A Multi-Year Observational Study of Atmospheric Transport Corridors and Processes in California

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Abstract

NOAA's Environmental Technology Laboratory (ETL, formerly the Wave Propagation Laboratory) used its network of boundary-layer 915-MHz radar wind profilers and supporting meteorological instrumentation to monitor and study major interbasin transport corridors for ozone and its precursors over two summer ozone seasons during 1991 and 1992. During this period wind profilers, some equipped with RASS temperature profiling, were deployed at twenty-five sites throughout California. Our goal was to provide data necessary to meet ARB needs to assess transport of ozone and its precursors in a number of transport couples throughout the State using wind and mixed layer depth determinations from profilers. In addition, we sought to provide a data base that could be used for future modeling exercises and to critically evaluate profiler technology for future applications in the State. In support of the study, we created a data base system and display software and installed a workstation for the Air Resources Board in Sacramento where data could be transferred in real-time over the Internet and again after reanalysis. In the course of the study we discovered contamination of the wind data by migrating birds. We found the effect to be significant along certain migratory paths in spring and early summer and again in late summer and early fall. Because of the seriousness of the problem, we redirected our internal resources and developed new editing methods to flag contaminated data after the fact and developed new signal processing routines that can now eliminate a substantial fraction of the contamination in real-time.

With the re-edited data, we carried out a number of analyses of meteorological conditions associated with high- and low-ozone periods in selected areas. In addition, a series of short term supplemental measurement campaigns suggested that the dynamics of the diurnal, thermally forced circulation along the major topographic boundaries of the Central Valley and the South Coast Basin play a significant role in the recirculation of pollutants in some cases and their transport into other air basins, in others. Analysis of profiler data adjacent to Banning and Cajon Passes in southern California suggest that such passes can be easily monitored with wind profilers so as to determine the direction and depth of transport from one basin to another.

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1 SUMMARY AND CONCLUSIONS

The study described in this report represents the first long-term use of newly developed 915-MHz radar wind profilers to monitor and study meteorological processes associated with the major ozone transport corridors in the State of California. In this study, one that spanned much of 1991 and 1992, our overall objectives were:

- ***To use 915-MHz wind profilers to create a data base of vertical profiles of winds and temperatures during two ozone seasons to address ARB transport assessment needs,***
- ***To deploy and test ETL's central data hub system for its network of research wind and temperature profilers at the ARB headquarters for data acquisition, processing, and display of wind and temperature data,***
- ***To improve the capability of radar wind profilers to infer mixing layer depths and to better understand the dynamics of local circulations along terrain-dominated transport corridors and to lead to improved use of ARB models with additional instrumentation and analyses,***
- ***To provide this new data base to ARB at the completion of the project, and***
- ***To improve the understanding of the meteorological processes that influence pollutant transport and dispersion within and between basin couples by analyzing the data collected.***

In particular, we sought to 1) advance and evaluate this new wind-profiler technology as it might be used for routine meteorological monitoring in the State of California, 2) carry out representative analyses that show how profiler data can be used to understand transport corridor processes, and 3) to provide a data base with which the Technical Support Division of the California Air Resources Board could assess the role of interbasin transport on ozone episodes in a number of key transport couples in the State. The major air basins on which we focused included the Sacramento Valley, the North Central Coast, and a broader area encompassing the South Coast and the Southeast Desert Air Basins.

Profiler Performance and Contamination by Migratory Birds

We found that the profilers, for the most part, operated well with minimal maintenance and could be moved relatively easily on a seasonal basis around the State. The twenty five sites used over the two-year study provide a cross section of operational environments in which profilers could operate effectively. ARB staff were involved in the initial siting of a number of the profilers and in their subsequent operation. Transferring ETL expertise in this fashion has provided a base of experience within the ARB for future installation and operation of profilers obtained from the commercial sector. Major restrictions on siting included the presence of power lines and towers, nearby highways, and forested areas. Coastal sites worked well when the profilers were situated on higher ground and/or some distance inland.

A few of the twenty-five profiler sites experienced persistent electronic or environmental problems that required continuing repair efforts. Of greatest concern, however, was a major problem in contamination of radar wind data by migratory birds during certain seasons of the year and in some locations. This problem was discovered initially through our analysis of audit data from the Sacramento Valley. Because birds follow favorable winds, their presence in the radar spectrum often modifies the calculated wind speed rather than the wind direction. Thus, the contamination by birds often tends not to be that apparent in observed wind patterns derived from profilers. Once this problem was discovered, two efforts ensued. The first entailed finding a signal processing solution that would guarantee the viability of the technology and the second focused on developing data-editing routines that could identify contaminated signals in existing data. Promising solutions have been found to both problems. The proposed signal processing option for future profiler deployments will require a significant but straightforward change in the profiler real-time software. The data-editing solution has required more care and experimentation, particularly in the lowest kilometer of the atmosphere where signal strengths are often comparable to those of birds, but data retention is essential for transport calculations. These latter routines process individual samples averaged by the radar for a period of a minute or less: audit data were used to check the efficacy of these routines after reprocessing. An extensive analysis and documentation of the bird-contamination problem (Appendix A) has now been completed and the effect of migratory birds and its potential solution has been well documented for not only the new 915-MHz profilers but also for the already well-established National Wind Profiler Demonstration Network. This latter network includes the 404-MHz profiler located at Vandenberg Air Force Base that may be used in future transport analyses. Although some data are lost in the process as described in detail in Appendix A, the remaining data show much reduced differences with rawinsondes as shown in Appendix B. As more advanced editing routines are developed in the future, reprocessing of the archived raw data can be accomplished easily. A byproduct of the new signal processing routine, currently being tested, may be a reduction in contamination of profiler data by vehicles on adjacent highways, thus allowing more latitude in siting requirements.

Data Audits

Data audits during the 1991 northern California study used optically tracked rawinsondes obtained at three-hour intervals, typically over a full diurnal cycle. This method differed from audit procedures used in the 1990 San Joaquin Valley Air Quality Study. That procedure used sodars and tethersondes with limited vertical range and thus missed the bird contamination problem. Past comparisons of profiler data with rawinsondes obtained at synoptic times of 00Z and 12Z also missed the problem because birds typically migrate between these two times. After removal of bird-contaminated data, root-mean-square differences in wind components at each site ranged from 1 to 2 ms^{-1}, comparable with commonly observed errors in rawinsonde-derived winds, particularly those obtained with optical tracking techniques.

We also compared profiler measurements at two sites located about 10 km apart in the Sacramento River delta. The greatest differences were found in the lowest 750 m above the ground, about 2 ms^{-1} in the root-mean-square error. The fact that smaller differences occurred further aloft, between 750 m and 1500 m, suggests that the low-level flow was subject to greater spatial variation over the 10 km separation of the sites, perhaps due to natural meteorological variability and/or nearby terrain influence. This result suggests that in areas more prone to natural variability in the boundary layer, Doppler sodars with a nominal range of 750 m might well supplement profiler-wind measurements at less cost.

Northern California Transport (NCT) Studies (1991)

In addition to operating the profiler networks to generate wind profiler data sets for the State's transport assessment needs, we carried out a number of analyses of the basic data set and supporting measurements. From the 1991 data set obtained in the Sacramento Valley as part of our Northern California Transport (NCT) study, we examined two distinct meteorological regimes. The first, associated with an upper-level ridge, produced higher ozone levels, particularly near the foothills of the Sierra Nevada. The second, associated with an upper-level trough, produced lower ozone levels. In summary:

- Wind fields, derived through weighted spatial interpolation of profiler and surface data, were segregated by high and low ozone concentrations in the Sacramento Valley. In both cases, winds in the Sacramento River Delta were similar. However, during high- and low-ozone periods, major differences in the vector wind fields occur once the southwesterly flow enters the Sacramento Valley. Most notable is the rapid deceleration of the winds upon entering the valley during high-ozone periods. This rapid deceleration appears to be associated with the strength of the thermal trough. As the winds enter the center of the valley they begin to encounter a counter pressure gradient causing the rapid deceleration. In the high ozone cases, computed streamlines show flow from the Carquinez Straits impinging on the foothills east of Sacramento; in low-ozone cases the boundary-layer streamlines show a northward transport through the Sacramento Valley.

- At sites within the valley, the wind patterns in the boundary layer are significantly influenced by diurnal heating patterns of the nearby terrain in the ridge case. However, the diurnal patterns do not appear significant in the trough case. A general diurnal pattern throughout most of the valley is a northerly drainage flow in the morning (amplified by the northerly synoptic flow in the ridge case), and a southerly up-valley flow in the afternoon.

