. A prediction methodology specifies procedures for (a) selecting the smoothing interval that will eliminate turbulence and site specific phenomena without distorting the wind speed time profile of the meteorological event, (b) determining the direction of propagation of the meteorological event, and (c) determining the proper propagation delays between the reference measurements at towers that encircle the array and the sites within the wind turbine cluster where prediction is desired.

This predictive model and methodology is the first known attempt to predict the very large rapid changes in wind power variation due to meteorological events. Meteorological event wind power variations are much larger and faster changing than turbulence induced variation or diurnal wind variations.

The predictive model and methodology is applied to four different meteorological event wind records on the SESAME array. These records were taken from 27 meteorological towers sited over an 80 x 80 mile square area in Oklahoma. The data are 1 minute averages of wind speed and direction at these 13 foot high towers. Turbulence is thus quite high and makes prediction of meteorological events more difficult. The predictor was tested on (1) a stationary front, (2) a fast south to north propagating front, (3) a fast northwest to southeast propagating front, and (4) a slow propagating large triangular wind speed increase associated with the transition from predominance of one frontal system to another. The conclusions of this investigation are that a ring of reference meteorological towers that encircle a set of wind turbine clusters should be located 100 miles away from the closest wind turbine cluster to allow sufficient delay for hour ahead prediction of fast propagating events. Several wind measurement sites should be located in each wind turbine cluster in order to permit the elimination of measurements at a site experiencing large site specific phenomena. The sites in the ring of reference measurements should be grouped based on high pairwise peak correlations, small delays, and close geographical proximity. The selection of the delays between each reference wind speed measurement site record in the ring of meteorological towers and the prediction site measurement record in the wind turbine cluster are most critical to the accuracy of the prediction. The delay from any reference site to any prediction site is to compute the correlation $P_{ij}(\tau)$ as a function of delay (τ). The delay T_{ij} is selected as the value of that maximizes this correlation. The use of several reference sites in groups and several wind measurement (prediction) sites in each wind turbine cluster helps eliminate inconsistent delays between pairs of reference and prediction sites.

The method for selecting the direction of propagation was successfully tested. The procedure determines the propagation direction by ordering sites in increasing distance in a hypothetical event propagation direction and then tests whether the peak correlation $P_{ij}(T_{ij})$ is greater for all ij or ji elements where $i > j$. If correlations are greater for all $i > j$, when the j^{th} record is advanced by T_{ij}, indicates the direction of propagation is in the hypothesized direction. The set of reference group sites that lie in front of and encircle the wind turbine cluster with delays greater than one hour are used to predict wind speeds at sites in the wind turbine clusters.

A procedure for changing reference sites and delays, when a transition from one frontal system to another is experienced, was determined. The delays and reference sites for the first fast propagating front are used for prediction until the slow propagating pulse wind speed increase associated with arrival of the second front first affects the first wind turbine cluster. The reference sites and delays are then selected based on prediction of the propagation of this slow propagating triangular wind speed pulse and reset again after it has passed all of the wind turbine clusters encircled by the ring of reference meteorological towers. The delays and reference sites are then selected based on the second fast propagating front.

Three predictive models were tested. The individual site predictive model predicts wind speed at each site i in the wind turbine cluster using several individual wind speed measurements j each with its own delay T_{ij}. The group/site predictive model predicts wind speeds at each prediction site i in the wind turbine cluster based on (a) an average record of wind speed in a group of reference sites, and (b) the average delay between that prediction site and the group of reference sites. Using average wind speed records with average delays from several reference groups was found to greatly improve prediction accuracy over that for one reference group. The group/group predictive model averages wind speed records at all prediction sites in a wind turbine cluster and all reference sites in a reference group and predicts the averaged wind speed record in the wind turbine cluster using a delay averaged over all prediction sites in the wind turbine cluster and all sites in the reference group. The group/group model had the poorest performance. The group/site model using more than one reference group of measurements had reasonable accuracy at reasonable computational requirements.

The individual site model had the best performance but at high computational requirements.

The predictive model and methodology was also applied to Goodnoe Hills data. Two minute averaged measurements of wind speed and direction were available from wind turbine #2 and wind turbine #3. The determination of two groups of sites, a meteorological event propagation direction, and the delays from the reference site (PNL tower) to each wind speed prediction site (wind turbine #3, wind turbine #2, BPA tower) was much easier than for the SESAME data. The low level of turbulence at hub height (200 ft.) made the prediction methodology more effective even though the close geographical distance between measurement sites would have been thought to make capturing propagation of the event very difficult. The wind speed prediction was performed for both 2 minute averaged and 10 minute moving average filtered data. The 2 minute moving average filtered data gave better prediction results because averaging over a period can cause a delay in the signal that depends on its shape and period. This delay can and does distort the propagation of a meteorological event and thus the smoothing interval must be kept small compared to the propagation delays to prevent this distortion of the propagation delays. This was also observed on the SESAME data.

Wind power was directly predicted at wind turbines 1, 2, and 3 using wind speed measurements at the BPA tower. The prediction was reasonably accurate if the wind speed and power did not exceed rated velocity and power. A multiple stage wind power predictor could be developed that would let each stage predict wind over a specific range of wind speed values. The range of wind speed values used for each predictor would be based on linearization of the wind power versus wind speed characteristics of the wind turbine in the array. A multiple stage wind power predictor would likely be more accurate. Direct wind power prediction at wind turbines could eliminate the need to predict wind speed at wind turbine sites and then simulate wind power from predicted wind speed using a static wind power versus wind speed model of a wind turbine.

The detection of the arrival of meteorological events, the determination of the direction of propagation for the meteorological events, and the determination of delays between the groups of reference sites and each prediction site is difficult using solely wind speed and direction measurements. It is suggested that (1) forecasts of the time of arrival and direction of propagation of the meteorological event be utilized, (2) pressure and temperature measurements at the ring of meteorological towers encircling the wind turbine cluster be taken in addition to wind speed and direction, and (3) pressure and temperature gradients based on the pressure and temperature measurements be provided. This information may be incorporated in an improved prediction methodology that may be even more accurate and may require far less computation. The results of this study are so encouraging that such refinements are expected to even further improve the applicability and accuracy of the prediction.

SECTION 1

INTRODUCTION

Previous research has shown that present power system operation practice can only handle relatively small penetrations of wind generation without accurate wind power prediction. Present methods of connecting units in anticipation of load change (unit commitment) are based on accurate prediction (<2% error) of load 24 hours ahead. Since wind power variations can be considered as negative load, an inability to predict wind power variation would require connecting additional conventional generation since the wind generation could not be counted as meeting any significant load based on reliability measures. However, accurate prediction of minute and hourly wind power variations would allow shutting down an amount of conventional generation proportional to the wind generation, which is predicted to occur. This reduction in reserves could be accomplished without losing reliability as measured by loss of load probability measures or NERC operating guidelines [19].

Prediction is also required for controlling conventional generating unit's and wind turbine cluster's power output so that the total generation accurately tracks total load variation. The large and rapid changes in wind power variation can place heavy burdens on present generation control strategies. Prediction would allow the coordination of automatic generation control of slow responding conventional steam turbine generation; feedforward control of fast responding hydro, diesels, gas turbines, etc.; and feedback control of the power output of wind turbine array clusters. Prediction also allows anticipation of wind power changes and thus assists in proper control of total power generation so that large mismatch between generation and load and large frequency deviations caused by such mismatch do not occur.

Section 2 of this report thoroughly discusses this unit commitment and generation control problem associated with large wind generation penetrations. Alternate solutions to the unit commitment and generation control problems are compared and discussed. A modified unit commitment and generation control is then discussed that requires prediction of wind power variation 1 hour ahead (updated quarter hourly) and 15 minutes ahead (updated every minute). A 24 hour updated unit commitment, quarter hour updated unit commitment, and minute updated unit commitment would share the task of providing sufficient generation capacity based on the predictions of different components of wind power variation. The methods of setting and the constraints for meeting spinning reserve, unloadable generation, and load following requirements in the modified unit commitment are discussed in Section 2.4. Measures for calculating the trend and cyclic/error component of wind power variation for the spinning reserve, unloadable generation, and load following requirements are derived. The measures for the quarter-hourly updated unit commitment based on the hour ahead wind prediction $W_1(t)$, and the measures for the minute updated unit commitment based on the quarter-hour wind power prediction $W_2(t)$, are derived and justified in Section 2.5. A discussion of the coordination and capabilities of the quarter-hour and minute updated unit commitment based on these measures is also included. The update interval and the proper prediction interval for each of these unit commitment updates is then justified based on (a) the rate of change of wind power variation to be handled by that unit commitment update and (b) the type of generating units available to that particular unit commitment update.

A modified generation control is also discussed in Section 2.6 that utilizes the predicted trend and turbulence components of wind power variation. The modified generation control is composed of

(a) automatic generation control that would better track the hour ahead predicted trend and 15 minute ahead predicted cyclic wind variation because these variations are anticipated;

(b) a supplementary automatic generation control of the peaking, regulating, quick pickup units commited by the quarter-hourly and minute updated unit commitment to respond to the predicted trend and cyclic wind variation. These units have a fast response that either is not utilized fully or is not included in present automatic generation control strategies. This is called feedforward generation control in [8];

(c) a coordinated blade pitch control on all wind turbines in single or multiple arrays that can clip predicted cyclic wind power variation and smooth rapid hour ahead predicted trend changes that cannot be easily handled by automatic generation control of the feedforward generation control. This is called feedback array control in [8].

The reduction or elimination of unloadable generation requirements by closed loop array control and the sharing of load following and spinning reserve generation control responsibility between automatic generation control, feedforward generation control, and closed loop wind array control is discussed in Section 2.6.

Section 3 of this report initially discusses the known literature on prediction of diurnal, meteorological, and turbulence induced wind power variation and how they can be utilized within the modified unit commitment/generation control strategy. A recursive least squares model, that can be utilized to predict wind speed at a site based on wind speed measurement at several reference sites, is derived. A methodology for determining the predictor based on this least squares model is discussed that indicates how to

(a) select the smoothing interval to properly capture the propagation of the meteorological event and yet eliminate turbulence and site specific effects;

(b) determine the direction of propagation of the event which may at times be different than the wind speed direction;

(c) properly determine the set of reference sites, where the measurements should be used for prediction of wind speeds not in this reference group;

(d) properly select delay from the reference sites to the prediction site.

Chapter 4 applies the least squares prediction model and prediction methodology to four wind speed records on the SESAME array during April and May of 1979. The four records have the following characteristics:

(1) a stationary high on April 14, 1979 where no propagation is evident but wind speed at all sites increase and decrease;

(2) a slow propagation of wind speed increase associated with the transition from a south to north propagating front to a north to south propagating front. The wind speed increase requires 5 hours to propagate from north to south on the 80 x 80 mile SESAME array;

(3) a fast propagation of a ramp increase in wind speed that takes only 40 minutes to propagate from south to north. The pressure and temperature gradients can propagate faster than the wind speed and this was observed in this case;

(4) a fast propagation of a front from northwest to southeast.

The results on all four of these cases are quite good and the prediction methodology is judged to have considerable promise.

Chapter 5 presents results on applying the prediction methodology to estimating wind speed and power on the wind turbines using wind speed and direction measurements at two meteorological towers at the Goodnoe Hills site. The purpose of the research is to show that the wind speed prediction methodology developed using SESAME data can also be applied to a wind enhancement site such as Goodnoe Hills. The differences in the effects of turbulence and site specific phenomena will be investigated. Finally, a method for direct prediction of wind power variation on two wind turbines based on wind speed measurements at the PNL and BPA meteorological towers will be demonstrated.

Chapter 6 will discuss the conclusions of the research and the implementation requirements for prediction based on the results of this study. The need for multiple reference wind speed, wind direction, pressure and temperature measurements in a ring encircling the wind turbine clusters; the methods and need for grouping measurements from the measurement sites in this ring and at the wind turbine clusters; the method and need for determining the direction of event propagation; the method for determining the delays between reference measurement site and prediction sites; the selection of proper smoothing interval for eliminating turbulence and site specific phenomena without distorting the meteorological event characteristics; the method of changing reference sites when a wind direction shift occurs; and the choice of predictive models in terms of accuracy and computational requirements are all reviewed and discussed. Some remarks concerning future research are also included.

SECTION 2

JUSTIFICATION AND USE OF WIND POWER PREDICTION IN UNIT COMMITMENT AND GENERATION CONTROL

An analysis and simulation of wind power variations for square and rectangular arrays [3,16] was recently made based on wind speed measurements and the wind model developed from these wind speed measurements. These results indicate the worst case magnitude of wind power change for passage of meteorological events could be much larger than any utility could cope with and maintain operation. It was shown that the magnitude of wind power changes for passage of meteorological events on a single 350 MW array in a 7000 MW utility can seriously reduce operating reliability and economy by significantly changing the unit commitment, automatic generation control and economic dispatch schedules and operation. Moreover, it was shown that total array capacity changes can occur within 10 minutes and can occur repeatedly for passage of a front or storm. Finally, it was shown that near total capacity power variations can occur simultaneously on different arrays 20-40 miles apart in the direction of motion of the meteorological event. These results clearly indicate that infrequent meteorological events can cause serious operating problems on single wind turbine arrays with less than 5% penetration. The 350 MW arrays contemplated in the Pacific Gas and Electric and Southern California Edison systems would have operating problems for the very infrequent occasion that meteorological events occur on these sites. It was also pointed out that there is a need for a modified unit commitment and generation control if wind power penetration exceeds 5%. Penetrations above 5% appear to be feasible as wind technology improves and the installation of large wind turbine arrays increase. A discussion of a modified unit commitment and generation control strategy is given in Subsection 2.3.

The effects of turbulence were shown [16] to be quite large on a single wind turbine but were shown to cause small variation as a percentage of utility capacity for wind turbine array penetrations of 5% on larger utilities. The difference in the effects of turbulence and meteorological events in terms of the magnitude of array wind power variations and thus their effect on a utility is due to the fact that:

(1) the weather map fluctuations associated with energy spectrum below 5 cycles/hour are generally correlated between sites in an array and have relatively larger energy than "gusts". The high correlations make the power variations on each wind turbine appear quite similar and thus cause large power variations out of the array;

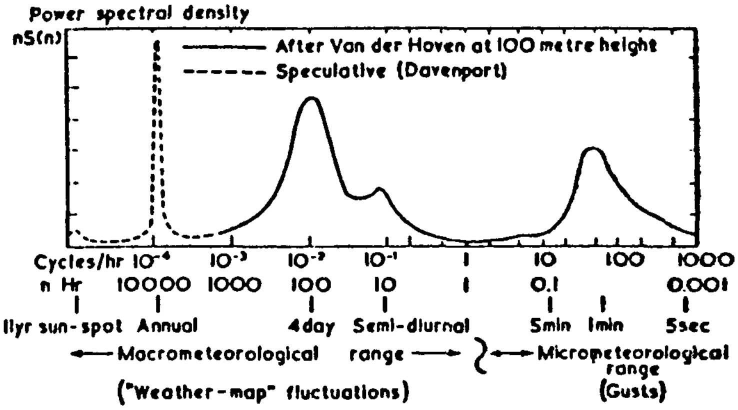


Figure 1. Power spectral density of the wind.

(2) the turbulence or "gusts" wind speed variation component associated with the spectrum above 5 cycles/hour has less energy than the "weather map fluctuation" component and is generally uncorrelated between sites. The lack of correlation of turbulence between sites generally will cause cancellation of wind variation between the different wind turbine sites which greatly reduces the turbulence induced power variations out of an array.

It is impossible to determine whether there are or are not any meteorological events in the energy spectrum of Figure 1 since information is lost in the calculation of energy spectrum. However, the conclusion that the wind speed variation associated with the energy spectrum below 5 cycles/hour is of concern in operation and control of utilities is valid whether there are meteorological events in this spectrum or not. The validity of the concern is based on the energy of these variations and the high correlation between wind turbines in an array for such variation. It will be our custom to refer to weather map fluctuations as meteorological events in our discussion.

2.1 THE UNIT COMMITMENT AND GENERATION CONTROL PROBLEMS

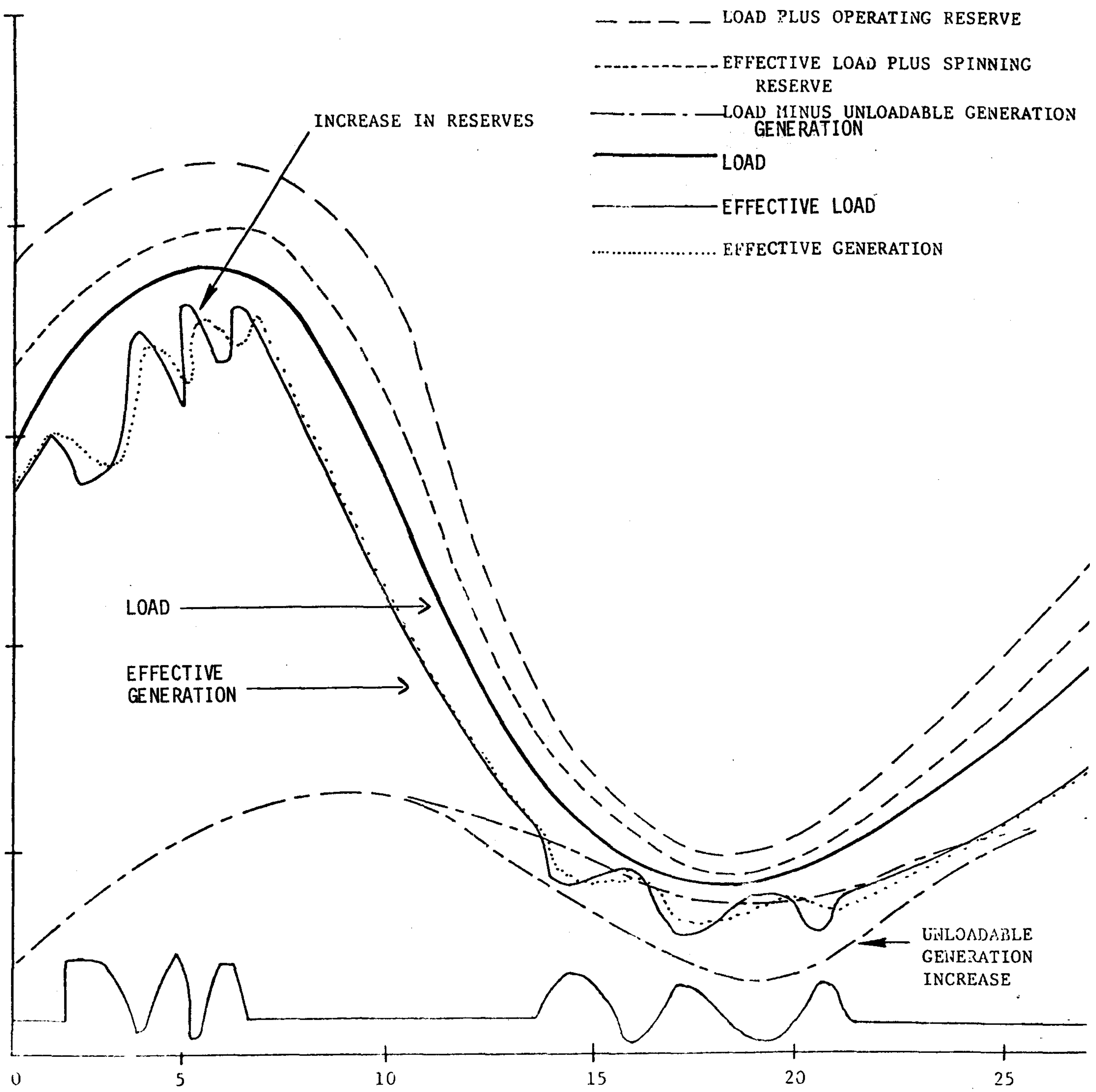
Research performed by Michigan State [17,18] and others [9,10,11] has shown that large wind power variations from an array of wind turbines can cause significant operating problems for a utility. These problems occur because a utility's unit commitment and generation control is based on (1) handling small cyclic load variation rather than the larger cyclic wind power variation and (2) large load trend change can be accurately predicted 24 hours ahead but trend wind cyclic wind power variations have not been predicted accurately. Utility practice for conventional loads, which can be predicted on a 24 hour basis within 2%, has been to _connect_ or _commit_ units in advance using a "unit commitment" schedule, and to _control_ operating units already connected via set point adjustments to unit governors as load varies about the predicted value. Since wind power variations exceed load variations on a percentage basis, this practice must be modified. Fast cyclic and slow trend wind power variations are both large and unpredictable 24 hours ahead of real time. Since wind power variations are usually viewed as negative load to the utility's unit commitment procedures, which provide fast responding generation (load following requirement) and reserves (operating reserve), there is a _unit commitment problem_ in providing the proper additional reserves for wind power variations. Trend and cyclic wind power variations due to meteorological events can, for wind penetration levels above normal spinning reserve levels (5% of a utility's capacity), greatly exceed both the systems spinning reserve, unloadable generation and load following capability. This can cause a serious reduction in system reliability and a violation of the utility guidelines for reliable operation (NERC Minimum Criteria for Operating Reliability) [19].

Two control problems associated with power system operation for wind power variations are:

(1) The utility's automatic generation control will saturate for long periods when the total change in wind generation and a simultaneous load change will require conventional generation change that exceeds load following capability in a ten minute interval. This problem violates NERC performance guidelines [19]. However, it can be eliminated by imposing a farm penetration constraint on the capacity of all wind turbine generators that can be affected by a single thunderstorm front. This farm constraint is the same as the constraint that solves the unit commitment problem.

(2) Steam turbine units will cycle as a result of simultaneous load and generation changes that induce frequency deviations that exceed governor deadband of conventional units. This continual cycling of units is objectionable to generator operators and can cause increased maintenance costs, increased forced outage rates and ultimately reduced unit life. The cycling of nuclear units is of concern for safety reasons in addition to those mentioned above. The cycling problem can occur due to a storm front sweeping through a wind generator array causing large power variations on successive echelons. An echelon penetration constraint on the capacity of all WTGs in a straight line normal to motion of the meteorological event that experience simultaneous wind speed changes will eliminate this cycling problem. The fast cyclic wind variation, which lie in a range between 2.7 x 10^{-4} hz and 1.6 x 10^{-3} hz, can be quite large and cannot be eliminated by the echelon penetration constraint because these cyclic variations come from wind variations in a front or storm that affect widely separated echelons or possibly different arrays. The cyclic variations, around trend wind speed variations, can be compensated by increasing the response capability of automatic generation control.

These two control problems, like the unit commitment problem, result from the fact that there are large cyclic and trend wind power variations. The difference between the unit commitment problem and the control problem is one of providing sufficient generation reserves that can respond rapidly enough in the unit commitment and have sufficient control action within the generation controls to properly compensate for fast wind power variation. The farm penetration constraint acts to limit instantaneous maximum wind power increase or decrease so that unit commitment and control can cope with trend and cyclic wind variations.



Time in Hours

Figure 2. Unit commitment solution that increases operating and spinning reserve by the wind turbine array capability.

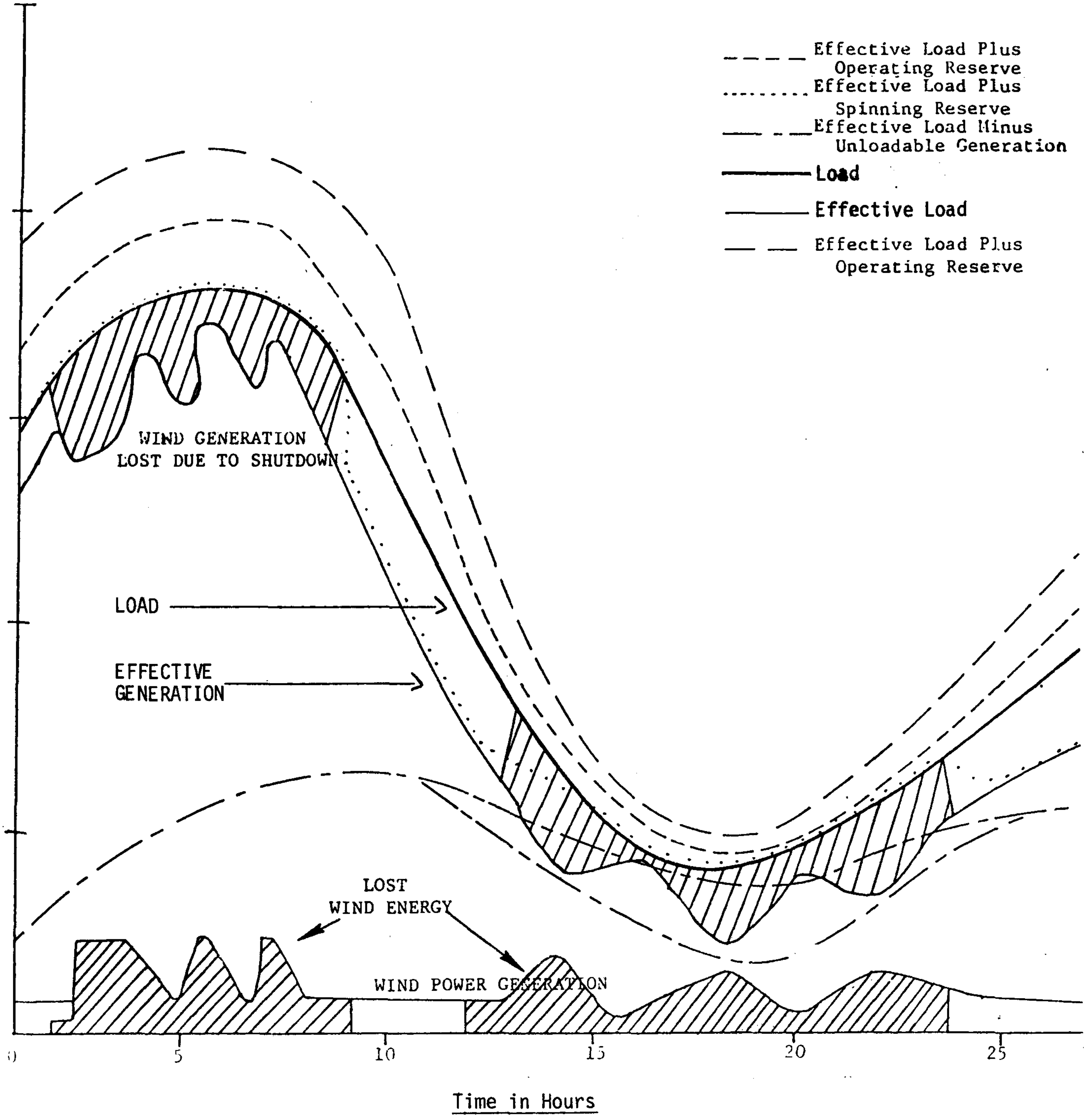


Figure 3. A generation control strategy that shuts down the array for passage of meteorological event.

Three solutions to the unit commitment and generation control problem discussed above can now be explained using Figures 2-4. A hypothetical daily load curve is used for illustration. The diurnal wind generation is shown as a constant and the wind generation variation due to meteorological events is shown as a set of cyclic and ramp variations. The effective load is shown as the difference between the daily load curve and the wind generation. It is met using a unit commitment that starts up and shuts down units to provide sufficient generation to meet this effective load as well as sufficient reserves to insure operating reliability. The operating reserve is composed of both nonspinning reserve and spinning reserve; which is generation connected to the system and running, quick start units such as gas or hydro turbines, and all load curtailment capability available to the operator. The operating reserve and spinning reserve for each of these three solutions to the unit commitment and control problem are shown in Figures 2-4. The unloadable generation reserve, also shown in Figure 2-4, is negative reserve that permits backing off conventional generation. Units having unloadable generation reserve are operated above their minimum generation levels so that wind generation increases can be accommodated by conventional generation without tripping units off line.

The automatic generation control (AGC) matches the effective generation to effective load variation and thus keeps area control error and frequency deviations small.

The first solution [9], which adds the capacity of the wind turbine array to spinning reserve, unloadable generation and operating reserve, can be observed in Figure 2. Spinning reserve and operating reserve on non-wind generation unit commitment are maintained at levels that totally ignore the presence of the wind generation that reduces the load carried by the units and thus increases system spinning and operating reserve. The unloadable generation level on non-wind generation unit commitment is modified at night when wind generation is available. This allows for wind generation increases that equal the total capacity of all wind turbine arrays in the utility. The unloadable generation reserve level, shown in Figure 1, is so large at other times of the day that the need to accommodate wind generation increases places no constraint on the non-wind generation unit commitment. The effective generation curve shows that automatic generation control response set without consideration of wind generation variation cannot effectively track effective load changes during passage of meteorological events. Under these conditions, large frequency and area control error deviations occur during passage of meteorological events that would continually violate NERC Minimum Criteria for Operating Reliability [19]. No adjustment to automatic generation control to increase response rate capability was discussed in this solution and so none is indicated in Figure 2. The spinning reserve and operating reserve levels in this solution to the unit commitment are large. This results in commitment of additional units and thus in increased fuel and maintenance costs than would be necessary if operating reserve were adjusted in accordance with wind generation changes.

The second solution [2] would alleviate the large area control error and frequency deviations by shutting down the wind turbine arrays during the passage of meteorological events. The ramp and cyclic variations will be shown to be as large as the capacity of all wind turbine arrays capacity and occur in as short a period as 10 minutes and possibly cycle with periods of 20 minutes to an hour or more. A utility's automatic generation control must attempt to track such variations in order to keep tie lines at scheduled load levels. This means that the ties are available to provide power for a loss of generation or export contingency. The solution to shutdown the wind turbine arrays during passage of meteorological events appears attractive except that the units may be shutdown for long periods if prediction of the meteorological event were not undertaken. If such predictions were undertaken, which seems feasible from results of this study, it appears this severe cyclic variation can be met by a combination of automatic generation control, generation control of units commited to cope with this wind power variation, and control of power variation out of the wind turbine arrays themselves. This alternative eliminates the need to lose the wind energy due to shutdown of the array shown in Figure 3. This second solution does not address the unit commitment problem and thus the same unit commitment strategy is used which adds the wind array capacity to operating reserve, spinning reserve, and unloadable generation reserve. Note that the first solution did not address the control problem and that the second solution did not address the unit commitment problem.

The third solution proposed in [18] addressed both the unit commitment and control problem (utilizing no prediction of wind power variation) by limiting wind power variation via the farm and echelon penetration constraints mentioned earlier. The satisfaction of the farm penetration constraint can be observed in smaller levels of wind generation and variation in Figure 4. The result is a modification of spinning reserve and unloadable generation to track effective load and would increase these reserves during passage of meteorological events as shown in Figure 4. Operating reserve modification with wind generation change was not discussed in this study [18] and thus no modification from that utilized, when no wind generation is present, is shown in Figure 4. Unloadable generation may be slightly increased in this solution due to wind generation but not equal to the capacity of all wind turbine arrays as in the

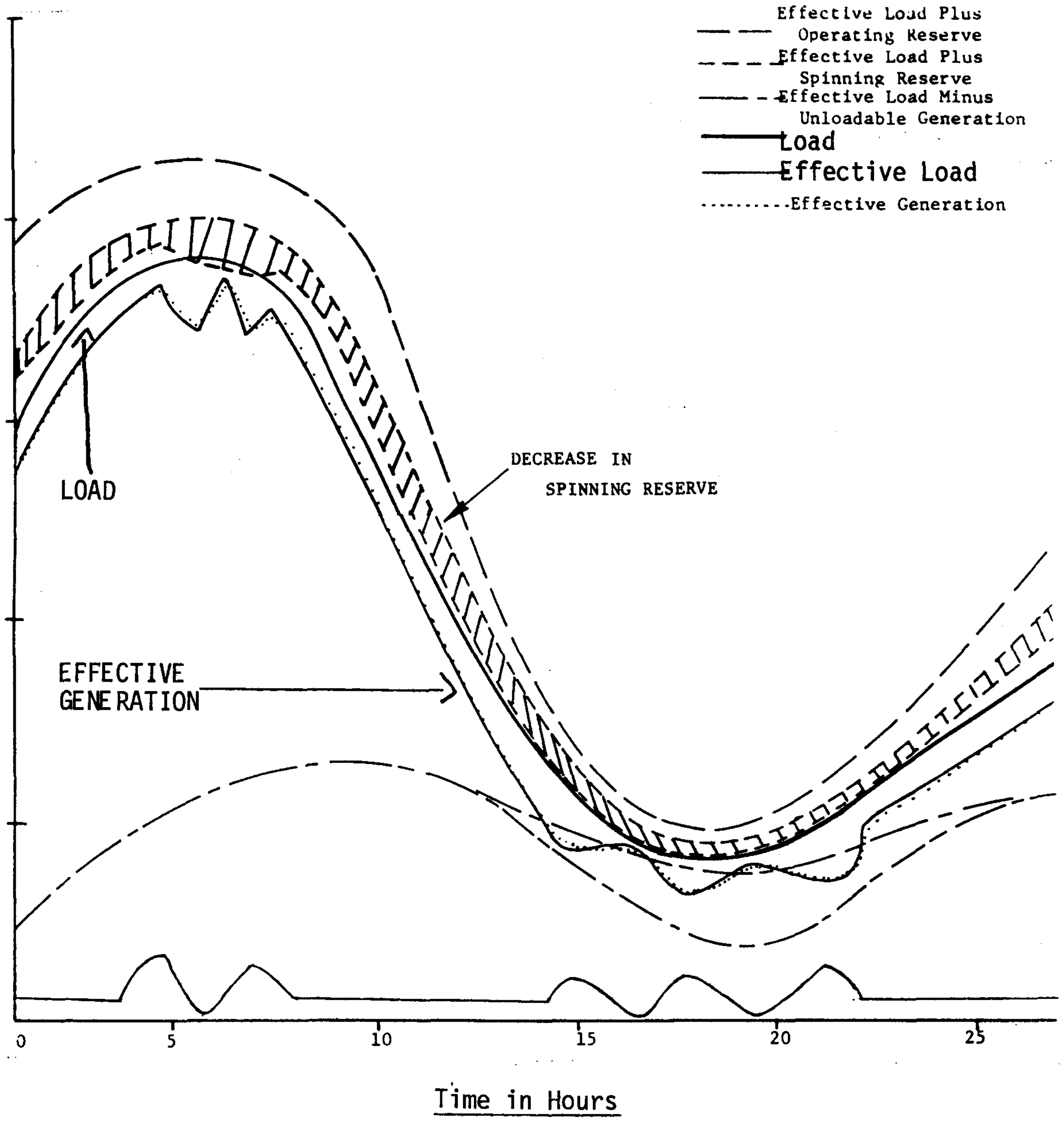


Figure 4. A unit commitment and generation control procedure that adjusts unit commitment and load following generation control capability for wind power variation.

previous solutions discussed. The increase in unloadable generation would occur if the maximum increase in wind generation exceeded maximum first contingency loss of export or load which would violate the farm penetration constraint. If the farm penetration constraint were satisfied, an increase in unloadable generation would only be needed during meteorological events. Spinning reserve would not be increased by the capacity of the array as in previous solutions. Spinning reserve would not increase significantly if the farm penetration constraint were satisfied.

The increase in spinning reserve due to wind generation would then only be large enough to insure reliable operation for the continual large power variations observed for passage of meteorological events. This increase in spinning reserve can be observed in Figure 4. Note also the step change in spinning reserve lags the step change in wind power output due to a change in the wind speed in the array. The step change in spinning reserve is delayed from the change in wind speed to confirm apriori wind speed forecasts that the change in wind speed will be maintained over the next few hours. The step decrease in spinning reserve with no change in operating reserve is accomplished by either shutting down quick pickup units which automatically places them into operating reserve or by shutting down steam turbine generators and placing them in standby so they would be counted in operating reserve. Increasing spinning reserve without changing operating reserve during passage of the meteorological events is accomplished by connecting quick pickup units or connecting those on standby that were counted in operating reserve but not spinning reserve before being brought on-line. The reduction in spinning reserve and unloadable generation reserve over that in the previous solutions will significantly reduce fuel and operating costs. The automatic generation control will not adequately track the ramp and cyclic variations due to passage of meteorological events although significant reduction in area control error and frequency deviation is possible by (1) the addition of load following and spinning reserve capability to unit commitment during passage of meteorological events and (2) increasing automatic generation control response and response rate capability through adjustment of AGC control parameters to exploit these additional reserves supplied by unit commitment. Methods for deciding the additions to spinning reserve, unloadable generation, and load following reserves for continual large wind power variation was very briefly discussed in [18] but no detailed procedure was given.

2.2 A MODIFIED UNIT COMMITMENT AND GENERATION CONTROL STRATEGY

The modified unit commitment and generation control strategy discussed in this section and in Section 4 requires accurate quarter-hour ahead prediction of cyclic wind power variation and an accurate hour ahead prediction of trend wind power variation. It is shown in [3] that both predictions may be feasible which is confirmed in this study. The solution to the unit commitment problem includes an update of the unit commitment on three different time cycles (daily, quarter hourly, and each minute) using wind power predictions of 24 hours, 1 hour, and quarter hour, respectively. The normal _24 hour ahead commitment_ schedule would only include very _slow trend_ (diurnal) variations in wind power that could be accurately predicted 24 hours ahead of real time.

The 24 hour unit commitment schedule would be updated quarter hourly utilizing a quarter hourly updated one hour prediction of both _fast trend_ and _cyclic_ wind power variation components. The _quarter-hourly updated unit commitment_ procedure will utilize these hour ahead fast trend and cyclic predictions to adjust operating reserve and to a lesser extent load following, spinning reserve and unloadable generation requirements. This quarter-hourly updated unit commitment program would then start up regulating, peaking or possibly economic units that can be brought on-line in an hour. Larger economic steam units could take several hours to be brought up and thus would not generally be candidates for start up in the one hour unit commitment procedure unless they were kept close to standby status or the period after it was shutdown is not long.

The very large cyclic variation around the trend change experienced in fronts, storms, and thunderstorms is not likely to be predicted accurately one hour head because the shape and magnitude of these fluctuations change over time as the front, storm, or thunderstorm propagates. Thus, the quarter-hourly updated unit commitment would not be able to compensate for the 10 to 30 minute cyclic wind variations.

A minute-updated quarter-hour ahead prediction of cyclic wind power variation would be used to reset the load following, spinning reserve, and unloadable generation requirement in a minute updated unit commitment procedure. This minute-updated unit commitment would start up or shutdown quick pickup units (hydro, gas turbines, etc.) and wind turbines that can be brought on-line with 10-15 minutes notice. A procedure is given for setting unit commitment reserve levels in [3] for the large cyclic power variations resulting from fronts, storms, and thunderstorms passing through single or multiple wind turbine arrays.

The ability to quickly switch quick pickup units from the nonspinning component of operating reserve to the spinning reserve component of operating reserve allows a much larger wind generation penetration without causing reduction of operating reliability or deliberate continual violation of NERC guidelines

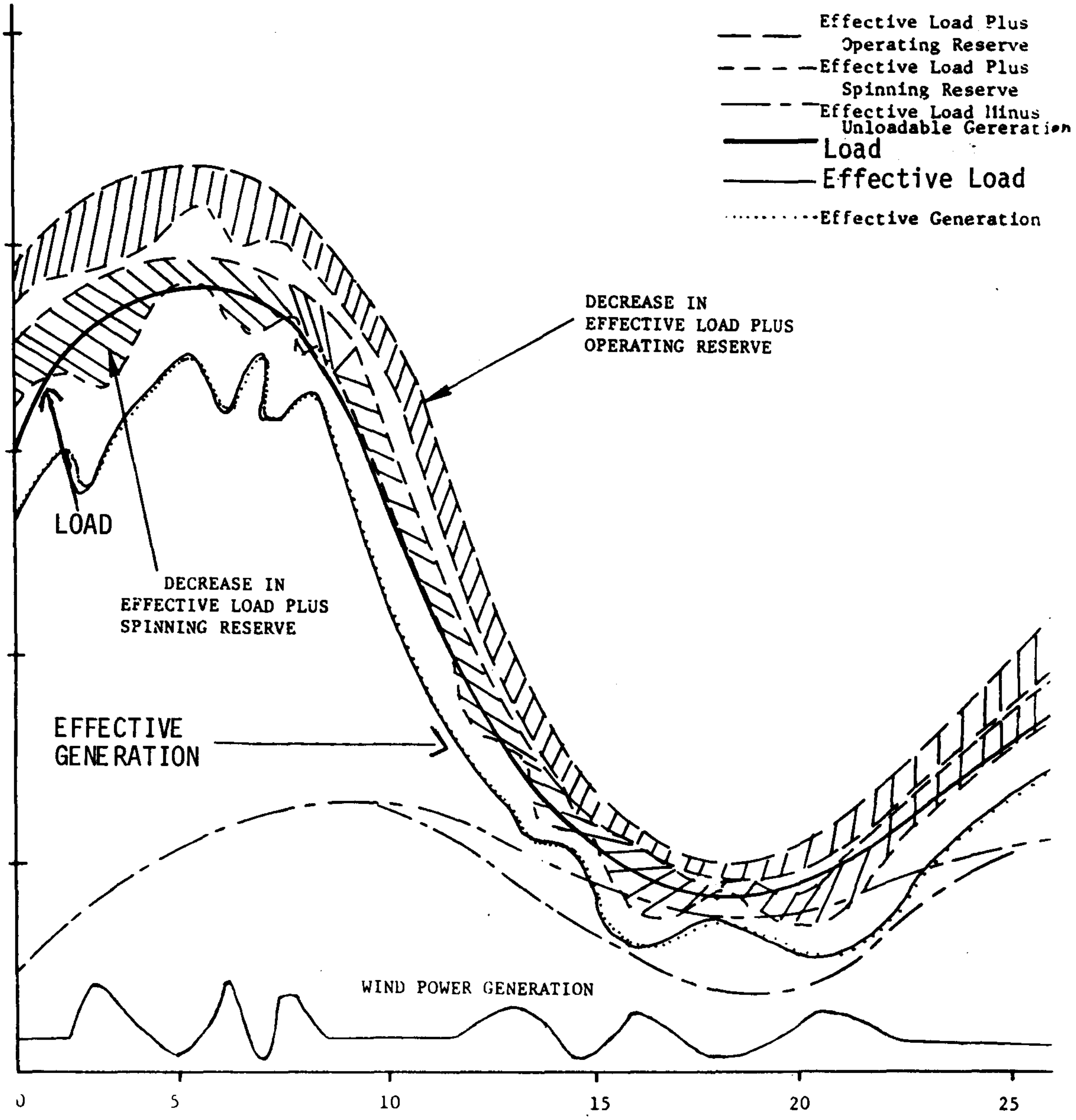


Figure 5. A modified unit commitment and generation control procedure that utilized predicted wind power variation to adjust unit commitment and load following generation control capability.

[19]. The farm penetration constraint level, which is a threshold on the maximum wind generation level that can be lost without violation of NERC Minimum Criteria for Operating Reliability, can be increased by the capacity of quick pickup units that can be switched to spinning reserve. This ability to quickly add quick pickup capacity to spinning reserve for wind power decreases requires (a) prediction of trend wind power variation so that there are regulating, peaking, or economic units to replace quick pickup units taken from nonspinning reserve with no more than a 15 minute delay and (b) accurate minute updated quarter-hour ahead prediction of cyclic wind power variation to permit switching quick pickup units to spinning reserve exactly at the time the wind generation decreases. The ability to adequately cope with larger wind penetrations due to this modified unit commitment and generation control is clearly observed in Figure 5.

The solution to the _control problem_ proposed in this research should only be concerned with the fast trend and cyclic components of wind power variation because the slow trend (diurnal) wind component can be accurately predicted and handled as the slow trend load component via normal 24 hour unit commitment and economic dispatch. The control solution proposes to utilize:

(a) automatic generation control that would better track the hour ahead predicted trend and 15 minute ahead predicted cyclic wind variation because these variations are anticipated;

(b) a supplementary automatic generation control of the peaking, regulating, quick pickup units committed by the quarter-hourly and minute updated unit commitment to respond to the predicted trend and cyclic wind variation. These units have a fast response that either is not utilized fully or is not included in present automatic generation control strategies. This is called _feedforward generation control_ in [8];

(c) a coordinated blade pitch control on all wind turbines in single or multiple arrays that can clip predicted cyclic wind power variation and smooth rapid hour ahead predicted trend changes that cannot be easily handled by automatic generation control or the feedforward generation control. This is called _feedback array control_ in [8].

The coordination of these three controls would be permitted through the hour ahead prediction of trend and quarter-hour ahead prediction of cyclic wind power variation. The modified generation control has more than ample control capability for tracking the very large cyclic and trend variation which could be expected when wind penetrations range from 5-15% of a utility's capacity.

2.3 SPINNING RESERVE, UNLOADABLE GENERATION, AND LOAD FOLLOWING REQUIREMENTS IN THE MODIFIED UNIT COMMITMENT

Spinning reserve, unloadable generation reserve, and load following reserve requirements are discussed in this section.

The spinning reserve, unloadable generation, and load following requirements include a trend and a cyclic component based on the hour ahead prediction and a cyclic component based on the 15 minute ahead prediction of wind power variation. The spinning reserve SR(k), unloadable generation UG(k) and load following reserve requirements are set based on the following formulas:

$$SR(k) = \max\{D_R(k) + (L_{k+1} - L_k)T + Q^{+}_{Wk} - (W_{k+1} - W_k)T + Q^{+}_{Wk};\ 0\} \qquad (1)$$

$$UG(k) = \max\{D_c(k) - (L_{k+1} - L_k)T + Q^{-}_{Lk} + (W_{K+1} - W_k)T + Q^{-}_{Wk};\ 0\} \qquad (2)$$

$$LF(k) = \max\{UG(k),\ SR(k)\} \qquad (3)$$

$D_R(k)$,($D_c(k)$) the maximum first contingency loss of reserve (commitment) or increase (decrease) in wind generation at hour k (megawatts)

L_k	the 24-hour ahead predicted load at hour k (megawatts)
W_{k+1}	the hour ahead predicted trend wind generation at hour k+1 made at hour k (megawatts)
T	.1667 hours/hours - fraction of an hour
$(L_{k+1} - L_k) - (W_{k+1} - W_k)T$	the predicted effective load change in ten minutes during [k, k+1) (megawatts)
Q^+_{Lk}, Q^-_{Lk}	the effects of load forecasting error and minute by minute load variation above (below) trend load variation that requires regulation (megawatts)
Q^+_{Wk}, Q^-_{Wk}	the effect of trend wind power forecasting error, turbulence, and meteorological events below (above) the predicted trend $(W_{k+1} - W_k)T + W_k$ (megawatts)

The unit commitment can meet these spinning reserve, unloadable generation, and load following requirements through components from each generator connected, quick pickup units and interruptible load. The constraints on unit commitment for spinning reserve, unloadable generation, and load following are:

$$\alpha_k I(k) + \beta_k QP(k) + \sum_{i \varepsilon A} \min\{DC_i - P_i(k), MSR_i\} > SR(k) \tag{4}$$

I(k)	the capacity of interruptible load via contract with the customer at hour k (megawatts)
QP(k)	the capacity of all quick pickup and storage that could be brought on line in 10-60 minutes (megawatts)
A	set of generators connected to the transmission grid

α_k	percentage of interruptible load counted in spinning reserve at hour k
β_k	percentage of quick pickup capacity in operating reserve counted in spinning reserve at hour k
DC_i	desired maximum generation level of unit i (megawatts)
$P_i(k)$	generation level of generator i at hour k (megawatts)
MSR_i	maximum spinning reserve level allowed on unit i (megawatts)

$$\delta_k I(k) + \xi_k QP(k) + \sum_{i \epsilon A} \min(P_i(k) - MC_i; \; MUG_i) > UG(k) \qquad (5)$$

δ_k	percentage of interruptible load actually interrupted at hour k
ξ_k	percentage of quick pickup capacity that could be unloaded at hour k
MC_i	minimum desired generation level on generator i (megawatts)
MUG_i	maximum unloadable generation allowed on unit i (megawatts)

$$\sum_{i \epsilon A} 10R_i P_i(k) > LF(k) \qquad (6)$$

R_i	rate of response in MW/min of generator i

Note that these constraints allow use of quick pickup and interruptible load to be counted in spinning reserve and unloadable generation as required in quarter-hourly and minute updated unit commitments. The expressions for setting (1,2,3) and meeting (4,5,6) spinning reserve, unloadable generation and load following are based on hourly updates (k) because such updates are those for the normal 24 hour unit commitment. The variables such as L_k, W_k, Q_{Wk} etc. in (1,2,3) must be specified every hour. These same expressions (1,2,3,4,5,6) will be used for setting and meeting spinning reserve, unloadable generation in the quarter hour ($k + j/4$; $j = 0,1,2,3$) and in the minute ($k + \ell/60$; $\ell = 1,2\ldots,60$) updated unit commitments.

2.4 COMPUTATION, JUSTIFICATION, AND UPDATE OF SPINNING RESERVE, UNLOADABLE GENERATION, AND LOAD FOLLOWING REQUIREMENTS QUARTER-HOUR AND MINUTE UPDATED UNIT COMMITMENTS

Measures of the trend and cyclic wind power variation in the hour ahead wind power prediction $W_1(t)$ (updated quarter-hourly) and a measure of the cyclic variation in the quarter-hour prediction $W_2(t)$ (updated every minute) are used in setting the spinning reserve, unloadable generation and load following requirements in the quarter-hour updated unit commitment (SR$(k + j/4 - 1)$, UG$(k + j/4 - 1)$, LF$(k + j/4 -1)$ and minute updated unit commitment (SR$(k + \frac{\ell-15}{60})$, UG$(k + \frac{\ell-15}{60})$, LF$(k + \frac{\ell-15}{60})$; $k = 1,2,\ldots,24$, $\ell = 1,2,\ldots,60$).

The quarter-hourly updated unit commitment requires setting W_{k+1}, W_k, Q^+_{Wk}, Q^-_{Wk} at quarter-hourly intervals in order to set SR$(k + j/4 - 1)$, UG$(k + j/4 - 1)$ and LF$(k + j/4 - 1)$ in (1), (2), and (3) for constraints (4), (5), and (6) respectively. The constants $W_{k+1} = W(k + j/4)$, $W_k = W(k + j/4 - 1)$, $Q^+_{Wk} = Q^+_W(k + j/4 - 1)$ and $Q^-_{Wk} = Q^-_W(k + j/4 - 1)$ since the levels over $(k + j/4 - 1, k + j)$ must be decided on at $k + j/4 - 1$ based on a prediction record of wind power variation $W_1(t)$ for $t \epsilon (k + j/4 - 1, k + j/4)$. Spinning reserve, unloadable generation, and load following levels are likewise updated at $k + \frac{j+1}{4} - 1$ to cover the period $(k + \frac{j+1}{4} - 1, k + \frac{j+1}{4})$ for the quarter hour updated unit commitment computed at $k + \frac{j+1}{4} - 1$ for any unit $k = 1,2,\ldots,24$, $j = 0,1,2,3$.

The measures $W(k + j/4 - 1)$, $W(k + j/4)$, $Q^+_W(k + j/4 - 1)$ and $Q^-_W(k + j/4 - 1)$ used in setting spinning reserve (1) and unloadable generation (2) can be illustrated in part by Figures 6 and 7. In Figure 6, the load $L(t)$ is constant and shows no variation. The wind variation is represented by a ramp increase over 5 hours leveling off to a constant level. There is no error in predicting cyclic or trend wind power variation and no cyclic wind or load variation so that $Q^+_W(k + j/4 - 1)$, $Q^-_W(k + j/4 - 1)$, $Q^+_L(k + j/4 - 1)$, $Q^-_L(k + j/4 - 1)$ are zero. The effective load to be coped with by conventional steam generation is also shown in Figure 6. The basic spinning reserve level is D_R, where D_R, is

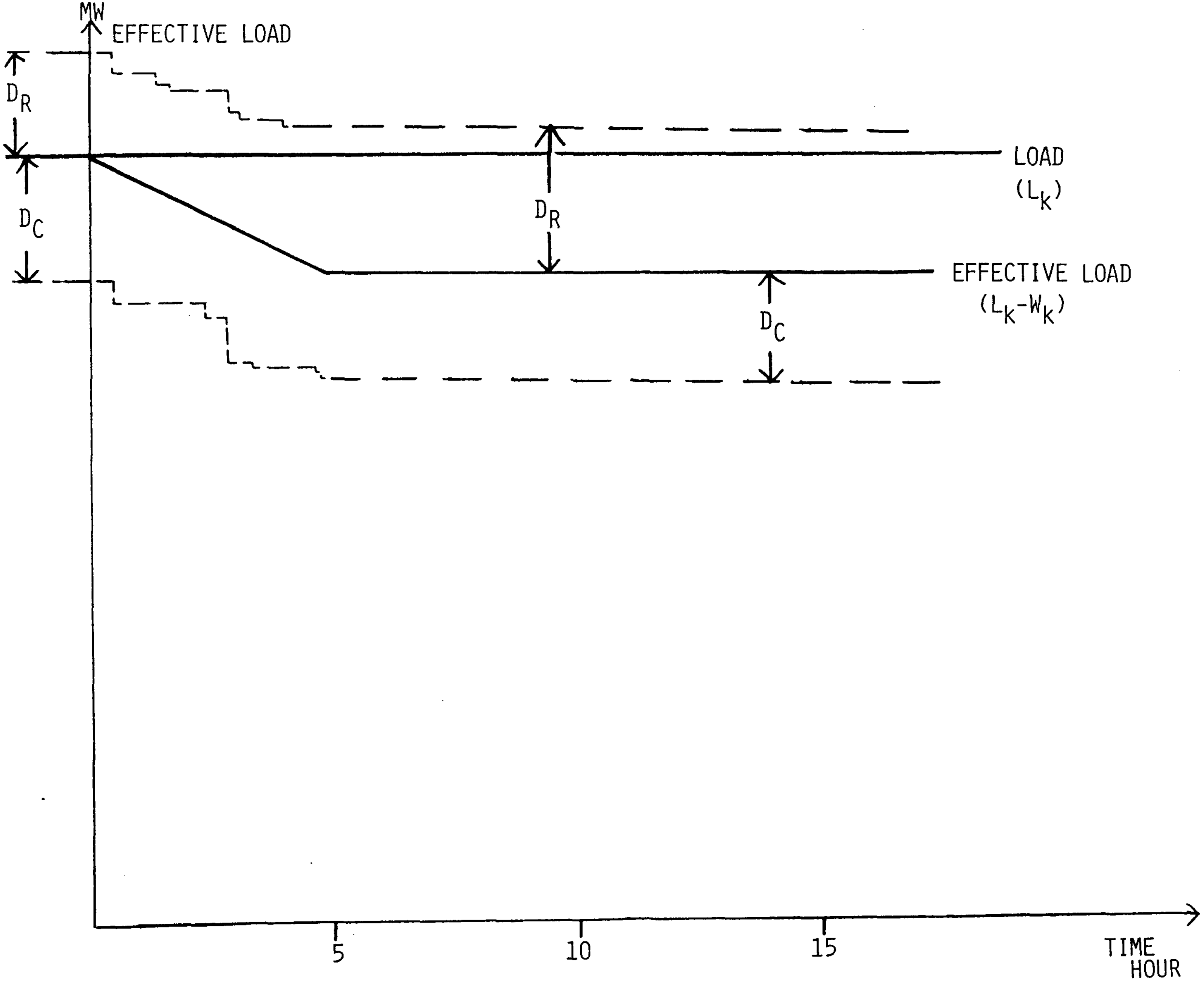


Figure 6. Spinning reserve and unloadable generation requirements for trend wind power variation.

the maximum first contingency loss of generation reserve component that is shown as a dotted line that tracks the variation in L(t). The actual adjustment of total connected generation capacity $P_M(t) = L(t) + D_R$ is not continuous but occurs at discrete times, which is indicated by the staircase. The spinning reserve formula reflects this staircase effect by requiring unit commitment supplied capacity to always provide the basic reserve D_R plus the change in L(t) - W(t) over ten minutes; i.e.

$$D_R + [(L_k - W_{k+j/4}) - L_{k-1} - W_{k+j/4-1})]T$$

The unloadable generation is seen as negative reserve in Figure 6. The basic reserve level is D_C, which is the maximum of the maximum first contingency loss of load or export from the utility or the maximum first contingency increase in wind generation. The unloadable generation formula (2) again reflects the need for the basic unloadable generation reserve minus the projected change in effective load in ten minutes or an hour; i.e. $D_C - [(L_k - W_{k+j/4} - (L_{k-1} - W_{k+j/4-1})]T$. The unloadable generation changes again change in a staircase reflecting discrete time unit commitment changes that always supply at least the unloadable generation in the formula (2).

Figure 7 is identical to Figure 6 except that large cyclic wind variations are imposed on L(t) - W(t). Note then an additional reserve $Q_W^+(k + j/4 - 1)$ and $Q_W^-(k + j/4 - 1)$ to spinning and unloadable generation respectively are required for j = 0,1,2,3 and for k as long as the cyclic variation persists. Note that as the cyclic variation increases the values of $Q_W^+(k + j/4 - 1)$ and $Q_W^-(k + j/4 - 1)$ increase also.

The one hour prediction interval and the quarter-hourly update of the quarter-hourly updated unit commitment are both too long to accurately assess minute by minute changes in spinning reserve, unloadable generation, and load following requirements and to properly meet these requirements on a minute to minute bases. A fifteen minute prediction interval allows a much more accurate prediction $W_2(t)$ of the wind power variation record over $(k + \frac{\ell-15}{60}, k + \ell/60)$ at $k + \frac{\ell-15}{60}$ than that provided by $W_1(t)$ over $(k + \ell/60 - 1, k + \frac{\ell}{60})$ at $k + \frac{\ell}{60} - 1$ but especially over (k

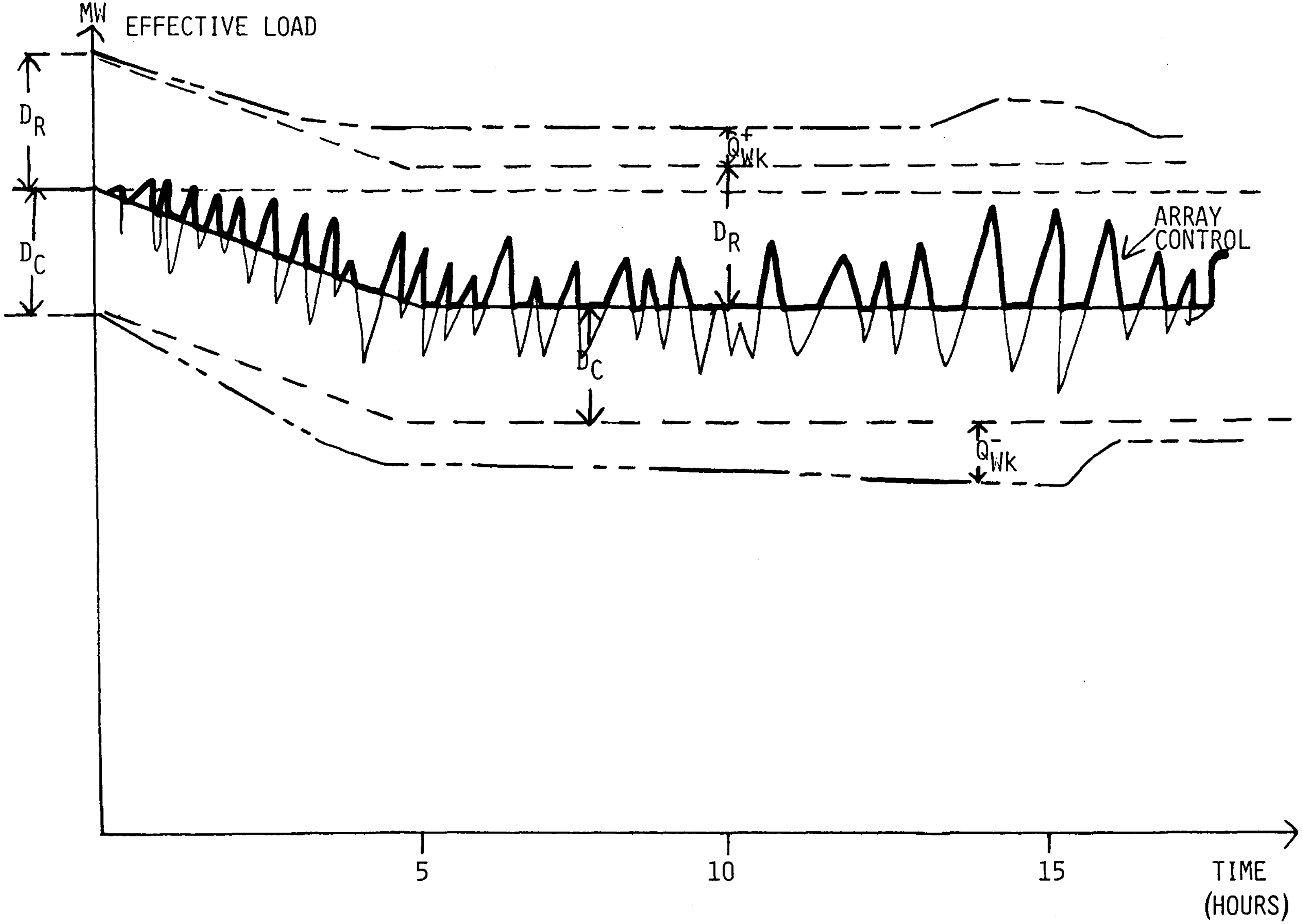


Figure 7. Spinning reserve and unloadable generation requirements for trend and cyclic wind power variation and the use of blade pitch control to eliminate unloadable generation requirement.

$- \frac{\ell-15}{60}$, $k + \ell/60$). The measure of cyclic and error variation $Q_W^+(k + \frac{\ell-15}{60})$ $Q_W^-(k + \frac{\ell-15}{60})$ is set at $k + \frac{\ell-15}{60}$ and measures the cyclic variation around $W_2(t)$ and the error in predicting $W_2(t)$.

The $Q_W^+(k + j/4 - 1)$ and $Q_W^-(k + j/4 - 1)$ terms in the quarter-hour updated unit commitment measure the cyclic variation due to turbulence or meteorological events as well as the error in predicting the magnitude of the trend $W_1(t)$ component. The terms $Q_W^+(k + \frac{\ell-15}{60})$ and $Q_W^-(k + \frac{\ell-15}{60})$ in the minute updated unit commitment measure (a) the cyclic variation due to turbulence, during both normal conditions and meteorological events, and (b) the magnitude of the error in predicting trend. The procedure [2] for determining the peak turbulence induced wind power variation on an array over ten minutes based on a normalized Kaimal spectrum, measurement of the average wind speed, and parameters that indicate atmospheric stability is an excellent procedure for estimating the turbulence induced component of cyclic wind variation. The procedure can also be used for estimating peak meteorological event induced cyclic wind power variation over ten minutes from an array.

