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OBSERVATIONS, INTERPOLATIONS, AND TACTICAL DECISION AIDS

September 1992

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13. ABSTRACT (*Maximum 200 words*)

This report investigates the accuracy to which observations of meteorological parameters can be interpolated to a grid. The interpolation accuracy defines the accuracy that a Tactical Decision Aid (TDA) can achieve.

Observations of temperature, relative humidity, windspeed, and wind direction were interpolated to a grid from a set of very carefully chosen observation stations. Hypothetical chemical spill sites were selected at five different observation points. Six different experiments were performed in which meteorological parameters were compared between observations at the hypothetical spill sites and values from nearby, interpolated grid points.

Variations in the observed meteorological parameters caused by interpolation inaccuracies were applied to a heat stress casualty TDA. Sensitivity studies were performed to show the amount of variability in the TDA output.

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1. INTRODUCTION

The U. S. Army needs weather information such as observations and forecasts to plan for favorable or unfavorable conditions that may render tactical advantages or disadvantages. TDA's have been developed that use weather information to assess equipment and personnel performance, weapon system capability, chemical/nuclear hazards, aircraft operations, etc. The accuracy, timeliness, and availability of raw weather data defines how well the TDA's represent the real world environment in which military tactical strategies are performed.

The problem addressed in this report concerns the collection and proper use of the weather data. The most comprehensive TDA will produce useless results if its input weather data is out of date, incorrect, or not representative of the area where the TDA is being applied. The problem is illustrated throughout the report with the following example.

A chemical spill has occurred and personnel must wear protective clothing to clean up the disaster. Time is of the essence. The spill must be cleaned up as fast as possible. The number of personnel needed must be decided. A TDA must be consulted to help decide how long personnel can perform heavy work in protective clothing before needing rest or relief. The decisions need to be final and need to be made before personnel are sent out. Weather data is needed as input to a Tactical Decision Aid (TDA) to assess work rates for personnel in chemical protective clothing.

Surface weather observations are collected every half hour from 10 stations scattered within the 100-km by 100-km area where the disaster took place. This is the only available data from the area, and the chemicals did not spill on or near any of the meteorological sensors. This report does not address real-time communications between the observation sites and the centralized data collection platform or archiving and managing of the data as it flows into the central data depository. These concerns are not trivial and need serious consideration apart from this present study.

Frequent observations provide representative environmental variables for TDA use. The meteorological data used in this report has been carefully scrutinized and adjusted to minimize the effects of temporal variations of meteorological data, sensor calibration, and accuracy.

How can the weather observations collected at the 10 sensor sites be used so that the TDA produces the most accurate results? What is the range of variability in the TDA output since there are only 10 observations in a 10,000-km^2 area? The mission oriented protective posture (MOPP) TDA depends on windspeed, temperature, and relative humidity as input. A good possibility exists that these meteorological parameters will vary widely across the area of interest. Mountains, valleys, and plains contribute complicating influences to the environmental conditions.

Weather observations taken at any of the 10 surface stations may not represent the conditions where the cleanup operation will be performed. Remember, there are only 10 observation points in a 10,000-km^2 area. Using nonrepresentative meteorological values to calculate work stress levels may result in erroneous estimates of work times and fatigue factors. Personnel could be jeopardized because of inaccurate weather data used by the TDA or errors within the TDA itself.

2. CONSIDERATIONS

The question is what weather data should be used by the TDA. First assume that the weather conditions at the spill site are the same as the conditions at the nearest meteorological station. This approach is very fast on a computer since a program only has to access and use the values from the nearest station. This assumption is not bad if the distance between the spill site and observation point is small and the surrounding terrain is uniform. However, as the distance grows between the spill site and the meteorological observation site and the terrain variability increases, this assumption will produce bad input data for the TDA.

The next level of sophistication would be to use data from several stations and to use some scheme to interpolate the meteorological observations to the spill site. This report uses this approach to show what meteorological data is best for TDA input.

Given that interpolation is the best way to proceed, other questions must and will be answered later.

- Which interpolation method is best, and can it be optimized in any way?

- Do some meteorological parameters lend themselves to be interpolated more readily than others?

- Is the interpolation of any given meteorological parameter sensitive to the time of day or other environmental conditions?

- Does the geometrical pattern between the meteorological stations and the spill site affect the accuracy of the interpolation?

The next step in sophistication, which was not taken, would be to use a diagnostic numerical model instead of a straight interpolation scheme. This type of numerical model is a simple numerical model, but more computationally intensive than a simple interpolation. A diagnostic model would interpolate the meteorological observations to a grid and then impose some physical attributes of the real atmosphere to the model domain. Adjustments would be made to make the meteorological parameters consistent with each other and consistent with physical atmospheric processes. This approach would attempt to improve upon the simple interpolation by imposing dynamic and thermodynamic constraints that operate in the real atmosphere.

However, these diagnostic models tend to be computationally intensive and take a long time to run. With today's present computing technology, personnel may not be able to derive the necessary meteorological parameters in a real-time, tactical situation.

A study by Tucker and Henmi (1990) revealed that simple diagnostic wind model methods did not produce better agreement with observations than did simple interpolation methods. Therefore, there is no reason to run computationally intensive diagnostic wind models when interpolation methods work as well. Results presented in section 6.1 show that the temperature and relative humidity can be interpolated with good accuracy. Wind direction and windspeed cannot be interpolated with very good results. However, Tucker and Henmi (1990) suggest that nothing can be gained by using simple diagnostic models to determine wind direction and windspeed. Therefore, straight interpolation is used in this report for all weather parameters studied. (Complicated wind models may produce better results; however, these complicated models will not run on small, tactical computers at the present time.)

As the number of meteorological parameters and the number of meteorological observation sites increase, so does the time required to perform the interpolation. With real-time, tactical weather analysis in mind, it would become impractical to interpolate all meteorological parameters from all stations every time a different point of interest was selected. One TDA may require meteorological data at point A while another TDA may need data at point B. An integrated system that can service many different TDA's over an area may need to perform many different interpolations, depending on where the different TDA's require data. A practical approach to solving this problem is to access preinterpolated meteorological values rather than interpolate them every time they are needed. The interpolation has to be done at some point; but by handling the problem in a certain way, program performance can be improved to achieve real-time, tactical meteorological analysis.

Since new meteorological data is collected every half hour, the interpolation only needs to be performed once every half hour. Many different TDA's could be run in that half hour; however, to have each TDA perform the same interpolation repeatedly in that half hour is not logical. The solution is to perform the interpolation once over a grid that covers the entire area. Then, each TDA simply accesses the interpolated values at an interpolated grid point that is close to the site of the chemical spill. Grid size and spacing can be dynamically set by the meteorologist in charge of the meteorological analysis to achieve optimum grid coverage over the observation area. By interpolating the observed meteorological variables from the 10 observation sites to a grid that covers the area once every data collection cycle (every half hour in the current example), a TDA can find a grid point closest to any spot within the grid (that is, the point of the chemical spill) and access the interpolated weather data at the grid point. This approach has an advantage because the TDA's simply access the interpolated weather data. Another added benefit is that if the gridded interpolated values are stored, they can easily be accessed by other programs to display analyses of the interpolated weather data.

Several problems can be solved if weather data is interpolated to a grid. The meteorological data interpolated to a grid point near the chemical spill site is more representative of the true conditions at the spill site as compared to using the meteorological observations from the nearest observation station that may be some distance away. The interpolated grid data can be used by other programs to display an analysis of meteorological data over the entire area covered by the grid. The interpolation approach allows the meteorological analysis to be performed in real time on the battlefield, an environment that cannot yet support the computing power needed to run large numerical models.

However, the introduction of a gridding scheme also raises some questions. The question here is what is the best grid resolution to use. If too many points are used, the processing time increases. If too few grid points are used, the accuracy of the interpolation may suffer. Another question to be answered is whether selecting the interpolated data at the nearest grid point is accurate enough or whether additional interpolations should be performed from surrounding grid points to the exact spot of the chemical spill. This report addresses the answers to these questions.

3. EXPERIMENTAL APPROACH

3.1 Meteorological Data

To answer the questions raised in the earlier sections, several experiments were designed to test how accurately meteorological variables could be interpolated to specific points within an area of interest. The authors decided that absolute best case scenarios should be developed. The meteorological data used in this report has been carefully scrutinized and adjusted to minimize any effect that would reduce the accuracy of the interpolation results. Stations were selected for their location on the basin floor. This was done to minimize the effects of terrain. Stations with accurately calibrated sensors were chosen to minimize calibration errors. An effort was also made to select stations not strongly influenced by the local terrain. (Station 3 may not entirely meet this criteria, but it was needed in order to have as many measurement sites as possible.)

Figure 1 shows an area of approximately 80 km by 160 km in south-central New Mexico within the confines of the White Sands Missile Range (WSMR). The nine stations depicted in figure 1 were selected, based on Brock (1990), since they best satisfied the station selection criteria. The stations selected are all representative of the Tularosa Basin floor. Mountain sites and terrain influenced sites, as best as possible, were not included. The following stations were selected: 1, 2, 7, 15, 19, 11, 16, 18, and 3. Brock (1990) also describes all the stations and sensors shown in figure 1 and the data that was collected during March and April 1990. Approximately 60 days x 24 hours/day x 4 reports/hour x 4 meteorological parameters x 9 stations = 207,360 numbers, which were used in each interpolation evaluation.

Because the stations were carefully chosen and the meteorological data had been edited by Brock to remove bad or questionable data, the authors feel that the data used in the interpolation evaluations represent an absolute best case scenario. In a sense, the interpolation and TDA results shown below will not be representative of the real world. Real world measurements and interpolations will be much more inaccurate than the results obtained in this study.

Because the meteorological data used in this report represents a best case scenario, the interpolation results will reflect this best case. After being initialized with interpolated meteorological data, the resulting accuracy of the TDA sensitivity study will also illustrate a best case scenario that can be achieved from these idealized data interpolations. Under different circumstances of meteorological data collection, inaccuracies would be introduced due to data errors, missing data, sensor miscalibration, data collection delay times, terrain influences, etc. This report should be taken as a baseline point. Real world interpolations of meteorological data for TDA's will be much more inaccurate.