- At sites near the passes to the Pacific Ocean, the diurnal patterns are not important in either the trough or ridge case as the on-shore ocean breeze is continuous throughout the day. The flow from the ocean into the valley is stronger in the trough case than in the ridge case and, in both cases, it is very shallow.

- In the center of the valley, the winds at most levels in the ridge case are light and variable throughout the day with little indication of diurnal patterns.

- The sea breeze penetrates to Davis by around midday in the ridge case and to Oroville late in the afternoon. This sea breeze is highly modified and is in nearly the same direction as the already existing up-valley flow at each of these sites.

- A spatial correlation analysis was carried out for the NCT network of profilers that showed the sensitivity of the correlation to dominant flow patterns in the Sacramento Valley: in general, the streamwise correlations were high, cross stream correlations were low. These results suggest that long-term siting requirements be developed using analysis of existing data sets and characterization of dominant flow patterns.

A similar series of analyses were carried out for the small network of profilers relocated to the North Central Coast Air Basin (NCCAB) during 1991. In a brief summary of the North Central Coast Transport (NCCT) Study wind patterns, we observed the following:

- There is a marked contrast between the high- and low-ozone cases at all three North Central Coast (NCC) sites.
- The high-ozone case exhibits less on-shore flow than the low-ozone case. There appears to be significant transport down the Santa Clara Valley from the southern portion of San Francisco Bay. From the profiler wind data there is a strong indication of direct transport of pollutants from the south San Francisco Bay Area into the NCCAB and on to Pinnacles National Monument.
- In the low-ozone situation, the on-shore breeze from Monterey Bay is much more pronounced than during high ozone cases, and this presumably relatively clean air is channeled southeastward toward Pinnacles National Monument.
- The high-ozone case shows the northerly-component tendency associated with the NCT ridge conditions discussed above, but, for the NCC low-ozone case, the southerly-component flow prevalent during the trough cases in the NCT study did not appear during NCCT Study.

Southern California Transport (SCT) Studies (1992)

The primary focus of the Southern California Transport (SCT) study was to examine the transport corridors from the South Coast Air Basin (SoCAB) to the Southeast Desert Air Basin (SEDAB). The major corridors investigated included Cajon and Banning Passes and to a lessor degree, Soledad Canyon and Tehachapi Passes. A minor effort was instituted to provide data with which to examine meteorological conditions associated with high ozone concentrations in San Diego, including over-water transport.

- Profiler wind fields show almost continuous daytime transport in the lowest 500 to 1000 m through the Cajon and Banning Passes during the summer months. The direction of transport is from the SoCAB to the SEDAB.
- Synoptic weather patterns appear to have only a small influence on the wind fields in both the SoCAB and the SEDAB. The patterns do, however, have an effect on the mixed layer heights. Violations of state ozone standards at San Bernardino are directly related to the mixed layer depth which in turn is related to the 500-mb pattern.
- The depth of the mixed layer appears to influence the amount of pollutants transported into the SEDAB through the Cajon Pass. Large differences in ozone levels occur between San Bernardino and Hesperia when the height of the mixed layer is below the height of the Cajon Pass. Ozone violations at Hesperia occur with good transport through the Cajon Pass and with mixed layer depth in the San Bernardino area exceeding the height of the pass.
- During both high- and low-ozone days at Barstow, the flow of air in the late afternoon is from the SoCAB and the SJVAB into the SEDAB. The difference is that for high-ozone days in

Barstow, the flow of air at the surface and aloft is directly through the Cajon Pass towards Barstow. During low ozone days, air passing through the Cajon Pass passes south of Barstow while air passing through the Tehachapi Pass passes to the north. These patterns continue throughout the evening hours.

- During the summer and early fall, the flow of air is almost continuously from the SoCAB and the SJVAB into the SEDAB. The strength and depth of this flow appears to be related to the synoptic conditions although strong relationships do not exist as they did with the NCT study. High-ozone cases within the SEDAB appear to be related to the depth of the marine layer within the SoCAB and the strength and depth of the transport through the various canyons and passes.
- Because of the limited array associated with the San Diego portion of the study, interpolated wind fields were not available. However, the profiler data are located in the data archive provided to the ARB for their analysis activities.

Supplemental Studies

We provided a number of supplemental efforts to assist the State in its air quality monitoring efforts. These included:

- A study of diurnally forced flow in the side canyons of the Sierra Nevada: we examined data from the King's River Canyon in the southern Central Valley, and the Feather River Canyon northeast of Oroville. We documented the existence of deep, strong drainage flows channeled through two different river canyons on the western slope of the Sierra Nevada Mountains. Several of these canyons drain into the east sides of the San Joaquin and Sacramento Valleys. The profiler located near Oroville documented the depth and strength of one of these drainage jets as it exited well into the Sacramento Valley. Considering the large volume of air transported by these drainages, a substantial portion of the polluted air advected into the mountains by the daytime upslope winds may be returned to the valleys during the nighttime and early morning hours. The results suggest that current simulations may not correctly model these drainage flows. Past model results prior to the SJVAQS suggested an inertial rotation of winds over the Sierra Nevada resulting in easterly winds over this elevated terrain by early morning. However, our observations show an abrupt transition (0.5 h) between upslope and downslope winds in the evening in both canyons. A substantial improvement in numerical models may occur with the incorporation of these terrain-associated flows, perhaps through the local assimilation of profiler observations obtained in major mountain air sheds or improved parameterization of thermally forced circulations.
- We developed a data base system with a UNIX workstation available to Technical Support Division staff for the course of the study. The software available on this system included graphical displays of winds, temperature, and mixed layer depth as well as meteorological station data obtained at the profiler sites. The draft technical report on this in-kind contribution is contained in Appendix G.
- We explored a variety of derived fields from the wind profiler data, providing a discussion, in particular, of mixed layer depth and turbulence inference techniques. Furthermore, in lieu of

primitive equation simulations for analysis, we used the profiler network data from the Sacramento Valley and the SEDAB to generate simple interpolated wind fields and mixed-layer surface topology for visualization purposes.

In summary, the data sets gathered are extensive and can be applied to transport analyses as well as serving as a detailed research data set with which to understand the meteorological processes that determine pollutant transport among the major air basins of California. As we describe below, however, much can still be accomplished and the experience gained in this program can be used to design and implement a regional observing network in California.

2 RECOMMENDATIONS

2.1 Technological Applications

In summary, the wind profiler network as deployed proved reliable and issues such as the removal of contaminated data have, to a large extent, been resolved for the future. Depending on the availability of resources, we would recommend the continuous operation of wind profilers to provide data on winds and mixed-layer depth on a routine basis. In general, we consider the determination of the mixed-layer depth from the radar echo strength to be preferable and more reliable than the use of RASS temperature profiling under clear sky conditions: this would be particularly useful in populated areas where the acoustic source used to provide RASS signals might prove annoying to local residents. As pointed out in Section 8.1, the presence of clouds confuses the mixed layer algorithm: when clouds are frequent in a study area, a ceilometer should be collocated with the radar. In applications requiring detection of boundary-layer thickness less than 200 m, a monostatic sodar should be collocated with the radar.

During measurements carried out in the fall and early winter of 1993, our profilers operated near the forest fires in southern California and documented the behavior of the Santa Ana winds during that period. Multiple use applications of profiler networks in California might include:

- Air Pollution Transport Monitoring and Modeling.
- Fire Weather Forecasting.
- Marine Weather Forecasting and Coastal Ecology Studies.
- Agricultural Burn Controls and Forecasting.

Based on our experience with profiler technology and modeling applications, we feel that an integrated system is now possible in which remotely sensed meteorological fields can be integrated in an advanced workstation modeling environment. While requiring some development effort, such an integrated system could eventually incorporate other data streams such as those from ozone profiling lidars.

2.2 Scientific Issues

We consider there to be a number of remaining scientific issues and opportunities, mostly focused on the use of the data set, now provided to the ARB, in high resolution numerical models. Because of the delays associated with solving the bird-contamination problem, limited ARB resources, and the departure of key staff at the ARB we were not able to produce trajectory analyses using ARB diagnostic and primitive equation model output as originally envisioned in our proposal. However, we have provided a rich data set for future model applications, particularly in the Sacramento River Delta area where only limited observations were obtained during the San Joaquin Valley Air Quality Study. Several other areas of model research and possible supporting observations are indicated:

- This study, as well as the previous San Joaquin Valley Air Quality Study, did not focus on thermally driven circulation along the mountain sidewalls of the major valley air basins of California. Our preliminary field work suggests that these flows have a significant influence on the adjacent valley circulations and should be addressed with future measurement programs and modeling exercises. In particular, peak episodes in the NCT study were, for the most part, found at a foothills monitoring site, raising the question of upslope transport into the mountain air basins and/or recirculation aloft back from the mountains. In the SCT study, mixed layer depth and winds were measured upwind and downwind of two major passes. These data should provide a challenge for future modeling and data assimilation activities.