It should be noted that turbulence induced wind variation over periods of less than ten minutes were studied in [2] and could be also included in spinning reserve, unloadable generation, and load following requirements. This fast component of turbulence induced wind power variation with frequencies above generator units that generator unit operators would raise such strong objections that these fast turbulence induced cyclic wind power variations must either:

(a) be clipped by the coordinated blade pitch controls of wind turbines,

(b) be compensated for by diesel's combustion turbines, or other very fast responding units. These units could compensate for this fast cyclic component without incurring excessive maintenance costs, loss of availability, or reduced unit life.

Thus, these fast turbulence induced cyclic wind power variations need not be compensated for by conventional steam turbine generators but must be estimated and compensated for by other fast responding generation units under feedforward control as discussed more completely in the next subsection.

Methods for predicting the trend for diurnal wind power variation [5,6] and the trend components for meteorological events and their errors are discussed in Section 3 of this report. The diurnal wind power variation must be predicted for the 24 hour updated unit commitment. The meteorological event wind power variation can be significantly larger than turbulence or diurnal wind power variation from the energy spectrum plotted in Figure 1 and the fact that meteorological event variations are strongly correlated for all wind turbines in a cluster and may be correlated between wind turbine clusters. The prediction of the meteorological event trend wind power variation for both the quarter hour $W_1(t)$ and minute updated unit commitment $W_2(t)$, which is the subject of this report, is thus essential to this modified unit commitment strategy. The modified unit commitment based on these predictions would be then able to handle larger wind generation penetrations up to 15% of a utility's capacity both reliably and economically.

There is no ability to clip wind power variations below the trend W(t) unless the wind turbine arrays are scheduled to operate below the hour ahead predicted trend W(t) obtained from the hour ahead prediction record $W_1(t)$. This operation of the blade pitch control to clip wind power variation to either $W_1(t) - \overset{+}{Q}_W(k + j/4 - 1)$ or $W_2(t) - \overset{+}{Q}_W(k + \frac{\ell-15}{60})$ as shown in Figure 8 does not eliminate spinning reserve or load following responsibility from either the quarter-hourly updated or minute updated unit commitment since the "free" wind power clipped below W(t) must be provided by the economic, peaking, or regulating units of the quarter-hourly updated unit commitment based on the $\overset{+}{Q}_W(k + j/4 - 1)$ component and the startup of quick pickup or disconnection of interruptible load by the minute updated unit commitment based on the additional $\overset{+}{Q}_W(k + \frac{\ell-15}{60}) - \overset{+}{Q}_W(k + j/4 - 1)$ component of minute by minute spinning reserve and load following requirement reflected in $\overset{+}{Q}_W(k + \frac{\ell-15}{60})$.

It should be noted that the option to clip wind power by part or all of $\overset{+}{Q}_W(k + \frac{\ell-15}{60})$ or $\overset{+}{Q}_W(k + j/4 - 1)$ below W(t) or not at all is solely the function of generation control and has no effect on unit commitment. It is mentioned here since clipping wind power variation above W(t) eliminated unloadable generation

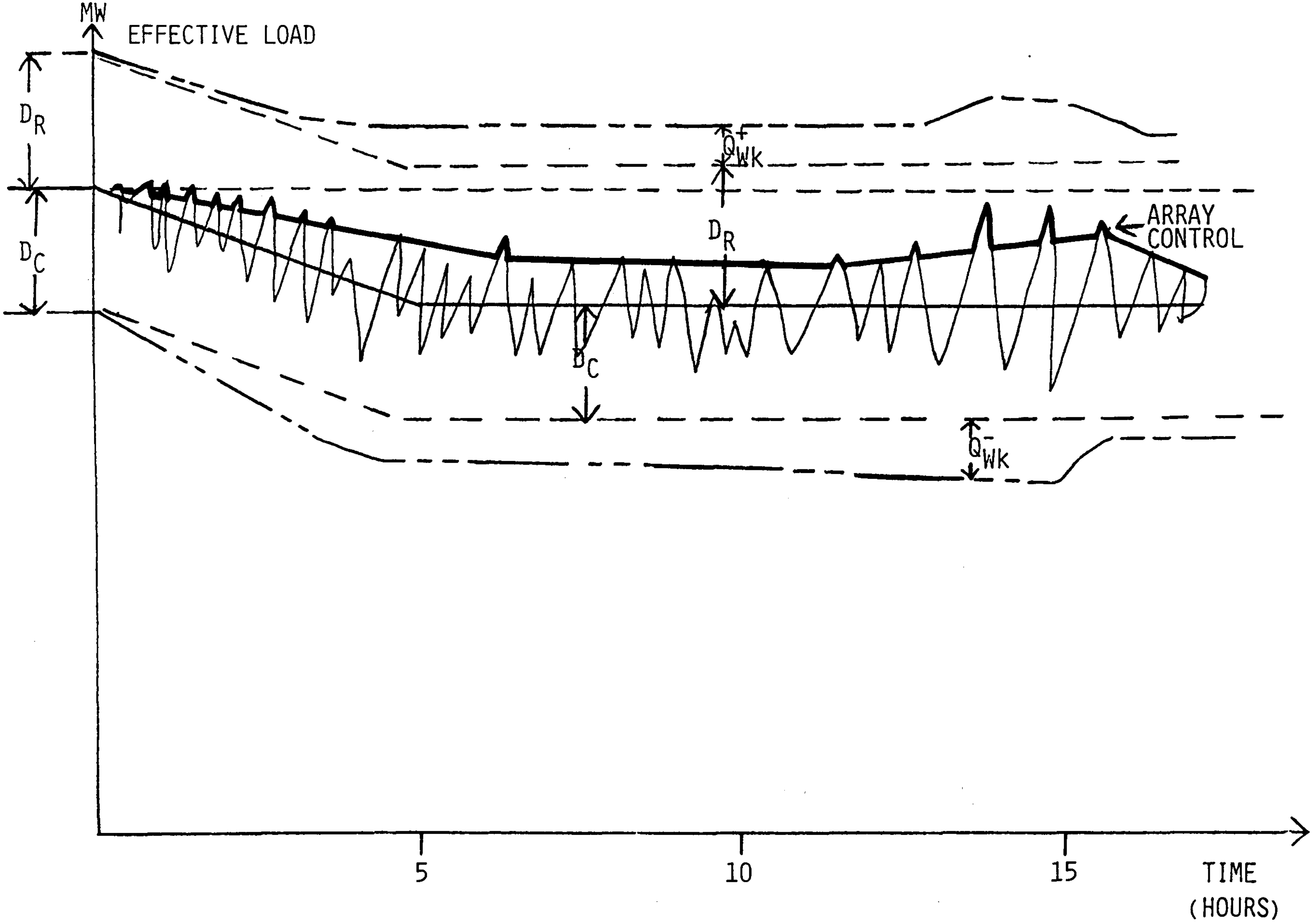


Figure 8. Effect of coordinated blade pitch control in smoothing wind power variations below the predicted trend.

requirement from both quarter-hourly and minute updated unit commitment and is discussed in the following subsection.

2.5 MODIFIED GENERATION CONTROL

The automatic generation control has generally performed the regulation function of attempting to maintain frequency close to a nominal value and matching generation to load change thus nulling area control error which is a measure of the mismatch in load and generation. The load following requirement on automatic generation control requires that the parameters of the AGC are set to command sufficient generation change in 10 minutes to null area control error. The automatic generation control load following capability is of no value unless the unit commitment has provided through constraint (6) the load following capability given by (3). The load following capability within the automatic generation control must also meet or exceed that given by (3). Results in [8] indicate that insufficient load following capability in either unit commitment or automatic generation control will cause large excessive area control errors that are sustained for periods much longer than 10 minutes which violates the NERC guidelines [19] that require (a) the area control error maxima and average values over ten minutes to be below a certain threshold based on system size and (b) that area control error must pass through zero in every ten minute period.

It is conceivable that automatic generation control response capability could be adjusted to each update of the quarter-hourly unit commitment to provide $LF(k + j/4 - 1)$ given by (3) for the unit commitment. However, the use of conventional generation to meet these requirements for wind power variation due to significant wind speeds changes or passage of meteorological events would:

(1) increase fuel costs on the units committed to providing $LF(k + j/4 - 1)$ in (6);

(2) increase maintenance costs, increase forced outage rates, and reduce unit lifetime due to the large continual cycling of these units.

An improved generation control strategy would utilize:

(1) normal automatic generation control that without wind variation is totally responsible under normal conditions to maintain system electrical frequency at 60 hz and regulate total system generation to track load variations;

(2) array controls that would smooth the effects of turbulence; slow trend; fast trend variations due to fronts, storms, and thunderstorms; and cyclic variations due to turbulence

fronts, storms, and thunderstorms from single and multiple arrays. The closed loop array controls would utilize a coordinated blade pitch control of all wind turbines in an array based on information about the capability of the utility's controls to handle these wind power variation components. Such closed loop array controls were discussed in [8]. These array controls utilized fast wind power variation prediction but make no effort to predict power variation from meteorological events since the application of the proposed control does not emphasize meteorological events;

(3) a feedforward generation control developed to control the fast responding regulation and peaking units committed by the quarter-hour unit commitment update and even faster responding quick pickup units that would be committed in the minute unit commitment update. At present, quick pickup units are not generally utilized in automatic generation control and generally not all peaking and regulation units are utilized. If peaking, regulating, and quick pickup units are under the automatic generation control, their response rate capabilities are generally not fully exploited. Thus, this feedforward generation control would control these units committed by quarter hour and minute updated unit commitments. This feedforward control would utilize the response capabilities of these units to compensate for normal turbulence and fast trend and turbulence for meteorological events.

The normal automatic generation control, closed loop array control, and feedforward generation control would be coordinated to provide the best control performance needed to maintain reliable operation and minimize the total cost of regulation of these wind power variation components.

It is clear that the proposed unit commitment procedure requires the development of the one or more hour trend wind predictor and the quarter-hour cyclic wind power predictor to compensate for the inherent delays in starting up regulation and peaking, quick pickup units, and wind turbines, respectively. The proposed control procedure requires prediction to (1) permit the units under automatic generation control and the peaking, regulating, and quick pickup units under feedforward generation control to anticipate the large trend and turbulence (cyclic) wind power variations predicted and thus effectively increase their ability to respond; (2) the closed loop array control to anticipate and thus reduce total wind power change and rate of change by (a) beginning the wind generation increase or decrease before it actually occurs and (b) by clipping cyclic wind power variation making the wind generation change easier to cope with by AGC or feedfoward generation control; and (3) to properly coordinate the system AGC, feedforward generation control, and closed loop array control portion of the control task. It should be noted that if the array control is capable of anticipating a wind generation increase or clipping cyclic wind power variations below the trend wind power variation $W_1(t)$ or $W_2(t)$ requires the array to operate below the level possible with the wind speeds observed at all wind turbines in the array. If the closed loop array controls operate the array below the predicted trend $W_1(t)$ or $W_2(t)$, the closed loop array control can compensate for positive or small negative errors in predicting $W_1(t)$ or $W_2(t)$ since small negative errors and all positive errors in predicting wind array power are eliminated. This type of control of wind array power might be necessary if errors in predicting wind power trend $W_1(t)$ or $W_2(t)$ are large and can change rapidly during meteorological events.

If either the quarter-hour cyclic wind power or hour trend wind power predictors were not feasible, the solution to the unit commitment and control problems proposed in [17] would be implemented with the following consequences:

(1) the maximum wind penetration would be limited by the farm penetration constraint to the maximum first contingency loss of conventional generation [17]. If the spinning reserve and load following capability were increased with array capacity, significant fuel, operating, and maintenance costs, that would be added would significantly hurt the economics of wind generation, would be added;

(2) addition to spinning reserve and load following requirements on unit commitment would be required in proportion to the maximum cyclic power variations anticipated for the next 24 hour period. These maximum cyclic deviations would be for the wind turbulence during the worst front, storm, or thunderstorm that can be anticipated for that day whether it occurs or not. These additional spinning and load following reserves would be included in these requirements (3) for the entire day or a significant portion of it since the time of arrival of meteorological events could not be predicted accurately 24 hours ahead. This addition to spinning reserve, unloadable generation, and load following could be significant and again reduce the economic viability of wind generation;

(3) a response and response rate capability would be provided in excess of that required of the automatic generation control

and closed loop array control. These control actions increase operating costs since this constant adjustment of generation levels increases fuel costs and operating and maintenance costs, and since the use of array control to smooth total wind power variation reduces the energy output of the array. These costs are in addition to the above costs that exist purely for connecting the additional generation since these regulations costs are attributed to continually changing generation levels and costs for the lost energy from arrays required to clip or smooth cyclic and trend wind power variations;

(4) the reduced control performance by lack of feedforward generation control units and the lack of anticipation and coordination in the system automatic generation control, closed loop array control, and feedforward generation control;

(5) the operating reserve would not be adjusted for arrival of meteorological events but will be set 24 hours ahead based on the worst anticipated drops in wind generation over the next 24 hour period.

The recent HECO decision to install an 8% penetration wind array that exceeds typical spinning reserve and load following capability points out the need for this new solution [3] to the unit commitment and control problems because possibly severe reliability or economic penalties can be anticipated if the entire array is built and exceeds the farm penetration constraint. It is anticipated that other utilities will eventually desire to install higher penetrations (% wind capacity) than typical spinning reserve levels (5%) as wind technology improves resulting in larger and more efficient wind turbines and thus larger wind generation penetrations.

SECTION 3

WIND POWER PREDICTION METHODS

Wind power prediction of diurnal trend, turbulence, and meteorological event trend wind power variation is required for the modified unit commitment and for the modified generation control strategy. The methods required for predicting each of these wind power components is different and obviously their use in the 24, quarter-hour, and minute updated unit commitment, and in the automatic generation control, feedforward generation control, and closed loop array control are different as discussed in Section 2. The prediction of the weather map (meteorological event) trend wind power change is by far the most important because

(1) the energy spectrum shows the energy associated with weather map fluctuations is much larger than for turbulence or diurnal variation in Figure 1;

(2) the wind speeds at various sites in a small geographical area for weather map fluctuations are highly correlated and thus the large wind power variation on all wind turbines in an array are nearly identical and are additive. Turbulence induced variation are poorly correlated and thus the cyclic variations on wind turbines in the array tend to cancel in the total power out of the array.

The prediction of meteorological event wind power variation is thus the most important component of the wind power variation to be predicted. The research performed in this study is the only known study of prediction of meteorological event wind speed variation for application to wind power prediction although studies have been conducted on and reported on meteorological event prediction in the atmospheric sciences literature.

This section first reviews previous literature on prediction of diurnal, meteorological event, and turbulence induced wind power variation. The least squares models used for prediction of meteorological events in this research is then presented. Finally, the methodology for properly filtering, determining the direction of the meteorological event, and determining propagation delay for the event is presented. The application of the least squares model and prediction methodology to data from the SESAME array of wind measurement sites is given in Section 4.

3.1 REVIEW OF PREVIOUS LITERATURE

The previous literature on prediction of diurnal trend wind power variation and the estimation of turbulence induced wind power variation for use in the 24 hour, quarter hour, and minute updated unit commitments is now reviewed.

The turbulence prediction method developed in [2] would attempt to estimate the peak W_o turbulence induced wind power variation defined by

$$P\{W(t) \leq W_o\} = .99$$

based on a Kaimal spectrum of wind speed, a model of correlation of wind speed between wind turbine sites, and a transformation of wind speed to wind power variation for the wind turbine models in the particular array. The estimation of the peak wind power W_o would also depend on the average wind speed measured at the wind turbines in the cluster and on the stability of the meteorological conditions at the cluster. The estimation procedure would eliminate the need to estimate both the actual wind power and the error in this estimate which are both imbedded in $Q_W^+(\quad)$ and $Q_W^-(\quad)$ for the quarter hour and minute updated unit commitments. Moreover, the Kaimal spectrum used in [2] is considered to be more accurate than the Davenport spectrum used in [8]. Finally, since the estimation can be updated every quarter hour (or minute if necessary), since the error is included in the estimate, and since the actual magnitude of turbulence induced variation out of arrays [3] even for meteorological events is small, there is no need for prediction of turbulence induced wind power variation. Thus, the effects of turbulence for normal or meteorological event wind conditions can be included by estimating the turbulence $Q_W^+(k + j/4-1)$ and $Q_W^-(k + j/4-1)$ every quarter hour for the quarter hour updated unit commitment. A minute update of the turbulence component for $Q_W^+(k + \frac{\ell-15}{60})$ and $Q_W^-(k + \frac{\ell-15}{60})$ would not be generally necessary unless there was very rapid and large changes in turbulence due to a meteorological event and associated atmospheric instability.

A methodology for subhour wind forecasts was developed in [6]. The approach was developed to provide forecasts of trend 10 minutes ahead for the modified generation control as well as one to six hours ahead for the modified unit commitment strategies. The OEM method, a regression method, and a persistence method were selected for evaluation in [6] based on the following criteria for a good predictor:

- techniques should be easily automatable
- ideally techniques should have some physically meaningful basis

- any predictors used must be available in real time
- techniques should be applicable to a variety of forecast output formats to meet users needs
- techniques should be applicable for prediction in time frames ranging from 10 minutes to a few hours
- techniques should permit update to be made easily upon demand

The mean, standard deviation about the mean, the trend, and the standard deviation were predicted at successive 10 minute time steps from 10-60 minutes ahead using a persistence, an autoregressive, and a OEM model. The same four variables were also predicted using the persistence, autoregressive, and OEM models for successive hour time steps from 1-6 hours and for successive half hour time steps from 1/2 to 3 hours. The results are quite preliminary since the research is at an early stage. The persistence model and OEM were clearly superior to the autoregressive model for predicting all four variable and for all prediction intervals. Persistence performs nearly as well as OEM for shorter (fewer iterations) prediction intervals using each basic time step (either 10 minutes, 30 mintues, or 1 hour). Trend forecasts were generally poor using all three methods and improvements could be made if there was a method of descriminating whether there would be speed change for a site. The large number of cases in the dependent set, where no change occurs, and the smaller number of cases where change occurs in the set of dependent cases, makes the techniques studied relatively less effective in predicting changes. The research performed in the study, documented in this report, suggest:

(1) knowledge of apriori meteorological information about the arrival of meteorological events;

(2) measurements of wind speed and direction at wind measurement sites that encircle the wind turbine cluster and that experience the meteorological event;

(3) measurement of pressure and temperature and their changes at the wind measurement sites that encircle the turbine array;

(4) determination of the speed of the meteorological events from wind speed, wind speed direction, pressure and temperature measurements and their gradients over time and space;

would provide the information required to accurately predict meteorological event induced wind power changes.

The setting of $Q_W^+(k + j/4-1)$ and $Q_W^-(k + j/4-1)$ for the quarter hour updated unit commitment and $Q_W^+(k + \frac{\ell-15}{60})$ and $Q_W^-(k + \frac{\ell-15}{60})$ for the minute updated unit commitment requires estimating the error in the prediction of the appropriate trend as well as estimation of the maximum turbulence (cyclic) variation for either normal or meteorological event wind conditions using the method [2] discussed previously. Methods for estimating the error for trend wind power variation must be developed.

A method for forecasting trend wind power variation hourly over a 24 hour interval is proposed in [5]. This type of prediction would be useful in setting operating reserve, spinning reserve, unloadable generation and load following reserve in the 24 hour unit commitment. The model first develops a static probabilistic transformation that relates hourly average wind power to hourly averaged wind speed at a particular wind turbine site for a particular wind turbine model (MOD-2, MOD-1, etc.). This static probabilistic transformation of a wind turbine was then used in conjunction with semiobjective and model output statistics wind forecasts. The performance of the wind power forecasts in properly forecasting whether average wind power output for a MOD-2 lies above or below 600, 1200, 1800, or 2400 kilowatts. The reliability and skill level for these two wind power forecasts was encouraging.

3.2 WIND SPEED PREDICTION METHODOLOGY FOR METEOROLOGICAL EVENTS

An effort was made in [3] to establish the feasibility of predicting wind speeds at 26 sites in SESAME array of 27 wind measurement sites in a 80 by 80 miles area in Oklahoma. The wind speed measurements were taken at a height of 13 feet and at a sampling rate one per minute. A correlated echelon model was used

$$W_i(t) = m_i + A_{ij}(T)[W_j(t - T) - m_j]$$

where $$A_{ij} = \frac{P_{ij}(T)\sigma_i}{\sigma_j} \qquad (7)$$

m_i, m_j	means of wind speed at sites i and j over time interval
σ_i, σ_j	standard deviation of wind speed at sites i and j over the time interval $(0, N\Delta)$

$T_{ij} = k_{ij}\Delta$	delay between the arrival of meteorological event at site i and j prediction interval
$P_{ij}(T_{ij})$	correlation coefficient of wind speed at site i and the wind speed at site j delayed by T_{ij}.
Δ	1 minute sampling period for wind data

The correlated echelon model assumes the wind speeds at the two sites i and j are both stationary processes that can have different mean and variance due to different surface roughness and site specific effects. The principal characteristics of the meteorological event captured in the wind speed records is assumed to propagate from site i to j with the speed and direction of the motion of the meteorological event itself.

The methodology used to determine the model (7) is

(1) filter each wind record over time interval $[0,N\Delta]$ using a moving average filter

(2) Calculate m_i, m_j, σ_i and, σ_j of the filtered reference wind measurement record $W_j(t)$ and the wind measurement record $W_i(t)$ where prediction is desired

(3) Calculate the correlation

$$P_{ij}(\tau) = \frac{C_{ij}(\tau)}{\sigma_i \sigma_j}$$

$$C_{ij}(\tau) = \sum_{k=1}^{N} \frac{X_i(k\Delta)X_j(k\Delta - \tau)}{N}$$

(4) find the value of T_{ij} and $P_{ij}(T_{ij})$ that maximize $P_{ij}(\tau)$

(5) Predict $W_i(t)$ using

$$\hat{W}_i(t + T_{ij}) = m_i + \frac{P_{ij}(T_{ij})\sigma_i}{\sigma_j}[W_j(t) - m_j]$$

given record of $W_j(t)$. Determine the mean square error for the predictor based on error $|W_i(t) - \hat{W}_i(t)|$.

The results obtained from the SESAME data for ten minute moving average filtered data showed that accurate estimates were possible at small geographical distances from the reference site.

The prediction intervals T_{ij} were also very small. The estimation errors were much larger at longer geographical distances. Although there was good quality estimation at small geographical distances, the prediction intervals were so small that it was questionable whether prediction was actually being accomplished.

The results obtained for filtering data with an hour moving average filter were encouraging because reasonable quality estimation was observed for sites reasonable distant from the reference site. The delays T_{ij} for some of the sites with reasonable quality estimation was 15 minutes and thus the possibility that prediction could be performed was indicated.

A correlated echelon model that would utilize wind speed measurements at several reference sites has the form

$$\hat{W}_i(t) = m_i + \frac{1}{M_i} \sum_{j=1}^{M_i} P_{ij} (T_{ij}) \frac{\sigma i}{\sigma j} [W_j(t - T_{ij}) - m_j] \qquad (8)$$

where

M_i	number sites where measurements are taken
$\hat{W}_i(t)$	wind speed estimate at site i
m_i, m_j	mean wind speed at site i and sites j = 1,2,...,N
σ_i, σ_j	standard deviation of the wind speed at site i and sites j = 1,2,...N
$P_{ij}(\tau)$	normalized cross correlation of wind speed at site i and site j
T_{ij}	delay between the time meteorological event first effects site j and the time it first effects site i. This delay T_{ij} is chosen as the value τ where normalized cross correlation $P_{ij}(\tau)$ is maximum
$W_j(t-T_{ij})$	delayed wind speed measurement record at site j

A similar recursive least squares model is proposed that has the form

$$W_i(N\Delta) = \sum_{j=1}^{M_i} a_{ij}(N) W_j([N-k_{ij}]\Delta) + b_i(N) \qquad (9)$$

where $\{a_{ij},\}_{j=1}^{M_i}$ and b_i are chosen to minimize
$J(a_{11}, a_{12}, \ldots, a_{iMi}, b_i) =$

$$\sum_{n=1}^{N} [W_i(n\Delta) - \sum_{j=1}^{M_i} a_{ij}(n)W_j([n - k_{ij}]\Delta) - b_i(n)]^2$$

where $t = n\Delta$ and $T_{ij} = k_{ij}\Delta$. If the processes are stationary then

$$a_{ij}(N) = \frac{1}{m_i} P_{ij}(T_{ij})\frac{\sigma i}{\sigma_j} = a_{ij}$$

$$b_i(N) = m_i - \sum_{j=1}^{M_i} a_{ij} m_j = b_i$$

A recursive least squares algorithm requires apriori knowledge of $T_{ij} = k_{ij}\Delta$ but allows $\{a_{ij}(n)\}_{j=1}^{M_i}$ and $b_i(n)$ to be updated at every sampling period $t_n = N\Delta$. The method for selecting $T_{ij} = k_{ij}$ is critical to the performance of the predictor and is discussed in the next section.

A comparison of the predictors obtained using the correlation model (7) and a recursive least squares model (9) was performed. The comparison was made for predictions of wind speeds at sites i=1,...,2), i=25 using site 25 as the reference on data taken from the SESAME array of wind measurement sites on April 14, 1979. The results are tabulated in Table 1.

The errors obtained by the correlation method and recursive least squares algorithm were nearly identical at sites 18, 19, 21-24, 27 at which good quality estimation occurred. The parameters of the least squares model for prediction at site i from reference measurements at site 25 $(a_{i25}(n), b_i(n))$ quickly converged to steady state values $(a_{i25}(N)_1 b_i(N))$ that were very close to the values produced by the correlation model (a_{i25}, a_i) at sites 18, 19, 21-24, 27 where quality estimation were achieved. The parameters and errors obtained using the recursive least squares model and correlation model was generally quite different at sites where good quality estimation was not possible.

A recursive least square model which uses multiple samples (L_{ij} + 1) at each of M_i reference sites was also studied. The recursive least model has the form

$$W_i(n\Delta) = \sum_{j=1}^{M_i} \sum_{\ell_j=0}^{L_{ij}} a_{ij\,\ell j}(n)W_j\,((n - k_{ij} - \ell_j)\Delta) + b_i(n)$$

where $a_{ij}\ell_j(n)$ and b_i are chosen to minimize

$$J_i = \sum_{n=1}^{N} \alpha^{N-n} [W_i(n\Delta) - \sum_{j=1}^{M_i} \sum_{\ell_j=0}^{L_{ij}} a_{ij\ell_j}(n)W_j((n-k_{ij} - \ell_j)\Delta) - b_i(n)]^2$$

The parameter α allows reducing the effect of previous measurements in the recursive least squares and allows the estimate to be more adaptive.

The effectiveness of using more than one sample and of changing the weight α on past measurements is given in Table 2 for estimates at all 26 sites given site 25 as reference. It is clear that using additional samples at k_{i25} + 1, k_{i25} + 2 delays, which are near the one specified k_{i25} in Table 1 for each site, always reduces the errors but very marginally. An F test was performed to decide if the extra measurement was required with a 5% Type 1 error probability and it was clear that 1 measurement was sufficient. A reduction in the weight of previous measurements from 1 to .99 and .95 increased the errors as shown in Table 2 and in some cases very signficantly. Thus, the concept of reducing the importance of previous measurements was discarded also.

3.3 WIND SPEED PREDICTION METHODOLOGY FOR METEOROLOGICAL EVENTS

The estimation performed using site 25 on April 14th and summarized in Tables 1 and 2 was only of good quality at sites 18, 19, 21-24, and 27 where the delay $T_{i25} = k_{i25}$ was either zero or very small. Thus, the objective of producing a prediction of wind speed was not being accomplished. Much work was devoted to determining a procedure for

(1) properly filtering the wind speed records at all sites based on the propagation speed of the meteorological event being predicted;

(2) properly determining the direction of propagation of the meteorological event which may or may not be identical with wind speed direction at individual wind measurement sites;

Site No.	$a_{i,25}$	b_i	$a^*_{i,25}$	b^*_i	T
1	1.157	-5.9576	1.163	-6.1	0
2	1.0876	-3.0583	0.9636	-1.016	35
3	0.0024	9.172	0.6053	4.6939	256
4	0.75199	6.4053	0.7878	5.800	0
5	1.0432	-3.3992	1.0594	-3.6841	0
6	0.3432	13.2958	0.3030	14.074	51
7	0.0792	7.5179	0.3784	5.423	241
8	0.60452	6.2466	0.5984	6.3753	0
9	0.3029	9.3047	0.4110	9.7534	235
11	0.3662	5.2101	0.4745	5.826	242
12	0.700	5.00	0.6840	5.3216	0
13	0.4432	5.3295	0.4807	4.7111	0
14	0.3628	9.1468	0.3221	9.9028	18
15	0.3199	12.2667	0.3236	12.2460	0
16	0.5624	6.8837	0.520	7.027	62
17	0.6498	3.3536	0.6774	2.9019	0
18	0.6770	3.8444	0.6759	3.8690	0
19	0.5477	8.309	0.5224	8.773	4
20	0.3425	6.8674	0.3519	8.1925	248
21	0.5733	7.0121	0.5729	7.0396	0
22	0.3457	9.3716	0.3348	9.596	1
23	0.6651	5.2639	0.6675	5.227	0
24	0.9894	2.1883	0.9763	2.4153	0
26	0.6826	7.3393	0.5996	7.012	117
27	0.5736	8.9151	0.5671	9.065	0

Table 1. Comparison of parameters of the least squares ($a_{i,25}$,b_i) and correlation ($a^*_{i,25}$,b^*_i) based models.

	Weight for Past Measurement Samples								
	α = 1			α = .99			α = .95		
	Number of Measurement Samples at Site twenty-five								
Site Number	1	2	4	1	2	4	1	2	4
1	2.194	2.192	2.185	3.709	3.739	2.291	3.709	3.739	3.772
2	2.990	2.958	2.907	3.658	3.660	2.984	3.658	3.660	3.651
3	3.024	2.962	2.913	5.567	5.542	3.812	5.567	5.542	5.440
4	2.651	2.648	2.645	4.681	4.680	2.833	4.681	4.680	4.665
5	3.217	3.215	3.225	5.480	5.490	3.646	5.480	5.490	5.555
6	1.398	1.391	1.380	2.280	2.338	1.648	2.280	2.338	2.337
7	2.515	2.466	2.443	3.998	4.001	2.929	3.998	4.001	3.947
8	2.036	2.038	2.032	3.185	3.186	2.395	3.185	3.186	3.231
9	2.226	2.207	2.197	4.569	4.583	2.498	4.569	4.583	4.557
11	2.576	2.523	2.470	5.010	5.006	2.993	5.010	5.006	4.987
12	2.839	2.827	2.813	5.790	5.793	3.517	5.790	5.793	5.780
13	2.118	2.078	2.058	3.009	3.028	2.597	3.009	3.028	3.038
14	1.554	1.553	1.545	2.463	2.465	1.739	2.463	2.465	2.470
15	1.489	1.490	1.494	2.489	2.494	1.678	2.489	2.494	2.490
16	2.154	2.097	2.062	2.867	2.905	2.200	2.867	2.905	3.005
17	2.717	2.653	2.616	4.616	4.617	3.096	4.616	4.617	4.575
18	1.196	1.168	1.141	1.411	1.374	1.161	1.411	1.374	1.365
19	1.713	1.702	1.686	2.688	2.676	1.837	2.688	2.676	2.681
20	1.595	1.586	1.580	3.096	3.103	1.918	3.096	3.103	3.117
21	1.583	1.579	1.579	1.991	1.987	1.743	1.991	1.987	1.999
22	.724	.719	.708	1.009	1.007	.780	1.009	1.007	.990
23	1.651	1.616	1.582	2.336	2.311	1.880	2.336	2.311	2.318
24	1.371	1.318	1.236	1.870	1.836	1.290	1.874	1.836	1.794
26	2.906	2.855	2.802	3.927	3.915	3.384	3.927	3.915	3.911
27	1.965	1.960	1.956	3.075	3.072	2.257	3.075	3.072	3.080

Table 2. Rms errors using different number of samples at reference site 25 when past samples are discounted (α) for April 14, 1979 data.

(3) properly determining the delay between the reference wind measurement sites and those where prediction is being attempted.

It is clear that although accurate prediction has been accomplished in all cases studied, the procedure would be much more accurate and be able to be implemented more successfully on-line if

(1) meteorological forecasts of the time of arrival and departure as well as the speed and direction of motion of the meteorological event were available;

(2) measurement of pressure and temperature, and their gradients were available.

The need to (a) very carefully filter the records, (b) utilize several reference wind speed measurements, (c) utilize several wind speed measurements in the geographical region of the wind turbine cluster where prediction is desired, and (d) compute correlation $(P_{ij}(T_{ij}))$ and delay (T_{ij}) between all pairs of wind measurement sites indicates that wind speed and direction measurements are very much corrupted by turbulence and site specific variations that mask the meteorological event information. Thus, the need for additional measurements and forecasts is apparent.

The interval over which the moving average filter smooths the minute sampled wind speed records must be chosen based on the time interval for the meteorological event to propagate from the cluster of reference wind speed measurement sites to the set of sites where prediction is desired. If the meteorological event propagates slowly and takes four hours to propagate from one end of the 80 x 80 mile area, where reference wind speed measurements are taken to the other side, where wind speed prediction is desired, the moving average filter should smooth over an interval of less than 2-3 hours duration to eliminate higher frequency turbulence and site specific variations. However if the propagation of a front takes only a half hour or hour to propagate from one end of the 80 x 80 mile area, to the other end the moving average filter should smooth over an interval of approximately ten minutes to eliminate the faster turbulence that is not associated with the propagation of this event. Apriori information of the speed of the propagation from meteorological forecasts would indicate the proper smoothing interval, which is less than half the expected propagation delay from reference sites to sites where prediction is desired.

The direction of propagation of the meteorological event was not always identical to the wind speed direction at individual sites or clusters of wind measurement sites. A procedure for determining the direction of propagation of the meteorological event was determined by calculating the peak correlation $P_{ij}(T_{ij})$ for all pairs of wind measurement sites

$$P_{ij}(T_{ij}) = \frac{1}{N} \sum_{n=}^{N} \frac{[W_i(m\Delta) - m_i][W_j([n - k_{ij}]\Delta) - m_j]}{\sigma_i \ \sigma_j}$$

$$m_i = \frac{1}{N} \sum_{n=1}^{N} W_i(n\Delta)$$

$$\sigma_i = \frac{1}{N-1} \sum_{n=1}^{N} (W_i(n\Delta) - m_i)^2$$

If sites $i_o \ j_o \varepsilon I\alpha$ are the sites of the system ordered in increasing distance in a particular direction α and $P_{i_o j_o}(T_{i_o j_o}) > P_{j_o i_o}(T_{j_o i_o})$ for all $i_o > j_o$ then wind is blowing from j_o to i_o since $P_{i_o j_o}(T_{i_o j_o})$ indicates site j_o is advanced by $T_{i_o j_o}$ from the record i_o. Thus $P_{iojo}(T_{iojo})$ being larger than $P_{joio}(T_{joio})$ implies that the phenomena hits j_o first then i_o and not vice versa since delaying j_o, where the event effects first, achieves the larger correlation. If the record is not properly filtered, a very inconsistent pattern will exist among the various sites $i_o j_o$ that are ordered by distance in direction α. A proper smoothing interval based on the propagation delay T_{iojo} will cause all or almost all pairs $i_o j_o \varepsilon I$ to indicate the meteorological event is moving in the same direction. Accurate forecasts of the direction of movement of a meteorological event based on other meteorological information than wind speed could eliminate or simplify this procedure.

Selecting the proper delay $T_{i_o j_o}$ between reference site j_o and prediction site i_o is difficult and can not be based on a single pair of sites. The smoothing interval must be properly chosen or the delays between reference sites and prediction sites may be meaningless since the delays for different references sites j_o geographically close may give very different values of delay $T_{i_o j_o}$ to the site i_o where prediction is desired.

Moreover if the smoothing interval is not selected properly, the delays between reference site j_o and different prediction site i_o will not be monotone increasing with geographical distance between the sites. The procedure to determine the delay is to

(1) find a set of several reference sites $j \varepsilon J_r$ in a small geographical region with very high correlation $P_{j1j2}(T_{j1j2}) > .90$.

(2) find a set of several wind speed measurement sites I in a small geographical region (where the wind turbine cluster is located) that have high corelations $P_{j1j2}(T_{j1j2}) > .90$.

(3) check whether for every pair $i \varepsilon I$ and $j \varepsilon J$, T_{ij} is nearly identical. If not, the smoothing interval is incorrect and repeat steps 1 and 2 for a different smoothing interval.

(4) If T_{ij} are fairly consistent for all $i \varepsilon I$ $j \varepsilon I$ $P_{ij}(T_{ij}) > .60$ for all pairs $i \varepsilon I$ and $j \varepsilon J$, utilize the set of reference $j \varepsilon J$ with delays T_{ij} to predict each site $i \varepsilon I$.

One can see that this procedure is iterative and if one had accurate forecasts of the speed of propagation of possibly other information on pressure and temperature gradients one might eliminate the iterative nature of the procedure or might eliminate the need for the procedure altogether.

The application of the prediction methodology to prediction of meteorological events is given in Section 4.

SECTION 4

EVALUATION OF THE PREDICTION METHODOLOGY FOR METEOROLOGICAL EVENTS

The methodology for predicting wind speeds developed in the previous section is now tested on data from the SESAME array. This array of 27 meteorological measurement sites are located in an 80 x 80 mile square area near Tulsa, Oklahoma. The data utilized in this study was collected over a 3 month period in the spring of 1979. The wind speed in longitudinal and latitudinal directions, the nondirectional wind speed, pressure, temperature, and rainfall were all measured at these sites. The latitudinal and longitudinal wind speeds were used to determine wind velocity, magnitude, and direction of every site in the array. The nondirectional wind speed measurements were also retained, but the other meteorological data was unfortunately discarded at an earlier stage of the research [3]. This pressure and temperature information could have been quite useful in determining and confirming the speed and direction of motion of the meteorological event as indicated in Section 3.

4.1 SLOW PROPAGATION OF WIND SHIFT

The initial application of the prediction methodology discussed in Section 3 is the arrival of a front from the north and the associated wind shift shown in Figure 9 for data obtained from 3:40 - 8:20 p.m. on May 2, 1979. The front begins to arrive as early as 3:00 on sites 1-5 and is observed as a wide triangular pulse increase in wind speed at these sites. These wind measurement sites do not begin to experience a wind direction change until 6:40 p.m. The large increase in wind speed that first affects sites 1-5 at 3:00 p.m. and the subsequent wind direction change both propagate from north to south. The triangular pulse wind speed increase takes almost 5 hours to propagate from north to south but the wind direction change takes only 2 hours to propagate. Thus, the triangular pulse wind speed increase that propagates from north to south is very broad in the northern sites (2 hours) but becomes as narrow as 40 minutes at southern sites 22-24 nearly five hours later. This propagation of the wind shift line is clear in Figure 9 but the propagation of the triangular pulse wind speed increase and its decrease in width as it propagates can be seen in Figure 10 by observing the wind speed records at site 1-5 and at 22-24. This conclusion on the propagation of the triangular pulse wind speed could not be justified based solely on the observation of these time plots. Much effort was devoted to developing the procedure, documented in the previous section, that could successfully detect the direction of propagation of the event and the proper set of delays that truly reflect the propagation of an event and lead to accurate wind speed prediction.

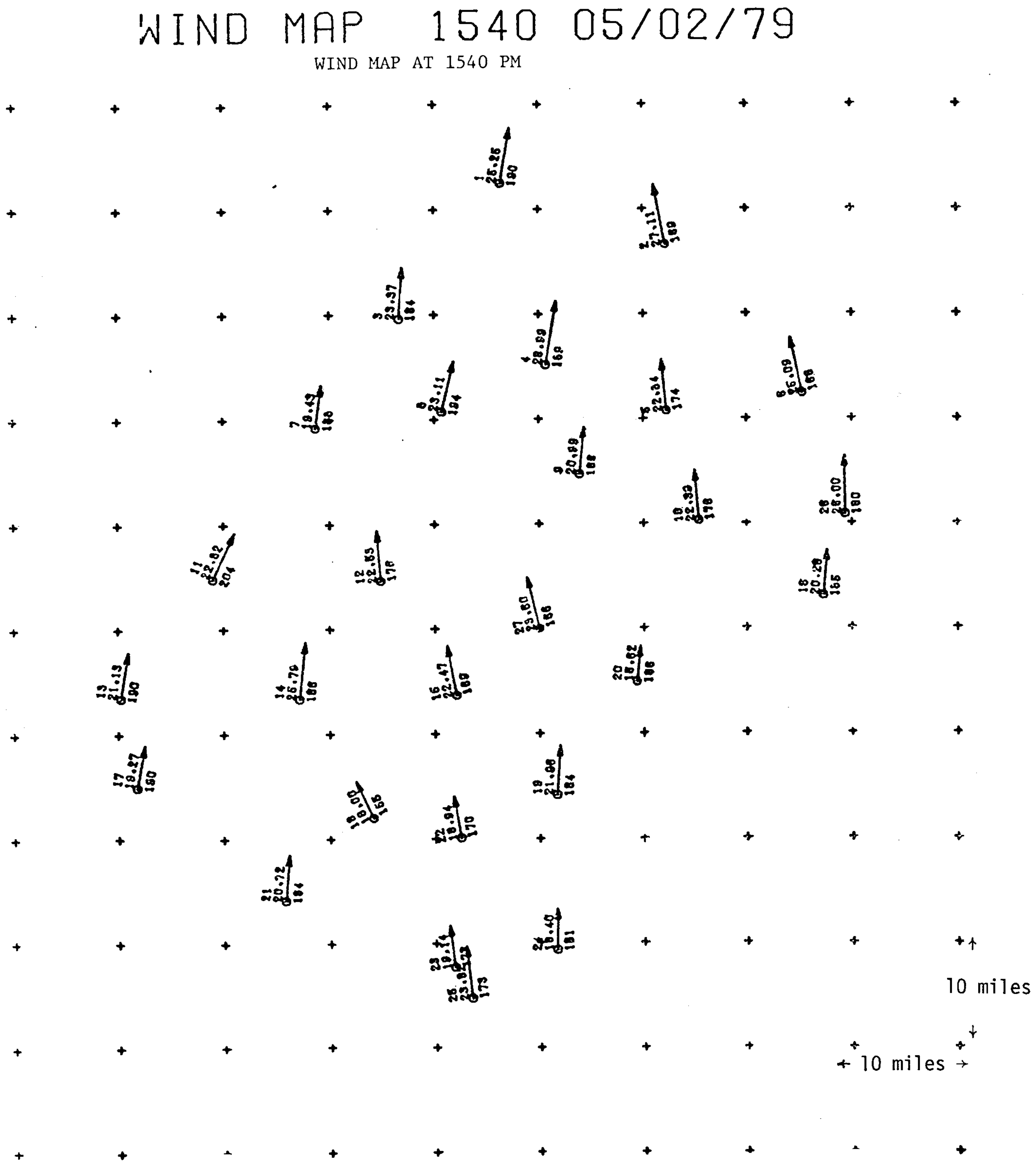


Figure 9. Wind speed and direction maps for a front for the SESAME array for 20 minute periods from 3:40 - 8:20 p.m.

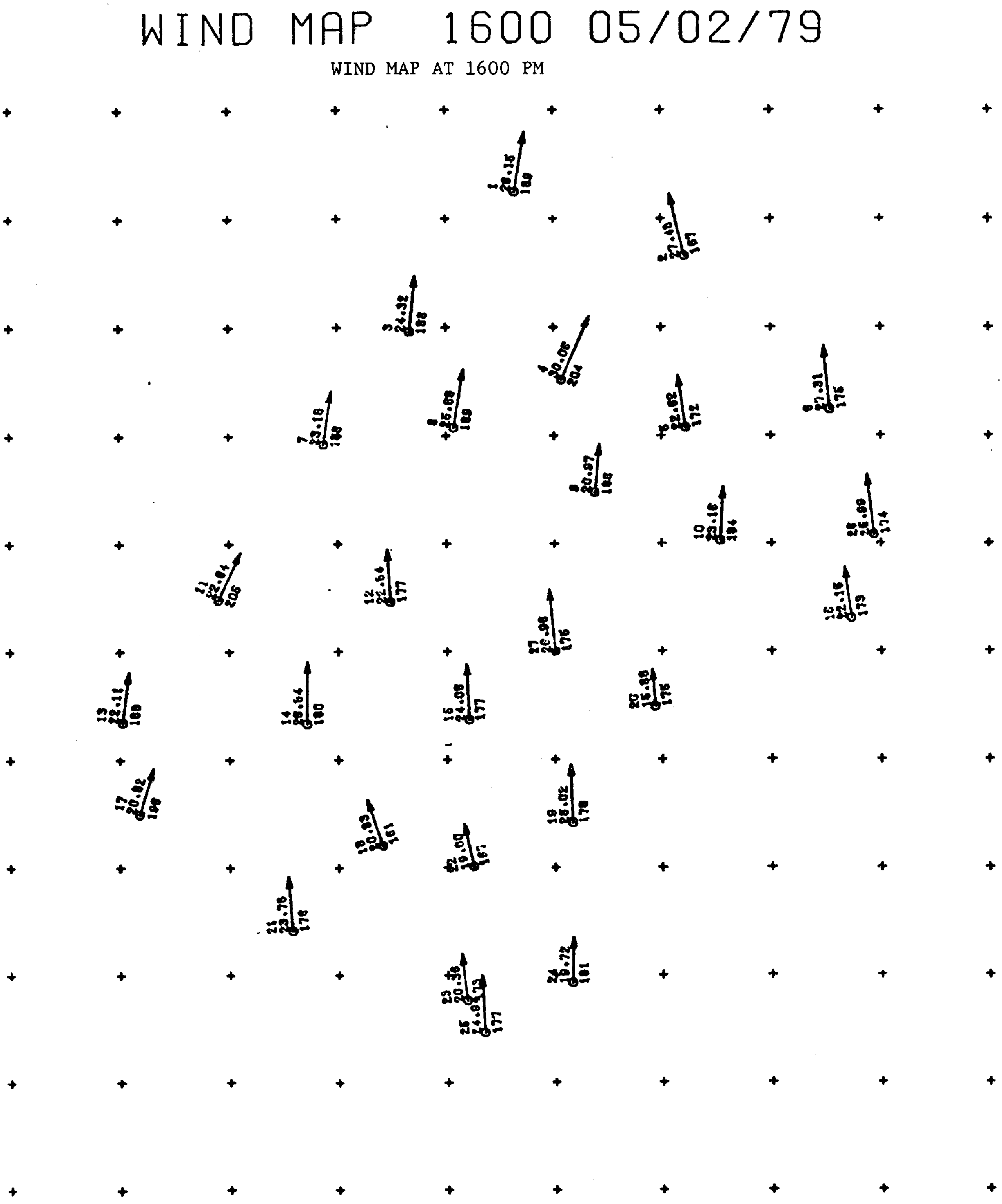


Figure 9a. Wind speed and direction maps for a front for the SESAME array for 20 minute periods from 3:40 - 8:20 p.m.

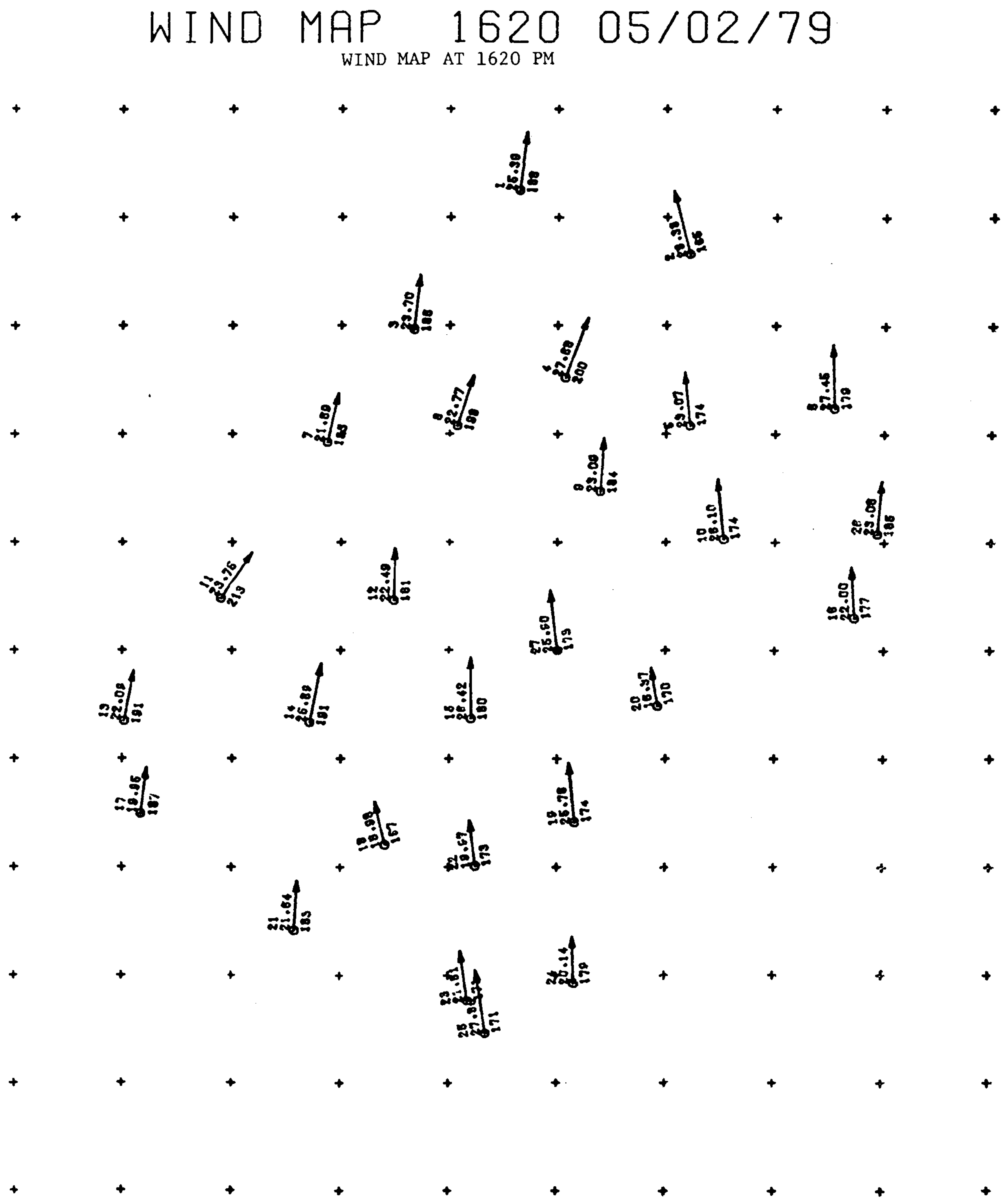


Figure 9b. Wind speed and direction maps for a front for the SESAME array for 20 minute periods from 3:40 - 8:20 p.m.

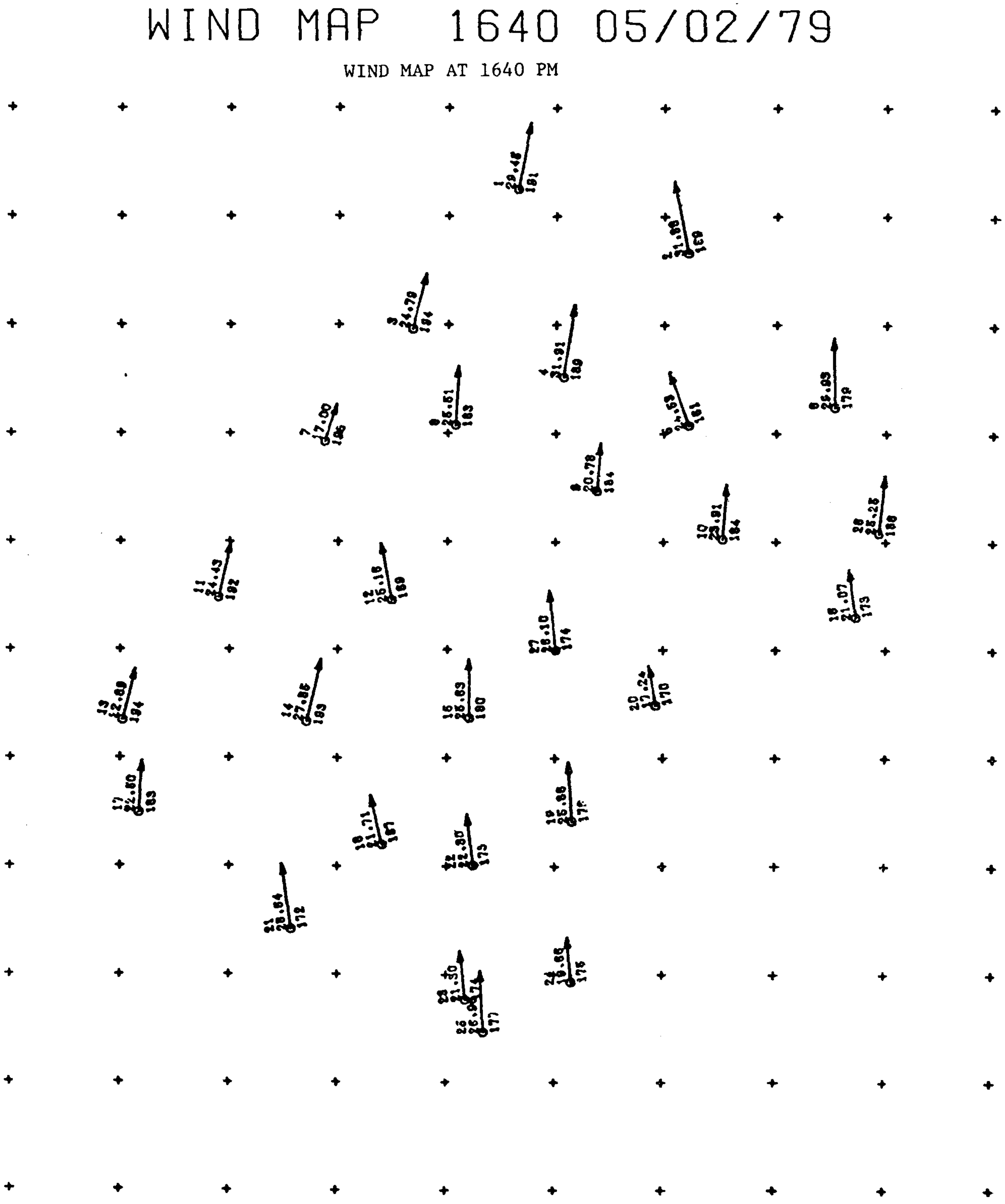


Figure 9c. Wind speed and direction maps for a front for the SESAME array for 20 minute periods from 3:40 - 8:20 p.m.

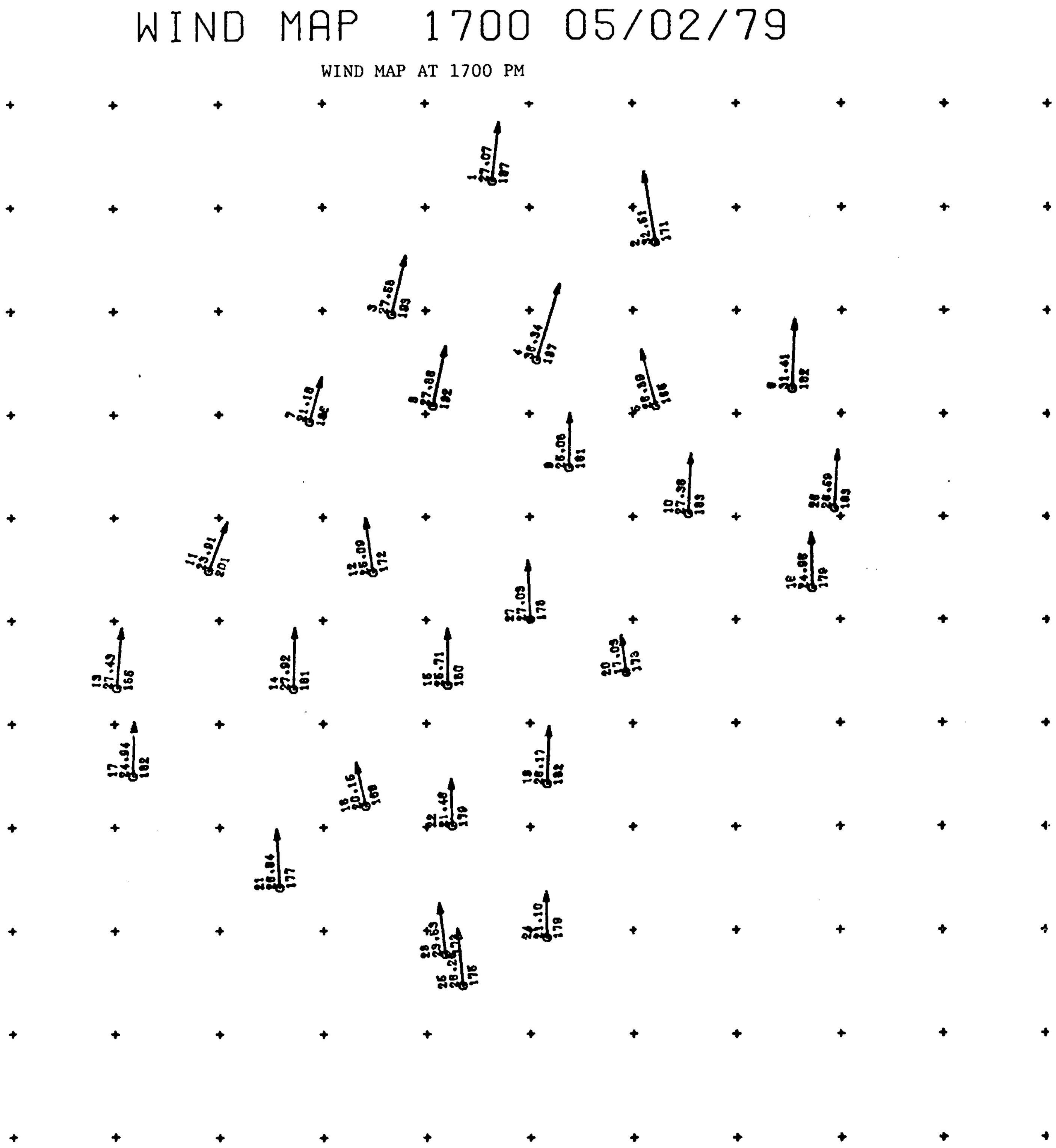


Figure 9d. Wind speed and direction maps for a front for the SESAME array for 20 minute periods from 3:40 - 8:20 p.m.

WIND MAP 1720 05/02/79

WIND MAP AT 1720 PM

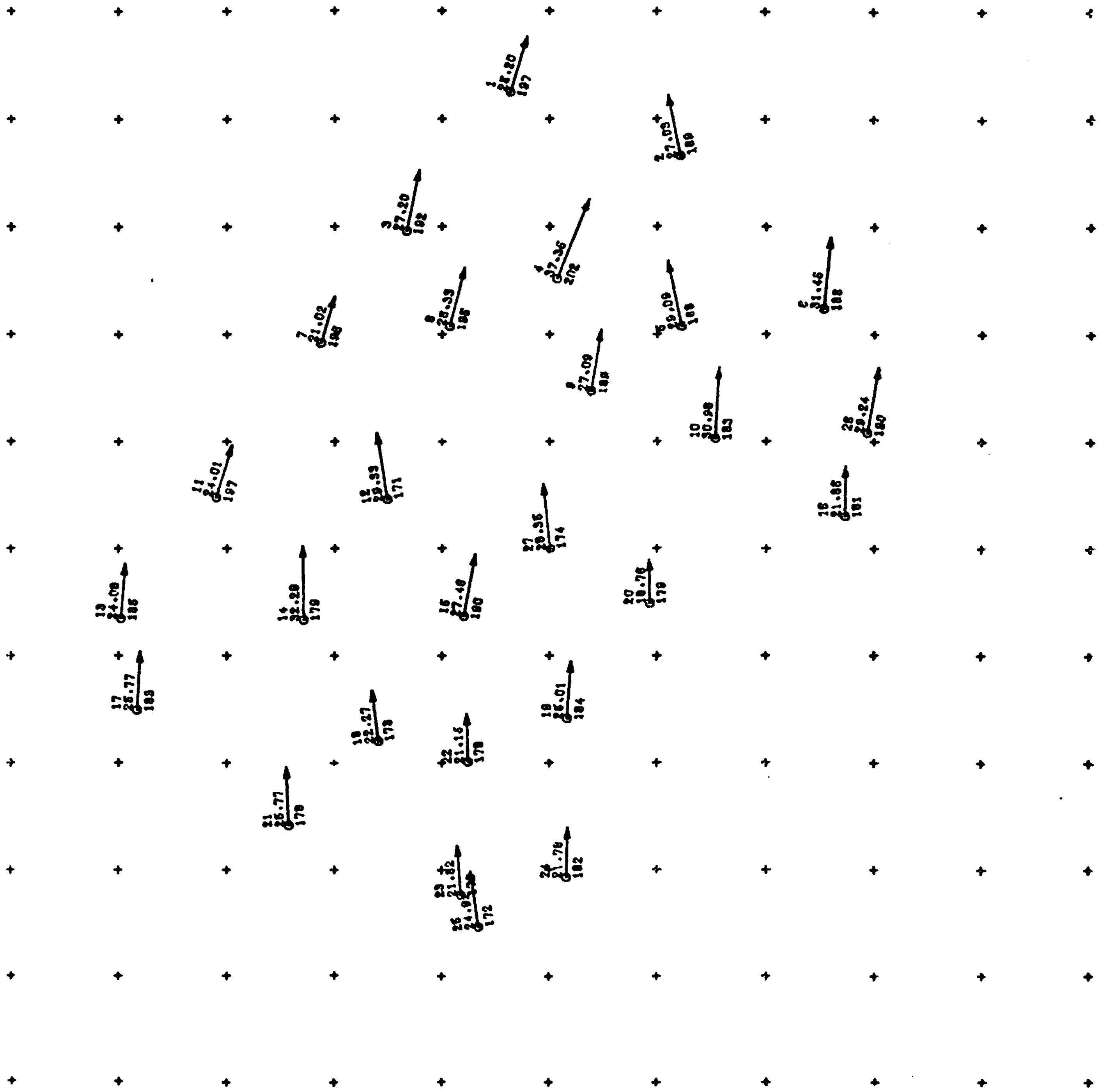


Figure 9e. Wind speed and direction maps for a front for the SESAME array for 20 minute periods from 3:40 - 8:20 p.m.