Data from only nine observation stations was selected from within the 80-km by 160-km = 12,800 km^2 area. Since a hypothetical chemical spill could occur anywhere in the area defined by figure 1, some data was needed to interpolate points to the grid and some data was needed as ground truth measurements to determine the accuracy of the interpolation.

At this point, it becomes obvious that the interpolation accuracy is going to depend on the pattern of the observation points. If all of the meteorological data were collected in one small corner or only on one side of the region, the resulting interpolations would be extremely biased. Stations should be selected (or positioned if possible) so they are spread as evenly as possible over the entire area to achieve the greatest interpolation accuracy. Veazey and Tabor (1985), Motte (1986), Tabor et al. (1986), Motte (1987), Tabor and Motte (1987), Tabor and Hall (1987), Tabor et al. (1987), Tabor and Motte (1989), and Clark et al. (1990) have addressed the sensor placement problem. Results from these studies suggest there is more to the problem than this simplistic rule of thumb. Interpolations that are made near to and between observational points are expected to be more accurate than interpolations made outside and far away from the grouping of observation points.

Considering all the constraints of the data and the desire to develop a best-case scenario, meteorological observations from stations 3, 11, 16, and 18 were interpolated to a grid. Locations 1, 2, 7, 15, and 19 were used as potential chemical spill points. Mostly, the ground truth observation sites (1, 2, 7, 15, and 19) are between the observation stations. The interpolation experiments performed for this report reveal how well the grid point interpolated data agrees with ground truth observations at the hypothetical chemical spill locations.

3.2 Interpolation Method

Henmi (1989) evaluated seven different interpolation methods and their performance by comparing calculated and observed wind vectors. Results showed there were no significant differences among the seven different interpolation methods that were compared. Barnes' interpolation method, one of the seven, was used in the present study to interpolate observed meteorological parameters to the grid.

Barnes (1964) describes an interpolation method that uses a Gaussian weight function and was developed specifically for two-dimensional meteorological fields. Henmi (1989) also gives a detailed description of this approach.

The Barnes interpolation method, as implemented in this study, allows for some degree of optimization. The interpolation designer is free to specify how many of the nearest stations should be considered when deciding which stations should contribute to the interpolation value at a given grid point. For example, if the number of contributing stations is set to three, then the three nearest stations are determined for each grid point, the meteorological parameters from each contributing station are weighted according to their distance from the grid point, and the interpolation is made. If the number of contributing stations is set to five, then the five nearest stations are determined for each grid point and the distance weighted interpolations are made. The interpolation procedure can be optimized by varying the number of contributing stations.

The interpolation results will be different for different numbers of contributing stations. The interpolation experiments discussed will examine the sensitivity of the Barnes interpolation method to the number of contributing stations. This factor is important because as the number of contributing stations goes up so does the amount of time needed to perform the interpolation over the entire grid.

The wind interpolation was performed on u (x-axis) and v (y-axis) components instead of on wind direction and windspeed directly. Wind directions and windspeeds were decomposed into components by using equations (1), (2), and (3).

$$wd = wd * \frac{\pi}{180} \qquad (1)$$

$$v = -ws * \sin(wd) \qquad (2)$$

$$u = -ws * \cos(wd) \qquad (3)$$

where wd = wind direction, ws = windspeed, π = 3.141592

After converting the wind from speed and direction to u and v, at each observation station, the components were interpolated to the grid. Then the u and v components from the nearest grid points to each chemical spill site were converted back to direction and speed. This procedure is shown in equations (4) and (5).

$$ws = \sqrt{u^2 + v^2} \qquad (4)$$

$$wd = 270 - \left(\arctan\left(\frac{v}{u}\right) * \frac{180}{\pi}\right) \qquad (5)$$

After the interpolated u and v components were recombined into direction and speed, the interpolated directions and speeds were statistically compared with the observed directions and speeds.

4. STATISTICAL METHODS

The interpolated values and observed ground truth values were compared by using various statistical methods to get an idea of how well the interpolation performed. In the following equations y = observed value, x = interpolated value, and N = total number of xy pairs.

The first statistic calculated was the correlation coefficient. The correlation coefficient (r) is given as

$$r = \frac{\Sigma(x - xmean)(y - ymean)}{\sqrt{\Sigma(x - xmean)^2} * \sqrt{\Sigma(y - ymean)^2}} \tag{6}$$

The second statistic used is the root-mean-square (rms) error, defined as follows:

$$E = \sqrt{\frac{\Sigma(y - x)^2}{N}} \tag{7}$$

The third statistic used is the Agreement Measure, defined as follows:

$$A = 1 - \frac{\Sigma(y - x)^2}{\Sigma(abs(y - ymean) + abs(x - ymean))^2} \tag{8}$$

For further information concerning the development and application of these statistics, see Panofsky and Brier (1958), Mielke (1984), and Tucker and Henmi (1990).

5. DESCRIPTION AND RESULTS OF INTERPOLATION EXPERIMENTS

Each experiment consisted of reading 60 days of data (March and April 1990) taken every 15 min from 4 observation stations at 3, 11, 16, and 18 in figure 1. Four meteorological parameters (temperature, relative humidity, windspeed, and wind direction) were interpolated to various size grids using the Barnes objective analysis. Interpolated values were then compared to ground truth values (possible chemical spill sites) at 1, 2, 7, 15, and 19 in figure 1. Statistics, as described above, were then calculated for the comparisons.

5.1 Experiment 1

The first experiment was designed as a baseline point from which all other experiments were varied. A 10 by 20 grid was fixed over the entire study area. The number of contributing stations was set to three. In other words, the interpolation is calculated using a distance weighted average between each grid point and the nearest three observation stations. The grid point nearest to each of the potential chemical spill sites was determined. The interpolated values at these grid points were compared to each of the observed values at the potential spill site. Results are shown in table 1.

Note that at this course grid mesh, it is possible that the potential spill sites 1 and 19 fall within the same 4 grid point area as station 3. The interpolation tends to smear out the grid values because of the distance weighting from the three nearest observation sites. Therefore, interpolations around observation station 3 will not be exactly as observed at station 3. The interpolations at the nearest grid points to potential spill sites 1 and 19 will not necessarily be exactly as observed at observation site 3. However, due to their near proximity, the interpolations at the grid points nearest to the potential spill sites 1 and 19 should be in close agreement with the observations taken at locations 1 and 19.

5.2 Experiment 2

The second experiment used the same 10 by 20 grid and nearest grid point data; but this time the number of contributing stations was reduced to two. This experiment seeks to find how sensitive the Barnes analysis is to the number of contributing stations. Results are shown in table 2.

5.3 Experiment 3

The third experiment tested the sensitivity of the interpolation to the number of contributing stations again. This time the number was increased to six. All other parameters from the first baseline experiments remained the same. Only two of the five original possible spill sites were considered in order to have time to make additional experimental tests. Results are shown in table 3

5.4 Experiment 4

The fourth experiment tested the interpolation sensitivity to the grid resolution. The grid resolution was increased to 30 by 40 over the entire area. As in the baseline test, three contributing stations and data from the nearest grid point were used. Results are shown in table 4.

5.5 Experiment 5

The fifth experiment tested the sensitivity of the interpolation to different times of the day. The atmosphere behaves differently in the morning, afternoon, evening, and night. Therefore, the entire data set was broken into four different periods: morning transition (4 am to 10 am), day (10 am to 4 pm), evening transition (4 pm to 10 pm), and night (10 pm to 4 am). This experiment was designed exactly as the initial baseline experiment except the data set was divided with respect to time of day. Results are shown in tables 5 through 8.

5.6 Experiment 6

A sixth and final experiment was performed to test the assumption that the meteorological variables interpolated to the nearest grid point represented the actual chemical spill site some distance away. The question is whether the interpolation can be improved if an additional bilinear interpolation of surrounding grid points is performed. Data interpolated to the four nearest grid points surrounding each potential chemical spill site were interpolated, weighted by distance, and compared with the ground truth observations. Grids of 10 by 20 and 30 by 40 were tested using this additional bilinear interpolation that was performed after the grid was interpolated using the Barnes objective analysis. The number of contributing stations was set to three. This experiment examines the trade-off between the cost of additional processing time and a potential increase in accuracy. Results are shown in tables 9 and 10.

6. DISCUSSION

6.1 Overall Statistical Results

Figures 2 through 5 compare correlation coefficients between observed and interpolated values of temperature, relative humidity, wind direction, and windspeed for experiments 1 through 4. As expected, the interpolations made at sites 2 and 7 have smaller correlation coefficients because they are located farthest away from the observation stations.

The statistics from all experiments show that temperature and relative humidity can be interpolated with a great degree of accuracy. Temperature correlates between 0.84 and 0.97 while relative humidity correlates between 0.75 and 0.97. The interpolation accuracy for windspeed and wind direction is significantly less (from 0.54 to 0.69 for windspeed and from 0.07 to 0.33 for wind direction). These results are not surprising. These experiments have shown that, even under the most ideal conditions, arrangement of stations, and integrity of data, the interpolation accuracy of winds is very poor.

Henmi (1989) performed a similar type of experiment in which interpolated winds and observed winds were compared. Wind data was collected during Project WIND, for a 24-h period in the Sacramento River Valley north of Sacramento (Cionco, 1989) and comparisons between interpolated and observed values were made. Correlation coefficients for wind directions (0.60 - 0.90) were consistently higher than those for windspeed (0.00 - 0.40). Interpolation of wind direction during the nighttime was more difficult than the daytime. These conclusions differ from the present study. The differences are attributed to dissimilar locations, time of the year, length of data record, and the complexity of the terrain found in the domain of Project WIND.