- The current data set should be used as a test bed for four-dimensional data assimilation in high-resolution numerical models. However, we add a caveat that measurements should be made in the Sierra Nevada air sheds adjacent to Sacramento to fully test model capabilities for data assimilation and prediction over more complex terrain. We are also currently using the CSU-RAMS model in related research to study the generation of coastal eddies and the propagation of topographically trapped eddies northward along the coast. This program extends northward from the Monterey Bay area to the California-Oregon border. A network of six profilers in the coastal region from Pt. Sur to Crescent City will operate during most of 1994. Initial simulations of the coastal circulation with a 90-m lowest grid point fail to reproduce nighttime drainage flows from the Salinas Valley as observed in our NCCT study data. Fundamental issues need to be addressed in the use of models to simulate nocturnal flows generated over the Sierra Nevada and the coastal ranges of California.

- We obtained a year-long data set in the Southern California Bight area during 1993, in a U.S. Navy sponsored study that essentially extended operations from the termination of the SCT study in late October 1992. Two coastal sites (Point Mugu and Point Loma) and one island site (San Clemente) operated through October 1993. A desert site (Edwards Air Force Base) was operated through August 1993. These data, combined with the extensive existing surface meteorological data in the Los Angeles basin, could be used with models to examine over-water transport paths.

3 BACKGROUND FOR THE PROJECT

3.1 The Need

The California Clean Air Act (CCAA) of 1988 required the Air Resources Board (ARB) to take a number of specific actions related to the transport of ozone and its precursors. At a hearing on December 14, 1989, the ARB adopted a regulation identifying 14 transport couples in which air pollutants transported from upwind areas may contribute to exceedances of the state ozone standard in downwind areas. Subsequently, at a hearing on August 12, 1993, six additional transport couples were identified (ARB, 1993). Under the provisions of the CCAA, the ARB must assess the relative contributions of upwind emissions to ambient pollution levels in downwind areas. The CCAA also requires the ARB to establish mitigation requirements commensurate with the degree of contribution.

In assessing transport between air basins, the ARB (1990) referenced or used upper-wind data in the evaluation of virtually all the source-receptor couples. However, in California, vertical wind and temperature profiles are routinely recorded at only three locations twice daily. These locations are San Diego, Vandenburg AFB, and Oakland with soundings at 0400 PST and 1600 PST. Most of the transport classifications for the 14 transport couples were based on analyses of this limited data base and were not completely convincing to the local districts involved. Only limited use was made of photochemical air quality models for identification of transport mitigation measures required by the CCAA. ARB staff (ARB, 1990) plan to refine their transport assessments over time as new data are collected and analyzed and as additional photochemical modeling studies are completed.

Application of photochemical modeling, however useful it might be to transport assessment, will require significant increases in upper-air sounding data. For example, a Technical Guidance Document for photochemical modeling published by the ARB (ARB, August, 1990) identifies four classes of data bases in order of their completeness. Class I data bases are the most complete: This document asserts that "Modeling studies which use Class I data bases will assist decision makers in determining the most cost-effective control strategy while also providing a high degree of certainty that improvements in air quality will be achieved". The upper-air meteorology section of the classification section requires, as a minimum, that 4 to 8 soundings a day be available. It also specifies that one sounding is representative of only the region within 50 km of the site where the sounding is taken. Near complex terrain, however, a 50-km radius of influence may not be adequate and either more detailed data will need to be collected or atmospheric processes will need to be better understood so that the most representative data will be collected.

Because of the need for dense upper air sounding networks, full scale studies of the transport and transformation of ozone and its precursors, in the past, have been complex and expensive. For example, considerable planning and resources were expended for the recent San Joaquin Valley Air Quality Study (SJVAQS) and the Atmospheric Utilities Signatures, Predictions, and Experiments (AUSPEX) field programs. In these programs, addressing one major air basin, detailed measurement of ozone and its precursors (using primarily surface-based sampling with some aircraft sampling during short duration episodes) were integrated with one of the most extensive meteorological networks ever deployed within the San Joaquin Valley. These studies made a major effort to measure winds aloft as well as intermittent profiles of temperature and humidity (typically 4 to 8 soundings per day on intensive study days) to provide guidance to numerical models and to develop better conceptual models of transport processes within the valley. Because of their high cost only a few tracer studies were used in this study. When used as part of full model development and validation exercises such as the SJVAQS/AUSPEX, tracer techniques can provide an essential complement to the full set of meteorological and chemical measurements. However, the usefulness of inert tracers in routine assessment activities in California appears to have been much more limited. This is probably due not only to their high cost but also to the difficulty of releasing tracers at the appropriate locations at the appropriate times under the appropriate meteorological conditions to provide the information needed for the classification of the sources responsible for a particular ozone exceedance in a downwind area. Fortunately, however, a result of full scale air quality field experiments and ongoing model development and research is that mesoscale meteorological models are becoming increasingly able to assimilate continuous as well as intermittent wind and temperature profile information and represent a broader range of atmospheric motions. Thus, when the output from these meteorological models is coupled with rapidly advancing air quality models, a useful assessment tool can result.

The ARB staff published a report (ARB, 1990) that characterized the impact of transported emissions as "overwhelming", "significant", or as "inconsequential" for each of the 14 transport couples identified in California. The ARB, in this report, also recognized that transport of ozone and its precursors along interbasin transport corridors often occurs in atmospheric layers well above the surface. Vertical temperature and wind variations then determine the vertical extent to which pollutants are mixed. Furthermore, the direction and speed of transport aloft may differ significantly from that inferred from surface wind measurements and vertical mixing may vary strongly as a function of time of day and as a function of position along the transport corridor. Thus, not only must winds aloft be measured but also the evolution of the mixed layer, which determines if and when ozone located in elevated layers can be mixed to the surface, must be documented. However, continuous, unattended observations of winds and vertical mixing processes have not been available in the past. For example, conventional remote sensing systems such as Doppler sodars only measure to a fraction of a kilometer above the surface whereas in situ systems such as free or tethered sondes are limited by their cost, need for continuous attendance, and intermittency. Thus, the need has existed for systems that operate, unattended and continuously, to profile the first several kilometers of the atmosphere for wind, temperature, and mixing layer depth. As a critical first step in meeting this need, the Environmental Technology Laboratory (ETL) of the National Oceanic and Atmospheric Administration (NOAA), using the recently developed NOAA 915-MHz radar wind profiler, demonstrated a new ability to monitor atmospheric transport on a continuous basis during the 1990 SJVAQS/AUSPEX field programs (Neff et al., 1991) and provided the basis for the program described here.

Based on contacts with the ARB staff during the SJVAQS/AUSPEX , it appeared to us that the availability of such continuously operating systems, if deployed in quasi-operational networks, would overcome a major limitation of past transport assessment studies -- inadequate upper air wind data along the transport corridor at the time of an exceedance. The benefit of continuous meteorological profile data is that the archived data can be used to compute back-trajectories using either diagnostic wind field models (with limited atmospheric physics) or primitive equation models that assimilate data in time and space that can be run in an analysis mode (with much more complete atmospheric physics). Thus, with the technology that ETL proposed to demonstrate, assessment data could be made available for each observed exceedance, even though such exceedences might occur only rarely. Furthermore, the data base from an ongoing network of profilers could provide an additional benefit -- transport patterns occurring each ozone season can be monitored on a year-to-year basis. As a result, the impact of ongoing mitigation measures can be assessed against a strongly changing meteorological background.

Surface ozone concentrations depend on the vertical mixing within the atmosphere both for the trapping and transformation of ozone and its locally generated precursors in shallow surface layers as well as in the potential mixing of ozone, generated previously and/or transported aloft, to the surface during the breakup of inversions. The monitoring of these processes requires information beyond that of just a vertical profile of the horizontal wind. In a simple convective boundary layer, a temperature profile can provide an effective measurement of the mixed layer depth. In the past, however, this depth could only be measured by labor intensive, expensive, and intermittent means using disposable sondes. Alternative methods also exist that use surface parameters to estimate the mixed layer depth (similar to the methods used in numerical models). However, these techniques apply primarily to simple atmospheric conditions.