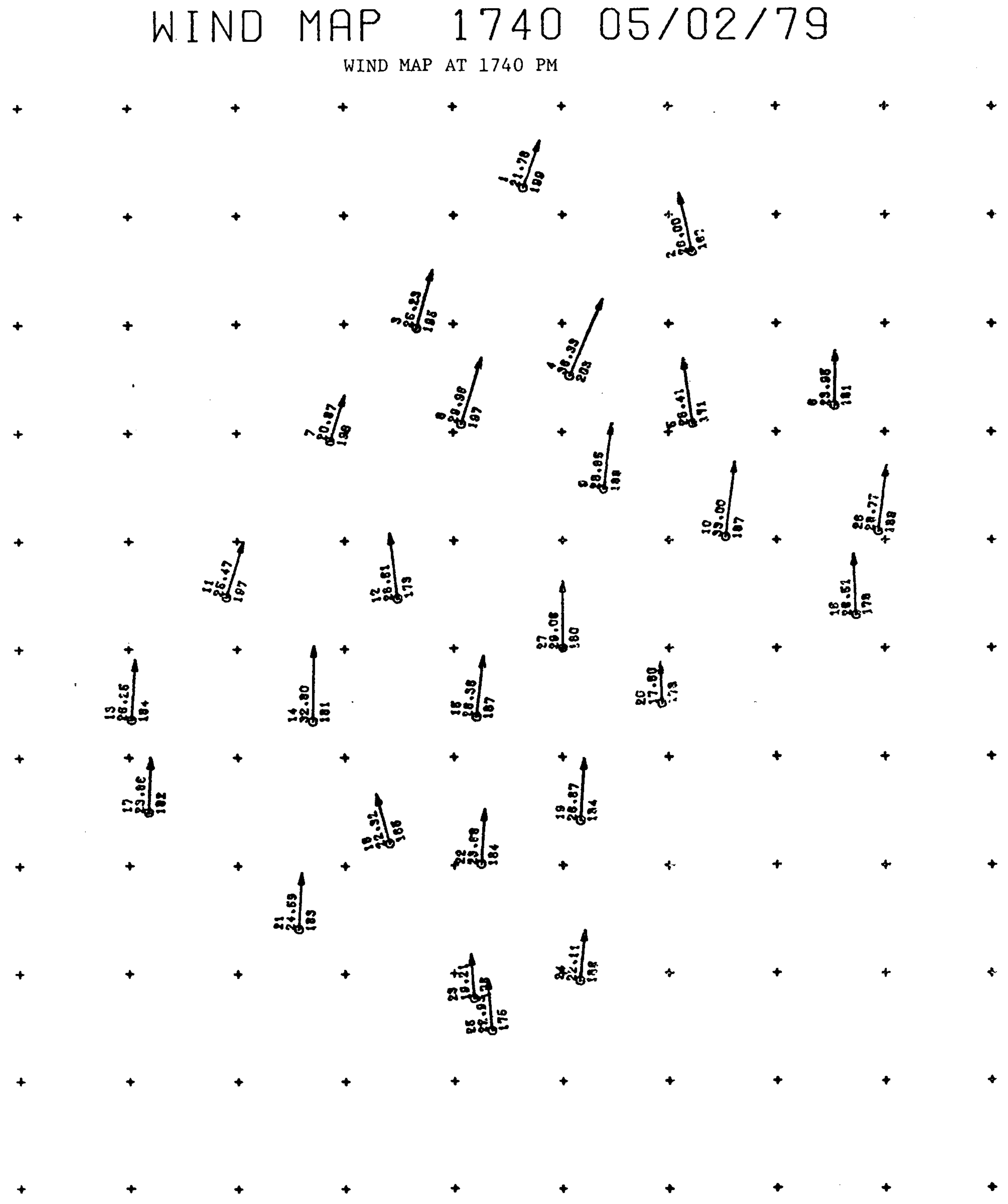


Figure 9f. Wind speed and direction maps for a front for the SESAME array for 20 minute periods from 3:40 - 8:20 p.m.

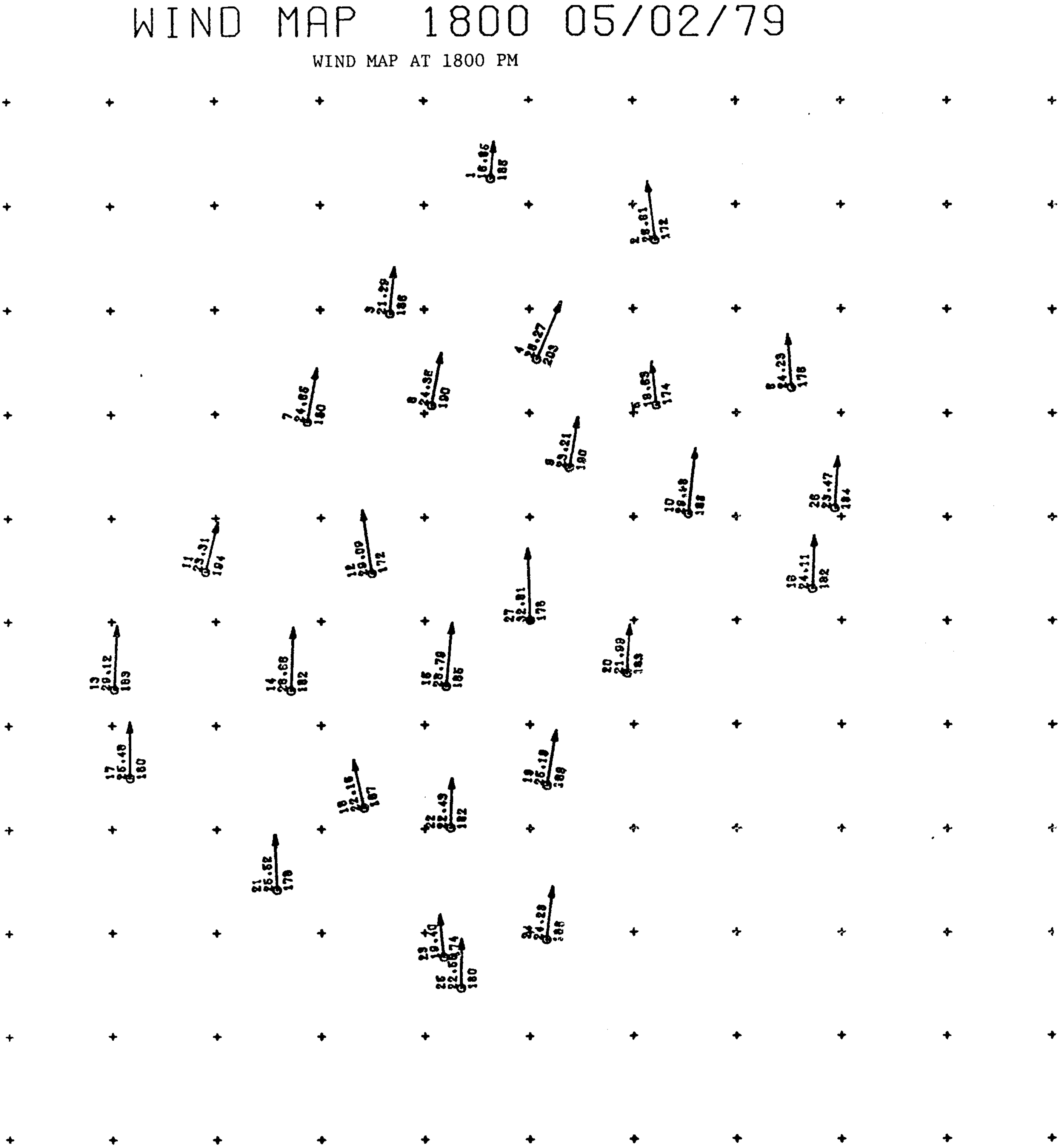


Figure 9g. Wind speed and direction maps for a front for the SESAME array for 20 minute periods from 3:40 - 8:20 p.m.

WIND MAP 1820 05/02/79

WIND MAP AT 1820 PM

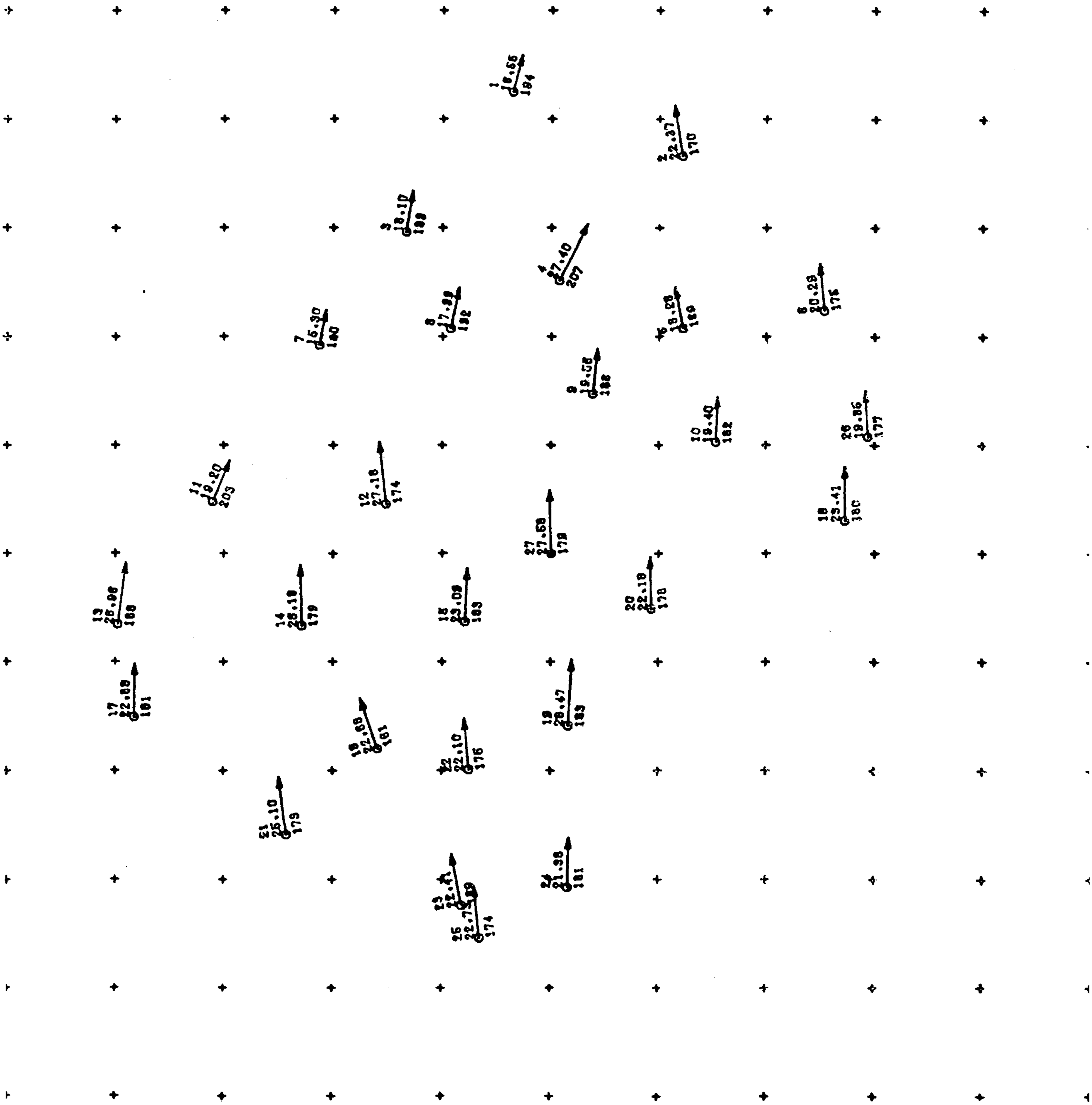


Figure 9h. Wind speed and direction maps for a front for the SESAME array for 20 minute periods from 3:40 - 8:20 p.m.

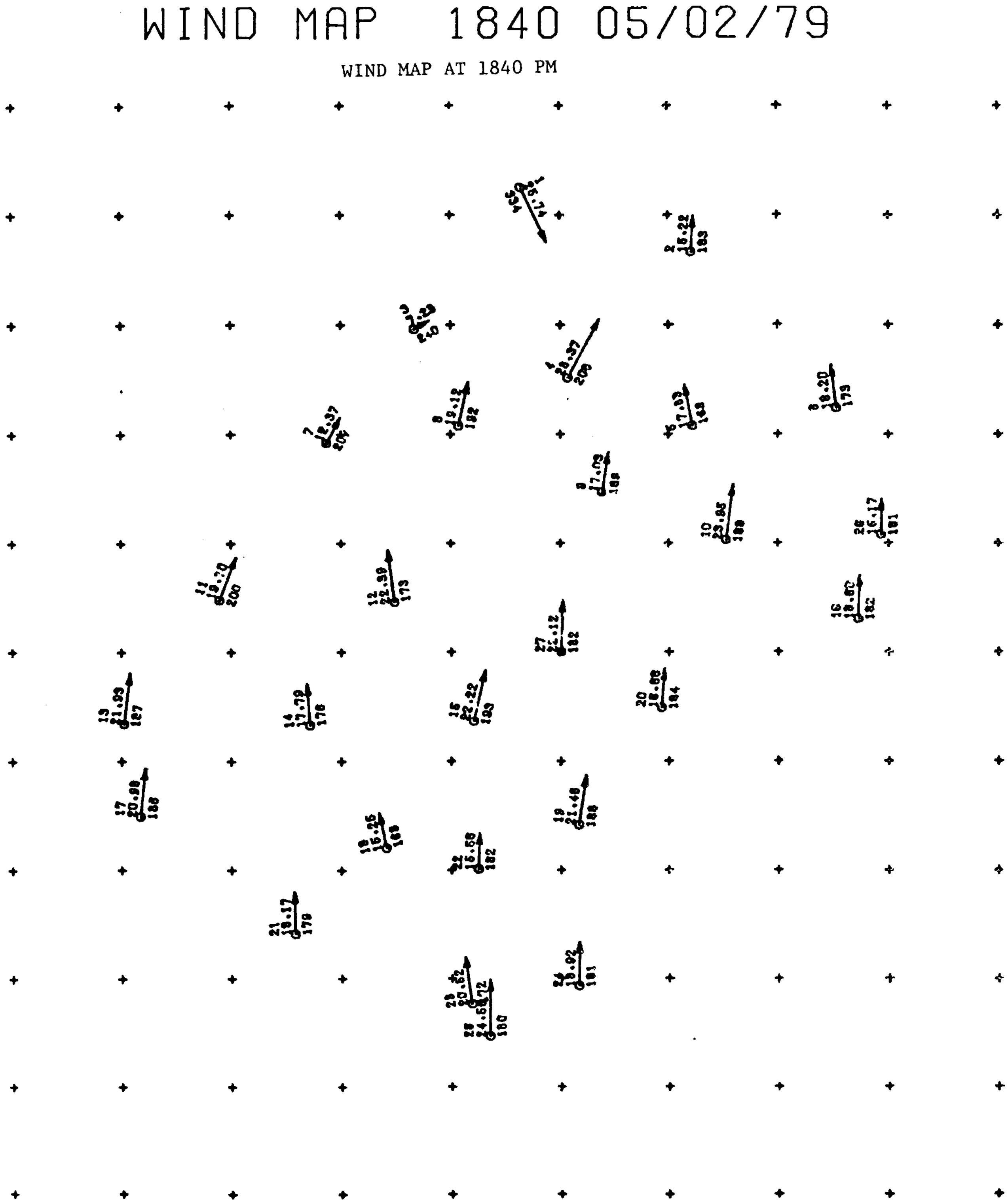
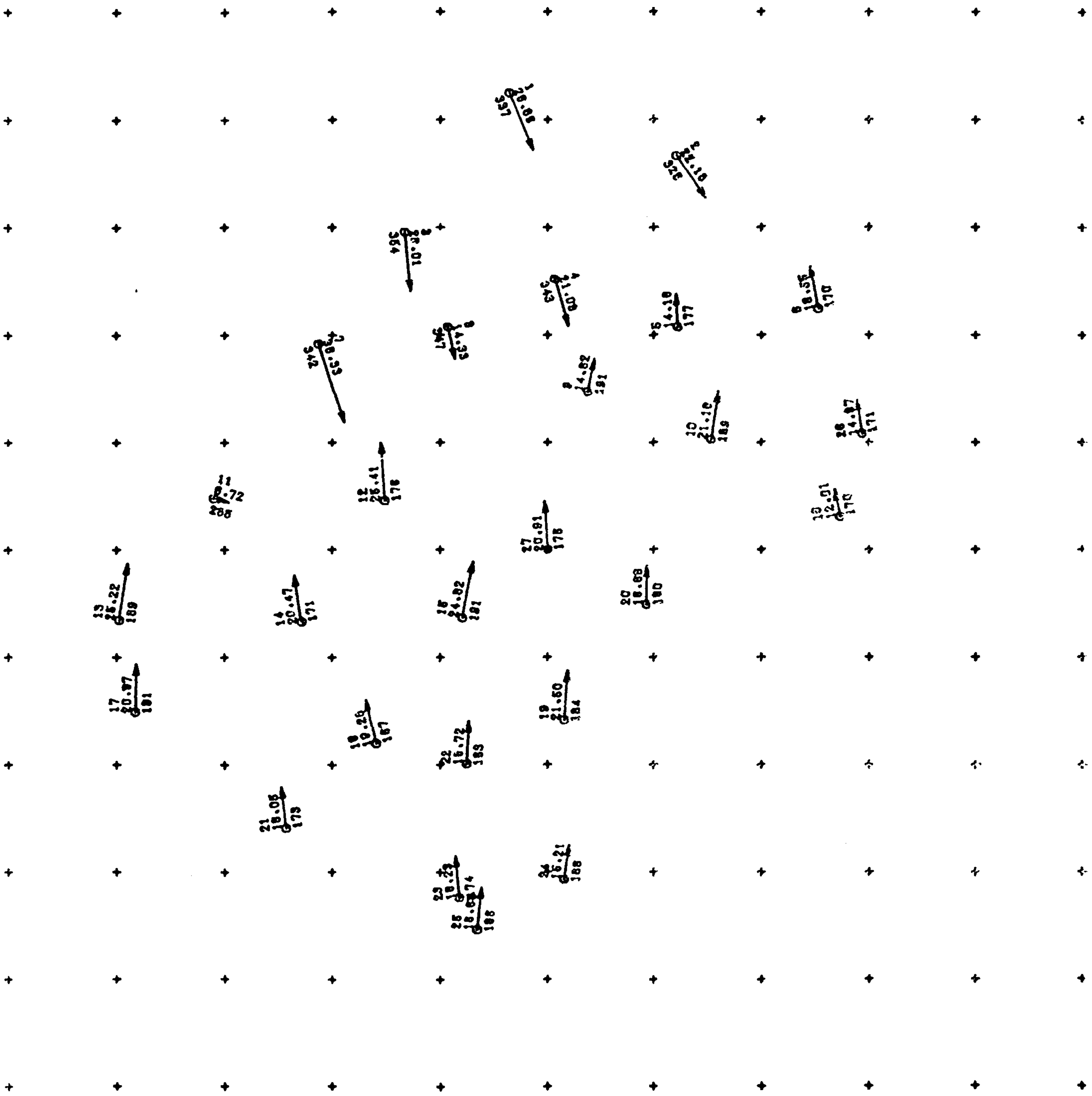


Figure 9i. Wind speed and direction maps for a front for the SESAME array for 20 minute periods from 3:40 - 8:20 p.m.


WIND MAP 1900 05/02/79

WIND MAP AT 1900 PM

Figure 9j. Wind speed and direction maps for a front for the SESAME array for 20 minute periods from 3:40 - 8:20 p.m.

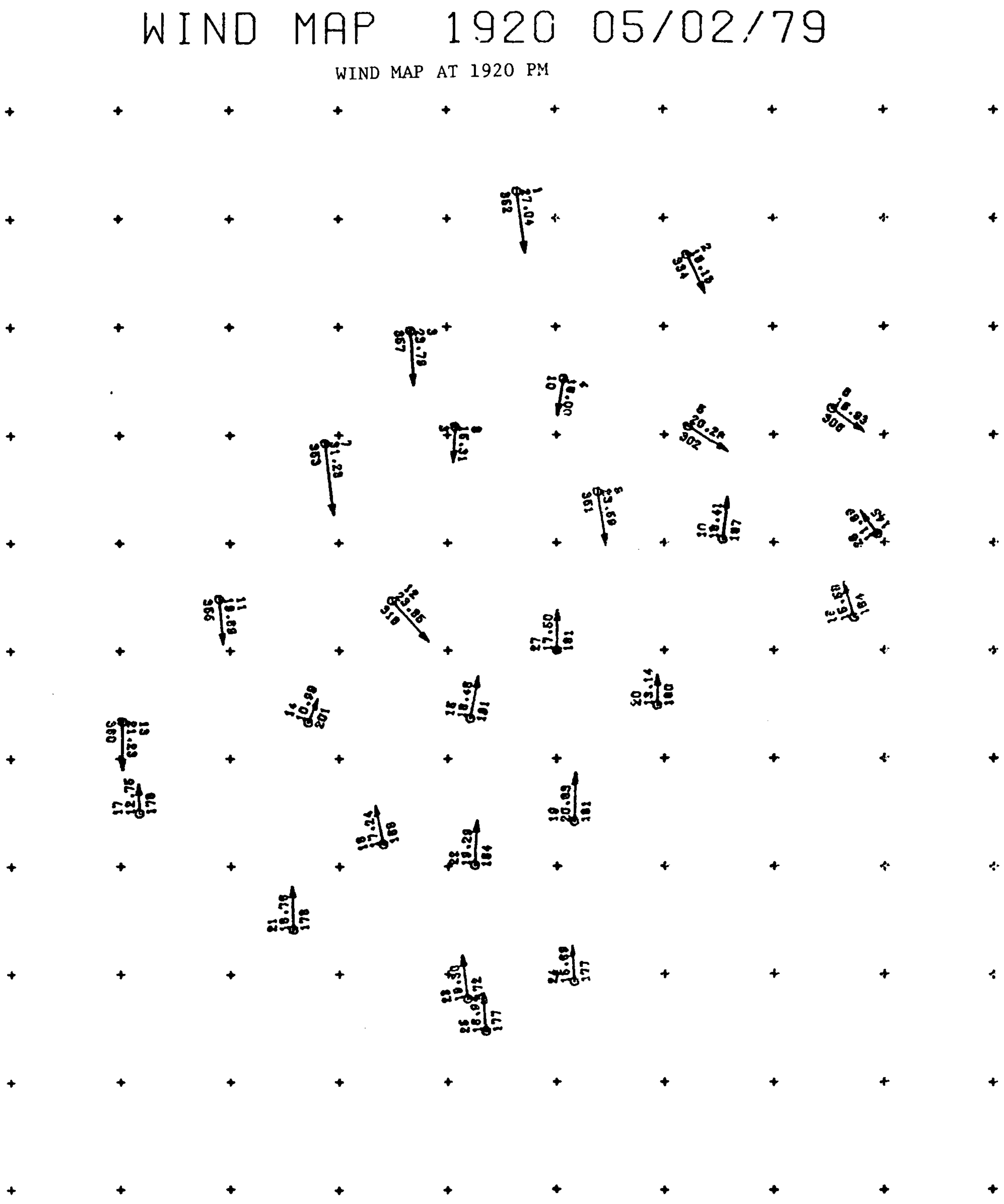
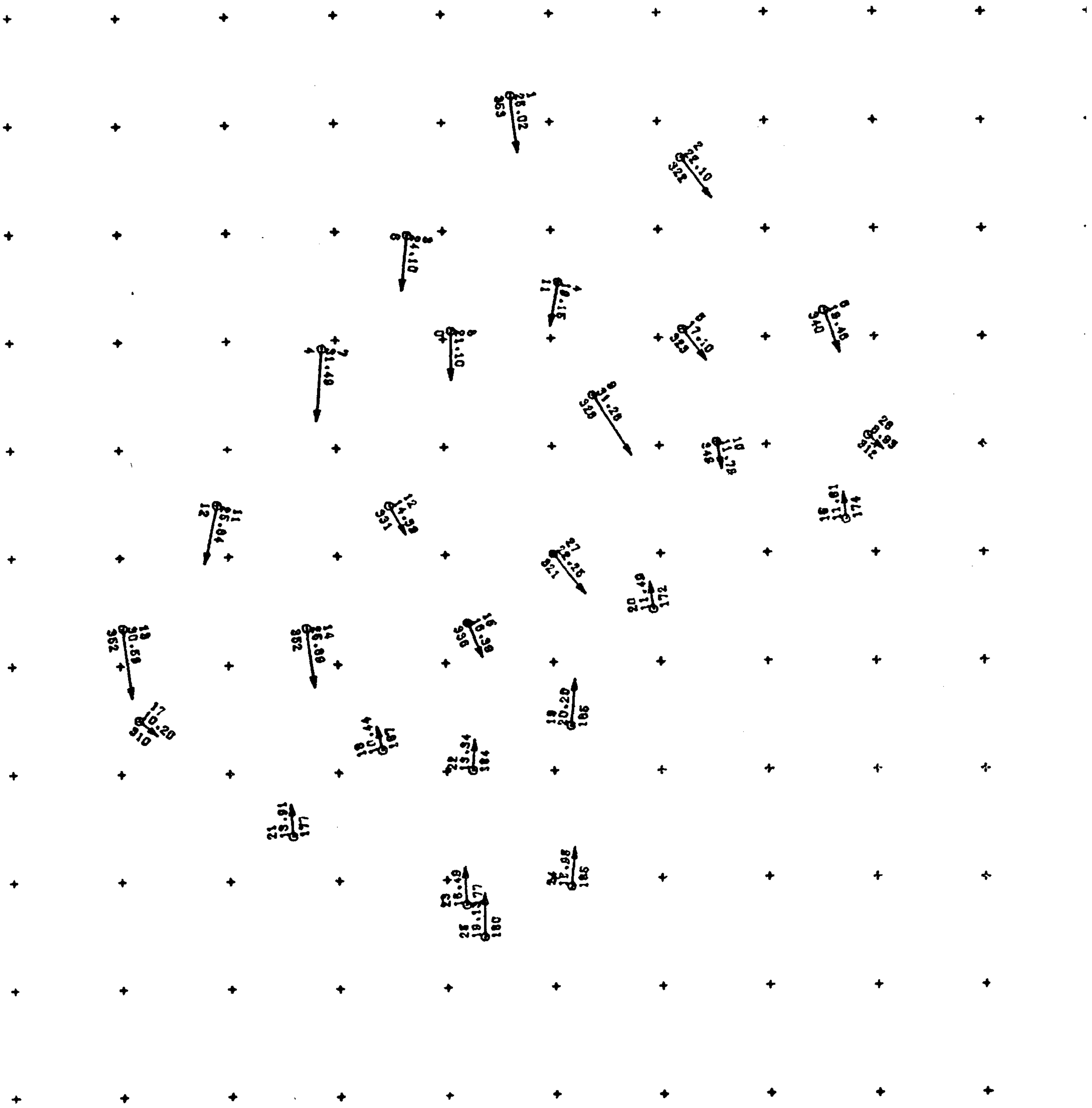


Figure 9k. Wind speed and direction maps for a front for the SESAME array for 20 minute periods from 3:40 - 8:20 p.m.



WIND MAP 1940 05/02/79

WIND MAP AT 1940 PM

Figure 91. Wind speed and direction maps for a front for the SESAME array for 20 minute periods from 3:40 - 8:20 p.m.

WIND MAP 2000 05/02/79

WIND MAP AT 2000 PM

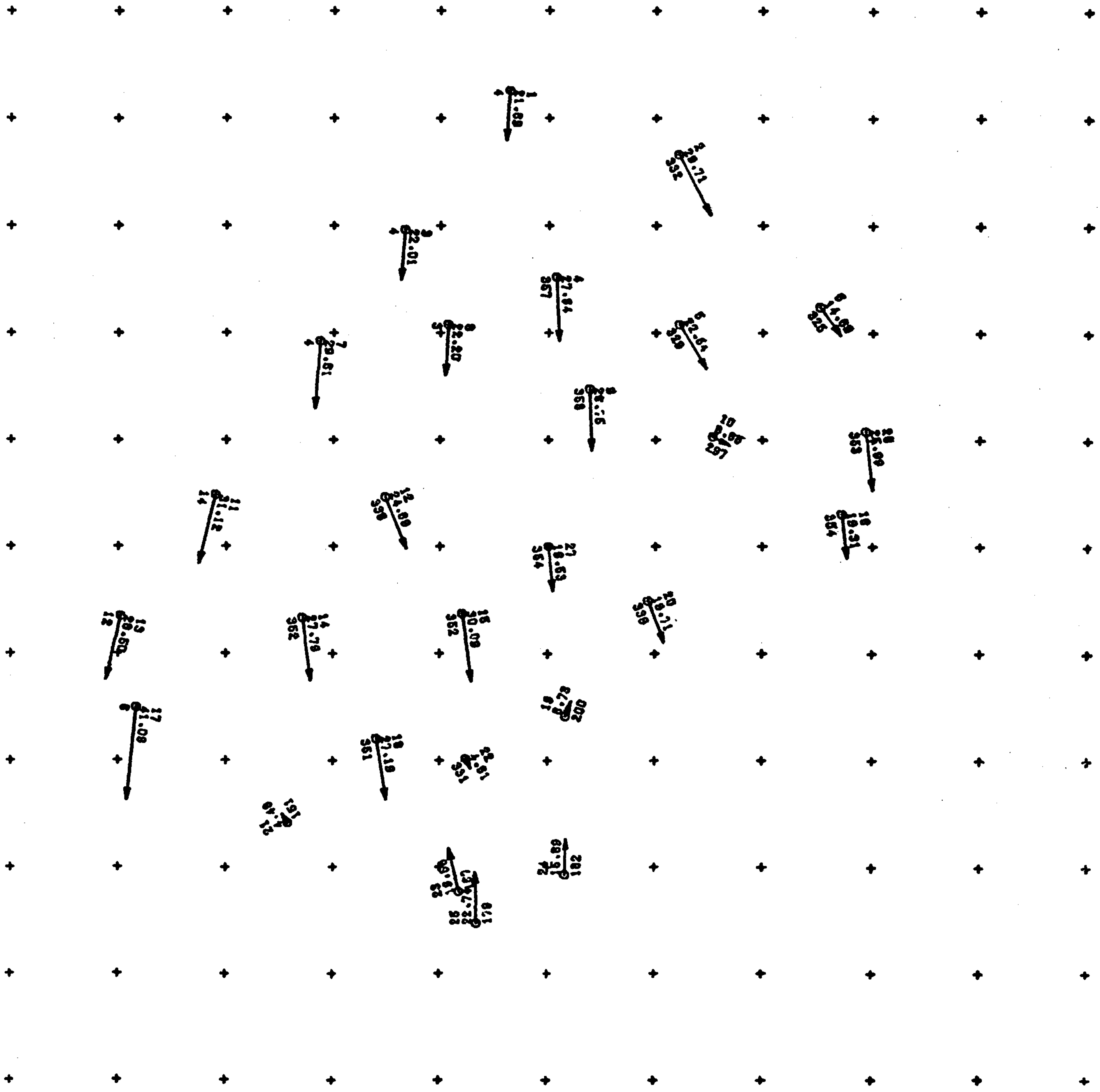


Figure 9m. Wind speed and direction maps for a front for the SESAME array for 20 minute periods from 3:40 - 8:20 p.m.

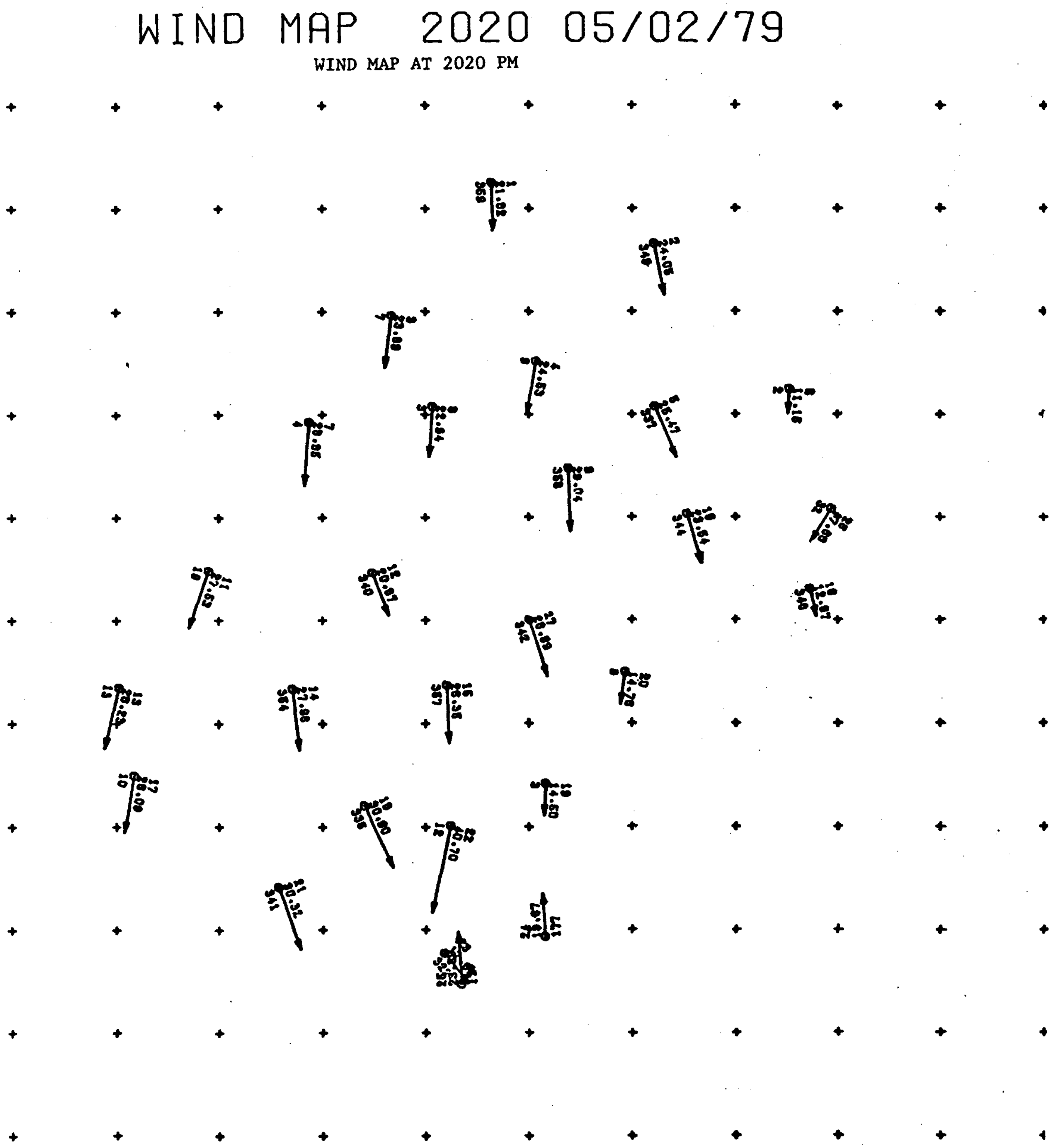


Figure 9n. Wind speed and direction maps for a front for the SESAME array for 20 minute periods from 3:40 - 8:20 p.m.

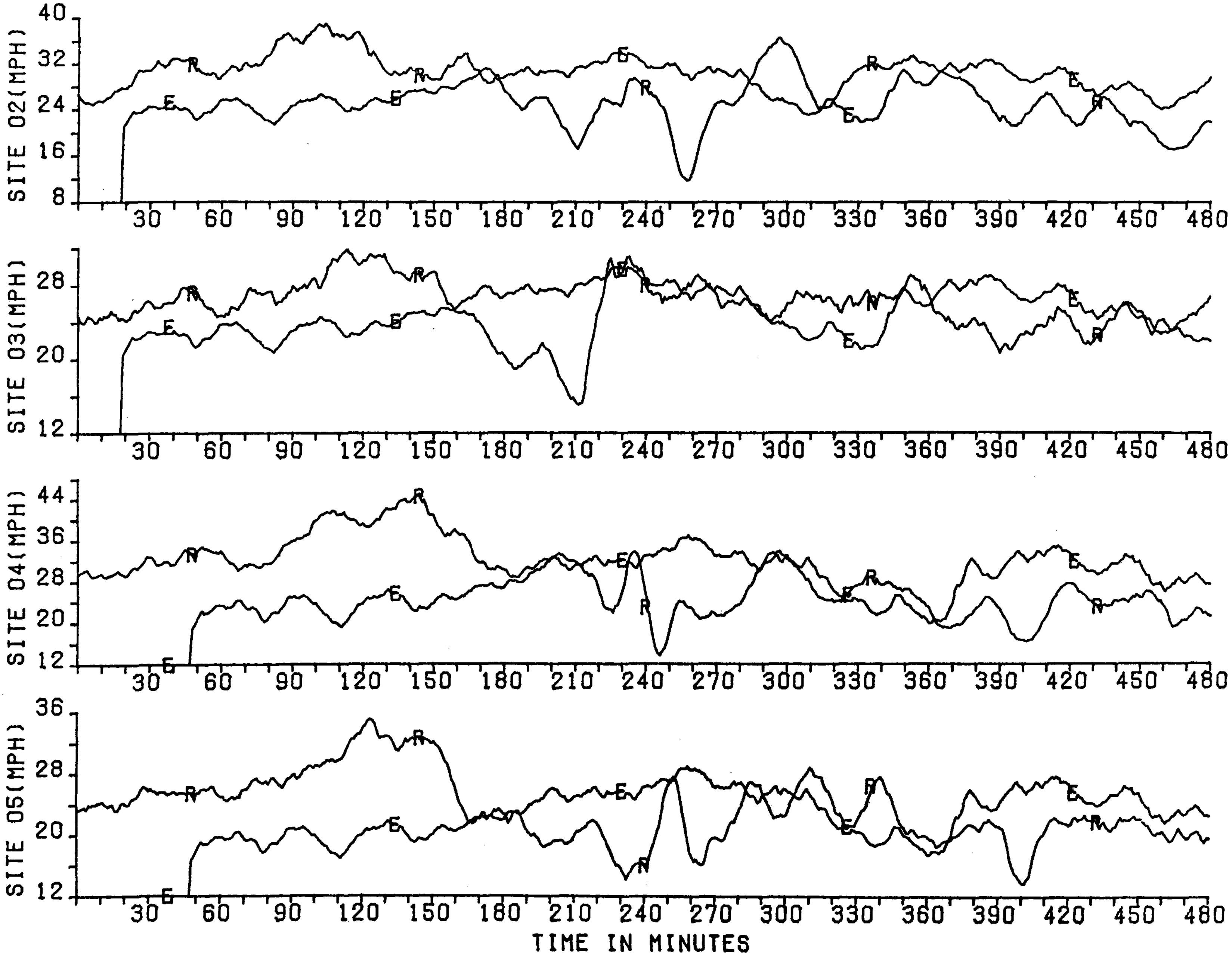


Figure 10. Actual and predicted wind speed records for 3:00 - 10:00 p.m. May 2, 1979 using 10 minute moving average filtered data and site 1 as reference.

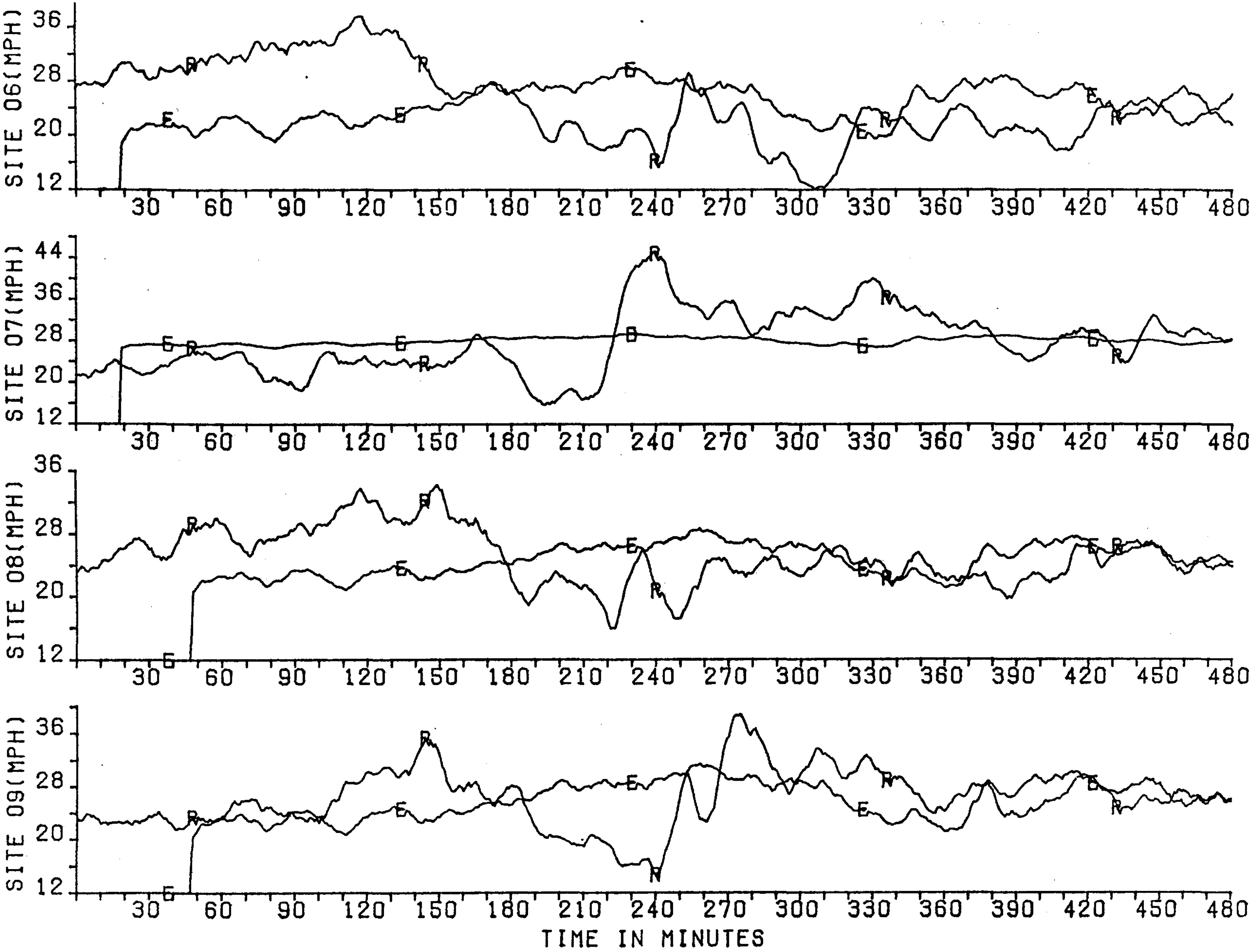


Figure 10a. Actual and predicted wind speed records for 3:00 - 10:00 p.m. May 2, 1979 using 10 minute moving average filtered data and site 1 as reference.

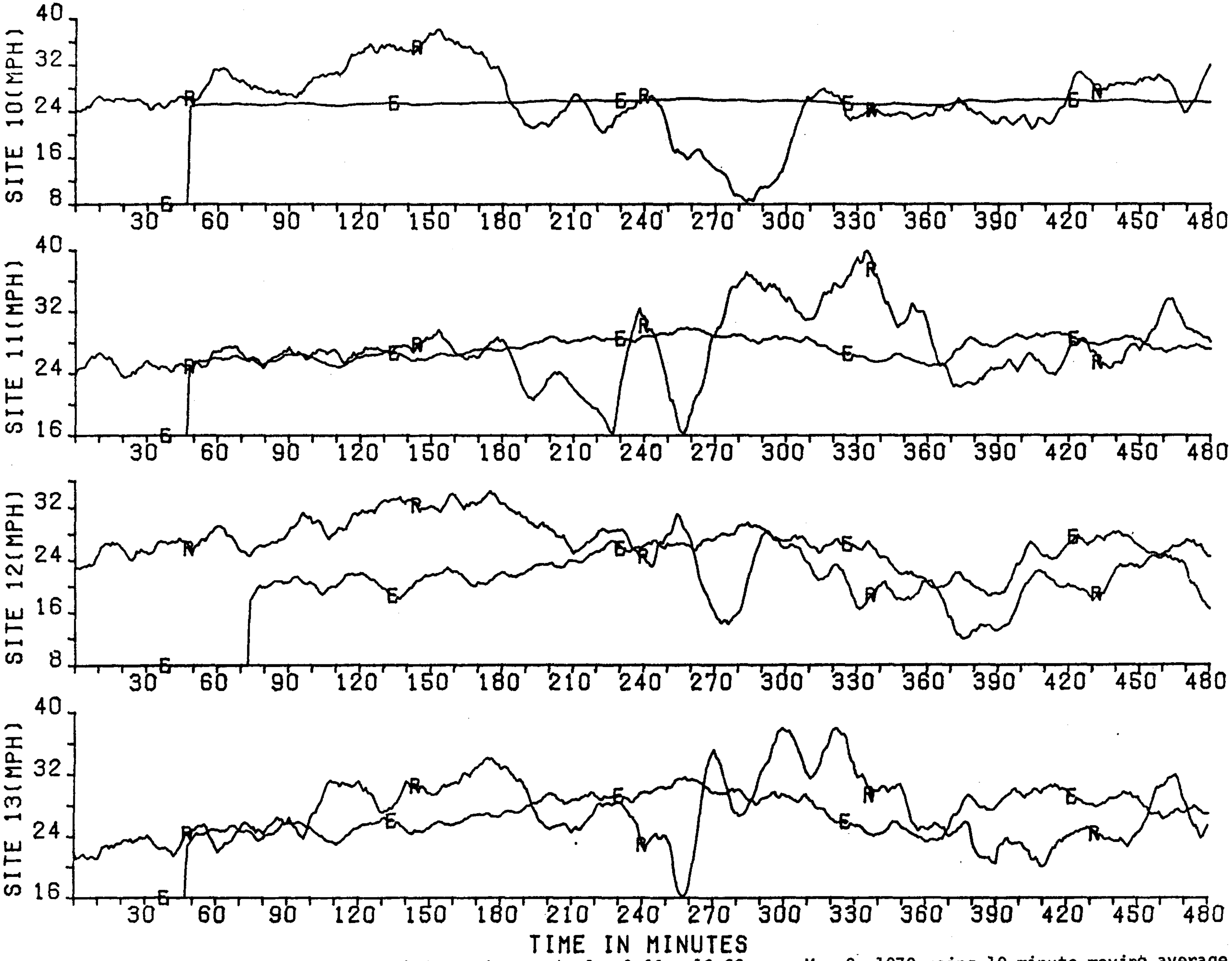


Figure 10b. Actual and predicted wind speed records for 3:00 - 10:00 p.m. May 2, 1979 using 10 minute moving average filtered data and site 1 as reference.

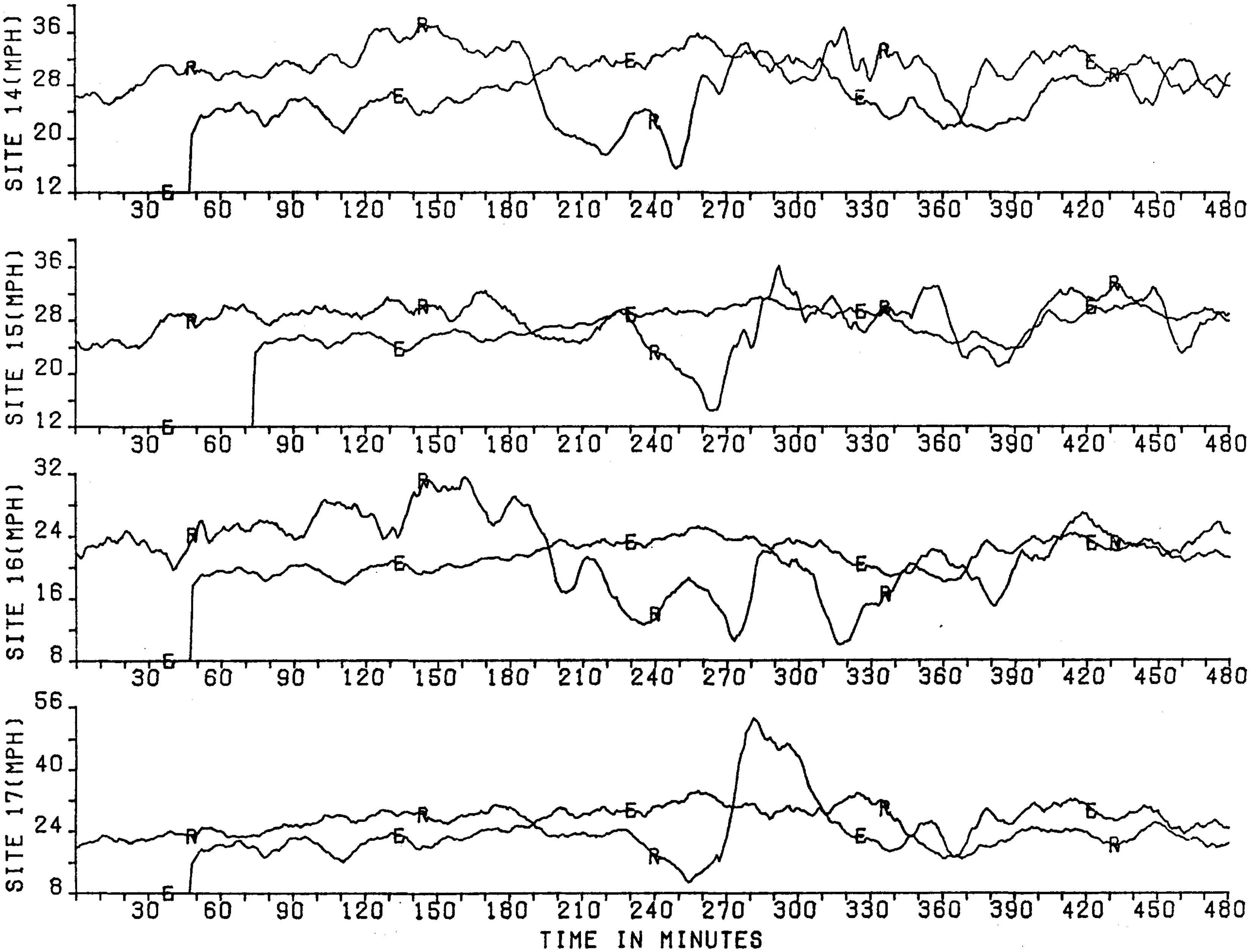


Figure 10c. Actual and predicted wind speed records for 3:00 - 10:00 p.m. May 2, 1979 using 10 minute moving average filtered data and site 1 as reference.

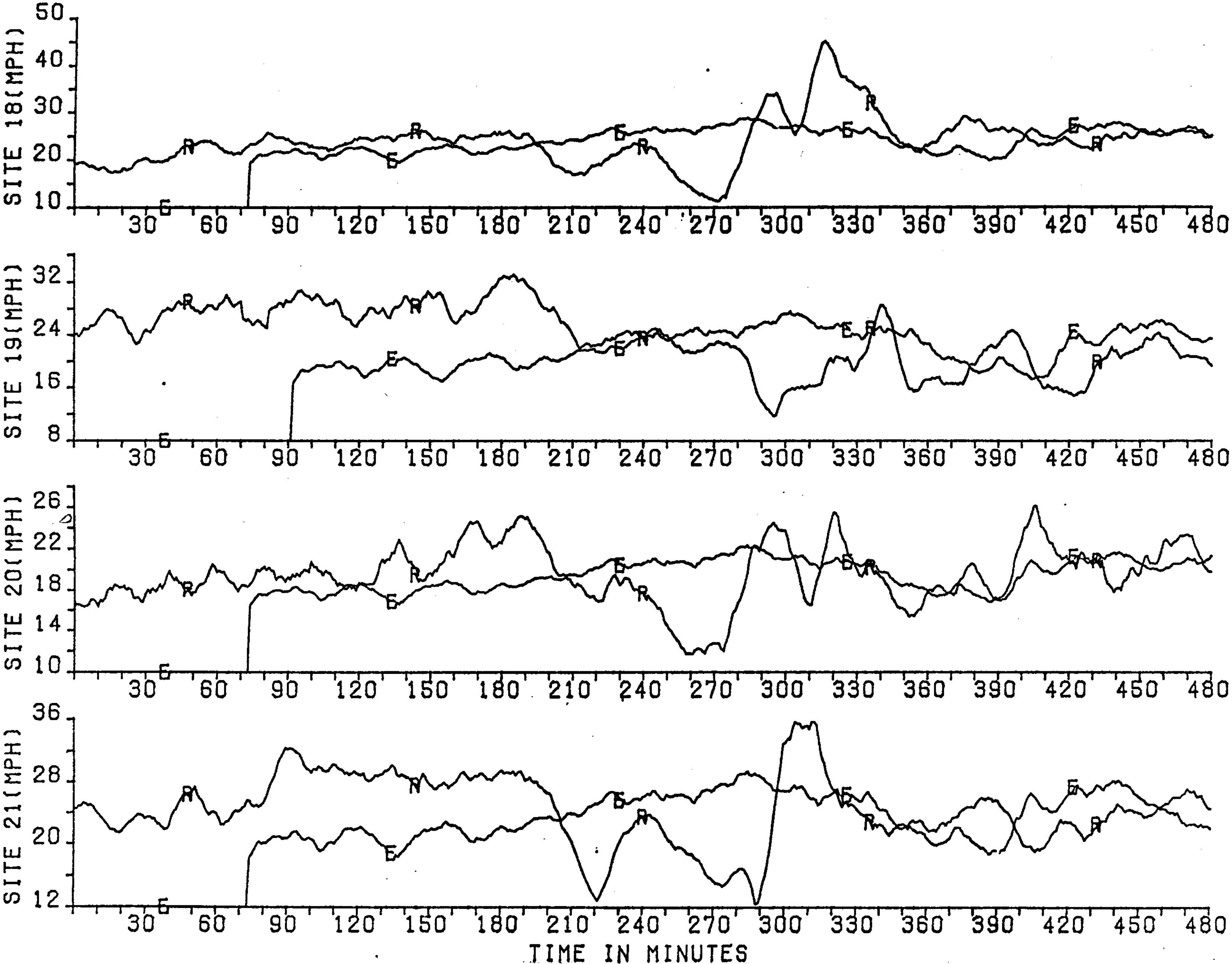


Figure 10d. Actual and predicted wind speed records for 3:00 - 10:00 p.m. May 2, 1979 using 10 minute moving average filtered data and site 1 as reference.

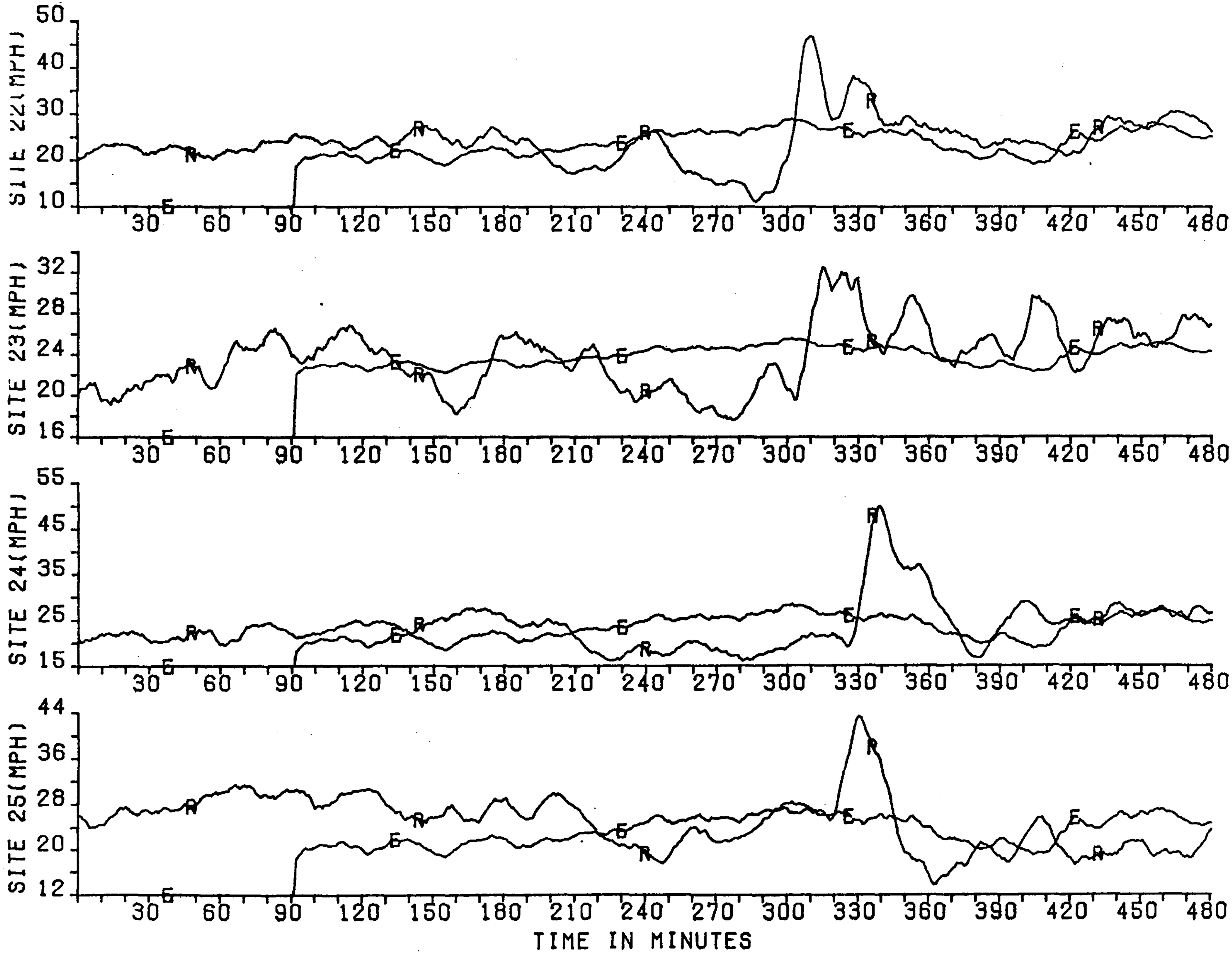


Figure 10e. Actual and predicted wind speed records for 3:00 - 10:00 p.m. May 2, 1979 using 10 minute moving average filtered data and site 1 as reference.

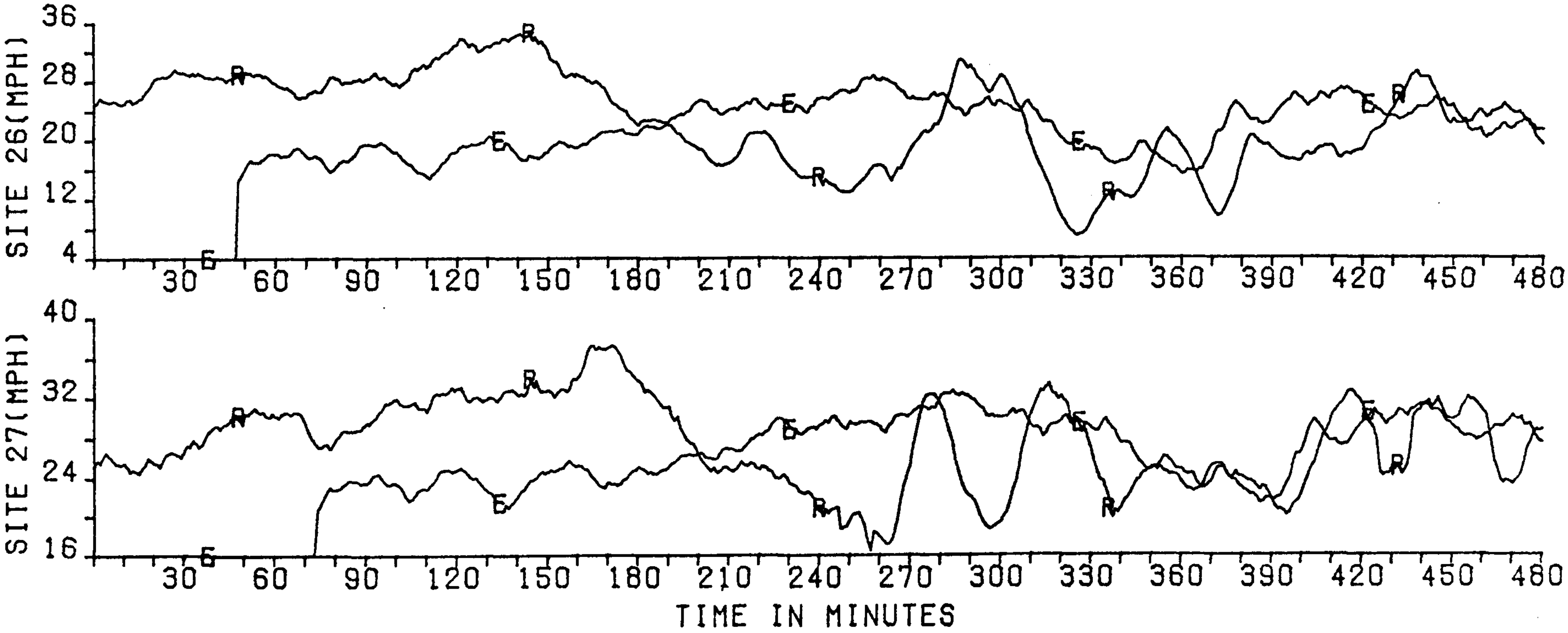


Figure 10f. Actual and predicted wind speed records for 3:00 - 10:00 p.m. May 2, 1979 using 10 minute moving average filtered data and site 1 as reference.

It was found that a smoothing interval of 2 hours or greater is required if the wind speed direction and delays associated with propagation of the large triangular pulse increase in wind speed is to be determined accurately. If one were to infer the smoothing interval from the speed of the propagation of the wind direction shift, a 2 hour or three hour smoothing interval would be expected to have totally filtered out the event propagation since the wind direction shift propagated in 2 hours. A further indication that wind direction change and its propagation rate is not an accurate prediction of the propagation rate of the triangular pulse wind speed increase is that the triangular pulse wind speed increase first appears at 3:00 p.m. at sites 1-5 and begins to propagate from north to south when the wind direction at these sites is from south to north until 6:40 p.m.