6.2 Experiments 1 through 4: Number of Contributing Stations and Grid Density

Experiments 1, 2, and 3 show that as the number of contributing stations increases, so do the correlation coefficients. (See figures 2 through 5.) Thus, the interpolated values most accurately represent the real meteorological conditions at a location when the number of contributing stations go up. The increase in correlation that results when the number of contributing stations is increased is roughly 0.10 or less for all meteorological variables. This is not a significant improvement. (Note: The connecting lines in figures 2 through 8 are shown only so that the differences between the various experiments can be seen more clearly.)

Experiment 4 also shows that increasing the number of grid points (grid density) causes the interpolation accuracy to improve. (See figures 2 through 5). The increase in interpolation performance by increasing the grid density is similar to the accuracy increases obtained by increasing the number of contributing stations, that is, correlation coefficients increased by 0.10 or less.

It appears that sites 2 and 7, the sites located farthest from any observation stations, benefitted the most by increasing the number of contributing stations and grid density. If this is the case, then a desired result has been achieved. The interpolation accuracy increases achieved by increasing the number of contributing stations and grid density are realized most at sites that are far away from the observation stations.

An increase of 0.10 in correlation coefficient is not very large. That is that if temperatures are interpolated with a 0.80 correlation, an increase to 0.90 probably will not affect the TDA results very much. Nevertheless, a TDA sensitivity study will address the significance of a hypothetical correlation coefficient increase of 0.10.

6.3 Experiment 5: Time of Day Sensitivity

An experiment was designed to test the sensitivity of the interpolation scheme to the different meteorological variables and the time of day that they were observed. There were negligible differences (less than 0.10) of correlation coefficients for interpolating temperature and relative humidity across the different periods. These results are not shown graphically but are presented in tables 5 through 8.

Figures 6 and 7 show the correlation coefficients for windspeed and wind direction (respectively) of interpolations performed on sets of data that were divided into four different time periods. Daytime winds should be easier to predict or interpolate because airflow is more uniformly forced over large areas during the day. Less forcing during the nighttime hours allows the terrain to affect the winds that result in more complicated drainage and gravity and decoupled airflow.

These results show that correlation coefficient increases of 0.20 (windspeed) and 0.40 (wind direction) were realized when wind interpolations were made during the day as opposed to the night. Tables 11 and 12 show the mean windspeed, standard deviation, and variance for the different periods. This data supports the hypothesis that winds should be easier to interpolate or predict during the day as opposed to the night. These results are consistent with similar conclusions made by Henmi and Tabor (1988). However, they found that wind directions were more accurately interpolated than windspeeds. As stated earlier, the differences may be due to time of year, location of study, or length of observation record.

The interpolations tend to underestimate the windspeeds by approximately 1 m/s compared to the observed values. The underestimates are strongest during the daylight hours. This data also shows that the wind is gustier (higher variances in windspeed) during the day. This is expected due to the greater degree of mixing that occurs during the daylight hours.

6.4 Experiment 6: Bilinear Interpolation

Figure 8 shows a plot of correlation coefficients for relative humidity from experiments 3, 4, 6A, and 6B. This figure shows that the additional bilinear interpolation did not increase the interpolation performance. (This fact was true for temperature, wind direction, and windspeed as well but are not shown). The bilinear interpolation performance at site 7 was better than that achieved by experiment 2 but still worse than experiment 4. However, performance at the other spill sites was worse when the additional bilinear interpolation was used. Accessing interpolated meteorological values at the nearest grid point, a faster process, achieved results that were better than when an additional bilinear interpolation using the four nearest grid points was employed.

The bilinear interpolation correlation coefficients were smaller than the correlation coefficients of the other experiments by 0.10 or less. Using the added bilinear interpolation scheme reduces the accuracy of the interpolation. However, as mentioned above, a drop of correlation coefficient by 0.10 is small. The largest decreases were realized at sites 2 and 7. Therefore, the authors recommend that the bilinear interpolation not be used in order to save computational time. They also recommend that additional interpolation approaches be investigated to find ways of improving the interpolation accuracy.

7. TDA SENSITIVITY STUDY

7.1 Description of the MOPP TDA

The MOPP program estimates the probability of occurrence of heat stress casualties under given conditions of air temperature, relative humidity, windspeed for MOPP levels 1 through 4, and a variety of sustained and intermittent activities. The program is based on the rise in body core temperature as predicted by the Ballistic Research Laboratory Program "TCORE."

The TCORE program provides information on the maximum probability of casualties and time to reach that maximum probability under the current conditions of temperature, windspeed, and relative humidity for various levels of work. The TDA produces a table of probabilities of casualties ranging from 0.0 to 1.0. Times to casualties in minutes for the four MOPP levels are given for several different activities. The list of activities is subdivided into "sustained" and "intermittent" forms. The intermittent activities have intervals of light activity, or even rest, interspersed with intervals of heavy activity. Therefore, a sustained activity that appears to be less strenuous than many intermittent activities may be more likely to produce heat stress casualties in a given period.

The sensitivity studies shown below do not account for errors inherent in the MOPP TDA calculations. The assumption is made that the probability of heat stress that is calculated and shown is accurate. This assumption is poor, but there is no information concerning the absolute accuracy of this TDA. The sensitivity studies shown will define the error budget of the TDA but will not address its absolute accuracy.

7.2 Meteorological Data

Once all the experiments were completed, it was possible to generate sets of meteorological parameters used by a TDA that assesses heat stress casualties. The question to be answered is: "If the interpolation algorithm can be modified (either by increasing the number of contributing stations or increasing the grid density) to increase the correlation coefficients of observed and interpolated values, will the MOPP TDA give better recommendations?" Two cases were chosen from among the experiments to investigate this phenomenon.

The first case consists of experiment 1, site 7, to represent a worst case scenario. The second case consists of experiment 3, site 7, to represent an increase of interpolation accuracy. For the second case, the number of contributing stations was increased and the resulting correlation coefficients between observed and interpolated values were improved. Tables 13 through 15 show some pertinent information.

The variability of the meteorological parameters due solely to interpolation errors was determined. This variability was based on the information presented in tables 13 through 15. The variability values are presented in table 16.

7.3 Sensitivity Study Results

Before the results are presented, a review of the situation will be given. A dangerous chemical spill has occurred at site 7 (shown in figure 1). A TDA needs to be consulted concerning the maximum probabilities and time to maximum probabilities of heat stress since workers will need to be in MOPP gear. The problem is that the interpolation method used to determine the meteorological values at the spill site generates values not truly representative of the actual contamination areas. The question here is what variation is expected of the TDA when erroneous interpolated meteorological input data is used. Using the values from table 16, table 17 shows the meteorological values used to test the TDA sensitivity.

These values were arrived at by applying the rms errors to the observed mean values of the interpolated data so as to cause the TDA to predict maximum and minimum MOPP values. Temperatures were varied by adding the rms error to the mean. The relative humidities were varied by adding the error to the mean. The windspeeds were varied by subtracting the error from the mean. Higher temperatures, higher relative humidities, and lower windspeeds cause the person in MOPP to experience more severe heat stress. This is what is meant by "Worst for MOPP" in table 17. The converse situation was applied to achieve a situation that was "Best for MOPP" since lower temperatures, lower relative humidities, and higher windspeeds ease heat stress.

Table 17 shows that variations between best and worst for case 1 are higher than the variations between best and worst for case 2. This is a result of the fact that the correlation coefficients between observed and interpolated values for case 2 are higher than for case 1.

Tables 18 through 21 show the MOPP TDA results for the data displayed in table 17. For each combination of temperature, relative humidity, and windspeed, probabilities of casualties (in percent) and time to reach those probabilities (in minutes) are given. For example, table 18 shows that personnel in a fire fight, under MOPP 2 conditions, after 131 min, will experience a 65 percent probability of heat stress casualties.

A comparison of the TDA results between best for MOPP case 1 (table 19) and best for MOPP case 2 (table 21) reveals differences in probabilities of 10 percent and differences in time to reach those probabilities of 5 min. Recall that best for MOPP case 2 was generated from the better interpolation results. This suggests that MOPP TDA results for best for MOPP case 2 are more accurate. However, the increased accuracy only affected the probabilities by 10 percent and the times by 5 min. An analyst would consider these differences insignificant considering the absolute accuracy of the TDA calculations (which are unknown). The improvement of TDA accuracy due to increased meteorological interpolation accuracy is negligible. A comparison of TDA results between worst for MOPP case 1 and worst for MOPP case 2 is similar in magnitude.

If the interpolation accuracy were to increase to perfection, the rms error for each parameter would reduce to zero. Since perfect interpolation is not possible, each parameter still has an rms error due to the interpolation. By comparing the worst for MOPP case 2 (table 20) and the best for MOPP case 2 (table 21), the variability of the TDA results due to the rms errors of each parameter can be seen. The inherent error left in each parameter, even after improving the interpolation scheme, still causes the TDA to produce wildly different results between its best and worst case scenarios.

Probability of casualties varies up to 57 percent and times to reach those probabilities vary up to 30 min at site 7. These values show the range of variability from best to worst. Errors in any specific TDA output would fall somewhere inside this range. For example, a comparison of table 22 (TDA output generated from case 2 mean conditions) with table 20 (TDA output generated from case 2 worst conditions) shows that probabilities vary by 36 percent and times to reach those probabilities vary by 18 min.

A sensitivity study similar to the one just outlined was performed on data taken from site 1. This site had the highest correlation coefficients from all interpolations (see figures 2 through 5). TDA output sensitivity should be minimized at this site. Meteorological parameter means and rms errors were determined; TDA inputs were derived for worst, mean, and best cases; TDA outputs were compared. The results (not shown) revealed less variation in TDA outputs than for site 7 because of the increased accuracy of the correlation coefficients. Probability of casualties varies up to 48 percent and times to reach those probabilities vary up to 23 min between best and worst cases. TDA output generated from mean conditions compared with TDA output generated from worst conditions shows that probabilities vary by 30 percent and times to reach those probabilities vary by 13 min.