For these reasons, ETL has pursued a remote sensing research program to determine mixing layer depths, static stability, and turbulence mixing parameters from ground-based remote sensors that use radio and sound waves to probe the atmosphere. To date, wind profile measurements using radio wave techniques are well proven. A Radio Acoustic Sounding System (RASS) approach is now providing the ability to continuously profile temperature to heights of about 1 km. We thus have pursued a program to use these data together with vertical profiles of radar and sodar signal intensities and velocity fluctuations to determine mixed layer depth (White et al., 1991). As part of this program, we explored the applicability of new expert system pattern recognition techniques being tested at Pennsylvania State University by Steven Fine (personal communication) for weather front identification. Because these patterns are very similar to those associated with time-height cross sections of inversion growth and destruction, the real-time application of these expert system methods had some potential. In cloud-free conditions, however, a simple profile of radar echo intensity provides a viable alternative to more sophisticated techniques.

New environmental monitoring techniques such as those that we proposed will prove highly cost effective: the cost of remote sensing methods to measure continuous profiles of wind and temperature is about one third of that to use balloon-based systems to measure wind and temperature four times a day over a 90-day period at the same site. In addition, many other atmospheric parameters may become available from the same sensors. Furthermore, ETL has developed a ground-based ozone lidar and begun testing its performance in collaboration with ARB, that can be collocated with radar wind profilers and is designed to measure profiles of ozone in the first several kilometers with 10 to 20 m range resolution.

The deployment of profiling systems over mesoscale domains raises the additional issue of representativeness. A first step in resolving this issue for California monitoring networks was the deployment by ETL of seven radar wind profilers in the SJVAQS/AUSPEX summer field program. This deployment represented a fairly dense network of wind profilers focused primarily on the transport of ozone and its precursors into and out from the San Joaquin Valley. However, even the number and density of profilers available for this study was not sufficient to address all scales of motion and physical processes controlling the transport and transformation of ozone and its precursors in the limited area of the San Joaquin Valley. However, the information gained in the analysis of ETL profiler data from this and ongoing experiments will certainly aid in optimizing the placement of radars in networks addressing transport between other California basin couples.

Past experience has also demonstrated that a better understanding of the dynamics of mesoscale circulations can aid directly in the wise deployment of limited observing resources. For this reason, NOAA/ETL maintains a strong program in mesoscale weather research and in the analysis of terrain-influenced circulations using suites of in situ and remote sensors and numerical models (e.g. Neff, 1990; Wilczak et al., 1988,1990,1991). Because of the significant effect of topography on mesoscale transport phenomena within and among California's air basins, NOAA/ETL's basic research program can thus contribute significantly to the Air Resources Board's (ARB) Transport Assessment Analyses: in the analysis of new and existing data, in the improvement and evaluation of diagnostic wind field and primitive equation models that can support photochemical grid models, and in the development of a statewide observational network.

For these reasons, we proposed an effort in support of ARB's technical goals for interbasin transport assessment (ARB 1989,1990) and a focusing of several internal NOAA/ETL basic research activities on the resulting data sets that would greatly augment this program. This effort, described below, required the deployment of ETL's network of 915-Mhz wind/temperature profilers, monostatic sodars, surface energy budget facility, airsonde/tethersonde systems, and surface meteorological network. It also focused the efforts of a number of ETL staff involved in mesoscale and boundary layer research on the analysis of the new observational data set that emerged. Meteorological-based assessment was thus focused on a number of questions that could potentially be addressed using the measurement/analysis methods proposed by ETL.

- ***What is the depth of the mixed layer in the source area and what is the direction of transport as a function of height within the mixed layer (for fresh emissions) and above the mixed layer (for aged emissions)?***
- ***What are the trajectories of air masses, as a function of height, along the path from source region to receptor region?***
- ***What is the depth of the mixed layer in the receptor area and can a shallow mixed layer account for high concentrations of local emissions or are pollutants that have been transported aloft mixed to the surface?***

3.2 General Project Objectives

ARB objectives addressed by this proposal include assessment of the relative contribution of upwind emissions to downwind ambient pollutant levels and the determinations of the transport of ozone and ozone precursors from upwind air basins to downwind air basins. The full scale study of air basin couples such as that carried out in the SJVAQS/AUSPEX requires significant resources. The objectives of this project include the collection of wind and temperature aloft together with mixing layer height coupled with analyses that contribute to the determination of transport. The project used new remote sensing technology that operates continuously and unattended to provide a cost effective response to the limited resources available. A number of NOAA basic research activities and additional instrumentation enhanced the project by providing additional data and analyses that would otherwise not be available. Specifically, the objectives were

- ***To use 915-MHz wind profilers to create a data base of vertical profiles of winds and temperatures during two ozone seasons to address ARB transport assessment needs.***

- ***To deploy and test ETL's central data hub system for its network of research wind and temperature profilers at the ARB headquarters for data acquisition, processing, and display of wind and temperature data.***

- ***To improve the capability of radar wind profilers to infer mixing layer depths and to better understand the dynamics of local circulations along terrain-dominated transport corridors and to lead to improved use of ARB models with additional instrumentation and analyses.***

- ***To provide this new data base to ARB at the completion of the project.***

- ***To improve the understanding of the meteorological processes that influence pollutant transport and dispersion within and between basin couples by analyzing the data collected.***

3.2.1Vertical mixing processes

Transport of ozone and its precursors aloft will bare little relation to surface ozone measurements unless sufficient vertical mixing occurs (Reible et al, 1982,1983). For this reason, vertical stability and mixing layer depth needed to be assessed in a routine fashion. Several methods were promising: the first used RASS techniques to measure the temperature profile directly to heights of 1 km or less. A second method used the profile of radar reflectivity to indirectly infer the mixing layer depth. In the latter case, turbulence produces the radar return: the height at which the radar signal decreases rapidly thus should indicate the mixing layer height. Because these data are obtained routinely from radar wind profilers they may provide a new method to obtain a climatology of mixing layer depth.

Because RASS operations (involving the tracking of the speed of sound transmitted vertically using radar waves) produce unwelcome noise contamination, its use was limited to areas remote from residential development. We thus acquired RASS-derived temperature profile at 3 to 4 sites each year but also archived reflectivity profiles at all sites. It should be noted that the ability of numerical models to simulate the radar reflectivity profile may be a stringent test also of their ability to simulate vertical profiles of eddy diffusion coefficients. If this technique can be proven, it may extend the height of and/or replace information obtained from the RASS-derived temperature profile. Furthermore, the availability of mean wind and temperature profiles together with a reflectivity profile (that depends on both mean and turbulence fields) may provide a means to deduce profiles of the vertical exchange coefficients). This would be quite valuable in the application of meteorology/air quality models (e.g. Kessler and Douglas, 1989) in California.

3.2.2 Local-flow studies

Quantification of local flows including thermally driven slope flows are a relatively neglected facet of circulations within and among California air basins. The importance of transport of pollutants into the Sierra Nevada has previously been documented (e.g. Carroll and Baskett, 1979; Ewell et al., 1989). Most simulations describe daytime thermally driven upslope adequately (e.g. Kessler and Douglas, 1989). In the daytime cases, heating of mountain slopes and transport of air through passes provide effective venting mechanisms for areas such as the South Coast Air Basin but may also provide a return mechanism aloft driven by the temperature contrasts between the free atmosphere over the desert and that over the basin (Ulrickson and Mass, 1990b). A similar effect may also be evident in airborne lidar data shown by Roberts et al (1990) in their Figure 5-6 for a cross section over the coastal range from Morgan Hill to Modesto. Such venting mechanisms will obviously modify flows along transport corridors and need to be addressed in any comprehensive study using more dense profiler networks. Similar observations have been documented in the South Coast Air Basin using airborne lidar (Wakamoto and McElroy, 1986)

Unfortunately, only limited observations of nighttime drainage winds exist even though they may be responsible for the return of a substantial portion of aged pollution from the mountain slopes and valleys. Furthermore, model simulations do not adequately describe slope flows from the Sierra Nevada. For example, in the simulations described by Kessler and Douglas (1989), drainage winds are confined to the lowest 50 m AGL in some cases or are nonexistent in the first 750 m ASL in other cases; the only nighttime easterly winds from the Sierra Nevada appear to come from the model-computed inertial rotation of daytime upslope winds over the higher terrain of the Sierra Nevada. During the 1990 SJVAQS/AUSPEX field program, ETL carried out a special series of measurements in the Kings River canyon, a location previously studied briefly by Morgan (personal communication). These measurements revealed the rapid (within a few tens of minutes) development of down-canyon winds of 3 to 4 ms^{-1} to depths of at least 1 km, suggesting that drainage winds are a significant facet of Sierra Nevada meteorology. Without better observations of terrain-associated flows and their subsequent incorporation into models, those models are unlikely to be substantially improved. Atmospheric circulations along the coastal regions also show a strong variation with height as shown in detailed ETL Doppler lidar near Moss Landing (Intrieri, et al., 1990) and in 915-MHz profiler wind data near Hollister (Neff, et al., 1991). The objective of the studies here was to use supplemental measuring systems to document the structure of thermally forced winds within and over the mountain boundaries of the Central Valley.