The successful prediction using the 2 hour moving average filtered data and 3 hour moving average filtered data is now discussed. The difficulties in establishing the direction of propagation and speed of propagation using 1 hour and 10 minute moving average filtered data is then described.

The direction of motion of the wind speed increase can not be detected from the peak correlation $p_{ij}(T_{ij})$ in Table 3 using the procedure given in Section 3. The peak correlation $p_{ij}(T_{ij})$ for elements ij in columns 1-5 are not consistently larger than the elements ji in rows 1-5 that would indicate the wind speed increase was propagating from north to south. Although the procedure did not work as expected, the elements in column 1 are generally larger than row 1 except for element (1,9) (1,11) and (1,13). This data would indicate the meteorological event was moving from north to south and that site 1 would be a reference site for prediction. Later studies showed site 1 was the best reference site in the set of reference sites 1-5 and thus the site with the best predictive information concerning the direction of motion of the meteorological event.

The procedure for detecting the direction of motion required ranking sites in an increasing distance in a direction as is done for the north to south direction in Table 3. The procedure developed in Section 3 requires that the column values (ij) for $i > j$ be larger than corresponding row values (ji) for propagation to occur in this north to south direction. This result occurred only for $j = 1$ and not for all sites j. The inability of this procedure to clearly indicate direction of propagation for all $i > j$ may be in part due to the complex wind speed characteristics associated with the transition from predominance of one front to another front. Pressure and temperature measurements and gradients would certainly be helpful in such a case to determine the propagation direction and speed of a meteorological event.

	SITES																										
SITES	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	---	.76	.90	.72	.73	.51	.37	.50	.38	.11	.44	.68	.62	.48	.17	.11	.58	.40	.60	.31	.49	.34	.37	.33	.88	.47	.33
2	.76	---	.88	.79	.92	.72	.46	.81	.50	.58	.60	.54	.57	.78	.40	.55	.66	.49	.59	.35	.85	.42	.48	.42	.89	.64	.69
3	.90	.88	---	.66	.81	.53	.39	.62	.46	.34	.52	.50	.55	.69	.29	.32	.60	.44	.45	.35	.66	.35	.39	.35	.86	.46	.47
4	.72	.79	.66	---	.93	.87	.52	.86	.49	.66	.61	.92	.50	.72	.26	.69	.61	.53	.94	.35	.86	.48	.56	.49	.88	.89	.85
5	.73	.92	.81	.93	---	.88	.53	.93	.56	.67	.67	.76	.60	.86	.40	.66	.71	.56	.79	.40	.92	.49	.56	.49	.90	.85	.83
6	.51	.72	.53	.90	.88	---	.54	.96	.56	.84	.67	.89	.60	.76	.50	.88	.71	.56	.90	.40	.86	.50	.57	.50	.69	.97	.94
7	.49	.33	.40	.39	.33	.33	---	.22	.59	.59	.81	.46	.44	.18	.72	.57	.39	.80	.41	.77	.21	.86	.93	.85	.46	.39	.38
8	.52	.81	.62	.88	.93	.96	.54	---	.59	.86	.70	.81	.71	.88	.62	.86	.81	.58	.85	.43	.94	.49	.57	.50	.72	.93	.96
9	.36	.37	.34	.29	.28	.14	.45	.16	---	.27	.88	.25	.44	.42	.49	.27	.64	.87	.22	.40	.25	.82	.75	.78	.42	.24	.14
10	.66	.41	.53	.68	.62	.83	.44	.82	.47	---	.57	.79	.76	.65	.74	.98	.80	.47	.82	.67	.79	.41	.47	.42	.48	.84	.93
11	.38	.27	.30	.32	.26	.22	.74	.18	.89	.39	---	.34	.39	.20	.50	.42	.65	.90	.31	.61	.19	.84	.86	.82	.36	.29	.24
12	.68	.54	.50	.91	.73	.71	.47	.63	.39	.53	.49	---	.62	.45	.24	.56	.50	.47	.95	.31	.65	.44	.50	.45	.77	.76	.74
13	.51	.39	.51	.34	.32	.03	.32	.04	.44	.11	.40	.39	---	.26	.25	.13	.88	.38	.18	.21	.21	.42	.35	.39	.56	.08	.04
14	.49	.78	.62	.75	.86	.75	.45	.88	.55	.73	.66	.61	.76	---	.67	.71	.84	.52	.67	.43	.90	.39	.48	.41	.68	.73	.82
15	.61	.46	.57	.34	.38	.52	.25	.61	.37	.83	.44	.52	.75	.66	---	.79	.76	.37	.52	.80	.63	.61	.64	.69	.58	.50	.70
16	.65	.42	.52	.72	.64	.87	.44	.83	.47	.98	.57	.83	.72	.65	.70	---	.78	.48	.84	.63	.78	.41	.47	.41	.46	.88	.94
17	.53	.43	.60	.20	.30	.02	.36	.01	.64	.04	.67	.15	.88	.28	.18	.05	---	.56	.03	.28	.17	.38	.36	.38	.50	.03	.02
18	.40	.36	.31	.35	.31	.22	.49	.22	.81	.34	.81	.34	.29	.30	.49	.37	.32	---	.32	.56	.25	.93	.87	.91	.40	.32	.23
19	.60	.59	.45	.94	.78	.85	.49	.76	.42	.70	.52	.96	.62	.54	.24	.73	.55	.49	---	.32	.74	.46	.52	.47	.75	.87	.85
20	.50	.43	.52	.26	.33	.21	.16	.23	.37	.67	.41	.31	.61	.27	.74	.62	.67	.29	.32	---	.30	.39	.47	.56	.48	.27	.47
21	.52	.82	.57	.86	.90	.85	.50	.92	.54	.82	.66	.72	.72	.87	.59	.80	.82	.56	.79	.42	---	.45	.53	.46	.74	.82	.91
22	.49	.43	.41	.39	.35	.24	.26	.21	.63	.43	.56	.37	.40	.29	.63	.42	.34	.90	.33	.61	.26	---	.93	.95	.48	.35	.22
23	.45	.36	.37	.39	.34	.28	.17	.23	.47	.46	.39	.41	.37	.23	.69	.47	.30	.77	.36	.66	.24	.92	---	.93	.46	.35	.27
24	.47	.44	.42	.38	.37	.21	.07	.22	.42	.40	.30	.35	.42	.31	.69	.38	.36	.69	.31	.62	.29	.88	.91	---	.49	.31	.19
25	.88	.89	.86	.88	.90	.69	.45	.72	.43	.35	.52	.77	.58	.68	.22	.35	.50	.44	.75	.31	.74	.41	47	.42	---	.65	.58
26	.50	.64	.46	.91	.85	.97	.53	.93	.53	.84	.64	.92	.58	.73	.48	.88	.68	.54	.92	.37	.83	.49	.56	.49	.67	---	.93
27	.58	.59	.49	.85	.79	.90	.50	.89	.53	.93	.65	.86	.73	.75	.59	.93	.81	.55	.89	.50	.89	.47	.54	.47	.58	.91	---

Table 3. Peak correlation matrix $P_{ij}(T_{ij})$ for 2 hour filtered data from 3:00 - 10:00 p.m. on May 2, 1979.

The speed of propagation of the wind speed increase associated with the transition from predominance of one front to another (and the eventual wind shift) must also be determined to perform accurate prediction. The prediction methodology does not actually determine the speed of propagation but rather the delay required for the meteorological event (triangular pulse wind speed increase) to propagate from a set of reference meteorological tower wind measurement sites to the meteorological tower sites where prediction is desired.

The first step in determining the proper delays is to determine group of wind measurement sites that are in close geographical proximity with each other in the direction of propagation of the event, have correlations $p_{ij}(T_{ij})$ and $p_{ji}(T_{ij}) > 60$ for all pairs in each group, and have small delays T_{ij} and T_{ji} for all pairs in the group. The groups formed are shown in Figure 11.

The first set of reference sites used for prediction are sites $J_o = \{1,2,3,4,5\}$ that are the first to be affected by the event. Three methods were used to select the delays between the members of a prediction group of measurement sites $i \epsilon I$, where wind speed prediction is desired, and the reference set of measurement sites J_o. The methods also result in very different models because the wind speed records used to produce the recursive least squares predictive model are also different.

The first method utilizes all N_j reference sites $j \epsilon J_o$ to predict each prediction site i. The reference site record j is delayed by the delay T_{ij} associated with the peak correlation, where $p_{ij}(T_{ij}) > p_{ji}(T_{ji})$. The predictive model (9) is developed based on a recursive least squares algorithm.

The second method utilizes an average wind speed reference record

$$W_r(t) = \frac{1}{N_j} \sum_{j \epsilon J_o} W_j(t)$$

and a prediction site delay

$$T_i = \frac{1}{N_j} \sum_{j \epsilon J_o} T_{ij}$$

to predict site i. The single averaged reference record is delayed by the average prediction site delay to produce a recursive least squares prediction (9) for site i for

$$W_i(t) = a_{ir} W_r(t - T_i) + b_{ir}$$

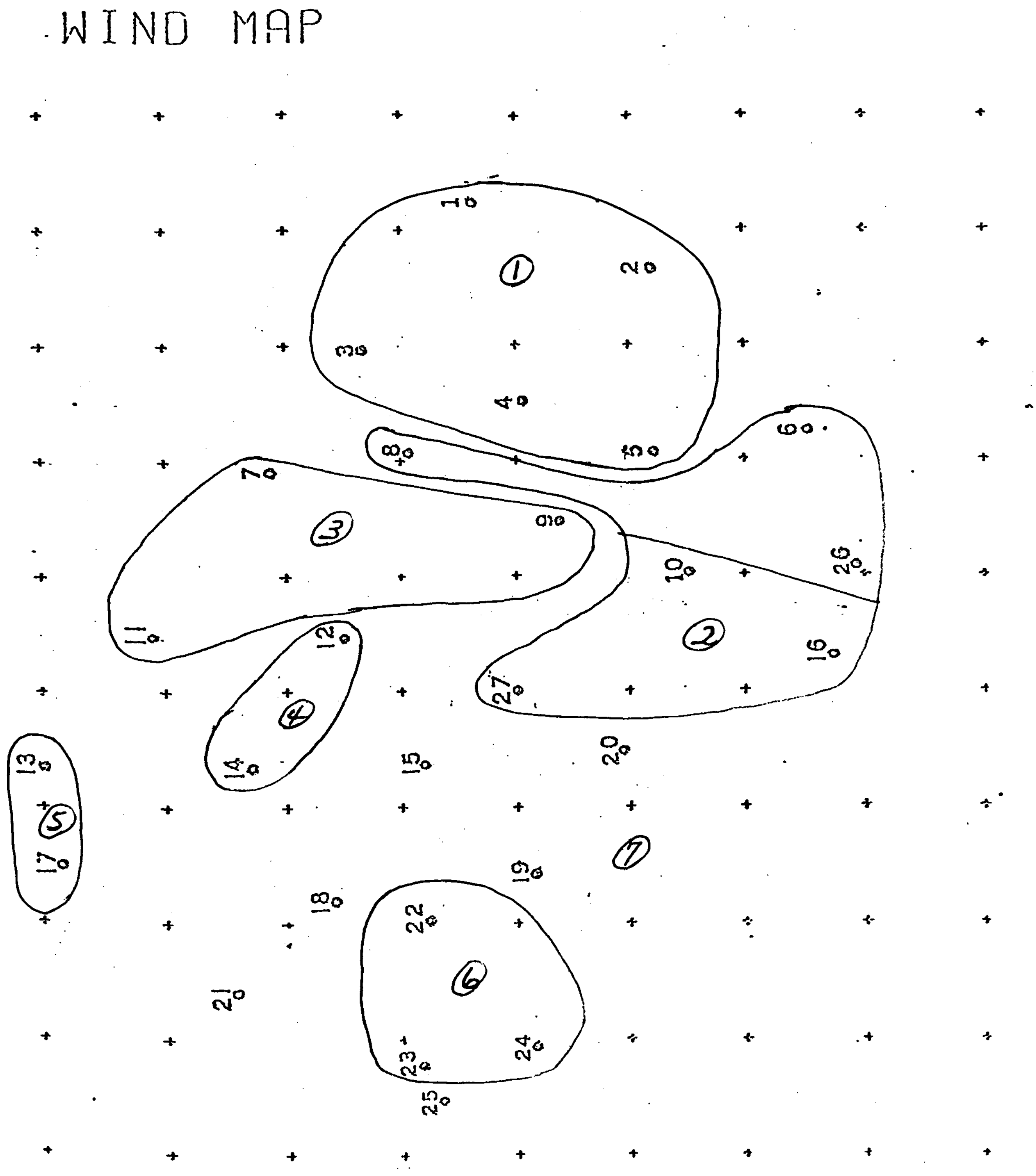


Figure 11. Groups of wind measurement sites for data from 3:00 - 10:00 p.m. on May 2, 1979.

The <u>third</u> method produced an average wind speed record for the N_j sites in the reference group,

$$W_r(t) = \frac{1}{N_j} \sum_{j \varepsilon J_o} W_j(t)$$

an averaged wind speed record for the N_k sites in prediction group k,

$$W_k(t) = \frac{1}{N_k} \sum_{i \varepsilon I_k} W_i(t)$$

and an average group delay between reference site $j \varepsilon J_o$ and prediction sites $i \varepsilon I_k$

$$T(k) = \frac{1}{N_n N_k} \sum_{j \varepsilon J_o} \sum_{i \varepsilon I_k} T_{ij}$$

The single averaged reference group signal $W_r(t)$ is delayed by T(k) to produce a recursive least squares predictor (9) of the averaged wind speed record for group k. The predictor has the form

$$W_k(t) = A_{kr} W_r(t - T(k)) + b_{kr}$$

The methods for selecting delay are justified because (1) the values of delay for sites within the reference group are small and the sites themselves are geographically close in the direction of motion of the meteorological event, and (2) because the delays T_{ij} vary greatly over the references j = 1,2,3,4,5 for any prediction site i. This large variation within the set $\{T_{ij}\}_{j=1}^{5}$ indicates the method for selecting the delay between any reference site j and prediction site i is corrupted by site specific phenomena other than just the propagation of the event. Thus, the methods of utilizing individual references with different delays T_{ij}, delay for prediction site i from all sites in the reference group, and averaging delays over all sites in prediction group I_k and all sites in the reference group J_o are ways of minimizing these site specific effects observed in T_{ij}.

The delays $\{T_{ij}\}_{j \varepsilon J_o}$, T_i and T(k) for prediction site i in group k are given in each row of Table 4 where prediction sites in the same group k are listed together. It is clear that the delays from one specific site in the reference group to one or more prediction sites in group 2, 3, and 5 are inconsistent with those from other sites in the reference group. The delays from all sites in the reference group to all sites in prediction group 6 are quite similar but delays from sites in the reference

		Individual Site Delays (Minutes)					Group/Site Delay	Group/Group Delay
Group	Site	T_{i1}	T_{i2}	T_{i3}	T_{i4}	T_{i5}	T_i	T(k)
1	6	1	1	1	1	1	1	2
1	8	5	1	8	1	1	1	2
1	26	1	1	1	1	1	1	2
2	10	54	40	58	1	23	35	30
2	27	34	30	41	1	20	25	30
2	16	47	41	51	1	17	31	30
3	7	208	205	204	189	198	201	198
3	9	231	221	21	207	215	179	198
3	11	227	216	222	200	210	215	198
4	12	1	16	1	13	24	11	55
4	14	29	1	18	1	2	10	55
4	15	338	24	48	301	12	145	55
5	13	37	200	19	166	191	123	118
5	17	22	198	1	172	188	116	118
6	22	275	275	270	259	266	269	279
6	23	290	288	289	271	281	284	279
6	24	290	289	288	276	287	286	279
7	19	1	22	1	1	20	9	9
8	20	362	351	353	318	345	346	346
9	21	30	12	26	1	10	16	16
10	25	1	1	1	1	1	1	1
11	18	259	243	249	224	237	242	242

Table 4. Delays associated with propagation of the triangular pulse wind speed increase for data from 3:00 - 10:00 p.m. on May 2, 1979.

group to sites in prediction group 4 are very inconsistent. This would suggest that the errors in prediction of group 4 may be inconsistent based on the method of determining the delay, which is confirmed in the results to be presented.

The prediction errors for the individual site model delay, the group/site model using the average site T_i delays, and group/group model using the average group delay are given in Table 5 for each of the sites where prediction is attempted. The value of the maximum of the individual site delays, the group/site delay, and the group/group delay is given in Table 5 next to the error for that particular modeling method.

The errors in mph for individual site delay model are consistently smaller than those for the group/site, and group/group models especially at sites 10, 27, 16, 12, 14, 22, 23, 24, 19, 20, and 18. The only case where the group/site model had a smaller error than the individual site model was for prediction site 21.

The errors for site 12, 14, in group 4; 13, 17 in group 5; and 22 in group 6 increased very dramatically for the group/site model when compared with the individual site model. Group/site delay values were chosen for sites 22, 13, and 17 that were closer to the maximum individual site delay values and the large errors decreased dramatically as shown in Table 6. The maximum individual site delay values for groups 1, 2, 3, 5, and 6 were roughly proportional to the geographical distance between these groups and reference group 1 and thus the excellent performance of the prediction using the individual site model is understandable. The difference in errors between the individual site delay and group/site delay model, when both models utilize similar delays, is due to the fact that the group/site delay method averages the wind speed records at the reference site as well as averaging the delays between a prediction site i and this reference group. The averaging of the reference group wind record loses important information that will result in better prediction. The results of Tables 5 and 6 indicate that selecting the proper delay is more important than whether individual reference site wind records or an average reference wind record is used. Utilizing individual reference site wind records increases data acquisition and computation requirements for the predictor. It would appear, however, that utilizing individual site reference wind records does improve the accuracy sufficiently to warrant the additional cost of hardware and computation.

The individual site delay, group/site delay, and group/group delay for group 4 sites is clearly not proportional to geographical distance from sites in group 4 to the reference group sites. The errors for the individual site delay, as shown in Table 5, are small but the group/site delay is much larger. A group/site delay for this group was selected as 145, which was proportional

Group	Site	No. Averaging		Reference Group Averaging		Reference and Prediction Group Averaging	
		Maximum Site Delay	Error (mph)	Group/Site Delay (minutes)	Error (mph)	Group/Group Delay (minutes)	Error (mph)
1	6	1	1.51	1	2.69	2	2.18
1	8	8	0.49	1	1.28	2	2.18
1	26	1	1.22	1	2.84	2	2.18
2	10	58	1.00	35	3.41	30	2.61
2	27	41	0.67	25	1.89	30	2.61
2	16	51	1.06	31	2.89	30	2.61
3	7	208	0.51	201	0.60	198	0.62
3	9	231	0.23	179	1.37	198	0.62
3	11	227	0.28	215	0.54	198	0.62
4	12	24	0.48	11	2.78	55	1.07
4	14	29	0.64	10	1.41	55	1.07
4	15	338	0.11	145	0.52	55	1.07
5	13	200	0.31	123	1.97	119	1.98
5	17	198	0.66	116	2.96	119	1.98
6	22	275	0.36	269	2.08	279	0.42
6	23	290	0.15	284	0.37	279	0.42
6	24	290	0.33	286	0.85	279	0.42
7	19	22	0.75	9	2.24	9	2.24
8	20	363	0.14	346	0.39	346	0.39
9	21	30	0.47	16	0.37	16	0.37
10	25	1	0.68	1	1.72	1	1.72
11	18	259	0.36	242	0.85	242	0.85

Table 5. Errors and delays for individual site, group/site, and group/group models

		No. Averaging		Reference Group Averaging		Reference Group Averaging	
Group	Site	Maximum Site Delay	Error (mph)	Group/Site Delay (minutes)	Error (mph)	Geographical Delay (minutes)	Error (mph)
3	9	231	0.23	179	1.37	200	0.81
4	12	24	0.48	11	2.78	145	1.44
4	14	29	0.64	10	1.41	145	1.19
5	13	200	0.31	123	1.97	200	0.47
5	17	198	0.66	116	2.96	200	0.79
6	22	275	0.36	269	2.08	284	0.83

Table 6. Delays and errors for individual site model and the group/site delay, and geographical distance based delay group/site model.

to geographical distance from sites in group 4 to the reference sites. The errors on sites 12 and 14 in Table 6 using the group/site delay of 145 was much smaller than the average site delays of 10 or 11 used previously. However, the group site delay of 145 did not achieve as small an error as the individual site delay model where the maximum individual site delays are 24 and 29. Thus, the prediction performance at site 12 and 14 with individual site delay model was again excellent and even though the individual site delays are not consistent with geographical distance, it would appear, from the errors and the time plots of the predicted and actual wind speed records (Figure 12) at these sites, that accurate prediction was being accomplished.

The final test for the accuracy of the prediction is to plot the predicted wind speed against the actual wind speed as shown in Figure 12. The accuracy of the prediction can be judged by comparing whether the peak of the two records is the same, whether the slope of the records during periods of increasing and decreasing wind speed are nearly identical, and whether the maximum and minimum and the average wind speed are nearly identical. The results of the prediction using the individual site delay model are plotted and the accuracy of the prediction for all sites is truly excellent. These results are slightly better than one would achieve if the wind speeds and the predicted wind speeds were not filtered using a 2 hour time average filter, which eliminates turbulence and site specific effects from the records and causes the triangular wind speed increase to appear to be similar in shape in all sites. Nonetheless, the prediction methodology is quite successful.

A second group of sites 6, 8, and 26 were used as reference to determine if this reference group could still obtain accurate prediction, whether the individual site delay model would still outperform the group/site delay model and the group/group delay model, whether the errors were comparable with those utilizing sites 1-5 as the reference group and finally whether the delays are still proportional to distance and related to the delays obtained for reference groups 1-5 by some constant delay.

The individual site delay T_{ij} from reference site 6, 8, 26 to each prediction site and the average site delay T_i are given in Table 7. The delays at prediction sites in groups 2, 3, 5, and 6 from reference sites 6, 8, 26 are approximately 30 minutes longer than the delays determined for these prediction sites from reference groups with sites 1-5 given in Table 5. The delays for the reference group sites 1-5 and for the reference group 6, 8, 26 are thus in excellent agreement since the group/group delay between sites 1-5 and sites 6, 8, 26 is 30 minutes from Table 5. The delays for group 4 and the sites are not quite as consistent in terms of differing by a constant 30 minute delay.

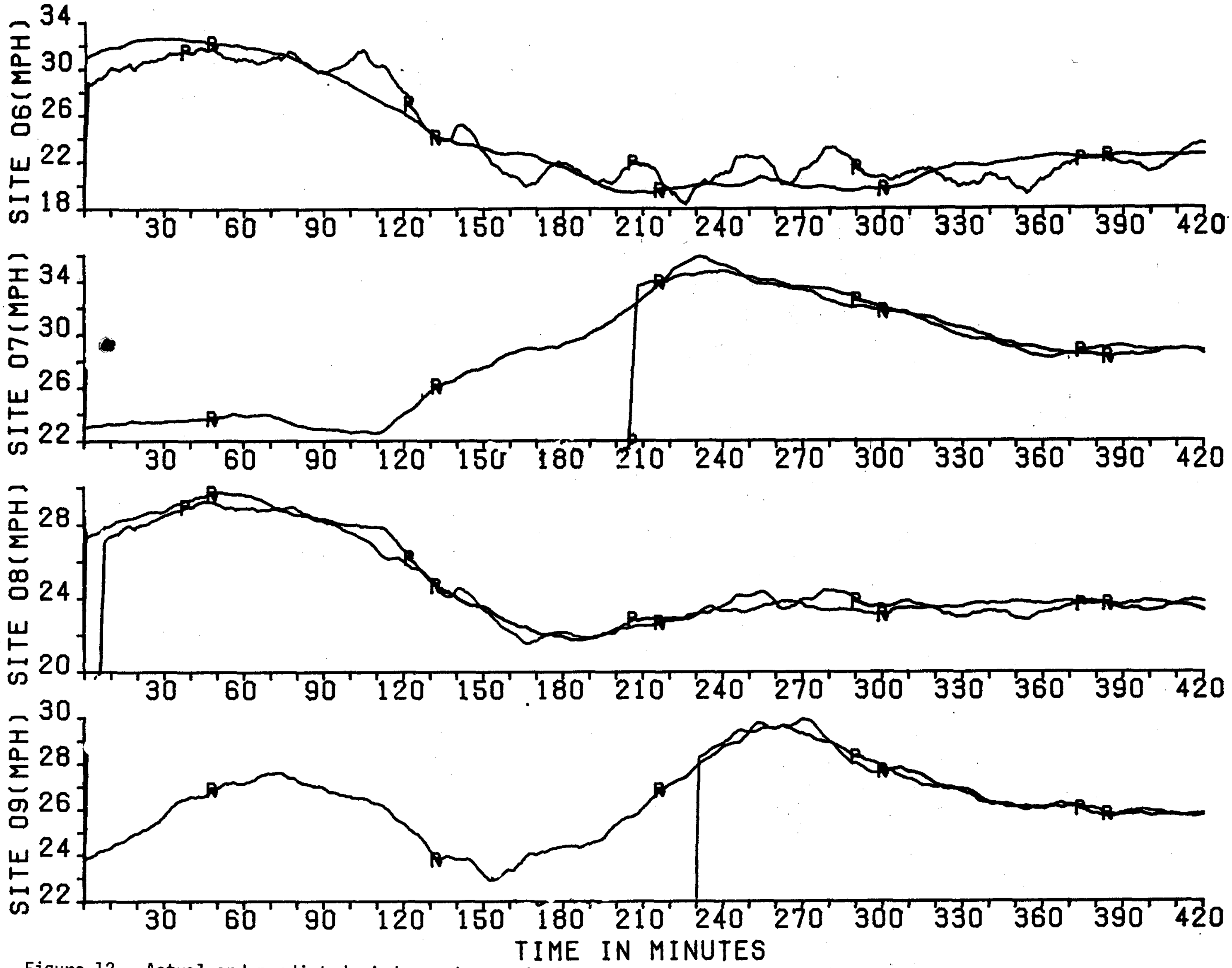


Figure 12. Actual and predicted wind speed records for 3:00 - 10:00 p.m. May 2, 1979 data using 2 hour moving average filtered records and sites 1-5 as reference.

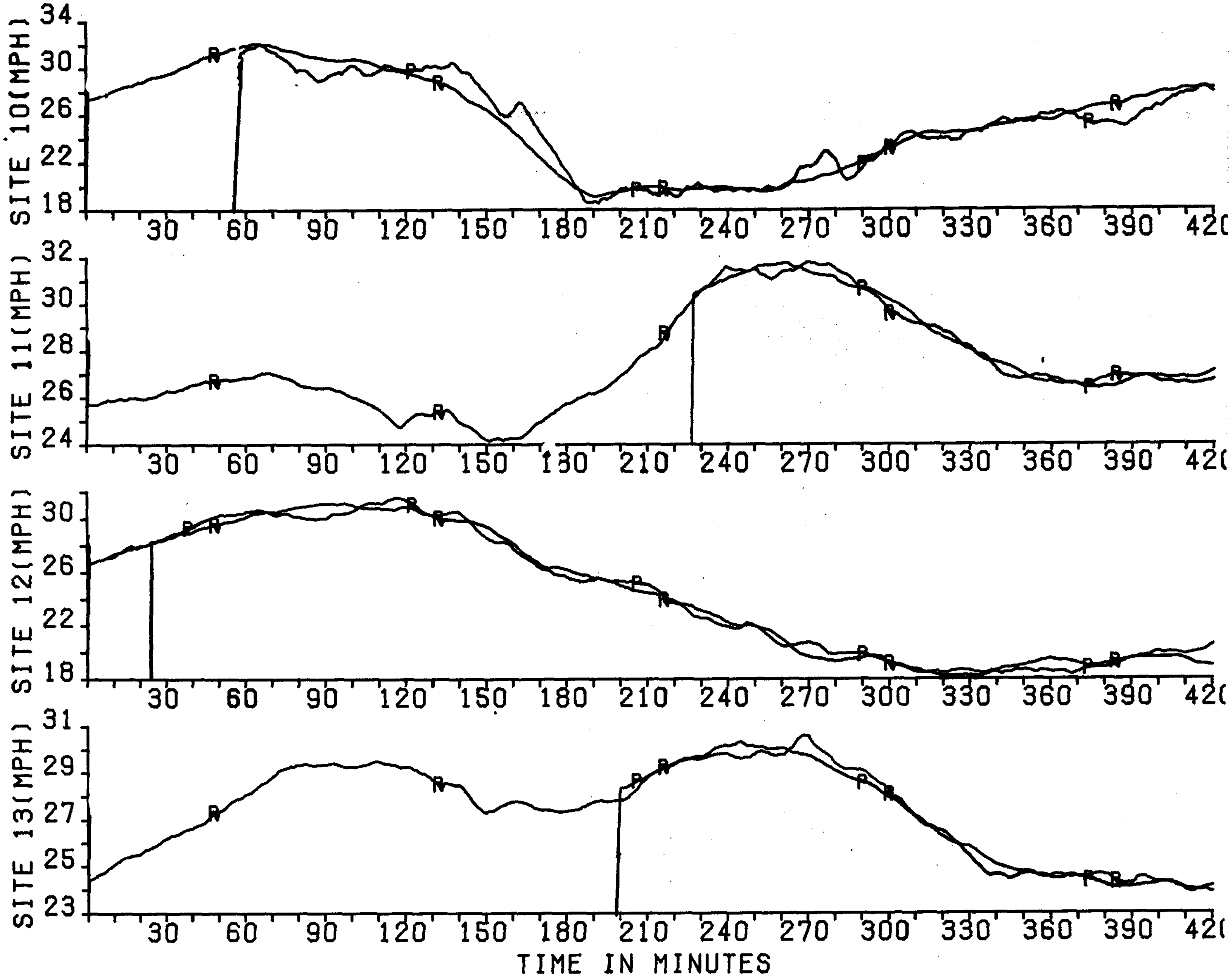


Figure 12a. Actual and predicted wind speed records for 3:00 - 10:00 p.m. May 2, 1979 data using 2 hour moving average filtered records and sites 1-5 as reference.

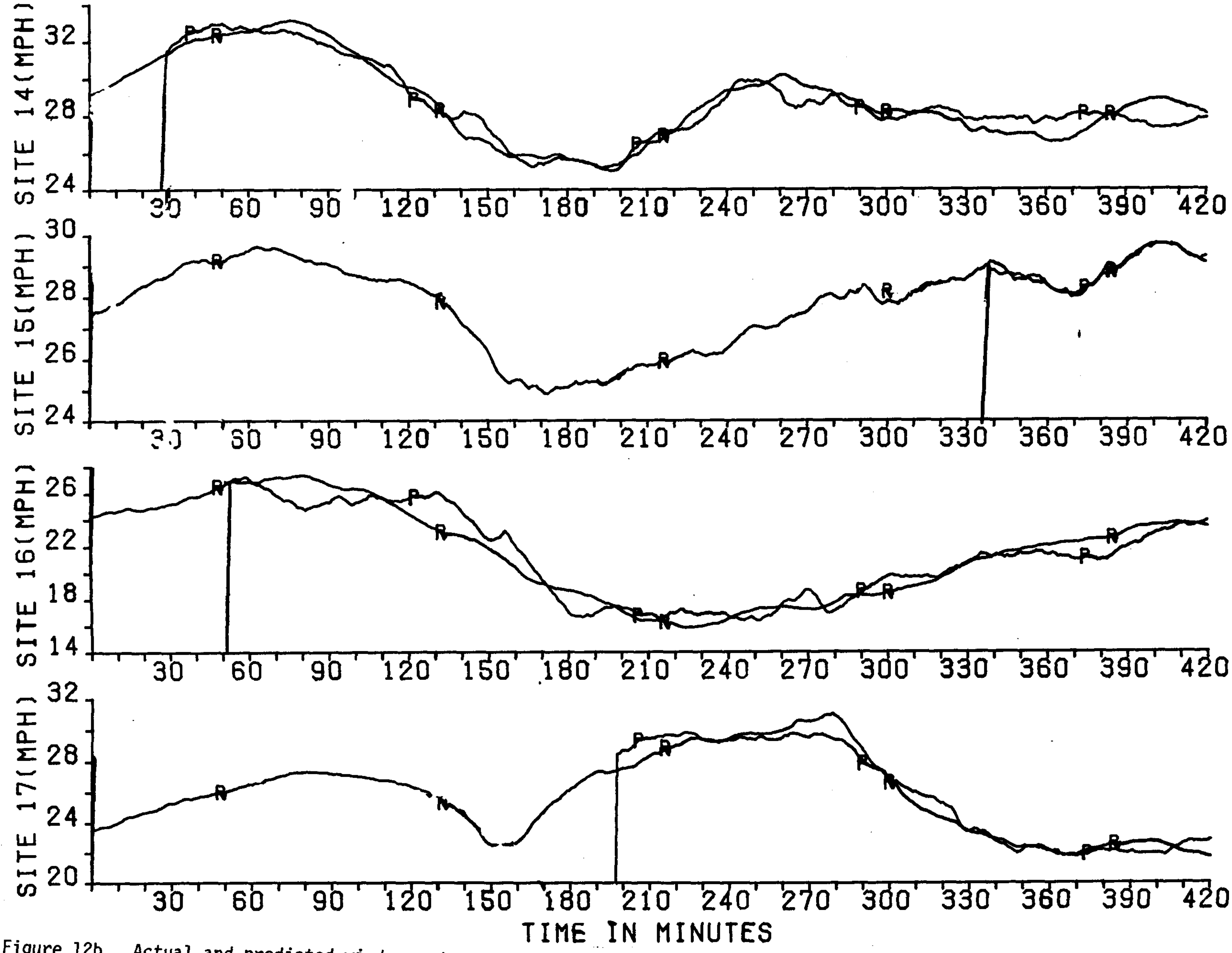


Figure 12b. Actual and predicted wind speed records for 3:00 - 10:00 p.m. May 2, 1979 data using 2 hour moving average filtered records and sites 1-5 as reference.

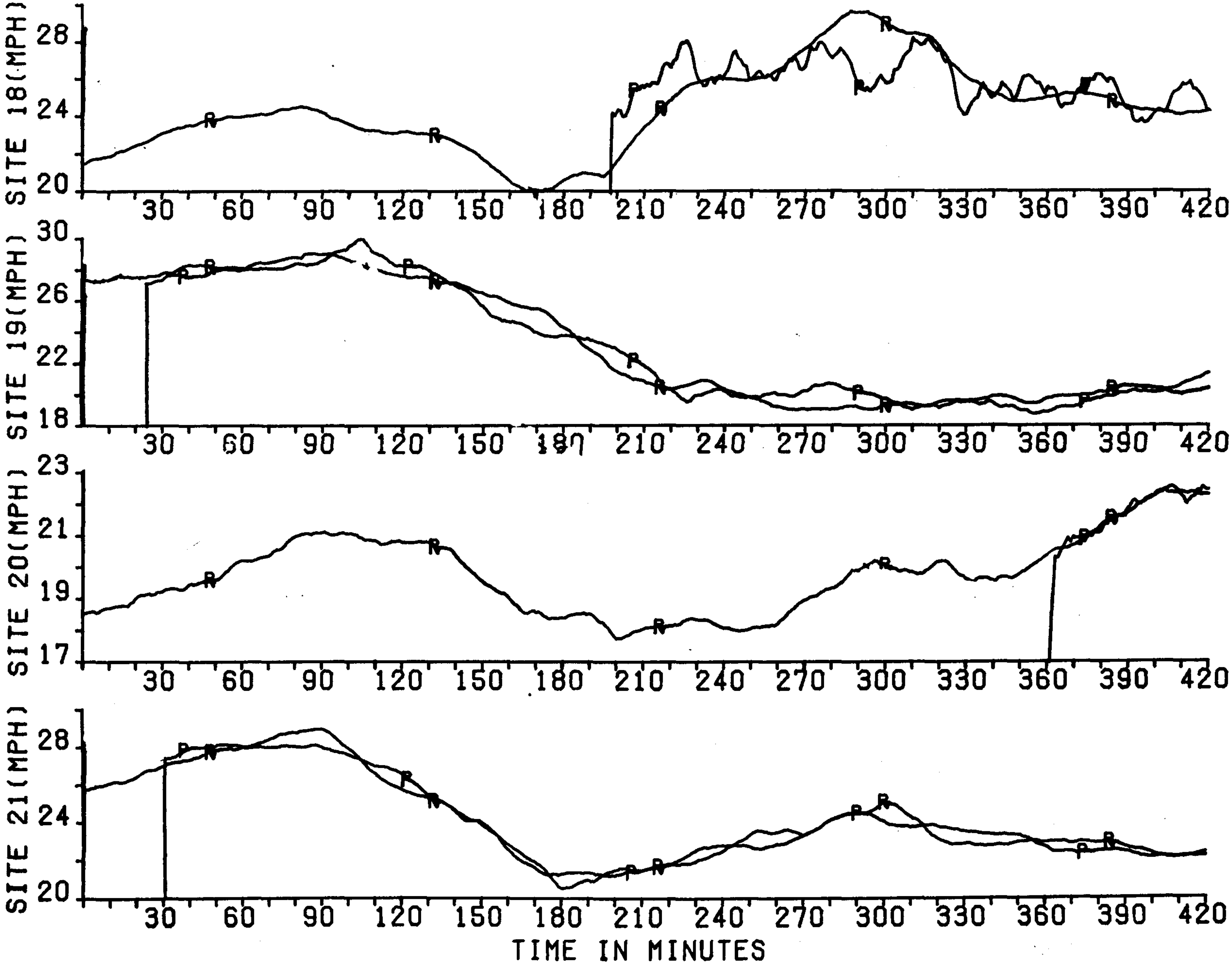


Figure 12c. Actual and predicted wind speed records for 3:00 - 10:00 p.m. May 2, 1979 data using 2 hour moving average filtered records and sites 1-5 as reference.

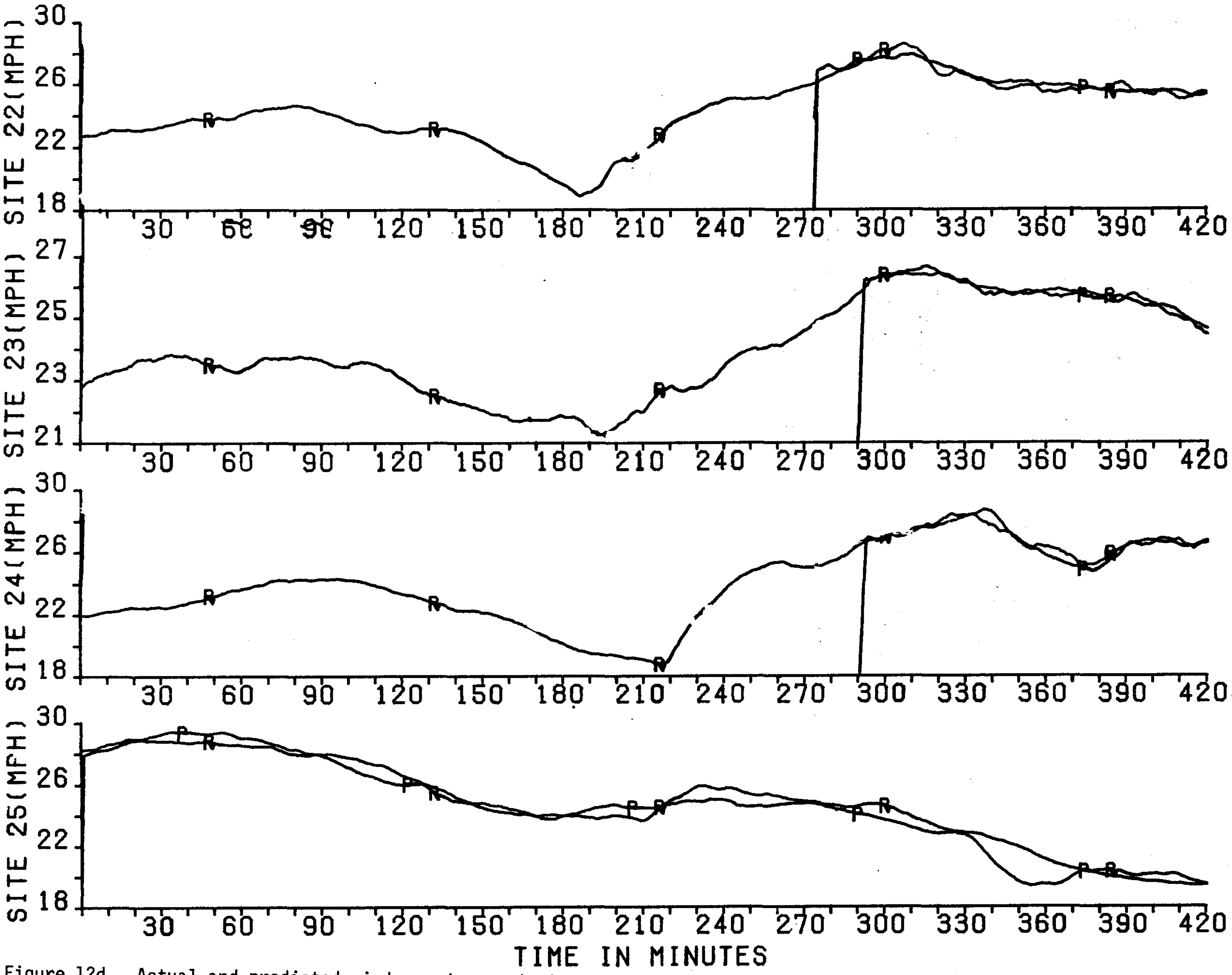


Figure 12d. Actual and predicted wind speed records for 3:00 - 10:00 p.m. May 2, 1979 data using 2 hour moving average filtered records and sites 1-5 as reference.

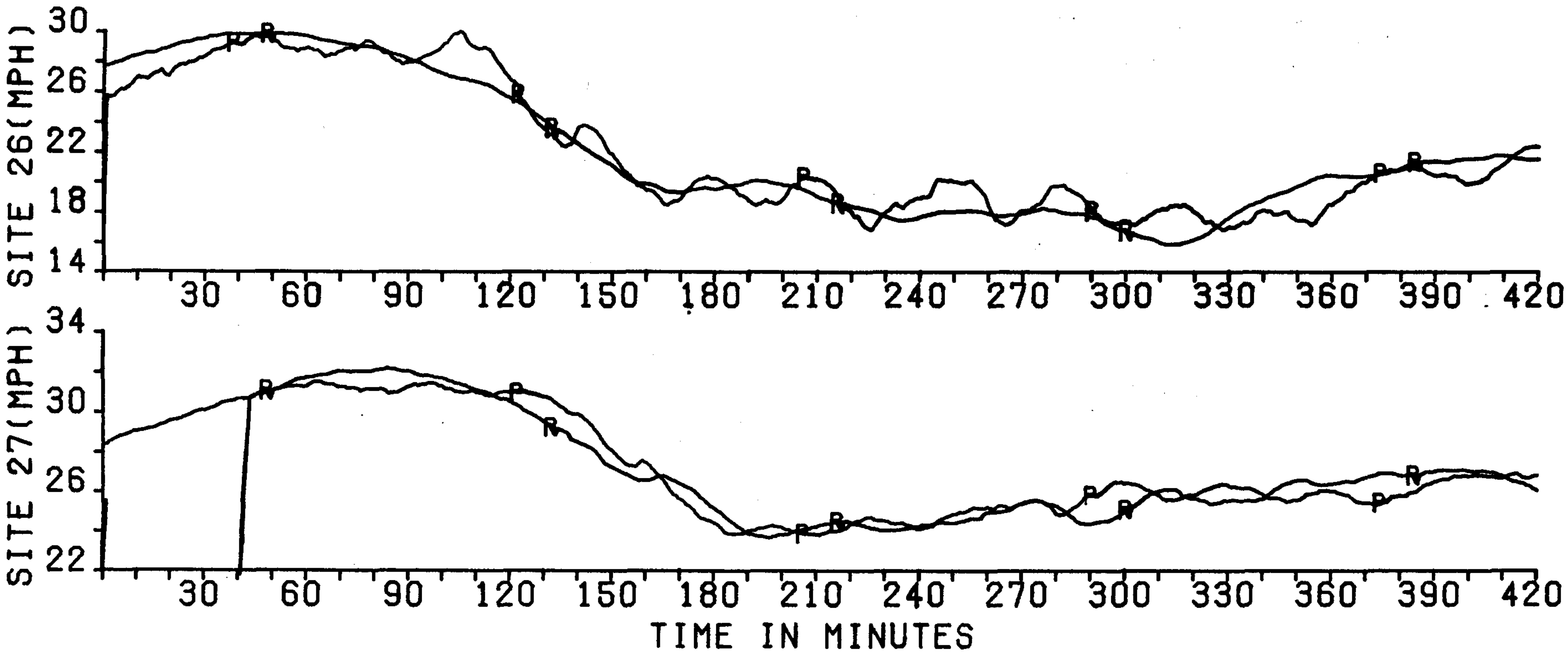


Figure 12e. Actual and predicted wind speed records for 3:00 - 10:00 p.m. May 2, 1979 data using 2 hour moving average filtered records and sites 1-5 as reference.

	Individual Site Delays (minutes)			Group/Site Delay
Sites	T_{i6}	T_{i8}	T_{i26}	T_i
1	148	166	135	150
2	1	1	1	1
3	1	1	1	1
4	20	16	17	18
5	1	1	1	1
6	---	1	1	1
7	204	199	200	201
8	1	---	1	1
9	219	215	216	217
10	11	19	6	12
11	216	211	210	212
12	52	54	44	50
13	188	190	177	185
14	5	3	3	4
15	1	7	1	3
16	7	17	1	8
17	186	188	179	184
18	244	237	236	239
19	31	38	32	34
20	354	36	351	247
21	8	11	11	10
22	271	265	267	268
23	287	283	281	284
24	289	286	285	287
25	1	1	23	8
26	1	1	---	1
27	18	21	13	17

Table 7. Individual and group/site delays from references 6, 8, 26 using the 3:00 - 10:00 p.m. May 2, 1979 data.

		Delays (minutes)		Errors (mph)		
Group	Sites	Group/Site Delays	Group/Group Delays	Group to Group	Group to Site	6, 8, 26 as Reference
1	1	150				1.06
	2	1				1.76
	3	1				1.18
	4	18				1.85
	5	1				1.05
2	10	12	12	1.50	1.04	1.96
	16	8			1.61	1.54
	27	17			2.07	2.04
3	7	201	209	1.53	1.66	.69
	9	217			.78	.47
	11	212			1.80	.58
4	12	50	27	.79	1.40	1.21
	14	4			1.23	.71
5	13	185	185	2.23	1.87	.45
	17	184			2.60	.76
6	22	268	280	1.67	2.06	.61
	23	284			.40	.18
	24	287			.87	.88
7	15	3			1.18	.71
	18	239			2.13	.73
	19	34			.23	.85
	20	247			1.16	.13
	21	10			.54	.57
	25	8			1.68	1.81

Table 8. Delays and error for 2 HR filtered data of May 2, 1979 from 3:00 - 10:00 p.m. with sites 6, 8, and 26 as the reference group.

The errors for the individual site model, group/site model, and group/group model are given in Table 8 for references group 6, 8, 26. The errors are generally larger for all prediction sites using the 6, 8, 26 reference group than the 1-5 reference group except for sites 14 and 20. This could be expected since the reference site 6, 8, 26 are less central in terms of the location of the prediction sites and the wind speed direction are more spread out, and are fewer in number than the site 1-5 reference group. The errors at 14 and 20 are smaller because they are geographically closer to sites 6, 8, and 26. The errors for reference group 6, 8, 26 are generally proportional to that for reference group 1-5. Prediction performance using either of the reference groups is quite good.

The results for prediction using a 3 hour and 1 hour moving average filtered data rather than the 2 hour moving average filtered data are now discussed. The correlation table, given in Table 9, for the three hour moving average data has consistently higher values. The higher correlation should be expected since the longer smoothing interval should remove variation and thus make any pair of site 5 better correlated. The results for wind direction assessment are again indecisive based on comparison of correlations in the first five rows and columns of Table 9. The correlation in the first column (i1) is consistently larger than the corresponding correlation in the first row (1i) suggesting that based on site 1 the wind direction is north to south. The groups, which are formed based on large correlations above .60, close geographical proximity, and small delays between pairs of sites in a group; are nearly the same as for the 2 hour filtered data. The delays between the reference sites 1-5 and each prediction site for the 3 hour moving average data is nearly identical to those for the 2 hour moving data but are proportionately smaller in general as shown in Table 10. The group/site, and group/group delays are thus also proportionately smaller. The errors for the individual site, group/site, and group/group models are also shown in Table 10. The errors are slightly smaller than for the 2 hour smoothing interval data due to the larger smoothing interval.

The results for 3 hour moving average filtered data is consistent with that for 2 hour moving average filtered data except at sites in group 4 and at sites 15, 18, 19-21. The delays and errors are quite different at these sites. This could be expected because the results at these sites do not belong to a group of sites, which is important in selecting delays, or belong to a group where the delays are quite inconsistent.

The performance of the predictor, based on 1 hour moving average filter data deteriorates very badly with respect to the predictors developed for 2 hour and 3 hour moving average data. The peak correlation table for the 1 hour moving average data,

	SITES																										
SITES	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	---	.78	.92	.80	.77	.54	.31	.53	.32	.21	.33	.83	.68	.41	.26	.26	.48	.35	.74	.25	.53	.33	.35	.36	.89	.57	.49
2	.78	---	.81	.86	.94	.81	.42	.87	.59	.58	.48	.73	.50	.83	.41	.63	.43	.52	.77	.40	.86	.57	.56	.56	.89	.81	.77
3	.92	.81	---	.69	.74	.51	.28	.53	.30	.17	.31	.66	.56	.45	.25	.21	.44	.31	.59	.22	.52	.32	.30	.30	.79	.49	.41
4	.80	.86	.69	---	.96	.90	.45	.88	.51	.72	.48	.97	.64	.77	.38	.76	.59	.50	.98	.38	.88	.52	.54	.53	.92	.93	.90
5	.77	.94	.74	.96	---	.92	.45	.94	.56	.73	.48	.87	.61	.87	.41	.78	.55	.51	.91	.39	.93	.56	.56	.55	.91	.93	.90
6	.59	.81	.51	.90	.92	---	.46	.98	.57	.92	.50	.85	.69	.88	.42	.94	.62	.52	.91	.40	.93	.57	.57	.57	.74	.97	.96
7	.57	.38	.50	.39	.34	.36	---	.34	.84	.52	.90	.46	.49	.33	.70	.52	.49	.88	.45	.63	.33	.88	.90	.88	.45	.39	.44
8	.54	.87	.53	.88	.94	.98	.46	---	.59	.89	.49	.78	.73	.95	.50	.92	.66	.53	.86	.43	.96	.58	.58	.58	.75	.97	.96
9	.48	.32	.44	.32	.30	.28	.66	.29	---	.36	.86	.35	.44	.30	.62	.38	.39	.90	.34	.56	.29	.95	.94	.92	.40	.32	.36
10	.65	.58	.42	.75	.73	.92	.40	.89	.51	---	.46	.82	.75	.80	.63	.98	.65	.48	.83	.65	.87	.50	.51	.51	.53	.88	.92
11	.53	.33	.45	.41	.34	.34	.86	.29	.86	.51	---	.46	.42	.28	.69	.48	.38	.92	.43	.66	.27	.90	.89	.90	.44	.36	.37
12	.83	.73	.66	.97	.87	.79	.43	.74	.43	.59	.46	---	.66	.60	.32	.64	.58	.46	.97	.33	.76	.45	.47	.48	.89	.84	.81
13	.68	.27	.56	.33	.24	.02	.38	.03	.45	.07	.43	.48	---	.03	.27	.07	.84	.45	.27	.32	.04	.46	.47	.47	.57	.03	.02
14	.52	.83	.45	.77	.87	.88	.43	.95	.61	.80	.44	.68	.78	---	.61	.86	.69	.54	.73	.56	.90	.60	.58	.58	.69	.88	.90
15	.52	.25	.43	.50	.36	.53	.17	.50	.37	.76	.29	.61	.61	.59	---	.67	.43	.30	.54	.88	.55	.52	.58	.63	.51	.48	.54
16	.64	.63	.42	.80	.78	.94	.42	.92	.53	.98	.45	.82	.80	.86	.62	---	.73	.48	.85	.63	.88	.52	.53	.52	.58	.93	.94
17	.48	.20	.44	.13	.12	.06	.40	.07	.39	.17	.50	.17	.84	.06	.38	.12	---	.41	.11	.36	.09	.37	.40	.39	.36	.08	.06
18	.48	.33	.41	.41	.36	.34	.66	.29	.75	.45	.87	.45	.42	.27	.58	.42	.30	---	.40	.60	.28	.96	.95	.95	.44	.33	.34
19	.74	.77	.59	.98	.91	.91	.45	.85	.50	.76	.48	.97	.68	.72	.37	.79	.61	.50	---	.37	.85	.51	.53	.52	.86	.93	.90
20	.53	.29	.43	.42	.32	.42	.13	.36	.25	.66	.20	.51	.63	.40	.85	.63	.56	.22	.46	---	.41	.37	.46	.54	.49	.38	.47
21	.53	.86	.52	.88	.93	.93	.44	.96	.61	.87	.51	.77	.74	.90	.49	.88	.65	.54	.86	.42	---	.59	.59	.59	.78	.93	.95
22	.46	.31	.41	.37	.32	.32	.42	.28	.51	.41	.63	.41	.42	.29	.59	.40	.32	.89	.38	.59	.27	---	.97	.95	.41	.32	.34
23	.44	.32	.38	.36	.33	.32	.37	.26	.48	.38	.57	.39	.40	.27	.60	.38	.34	.86	.36	.56	.29	.97	---	.96	.41	.30	.33
24	.44	.31	.39	.35	.32	.31	.27	.27	.38	.38	.43	.39	.38	.26	.64	.39	.30	.73	.37	.60	.29	.91	.95	---	.40	.32	.33
25	.89	.89	.79	.92	.91	.74	.39	.75	.49	.47	.41	.89	.57	.69	.35	.52	.47	.46	.86	.36	.78	.49	.49	.49	---	.76	.74
26	.61	.81	.49	.93	.93	.97	.46	.97	.55	.88	.47	.88	.72	.88	.41	.93	.69	.51	.93	.39	.93	.55	.55	.55	.76	---	.97
27	.64	.77	.43	.90	.90	.96	.45	.96	.55	.92	.48	.83	.80	.89	.48	.94	.75	.52	.90	.46	.95	.56	.56	.56	.74	.97	---

Table 9. Peak correlation matrix for 3 hour filtered data on May 2, 1979 from 3:00 - 10:00 p.m.

		Delays (minutes)		Errors (mph)		
Group	Sites	Group/Site Delays	Group/Group Delays	Group to Group	Group to Site	1-5 as Reference
	6	1			1.92	.88
1	8	1			.92	.20
	26	1	1	1.72	1.85	.61
	16	1			2.13	.58
2	10	2			2.57	.84
	27	1			1.85	.22
	7	190			.51	.29
3	9	228	20	.34	.44	.16
	11	208			.65	.17
4	12	1	1	180	1.69	.38
	14	1			.84	.32
5	13	74	78	1.40	1.06	.43
	17	81			1.81	.74
	22	274	271		.80	.18
6	23	270		.59	.45	.15
	24	269			.66	.21
	15	270			.14	.10
	18	238			.89	.34
	19	1			1.37	.46
	20	291			.12	.03
	21	1			.80	.31
	25	1			.70	.58

Table 10. Delays and errors for individual site/group/site and group/group models using 3 hour filtered data from 3:00 - 10:00 p.m. on May 2, 1979 with sites 1-5 as reference.

SITES

SITES	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	---	.54	.72	.51	.60	.44	.34	.48	.52	.36	.41	.35	.46	.59	.41	.31	.50	.34	.31	.36	.42	.32	.21	.29	.46	.38	.48
2	.47	---	.50	.63	.66	.48	.30	.54	.24	.51	.30	.39	.34	.45	.45	.57	.40	.32	.48	.26	.71	.28	.28	.28	.47	.44	.40
3	.59	.50	---	.39	.56	.43	.39	.56	.59	.41	.48	.30	.48	.61	.47	.37	.57	.43	.25	.66	.45	.38	.35	.26	.36	.34	.50
4	.42	.62	.36	---	.75	.59	.38	.72	.24	.66	.41	.75	.41	.51	.33	.56	.39	.34	.75	.21	.57	.19	.27	.23	.58	.70	.53
5	.44	.58	.49	.77	---	.60	.40	.75	.42	.63	.44	.56	.52	.66	.33	.57	.44	.33	.61	.38	.57	.31	.24	.27	.50	.65	.69
6	.44	.48	.36	.77	.65	---	.42	.68	.22	.59	.37	.78	.39	.44	.25	.74	.36	.25	.79	.35	.57	.18	.29	.24	.50	.81	.63
7	.25	.20	.35	.27	.19	.33	---	.31	.51	.41	.49	.28	.24	.21	.48	.41	.50	.59	.33	.34	.23	.63	.63	.63	.24	.31	.31
8	.35	.56	.51	.73	.73	.66	.44	---	.35	.70	.52	.61	.50	.69	.44	.71	.47	.25	.66	.41	.63	.22	.29	.28	.43	.68	.70
9	.20	.36	.22	.22	.43	.15	.20	.31	---	.27	.61	.16	.60	.70	.54	.19	.66	.62	.14	.48	.49	.60	.59	.53	.28	.30	.33
10	.44	.40	.30	.50	.46	.63	.31	.62	.20	---	.32	.58	.45	.33	.32	.61	.44	.26	.73	.27	.58	.42	.20	.30	.47	.42	.62
11	.18	.29	.16	.22	.25	.19	.45	.18	.54	.14	---	.19	.58	.53	.39	.22	.65	.58	.21	.28	.36	.56	.42	.49	.24	.27	.22
12	.45	.28	.21	.71	.49	.46	.31	.42	.20	.49	.30	---	.33	.30	.21	.52	.30	.25	.69	.26	.46	.20	.25	.22	.45	.58	.47
13	.19	.32	.18	.26	.22	.14	.33	.17	.50	.22	.58	.22	---	.49	.29	.22	.61	.58	.16	.37	.41	.49	.29	.38	.36	.22	.23
14	.25	.54	.36	.54	.58	.37	.37	.68	.61	.50	.56	.37	.55	---	.55	.53	.53	.39	.45	.46	.59	.36	.33	.42	.42	.48	.62
15	.34	.45	.28	.34	.31	.31	.23	.40	.19	.64	.34	.31	.28	.47	---	.43	.46	.47	.40	.58	.61	.67	.42	.43	.24	.39	.47
16	.45	.31	.31	.56	.48	.57	.34	.58	.20	.68	.40	.66	.48	.41	.43	---	.42	.21	.72	.43	.57	.17	.25	.20	.44	.72	.72
17	.13	.43	.09	.33	.32	.06	.20	.17	.53	.29	.65	.25	.62	.51	.53	.11	---	.65	.14	.49	.59	.72	.47	.63	.35	.25	.25
18	.27	.34	.24	.19	.26	.15	.26	.16	.29	.25	.56	.17	.50	.33	.43	.18	.38	---	.15	.58	.47	.74	.62	.82	.37	.17	.18
19	.45	.26	.22	.58	.38	.66	.31	.36	.20	.47	.20	.70	.44	.24	.14	.53	.32	.25	---	.16	.35	.24	.27	.26	.45	.46	.44
20	.25	.34	.25	.22	.19	.12	.23	.10	.17	.47	.40	.27	.41	.29	.55	.37	.36	.57	.23	---	.51	.47	.44	.42	.28	.15	.37
21	.39	.43	.27	.53	.52	.45	.36	.48	.29	.64	.42	.43	.36	.41	.29	.43	.37	.44	.50	.34	---	.58	.45	.50	.56	.34	.53
22	.31	.32	.21	.24	.23	.16	.22	.15	.18	.42	.36	.13	.27	.24	.25	.23	.15	.63	.15	.21	.55	---	.64	.73	.26	.26	.22
23	.40	.26	.26	.21	.25	.24	.14	.17	.23	.31	.23	.18	.14	.26	.40	.27	.29	.61	.18	.39	.23	.57	---	.58	.35	.17	.29
24	.26	.29	.24	.20	.23	.10	.08	.14	.11	.25	.31	.15	.20	.29	.34	.23	.17	.23	.11	.25	.14	.44	.41	---	.27	.26	.18
25	.46	.57	.36	.61	.53	.37	.22	.37	.20	.37	.24	.41	.33	.43	.35	.27	.32	.24	.48	.18	.36	.20	.21	.38	---	.23	.29
26	.38	.44	.27	.70	.65	.59	.35	.70	.17	.67	.29	.71	.42	.49	.42	.72	.36	.22	.79	.42	.65	.22	.28	.28	.67	---	.70
27	.32	.30	.32	.55	.48	.46	.37	.62	.32	.51	.38	.55	.45	.62	.47	.61	.37	.27	.56	.59	.50	.20	.25	.34	.42	.48	---

Table 11. Peak correlation matrix for 1 hour filtered data from 3:00 - 10:00 p.m. on May 2, 1979.

given in Table 11, has significantly lower values. The groups, which are formed based on large correlation between sites in a group, small delays between sites in a group, and geographical proximity; are not at all similar to those produced using the 2 hour or 3 hour moving average data. The group/site and group/group delay, given in Table 12 for the hour moving average data, are not at all similar to those obtained for this data with longer smoothing intervals. The errors using the hour filtered data given in Table 12 are very large compared to that found using the 2 hour or 3 hour smoothed data. Thus, the hour smoothing interval is too short because it does not sufficiently filter site specific site phenomena, that is not associated with the slow propagation of the wind speed increase which occurs with the transition from a south to north moving front to a north to south moving front.

Prediction was also attempted at an early stage in this research using 10 minute moving average data. The peak correlation and delays from all prediction sites from reference sites 1-4 is given in Table 13. The correlations are even lower than those for the hour moving average data in Table 11 and certainly do not suggest that sites 1-4 are a good set of references since the correlations between these sites are generally below 0.6. The delays between these four reference sites to each prediction site is quite inconsistent with each other and certainly different from those used for each prediction site in the two-three hour moving average filtered data. The delays from sites 1 and 3 and the first peak of the wind record is shown in Figure 13. The agreement between the delays suggested prediction is possible. However, the errors, shown in Table 14, indicate that prediction is quite poor using either site 1 only or both sites 1 and 3. The time records that compare the predicted wind speed and actual wind speed, shown in Figure 10, truly indicate there is no prediction. The actual and predicted wind speed do not have similar slopes, do not have minimums and maximums that occur simultaneously, do not have maximum, minimum and average values that have similar values. The conclusion is that prediction did not occur in any reasonable way for this 10 minute moving filtered data using one or two reference sites, and delays selected based on the peak correlations for the 10 minute moving average filtered data.