An analyst would consider these differences in probabilities and times to reach those probabilities significant. Yet, this is the error that remains due to the interpolation though the measured data. These cases illustrate the greatest degree of accuracy that can be achieved from measured meteorological values. Many errors accounted for in this study would be much larger under normal data collection conditions and the variation in the TDA output would be corresponding larger.

Since all three meteorological parameters combined to produce best and worst cases, additional TDA trials were made to assess the relative contribution of each parameter to the TDA output variability. Tables 23 through 25 show TDA outputs for successive trials in which each meteorological parameter was changed from its base state in table 20. For example, table 23 shows TDA results that were obtained when the temperature alone was changed from its worst case to its best case.

A comparison of tables 23, 25, and worst for MOPP case 2 (table 20) shows that errors in temperature and windspeed account for nearly equal amounts of TDA output variability. (TDA probabilities change nearly 30 percent and times to reach those probabilities change roughly 10 min.) A comparison of table 20 with table 24 shows that changes in relative humidity have a smaller effect on the TDA results. (TDA probabilities change about 10 percent and times to reach those probabilities change about 5 min.) Errors in temperatures and windspeeds contribute more to TDA output variability than do errors in relative humidity.

Four additional sensitivity studies were performed by spot checking several specific observations with interpolated results. Four different times (morning, afternoon, evening, and night) on four different days were picked at random from the data record at site 7. Observed and interpolated values of temperature, relative humidity, and windspeed were input into the MOPP TDA and results were generated. All four trials (not shown) revealed that the TDA outputs did not vary by more than 13 percent for probability of heat stress casualties and 5 min to reach those probabilities for interpolated versus observed trials. These results suggest that the interpolation performed very well during these four randomly selected times. However, it has been shown, that over the entire record, the interpolation did not do this well.

8. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This report has investigated the accuracy to which observations of meteorological parameters can be interpolated to a grid. The interpolation accuracy defines the accuracy that a TDA can achieve.

8.1 Interpolation Experiments

Observations of temperature, relative humidity, and windspeed were interpolated to a grid from a set of very carefully chosen observation stations. Hypothetical chemical spill sites were selected at different observation points. Six different experiments were performed in which comparisons of meteorological parameters were made between observations at the hypothetical spill sites and values from nearby, interpolated grid points.

The interpolation experiments show that temperature and relative humidity can be interpolated with a great degree of accuracy, while the interpolation of winds is poor. Correlation coefficients between observed and interpolated temperatures and relative humidities were nearly 0.76 to 0.96 for all stations and all experiments. Correlation coefficients for windspeed ranged from 0.54 to 0.69, and wind direction ranged from 0.7 to 0.34.

The results from this report suggest that a TDA user should be very careful with, and critical of, results obtained from TDA's that depend on windspeed and wind direction (NBC hazards and smoke dispersion are only two examples). Interpolation of wind direction, in particular, is not very good.

However, winds can be interpolated more accurately during the daytime. Interpolation correlation coefficients were better by a value of 0.20 or less for windspeed and 0.40 or less for wind direction in the daytime. Windspeeds can be interpolated with correlation coefficients of 0.75 - 0.80 during the day, while wind directions can only be interpolated with correlation coefficients of 0.50.

The authors highly recommend that actual measurements of the wind be made. Other methods should be found to measure the winds instead of interpolating them.

Satellite soundings, remote piloted vehicle observations, and atmospheric profilers offer future possibilities. Sophisticated numerical models may offer a chance for improvement over simple interpolation and diagnostic models. However, each of these methods should be tested in a study similar to this one to show if they can provide better estimates of the winds.

The farther away from an observation point a meteorological value is needed, the poorer the interpolated result will be. However, improvement of interpolation accuracy is greater at sites farther from observation stations when grid density and number of contributing stations are increased.

Correlation coefficients were increased 0.10 or less by considering more stations in the interpolation and increasing the grid density. The calculated 0.10 improvement of correlation coefficients between observed and interpolated values is deemed insignificant.

An additional bilinear interpolation technique did not significantly increase the accuracy of the interpolations. The correlation coefficients between observed and interpolated values were decreased (0.10 or less) when the bilinear interpolations were used. The bilinear interpolation should not be used in order to save computational resources. However, work should continue in identifying any approach that can interpolate meteorological observations as quickly and with a higher accuracy than is now possible.

The pattern of sensor placement has a large effect on the accuracy of resulting interpolations. This study has chosen a best case scenario over flat terrain with sensors spread out evenly over the area. Interpolations from data collected in time from operational sensors are expected to be less accurate than presented in this report.

8.2 Sensitivity Study

Variations in the observed meteorological parameters caused by interpolation inaccuracies were applied to a TDA. Sensitivity studies were performed to show the degree of variability of TDA output.

Interpolation errors in temperature and windspeed contribute more to MOPP TDA output variability than do errors in relative humidity. The inherent error left in each parameter, even after improving the interpolation scheme, caused the MOPP TDA to produce widely different results between its best and worst case scenarios. The best and worst case scenarios of the MOPP TDA were generated from interpolation variabilities of the input parameters. From best to worst conditions, probabilities of casualties vary up to 57 percent and times to reach those casualties vary up to 30 min. From mean to worst conditions, probabilities of casualties vary up to 36 percent and times to reach those casualties vary up to 18 min.

The best meteorological data was used. All terrain effects were minimized. Erroneous data were discarded or adjusted. Poorly calibrated sensors were eliminated. The data used was timely and not stale from a data collection point of view. An ideal arrangement of sensors was chosen. The interpolation method was optimized by increasing the number of contributing stations. Thus, the MOPP TDA is quite sensitive to changes in temperature, pressure, and windspeed. Any variation in input parameters due to interpolation error has a large effect on the TDA results.

The experiments in this report illustrate an attempt to achieve the greatest degree of accuracy from measured meteorological values. (Although another data set may give better results.) Many potential data acquisition problems accounted for in this study would be much larger under normal data collection conditions. The interpolation errors from real-time data acquisition would result in even larger variations in the TDA output.

Much work needs to be done to improve upon the interpolation accuracy. As mentioned before, remote sensing may offer the answer. It is clearly not possible to saturate an area, especially if it is a battlefield, with meteorological sensors. Clearly, the present approach, interpolation from a limited set of sensors, is the only option. However, as this report has shown, the inaccuracies of data interpolation lead to inaccuracies in TDA results, outputs, and recommendations.

The results presented in this report are specific to this data set. There is no guarantee that the results would be the same if the time of the year or the locations of observations and spill sites were changed. Therefore, this study should be considered as a baseline starting point. Other similar studies should be performed to verify these results. Time of year, station locations, site locations, and time dependency (data staleness) should all be varied. A similar study should also be performed using real-time observations and verifications over terrain that is not so specifically, artificially flat.

The authors recognize that the interpolations performed contain inherent errors. These errors arise from assumptions made and numerical shortcomings contained in the interpolation routine. The authors chose to interpolate the observations because this approach is currently feasible in the Army "field environment"; that is, computer processing power available to field units is sufficient to perform these types of interpolation calculations. However, more powerful computers will not be restricted to interpolations only. Numerical models and sufficient processing power will be available in the future. Therefore, we strongly recommend that the current data set be reanalyzed by replacing the interpolation routines with an atmospheric diagnostic model to establish which method produces better results.

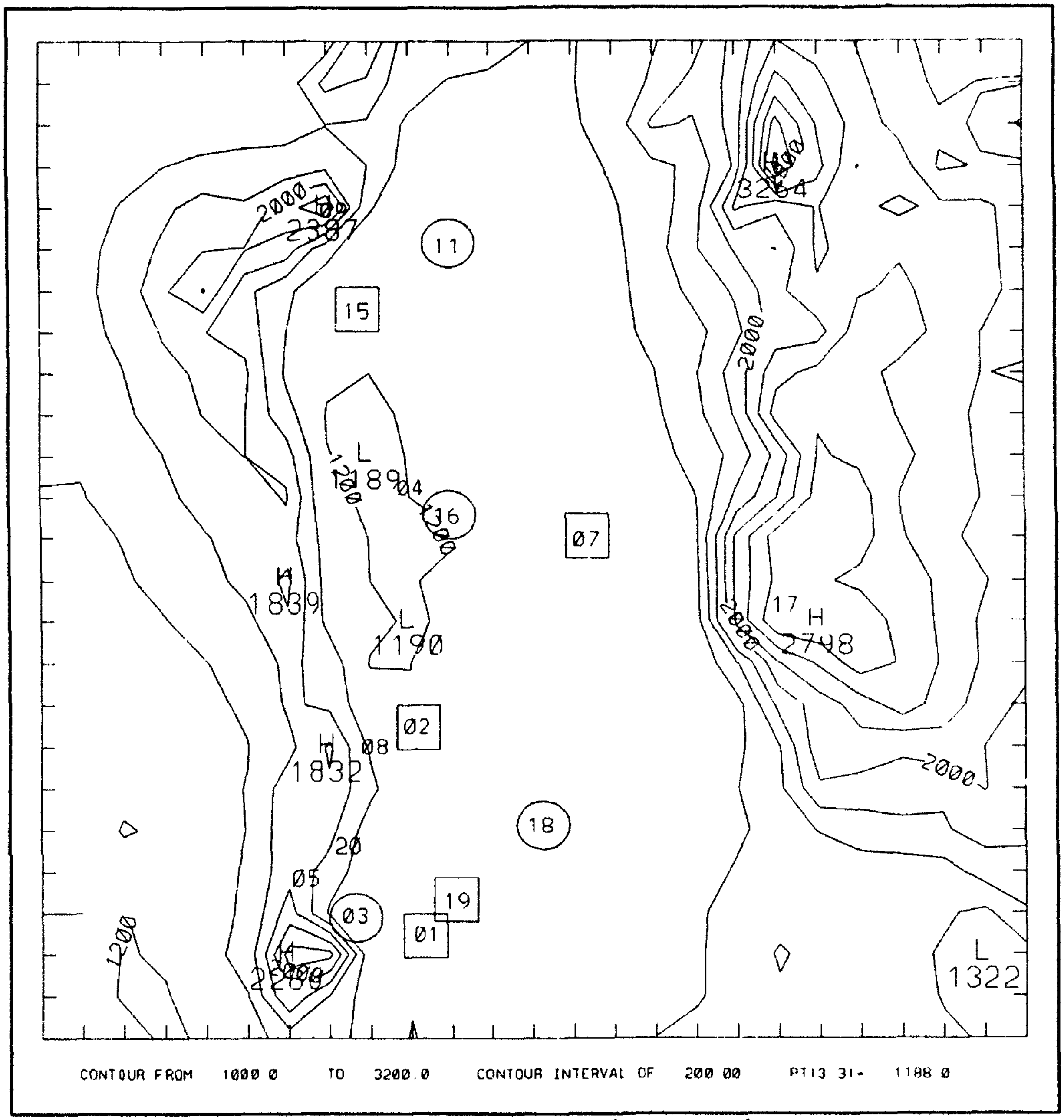

Figure 1. WSMR area and data collection stations.