4 SPECIFIC TASKS FOR ARB AND IN-KIND NOAA EFFORTS

The following tasks were proposed as a joint effort between NOAA and ARB with ARB providing approximately sixty percent of project costs. Tasks that related directly to NOAA/ETL activities but could contribute to meeting ARB assessment goals are indicated as exclusively in-kind services that were part of our cost sharing with ARB. Although we made significant progress on almost all these tasks, some work was delayed or inhibited because of the discovery of bird contamination in the data. This unexpected discovery required a serious redirection of NOAA/ETL in-kind resources and efforts in order to solve this problem and guarantee a viable transport assessment data base.

4.1 **Profiler Deployment and Data Base**

Task 1.1: Deploy eight radar wind profilers during the summer ozone season of 1991 and four during the summer season of 1992. The starting date for the initial six profilers is 2 months from the inception of the project with all eight in place within 2.5 months. If the project suffers contract delays profilers will be deployed according to ARB priorities and siting availability. Any profilers not deployed the first summer will be added to the number during the second summer. [Note: this task was augmented the second year to provide more extensive geographical coverage in southern California.]

Task 1.2: Develop a data hub capable of archiving wind, temperature, and mixing layer data from remotely situated profilers. During the first season, telephone communications will be set up to provide real-time data archival. A parallel effort will then begin to develop data display methods for a work station environment. This will be a continuing ETL R&D effort throughout the entire project and will be carried out in cooperation with ARB Technical Division staff. [ETL in-kind task].

Task 1.3: Provide operations summaries including data capture rates and equipment performance and maintenance requirements for each site within two months following the end of each summer and winter field season.

Task 1.4: Validate final data sets and transfer to ARB Technical Division on suitable magnetic medium.

> ***Retrospective:*** Profilers were deployed as planned for Task 1.1 as described in Section 5 of this report. In Task 1.2, we originally tried installing the data communications hub in the Sacramento ARB offices but found it difficult to continue development work and maintain the system. We then moved the data hub to ETL and downloaded data over the Internet on an hourly basis to an ETL workstation provided to ARB. The display product development effort is described in Appendix G. Operations summaries for Task 1.3 and overall performance are provided in Section 5; monthly data availability is available in summary form on the workstation. The major validation effort is described in Section 6; the complete analysis of the bird contamination issue is provided in Appendix A. The final data sets now reside on the ETL workstation on loan to ARB in Sacramento and can be easily transferred to another UNIX workstation environment as described in Appendix G.

4.2 Wind Field/Temperature Analyses

Task 2.1: Produce 24-h time/height graphical crosssections of hourly horizontal wind data obtained at each wind profiler location for all periods of operation. Level 1 data (automatic computer editing) will be provided within three months and Level 2 data (data with some analysis complete) within nine months.

Task 2.2: Produce wind roses plotted at 20° intervals at each radar location. The wind roses will be plotted at 150-m intervals throughout the entire vertical range that has continuous sampling (typically 3 km). The wind roses can be stratified according to other parameters determined to be useful, such as daytime, nighttime, 24-h day, periods of high-ozone concentrations, synoptic pattern type, and so forth.

Task 2.3: Estimate boundary layer mixing depths with 1-h temporal resolution from profiler backscattered power and/or RASS temperature profile measurements. [ETL in-kind task].

Task 2.4: In cooperation with ARB technical staff, perform objective analyses of profiler and surface data to obtain four dimensional velocity fields. For case studies, the objective analyses can be compared with wind fields determined through data assimilation using primitive equation models available to ARB.

Task 2.5: Calculate trajectories through the use of objectively analyzed wind fields and mixed layer depth obtained in Task 2.4 in cooperation with ARB technical staff.

Task 2.6: Use profilers located with 10 to 20 km of each other to evaluate representativeness of single profile measurements and develop siting criteria to guide future profiler placement.

> ***Retrospective:*** Tasks 2.1, 2.2, and 2.3 were carried out in the workstation environment as described in Appendix G. ETL made training available for the latest software products for the workstation in ARB offices after the final transfer of data. As experience is gained on the system over the next year, an operations manual will be prepared as a NOAA Technical Memorandum similar to Appendix G. In addition to workstation displays we also prepared wind-distribution bar-charts for a number of sites for high- and low-ozone episode days as described in the body of our report and appendices. Tasks 2.4 and 2.5 depended on the availability of ARB staff to provide access to ARB modeling tools and computational resources: this was not practical given the issue of delays due to bird-contamination and the limited resources of ARB. However, a simple interpolation scheme was implemented for the arrays of wind and mixed layer height data averaged for high and low-ozone days in several air basins. These fields provide streamlines rather than trajectories so only give a general indication of transport patterns. Further efforts are needed in four-dimensional data assimilation (FDDA) as well as improvements in model boundary layer physics to carry out full trajectory analyses. The results of Task 2.6 are described in Section 6: however, such closely placed profilers should be used independently in FDDA exercises to truly assess the impact of small profiler location changes on model predictions.

4.3 **Vertical Mixing Processes**

Task 3.1: Mixing depth study using expert system (IREW*) analyses: [ETL in-kind task].
a) Develop training data sets from first three weeks of data at each site.
b) Create IREW predictor matrix.
c) Run IREW analysis software to select predictors.
d) Apply IREW predictors to remaining data set and analyses the results.
e) Examine the generality of IREW predictors.
*Expert system approach developed at Pennsylvania State University.

Task 3.2: Analyze dispersion variables: [ETL in-kind task].
a) Compute variances from profiler data.
b) Examine relative contributions of turbulence and shear to horizontal dispersion.
c) Create a dispersion variable data base for case studies by NOAA, ARB, and university researchers.

Task 3.3: Examine boundary layer turbulence variables: [ETL in-kind task].
a) Calibrate radars and sodars to permit computation of microturbulence variables from backscatter intensity.
b) Develop methods to calculate dissipation rate from Doppler spectral width and evaluate the effectiveness of such methods.
c) Create a data base of microturbulence variables for each site.
d) Use microturbulence profiles to estimate surface fluxes and entrainment rates in the growing convective boundary layer. Compare to ground truth where available.

Task 3.4: Perform case studies to analyze various parameterizations and turbulence variables from boundary layer model embedded in mesoscale numerical model. This will require coordination with modelers on the ARB technical staff or with modelers associated with the SJVAQS/AUSPEX modeling effort. [ETL in-kind task].

Retrospective: To accomplish the goal of Task 3.1, we implemented a simple radar reflectivity profile analysis to detect the mixed layer depth as described in Section 8. Tasks 3.2 and 3.3 reflect ongoing research efforts within ETL that may eventually be useful to ARB but were delayed because of the effort required for the bird-issue: however, the state of the science is described in Section 8 and the collection and archiving of the spectral width data proved essential in the analysis and flagging of bird-contaminated data. Task 3.4 was not practical at this time because of other demands on ARB staff. Realizing the difficulties of coordinating external modeling efforts with our analysis of remotely sensed wind and temperature data, we have began a observations/modeling analysis effort using the CSU-RAMS and MM5 models on our RISC 600/580 workstation, including initial tests of the workstation version of MM5.

4.4 Local Circulations

Task 4.1: Carry out short term studies of nighttime drainage winds and daytime thermally forced upslope flows using supplemental measurement systems. Issues to be addressed are 1) the return of aged pollutants in nighttime flows and 2) the enhanced venting of pollutants over terrain barriers caused by flows generated or aided by sidewall heating during the daytime. [ETL in-kind task].

Task 4.2: Determine the utility of combined profiler wind/RASS temperature profiles for Froude number and stability calculations. The Froude number is a useful predictor, at times, of the potential for flow blocking by terrain (in the absence of sidewall heating). [ETL in-kind task].