4.2 A FAST NORTH PROPAGATING FRONT

The prediction methodology was applied to the same 10 minute moving average filtered data over the interval 1:00 - 6:00 p.m. where wind speed direction is from north to south. The data from 3:00 - 10:00 p.m. on May 2, 1979 has a wind shift starting at 6:00 p.m. and thus the 10 minute moving average data over this interval has propagation from south to north over 1:00 - 6:00 p.m. and propagation from northwest to southeast over 6:00 -

	Delays (minutes)		Errors (mph)		
Sites	Group/Site Delay	Group/Group Delay	Group to Group	Group to Site	1-5 as Reference
6	5	22	3.09	4.66	4.16
8	1			2.46	2.05
10	39			5.36	4.28
16	33			4.41	3.40
26	7			5.19	4.51
27	33			6.12	3.25
7	191	158	4.12	5.30	2.49
9	84			3.99	3.21
11	199			4.55	3.55
12	44	28	3.08	4.93	3.58
14	12			4.03	3.22
13	151	117	5.17	4.61	2.60
17	83			7.20	4.91
22	79	88	3.82	5.61	4.44
23	156			2.83	1.83
24	130			5.23	5.07
15	21			3.62	3.11
18	100			5.10	4.78
19	55			3.99	2.62
20	43			2.82	2.13
21	28			3.74	2.77
25	21			4.46	4.02

Table 12. Delays and errors for 1 hour filtered data of May 2, 1979 from 3:00 - 10:00 p.m. with sites 1-5 as reference.

	Delays from Reference Site (minutes)				Correlation with Reference Site			
Site	1	2	3	4	1	2	3	4
1	--	1	1	1	--	.68	.81	.57
2	19	--	1	1	.71	--	.73	.77
3	13	1	--	1	.86	.73	--	.56
4	35	6	8	--	.61	.77	.56	--
5	31	1	8	1	.70	.87	.76	.91
6	6	1	2	1	.48	.63	.48	.79
7	217	197	208	187	.41*	.43	.38	.50
8	34	2	13	1	.55	.73	.64	.83
9	46	219	26	199	.49	.34	.64	.32
10	83	42	71	12	.23	.52	.31	.61
11	227	217	205	191	.49	.47	.58	.49
12	1	30	1	11	.50	.49	.36	.89
13	61	209	41	172	.56	.45	.52	.47
14	50	1	30	1	.54	.59	.60	.62
15	68	18	56	1	.31	.36	.43	.33
16	60	50	45	1	.22*	.51	.36	.63
17	50	208	36	173	.58	.50	.54	.50
18	248	240	53	212	.38*	.41*	.41	.41
19	1	41	78	16	.45	.55	.30	.85
20	379	372	61	354	.27	.30	.42	.35
21	59	14	45	1	.58	.80	.64	.82
22	248	260	216	230	.30	.26	.36	.26
23	311	289	73	282	.24*	.33*	.27*	.40
24	262	278	71	292	.27*	.27*	.29*	.31
25	1	1	1	1	.64	.84	.55	.82
26	34	1	22	1	.41*	.51	.42	.81
27	64	33	47	3	.46	.59	.54	.79

Table 13. Table of peak correlation and its associated delay for site 1, 2, 3, 4 for hour moving average data on May 2, 1979 (3:00 - 11:00 p.m.).

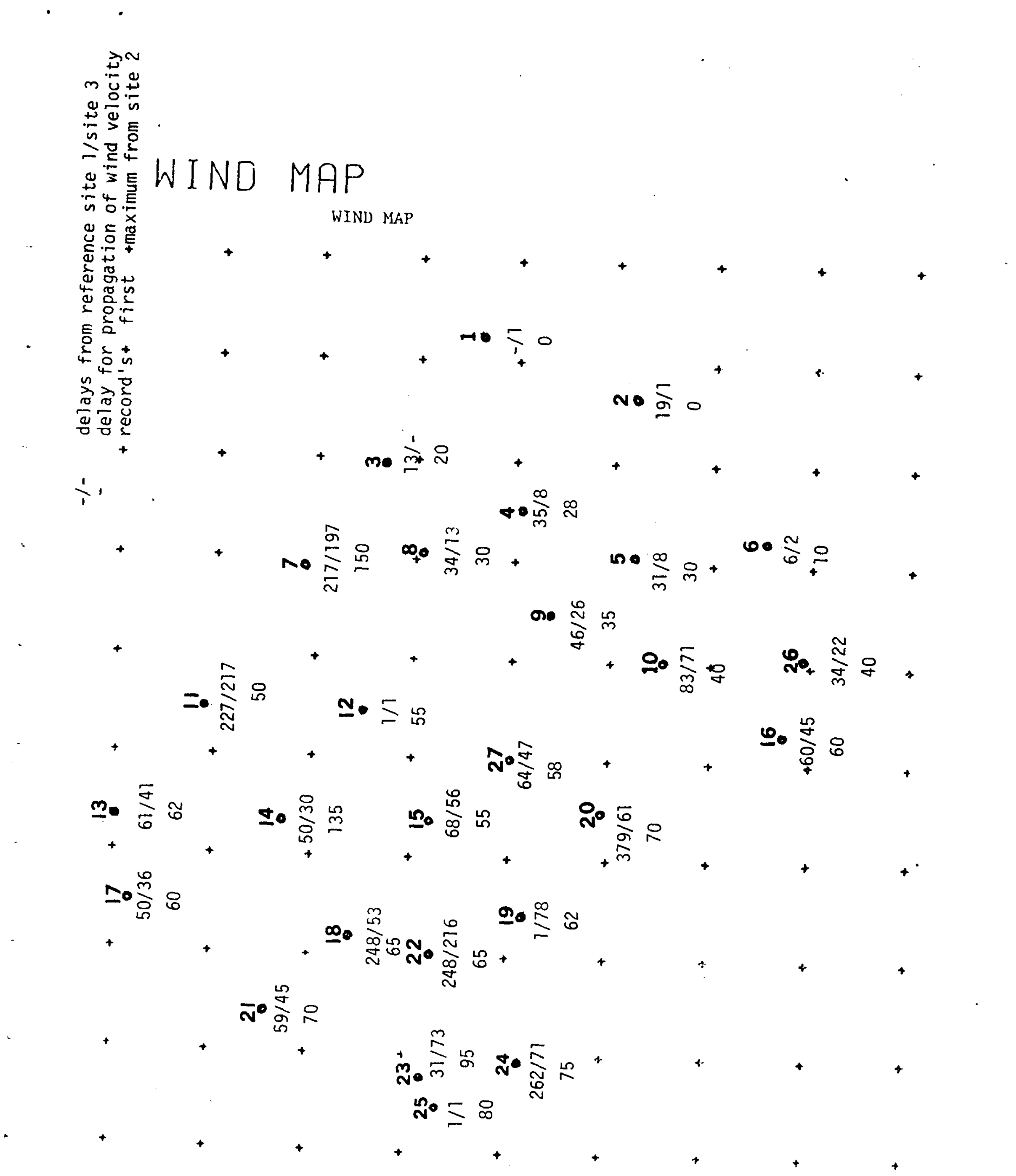


Figure 13. Map of delays from reference 1 and 3 and delay for first maximum in the wind velocity record to propagate from reference site 1 for hour moving average delay of May 2, 1979 (3:00 - 11:00 p.m.).

Sites	errors site 1 (mph)	errors site 1,3 (mph)
1	-----	-----
2	7.529	7.782
3	4.446	-----
4	10.165	10.004
5	6.673	6.910
6	7.562	7.586
7	6.070	6.233
8	5.064	5.140
9	5.452	5.584
10	6.350	6.545
11	5.031	4.965*
12	7.274	7.304
13	5.201	5.189
14	7.469	7.506
15	4.458	4.465
16	6.140	6.255
17	8.574	8.535*
18	5.950	6.016
19	6.937	6.815*
20	3.470	3.502*
21	6.711	6.700*
22	6.018	6.017*
23	3.379	3.404*
24	6.412	6.384*
25	6.102	6.045*
26	8.496	8.537*
27	6.477	6.507*

Table 14. Rms error using reference sites 1 and 1,3 with delays for May 2, 1979 on 10 minute moving average data.

10:00 p.m. The propagation over these two intervals is much faster and reflects the propagation of two separate fronts in different directions. These fronts will be shown to propagate across the 80 mile long SESAME array in approximately an hour. The propagation observed in the two hour moving average data over the interval 3:00 - 10:00 p.m. captures the slow 5 hour propagation of the triangular pulse wind speed increase associated with the wind shift. It is known that pressure gradients associated with fronts, which cause the wind speed changes associated with fronts, can propagate at speeds that are much greater than the wind speed. This will be seen in the prediction of wind speed profile from south to north over the 1:00 - 6:00 p.m. time interval and the propagation of the wind speed profile from northwest to southeast over the 8:00 to 10:00 p.m. interval. The slow propagation of the wind speed profile in the 3:00 - 10:00 p.m. record discussed previously was caused by collisions of two fast moving fronts and the slow transition from the predominance of one front to the other.

The prediction of wind speed over the 1:00 - 6:00 p.m. interval is considered first. The correlation table was produced for 10 minute, 30 minute, and 2 hour smoothing intervals in Table 15a, b, and c, respectively. The values of correlation decreased as the smoothing interval was decreased from 2 hours to 10 minutes. The correlation values in the first five rows were consistently larger than for the correlations in the first five columns which indicates the event propagation is opposite the direction assumed by the ordering of sites from 1 to 27 in these tables. The direction of event propagation is thus from south to north, which is the wind speed direction during this interval. The difference between the first five row and column correlations increased as the smoothing interval decreased, indicating that the direction of propagation of the front and the delays associated with this propagation should be more clearly observed in the 10 minute moving average filtered data.

The groups of wind measurement sites, which must have pairwise peak correlations above .60, must have close geographical proximity, and must have delays that are nearly equal are shown in Figure 14. Two reference groups (23,25) and (19,22) are used for prediction. The delays from these four reference sites (T_{ij}) as well as the group/site delay for sites 23 and 25 (T_i') and the group/site delay for reference 19 and 22 (T_i") are given in Table 16. The delay from sites 23 and 25 increase with geographical distance in groups 2-4. The sites in groups 5 and 6 are affected by the slow propagation associated with the wind shift from north to south and thus the delays in groups 5 and 6 decrease with geographical distance. The delays for sites 19 and 22 do not increase with geographical distance, and are generally small except at the eastern and western edges of the SESAME array.

SITES	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	---	.84	.83	.80	.80	.89	.57	.79	.78	.77	.73	.81	.71	.80	.79	.74	.78	.80	.71	.69	.78	.73	.71	.55	.73	.78	.75
2	.82	---	.84	.83	.82	.87	.65	.86	.86	.83	.77	.82	.74	.83	.86	.76	.79	.77	.74	.75	.76	.78	.77	.57	.76	.79	.80
3	.82	.83	---	.90	.92	.89	.71	.91	.86	.88	.84	.89	.77	.86	.84	.83	.85	.81	.75	.77	.73	.72	.62	.66	.64	.91	.85
4	.69	.79	.90	---	.91	.79	.71	.92	.90	.93	.83	.90	.83	.88	.83	.88	.86	.80	.73	.81	.73	.73	.54	.77	.54	.92	.87
5	.75	.75	.92	.92	---	.83	.67	.89	.88	.89	.78	.90	.81	.87	.79	.85	.87	.82	.69	.80	.73	.75	.62	.70	.60	.93	.88
6	.89	.88	.89	.88	.91	---	.62	.84	.85	.86	.79	.89	.78	.88	.81	.84	.85	.83	.74	.81	.80	.74	.76	.64	.75	.88	.86
7	.48	.63	.62	.64	.53	.58	---	.72	.67	.75	.70	.72	.67	.62	.81	.70	.69	.67	.73	.72	.61	.58	.53	.63	.60	.63	.81
8	.71	.84	.90	.92	.89	.82	.75	---	.86	.90	.87	.87	.77	.83	.88	.84	.86	.83	.76	.83	.72	.74	.55	.69	.66	.92	.87
9	.51	.62	.75	.84	.83	.65	.63	.83	---	.90	.81	.88	.73	.85	.79	.83	.79	.79	.67	.84	.71	.75	.49	.68	.45	.84	.81
10	.45	.66	.74	.85	.79	.64	.75	.87	.89	---	.84	.91	.80	.88	.86	.89	.85	.84	.71	.82	.67	.74	.41	.76	.50	.80	.89
11	.64	.73	.77	.78	.76	.70	.71	.83	.81	.84	---	.82	.72	.75	.85	.84	.-1	.77	.85	.78	.70	.77	.52	.66	.58	.75	.79
12	.41	.64	.63	.79	.71	.60	.72	.78	.83	.90	.80	---	.80	.87	.85	.82	.89	.83	.76	.86	.73	.78	.44	.69	.73	.73	.91
13	.25	.54	.56	.68	.58	.46	.64	.67	.73	.76	.72	.80	---	.81	.69	.82	.85	.75	.66	.74	.64	.69	.42	.77	.32	.57	.78
14	.45	.63	.71	.84	.78	.59	.64	.78	.85	.88	.75	.87	.81	---	.80	.80	.89	.85	.71	.77	.71	.76	.44	.71	.37	.78	.83
15	.66	.83	.78	.81	.74	.78	.81	.87	.80	.86	.85	.86	.72	.80	---	.82	.82	.87	.84	.81	.74	.76	.65	.65	.65	.79	.91
16	.47	.70	.72	.82	.72	.60	.70	.84	.83	.89	.84	.85	.84	.79	.78	---	.81	.79	.73	.78	.67	.76	.44	.76	.46	.74	.83
17	.43	.67	.66	.82	.72	.63	.69	.75	.80	.85	.75	.89	.85	.89	.82	.80	---	.84	.75	.83	.78	.78	.51	.73	.44	.71	.88
18	.59	.72	.73	.80	.76	.69	.67	.83	.79	.84	.79	.83	.78	.85	.87	.81	.84	---	.80	.76	.77	.77	.57	.69	.56	.77	.85
19	.65	.70	.71	.72	.68	.68	.73	.76	.67	.72	.85	.76	.70	.72	.84	.79	.75	.77	---	.71	.72	.81	.63	.59	.58	.68	.74
20	.34	.58	.51	.65	.49	.51	.72	.64	.65	.78	.69	.86	.78	.74	.80	.75	.83	.76	.72	---	.63	.75	.44	.66	.33	.59	.86
21	.48	.66	.59	.73	.65	.60	.45	.66	.69	.71	.60	.76	.74	.72	.68	.70	.79	.76	.61	.65	---	.70	.58	.52	.39	.62	.73
22	.52	.62	.68	.73	.70	.62	.63	.73	.75	.74	.77	.78	.77	.76	.75	.78	.78	.77	.82	.74	.67	---	.45	.58	.33	.73	.74
23	.70	.69	.68	.73	.74	.76	.40	.63	.74	.70	.56	.70	.69	.72	.59	.71	.69	.62	.52	.67	.71	.64	---	.64	.71	.64	.62
24	.14	.49	.43	.53	.46	.36	.60	.60	.63	.75	.59	.71	.77	.64	.64	.71	.73	.68	.46	.69	.54	.51	.30	---	.39	.47	.74
25	.74	.77	.70	.72	.73	.78	.54	.72	.73	.72	.69	.78	.71	.75	.68	.71	.74	.64	.63	.70	.76	.75	.74	.48	---	.67	.71
26	.73	.76	.91	.92	.93	.82	.74	.92	.86	.88	.85	.87	.79	.86	.84	.85	.81	.81	.75	.83	.65	.76	.52	.69	.55	---	.85
27	.43	.72	.65	.79	.66	.62	.81	.82	.81	.89	.78	.91	.78	.82	.91	.83	.88	.85	.74	.86	.73	.74	.49	.74	.52	.73	---

Table 15a. Peak correlation matrix for ten minute moving average filtered data of May 2, 1979 from 1:00 - 6:00 p.m.

	SITES																										
SITES	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	---	.88	.88	.81	.84	.94	.64	.84	.80	.78	.75	.81	.80	.82	.79	.77	.82	.83	.71	.73	.84	.80	.73	.65	.80	.82	.76
2	.88	---	.89	.87	.86	.93	.74	.90	.90	.85	.85	.86	.84	.86	.89	.81	.83	.84	.78	.81	.86	.87	.84	.66	.87	.83	.83
3	.87	.89	---	.93	.96	.94	.78	.95	.90	.89	.88	.90	.78	.89	.86	.85	.86	.87	.77	.82	.81	.81	.67	.72	.71	.95	.88
4	.70	.84	.92	---	.96	.83	.78	.96	.95	.96	.89	.95	.86	.94	.88	.91	.92	.88	.76	.87	.81	.83	.66	.82	.63	.94	.91
5	.79	.84	.96	.96	---	.90	.74	.95	.94	.93	.86	.92	.84	.93	.84	.88	.89	.87	.75	.87	.80	.84	.67	.77	.66	.96	.89
6	.94	.93	.94	.89	.92	---	.68	.89	.87	.86	.83	.88	.85	.89	.83	.84	.87	.87	.75	.84	.85	.85	.79	.70	.81	.89	.85
7	.57	.73	.73	.75	.70	.67	---	.84	.78	.83	.88	.83	.71	.76	.88	.81	.77	.83	.83	.82	.72	.70	.65	.72	.65	.78	.86
8	.79	.90	.95	.96	.95	.89	.85	---	.93	.93	.93	.94	.81	.90	.92	.90	.90	.91	.82	.87	.85	.86	.65	.76	.72	.96	.92
9	.52	.71	.78	.91	.87	.69	.78	.88	---	.97	.89	.95	.83	.92	.88	.91	.89	.87	.77	.89	.81	.88	.56	.79	.53	.87	.91
10	.50	.72	.78	.92	.85	.68	.83	.90	.97	---	.91	.96	.88	.94	.90	.95	.93	.89	.80	.91	.80	.85	.53	.87	.54	.86	.93
11	.68	.84	.85	.89	.84	.80	.88	.92	.89	.91	---	.93	.83	.85	.95	.94	.89	.89	.90	.87	.83	.88	.67	.77	.69	.86	.91
12	.40	.67	.64	.84	.73	.58	.78	.78	.92	.92	.87	---	.91	.94	.90	.94	.97	.93	.88	.91	.85	.90	.61	.85	.49	.73	.96
13	.21	.53	.52	.73	.59	.42	.67	.63	.78	.81	.76	.91	---	.89	.77	.89	.95	.86	.82	.89	.78	.83	.54	.89	.35	.55	.87
14	.44	.66	.71	.89	.81	.60	.76	.82	.92	.94	.8	.95	.91	---	.86	.91	.95	.91	.80	.86	.80	.85	.55	.83	.44	.80	.91
15	.68	.87	.80	.87	.81	.79	.88	.90	.88	.90	.95	.92	.80	.86	---	.93	.90	.94	.92	.86	.87	.85	.76	.76	.76	.83	.95
16	.48	.74	.72	.86	.76	.64	.81	.84	.91	.94	.93	.95	.92	.91	.92	---	.94	.92	.88	.91	.83	.91	.60	.88	.54	.77	.94
17	.40	.69	.67	.86	.75	.60	.74	.78	.89	.90	.85	.97	.95	.95	.89	.94	---	.94	.86	.89	.88	.88	.66	.87	.51	.72	.95
18	.52	.74	.68	.83	.74	.65	.76	.80	.87	.88	.87	.93	.86	.91	.94	.92	.94	---	.91	.89	.87	.89	.73	.81	.63	.73	.95
19	.57	.75	.66	.75	.66	.66	.79	.75	.76	.77	.88	.88	.82	.79	.91	.87	.86	.91	---	.90	.78	.89	.73	.71	.64	.67	.88
20	.26	.54	.44	.63	.49	.41	.69	.58	.74	.76	.77	.91	.89	.80	.83	.87	.89	.89	.90	---	.77	.87	.58	.83	.42	.52	.90
21	.46	.71	.62	.79	.70	.62	.51	.70	.80	.77	.73	.85	.80	.80	.79	.82	.83	.86	.75	.77	---	.83	.75	.69	.49	.64	.84
22	.51	.69	.70	.81	.74	.64	.70	.77	.85	.84	.87	.90	.87	.85	.85	.91	.88	.89	.90	.88	.83	---	.61	.70	.43	.75	.86
23	.72	.81	.76	.82	.83	.80	.49	.75	.79	.79	.66	.78	.80	.82	.74	.75	.79	.73	.73	.72	.78	.75	---	.68	.82	.74	.70
24	.14	.50	.41	.64	.50	.33	.65	.58	.76	.80	.72	.85	.89	.78	.75	.85	.87	.81	.71	.83	.69	.70	.45	---	.43	.48	.86
25	.81	.87	.76	.79	.80	.85	.63	.79	.80	.76	.75	.80	.79	.83	.77	.77	.81	.72	.68	.76	.84	.86	.84	.57	---	.76	.72
26	.78	.82	.95	.94	.96	.87	.81	.96	.91	.91	.89	.91	.80	.89	.87	.88	.85	.87	.81	.87	.76	.83	.57	.73	.63	---	.89
27	.44	.73	.66	.83	.72	.61	.84	.81	.90	.92	.88	.96	.87	.90	.94	.94	.95	.95	.88	.92	.84	.86	.64	.86	.59	.73	---

Table 15b. Peak correlation matrix for 30 minute averaging filtered data of May 2, 1979 from 1:00 - 6:00 p.m.

	SITES																										
SITES	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	---	.86	.94	.78	.80	.79	.43	.83	.81	.75	.85	.71	.74	.80	.81	.74	.77	.79	.77	.67	.82	.78	.86	.75	.-7	.69	.79
2	.86	---	.91	.90	.97	.97	.42	.98	.78	.85	.85	.72	.72	.90	.85	.89	.74	.81	.80	.72	.89	.83	.85	.76	.97	.95	.84
3	.94	.91	---	.87	.89	.82	.45	.92	.89	.84	.95	.80	.80	.84	.92	.83	.84	.88	.89	.79	.85	.87	.92	.77	.81	.77	.88
4	.71	.89	.87	---	.95	.80	.47	.95	.90	.97	.88	.84	.80	.95	.95	.97	.84	.93	.92	.83	.96	.95	.93	.90	.83	.85	.97
5	.77	.97	.89	.95	---	.93	.46	.99	.81	.91	.84	.74	.72	.96	.87	.95	.75	.83	.81	.74	.93	.86	.86	.83	.94	.96	.88
6	.79	.97	.82	.83	.93	---	.42	.93	.68	.79	.72	.64	.64	.87	.74	.84	.64	.72	.68	.63	.85	.74	.74	.73	.98	.97	.96
7	.38	.23	.35	.18	.24	.31	---	.21	.44	.17	.43	.55	.64	.24	.35	.22	.45	.39	.44	.54	.20	.30	.38	.17	.32	.34	.28
8	.82	.98	.92	.95	.99	.93	.46	---	.83	.90	.88	.77	.75	.94	.90	.94	.77	.85	.84	.76	.91	.87	.88	.81	.94	.94	.89
9	.72	.75	.88	.90	.80	.60	.50	.82	---	.88	.95	.92	.89	.84	.95	.83	.96	.96	.96	.92	.85	.93	.96	.86	.62	.62	.96
10	.63	.83	.82	.97	.90	.72	.47	.90	.88	---	.84	.86	.81	.92	.94	.96	.83	.94	.92	.85	.96	.97	.90	.94	.76	.79	.97
11	.87	.85	.95	.88	.84	.71	.46	.88	.95	.86	---	.87	.83	.83	.95	.84	.88	.92	.94	.85	.85	.91	.95	.81	.72	.67	.92
12	.54	.56	.73	.81	.63	.37	.60	.66	.92	.86	.82	---	.96	.69	.90	.74	.94	.96	.94	.99	.77	.91	.89	.86	.41	.41	.92
13	.39	.35	.58	.66	.44	.32	.65	.46	.85	.70	.72	.96	---	.54	.76	.57	.92	.86	.83	.96	.62	.78	.78	.76	.31	.33	.81
14	.64	.90	.82	.96	.96	.85	.53	.94	.84	.92	.82	.76	.73	---	.86	.97	.79	.85	.81	.76	.97	.87	.85	.90	.85	.90	.90
15	.80	.85	.92	.96	.88	.72	.47	.91	.95	.95	.95	.91	.86	.87	---	.90	.90	.97	.98	.90	.88	.97	.98	.84	.75	.73	.98
16	.63	.89	.81	.98	.96	.83	.51	.95	.84	.97	.82	.78	.74	.97	.90	---	.78	.88	.86	.78	.98	.92	.86	.91	.85	.89	.93
17	.58	.62	.76	.84	.70	.45	.53	.71	.96	.83	.88	.94	.92	.76	.90	.77	---	.94	.91	.94	.79	.88	.91	.85	.48	.49	.93
18	.68	.76	.85	.93	.81	.60	.49	.83	.96	.95	.92	.96	.90	.85	.97	.88	.94	---	.98	.95	.89	.98	.96	.89	.62	.63	.98
19	.76	.79	.89	.92	.81	.63	.50	.84	.96	.92	.94	.94	.88	.81	.98	.86	.91	.98	---	.93	.86	.97	.97	.85	.66	.63	.97
20	.51	.53	.69	.80	.60	.36	.63	.63	.90	.84	.81	.99	.96	.66	.88	.72	.94	.94	.93	---	.75	.90	.87	.85	.38	.38	.91
21	.60	.85	.79	.96	.92	.78	.53	.91	.84	.96	.80	.79	.77	.97	.88	.98	.80	.89	.86	.78	---	.93	.87	.92	.79	.84	.93
22	.70	.81	.87	.95	.86	.68	.49	.87	.93	.97	.90	.92	.87	.87	.97	.92	.88	.98	.97	.90	.92	---	.95	.90	.69	.70	.97
23	.81	.83	.92	.93	.86	.70	.46	.88	.96	.90	.95	.91	.86	.85	.98	.86	.91	.96	.97	.89	.87	.95	---	.81	.72	.69	.96
24	.39	.66	.64	.90	.77	.55	.60	.76	.84	.94	.73	.86	.81	.86	.84	.91	.83	.89	.85	.85	.92	.90	.80	---	.60	.65	.93
25	.77	.97	.81	.83	.94	.98	.37	.94	.67	.79	.72	.64	.65	.85	.77	.85	.62	.72	.69	.63	.82	.74	.75	.68	---	.97	.75
26	.68	.95	.77	.86	.96	.97	.42	.94	.64	.81	.69	.61	.60	.90	.74	.89	.59	.69	.66	.60	.85	.73	.70	.72	.97	---	.75
27	.68	.81	.86	.96	.87	.67	.53	.88	.96	.97	.91	.93	.87	.90	.98	.93	.93	.98	.97	.92	.93	.97	.96	.93	.71	.72	---

Table 15c. Peak correlation matrix for 2 hour moving average filtered data of May 2, 1979 from 1:00 - 6:00 p.m.

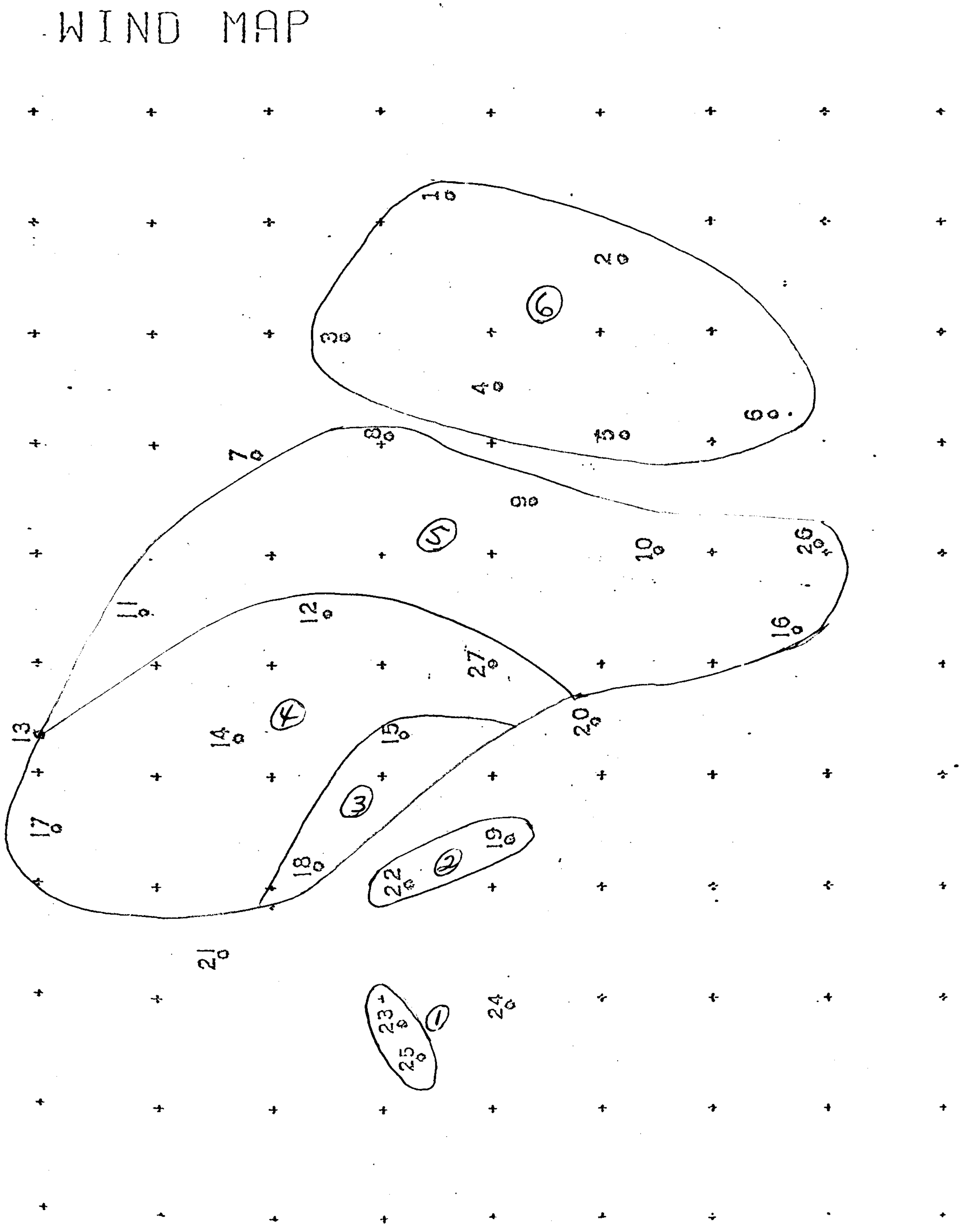


Figure 14. Groups of wind measurement sites for 10 minute filtered data of May 2, 1979 from 1:00 - 6:00 p.m.

	Individual Site Delays (minutes)		Group/Site Delay (minutes)
Site No.	T_{i23}	T_{i25}	Average for Sites 23 and 25 T'_i
1	10	6	8
2	1	11	6
3	10	28	19
4	25	29	27
5	10	31	20
6	1	10	6
7	38	47	43
8	25	30	28
9	33	35	34
10	38	44	41
11	24	33	29
12	52	46	49
13	43	54	49
14	43	65	54
15	23	17	20
16	34	36	34
17	45	53	49
18	25	19	22
19	28	38	33
20	55	47	51
21	23	33	28
22	36	51	43
24	49	53	51
26	18	35	27
27	50	48	49

Table 16a. Table of delays from reference sites 23 and 25 for the 10 minute moving average filtered data of May 5, 1979 from 1:00 - 6:00 p.m.

	Individual Site Delays (minutes)		Group 2/Site Delay (minutes)
Site No.	T_{i19}	T_{i22}	Average for Sites 19 and 22 T_i''
1	1	1	1
2	1	1	1
3	1	1	1
4	1	1	1
5	4	1	3
6	1	1	1
7	1	23	12
8	10	3	7
9	1	1	1
10	13	1	7
11	1	2	1
12	1	1	1
13	17	19	18
14	26	1	14
15	1	1	1
16	12	6	10
17	1	1	1
18	1	1	1
20	1	1	1
21	38	1	20
23	24	1	13
24	16	24	20
25	19	3	12
26	1	1	1
27	1	1	1

Table 16b. Table of delay from reference sites 19 and 22 for the 10 minute moving average filtered data of May 2, 1979 from 1:00 - 6:00 p.m.

	Error Ten Minute Moving Average (mph)		Error 2 Hour Moving Average (mph)	
Site No.	Individual Site Model With Reference Group (19,22,23,25)	Group/Site Model With Reference Groups (19,22) and (23,25)	Individual Site Model With Reference Group (19,22,23,25)	Group/Site Model With Reference Groups (19,22) and (23,25)
1	2.12	2.16	1.17	1.30
2	2.27	2.37	0.94	0.89
3	1.58	2.11	0.21	0.36
4	2.42	2.70	0.70	0.89
5	1.91	2.46	.74	1.36
6	1.80	2.29	0.83	1.20
7	1.63	2.04	1.33	2.10
8	1.57	1.76	0.73	0.63
9	2.13	3.07	0.69	0.96
10	2.06	3.45	0.84	1.41
11	0.99	1.67	0.46	0.48
12	1.12	2.91	0.35	1.54
13	1.86	2.67	0.41	1.96
14	1.17	2.35	0.94	0.89
15	1.52	1.77	0.94	0.89
16	1.25	2.29	0.21	0.36
17	1.36	2.01	0.74	1.36
18	1.55	1.86	0.24	0.91
20	1.08	1.93	0.30	0.89
21	1.44	2.37	0.43	0.95
24	1.08	1.61	0.55	0.58
26	2.11	2.25	1.60	2.48
27	1.93	2.70	0.57	0.97

Table 17. Table of prediction error for 10 minute and 2 hour filtered data of 5-2-79 from 1:00 - 6:00 p.m. using the individual site and group/site models.

The errors are given in Table 17 for the individual site model using references (19,22,23,25) and the group/site model using both an averaged wind speed record with a group/site delay for group (19,22) and an averaged wind speed record with group/site delay for group (23,25). The individual site delays and the group/site delays for both the (19,22) group and the (23,25) group are given in Table 16. The error for the group/site model using two groups is very similar to those for the individual site model except at site 6, 7, 10, 12, 13, 17, 18, 20, 26 that are at the eastern and western edges of the SESAME array where sites 19 and 22 provide less information. These results suggest that averaging measurements and delays from groups can almost perform as well as the individual site model and in some cases perform better. The group/site model using only 1 group always performed much poorer than the individual site model. Using several averaged groups of measurement sites records with their average delays may actually perform nearly as well or sometimes better than using the individual site model with the same groups of measurement sites. The errors are given for both 2 hour and 10 minute moving average data for these two model types in Table 17. The errors for the 10 minute moving average data is larger because the 2 hour moving average filter eliminates variation in the records as well as because it eliminates turbulence and site specific effects.

The predicted wind speed for all prediction sites and the actual wind speed record are plotted in Figure 15. The predicted and actual wind speeds are both smoothed using the 2 hour moving average filter. The prediction is very accurate which can be observed by noting the similar slope during periods of increasing and decreasing wind speed, the time of occurrence of maximums and minimums, and finally the agreement between maximums, minimums, and average values. The different values of delay for different site wind predictions is evidenced by when the prediction begins and indicates the sensitivity of the prediction methodology in obtaining proper delays to produce the accurate predictions indicated in these plots.

The predictions and the actual wind speed record for the 10 minute moving average records is shown in Figure 16. The errors are larger than for the 2 hour moving average records, but the time records for the predictions appear to even better capture the rates of change, time of occurrence of maximums and minimums, and average values because the rates of change are larger and the peak is narrower for the 10 minute moving average data. The prediction is accurate at every site and thus the results are quite encouraging.

Comparison of the 2 hour and 10 minute actual and predicted wind speed records in Figures 15 and 16 indicates the 2 hour filtering has significantly reduced maximum wind speeds, in-

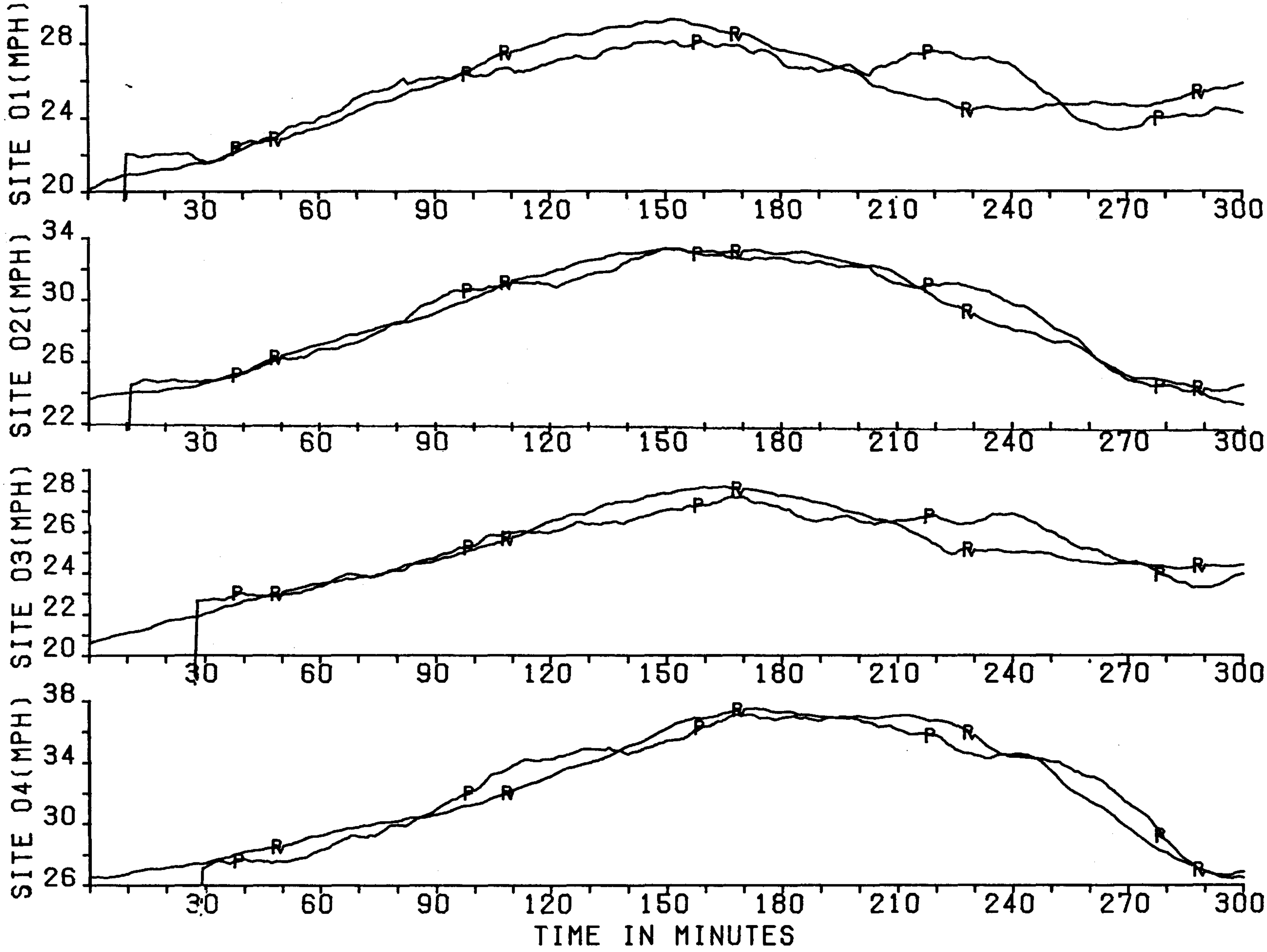


Figure 15. Actual and predicted wind speed records using 2 hour filtered data on May 2, 1979 from 1:00 - 6:00 p.m.

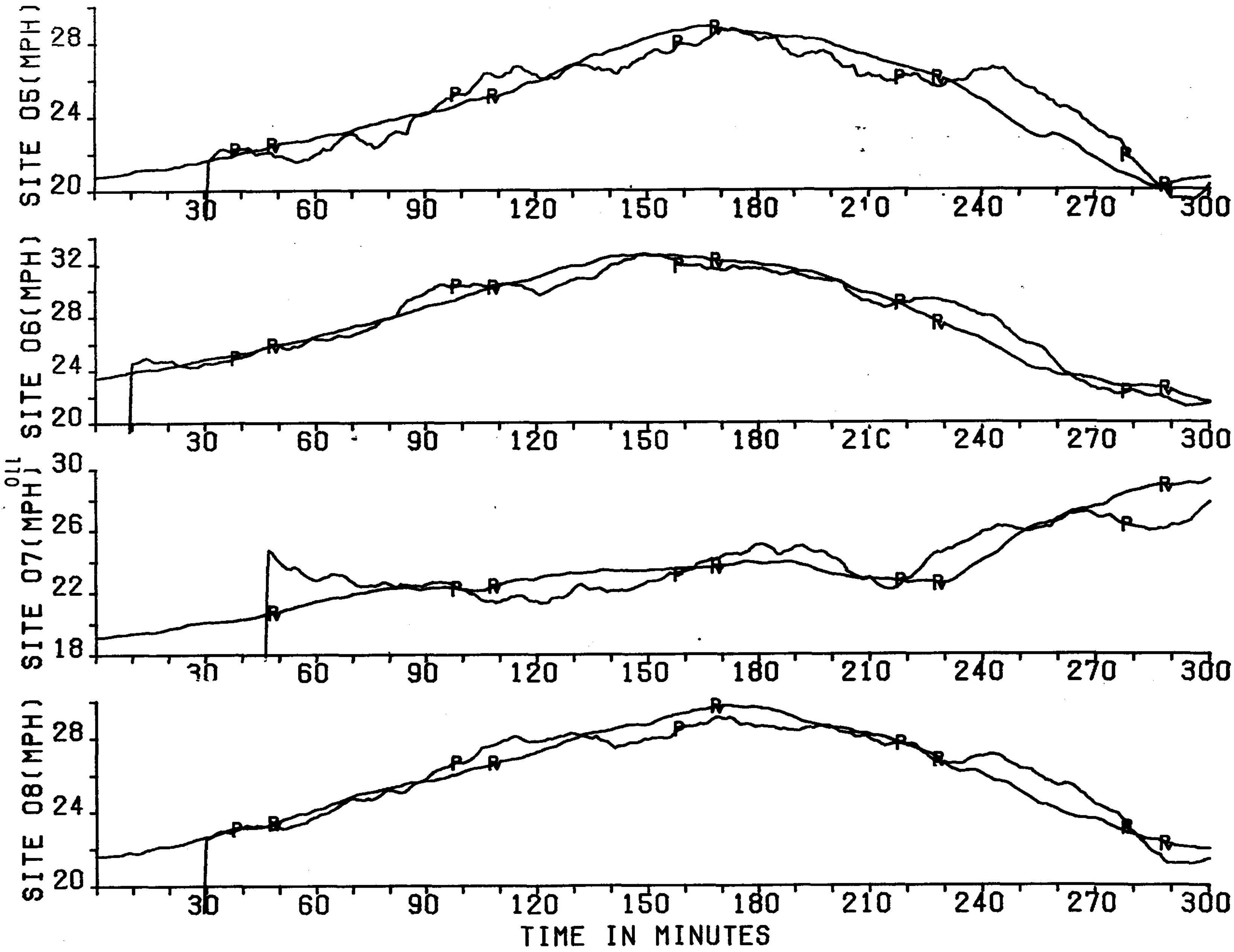


Figure 15a. Actual and predicted wind speed records using 2 hour filtered data on May 2, 1979 from 1:00 - 6:00 p.m.

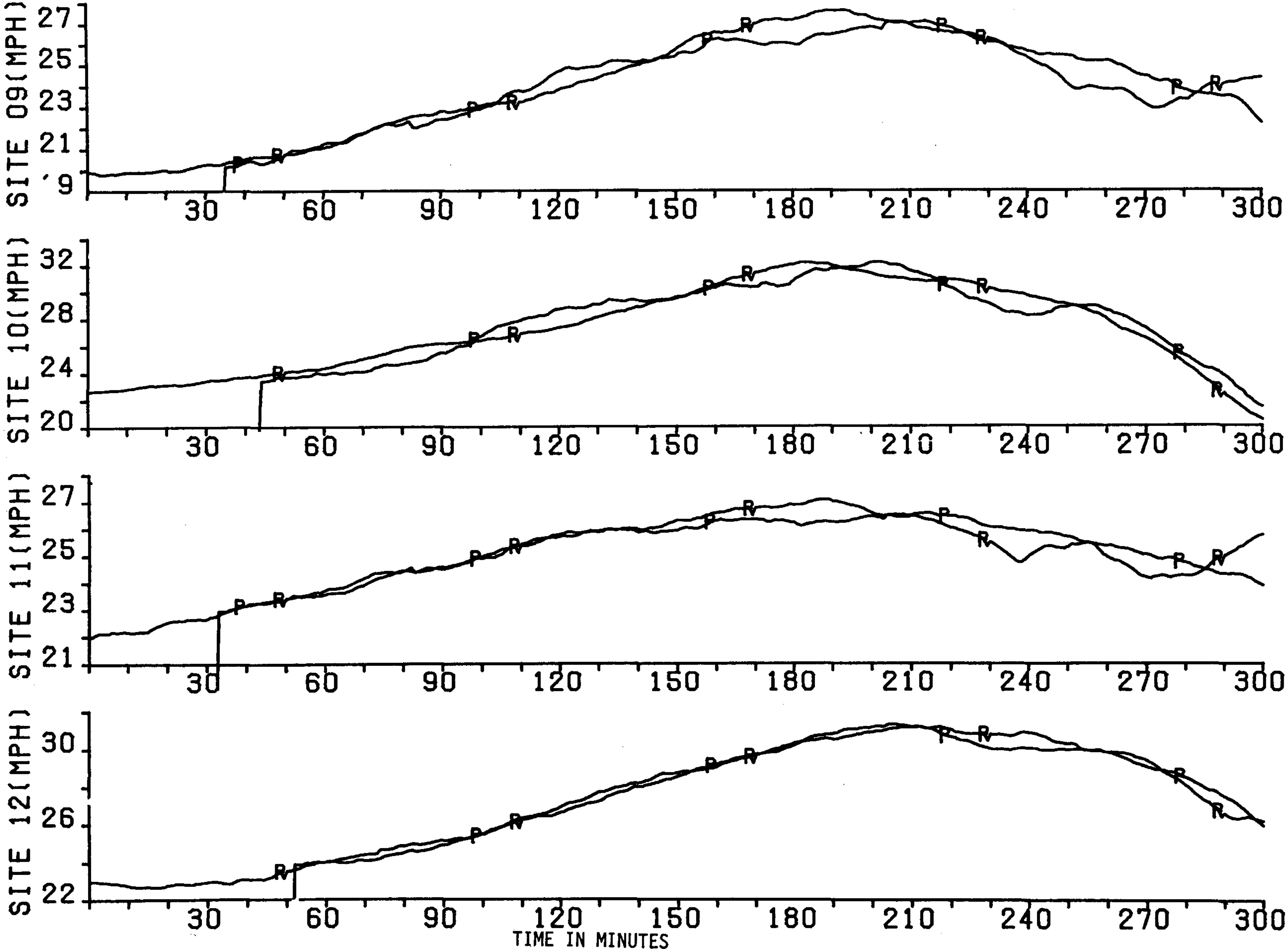


Figure 15b. Actual and predicted wind speed records using 2 hour filtered data on May 2, 1979 from 1:00 - 6:00 p.m.

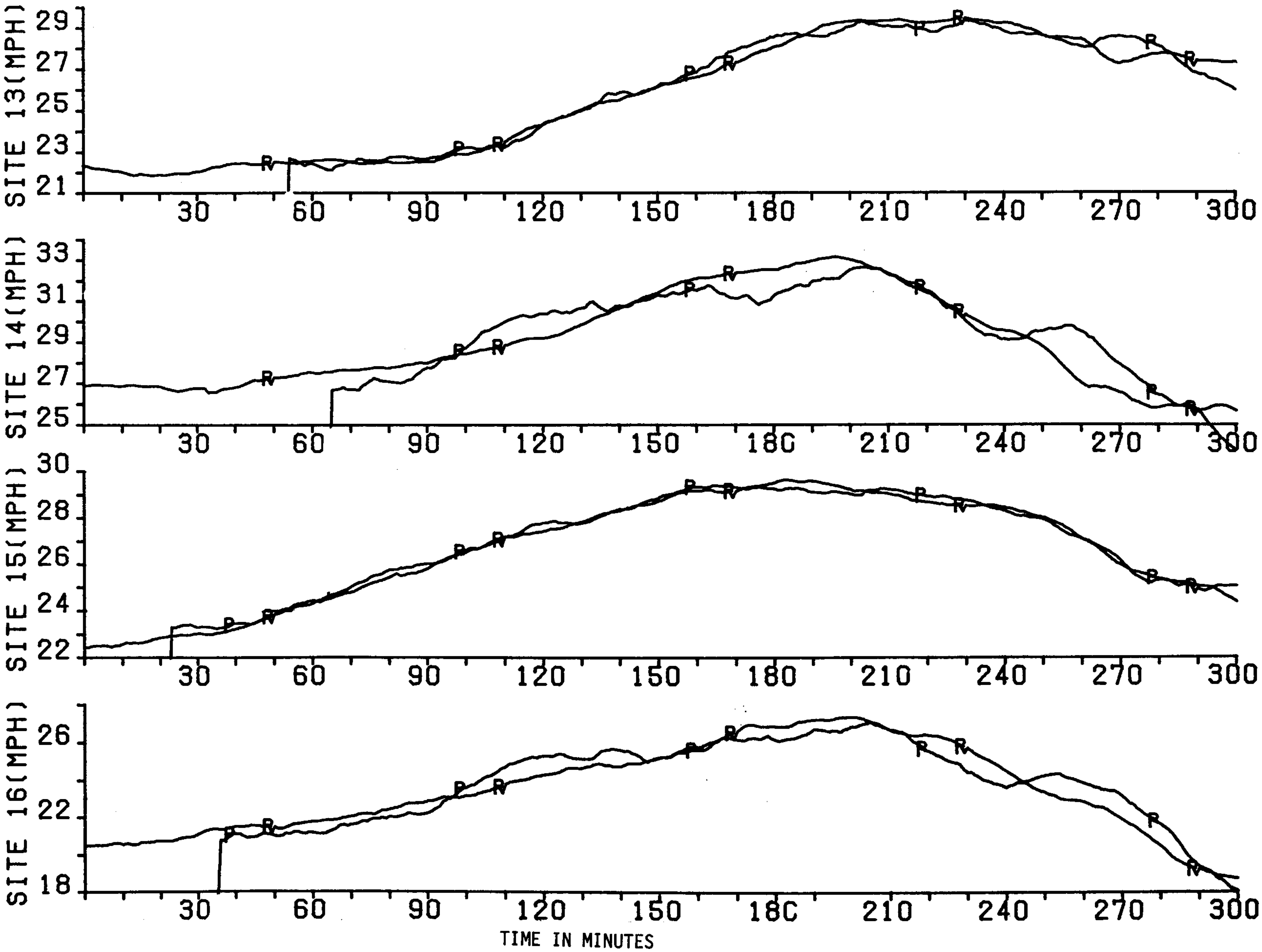


Figure 15c. Actual and predicted wind speed records using 2 hour filtered data on May 2, 1979 from 1:00 - 6:00 p.m.

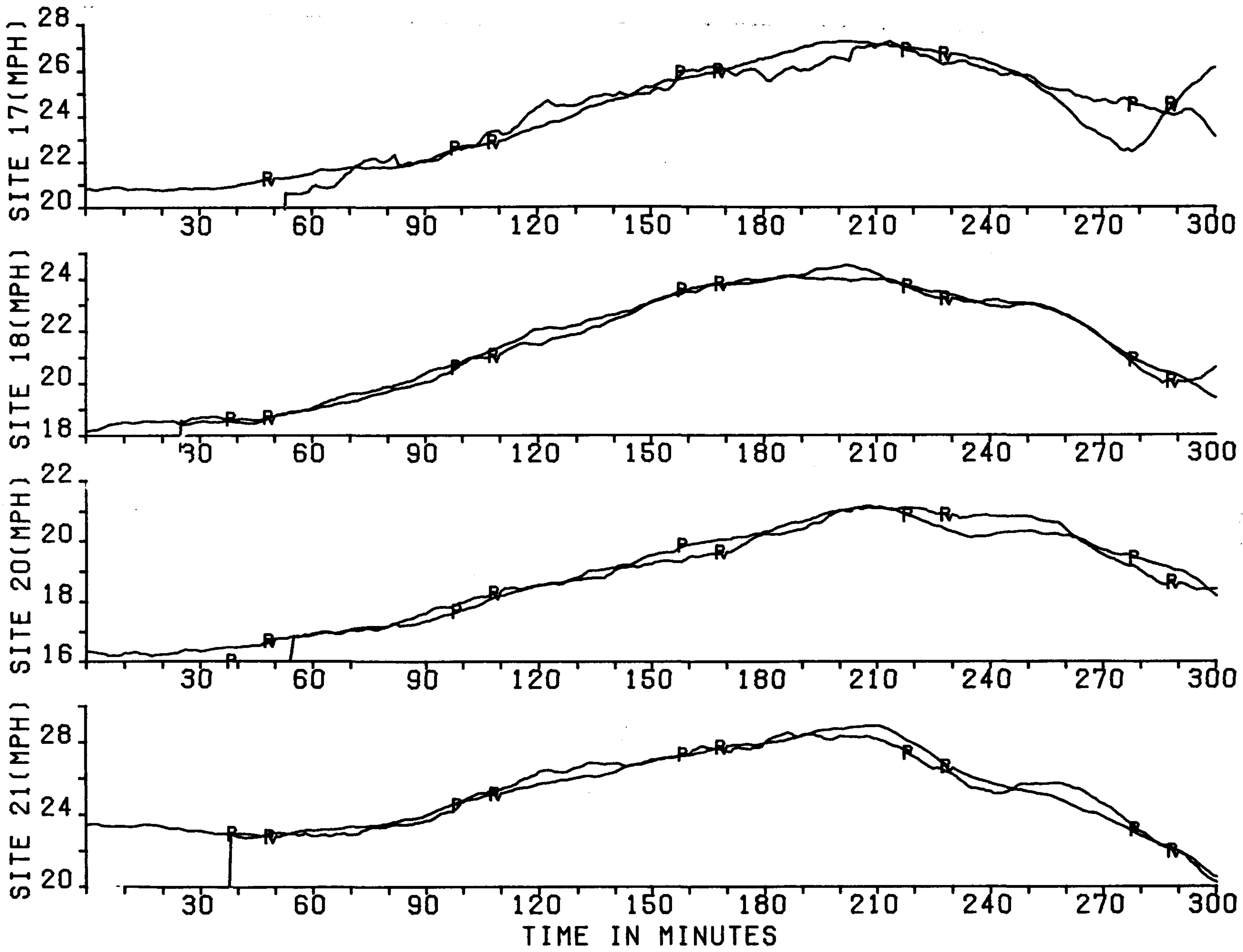


Figure 15d. Actual and predicted wind speed records using 2 hour filtered data on May 2, 1979 from 1:00 - 6:00 p.m.

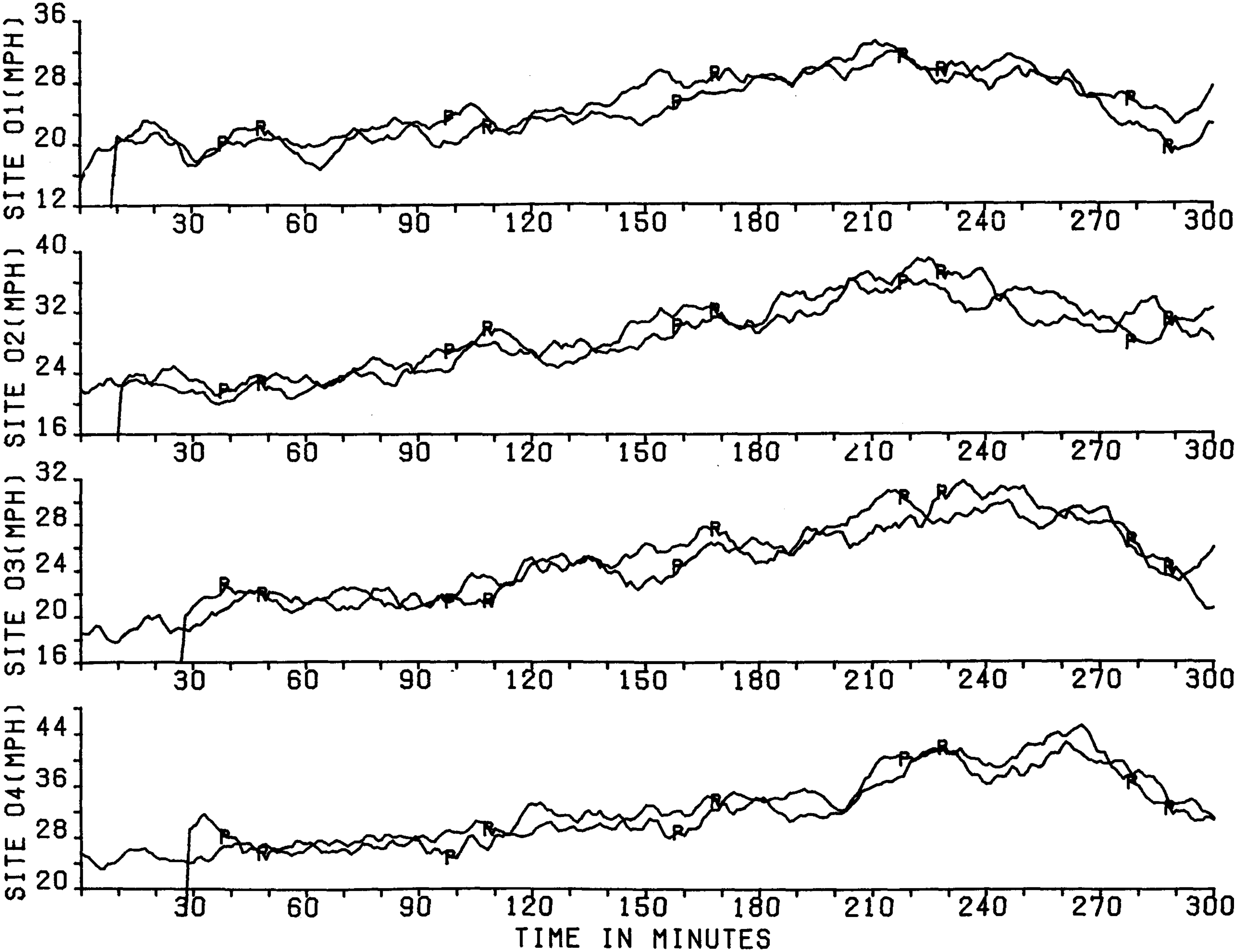


Figure 16. Actual and predicted wind records using 10 minute moving average filtered data on May 2, 1979 from 1:00 - 6:00 p.m.

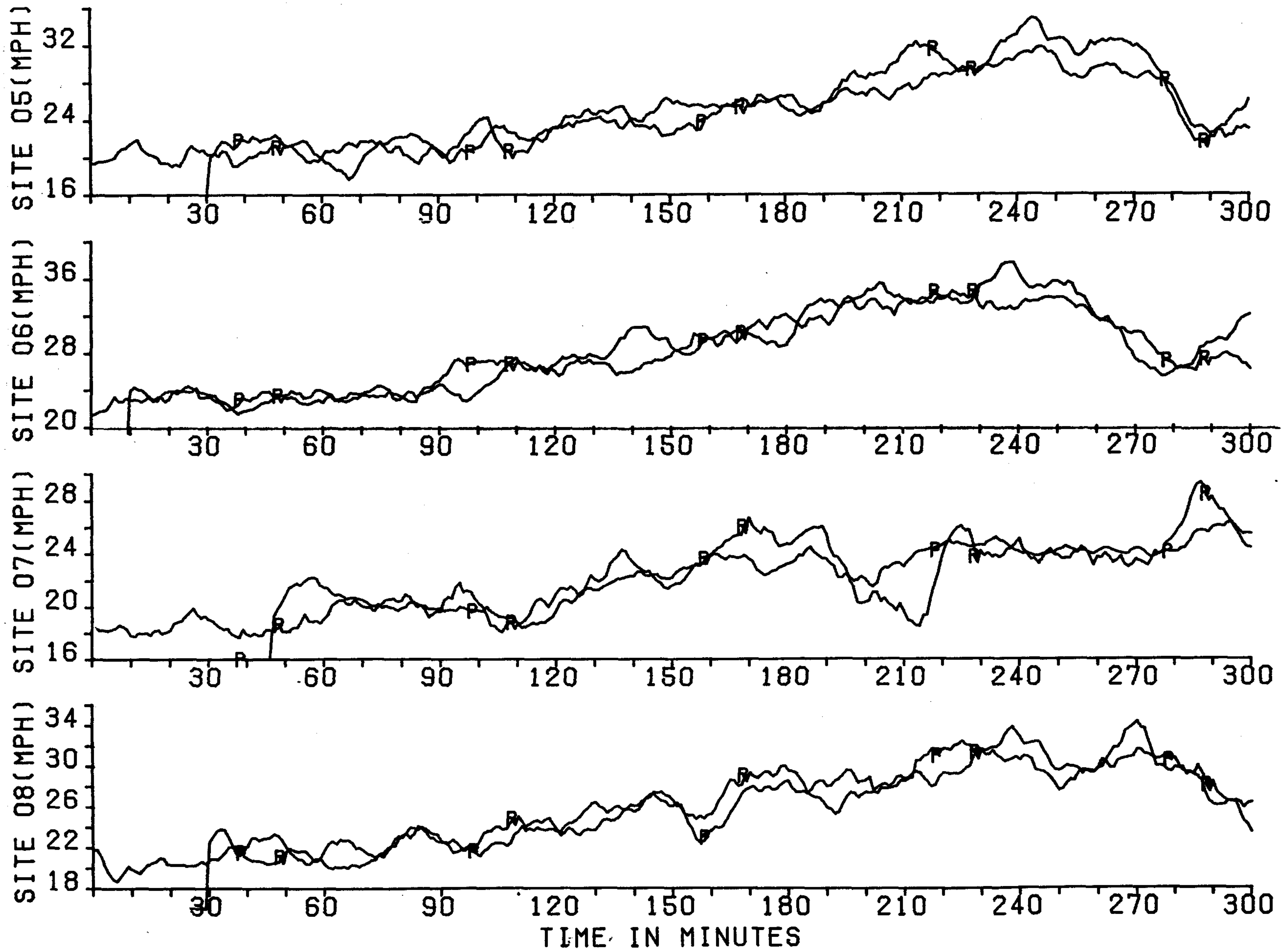


Figure 16a. Actual and predicted wind records using 10 minute moving average filtered data on May 2, 1979 from 1:00 - 6:00 p.m.