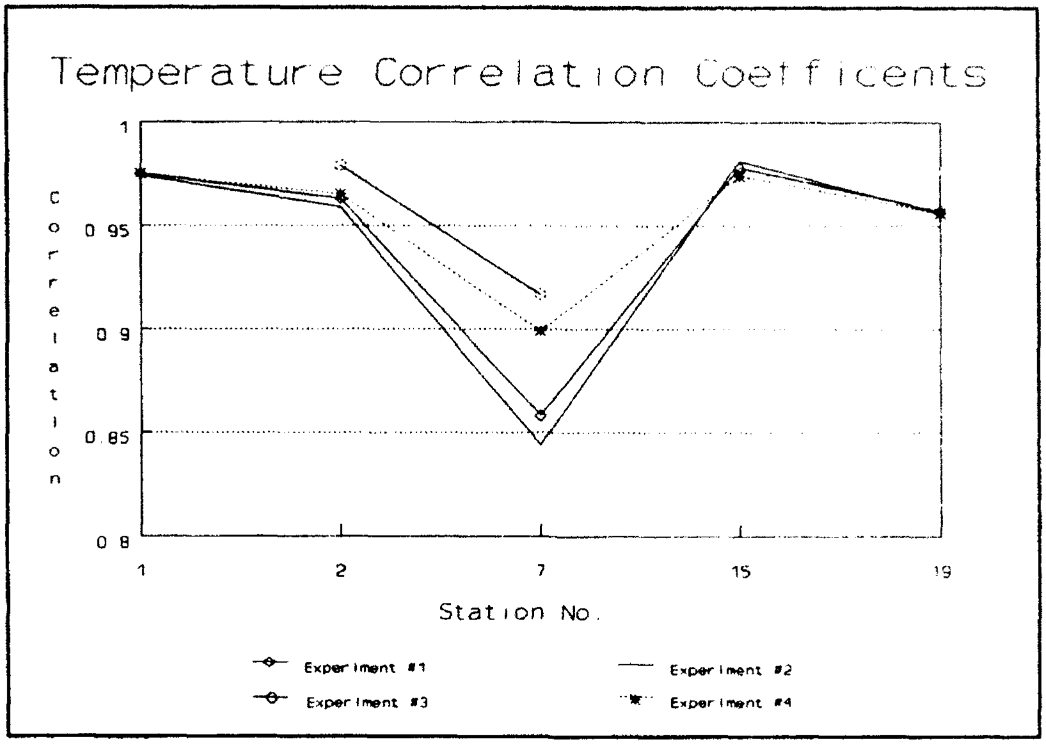

Figure 2. Correlation coefficients of temperature.

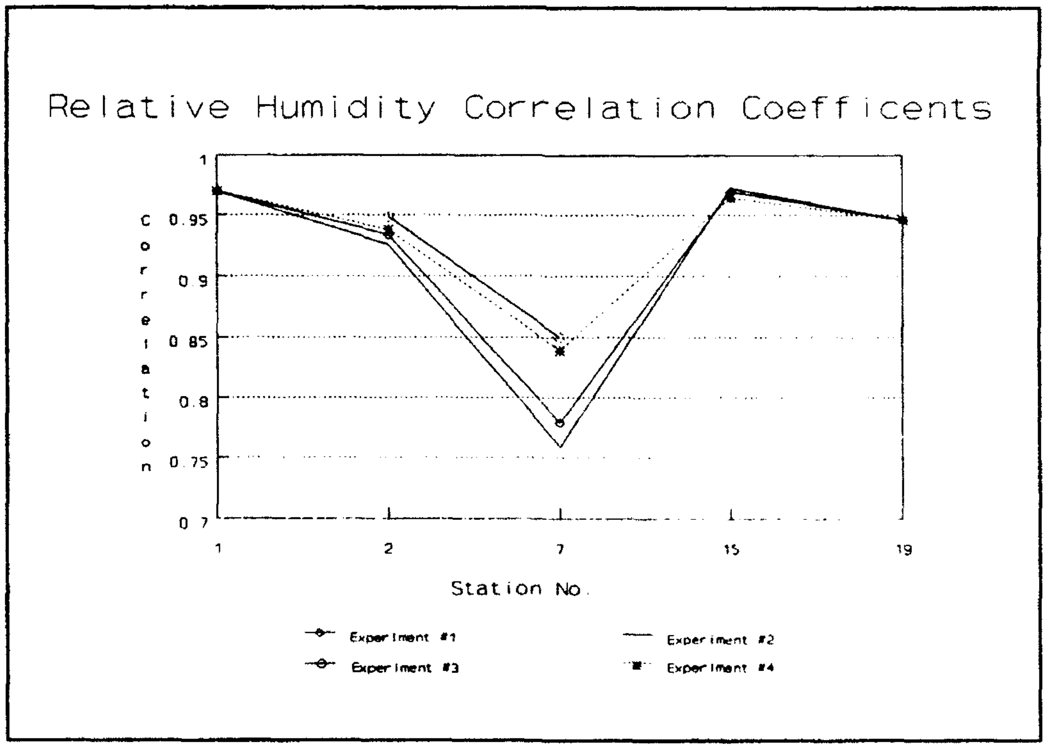

Figure 3. Relative humidity correlation coefficients.

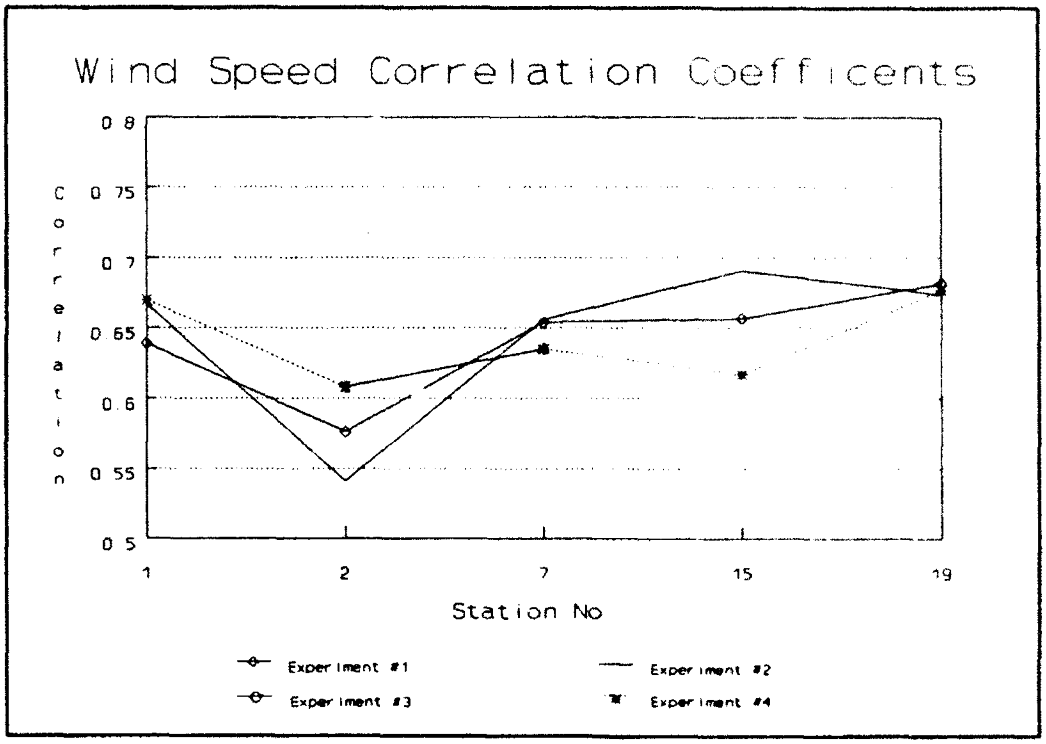

Figure 4. Windspeed correlation coefficients.