Task 4.3: To the extent possible with each profiler network deployment determine the frequency of occurrence of significant local flows including thermally forced flows as well as various eddy structures that have been observed in each California air basin (e.g. coastal eddies, the Fresno and Schultz eddies, etc.). [ETL in-kind task].

Task 4.4: To the extent possible with each profiler network deployment, determine the response of transport from one air basin to another to significant mesoscale events (e.g. increases or decreases in the marine inversion depth in response to frontal passage).

Task 4.5: For each network deployment, document new flow features observed serendipitously because of the new observing capabilities inherent in wind profilers. [ETL in-kind task].

> ***Retrospective:*** Initial results from Task 4.1 are described in Section 9 where comparisons of drainage flows in the Feather River Canyon are made with data from the Kings River Canyon obtained during the SJVAQS. Initial efforts in Task 4.2 showed Froude numbers as calculated from profiler data to be too crude because of the bulk character of the measurements and the noise inherent in the measurements. Efforts in Task 4.3 have begun with comparisons of eddies observed from interpolated wind fields to CSU-RAM model runs carried out at ETL. A number of model issues still remain to be resolved before these results can be reported in the scientific literature. In addition, the frequency of occurrence of a number of features was obscured by the recurring nocturnal bird migration patterns. Sections 7 and 10 address Task 4.4 in some detail and include statistical analyses of a variety of meteorological parameters. Task 4.5 was deferred for future research efforts pending the resolution of the bird-contamination issue.

5 OVERVIEW OF FIELD PROGRAMS

5.1 Northern California Transport Study (NCT) Sites

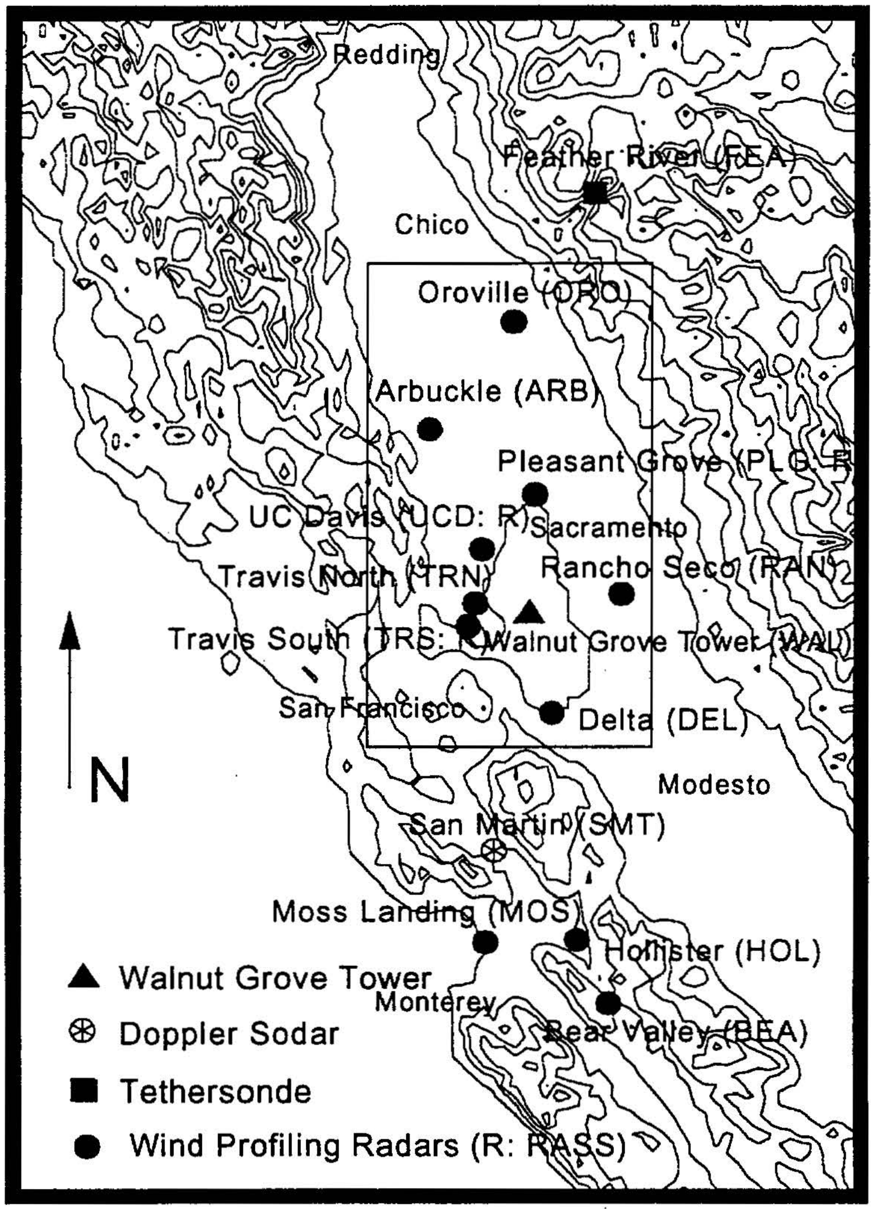

Figure 1. Deployment of wind profilers and RASS during the 1991 Northern California Transport Study. Profilers at Moss Landing, Hollister, and Bear Valley, just outside of the Pinnacles National Monument) were relocated in late summer from northern sites. The rectangular area within the figure shows the primary domain for the first phase of the study.

5.2 Operational Summaries Including Installation And Removal (NCT)

Arbuckle (ARB)

JD 136:	Profiler installed and running at the Air Resources Board monitoring site.
JD 175:	Moved profiler to a new site approximately 1 km northwest of the present site because of ground clutter problems.
JD 239:	Profiler removed and shipped to Moss Landing for installation.

Bear Valley (BEA)

JD 240:	Profiler installed and running.
JD 254:	Blown fuse in transmitter.
JD 256:	Profiler repaired.
JD 288:	Radar transmitter failure.
JD 295:	Transmitter replaced but failed within a few hours.
JD 307:	Profiler removed from site.

UC Davis (DAV)

JD 178:	Profiler with RASS installed at site.
JD 189:	System turned on and operational.
JD 299:	Radar transmitter failure.
JD 305:	Profiler and RASS removed from site.

Delta Island (DEL)

JD 165:	Profiler installed and running.
JD 268:	Radar PC hung.
JD 269:	System rebooted and operational.
JD 305:	Profiler removed from site.

Hollister (HOL)

JD 239:	Profiler installed and running.
JD 285:	Faulty switch in transmitter.
JD 290:	Profiler repaired and operational.
JD 306:	Profiler removed from site.

Moss Landing (MOS)

JD 240:	Profiler installed and running.
JD 277:	UPS battery failure.
JD 287:	UPS replaced, profiler operational.
JD 307:	Profiler removed from site.

Oroville (ORO)

JD 150:	Profiler installed and running.
JD 305:	Profiler removed from site.

Pleasant Grove (PLG)

JD 135:	Profiler installed and running.
JD 176:	RASS installed and operational.
JD 192:	RASS on continuously, profiler and RASS down.
JD 196:	System repaired, profiler and RASS operational
JD 203:	Radar PC hard disk filled. Technician could not gain access to ARB trailer at the site.
JD 212:	Data deleted from disk. Profiler and RASS operational.
JD 305:	Profiler and RASS removed from site.

Rancho Seco (RAN)

JD 151:	Profiler installed at site.
JD 157:	Power connected to site, profiler operational.
JD 202:	Developed oscillation in transmitter.
JD 221:	Transmitter repaired, profiler operational.
JD 239:	Profiler removed from site and shipped to Bear Valley for installation.

Travis North (TRN)

JD 178:	Profiler installed and running.
JD 193:	Power failure at site.
JD 194:	Power restored, profiler operational.
JD 238:	Profiler removed from site and shipped to Hollister for installation.

Travis South (TRS)

JD 164:	Profiler installed and running.
JD 177:	Profiler antennas were moved about 30 m west because of clutter problems.
JD 179:	RASS installed and operational.
JD 183:	Radar program (POP) software problem.
JD 189:	System rebooted and operational.
JD 193:	Radar PC hung.
JD 196:	System rebooted and operational.
JD 196:	Radar program software problem.
JD 197:	New radar program installed, profiler and RASS operational.
JD 220:	Intermittent transmit problem with RASS.
JD 228:	New power amplifier installed but intermittent transmit problem persisted.
JD 242:	Rewired compression drivers, RASS operational.
JD 299:	UPS battery failure.
JD 304:	UPS repaired, profiler and RASS operational.
JD 305:	Profiler and RASS removed from site.