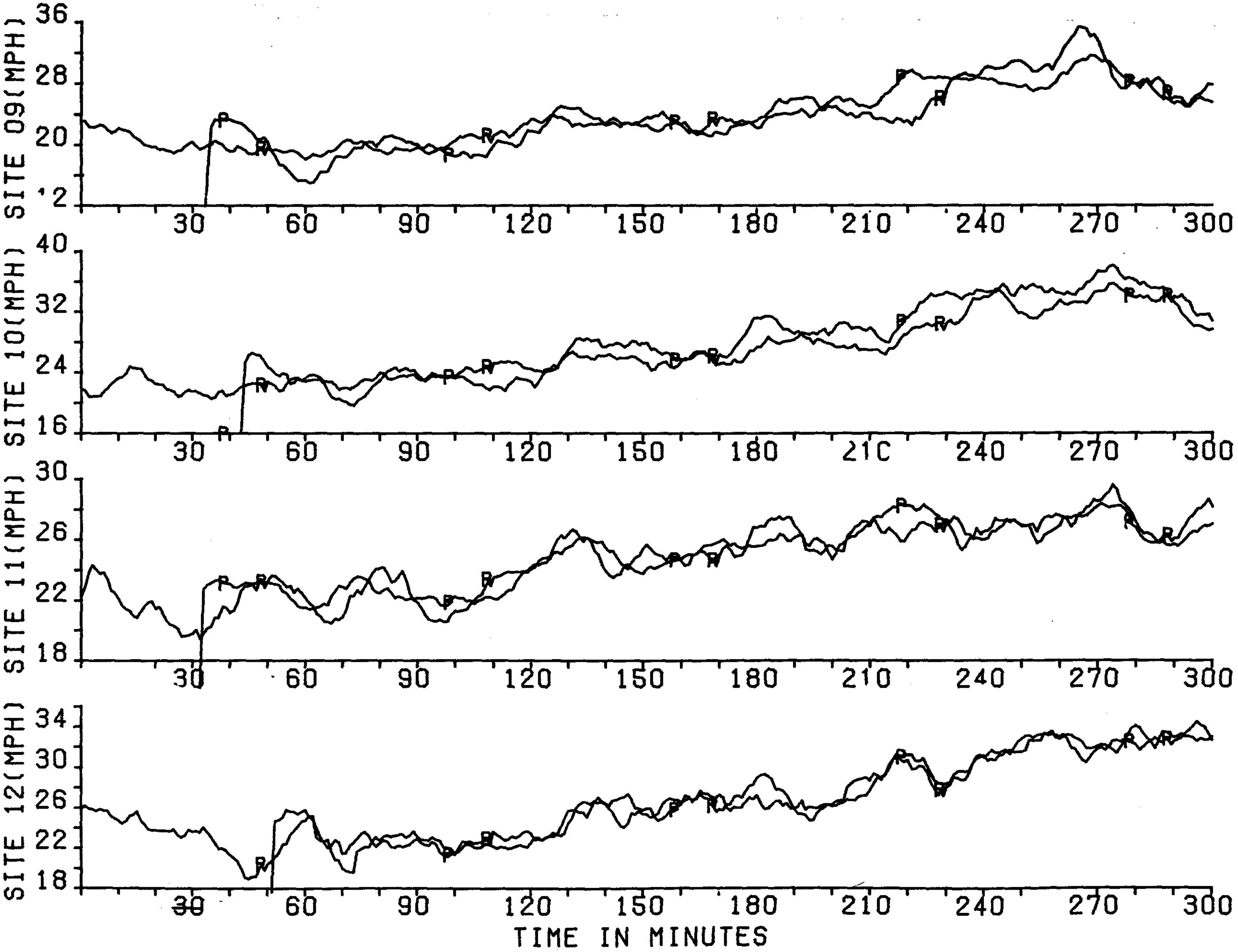


Figure 16b. Actual and predicted wind records using 10 minute moving average filtered data on May 2, 1979 from 1:00 - 6:00 p.m.

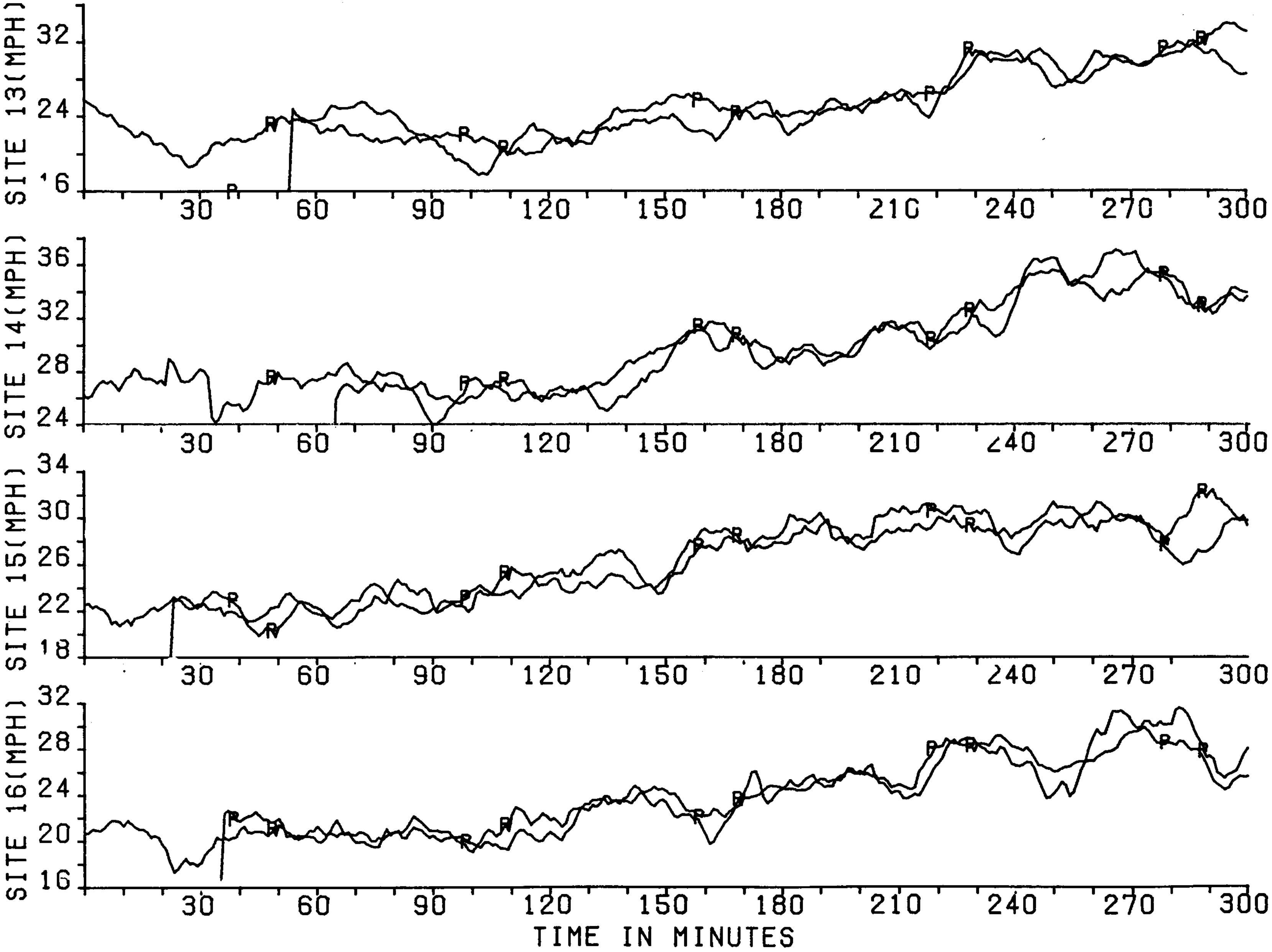


Figure 16c. Actual and predicted wind records using 10 minute moving average filtered data on May 2, 1979 from 1:00 - 6:00 p.m.

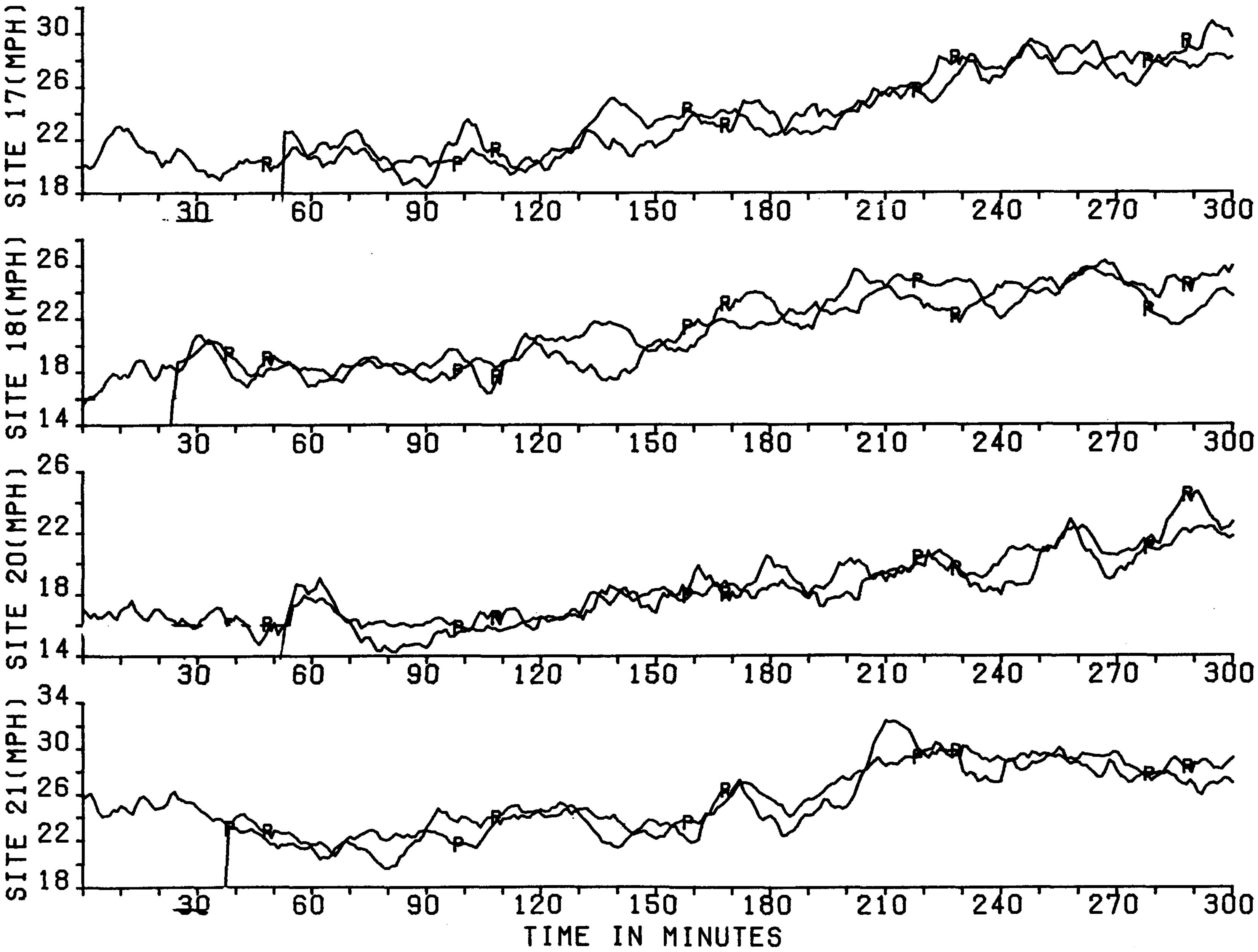


Figure 16d. Actual and predicted wind records using 10 minute moving average filtered data on May 2, 1979 from 1:00 - 6:00 p.m.

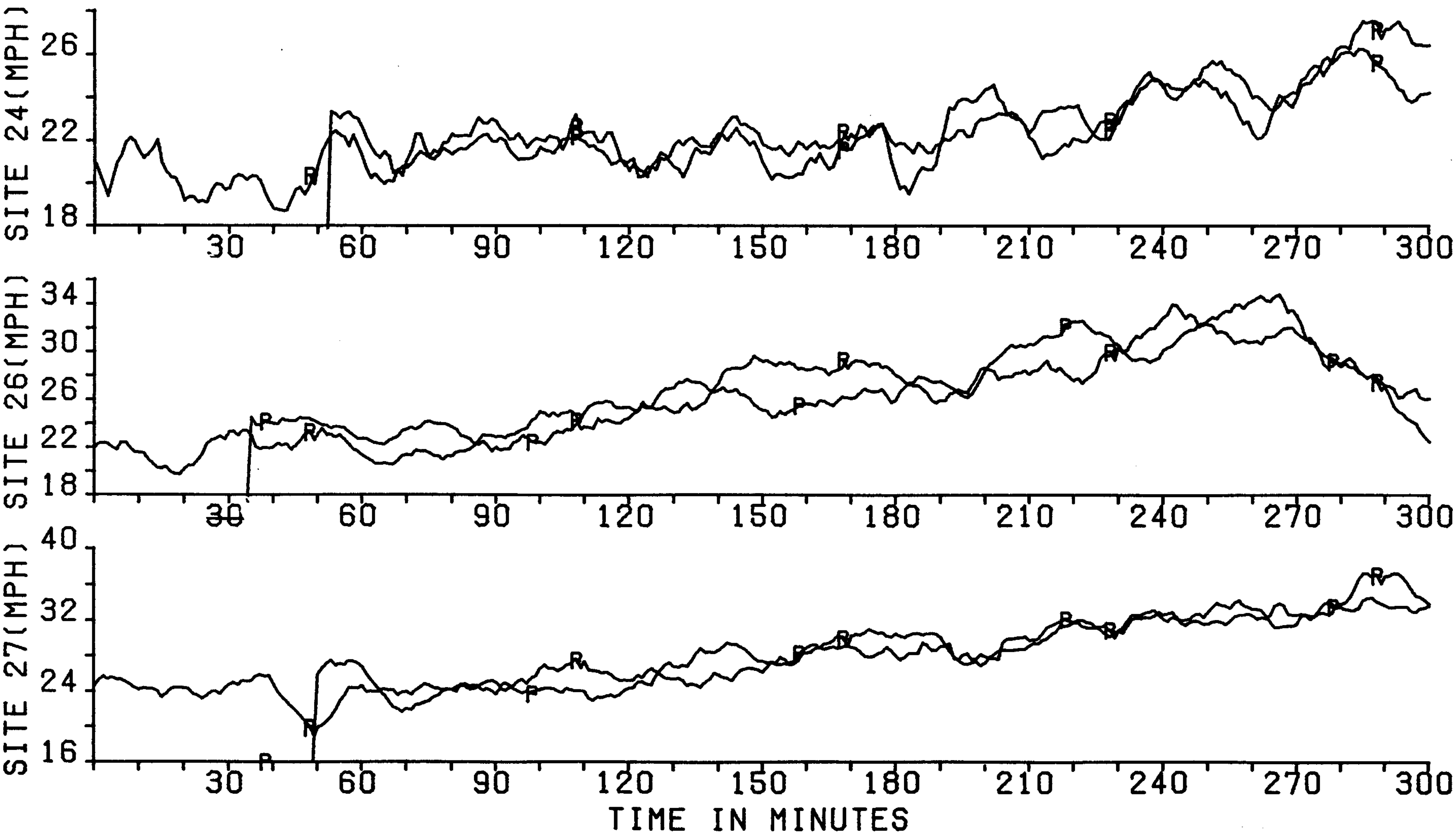


Figure 16e. Actual and predicted wind records using 10 minute moving average filtered data on May 2, 1979 from 1:00 - 6:00 p.m.

creased minimum wind speeds, shifted the time of occurrence of maximums and minimums, and reduced the slopes of the records. This distortion using the 2 hour filter should be avoided even though it would go undetected in solely observing Figure 15. A filtering interval of 10-30 minutes would likely eliminate some of the turbulence site specific effects without this distortion of the meteorological event characteristics.

4.3 A FAST SOUTHEAST PROPAGATING FRONT

The arrival of the southeast propagating front on May 2, 1979 data is initially observed by a north to south propagating triangular pulse that is first observed on northern sites 1-5 at 3:00 p.m. The wind direction shift is first experienced on the northern sites at 6:40 p.m. The slow propagation of the triangular wind speed pulse and the fast propagation of the wind direction shift affects the southern most sites in the SESAME array at approximately 8:30 p.m. Thus, the transition from the south to north moving front to the northwest to southeast moving front is nearly complete at 8:00 p.m. Thus, prediction of the fast moving front from northwest to southeast is attempted on the data record from 8:00 - 10:00 p.m.

The correlation tables for 2 hour and 10 minute moving average data are given in Tables 18a and 18b. Both tables suggest that the front is propagating in the direction associated with increasing site numbers because the peak correlation elements (ij) in the first five columns are larger than ji elements in the first five rows. The northwest to southeast direction of propagation is much more clearly observed in the 10 minute moving average data since the difference between the larger (ji) correlation in the first five columns and the smaller (ij) correlations in the five rows is significantly larger. These results suggest that the direction of propagation and the propagation delays can be more clearly observed in the 10 minute moving average filtered data. Moreover, these results indicate direction of propagation of the front is consistent with the wind speed direction.

The groups formed based on large pairwise peak correlations and small delays and close geographical proximity are shown in Figure 17 for the 2 hour moving averaged data. The two groups show an east west propagation since the reference group is on the eastern side of the SESAME array and the prediction group (6,10,16,19,20,26,27) is on the western side. Three subgroups of reference sites are used to produce wind speed predictions at sites in this prediction groups. The three sets of reference subgroups are selected to determine whether reference sites should be cited in attempt to partially encircle the prediction group or should be sited in a cluster at the point where the event first affects the group of reference sites.

	SITES																										
SITES	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	---	.99	.99	.84	.97	.31	.88	.35	.88	.45	.82	.34	.80	.40	.46	.40	.75	.84	.48	.49	.72	.80	.87	.65	.80	.39	.43
2	.99	---	.98	.86	.96	.32	.91	.37	.88	.45	.84	.35	.82	.40	.47	.40	.79	.84	.48	.50	.72	.82	.86	.69	.82	.39	.44
3	.99	.98	---	.78	.95	.31	.85	.34	.86	.41	.79	.33	.79	.38	.44	.36	.75	.83	.45	.45	.76	.81	.90	.58	.76	.36	.40
4	.85	.86	.81	---	.89	.30	.95	.39	.87	.44	.90	.37	.84	.43	.50	.40	.87	.83	.51	.48	.70	.83	.69	.79	.90	.39	.43
5	.97	.96	.95	.89	---	.30	.93	.37	.95	.44	.89	.38	.88	.44	.52	.39	.84	.93	.52	.49	.83	.89	.86	.58	.87	.38	.42
6	.47	.40	.46	.40	.45	---	.36	.74	.34	.83	.27	.78	.27	.61	.50	.93	.27	.33	.75	.68	.38	.28	.47	.51	.27	.90	.74
7	.88	.91	.85	.95	.93	.32	---	.38	.96	.50	.96	.42	.92	.49	.58	.45	.92	.93	.56	.55	.76	.92	.79	.74	.95	.42	.46
8	.42	.38	.42	.30	.39	.74	.29	---	.31	.61	.22	.74	.25	.65	.50	.67	.17	.30	.58	.66	.30	.26	.38	.39	.22	.76	.69
9	.88	.88	.86	.87	.95	.31	.96	.38	---	.50	.96	.44	.97	.51	.60	.45	.92	.99	.56	.56	.87	.97	.86	.67	.94	.40	.45
10	.41	.41	.42	.39	.38	.83	.36	.50	.32	---	.29	.69	.26	.52	.73	.96	.28	.30	.87	.93	.28	.28	.35	.41	.31	.92	.83
11	.82	.84	.79	.90	.89	.32	.96	.38	.96	.52	---	.45	.97	.51	.61	.47	.97	.97	.57	.58	.82	.94	.82	.77	.97	.42	.47
12	.49	.44	.50	.34	.46	.52	.35	.42	.36	.71	.27	---	.30	.67	.54	.69	.24	.36	.61	.80	.38	.30	.49	.50	.25	.79	.79
13	.80	.82	.79	.84	.88	.30	.92	.34	.97	.51	.97	.45	---	.51	.61	.46	.97	.98	.55	.57	.91	.96	.84	.69	.94	.40	.45
14	.52	.49	.54	.47	.45	.08	.39	.11	.33	.39	.25	.24	.27	---	.66	.17	.27	.30	.40	.64	.34	.28	.45	.54	.25	.11	.22
15	.26	.23	.25	.20	.24	.50	.18	.26	.25	.73	.26	.47	.25	.63	---	.69	.26	.28	.72	.72	.25	.23	.30	.28	.29	.60	.45
16	.47	.43	.47	.40	.45	.93	.37	.65	.36	.96	.38	.78	.27	.55	.69	---	.28	.34	.37	.81	.35	.29	.43	.49	.30	.98	.82
17	.75	.79	.87	.87	.84	.29	.92	.37	.92	.49	.97	.42	.97	.49	.58	.43	---	.93	.55	.54	.87	.93	.78	.70	.95	.38	.43
18	.84	.84	.83	.83	.92	.30	.93	.36	.99	.52	.97	.45	.98	.52	.61	.46	.93	---	.56	.58	.89	.96	.87	.71	.94	.40	.46
19	.37	.35	.37	.37	.36	.75	.33	.47	.29	.87	.30	.71	.25	.62	.75	.87	.31	.27	---	.83	.28	.25	.35	.42	.31	.84	.74
20	.42	.41	.42	.38	.38	.62	.35	.25	.31	.93	.30	.70	.27	.67	.72	.81	.26	.29	.83	---	.27	.28	.34	.34	.29	.78	.74
21	.72	.72	.76	.70	.83	.24	.76	.31	.87	.46	.82	.40	.91	.46	.56	.39	.87	.89	.49	.51	---	.91	.79	.56	.77	.33	.40
22	.80	.82	.81	.83	.89	.29	.92	.39	.97	.49	.94	.43	.96	.50	.60	.43	.93	.96	.57	.54	.91	---	.82	.66	.91	.38	.43
23	.87	.86	.90	.65	.86	.27	.79	.29	.86	.45	.82	.38	.84	.44	.52	.40	.78	.87	.46	.50	.77	.82	---	.51	.81	.36	.40
24	.65	.69	.60	.75	.58	.30	.68	.35	.50	.51	.57	.40	.42	.43	.50	.44	.53	.43	.44	.55	.30	.43	.41	---	.61	.41	.
25	.80	.82	.76	.90	.87	.32	.95	.42	.94	.51	.97	.43	.94	.50	.58	.46	.95	.94	.56	.56	.77	.91	.81	.83	---	.43	.
26	.50	.46	.50	.41	.48	.90	.40	.66	.38	.92	.27	.87	.30	.66	.60	.98	.26	.36	.84	.79	.38	.31	.47	.51	.29	---	.
27	.47	.46	.48	.40	.42	.74	.36	.69	.35	.84	.30	.80	.30	.71	.51	.82	.24	.33	.74	.90	.32	.31	.41	.40	.25	.84	-

Table 18a. Peak correlation matrix for 2 hour moving average filtered data of May 2, 1979 from 8:00 - 10:00 p.m.

	SITES																										
SITES	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	---	.73	.71	.-2	.60	.32	.53	.21	.26	.29	.43	.19	.40	.34	.27	.40	.18	.12	.40	.33	.31	.40	.13	.50	.17	.27	.34
2	.80	---	.72	.52	.46	.26	.70	.16	.26	.38	.49	.25	.46	.27	.25	.38	.24	.15	.39	.24	.27	.40	.14	.43	.24	.30	.21
3	.72	.72	---	.68	.57	.36	.78	.54	.49	.38	.71	.52	.64	.72	.56	.34	.47	.32	.31	.18	.28	.55	.28	.41	.36	.14	.27
4	.77	.58	.68	---	.80	.31	.68	.41	.61	.33	.67	.43	.65	.56	.29	.25	.68	.45	.32	.27	.55	.68	.36	.40	.54	.17	.22
5	.61	.53	.56	.78	---	.32	.60	.53	.69	.48	.74	.39	.74	.58	.25	.33	.51	.62	.23	.34	.65	.63	.49	.47	.48	.17	.29
6	.46	.38	.51	.51	.47	---	.45	.47	.43	.28	.25	.57	.35	.46	.65	.50	.36	.26	.40	.52	.33	.28	.24	.42	.25	.60	.49
7	.80	.73	.79	.71	.66	.30	---	.44	.69	.26	.85	.37	.79	.64	.23	.37	.58	.50	.33	.36	.23	.62	.30	.58	.72	.15	.24
8	.55	.53	.65	.45	.42	.30	.72	---	.61	.49	.66	.48	.58	.70	.59	.27	.48	.50	.33	.30	.28	.45	.49	.47	.50	.13	.71
9	.53	.64	.60	.67	.80	.31	.72	.63	---	.49	.79	.55	.76	.71	.27	.35	.64	.78	.40	.34	.61	.76	.44	.69	.68	.20	.47
10	.31	.29	.23	.26	.37	.40	.41	.4-	.32	---	.32	.28	.36	.25	.34	.28	.21	.63	.55	.44	.18	.43	.45	.58	.44	.27	.57
11	.68	.77	.76	.66	.55	.86	.85	.41	.55	.24	---	.48	.80	.80	.39	.39	.77	.57	.27	.32	.39	.64	.40	.63	.80	.17	.19
12	.56	.55	.64	.51	.54	.30	.78	.82	.74	.58	.63	---	.69	.67	.67	.29	.66	.65	.49	.39	.38	.64	.40	.55	.54	.30	.71
13	.56	.64	.70	.65	.62	.34	.83	.51	.76	.33	.83	.56	---	.65	.21	.41	.80	.68	.34	.29	.61	.84	.46	.49	.69	.20	.22
14	.71	.81	.81	.56	.57	.29	.87	.68	.53	.27	.81	.68	.68	---	.70	.29	.66	.50	.15	.28	.21	.53	.56	.52	.61	.17	.46
15	.45	.52	.61	.31	.36	.20	.59	.59	.44	.38	.39	.72	.39	.70	---	.34	.38	.30	.35	.18	.27	.31	.35	.41	.17	.26	.51
16	.43	.44	.49	.38	.41	.10	.47	.46	.40	.24	.32	.54	.34	.49	.59	---	.38	.29	.40	.34	.29	.25	.31	.25	.32	.50	.31
17	.67	.75	.78	.68	.62	.33	.84	.59	.71	.37	.79	.63	.80	.85	.45	.30	---	.61	.25	.33	.59	.80	.46	.56	.72	.22	.35
18	.63	.62	.61	.52	.54	.37	.69	.41	.61	.54	.75	.30	.71	.60	.46	.42	.60	---	.46	.43	.51	.61	.49	.87	.85	.20	.43
19	.19	.20	.28	.22	.20	.40	.19	.43	.19	.29	.17	.37	.14	.21	.70	.60	.12	.16	---	.37	.24	.12	.28	.48	.32	.44	.36
20	.37	.44	.53	.54	.44	.17	.38	.51	.48	.23	.42	.43	.36	.52	.44	.21	.37	.27	.37	---	.23	.29	.32	.46	.55	.08	.41
21	.69	.57	.61	.53	.65	.35	.65	.34	.61	.50	.68	.38	.65	.55	.35	.47	.59	.88	.41	.48	---	.73	.57	.74	.82	.32	.39
22	.54	.56	.55	.44	.63	.31	.70	.46	.70	.49	.67	.35	.68	.68	.26	.38	.50	.79	.40	.42	.62	---	.45	.68	.56	.24	.34
23	.61	.51	.42	.31	.34	.52	.53	.38	.31	.33	.51	.33	.25	.55	.41	.28	.32	.48	.38	.46	.13	.30	---	.59	.45	.28	.63
24	.57	.60	.48	.27	.17	.35	.30	.48	.26	.24	.41	.45	.19	.41	.57	.41	.11	.13	.48	.56	.18	.16	.28	---	.24	.23	.49
25	.71	.73	.78	.67	.63	.34	.72	.42	.64	.31	.80	.33	.59	.76	.52	.44	.69	.58	.44	.43	.18	.56	.36	.73	---	.17	.30
26	.34	.44	.51	.48	.48	.17	.38	.38	.47	.38	.40	.52	.31	.54	.70	.47	.34	.42	.68	.68	.38	.21	.44	.42	.61	---	.55
27	.52	.34	.41	.38	.39	.34	.57	.71	.45	.57	.60	.39	.44	.45	.41	.29	.39	.54	.48	.40	.18	.41	.64	.55	.63	.17	---

Table 18b. Peak correlation matrix for 10 minute moving average filtered data of May 2, 1979 from 6:00 - 8:00 p.m.

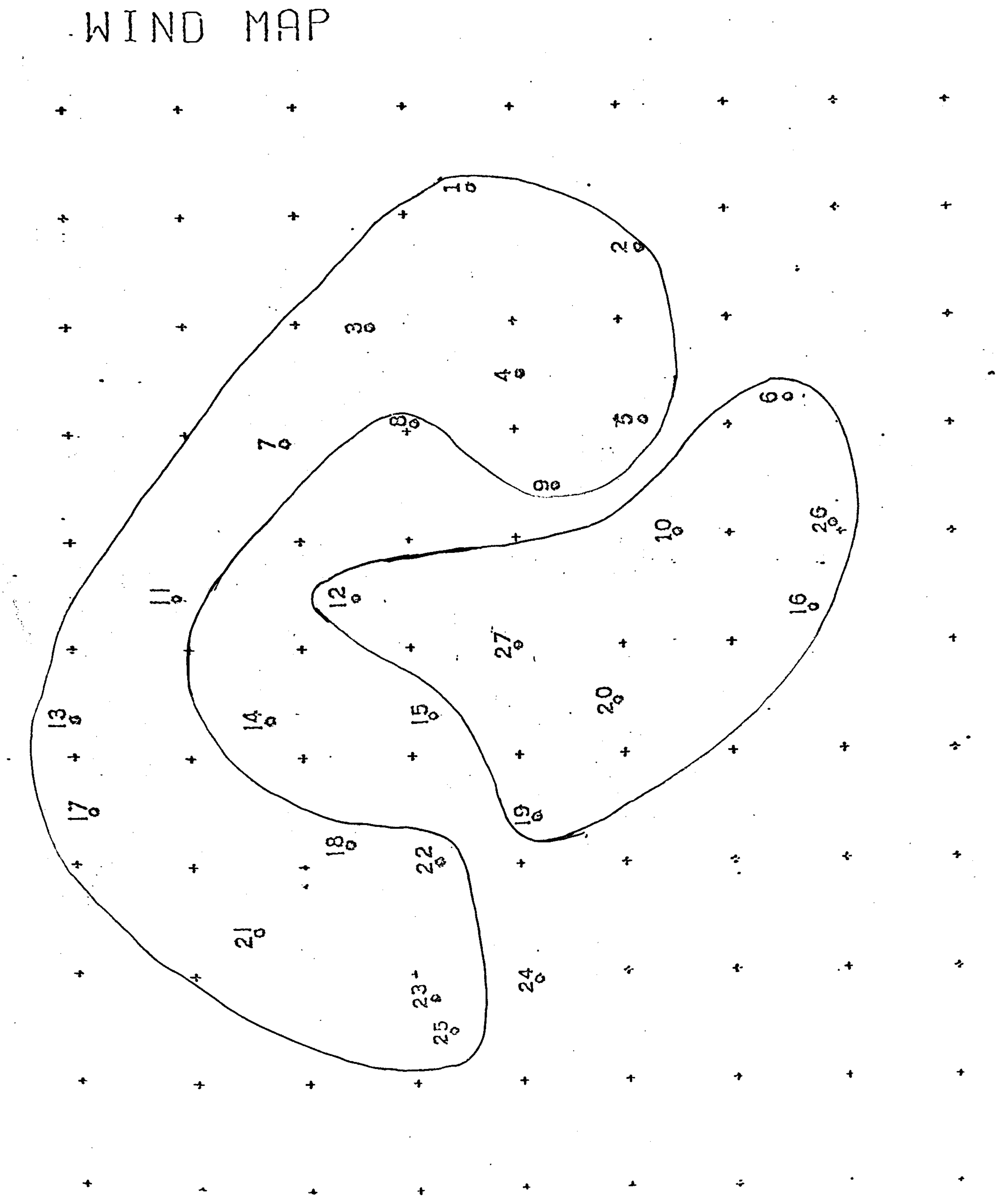


Figure 17. Groups of wind measurement sites for 2 hour moving average filtered data of May 2, 1979 from 8:00 - 10:00 p.m.

Sites 1-5 in the reference subgroup 1 are all in the north, references sites 1, 3, 7, 11, 13 in reference subgroup 2 are in the north and east, and sites 1, 7, 13, 21, and 25 in reference subgroup 3 partially encircle the prediction group sites from the north, east, and south. Tables 19 a-c show the individual delays to prediction sites are very similar from every site in all three reference subgroups. The delay and errors for the individual site, group/site, and group/group models are also given in Tables 19 a-c for the sites in the prediction group using reference subgroups 1-3, respectively. Note that the errors using data from reference subgroup 3 are smaller than the errors using data from reference subgroups 1 and 2 since the reference sites in subgroup 3 encircle the prediction group. The errors for prediction using data from reference subgroup 2 are smaller than for data from reference subgroup 1 because reference subgroup 2 provide reference measurement from both the north and east but reference subgroup 1 only provides measurements from the north. This result suggests that utilizing reference group measurements, that attempt to encircle a set of wind turbine clusters in the event propagation direction, will produce better prediction results.

Prediction was also attempted based for the 10 minute moving average filtered data for this 6:00 - 8:00 p.m. data on May 2, 1979. The groups formed based on large pairwise correlations and small delays within groups and close geographical proximity are shown in Figure 18. Groups 1, 2, 4, 6, and sites 23 and 25 lie in the reference group for the 2 hour moving average data shown in Figure 17. Note that the individual delays from sites 1-3 in Table 20 shows that the delay between these sites are not 1 as in the case of the 2 hour moving average data but progressively increase for sites and groups 2, 4, 6, and site 23, that are located progressively farther south. Thus, the 10 minute moving average data indicates a fast propagation of the event from group 1 through group 2, 4, 6 and then to site 23 which is masked using the 2 hour moving average data. The propagation then procedes to group 5 and 3 in a easterly direction. The results thus indicate a rather complicated circular propagation pattern.

The delays and errors for the individual site, group/site, and group/group predictor models are given in Table 20 using group 1 as reference. The errors are significantly larger in groups 2, 4, and 6 than what has been experienced on the 1:00 - 6:00 p.m. data for the 2 hour moving average data. The errors for groups 3 and 5 are small and comparable with those observed on the 1:00 - 6:00 p.m. for 2 hour moving average data.

The actual and predicted wind speed record for the 10 minute moving average filtered data is shown in Figure 19. The results show that prediction is being accomplished. However, the very large turbulence and site specific phenomena associated with the period after a transition from predominance of one frontal system

Sites	Individual Delays (minutes)					Group/Site Delay (minutes)	Group/Group Delay (minutes)	Errors (mph)		
	1	2	3	4	5			S-S	G-S	G-G
1	1	1	1	1	1	1				
2	1	1	1	1	1	1				
3	1	1	1	1	1	1	1			
4	1	1	1	1	1	1				
5	1	1	1	1	1	1				
6	65	65	61	81	78	70		.040	.052	
10	81	80	84	90	95	86		.058	.078	
12	85	85	57	88	88	81		.043	.208	
16	86	81	85	87	90	86	80	.053	.124	.094
19	80	80	83	85	83	82		.045	.125	
20	82	82	84	86	94	86		.044	.117	
26	77	78	77	81	80	79		.062	.114	
27	70	71	70	72	72	71		.071	.207	

S-S ≡ (1,2,3,4,5) as individual references to predict the wind at the other sites.

G-S ≡ (1,2,3,4,5) as a group to predict the wind at the other sites.

G-G ≡ (1,2,3,4,5) as a group to predict the (6,10,12,16,19,20,26,27) group.

Table 19a. Delays and errors for individual site, group/site and group/group models for 2 hour filtered data of May 2, 1979 from 8:00 - 10:00 p.m. using references 1,2,3,4,5.

Sites	Individual Delays					Group/Site	Group/Group		Errors	
	1	3	7	11	13	Delay	Delay	S-S	G-S	G-G
	(minutes)					(minutes)	(minutes)		(mph)	
1	1	1	1	1	1	1				
3	1	1	1	1	1	1				
7	1	1	1	1	1	1	1			
11	1	1	1	1	1	1				
13	1	1	1	1	1	1				
6	65	61	84	85	88	77		.027	.058	
10	81	84	91	93	96	89		.055	.122	
12	85	57	87	82	88	81		.051	.195	
16	86	85	89	91	93	89	85	.034	.115	.095
19	80	83	84	85	86	84		.052	.110	
20	82	84	91	93	95	89		.056	.163	
26	77	77	83	85	90	82		.052	.104	
27	70	70	75	77	87	76		.059	.203	

S-S ≡ (1,3,7,11,13) as individual references to predict the wind at the other sites.

G-S ≡ (1,3,7,11,13) as a group to predict the wind at the other sites.

G-G ≡ (1,3,7,11,13) as a group to predict the (6,10,12,16,19,20,26,27) group.

Table 19b. Delays and errors for individual site, group/site, and group/group models for 2 hour filtered data of May 2, 1979 from 8:00 - 10:00 p.m. using references 1,3,7,11,13.

Sites	Individual Delays (minutes)					Group/Site Delay (minutes)	Group/Group Delay (minutes)	Errors (mph)		
	1	7	13	21	25			S-S	G-S	G-G
1	1	1	1	1	1	1				
7	1	1	1	1	1	1				
13	1	1	1	1	1	1	1			
21	1	1	1	1	1	1				
25	1	1	1	1	1	1				
6	65	84	88	101	85	85		.020	.055	
10	81	91	96	102	90	92		.042	.113	
12	85	87	88	93	86	88		.054	.146	
16	86	89	93	101	89	92	86	.034	.085	.085
19	80	84	86	87	85	84		.043	.106	
20	82	91	95	102	89	92		.036	.133	
26	77	83	90	100	84	87		.044	.104	
27	70	75	87	92	75	80		.053	.212	

S-S = (1,7,13,21,25) as individual references to predict the wind at the other site

G-S = (1,7,13,21,25) as a group to predict the wind at the other sites.

G-G = (1,7,13,21,25) as a group to predict the (6,10,12,16,19,20,26,27) group.

Table 19c. Delays and errors for individual site, group/site, and group/group models for 2 hour filtered data of May 2, 1979 from 8:00 - 10:00 p.m. using references 1,7,13,21,25.

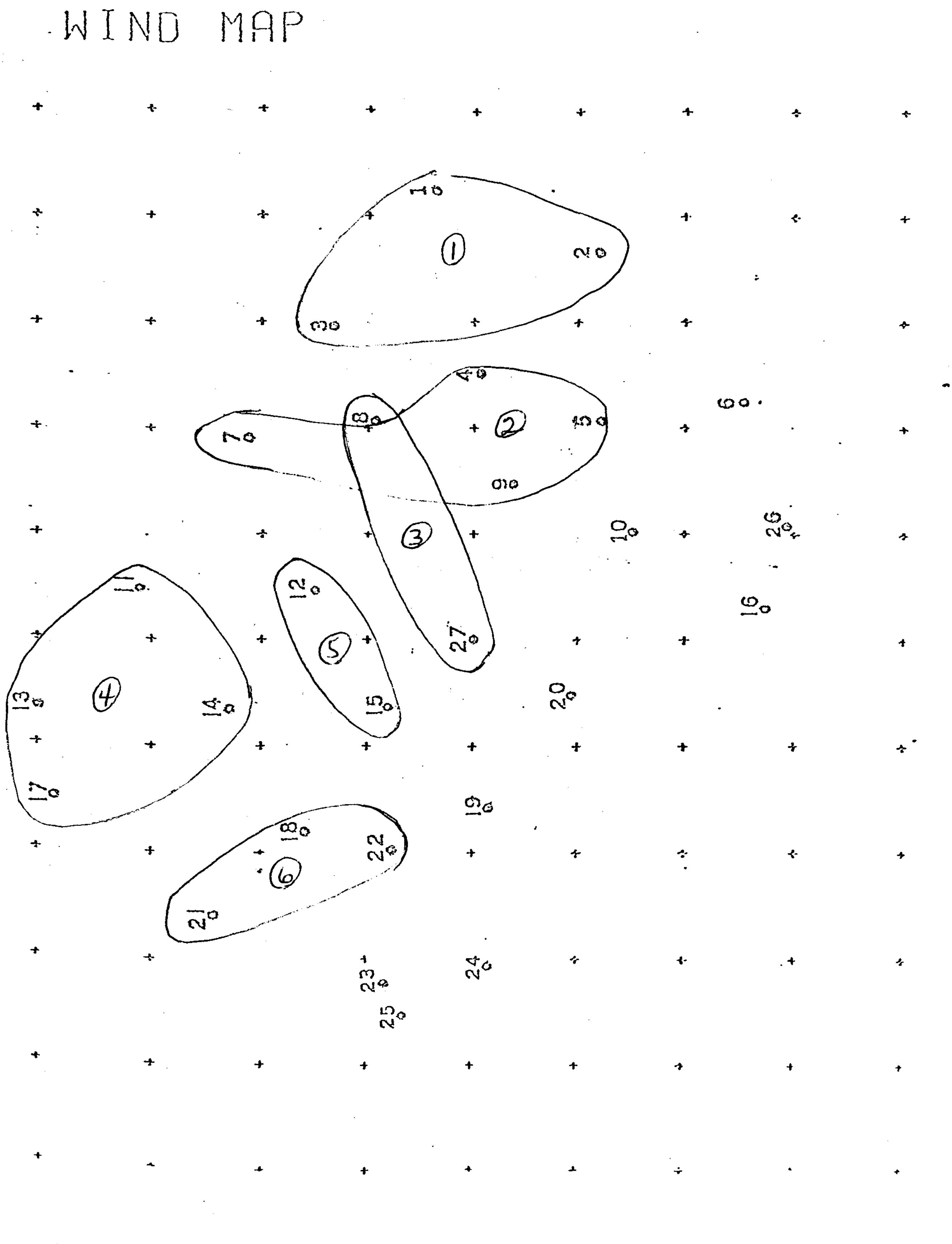


Figure 18. Groups of wind measurement sites for 10 minute moving average filtered data of May 2, 1979 from 8:00 - 10:00 p.m.

	Site	Delays (minutes)			Group/Site Delay (minutes)	Group/Group Delay (minutes)	Errors (mph)		
		1	2	3			S-S	G-S	G-G
1	1	1	5	3	1	1			
	2	1	1	1					
	3	1	1	1					
2	4	1	1	1	1	2	2.67	2.83	2.38
	5	1	8	3	4		2.66	2.86	
	7	1	1	1	1		2.49	3.02	
	9	1	3	1	2		2.44	2.69	
3	8	70	71	1	70	71	1.23	1.26	1.61
	27	71	79	2	71		1.28	2.35	
4	11	1	1	1	1	1	3.57	4.38	3.99
	13	1	1	1	1		4.10	4.56	
	17	1	1	1	1		4.34	4.93	
	14	1	1	1	1		2.65	3.91	
5	12	61	1	1	60	60	1.34	1.54	1.62
	15	63	57	1	60		1.45	2.13	
6	18	28	16	12	19	10	2.33	4.55	4.14
	21	5	11	2	6		2.54	3.45	
	22	4	7	2	4		5.04	5.49	
	6	25	26	19	23	23	1.27	1.50	1.50
	10	10	14	10	11	11	1.19	1.37	1.37
	16	63	62	61	62	62	1.50	1.69	1.69
	19	40	40	38	39	39	1.97	2.19	2.19
	20	64	74	98	79	79	1.15	2.60	2.60
	24	1	1	1	1	1	7.16	7.21	7.21
	26	51	55	51	52	52	1.23	1.89	1.89
	23	16	53	1	16	16	1.31	2.60	2.60
	25	1	1	1	1	1	6.75	7.21	7.21

Table 20. Delays and errors for individual site, group/site, and group/group models for 10 minute filtered data of May 2, 1979 from 8:00 - 10:00 p.m. using references (1,2,3).

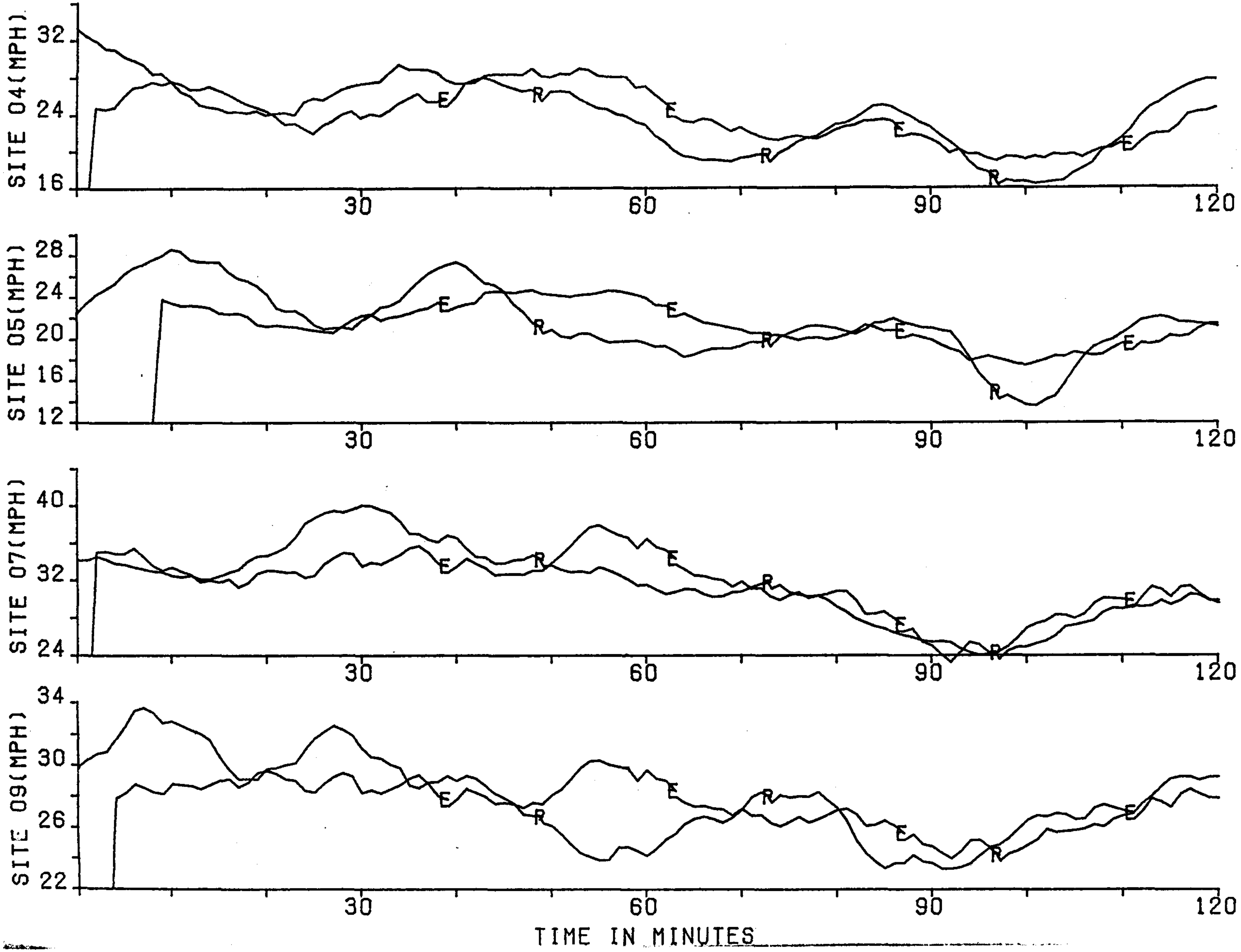


Figure 19. Actual and predicted wind speed records using 2 hour filtered data on May 2, 1979 from 8:00 - 10:00 p.m.

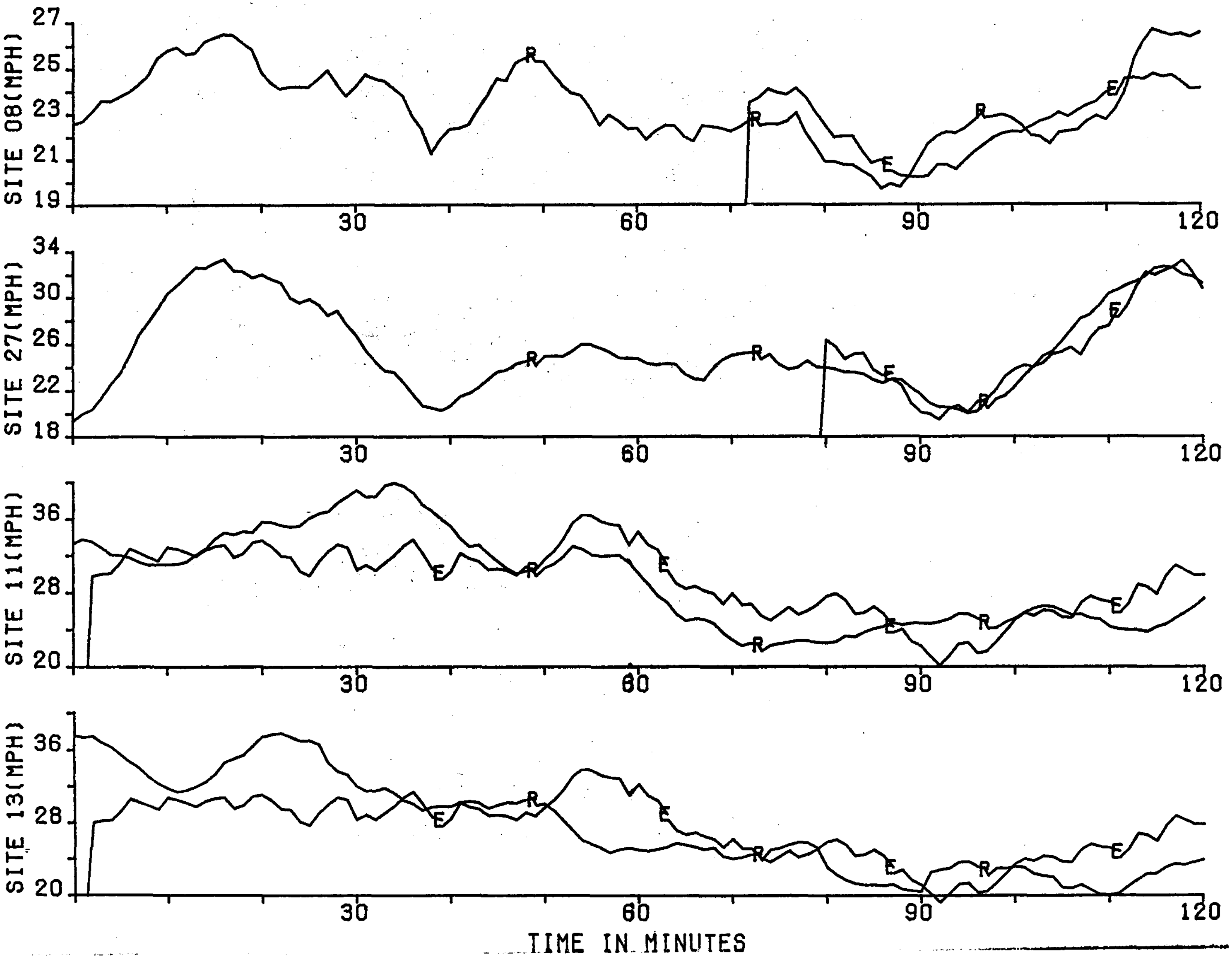


Figure 19a. Actual and predicted wind speed records using 2 hour filtered data on May 2, 1979 from 8:00 - 10:00 p.m.

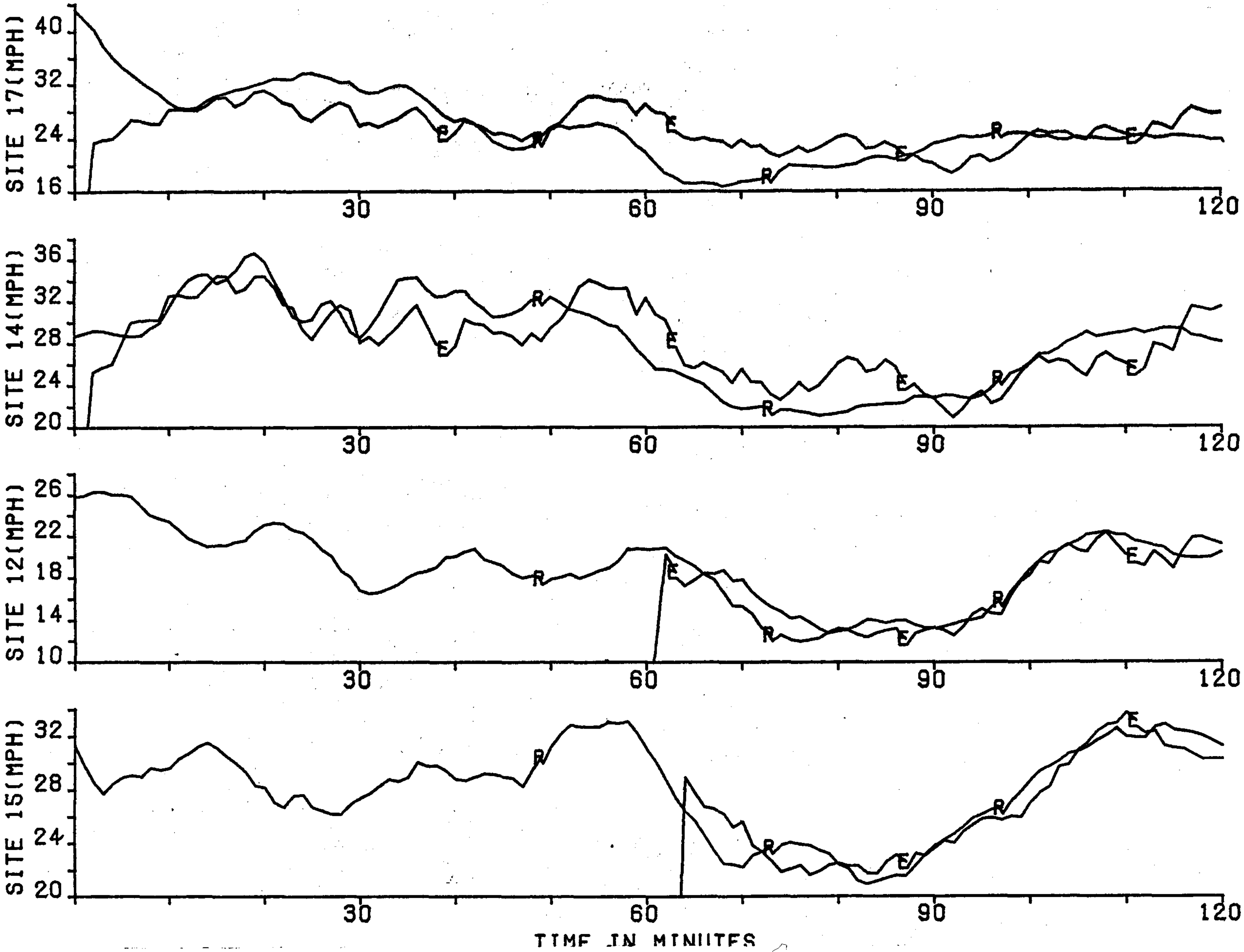


Figure 19b. Actual and predicted wind speed records using 2 hour filtered data on May 2, 1979 from 8:00 - 10:00 p.m.

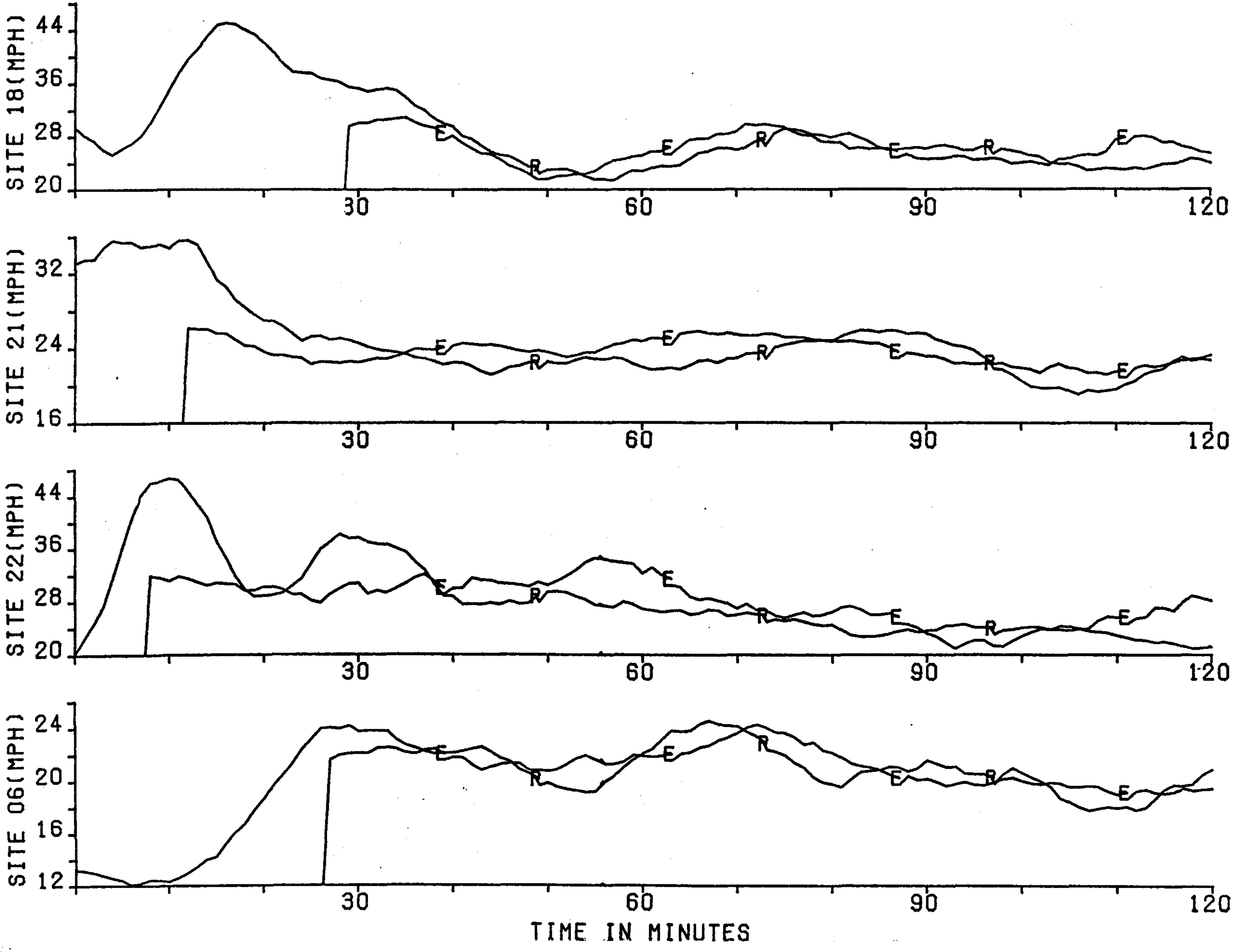


Figure 19c. Actual and predicted wind speed records using 2 hour filtered data on May 2, 1979 from 8:00 - 10:00 p.m.

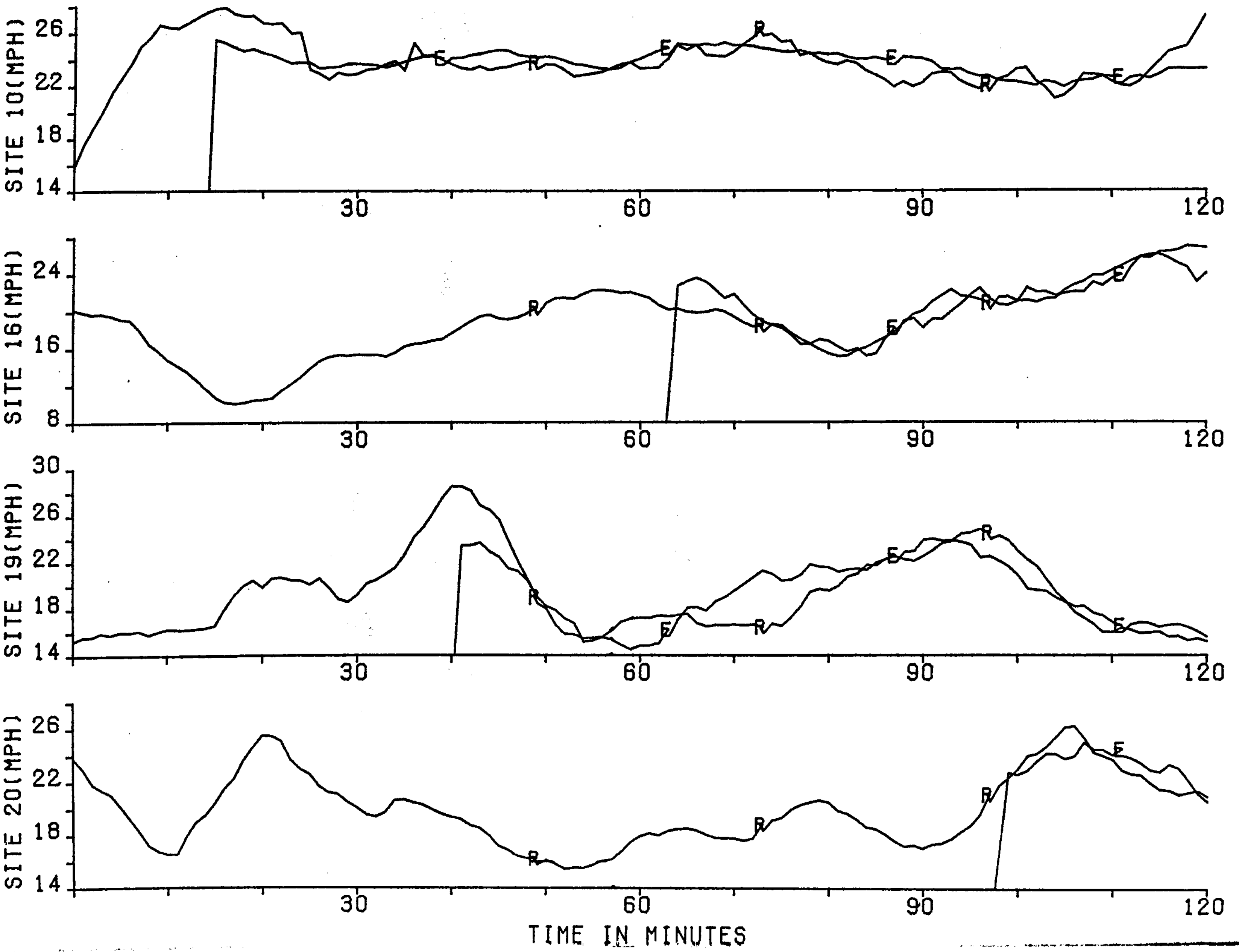


Figure 19d. Actual and predicted wind speed records using 2 hour filtered data on May 2, 1979 from 8:00 - 10:00 p.m.