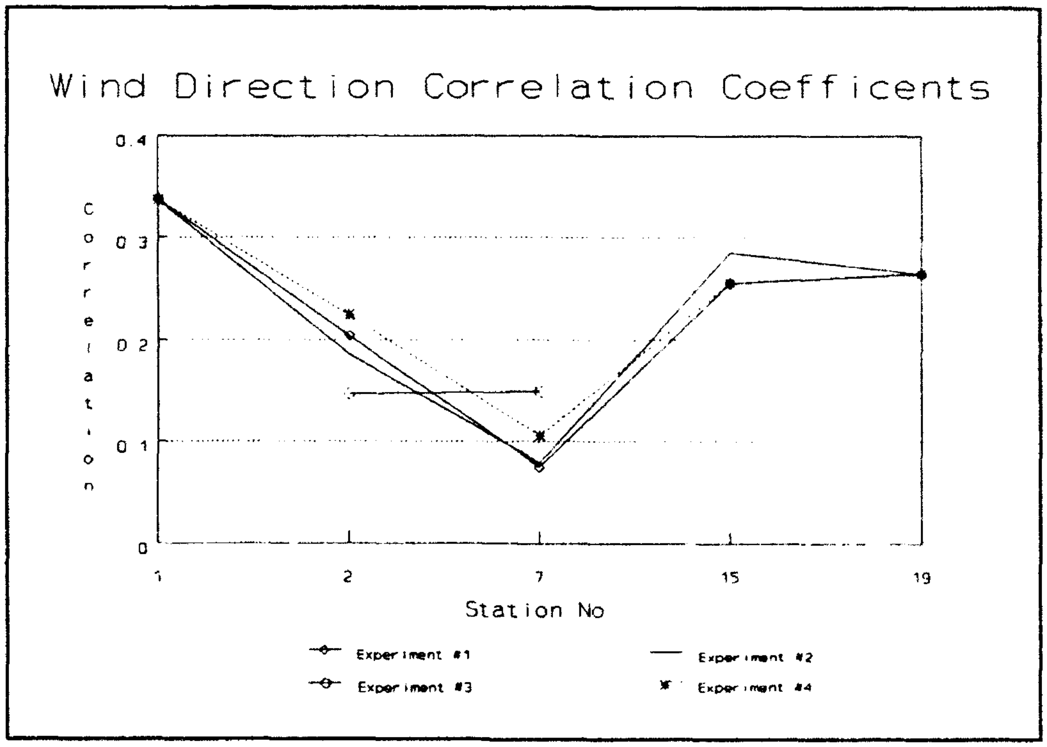

Figure 5. Wind direction correlation coefficients.

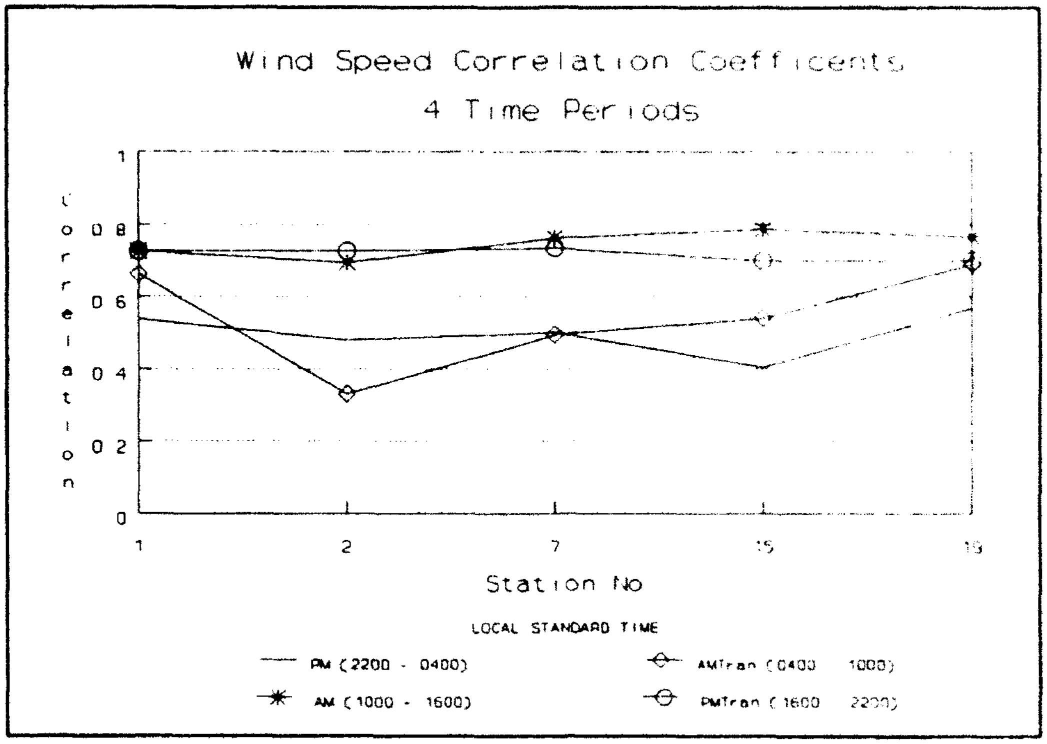

Figure 6. Correlation coefficients in time for windspeed.

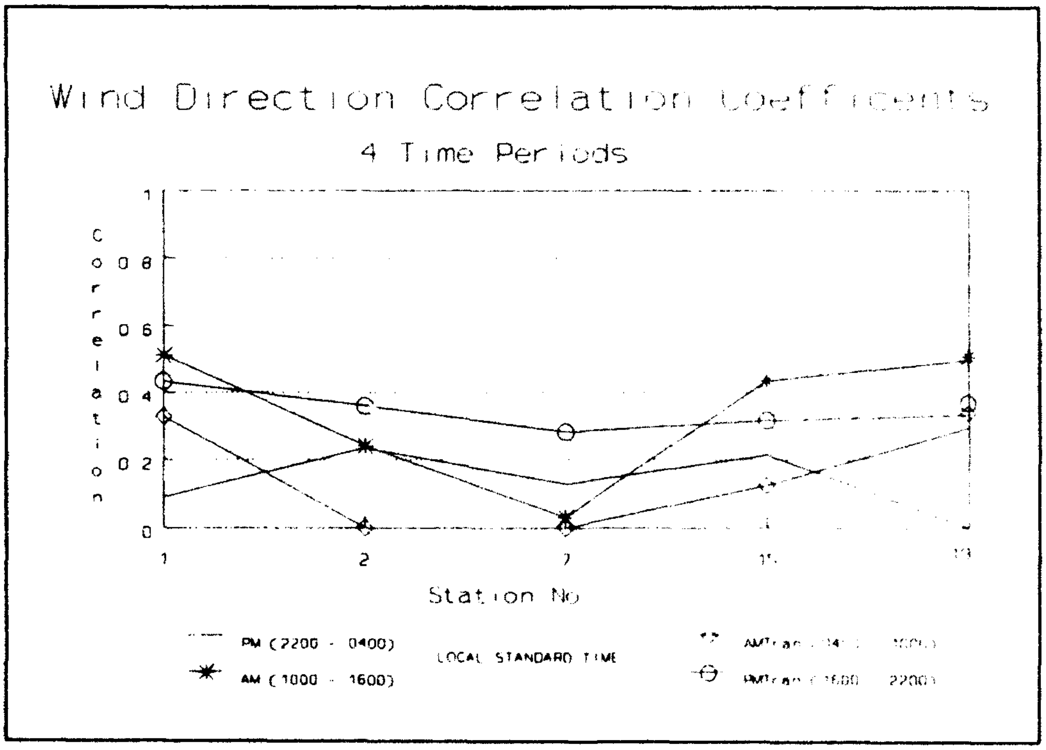

Figure 7. Correlation coefficients in time for wind direction.

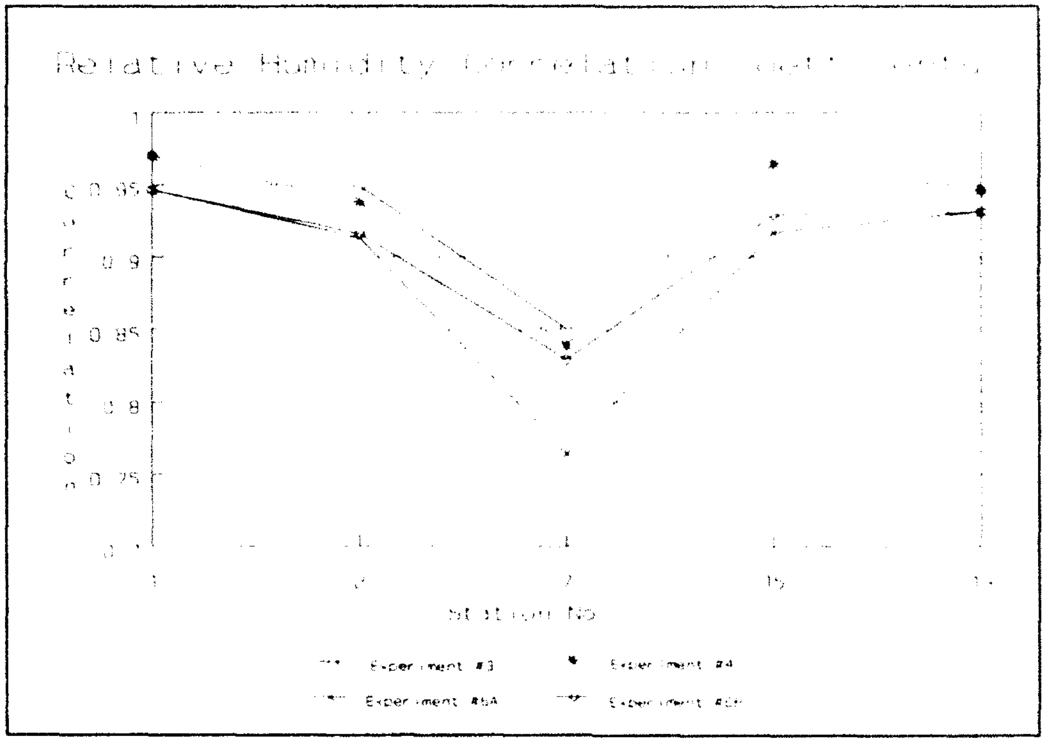

Figure 8. Correlation coefficients for improved bilinear interpolation.