5.3 Southern California Transport Study (SCT) Sites

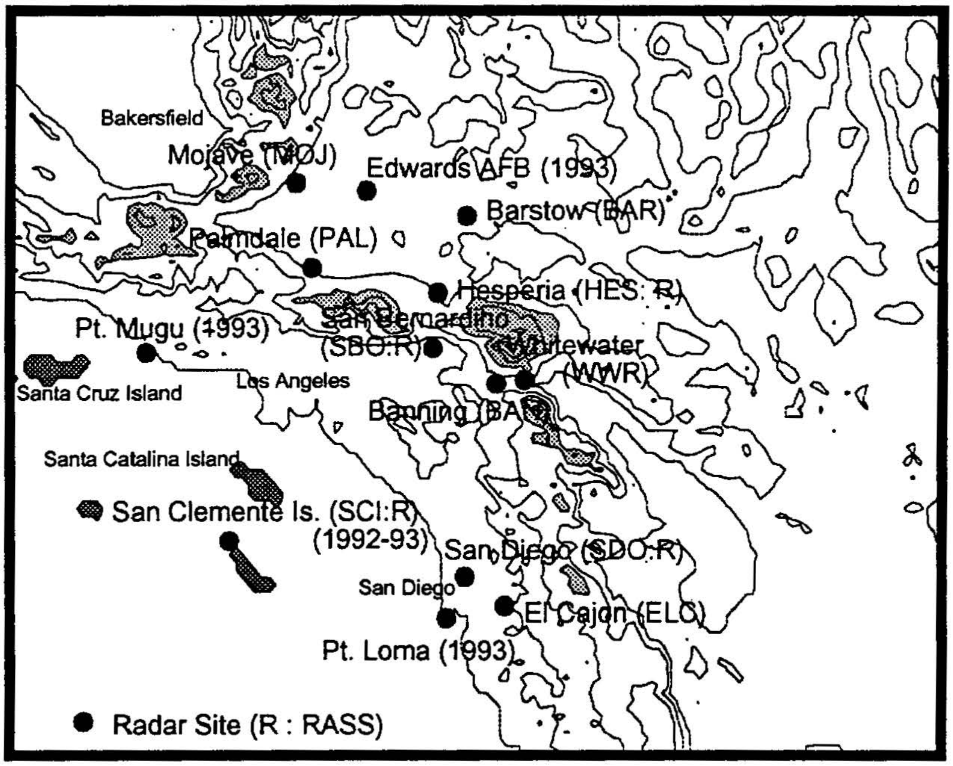

Figure 2. Profiler sites used during the 1992 Southern California Transport field program. The Banning site was operated to assess the frequent convergence of air masses from the desert and from the South Coast Air Basin. Additional sites were operated from late 1992 through the fall of 1993. These included Pt. Mugu, Pt. Loma, and Edwards Air Force Base. San Clemente Island began operations late because of delay in frequency authorization from the U.S. Navy, but continued until 1 November 1993. These additional data will be made available after final processing.

5.4 Operational Summaries Including Installation And Removal (SCT)

Banning (BAN)

JD 87:	Profiler installed, vertical antenna not working.
JD 100:	Vertical antenna replaced, profiler operational.
JD 105:	Power failure at site. System down for less than a day.
JD 129:	Profiler shut down because of an air conditioner failure in the equipment trailer.
JD 138:	Air conditioner repaired, profiler operational.
JD 176:	Profiler removed from site.

Barstow (BAR)

JD 114:	Profiler installed at site. Discovered that the radar PC needed a new motherboard.
JD 120:	Radar PC repaired. Profiler operational.
JD 272:	Profiler removed from site.

El Cajon (ELC)

JD 225:	Profiler installed and running at site. Encountered a RF interference problem.
JD 232:	Profiler antennas were moved and reoriented. This seemed to solve the interference problem.
JD 233:	Profiler operational.
JD 308:	Profiler removed from site.

Hesperia (HES)

JD 119:	Profiler and RASS installed and running at site.
JD 190:	Power failure at site.
JD 191:	Power restored, profiler and RASS operational.
JD 196:	Power failure at site.
JD 197:	Power restored, profiler and RASS operational.
JD 272:	Profiler and RASS removed from site.

Mojave (MOJ)

JD 85:	Profiler installed and running at site.
JD 85-181:	Because of the extremely strong surface winds at this site during this period, the antenna guy wire anchors were pulled from the ground several times causing the antennas to be out of level and orientation. This could cause some reliability problems with this data set for this particular period.
JD 223:	Profiler removed from site and shipped to San Clemente Island for installation.

Palmdale (PAL)

JD 99:	Profiler installed and running at site.
JD 130:	No transmit power, system down.
JD 139:	System repaired, profiler operational.
JD 146:	No transmit power, system down.
JD 156:	System repaired, profiler operational
JD 160:	RxTx bad, system down.
JD 173:	Transmitter repaired, profiler operational.
JD 185:	Transmitter problem, system down.
JD 188:	Transmitter repaired, profiler operational.
JD 191:	Bad OVP module in transmitter, system down.
JD 204:	Radar transmitter repaired (bad OVP module), profiler operational.
JD 317:	Blown fuse in radar transmitter.
JD 318:	Fuse replaced. Profiler operational.
JD 349:	Profiler removed from site.

San Bernardino (SBO)

JD 120:	Profiler and RASS installed and running at site.
JD 200:	Power failure at site. System down for less than a day.
JD 273:	Profiler and RASS removed from site.

San Clemente Island (SCI)

JD 232:	Profiler and RASS installed at site awaiting radio frequency authorization.
JD 267:	Profiler and RASS operational after final radio frequency analysis and authorization from the U.S. Navy.
JD 300:	Bad A/D channel in radar interface. This did not affect the RASS data.
JD 352:	Profiler repaired and operational.

1993

JD 262:	UPS battery failure because of low voltage at site.
JD 279:	Power to site repaired. Profiler and RASS operational.
JD 306:	Profiler and RASS removed from site.

San Diego (SDO)

JD 136:	Profiler and RASS installed and running at site.
JD 223:	Blown fuse in radar interface.
JD 225:	Fuse replaced. Profiler and RASS operational.
JD 307:	Profiler and RASS removed from site.

White Water (WWR)

JD 86:	Profiler installed and running at site.
JD 92:	Blown fuse in radar interface.
JD 100:	Fuse replaced, profiler operational.
JD 115:	Radar PC hung.
JD 120:	System rebooted, profiler operational.
JD 132:	Radar transmitter failure.
JD 140:	Radar transmitter replaced, profiler operational.
JD 158:	Radar antennas blown off blocks.
JD 163:	Antennas leveled and reoriented.
JD 200:	Bad A/D channel in radar interface.
JD 204:	Radar interface repaired, profiler operational.
JD 224:	Profiler removed from site and shipped to El Cajon for installation.

5.5 **Radar Failure Rates**

Figure 3 summarizes the various causes of radar downtime during the two experiment periods. The largest amount of downtime (more than 50%) resulted from failures in the radar electronics. These failures usually involved the radar transmitter. Another large contributor to profiler downtime resulted from problems with the Uninterruptable Power Supplies (UPS). These problems were caused by either extended power failures or low line voltages draining the battery power of the UPS. Actual power failures during both experiments resulted in only a small amount of radar downtime. Radar PC problems involved either software or hardware glitches that would hang the PC until it was rebooted. For both NCT '91 and SCT '92, the causes of radar downtime were quite similar, with the percentage of downtime contributed by each of the causes also quite similar.

During both NCT '91 and SCT '92, profilers operated during 93% of the days possible. Figures 4 and 5 show the percentage of possible days that each profiler operated during NCT '91 and SCT '92 respectively. Seven of the eleven NCT profilers operated during over 90% of the experiment days with four of these profilers operating during nearly 100% of the experiment days. Six of the ten SCT profilers operated during nearly 100% of the experiment days.

San Clemente Island presented particular difficulties as phone line quality was substandard and did not allow normal communications links even after attempts by the Navy to improve the service. Cellular phone service also failed. Because of the remote relocation and inability to monitor the site in real time, failures resulted in larger gaps in the data. However, after the last repair in 1992 the profiler operated without failure for 270 days into 1993. Future operations at this site should use satellite communications.