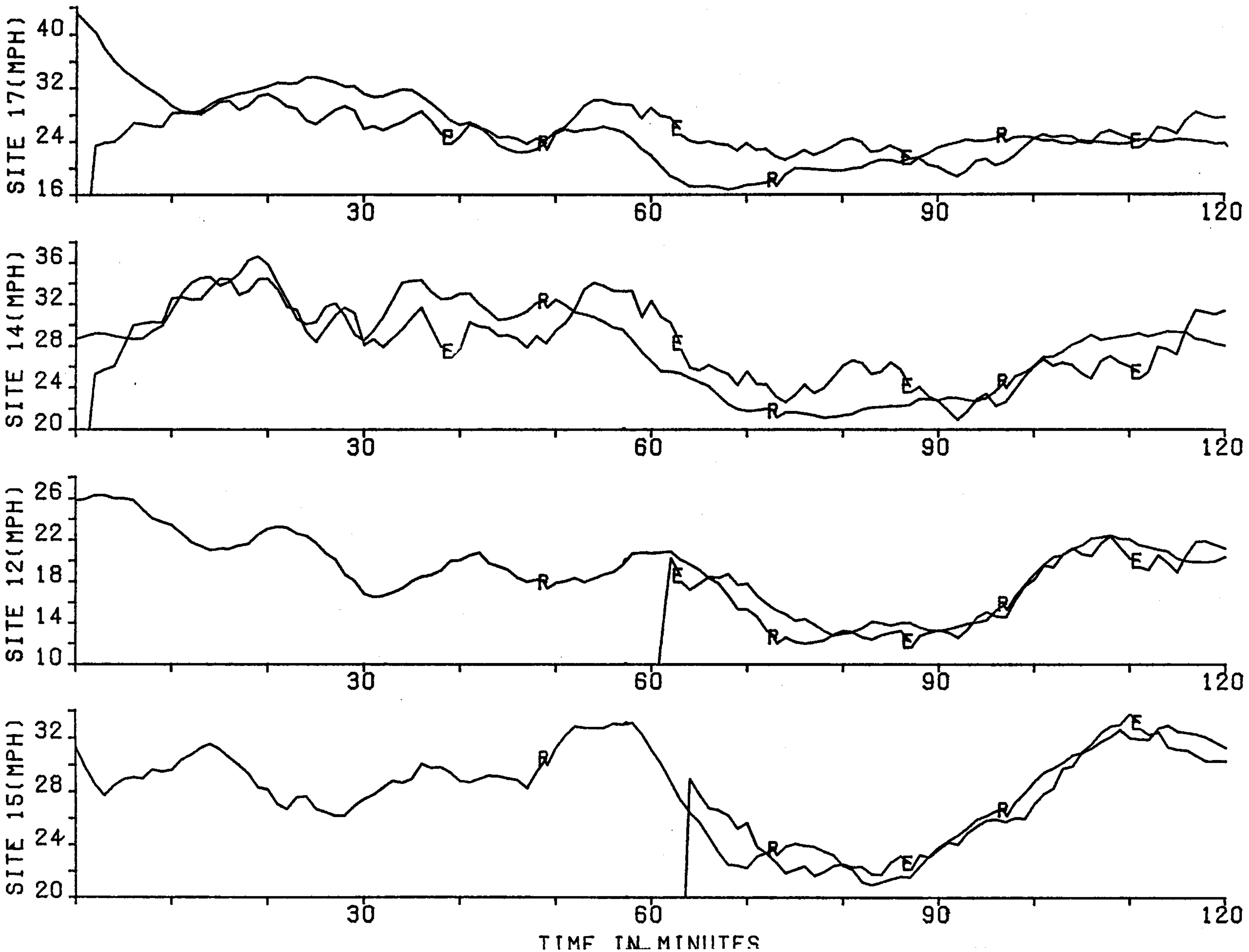


Figure 19e. Actual and predicted wind speed records using 2 hour filtered data on May 2, 1979 from 8:00 - 10:00 p.m.

to another frontal system is observed. Thus, the prediction accuracy is not quite as good as for the other cases studied.

The actual and predicted wind speed record for the 2 hour moving average filtered data are plotted in Figure 20. Note that the 2 hour moving average has slightly different delays. Comparison of Figures 19 and 20 indicates the 2 hour moving average filtering causes significant distortion by decreasing maximum wind speed, increasing minimum wind speed, shifting the time of occurrence of maximums and minimums, and changing the slope of the wind speed records. However, the 2 hour moving average filtered predicted wind speed better matched the 2 hour moving average filtered wind speed records because the filtering significantly reduces the variation in the records.

4.4 A STATIONARY FRONT

The prediction methodology is tested for a stationary front that occurred on the SESAME array on April 14, 1979 from 7:30 - 12:30 a.m. During this period, wind speeds increased from 16 mph to 32 mph and then subsided again.

The correlation table is given in Tables 21a and 21b, for 10 minute and 30 minute moving average data. The groups formed from the 10 minute and 30 minute smoothed data are similar. The groups formed based on the 10 minute smoothed data shown in Figure 21 were used because the number of groups is larger since the correlation values are smaller. The correlation table does not suggest a clear direction of propagation for this triangular pulse wind speed increase. The wind speed direction is from south to north and therefore the sites 18, 19, 22, 24, and 25 are chosen as the reference group.

The individual delays from reference sites 18, 19, 22, 24, and 25 and the group/site delay from the group of references to each prediction site is given in Table 22. The delays are one for almost every prediction site except 2, 21, 6, 14, 16, and 26, which are all to the far east or west edge of the SESAME array when wind direction is south to north. It should be noted that starred values of delay in the table were neglected in computing the group/site delay for a prediction site because they were quite different from the delays for the other references to that prediction site.

The errors for the individual site group/site and group/group predictive models was computed and tabulated in Table 22 for both 10 minute and 2 hour moving average filtered data. The errors for the individual site model were always smaller than the group/site model since the averaging of the wind speed record and utilizing an average delay loses information and flexibility. The errors for the 2 hour moving average filtered data is

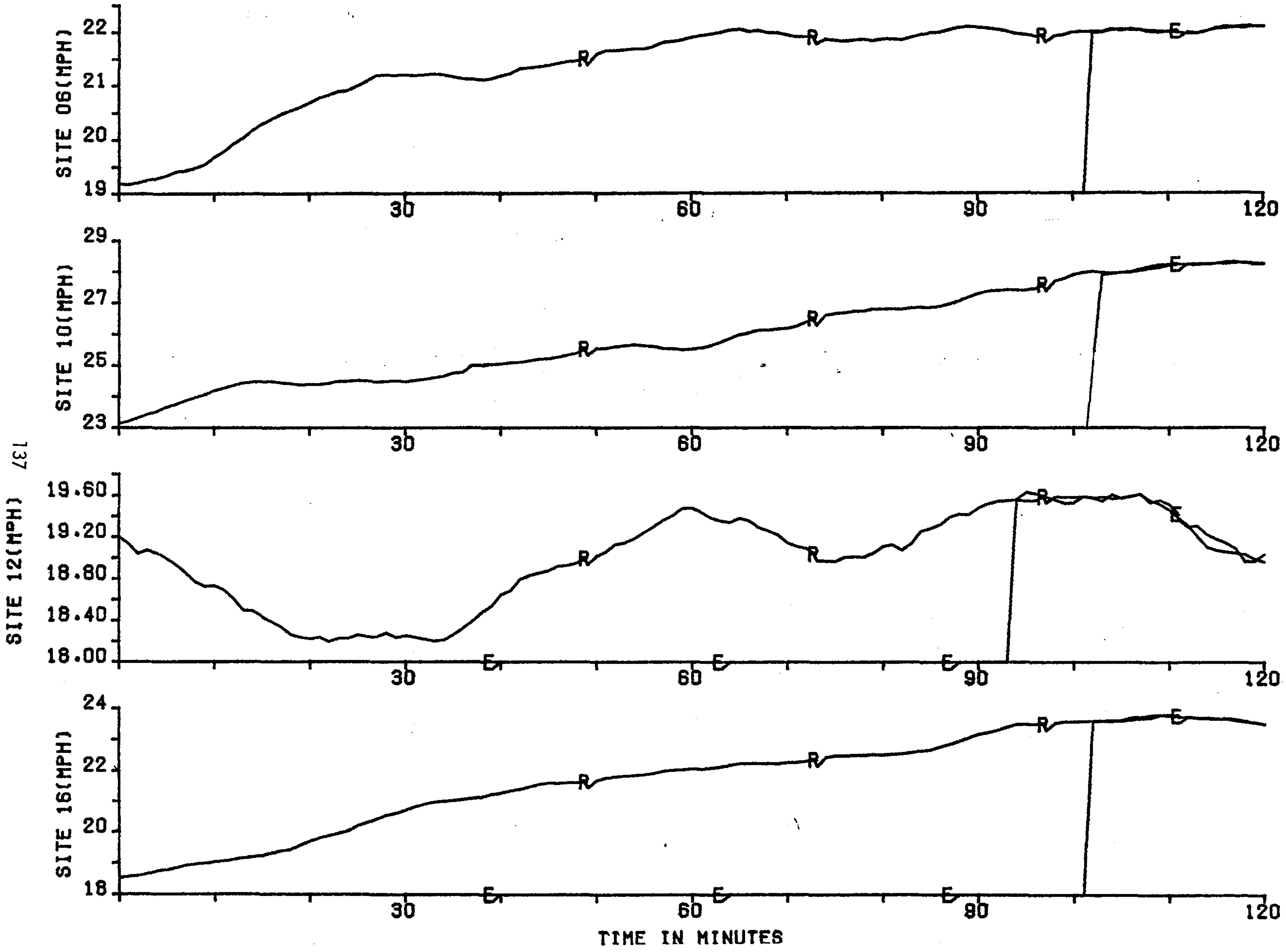


Figure 20. Actual and predicted wind speed records using 10 minute filtered data on May 2, 1979 from 8:00 - 10:00 p.m.

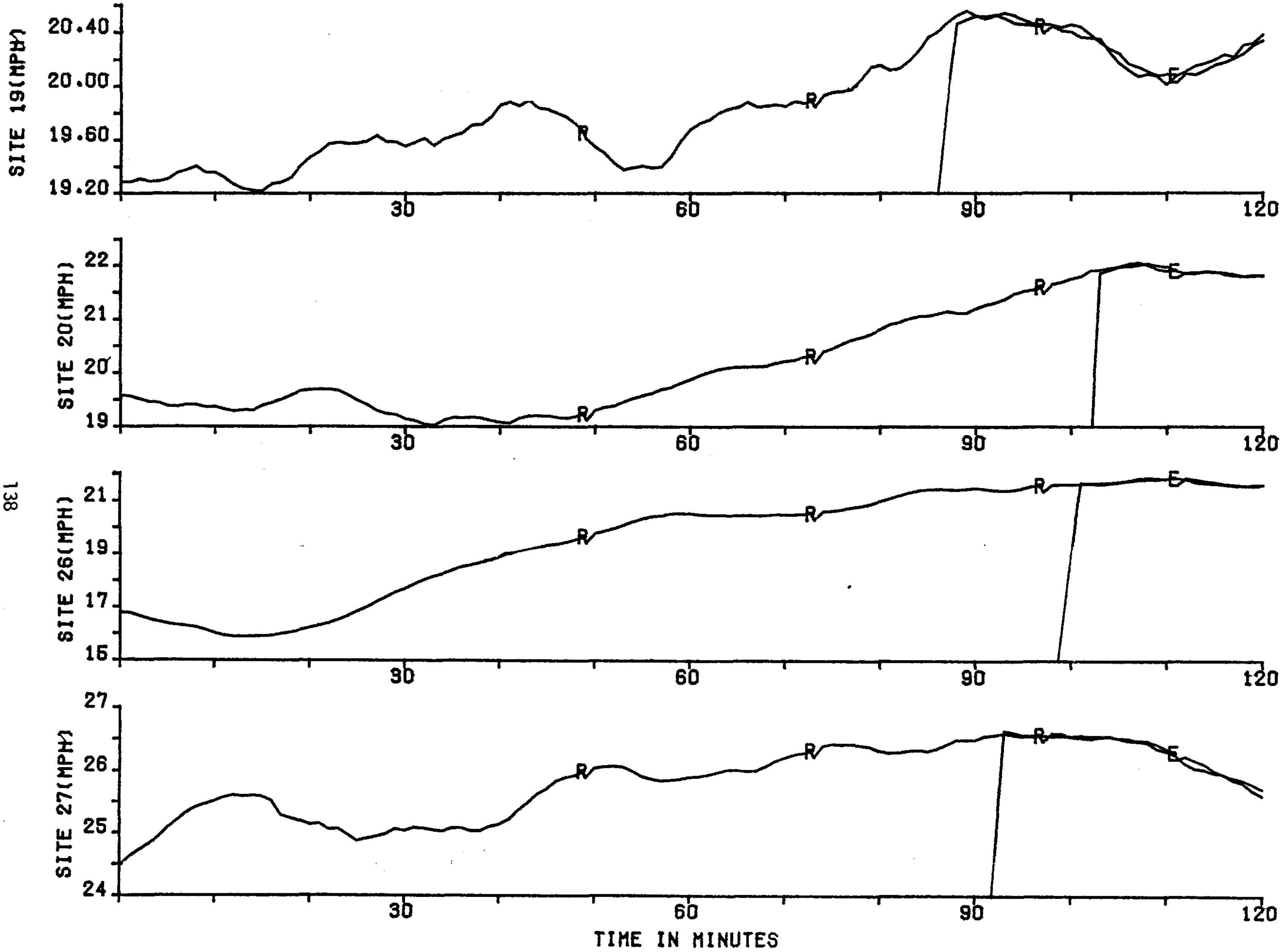


Figure 20a. Actual and predicted wind speed records using 10 minute filtered data on May 2, 1979 from 8:00 - 10:00 p.m.

SITES

SITES	1	2	3	4	5	6	7	8	9	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	---	.80	.61	.83	.79	.59	.53	.74	.65	.62	.71	.45	.73	.51	.55	.54	.72	.74	.59	.31	.62	.39	.86	.71	.54	.69
2	.66	---	.32	.51	.69	.71	.25	.58	.46	.32	.47	.26	.74	.24	.69	.28	.62	.59	.45	.36	.54	.21	.70	.54	.58	.54
3	.68	.57	---	.75	.74	.51	.80	.81	.78	.92	.93	.85	.66	.78	.31	.87	.50	.70	.77	.15	.63	.10	.62	.68	.42	.81
4	.83	.67	.75	---	.77	.63	.70	.70	.77	.77	.76	.66	.72	.55	.42	.65	.45	.70	.70	.16	.55	.14	.64	.53	.42	.67
5	.79	.74	.70	.77	---	.60	.55	.71	.75	.61	.75	.49	.70	.51	.43	.55	.55	.70	.70	.21	.61	.15	.65	.58	.43	.68
6	.35	.70	.23	.32	.44	---	.18	.34	.22	.21	.24	.18	.46	.16	.42	.20	.30	.23	.23	.22	.35	.20	.35	.43	.51	.37
7	.58	.55	.84	.73	.67	.54	---	.76	.81	.81	.79	.88	.64	.63	.39	.83	.51	.65	.68	.23	.63	.20	.56	.63	.37	.75
8	.74	.67	.79	.72	.73	.59	.66	---	.69	.75	.83	.64	.68	.63	.48	.62	.63	.83	.73	.26	.71	.24	.73	.72	.47	.81
9	.66	.64	.78	.77	.76	.68	.81	.74	---	.81	.77	.71	.69	.66	.26	.67	.36	.74	.79	.21	.57	.12	.50	.55	.38	.64
11	.71	.68	.93	.77	.83	.59	.77	.81	.82	---	.95	.74	.74	.83	.36	.81	.56	.78	.84	.17	.68	.13	.65	.66	.42	.85
12	.71	.69	.93	.76	.81	.58	.69	.84	.77	.92	---	.36	.64	.82	.39	.78	.62	.77	.84	.22	.69	.15	.68	.68	.44	.86
13	.60	.59	.88	.66	.66	.48	.88	.77	.69	.84	.83	---	.62	.68	.42	.88	.57	.65	.70	.26	.65	.20	.61	.64	.44	.74
14	.54	.74	.54	.57	.71	.67	.40	.68	.62	.55	.68	.68	---	.43	.51	.27	.49	.58	.76	.29	.58	.20	.55	.50	.50	.67
15	.71	.65	.78	.73	.75	.55	.75	.77	.78	.81	.33	.62	.43	---	.34	.68	.53	.82	.73	.18	.54	.14	.62	.51	.44	.69
16	.28	.66	.38	.37	.35	.60	.39	.31	.41	.40	.37	.37	.47	.29	---	.35	.23	.32	.42	.25	.32	.28	.34	.31	.64	.34
17	.65	.62	.87	.66	.64	.43	.82	.82	.67	.83	.84	.88	.59	.70	.49	---	.63	.72	.67	.34	.66	.31	.65	.74	.44	.81
18	.72	.73	.40	.45	.55	.45	.22	.63	.37	.44	.60	.26	.64	.46	.56	.28	---	.28	.69	.51	.67	.54	.87	.72	.50	.70
19	.74	.78	.68	.74	.72	.60	.60	.83	.71	.72	.77	.54	.73	.61	.55	.49	.69	---	.70	.34	.58	.27	.77	.57	.52	.80
20	.64	.62	.77	.66	.83	.62	.65	.75	.71	.79	.84	.68	.76	.70	.28	.64	.51	.70	---	.15	.62	.11	.54	.53	.36	.77
21	.20	.24	.23	.15	.24	.31	.16	.26	.21	.17	.21	.19	.26	.27	.33	.20	.53	.25	.18	---	.39	.57	.43	.57	.29	.29
22	.62	.65	.57	.50	.61	.54	.32	.72	.48	.56	.66	.41	.63	.48	.50	.47	.69	.63	.60	.39	---	.35	.69	.80	.49	.65
23	.39	.37	.28	.19	.37	.34	.20	.27	.27	.28	.28	.24	.37	.24	.51	.26	.60	.27	.28	.57	.30	---	.55	.48	.27	.31
24	.86	.83	.50	.64	.65	.54	.29	.73	.47	.54	.68	.28	.74	.43	.58	.36	.87	.77	.52	.48	.69	.55	---	.80	.56	.71
25	.71	.58	.57	.50	.58	.48	.30	.73	.40	.52	.68	.42	.58	.45	.46	.53	.73	.62	.51	.57	.80	.48	.80	---	.47	.67
26	.23	.21	.39	.35	.38	.38	.39	.31	.39	.40	.39	.35	.32	.34	.36	.35	.16	.32	.42	.34	.28	.25	.18	.32	---	.31
27	.71	.68	.77	.69	.76	.51	.53	.81	.63	.78	.85	.59	.75	.69	.49	.58	.71	.80	.77	.29	.61	.31	.72	.67	.46	---

Table 21a. Peak correlation matrix for 10 minute filtered data of April 14, 1979 from 7:30 - 12:30 p.m.

	SITES																									
SITES	1	2	3	4	5	6	7	8	9	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	---	.82	.77	.92	.88	.69	.65	.88	.82	.77	.85	.62	.83	.69	.55	.60	.78	.90	.80	.30	.80	.27	.91	.77	.53	.86
2	.74	---	.36	.61	.78	.82	.21	.63	.54	.34	.50	.25	.84	.20	.74	.26	.65	.65	.56	.43	.67	.27	.75	.57	.64	.60
3	.84	.65	---	.87	.82	.62	.88	.90	.87	.94	.96	.93	.74	.85	.38	.93	.63	.80	.88	.21	.81	.18	.76	.81	.46	.88
4	.92	.69	.86	---	.83	.73	.80	.84	.90	.85	.86	.76	.80	.71	.43	.73	.55	.84	.82	.20	.67	.09	.75	.65	.43	.83
5	.88	.81	.77	.83	---	.82	.64	.82	.83	.70	.81	.59	.87	.60	.46	.56	.63	.79	.85	.25	.78	.15	.74	.67	.47	.79
6	.50	.77	.29	.47	.58	---	.14	.48	.28	.17	.34	.17	.58	.12	.46	.18	.37	.31	.35	.22	.52	.19	.51	.59	.56	.46
7	.72	.61	.88	.83	.73	.66	---	.82	.89	.86	.84	.93	.71	.74	.40	.89	.57	.74	.77	.28	.77	.23	.67	.74	.41	.83
8	.88	.71	.87	.85	.82	.67	.73	---	.81	.81	.90	.74	.79	.74	.49	.72	.71	.90	.84	.27	.86	.28	.84	.84	.50	.90
9	.82	.70	.87	.90	.86	.82	.89	.82	---	.88	.87	.79	.82	.77	.30	.75	.42	.83	.89	.23	.75	.09	.62	.68	.43	.76
11	.87	.76	.95	.87	.92	.75	.83	.89	.89	---	.91	.85	.71	.89	.41	.87	.67	.85	.94	.20	.83	.17	.78	.75	.48	.91
12	.87	.74	.95	.86	.89	.70	.78	.91	.87	.95	---	.41	.71	.88	.43	.84	.70	.85	.93	.25	.84	.21	.80	.79	.48	.93
13	.77	.66	.94	.79	.75	.60	.93	.86	.79	.90	.74	---	.78	.78	.47	.97	.66	.76	.80	.31	.80	.29	.75	.79	.48	.86
14	.77	.85	.61	.70	.88	.80	.46	.74	.73	.61	.88	.78	---	.53	.58	.36	.63	.73	.84	.32	.75	.21	.72	.62	.53	.76
15	.85	.74	.85	.82	.83	.68	.78	.85	.85	.88	.88	.71	.72	---	.43	.79	.65	.89	.83	.26	.68	.22	.74	.60	.52	.80
16	.32	.73	.43	.41	.41	.56	.39	.38	.43	.42	.43	.40	.54	.33	---	.40	.22	.31	.48	.28	.36	.32	.29	.37	.70	.37
17	.77	.65	.93	.73	.70	.52	.88	.86	.75	.87	.89	.97	.65	.80	.50	---	.70	.78	.77	.37	.79	.39	.77	.81	.47	.86
18	.78	.75	.49	.55	.64	.50	.21	.71	.46	.52	.66	.26	.70	.57	.64	.27	---	.77	.56	.58	.79	.62	.92	.76	.56	.78
19	.90	.82	.77	.85	.83	.71	.70	.90	.83	.81	.85	.65	.81	.74	.58	.58	.77	---	.80	.39	.76	.30	.87	.68	.58	.87
20	.83	.72	.88	.83	.93	.78	.76	.86	.88	.87	.93	.76	.84	.81	.33	.74	.59	.80	---	.16	.80	.12	.69	.69	.41	.87
21	.19	.20	.16	.15	.18	.23	.15	.20	.19	.13	.25	.14	.16	.34	.35	.14	.57	.21	.13	---	.40	.75	.41	.58	.27	.34
22	.80	.74	.72	.67	.78	.75	.46	.86	.63	.68	.82	.54	.76	.60	.53	.58	.79	.75	.76	.40	---	.36	.85	.89	.51	.82
23	.27	.28	.21	.18	.25	.35	.21	.27	.26	.17	.21	.19	.34	.33	.52	.19	.65	.43	.18	.75	.36	---	.52	.49	.24	.42
24	.91	.81	.63	.75	.74	.61	.42	.84	.62	.64	.77	.44	.78	.60	.60	.44	.92	.87	.68	.47	.85	.52	---	.86	.59	.86
25	.77	.60	.70	.65	.66	.61	.42	.84	.51	.60	.78	.55	.63	.57	.46	.60	.76	.68	.66	.58	.89	.49	.86	---	.45	.81
26	.34	.23	.40	.43	.41	.41	.43	.34	.43	.41	.39	.38	.35	.33	.41	.35	.18	.37	.44	.27	.36	.18	.24	.37	---	.33
27	.87	.75	.86	.83	.85	.62	.61	.90	.76	.86	.93	.69	.82	.80	.54	.68	.78	.87	.87	.33	.82	.40	.86	.81	.48	---

Table 21b. Peak correlation matrix for 30 minute filtered data of April 14, 1979 from 7:30 - 12:30 p.m.

	Individual Site Delays					Group/Site	Errors for 2 Hour Filtered Data		Errors for 10 Minute Filtered Data	
Site	T_{i18}	T_{i19}	T_{i22}	T_{i24}	T_{i25}	T_i	Individual Site	Group/Site	Individual Site	Group/Site
		(minutes)					(mph)	(mph)	(mph)	(mph)
1	1	1	1	1	1	1	0.40	0.93	2.28	2.52
2	18	26	13	19	10	17	0.57	1.28	1.84	2.53
3	1	1	1	1	1	1	0.41	1.19	3.14	4.05
4	1	20	1	1	1	5	0.39	1.41	2.74	3.60
5	1	27	1	1	1	6	0.63	1.93	3.34	4.35
6	20	52	29	50	7	32	0.17	0.62	1.45	1.93
7	254*	1	1	1	1	1	0.03	1.69	0.39	3.69
8	1	1	4	1	5	2	0.36	0.98	1.89	2.47
9	21	22	1	1	1	9	0.67	1.39	2.31	3.18
11	1	1	1	1	1	1	0.29	1.59	2.48	3.00
12	1	1	2	1	1	1	0.46	1.88	2.86	3.34
13	255*	1	1	1	1	1	0.07	1.27	0.46	3.16
14	23	24	16	18	12	19	0.21	1.00	1.50	1.67
15	1	1	2	1	1	1	0.63	0.96	1.98	2.08
16	48	52	60	49	59	54	0.20	0.24	1.60	1.82
17	253*	1	1	1	1	1	0.53	1.66	0.78	4.31
20	1	1	1	1	1	1	0.29	0.62	1.76	2.11
21	123	121	1	125	1	74	0.15	0.97	0.99	2.50
23	1	1	6	1	1	2	0.60	0.89	2.18	2.40
26	101	90	111	112	117	101	0.18	0.38	1.40	2.09
27	1	1	6	1	1	2	0.29	0.86	1.92	2.31

Table 22. Delays and prediction errors of each site for reference sites 18, 19, 22, 24, and 25 with 2 hour and 10 minute filtered data of April 14, 1979.

*In taking the average of delays this delay is assumed 1.

smaller than the errors for the 10 minute moving average filtered data because turbulence and site specific effects are eliminated but also because wind speed variations in the meteorological event are smoothed and thus distorted.

The time plots of the predicted and actual wind speed records for 2 hour and 10 minute moving average data is given in Figures 22 and 23, respectively. The 2 hour ahead prediction appears very accurate compared to the 2 hour moving average filtered data in the sense of correctly predicting the maximums, minimums, and average values, the time of occurrence of the maximums and minimums, and the slopes. The errors for the 10 minute moving average prediction are considerably larger and clearly had peculiar site specific properties. Comparing the prediction on the 2 hour moving average filtered data with the predictions using 10 minute moving data, the longer smoothing caused serious distortions by reducing the maximum wind speed, increasing the minimum wind speed predictions, causing the increases in wind speed and decreases in wind speed to occur earlier, and shifting the time of occurrence of actual maximum and minimum wind speeds. Thus, although some filtering of the wind speed records is necessary, the 2 hour smoothing interval is too long. A 20 or 30 minute smoothing interval would appear to be appropriate in the sense of eliminating turbulence and site specific phenomena without distorting the characteristics of the wind speed associated with the meteorological event.

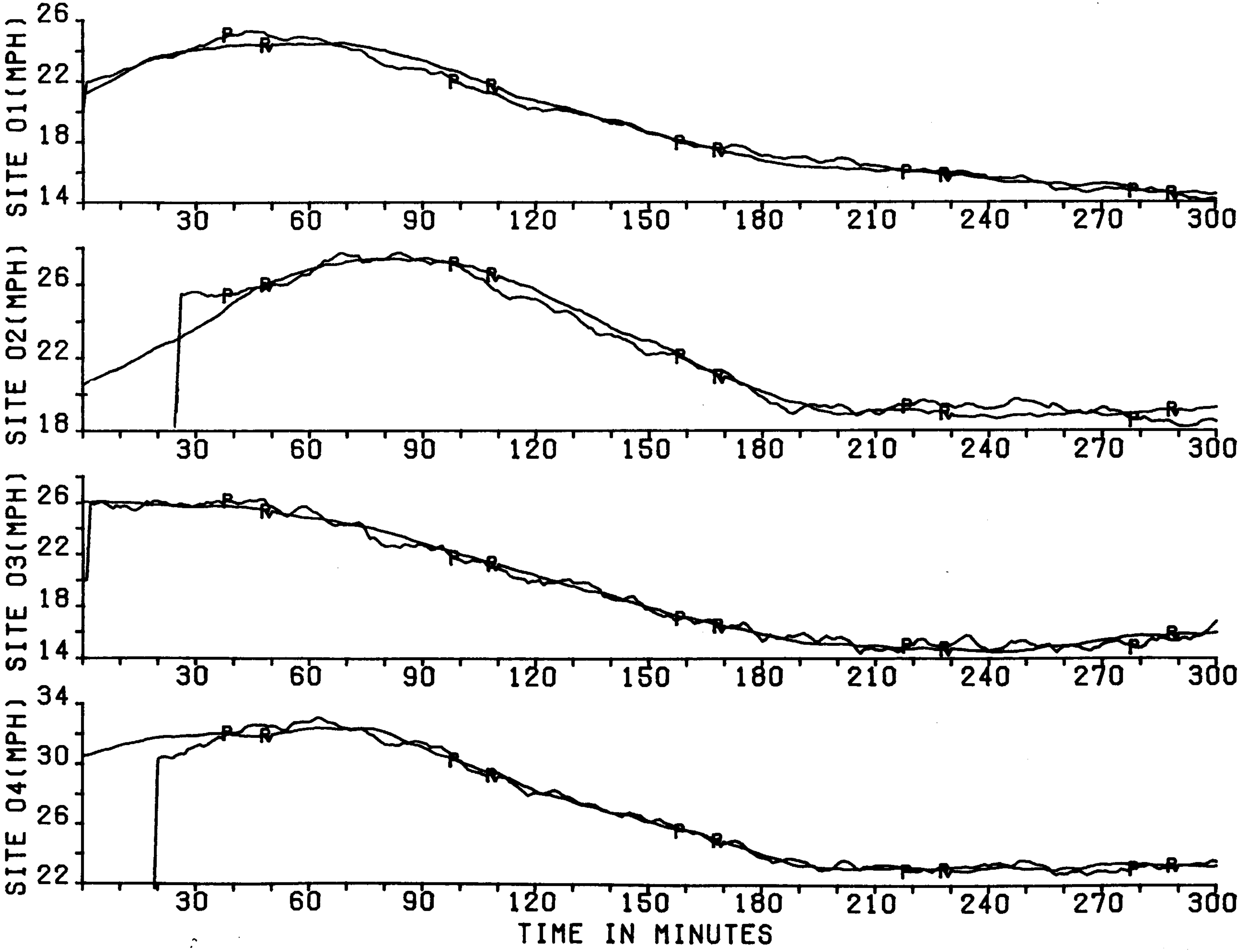


Figure 22. Actual and predicted wind speeds using 2 hour filtered data on April 14, 1979 from 7:30 - 12:30 p.m.

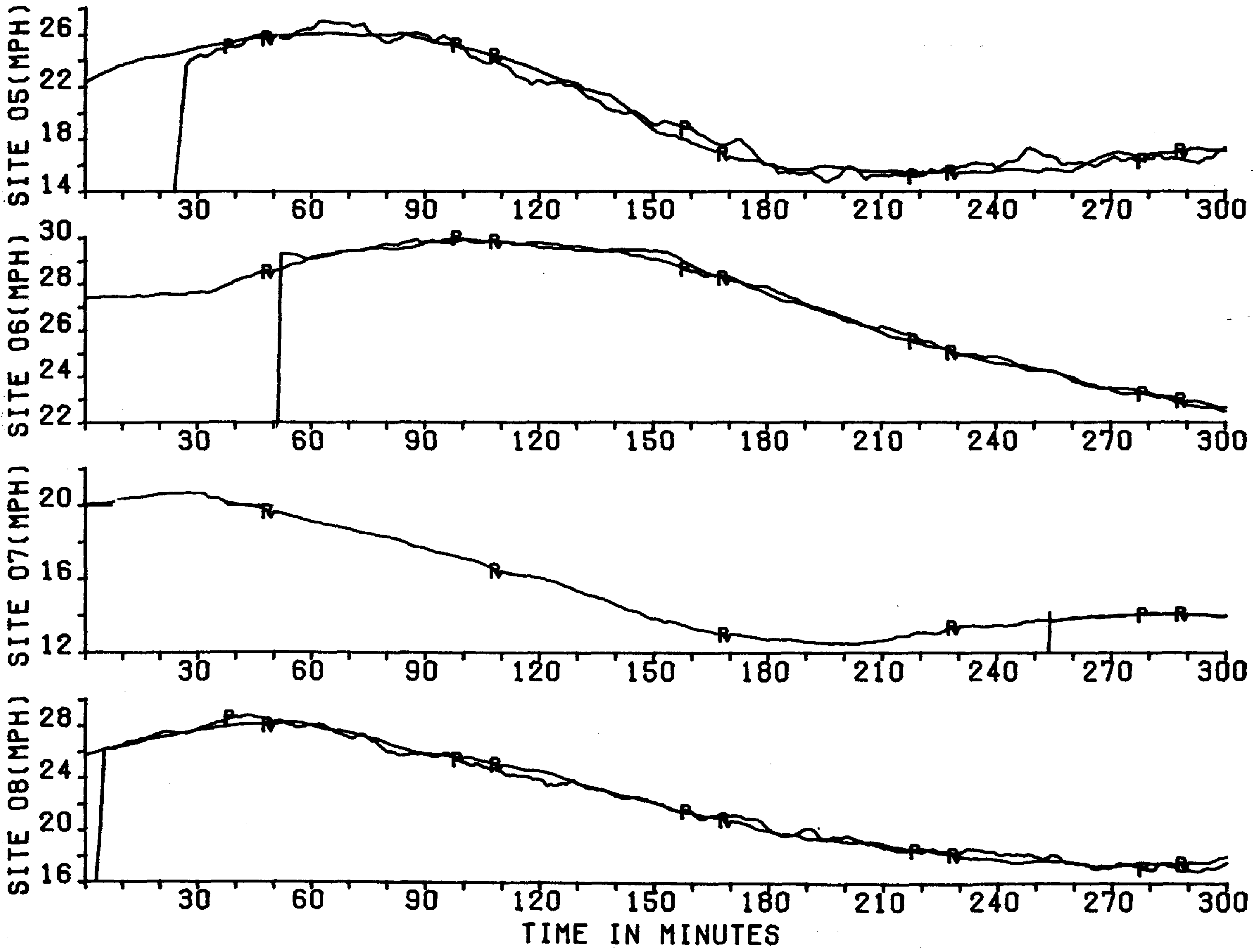


Figure 22a. Actual and predicted wind speeds using 2 hour filtered data on April 14, 1979 from 7:30 - 12:30 p.m.

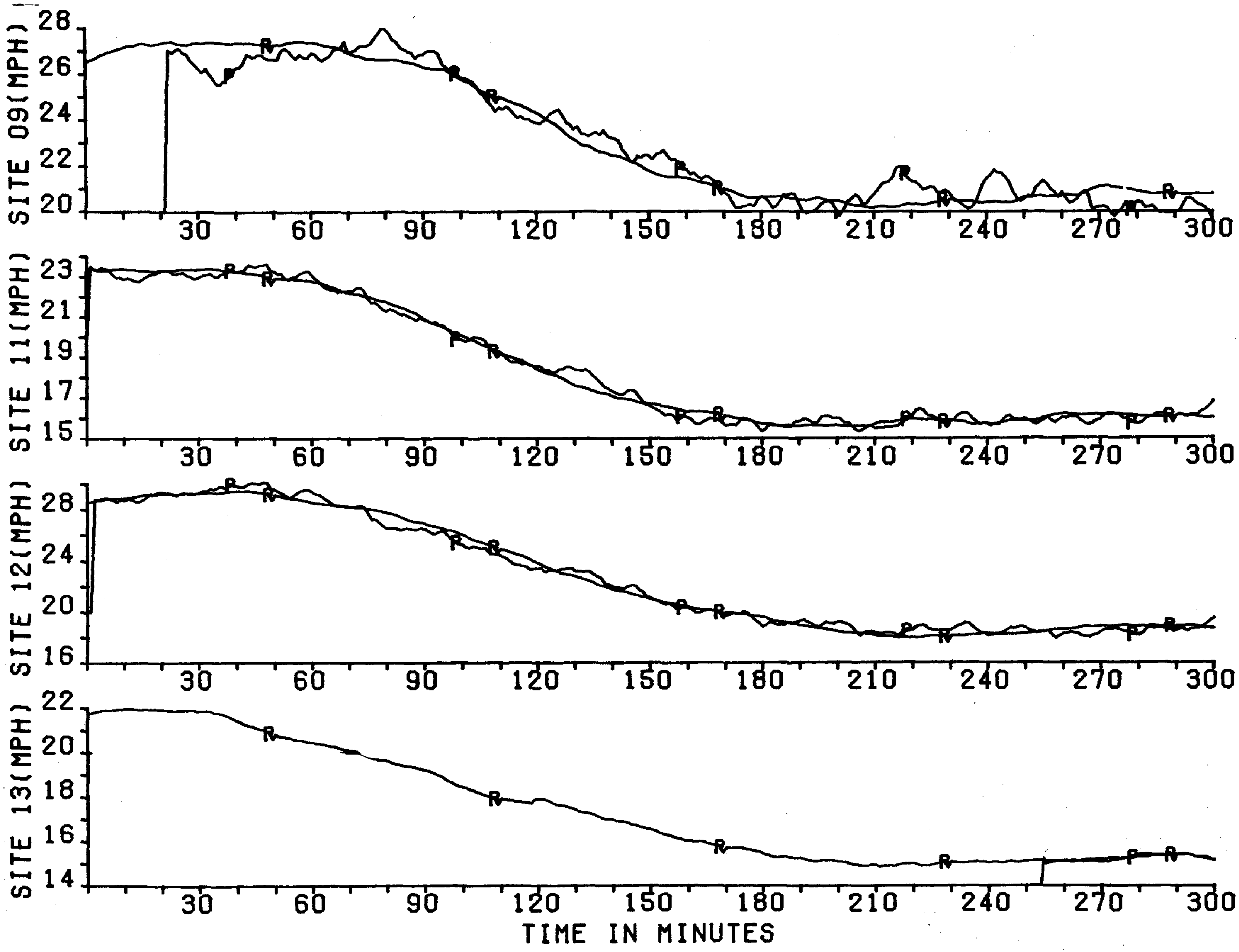


Figure 22b. Actual and predicted wind speeds using 2 hour filtered data on April 14, 1979 from 7:30 - 12:30 p.m.

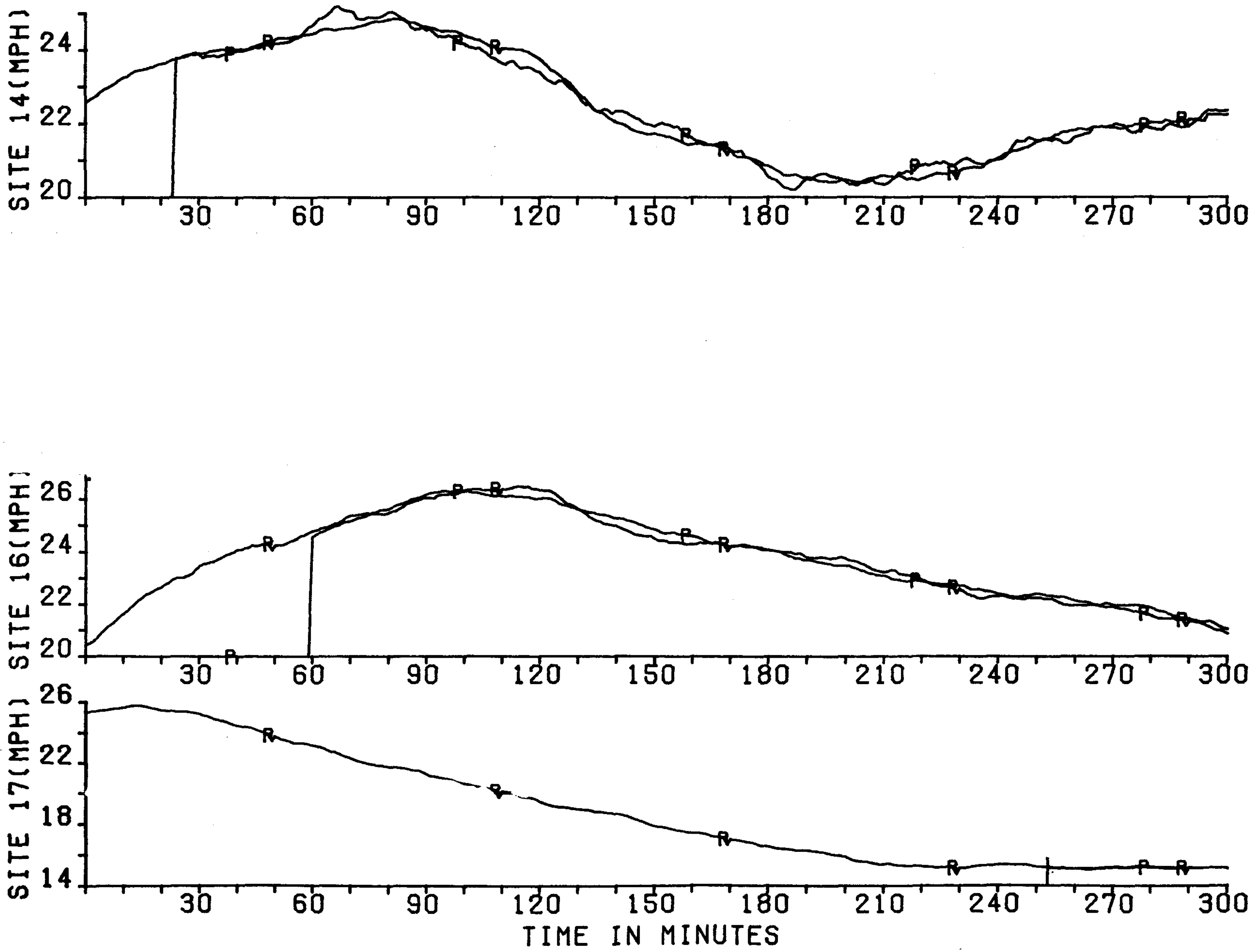


Figure 22c. Actual and predicted wind speeds using 2 hour filtered data on April 14, 1979 from 7:30 - 12:30 p.m.

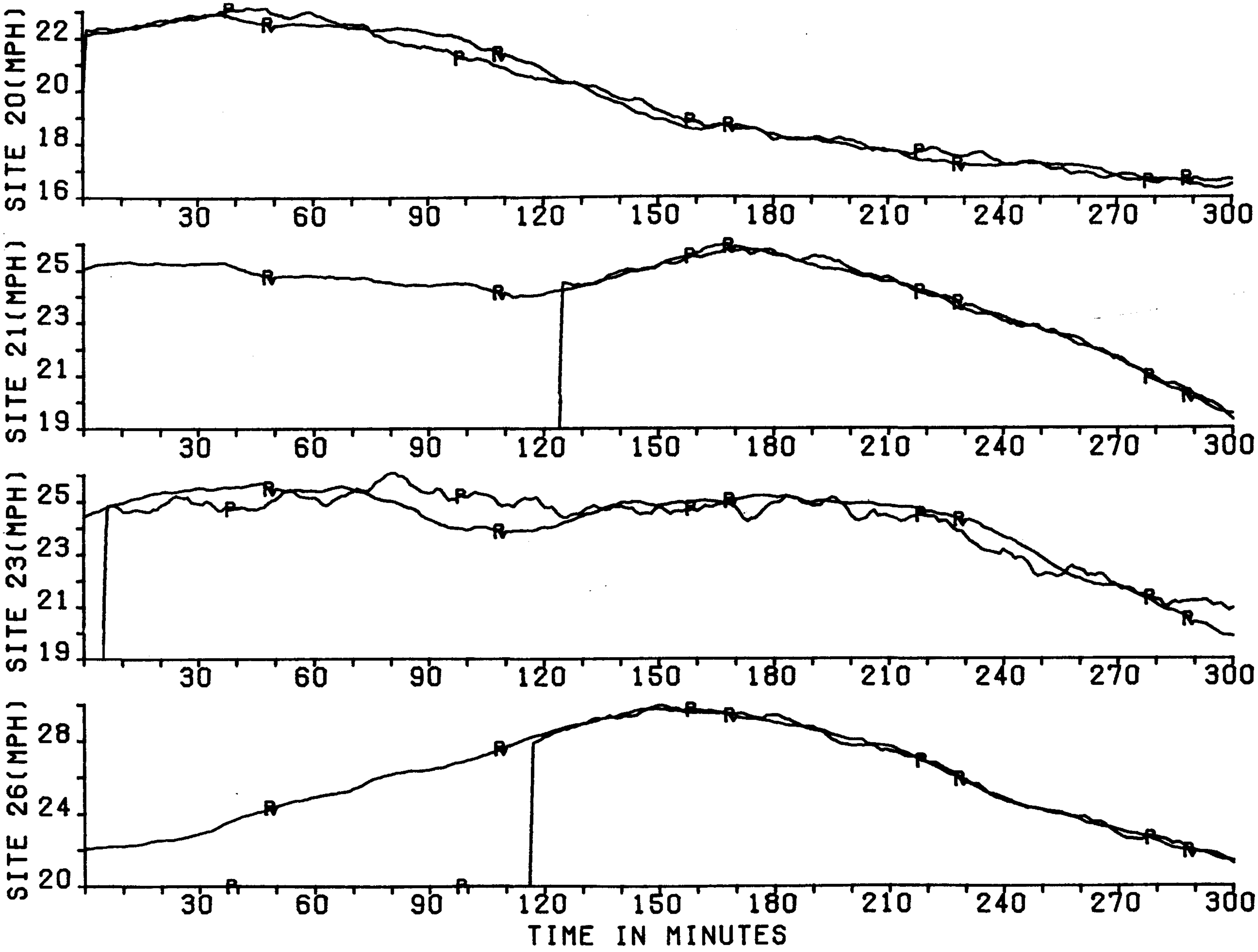


Figure 22d. Actual and predicted wind speeds using 2 hour filtered data on April 14, 1979 from 7:30 - 12:30 p.m.

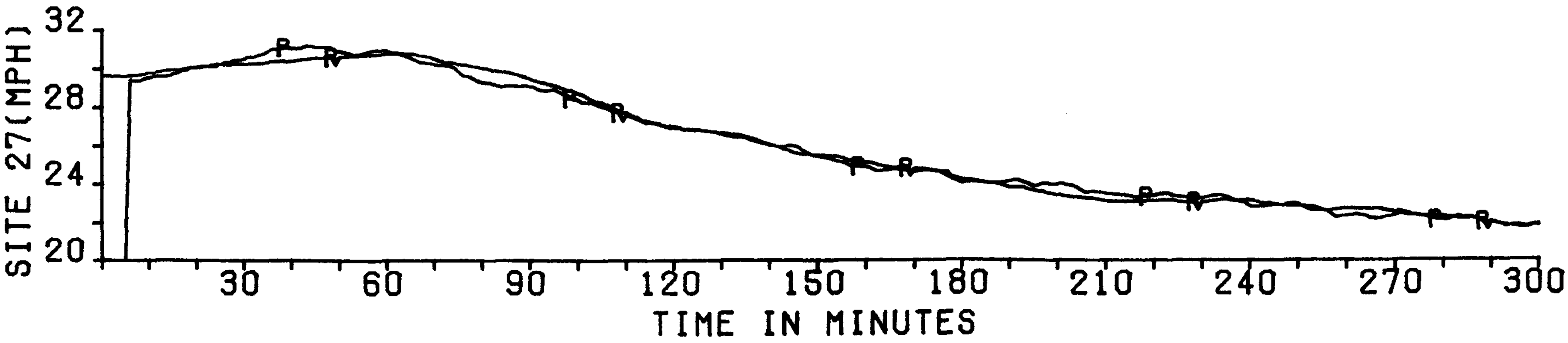


Figure 22e. Actual and predicted wind speeds using 2 hour filtered data on April 14, 1979 from 7:30 - 12:30 p.m.

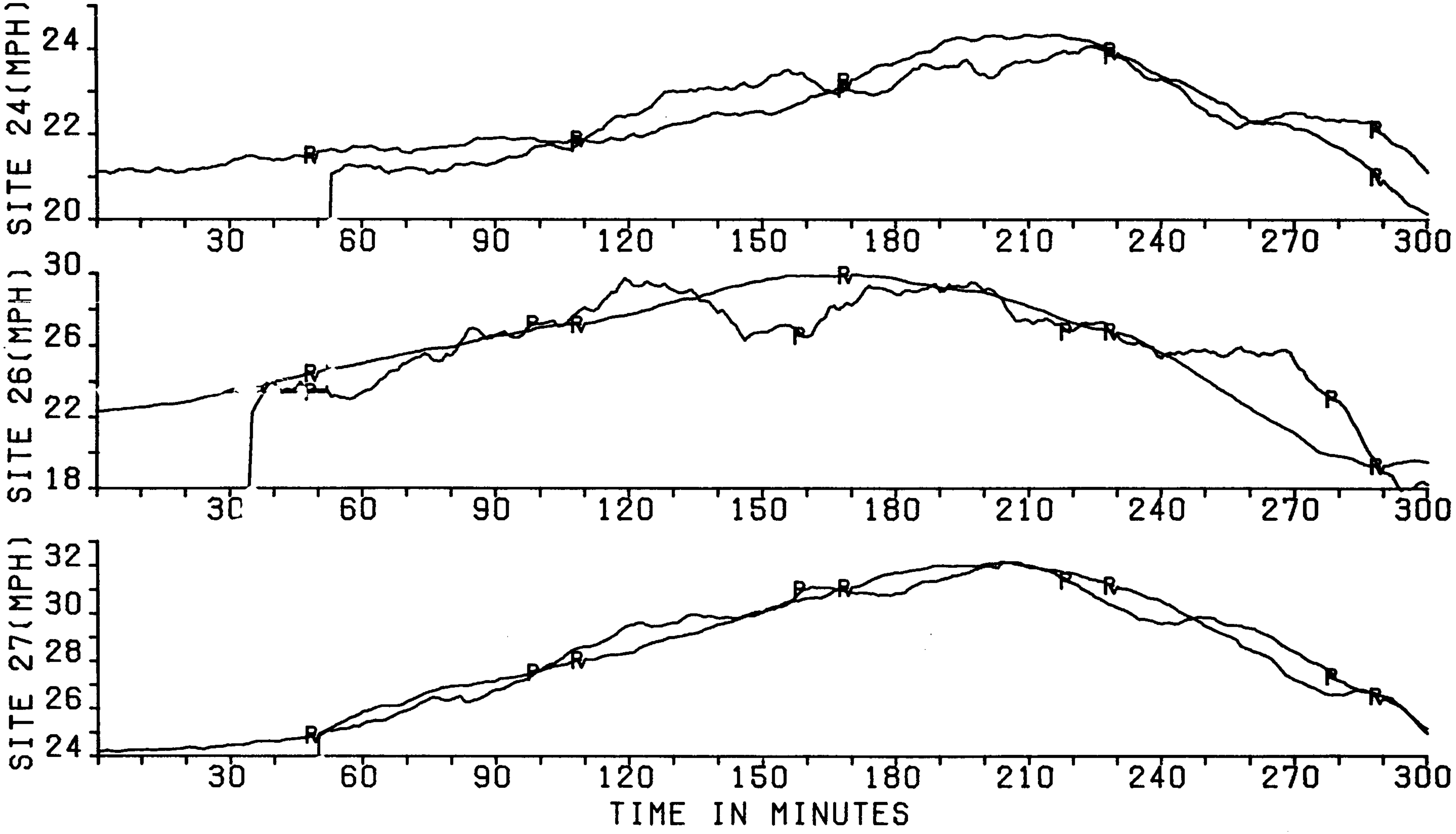


Figure 22f. Actual and predicted wind speeds using 2 hour filtered data on April 14, 1979 from 7:30 - 12:30 p.m.

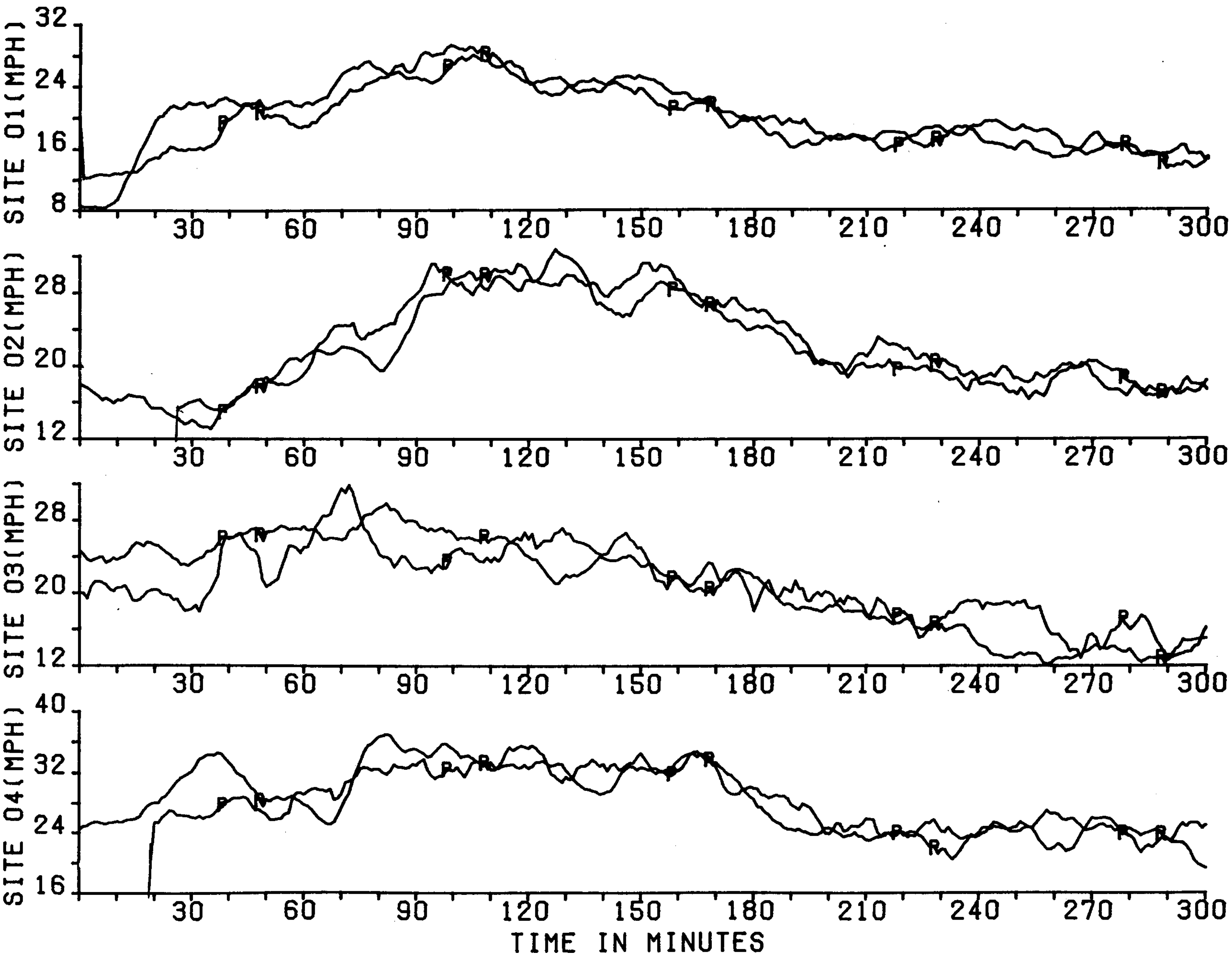


Figure 23. Actual and predicted wind speeds using 10 minute moving average data on April 14, 1979 from 7:30 - 12:30 p.m.

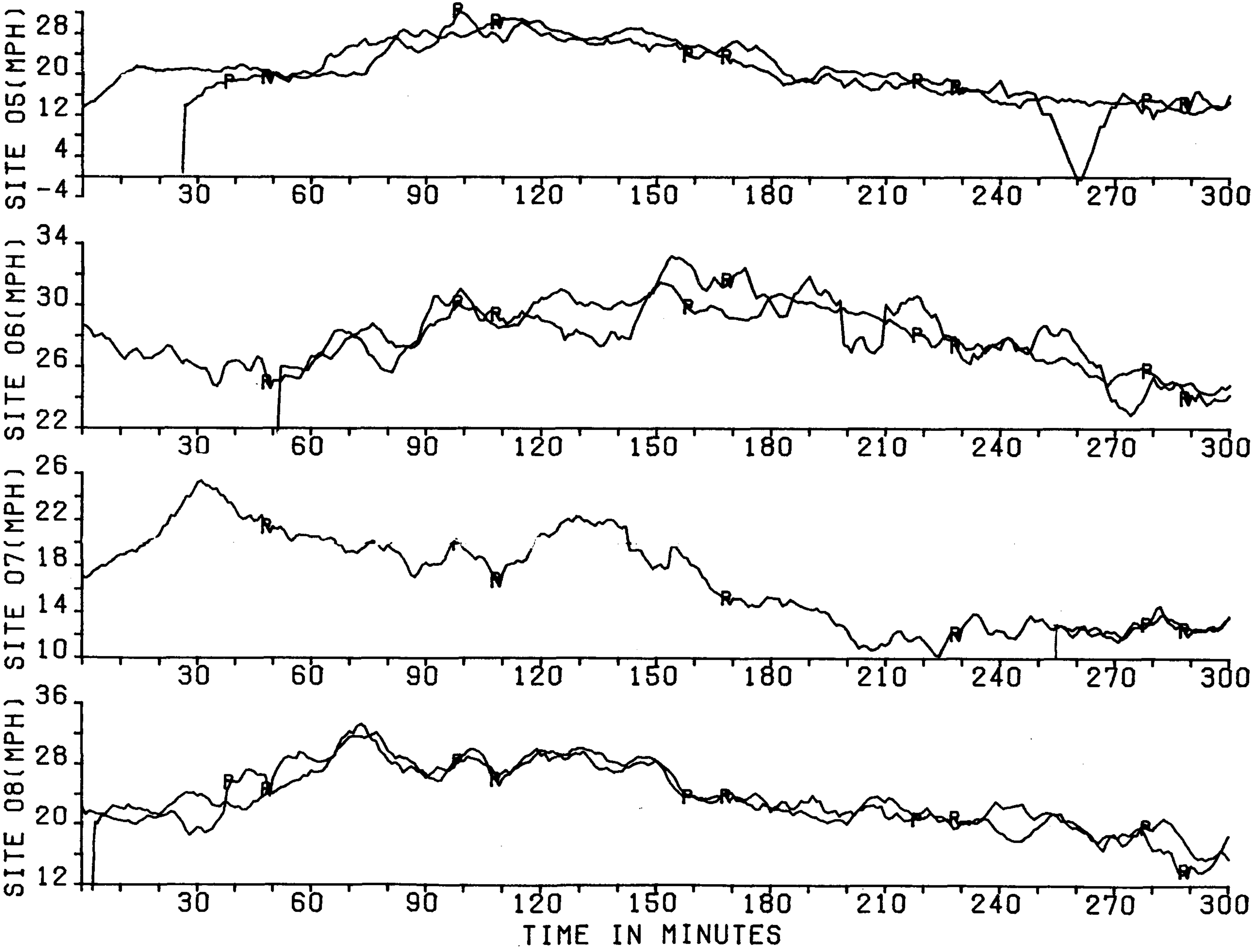


Figure 23a. Actual and predicted wind speeds using 10 minute moving average data on April 14, 1979 from 7:30 - 12:30 p.m.