TABLE 1. RESULTS FROM INTERPOLATION EXPERIMENT 1

10 X 20 Grid, 3 Contributing Stations, Nearest Grid Point

	Air Temp	RH	Windspeed	Wind Direction
Station 1				
Correlation	0.975	0.970	0.639	0.337
RMS Error	1.702	4.673	2.055	105.121
Agreement	0.985	0.985	0.782	0.630
Station 19				
Correlation	0.957	0.946	0.682	0.264
RMS Error	2.460	6.389	1.618	108.357
Agreement	0.972	0.971	0.821	0.585
Station 2				
Correlation	0.963	0.934	0.576	0.204
RMS Error	2.244	8.518	2.238	105.442
Agreement	0.976	0.954	0.743	0.561
Station 7				
Correlation	0.858	0.799	0.654	0.075
RMS Error	4.311	14.934	2.204	130.782
Agreement	0.917	0.866	0.776	0.503
Station 15				
Correlation	0.978	0.970	0.657	0.255
RMS Error	1.533	5.476	2.055	139.166
Agreement	0.988	0.983	0.782	0.589

TABLE 2. RESULTS FROM INTERPOLATION EXPERIMENT 2

10 X 20 Grid, 2 Contributing Stations, Nearest Grid Point

	Air Temp	RH	Windspeed	Wind Direction
Station 1				
Correlation	0.974	0.970	0.667	0.336
RMS Error	1.718	4.680	2.015	103.251
Agreement	0.985	0.985	0.796	0.629
Station 19				
Correlation	0.956	0.946	0.674	0.264
RMS Error	2.482	6.386	1.640	108.462
Agreement	0.971	0.971	0.816	0.584
Station 2				
Correlation	0.959	0.926	0.541	0.186
RMS Error	2.338	9.017	2.293	107.219
Agreement	0.974	0.945	0.725	0.548
Station 7				
Correlation	0.844	0.759	0.656	0.079
RMS Error	4.500	15.716	2.342	130.027
Agreement	0.910	0.853	0.765	0.505
Station 15				
Correlation	0.981	0.973	0.691	0.285
RMS Error	1.460	5.189	1.970	139.063
Agreement	0.990	0.985	0.806	0.602

TABLE 3. RESULTS FROM INTERPOLATION EXPERIMENT 3

10 X 20 Grid, 6 Contributing Stations, Nearest Grid Point

	Air Temp	RH	Windspeed	Wind Direction
Station 2				
Correlation	0.979	0.949	0.608	0.147
RMS Error	1.71	7.654	2.190	109.817
Agreement	0.987	0.960	0.760	0.531
Station 7				
Correlation	0.917	0.850	0.635	0.149
RMS Error	3.499	12.023	1.932	123.699
Agreement	0.947	0.911	0.788	0.543

TABLE 4. RESULTS FROM INTERPOLATION EXPERIMENT 4

30 X 40 Grid, 3 Contributing Stations, Nearest Grid Point

	Air Temp	RH	Windspeed	Wind Direction
Station 1				
Correlation	0.975	0.970	0.670	0.336
RMS Error	1.704	4.673	2.008	105.179
Agreement	0.985	0.985	0.797	0.629
Station 19				
Correlation	0.956	0.946	0.677	0.265
RMS Error	2.478	6.387	1.635	108.320
Agreement	0.971	0.971	0.817	0.585
Station 2				
Correlation	0.965	0.938	0.608	0.224
RMS Error	2.206	7.532	2.190	104.078
Agreement	0.976	0.960	0.760	0.574
Station 7				
Correlation	0.899	0.839	0.635	0.106
RMS Error	3.731	12.5640	1.932	129.595
Agreement	0.937	.903	0.788	0.520
Station 15				
Correlation	0.974	0.965	0.617	0.253
RMS Error	1.662	5.983	2.166	135.694
Agreement	0.986	0.979	0.755	0.593

TABLE 5. RESULTS FROM INTERPOLATION EXPERIMENT 5A

Nighttime Transition (PMTR)
10 X 20 Grid, 3 Contributing Stations, Nearest Grid Point

	Air Temp	RH	Windspeed	Wind Direction
Station 1				
Correlation	0.951	0.959	0.663	0.327
RMS Error	2.167	6.292	1.883	119.916
Agreement	0.969	0.797	0.808	0.621
Station 19				
Correlation	0.936	0.937	0.690	0.292
RMS Error	2.783	8.017	1.559	119.554
Agreement	0.955	0.967	0.824	0.599
Station 2				
Correlation	0.935	0.909	0.331	-0.007
RMS Error	2.530	10.459	2.508	134.683
Agreement	0.958	0.937	0.603	0.432
Station 7				
Correlation	0.788	0.740	0.494	-0.021
RMS Error	4.586	16.400	2.136	158.842
Agreement	0.873	0.836	0.681	0.438
Station 15				
Correlation	0.969	0.967	0.541	0.124
RMS Error	1.512	6.256	2.223	165.407
Agreement	0.984	0.979	0.701	0.528

TABLE 6. RESULTS FROM INTERPOLATION EXPERIMENT 5B

Night (PM)
10 X 20 Grid, 3 Contributing Stations, Nearest Grid Point

	Air Temp	RH	Windspeed	Wind Direction
Station 1				
			0.539	
Correlation	0.950	0.967	2.110	0.089
RMS Error	2.088	5.251	0.727	126.082
Agreement	0.965	0.983		0.479
Station 19				
Correlation	0.914	0.930	0.569	0.043
RMS Error	3.151	7.868	1.860	124.788
Agreement	0.926	0.962	0.707	0.422
Station 2				
Correlation	0.914	0.925	0.480	0.234
RMS Error	2.955	9.875	2.335	89.793
Agreement	0.935	0.939	0.701	0.542
Station 7				
Correlation	0.829	0.771	0.500	0.127
RMS Error	4.724	13.775	2.441	140.543
Agreement	0.830	0.8373	0.634	0.528
Station 15				
Correlation	0.931	0.961	0.405	0.213
RMS Error	1.981	6.586	2.067	166.329
Agreement	0.961	0.975	0.644	0.582

TABLE 7. RESULTS FROM INTERPOLATION EXPERIMENT 5C

Morning Transition (AMTR)
10 X 20 Grid, 3 Contributing Stations, Nearest Grid Point

	Air Temp	RH	Windspeed	Wind Direction
Station 1				
Correlation	0.984	0.964	0.727	0.432
RMS Error	1.071	3.693	2.010	83.162
Agreement	0.992	0.981	0.819	0.680
Station 19				
Correlation	0.969	0.950	0.700	0.330
RMS Error	1.662	4.489	1.587	89.339
Agreement	0.982	0.969	0.833	0.612
Station 2				
Correlation	0.973	0.938	0.726	0.359
RMS Error	1.555	6.349	1.978	78.971
Agreement	0.984	0.951	0.824	0.642
Station 7				
Correlation	0.862	0.753	0.735	0.281
RMS Error	3.458	12.065	2.132	102.848
Agreement	0.918	0.829	0.813	0.622
Station 15				
Correlation	0.971	0.961	0.700	0.316
RMS Error	1.496	4.705	2.035	115.731
Agreement	0.984	0.979	0.804	0.600

TABLE 8. RESULTS FROM INTERPOLATION EXPERIMENT 5D

Day (AM)
10 X 20 Grid, 3 Contributing Stations, Nearest Grid Point

	Air Temp	RH	Windspeed	Wind Direction
Station 1				
			0.726	
Correlation	0.987	0.987	2.015	0.511
RMS Error	1.194	2.691	0.788	89.868
Agreement	0.988	0.989		0.720
Station 19				
Correlation	0.978	0.976	0.766	0.496
RMS Error	1.989	4.288	1.428	95.531
Agreement	0.969	0.970	0.857	0.698
Station 2				
Correlation	0.982	0.953	0.695	0.240
RMS Error	1.638	4.531	2.061	111.233
Agreement	0.979	0.972	0.776	0.584
Station 7				
Correlation	0.820	0.780	0.762	0.031
RMS Error	4.397	17.082	2.070	115.665
Agreement	0.861	0.749	0.839	0.457
Station 15				
Correlation	0.985	0.974	0.787	0.434
RMS Error	0.973	3.851	1.847	99.901
Agreement	0.992	0.984	0.857	0.622

TABLE 9. RESULTS FROM INTERPOLATION EXPERIMENT 6A

10 X 20 Grid, 3 Contributing Stations, Bilinear Interpolation

	Air Temp	RH	Windspeed	Wind Direction
Station 1				
			0.658	
Correlation	0.945	0.946	2.041	0.341
RMS Error	2.445	6.822	0.791	104.714
Agreement	0.970	0.971		0.633
Station 19				
Correlation	0.932	0.931	0.682	0.261
RMS Error	2.988	7.849	1.623	108.23
Agreement	0.958	0.962	0.821	0.585
Station 2				
Correlation	0.945	0.913	0.650	0.275
RMS Error	2.637	8.931	2.130	101.584
Agreement	0.966	0.950	0.790	0.604
Station 7				
Correlation	0.886	0.764	0.635	0.060
RMS Error	3.394	16.142	2.401	130.817
Agreement	0.933	0.868	0.755	0.494
Station 15				
Correlation	0.943	0.917	0.550	0.217
RMS Error	2.418	9.449	2.357	131.284
Agreement	0.971	0.953	0.731	0.579

TABLE 10. RESULTS FROM INTERPOLATION EXPERIMENT 6B

30 X 40 Grid, 3 Contributing Stations, Bilinear Interpolation

	Air Temp	RH	Windspeed	Wind Direction
Station 1			0.657	
Correlation	0.945	0.946	2.044	0.341
RMS Error	2.45	6.823	0.791	104.813
Agreement	0.970	0.971		0.632
Station 19				
Correlation	0.932	0.931	0.683	0.261
RMS Error	2.986	7.851	1.621	108.232
Agreement	0.958	0.962	0.822	0.585
Station 2				
Correlation	0.945	0.916	0.648	0.259
RMS Error	2.628	8.838	2.137	101.821
Agreement	0.967	0.951	0.787	0.594
Station 7				
Correlation	0.902	0.829	0.623	0.080
RMS Error	3.676	13.666	2.156	130.714
Agreement	0.941	0.902	0.771	0.505
Station 15				
Correlation	0.948	0.929	0.550	0.227
RMS Error	2.314	8.670	2.347	132.092
Agreement	0.974	0.960	0.728	0.583

TABLE 11. **STATISTICS FOR INTERPOLATED AND OBSERVED DAYTIME WINDSPEEDS**

Windspeed in knots (daytime 1000-1600)

Station No.	1	2	7	15	19
Interpolated					
Mean	3.386	3.330	4.145	3.790	3.374
Standard Deviation	1.784	1.829	3.160	2.131	1.788
Variance	3.183	3.347	9.985	2.131	3.195
Observed					
Mean	4.288	4.320	4.387	4.273	3.818
Standard Deviation	2.614	[illegible].510	2.221	2.878	2.091
Variance	6.834	6.302	4.934	8.282	4.373

TABLE 12. **STATISTICS FOR INTERPOLATED AND OBSERVED NIGHTTIME WINDSPEEDS**

Windspeed in knots (nighttime 2200-0400)

Station No.	1	2	7	15	19
Interpolated					
Mean	2.937	2.815	3.981	2.987	2.913
Standard Deviation	2.161	2.160	2.630	1.637	2.158
Variance	4.670	4.665	6.913	2.679	4.658
Observed					
Mean	2.785	3.332	3.155	2.744	2.434
Standard Deviation	2.230	2.297	1.605	2.067	1.509
Variance	4.973	2.297	2.576	4.720	2.277

TABLE 13. CASE 1 AND CASE 2 STATISTICS FOR TEMPERATURE

	Mean	Std Dev	Correlation	Agreement	RMS Error
Case 1	15.0	6.9	0.84	0.91	4.5
Case 2	15.4	7.1	0.92	0.95	3.5

TABLE 14. CASE 1 AND CASE 2 STATISTICS FOR RELATIVE HUMIDITY

	Mean	Std Dev	Correlation	Agreement	RMS Error
Case 1	38.3	20.2	0.76	0.85	15.7
Case 2	36.2	19.4	0.85	0.91	12.0

TABLE 15. CASE 1 AND CASE 2 STATISTICS FOR WINDSPEED

	Mean	Std Dev	Correlation	Agreement	RMS Error
Case 1	4.2	3.0	0.61	0.73	2.5
Case 2	3.5	2.4	0.64	0.79	1.9

TABLE 16. CASE 1 AND CASE 2 VARIATIONS IN METEOROLOGICAL PARAMETERS

Trial Case	Temperature	Relative Humidity	Windspeed
Case 1	15.0 +/- 4.5 C	38.3 +/- 15.7 %	4.2 +/- 2.5 m/s
Case 2	15.4 +/- 3.5 C	36.2 +/- 12.0 %	3.5 +/- 1.9 m/s

TABLE 17. METEOROLOGICAL VALUES USED IN TDA SENSITIVITY STUDY

Experiment	Temp	RH	WS
Case 1 - Worst for MOPP	19.5	54.0	1.7
Case 1 - Best for MOPP	10.5	22.6	6.7
Case 2 - Worst for MOPP	18.9	48.2	1.6
Case 2 - Best for MOPP	11.9	24.2	5.4

TABLE 18. TDA RESULTS - WORST FOR MOPP CASE 1

MAXIMUM PROBABILITY OF CASUALTIES/TIME TO MAXIMUM

Temperature = 19.5 Deg C RH = 54.0 % Windspeed = 1.7 m/s

	MOPP1	MOPP2	MOPP3	MOPP4
SUSTAINED				
Walking very fast	1.00/102	1.00/93	1.00/86	1.00/79
INTERMITTENT				
Active Exercise:				
loading cannon	0.00/999	0.03/177	0.08/173	0.17/165
Severe exercise:				
assault	0.39/146	0.52/138	0.63/132	0.82/122
Fire fight	0.50/139	0.65/131	0.78/124	0.99/114
Running (5.3 mi/hr)	0.87/119	1.00/109	1.00/103	1.00/93
Running with load	1.00/112	1.00/103	1.00/96	1.00/87

TABLE 19. TDA RESULTS - BEST FOR MOPP CASE 1

MAXIMUM PROBABILITY OF CASUALTIES/TIME TO MAXIMUM

Temperature = 10.5 Deg C RH = 22.5 % Windspeed = 6.7 m/s

	MOPP1	MOPP2	MOPP3	MOPP4
SUSTAINED				
Walking very fast	0.46/140	0.61/131	0.76/123	1.00/111
INTERMITTENT				
Active exercise:				
loading cannon	0.00/999	0.00/999	0.00/999	0.00/999
Severe exercise:				
assault	0.00/999	0.06/171	0.12/166	0.23/158
Fire fight	0.06/171	0.13/165	0.20/160	0.32/150
Running (5.3 mi/hr)	0.26/154	0.37/147	0.47/140	0.66/129
Running with load	0.33/149	0.45/141	0.57/134	0.79/122

TABLE 20. TDA RESULTS - WORST FOR MOPP CASE 2

MAXIMUM PROBABILITY OF CASUALTIES/TIME TO MAXIMUM

Temperature = 18.9 Deg C RH = 48.2 % Windspeed = 1.6 m/s

	MOPP1	MOPP2	MOPP3	MOPP4
SUSTAINED				
Walking very fast	1.00/104	1.00/94	1.00/88	1.00/80
INTERMITTENT				
Active exercise:				
loading cannon	0.00/999	0.02/179	0.07/174	0.16/166
Severe exercise:				
assault	0.37/148	0.49/140	0.60/133	0.79/124
Fire fight	0.47/141	0.61/132	0.74/126	0.96/116
Running (5.3 mi/hr)	0.83/121	1.00/111	1.00/104	1.00/95
Running with load	0.97/114	1.00/105	1.00/98	1.00/89

TABLE 21. TDA RESULTS - BEST FOR MOPP CASE 2

MAXIMUM PROBABILITY OF CASUALTIES/TIME TO MAXIMUM

Temperature = 11.9 Deg C RH = 24.2 % Windspeed = 5.4 m/s

	MOPP1	MOPP2	MOPP3	MOPP4
SUSTAINED				
Walking very fast	0.55/135	0.72/125	0.89/117	1.00/105
INTERMITTENT				
Active exercise:				
loading cannon	0.00/999	0.00/999	0.00/999	0.00/999
Severe exercise:				
assault	0.04/173	0.11/167	0.18/161	0.30/152
Fire fight	0.11/167	0.19/160	0.27/154	0.40/145
Running (5.3 mi/hr)	0.32/149	0.44/141	0.56/134	0.77/123
Running with load	0.40/144	0.54/135	0.67/128	0.92/116

TABLE 22. TDA RESULTS - MEAN CASE 2

MAXIMUM PROBABILITY OF CASUALTIES/TIME TO MAXIMUM

Temperature = 15.4 Deg C RH = 36.2 % Windspeed = 3.5 m/s

	MOPP1	MOPP2	MOPP3	MOPP4
SUSTAINED				
Walking very fast	0.80/122	1.00/111	1.00/103	1.00/92
INTERMITTENT				
Active exercise:				
loading cannon	0.00/999	0.00/999	0.00/999	0.00/999
Severe exercise:				
assault	0.16/163	0.26/156	0.34/149	0.49/140
Fire fight	0.24/156	0.35/149	0.45/142	0.62/132
Running (5.3 mi/hr)	0.51/138	0.67/129	0.82/121	1.00/110
Running with load	0.61/132	0.79/122	0.97/114	1.00/103

TABLE 23. **TDA RESULTS - WORST FOR MOPP CASE 1 - TEMPERATURE ERROR ONLY**

MAXIMUM PROBABILITY OF CASUALTIES/TIME TO MAXIMUM

Temperature = 11.9 Deg C RH = 48.2 % Windspeed = 1.6 m/s

	MOPP1	MOPP2	MOPP3	MOPP4
SUSTAINED				
Walking very fast	0.87/118	1.00/108	1.00/100	1.00/90
INTERMITTENT				
Active exercise:				
loading cannon	0.00/999	0.00/999	0.00/999	0.03/177
Severe exercise:				
assault	0.20/160	0.30/152	0.40/146	0.55/136
Fire fight	0.28/153	0.40/145	0.50/139	0.68/129
Running (5.3 mi/hr)	0.56/134	0.74/125	0.90/118	1.00/107
Running with load	0.67/128	0.87/118	1.00/111	1.00/100

TABLE 24. **TDA RESULTS - WORST FOR MOPP CASE 1 - RELATIVE HUMIDITY ERROR ONLY**

MAXIMUM PROBABILITY OF CASUALTIES/TIME TO MAXIMUM

Temperature = 18.9 Deg C RH = 24.2 % Windspeed = 1.6 m/s

	MOPP1	MOPP2	MOPP3	MOPP4
SUSTAINED				
Walking very fast	1.00/109	1.00/99	1.00/92	1.00/83
INTERMITTENT				
Active exercise:				
loading cannon	0.00/999	0.00/999	0.04/176	0.13/169
Severe exercise:				
assault	0.32/151	0.43/143	0.54/137	0.72/127
Fire fight	0.41/145	0.54/136	0.67/130	0.88/119
Running (5.3 mi/hr)	0.73/125	0.94/116	1.00/108	1.00/98
Running with load	0.86/119	1.00/109	1.00/102	1.00/92

TABLE 25. TDA RESULTS - WORST FOR MOPP CASE 1 - WINDSPEED ERROR ONLY

WORST FOR MOPP DELTA WINDS

MAXIMUM PROBABILITY OF CASUALTIES/TIME TO MAXIMUM

Temperature - 18.9 Deg C RH - 48.2 % Windspeed - 5.4 m/s

	MOPP1	MOPP2	MOPP3	MOPP4
SUSTAINED				
Walking very fast	0.88/118	1.00/108	1.00/100	1.00/89
INTERMITTENT:				
Active exercise:				
loading cannon	0.00/999	0.00/999	0.00/999	0.02/179
Severe exercise:				
assault	0.20/160	0.29/153	0.38/147	0.54/137
Fire fight	0.28/154	0.39/146	0.50/139	0.68/129
Running (5.3 mi/hr)	0.56/134	0.73/125	0.90/118	1.00/106
Running with load	0.67/128	0.87/118	1.00/111	1.00/100

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