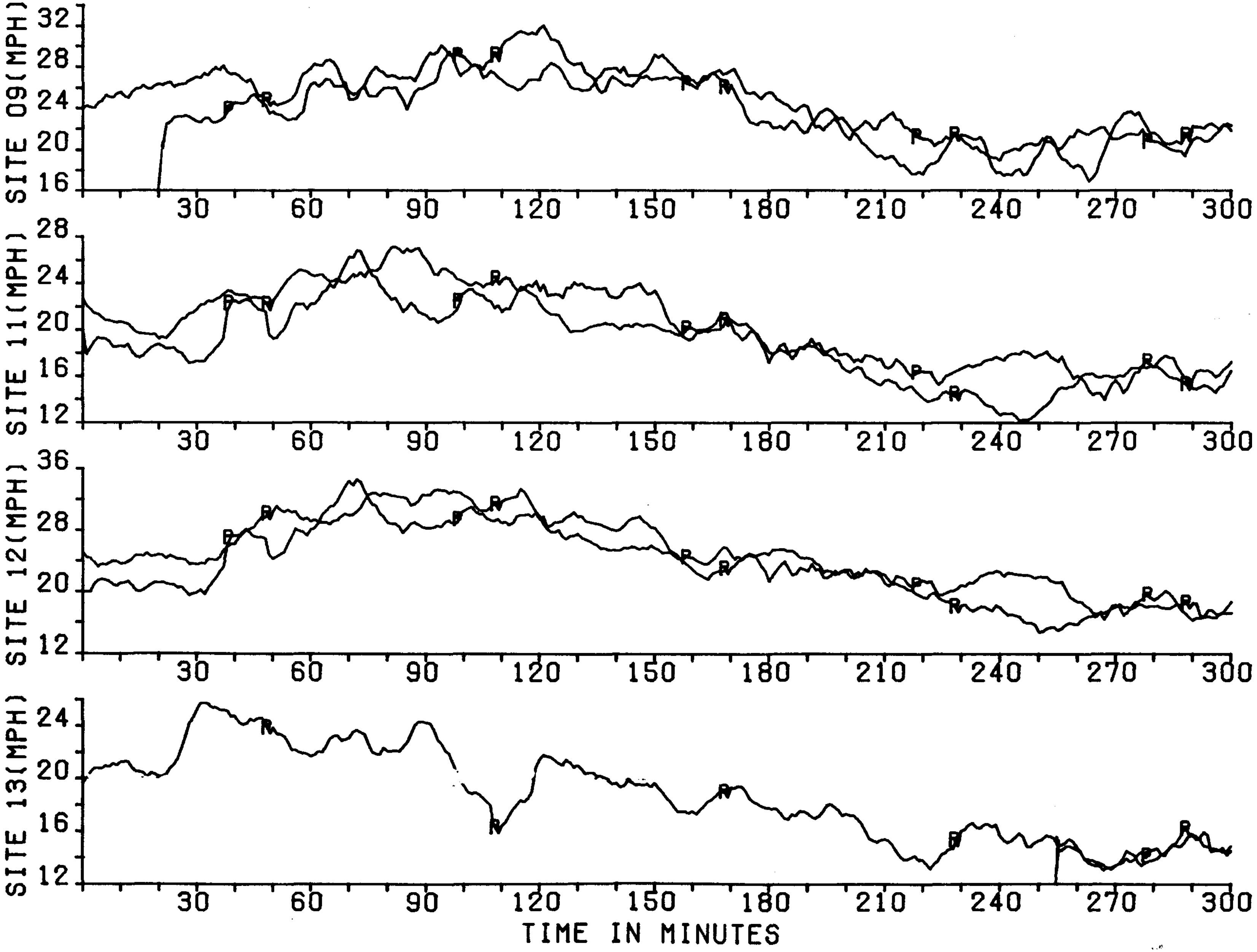


Figure 23b. Actual and predicted wind speeds using 10 minute moving average data on April 14, 1979 from 7:30 - 12:30 p.m.

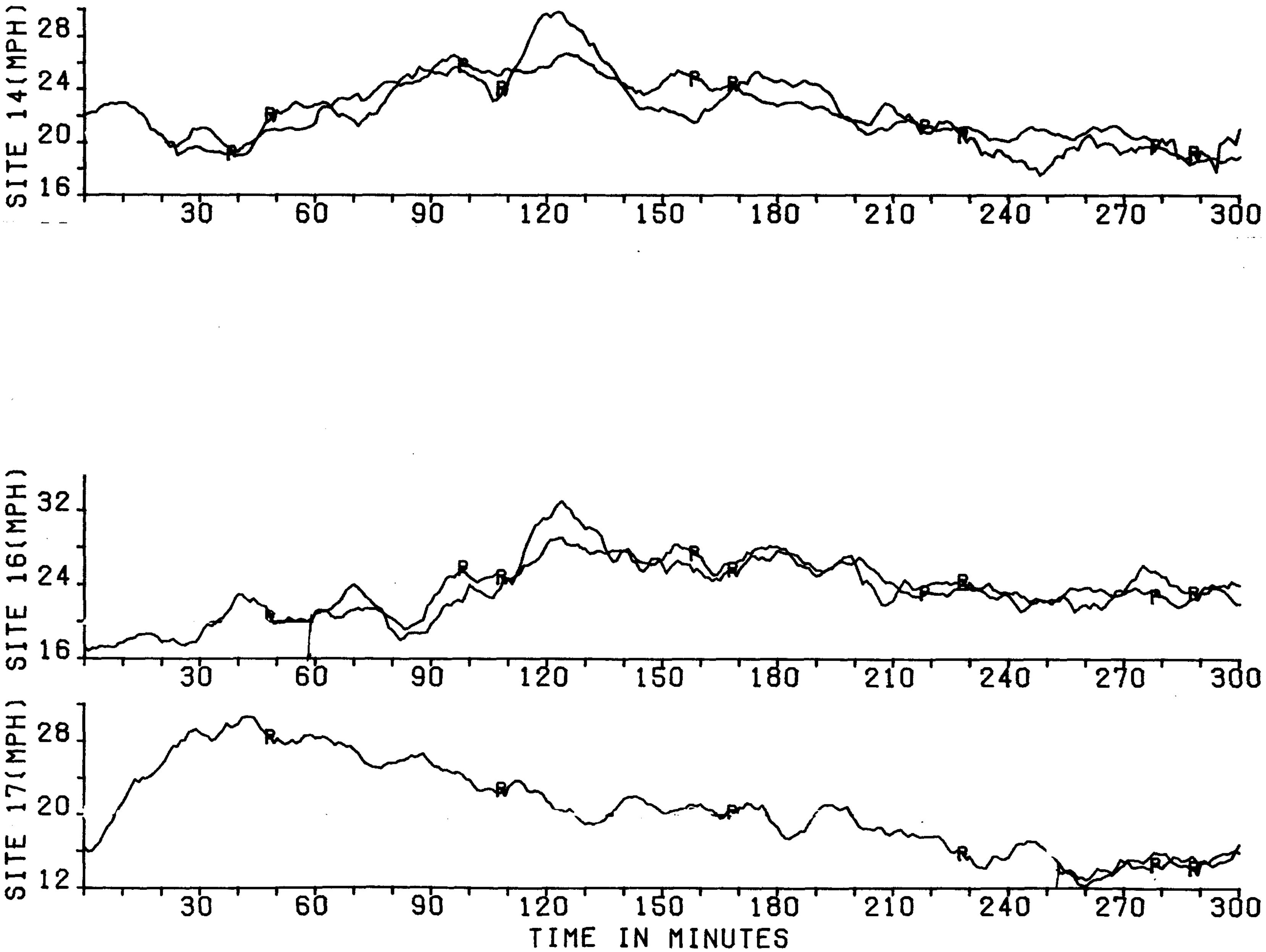


Figure 23c. Actual and predicted wind speeds using 10 minute moving average data on April 14, 1979 from 7:30 - 12:30 p.m.

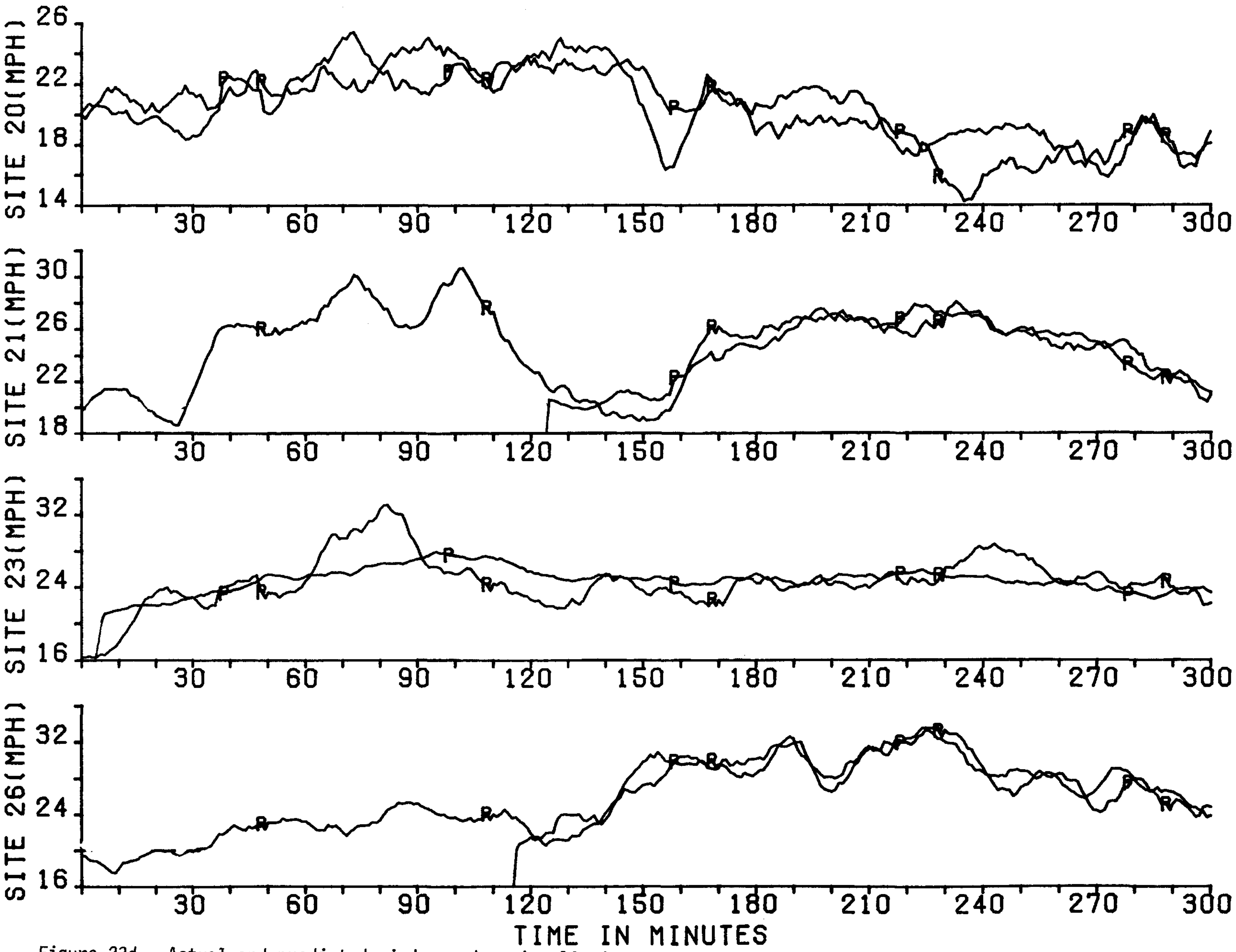


Figure 23d. Actual and predicted wind speeds using 10 minute moving average data on April 14, 1979 from 7:30 - 12:30 p.m.

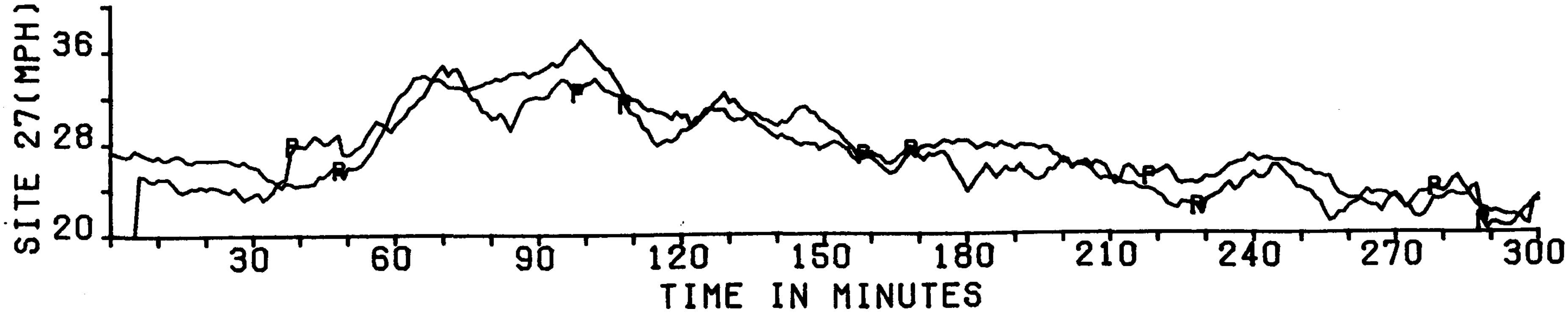


Figure 23e. Actual and predicted wind speeds using 10 minute moving average data on April 14, 1979 from 7:30 - 12:30 p.m.

SECTION 5

APPLICATION OF PREDICTION METHODOLOGY TO GOODNOE HILLS DATA

The application of the prediction methodology to Goodnoe Hills data is undertaken in this section. Goodnoe Hills is composed of three wind turbine sites and two meteorological towers as shown in Figure 24. The distances between wind turbines #1, #2, and #3 and the Pacific Northwest Laboratory Tower (PNL) and the Bonneville Power Administration (BPA) Tower and their elevations above sea level are given in Table 23. Wind speed and direction measurements are available on the two meteorological towers and wind speed, wind power, and yaw angle measurements are available at the wind turbines. The measurements are all taken at or about MOD-2 wind turbine hub height (200 ft), whereas the wind measurements on the SESAME array towers were taken at a height of 13 feet. The measurements in Goodnoe Hills will, therefore, not have the large turbulence component that existed on the SESAME data. The measurements at Goodnoe Hills are sampled 2 minute averages and the effects of turbulence and the averaging interval on this 2 minute sampled data on the prediction methodology will be investigated. The measurement locations are within two-thirds of a mile of each other and thus the delays between sites and the direction of propagation would be thought to be more difficult to determine than on the SESAME array where the locations were never closer than 2 miles apart and were spread over an 80 x 80 mile square area. The peak correlation between sites should be larger on the Goodnoe Hills data due to their geographical proximity.

The Goodnoe Hills study involves a study of wind speed prediction at wind turbine units 2 and 3 and the BPA tower based on wind speed measurements at the PNL tower. The groups of measurement sites, the direction of propagation, and the delay due to propagation of the event from the PNL site to wind turbines was determined for both 2 minute and 10 minute averaged data. The errors for both the 2 minute and 10 minute averaged data was computed and the actual and predicted wind speeds record at wind turbine #2 and #3 and the BPA tower were plotted.

A second study of direct prediction of power out of wind turbines #1, #2, and #3 were based on wind speed measurements at the BPA tower.

5.1 WIND SPEED PREDICTION

The wind speed prediction methodology is applied to wind speed measurements from wind turbines #2 and #3, the BPA tower, and the PNL tower. The peak correlation $P_{ij}(T_{ij})$ matrix, where the correlation between wind speed record at sites i and j is maximum as for function of delay (τ) for each pair of sites ij,

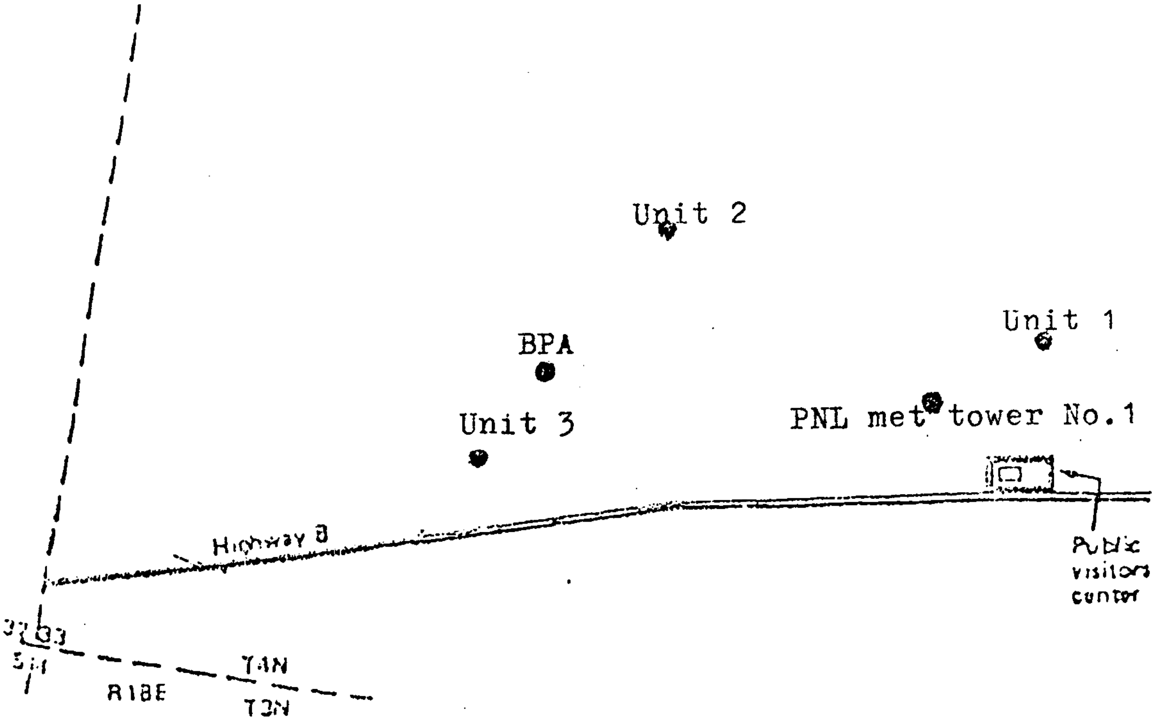


Figure 24a. Goodnoe Hills site location plan with original names.

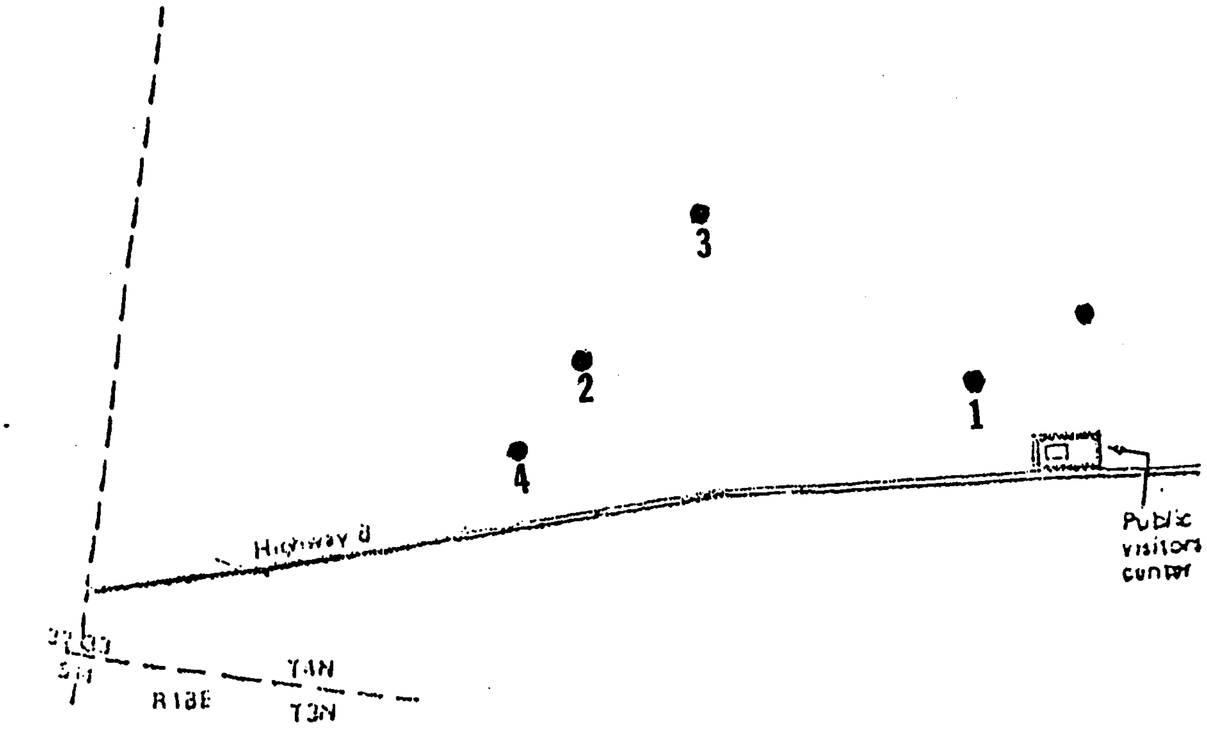


Figure 24b. Goodnoe Hills site location plan with number for each site used in calculations.

UNIT	#1	#2	#3	BPA TWR #2	PNL TWR #1	Base Elev. Above Sea Level
#1	---	2014	3046	2693	645	2622
#2	2014	---	1505	991	1726	2574
#3	3046	1505	---	523	2504	2568
BPA TWR	2693	991	523	---	2213	2577
PNL TWR	645	1726	2504	2213	---	2624

Table 23. Distances between major site features at Goodnoe Hills (all measurements in feet).

is given in Tables 24a and 24b for 2 minute averaged and 10 minute moving average filtered data, respectively. The peak correlations for the 10 minute moving average data are extremely large compared to those using 10 minute moving average data on the SESAME array. This result is expected due to the close proximity of these sites compared to sites in the SESAME array and because the Goodnoe Hills data is measured at MOD-2 wind turbine hub height (200 feet) rather than 13 feet and thus the data has a smaller turbulence component. The sites 2, 3, and 4, which represent the BPA tower, wind turbine #2, and wind turbine #3, respectively, are highly correlated and form a group and site 1 forms a single site group. Figure 24 shows that sites 2, 3, and 4 lie on a straight line and are very close together compared to the distances between these sites and site 1. The groups formed based on pairwise correlations and small delays correspond to groups based on geographical distances between sites.

The direction of propagation of the meteorological event can be detected from the correlation table by noting that the first column value i1 are much larger than correlation table elements 1i in the first row but the correlation ij and ji are identical for i,j = 2,3,4. The results suggest that the wind direction is from site 1 toward sites 2, 3, and 4 since the wind record i is advanced in time with respect to signal 2, 3, and 4 to produce the peak correlations in column 1. The number of samples k_{ij} that the wind record j is advanced relative to record j to produce peak correlation $P_{ij}(k_{ij}\Delta)$ where $\Delta = 2$ minutes is given in the delay Tables 25a and 25b for the 2 minute and 10 minute moving average filtered wind records. Note that the elements in these delay tables are all 1 except for column 1. A delay of 1 was the minimum value tested and thus indicates that advancing sites 2, 3, and 4 only reduced the correlation but advancing the time record of site 1 improved correlation, thus confirming site 1 was the first site affected by the propagation. The delays in the first column of the delay table for the 2 minute sampled data was 2 samples, which implies a 4 minute delay between the time the event affects site 1 and the time it affects sites 2-4. The delays for the 10 minute averaged data were slightly different but were ignored because the length of the smoothing interval was longer than the delay for the 2 minute data. A smoothing interval can shift the maximum and minimum of a periodic pulse waveform by a quarter of the period of the pulse waveform if the smoothing interval is half the period of the periodic signal. A shorter smoothing interval causes less time shift but still will distort the propagation delays. The determined was for the meteorological event, as observed by the drop in wind speed and the wind direction change, to propagate from the PNL tower and is not a dependent on the wind speed measured at these sites.

The errors for the prediction using the individual site prediction model are given in Table 26 for both the 2 minute and

	SITES			
SITES	1	2	3	4
1	---	.82	.78	.77
2	.87	---	.91	.90
3	.82	.91	---	.84
4	.79	.90	.84	---

Table 24a. Correlation table with 2 minute average data of Goodnoe Hills.

	SITES			
SITES	1	2	3	4
1	---	.94	.87	.90
2	.95	---	.95	.97
3	.89	.96	---	.97
4	.90	.97	.96	---

Table 24b. Correlation table with 10 minute moving average data of Goodnoe Hills.

	SITES (samples)			
SITES	1	2	3	4
1	---	1	1	1
2	2	---	1	1
3	2	1	---	1
4	2	1	1	---

Table 25a. Delay table 2 minute average data of Goodnoe Hills.

	SITES (samples)			
SITES	1	2	3	4
1	---	1	1	1
2	2	---	1	1
3	3	2	---	3
4	1	1	1	---

Table 25b. Delay table of 10 minute average data of Goodnoe Hills.

Site No.	Error with 2 Minute Data (mph)	Error with 10 Minute Filtered Data (mph)
2	1.86	0.95
3	2.00	1.29
4	2.23	1.31

Table 26. Errors for prediction with 2 minute and 10 minute moving average filtered data of Goodnoe-Hills using site 1 as reference.

10 minute averaged data using the delays for each given in Tables 25a and 25b. The errors for the 10 minute averaged data are much smaller than for 10 minute averaged signals on the SESAME array indicating the excellent quality of the prediction due to the proximity of the reference and prediction sites and thus the high correlation. The 10 minute moving average data also had much smaller turbulence because it was measured at a height of 200 feet rather than at 13 feet. The excellent performance of the 10 minute moving average predictions and the relative small level of turbulence is observed in the time plots of the predicted and actual wind speed records at sites 2-4 in Figure 25.

The errors for the 2 minute averaged data are larger than the error for the 10 minute averaged data from Table 26. The plot of the actual and predicted wind speed records at sites 2-4 for the 2 minute averaged data is shown in Figure 26. The turbulence effects are clearly seen in these records. This turbulence will cause the cyclic wind power variations on wind power that must be handled by feedforward control of fast responding diesels, gas turbines, and hydro units so that excessive maintenance, loss of unit life and reduced availability are not experienced by conventional steam turbine generator units in attempting to cope with this cyclic turbulence induced wind power variation. The significant drop in wind speeds in these records accompanied by wind direction change from west to east to a direction of east to west. This wind direction change first affects wind turbine unit #2 and then affects the BPA tower and wind turbine unit #3 in that order, which is observed by noting the time instants at which the drop in wind speed record reaches a minimum. This result further confirms the earlier results from the correlation table and delay table that suggests the meteorological event is propagating from east to west and thus affects the PNL tower first. This result at first appears to contradict the measured wind speed direction which is west to east. However, the event propagation being indicated in the correlation and delay tables is not an event that propagates with wind speed but rather the propagation of the wind direction shift and the concurrent drop in wind speed. The wind direction is observed to change from west to east to east to west for a short period during this drop in wind speed. The propagation of this drop in wind speed is also observed to be from east to west in Figures 25 and 26 confirming the results from the correlation and delay tables.

The sensitivity of the grouping, propagation direction determination, and the delay determination procedure for Goodnoe Hills data suggests that the prediction methodology may be more accurate and sensitive for wind speed measurements taken at hub height where the larger turbulence and site specific phenomena observed on the SESAME array data will not be present and thus will not cause the difficulties encountered in prediction on the SESAME data.

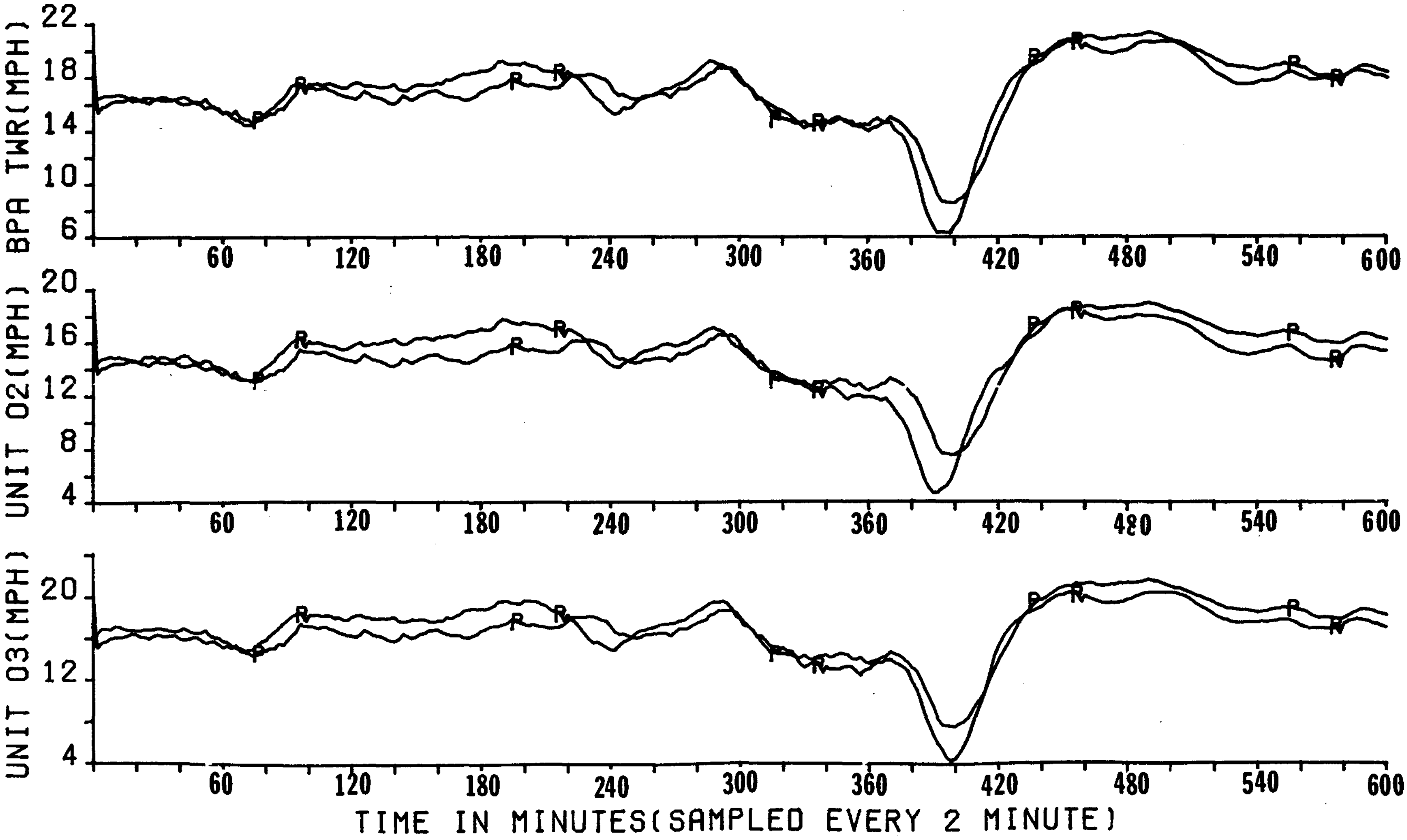


Figure 25. Wind speed prediction with PNL met tower No. 1 as reference with 10 minute filtered data of Goodnoe Hills.

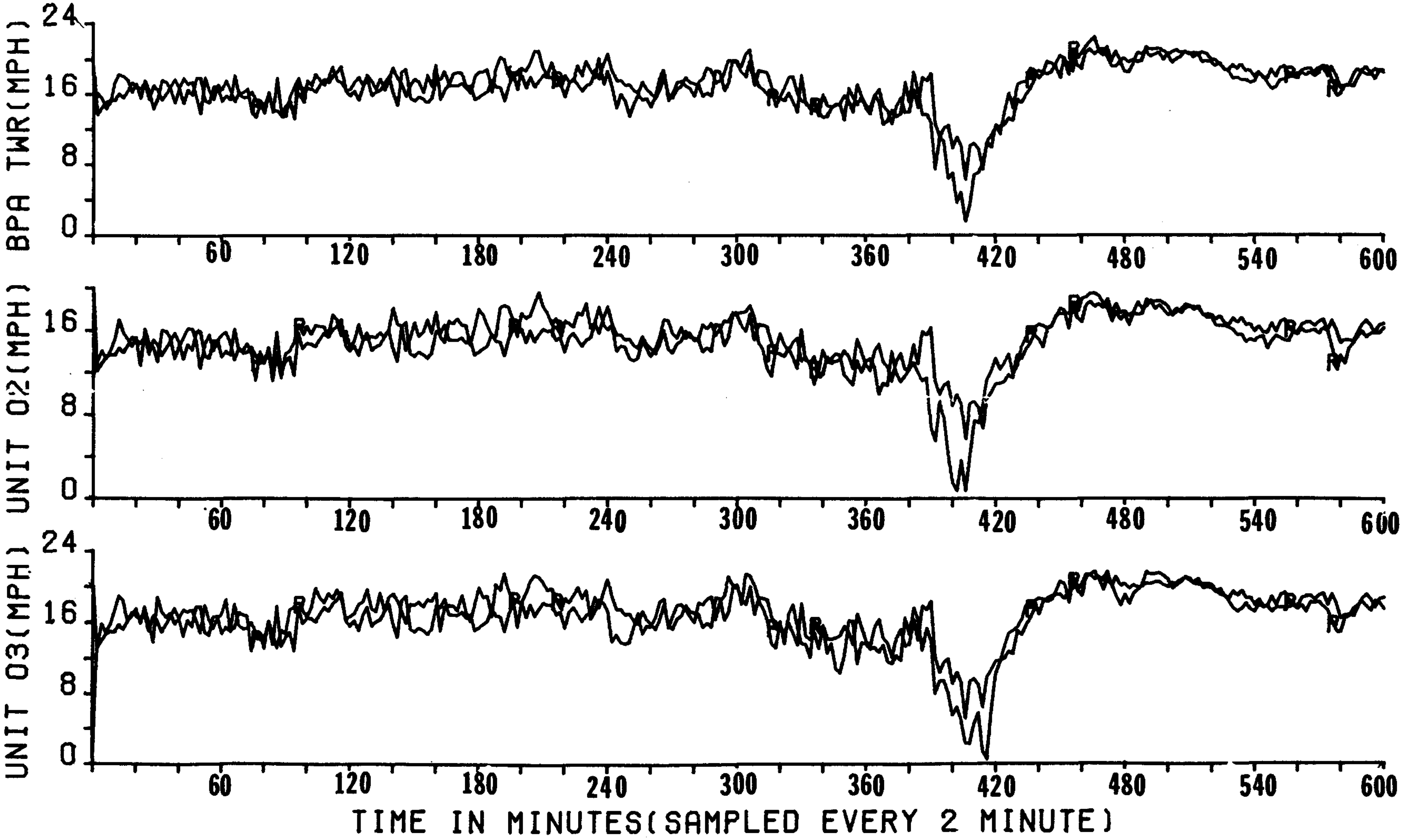


Figure 26. Wind speed prediction with PNL met tower No. 1 as reference with unfiltered data of Goodnoe Hills.

5.2 WIND POWER PREDICTION

A second study of direct prediction of wind power variations on wind turbines #1, #2, and #3 using wind speed measurements at the PNL and BPA towers and wind power measurements at the three wind turbines. The prediction of wind power at the three wind turbines would utilize the same recursive least squares models (9) used for wind speed prediction at site i,

$$W_i(t) = \sum_{j=1} a_{ij} W_j(t - T_{ij}) + b_i$$

$W_i(t)$ is now power at a wind turbine rather than wind speed, and $W_j(t)$ is now the reference wind speed measurements at a meteorological tower. This least squares prediction of power rather than wind speed eliminates the need to simulate wind power from a predicted wind speed record using a nonlinear algebraic model, shown in Figure 27, that relates power and wind speed on a MOD-2 wind turbine. The only modification to our program was that after the power was predicted from wind speed, the power level above rated power was set at rated MOD-2 wind power levels of 2.5 MW when it exceeded 2.5 MW. The errors for the prediction were computed for this wind turbine predicted power signal which is limited to a 2.5 MW maximum power level and the time plot of this predicted wind power shows this saturation of predicted wind turbine power output.

The peak correlation table is given in Tables 27a and 27b for 2 minute and 10 minute moving average filtered data, respectively. The correlation is larger for the 10 minute average than for the 2 minute average data. The correlation for the 2 minute data shows complete symmetry which indicates there is no event propagation in the data record. Since the data is taken for a wind enhancement site and since no meteorological event propagation is detected, the wind speed direction is taken as the propagation direction. The westerly wind speed direction indicates that the BPA tower should be used to predict power at the three wind turbine sites and wind speed at the PNL tower.

The delays at which the peak correlation occurs using the BPA tower as reference are given in Tables 28a and 28b for the 2 minute and 10 minute moving average filtered data. The unit delays between every prediction site and the reference site for both 2 minute and 10 minute averaged data is consistent with the lack of meteorological event propagation in the record. The error for pedicting wind power at all three wind turbines and the wind speed at the PNL tower are also given in Tables 28a and 28b for the 2 minute and 10 minute moving averaged data. The errors in predicting wind power at the three wind turbines for 2 minute averaged data are less than 5% of the MOD-2 wind turbine power

	Unit 1	Unit 2	Unit 3	BPATWR	PNLTWR
Unit 1	---	.81	.89	.88	.82
Unit 2	.81	---	.88	.83	.77
Unit 3	.90	.88	---	.95	.90
BPATWR	.88	.83	.95	---	.90
PNLTWR	.82	.77	.90	.90	---

Table 27a. Table of peak correlation for 2 minute average unfiltered data of Goodnoe-Hills.

	Unit 1	Unit 2	Unit 3	PBATWR	PNLTWR
Unit 1	---	.90	.94	.92	.89
Unit 2	.91	---	.95	.92	.89
Unit 3	.94	.95	---	.98	.96
BPATWR	.93	.92	.98	---	.97
PNLTWR	.90	.89	.96	.96	---

Table 27b. Table of peak correlation for 10 minute moving average filtered data of Goodnoe-Hills.

	Delay with BPA Tower (minutes)	Error of Power Prediction(kw)	Error of Wind Speed Prediction(mph)
Unit 1	1	163.45	----
Unit 2	1	227.27	----
Unit 3	1	149.56	----
PNLTWR	1	------	2.14

Table 28a. Delays and errors of power and wind speed prediction with 2 minute average unfiltered data of Goodnoe Hills. BPA met tower No. 2 is chosen as the reference.

	Delay with BPA Tower (minutes)	Error of Power Prediction(kw)	Error of Wind Speed Prediction(mph)
Unit 1	1	110.75	----
Unit 2	1	133.10	----
Unit 3	1	69.30	----
PNLTWR	1	------	0.96

Table 28b. Delays and errors of power and wind speed prediction with 10 minute moving average filtered data of Goodnoe Hills. BPA met tower No. 2 is chosen as the reference.

rating for the 10 minute moving average data and less than 8% of the MOD-2 wind turbine power rating for the 2 minute moving average data. These errors are for the predicted wind power that is limited to the MOD-2 wind turbine power rating.

The actual and predicted wind power at the three wind turbines are plotted in Figures 28 and 29 for the 2 minute and 10 minute averaged data, respectively. Note that the actual and predicted wind power at wind turbine #2 experience saturation and also have the largest errors. The accuracy of the prediction is far greater when saturation does not occur as indicated by the errors for wind turbines #2 and the comparison of actual and predicted wind power records for these wind turbines in Figures 28 and 29. This suggests that a multiple stage predictor for wind power where each stage would predict power for wind speed over a certain range be developed. The range of wind speed for each predictor stage could be chosen based on linearization of the power versus wind speed characteristics. Thus, each wind power predictor stage would approximately satisfy the linearity assumption imbedded in the model (9) and thus provide more accurate prediction results.

Note the very large variations in wind power in both the 10 minute and 2 minute moving average data and the similarity in the variations in the 10 minute averaged data. The cyclic turbulence induced variations that appear in the 2 minute averaged data can be reasonably large but are not very highly correlated between wind turbines. The turbulence is, however, small compared to the slower variation found in the 10 minute records that are highly correlated between wind turbines. The highly correlated slower wind power variation can cause the severe operating problems on utilities with significant wind penetrations. The smaller poorly correlated turbulence induced variation may cause annoying cyclic variations on conventional steam turbine units, but cannot cause the severe economic and reliability problems associated with the slower more highly correlated variations.

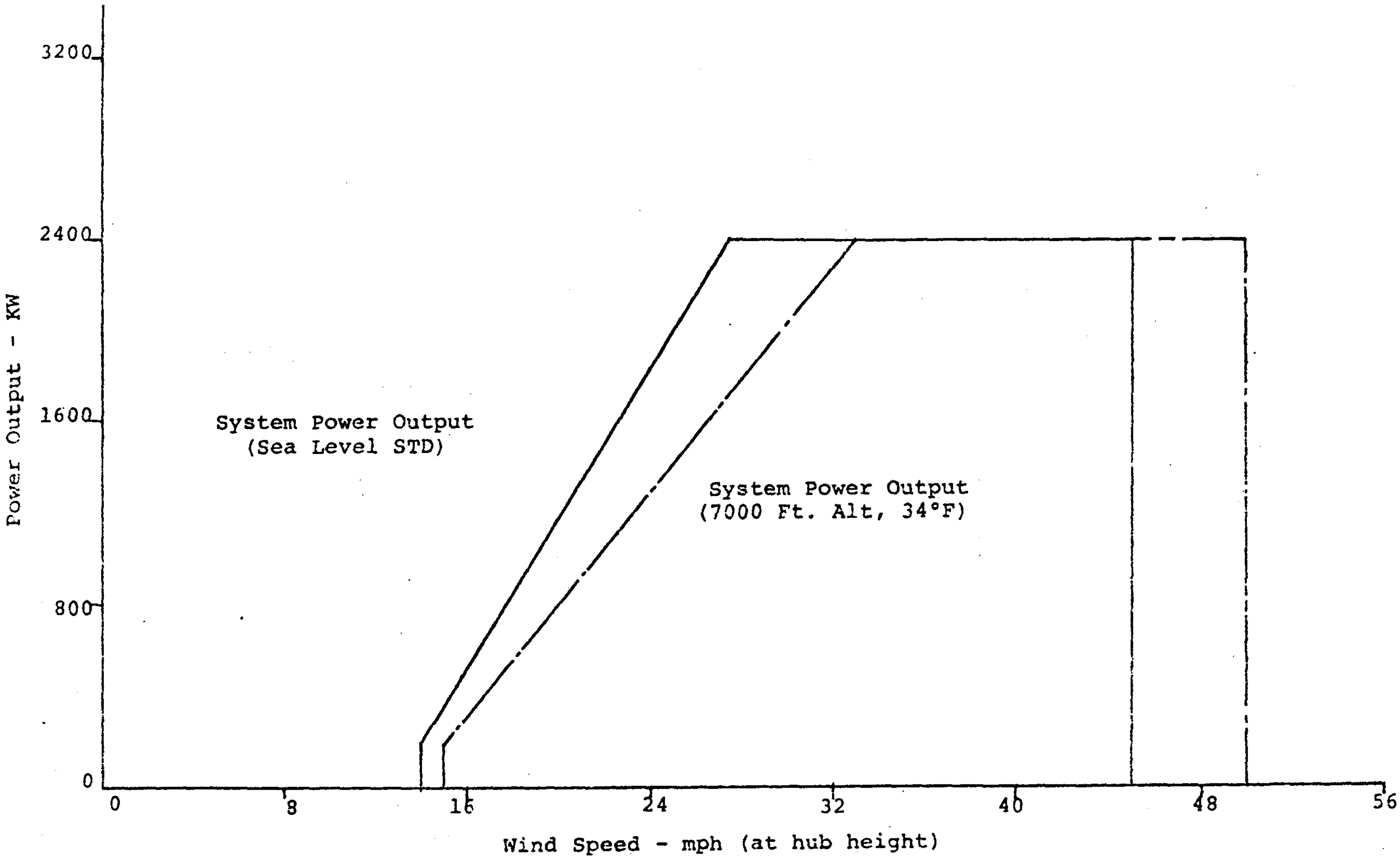


Figure 27. MOD-2 power characteristics.

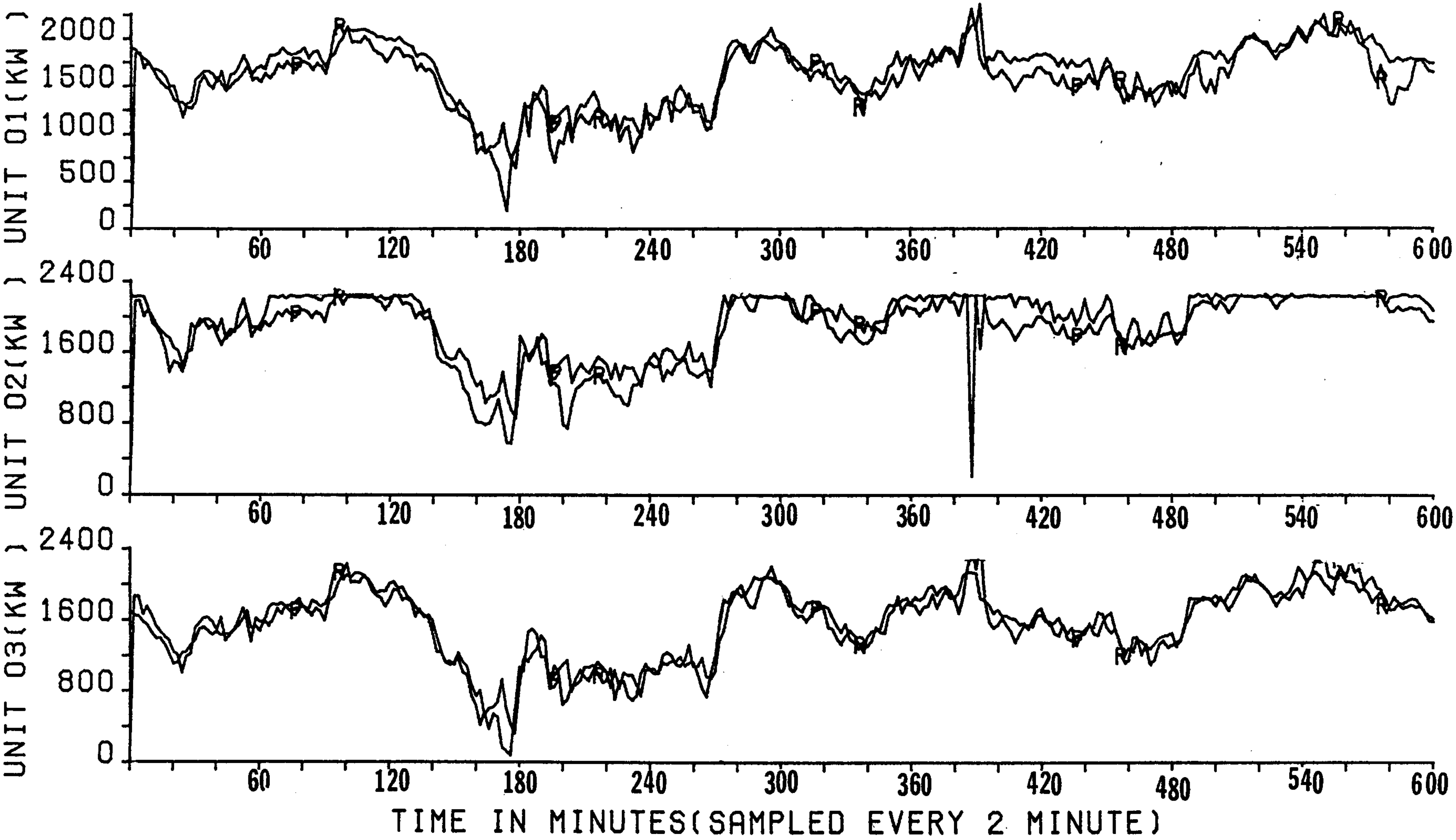


Figure 28. Wind power prediction with BPA met tower No. 2 as reference with unfiltered data of Goodnoe Hills.

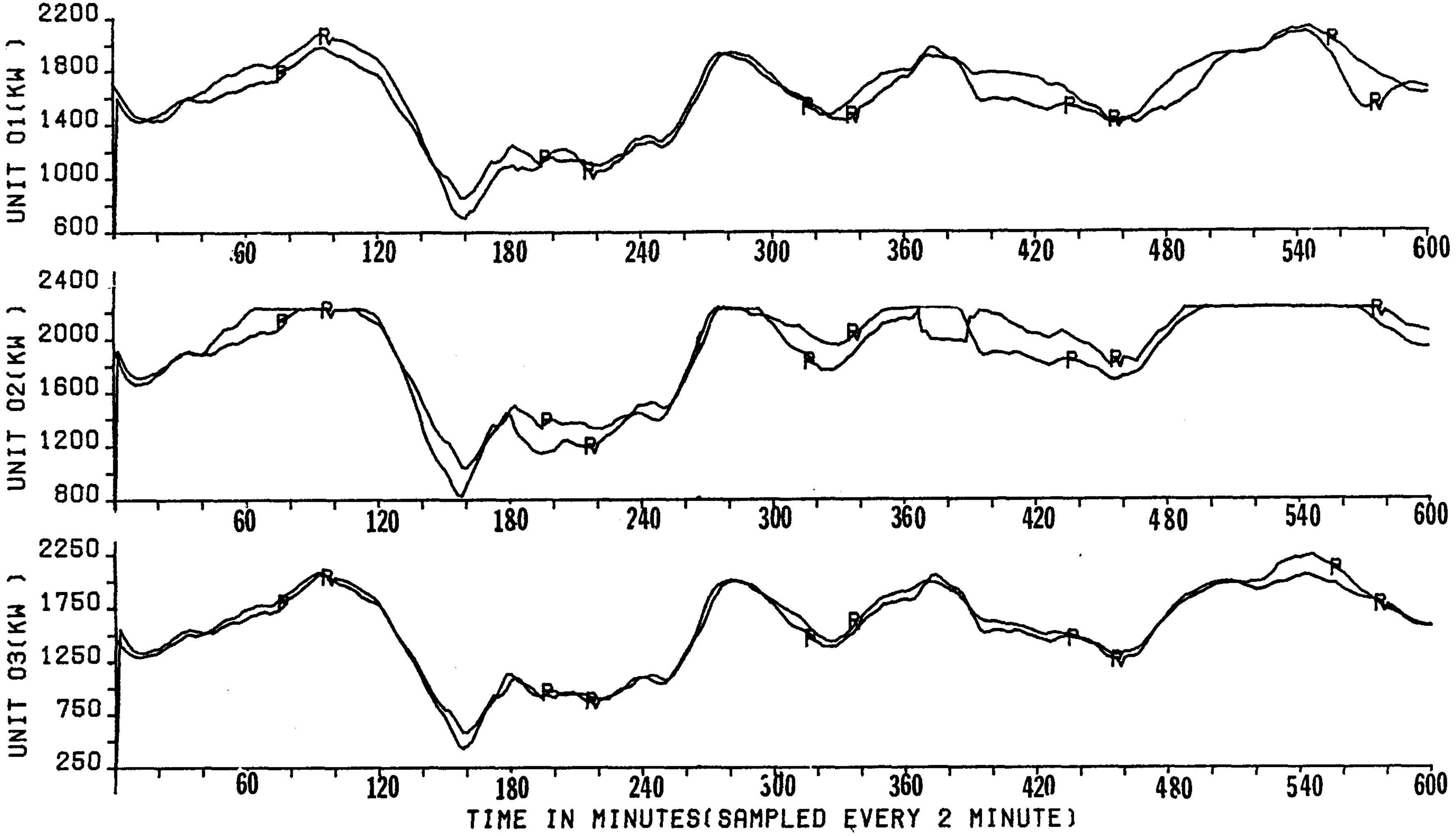


Figure 29. Wind power prediction with BPA met tower No. 2 as reference with 10 minute filtered data of Goodnoe Hills.

SECTION 6

CONCLUSIONS AND FUTURE RESEARCH

The prediction methodology and the results on utilizing this prediction methodology on stationary fronts, fast propagating fronts and slow transitions from one frontal system to another provide the basis for the following conclusions. Three types of predictions are required:

(1) an hourly prediction of diurnal trend wind power variation for the 24 hour and quarter hour updated unit commitment;

(2) a prediction of trend wind power variation and its error for meteorological events one or more hours ahead for the quarter hour updated unit commitment;

(3) a prediction of trend wind power variation and its error 15 minutes ahead for meteorological events for the minute updated unit commitment.

It should be noted that diurnal wind power prediction would be forecasted for each hour 24 hours ahead for the 24 hour unit commitment schedule based on the statistics on the wind power output for a particular period such as a season [5] using no wind or meteorological measurements at towers that encircle the wind turbine clusters. The prediction of trend and its error one more hour ahead could be provided by wind speed and direction measurements from a ring of meteorological towers that encircle all of the wind turbine array clusters in a particular region. The ring should be located at a distance of at least 100 miles from the closest wind turbine cluster so that hour ahead prediction could be performed for the fast propagating fronts that moved across the 80 x 80 mile SESAME array in 40 minutes. The proper subset of these meteorological towers for prediction could be determined by calculating a peak correlation table based on all the wind speed measurements in this ring and then forming groups that have large pairwise correlations, have small delays between pairs of sites in the group, and lie in the same geographical area. The results obtained on the 8:00 - 10:00 p.m. May 2nd data suggest all groups of reference sites that lie in the wind direction and that partially encircle the array should be used for prediction. However, if an hour ahead predictor is desired, the delays from all reference sites in front of and encircling the wind turbine cluster measurement sites in the front propagation direction must be at least an hour duration, which restricts the number of reference sites that can be used.

The direction of propagation for the meteorological event could be determined by ordering the sites in increasing distance in a hypothetical propagation direction and then testing whether the column correlations (ij) for i > j are larger than the corresponding row correlations (ji). This method for determining direction of propagation worked very well when only one propagating event was observed in the data but requires considerable computation. The direction of propagation was always in the wind speed direction when the method worked very well. The only time a direction of propagation test would appear to be necessary is when the arrival of a front is forecasted. The forecasted direction of propagation, the forecasted time of arrival, pressure and temperature measurements and their computed gradients at the ring of measurement towers could be utilized along with wind speed measurements processed into a correlation table to indicate propagation direction of triangular pulse wind speed increase associated with the slow transition from predominance of one front to another front. The propagation direction was not clear for the slow transition from a north propagating to a south propagating front on May 2, 1979 data. Thus, this forecast of the time of arrival, the pressure and temperature measurements, and the computed pressure and temperature gradients should greatly assist the detection of the arrival and determination of its direction of propagation.

The determination of the proper delays between the reference meteorological towers in the ring and meteorological towers in each wind turbine cluster requires more than one wind measurement tower be located in each cluster. This requirement is made so that site specific effects do not cause inaccurate determination of the delay between the meteorological tower measurements in the ring encircling the wind turbine clusters and the meteorological tower in a wind turbine cluster. The delay between any reference site in the ring of meteorological tower wind speed measurements and the wind speed measurement at a meteorological tower in a wind turbine cluster is obtained by determining the delay at which the peak correlation $p_{ij}(T_{ij})$ occurs. This method was always rather consistent when viewed over several prediction sites in a group and several reference sites. However, there were prediction sites that were located geographically close to a prediction group but had rather poor prediction performance. However, on every occasion when a group of prediction sites could be identified with large pairwise correlations and small delays in a small geographical region, good prediction performance was achieved. Using more than one meteorological tower in a wind turbine cluster and checking whether these towers would form a single group indicates if one or more of the towers is affected by some site specific phenomena and should be disregarded in terms of predicting wind speeds for the cluster of wind turbines located near these meteorological towers. Using several reference sites that are geographically close together for predicting turbine cluster allows comparison of delays between this meteorological tower and the several reference sites. Values of delay that are inconsistent can then be ignored in determining the proper delay between this reference group and the prediction site.

The selection of the smoothing interval for prediction is very important to selecting the proper groups of reference sites, selecting the proper wind direction, and selecting the proper delay, which are all needed to produce the particular predictive model selected. The smoothing interval also can filter out site specific phenomena from the reference wind record and from the wind record at the prediction site, which makes the prediction appear more accurate. However, too long a smoothing interval for a particular event will reduce the wind speed maximums, increase wind speed minimums, cause shifting of the time of occurrence of maximums and minimums, and reduce the slopes of the wind speed records. A 10-30 minute smoothing interval will produce the proper reference and prediction groups, permit more accurate determination of delays between reference sites and prediction sites, permit more accurate determination of event propagation direction, and eliminate the turbulence and site specific effects without distorting the characteristics of the wind speed profile associated with a fast propagating meteorological event. A 2 hour smoothing interval not only reduces the sensitivity and accuracy of the prediction methodology in terms of determining groups, event propagation direction, and delays between reference and prediction sites but also seriously distorts the characteristics of the fast propagating meteorological event. However, a 2 hour smoothing interval is required to accurately determine the reference and prediction groups and the delays between reference and prediction sites for the slow propagating triangular pulse wind speed increase associated with the transition from the fast south to north propagating front to the fast northwest to southeast propagating front. It is known that the 2 hour smoothing interval distorts the wind speed profiles on the northern sites where the triangular pulse is broad. The predictions on the southern sites are even less accurate because the pulse becomes narrower as it propagates in addition to the distortion caused by the 2 hour moving average filter. It would thus appear that the 2 hour smoothing interval is needed to determine prediction and reference groups for a slow propagating event but the actual prediction should be performed using data smoothed over a 10-30 minute interval as for the case of fast propagating fronts.

The prediction associated with the transition from one fast propagating front to another propagating in different directions poses special problems. The results obtained on the May 2, 1979 data suggest that prediction should be performed based on the delays and reference sites for the first fast propagating front until the triangular pulse associated with the arrival of a second front begins to affect sites where prediction is desired. The prediction should then switch to the longer delays and the reference sites associated with the propagation of the triangular pulse. Since one does not switch to this slow event prediction until it affects wind turbine clusters where prediction is desired, there is ample time to detect the arrival of this slow propagating triangular pulse at the ring of meteorological towers that encircle the sets of wind turbine clusters and to determine the delay for the event to propagate from the ring of meteorological towers to the wind turbine clusters. After this slow propagating triangular pulse has passed through all of the wind turbine clusters, the reference and prediction groups and delays and thus the predictions should be based on the second fast propagating front. Thus the prediction would have three stages for transition from one fast propagating front to another.

(a) prediction based on the first fast propagating front until the triangular pulse wind speed increase first hits the first wind turbine cluster;

(b) prediction based on the slow propagation of the triangular pulse until it passes through all wind turbine clusters;

c) prediction based on fast propagation of the second event.

A 15 minute ahead prediction may be necessary in some cases to more accurately predict the minimum, maximum, time of arrival and departure, time of occurrence of maximums and minimums, and the slope or rate of change of wind speed. A second ring at 25 miles from any wind turbine cluster would be necessary to allow a 15 minute prediction interval for the fast propagating events such as the fronts from 1:00 - 6:00 p.m. and 8:00 - 10:00 p.m. on May 2, 1979. The comments on the prediction methodology for the hour ahead prediction based on a ring of measurements at 100 miles from all wind turbine clusters would apply to this 15 minute ahead prediction. The 15 minute prediction would capture changes in the meteorological event over time as it propagates as was observed on the slow propagation of the triangular pulse due to the transition from one front to another and the associated wind shift. The 15 minute ahead prediction would also capture small events that may pass through the 100 mile ring of meteorological towers or that may develop within the 100 mile ring of meteorological towers. The need for this 15 minute ahead prediction and the associated 25 mile ring of meteorological towers is unclear because a 15 minute ahead prediction could be developed based on the predictions based on the 100 mile ring of measurements. In fact, both the 15 minute and hour ahead predictions would need to be interpolated from the prediction based on the greater than 1 hour delays between the 100 mile ring of reference sites and prediction site in the wind turbine clusters. Thus, before a 15 minute ahead prediction is developed using a 25 mile ring of reference measurements,

(1) the accuracy and reliability of the interpolated prediction based on measurements using the 100 mile ring should be established;

(2) the need for improved accuracy and reliability over that provided using measurements from the 100 mile ring should be established in terms of improved economy and reliability of operation.

An individual site, group/site or group/group predictive model can be developed. The individual site predictive model, where a prediction model is developed for each prediction site in a wind turbine cluster, is based on individual reference wind speed records delayed by the appropriate individual prediction site i, reference site j, delay T_{ij}. The individual site predictive model is the most accurate but requires significant computation since several reference site records are used.

The group/site predictive model utilizes an averaged wind record and an average delay for each reference group. This procedure would greatly reduce computational requirements if a large number of reference sites existed and formed several groups. The computation of the predictor for each prediction site in a wind turbine cluster based on appropriately delayed, averaged records for several groups would be much less than the individual site method. The group/site method would likely give excellent performance if the reference groups are spread out to partially encircle the wind turbine cluster in the event direction of motion.

The group/group predictive model produces a predicted average wind speed record for all meteorological towers in an array based on averaged wind speed records for each reference group in the ring of meteorological towers. This model requires the least computation and produces the largest errors. Moreover, predicting wind speeds at individual meteorological towers in the array using either the individual site or group/site models allows far greater flexibility and accuracy in estimating wind speeds and thus wind power at wind turbines in the cluster.

The group/site model would be the preferred model if a large number of reference measurements are required (a) to reliably detect occurrence of events quickly, (b) to accurately assess the proper delays that reflect speed of propagation, and (c) to detect the direction of propagation. Forecasts of arrival and direction of propagation, measurement of temperature and pressure at the ring of meteorological towers, and computation of gradients reduce the need for larger numbers of meteorological towers due to the resulting improved sensitivity and accuracy of methods for determining time of arrival and speed and direction of meteorological events using these additional measurements and forecasts. If a smaller number of meteorological towers could be used, the computation associated with the individual site predictive model would be reasonable. The improved accuracy of the individual site predictive model would then likely justify its use against the additional computation. The significant reduction in turbulence from measurements at MOD-2 wind turbine hub height rather than at 13 feet on the SESAME array may make the determination of propagation direction and delay much more sensitive and accurate as suggested by Goodnoe Hills results. Fewer reference sites in the ring and fewer prediction sites may then be required, which would again suggest an individual site model may be preferred. Significant reduction in computation may be achieved by directly predicting wind power at selected wind turbines in a wind turbine cluster and then interpolating wind power at other wind turbines in the cluster. A multiple stage wind power predictive model would be required to predict wind power when wind speed at reference sites in the ring are below cutin wind speed, between cutin and rated wind speed, between rated and cutout wind speed, and above cutout wind speed.

Future research could be performed on how to utilize forecasts of the time of arrival and the direction of a meteorological event in the wind speed for wind power prediction. Research could also be performed on using measurements of pressure, temperature, and rainfall at reference and prediction meteorological tower sites and computed temperature and pressure gradients at these sites to more accurately determine time of arrival, direction of propagation, and the delays between reference and prediction sites for prediction of wind speed or power for meteorological events. Research on (a) developing a multiple stage wind power predictive model at selected wind turbine sites and (b) developing methods for interpolating to obtain wind power at the other wind turbine sites in each cluster could be performed.

Research can also be performed in utilizing the wind speed predictions for increasing the penetration, economy, and operating reliability of utilities with significant wind penetration. The accuracy of predicting trend and cyclic wind power variations one or more hours and one quarter hour ahead could be investigated for different wind conditions, different WTG array siting configurations, and as a function of the number and location of wind speed and direction met tower measurements that are used for prediction. This study would address the prediction accuracy of total wind power from arrays rather than the accuracy of wind speed prediction at individual WTG sites as in the present study. Methods of utilizing the various prediction algorithms for setting unit commitment could also be studied. The effects of the accuracy of predicting trend and cyclic wind power variation 24 hours, one or more hours, and quarter hour ahead for each wind condition and WTG siting configuration on (a) the role of the 24 hour, quarter hour, and minute updated unit commitments and on (b) the role of coordinated blade pitch control of wind turbine generator arrays (closed loop control), supplementary automatic generation control of generator unit commitments (feedforward control), and automatic generation control of units committed by the 24 hour ahead unit commitment. A tradeoff of the costs of providing accurate one or more hour and quarter hour prediction for various wind conditions and WTG siting configurations versus the production cost savings on unit commitment, regulation cost savings in generation control, improved reliability of operation could be conducted.

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