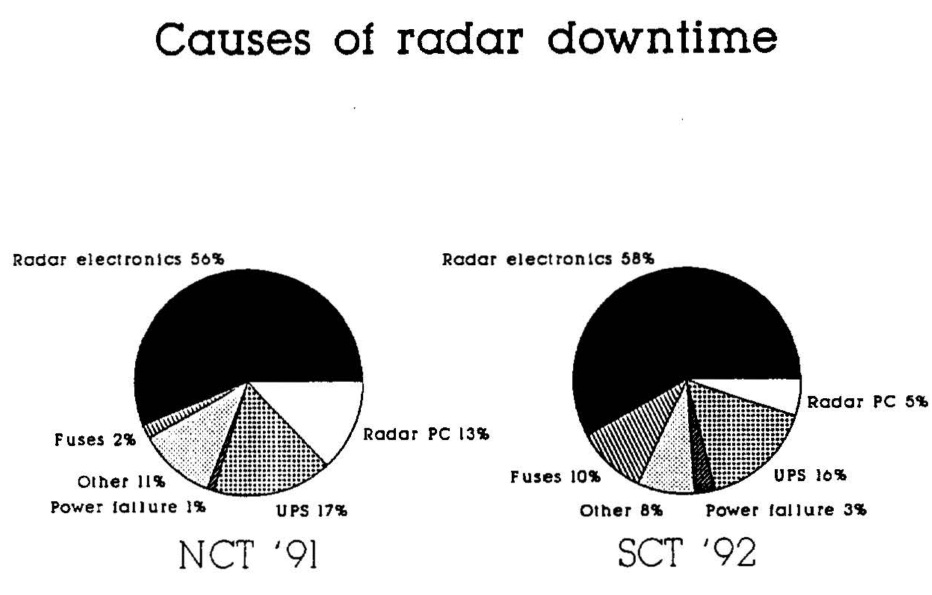

Figure 3. Causes of radar downtime during NCT'91 and SCT'92.

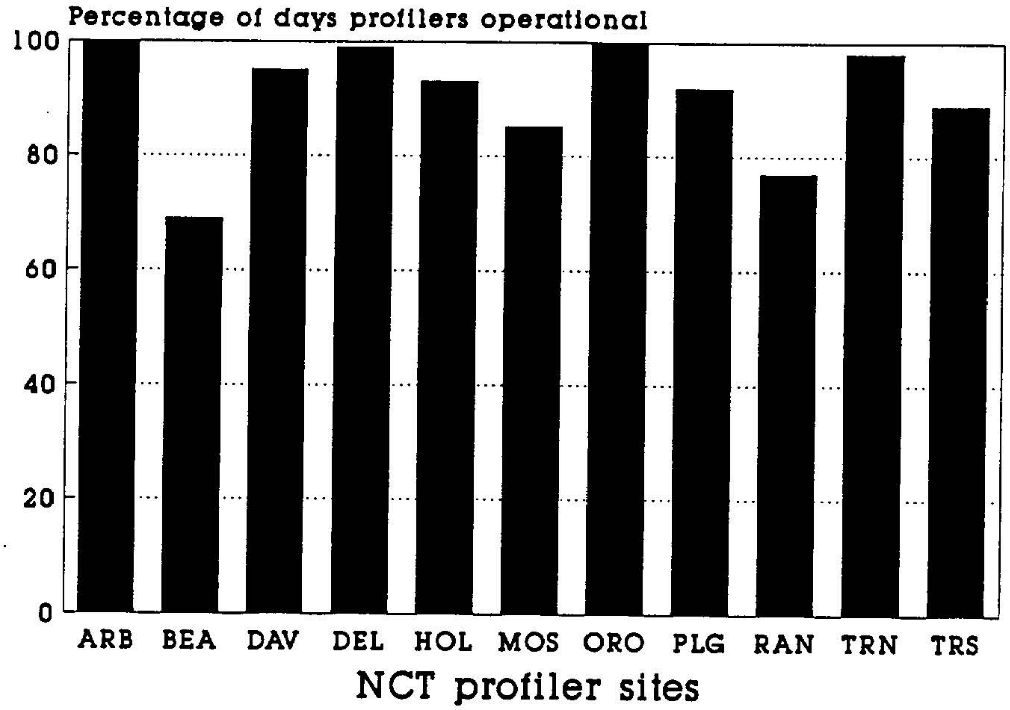

Figure 4 Percentage of possible days profilers operated during NCT '91.

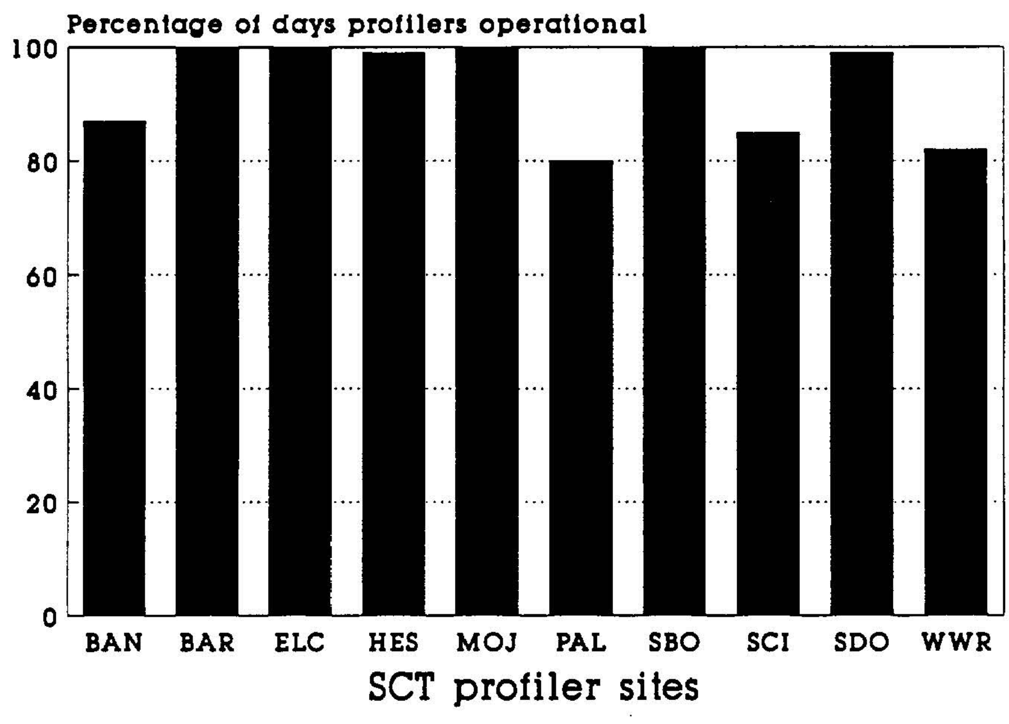

Figure 5 Percentage of possible days profilers operated during SCT '92.

6 DATA EVALUATION

6.1 Northern California Transport 1991 Rawinsonde/915 MHz Wind Profiler Comparison

This section presents a statistical comparison of the 915 MHz wind profiler radar performance with a rawinsonde standard during the 1991 Northern California Transport (NCT) experiment. During a 10-day period, an intensive site audit was conducted at each of the eight radar sites, where a rawinsonde profile was taken every three hours during a 24-hour period. It was during the analysis of these data that contamination of radar echoes with birds was discovered. Characteristics of this contamination are:

- Signal strength when a bird is in the main lobe of the radar beam is much larger than normal.
- It occurs primarily at nighttime.
- The width of the Doppler spectrum averaged over several tens of seconds tends to be much larger than normal atmospheric signatures.

The primary data editor used on the so-called moment data (individual radial components of the wind averaged along the radar beam for a few tens of seconds) is the Weber-Wuertz method modified by a preprocessor that flags data that may have been contaminated by birds. This is referred to as "thresholded data" because of the dominant influence of the signal strength. In the comparisons described here, our rawinsonde data have been processed for comparison with the non-thresholded and thresholded Weber-Wuertz versions of the radar data. The term non-thresholded refers to the 1991 version of the Weber-Wuertz wind profiler editing without bird contamination thresholding. The term thresholded refers to the 1993 version of the Weber-Wuertz wind profiler editing including bird contamination and C_n^2 (the refractive index structure parameter which is a measure of the radar signal intensity) thresholding.

Highlights of the analysis presented below include:

- methodology in processing the rawinsonde data for radar comparison.
- graphic and quantitative displays of the statistical comparison.
- summary tables of the root mean square error (RMSE) before and after thresholding.
- statistically significant decrease in RMSE after thresholding.

6.1.1 Methodology

6.1.1.1 Rawinsonde

The rawinsonde data undergo several levels of processing before comparison with profiler winds. The levels are as follows:

1) Wind-flagging: This level-1 of processing flags wind anomalies such as obvious wind speed and direction outliers, and false winds caused by theodolite tracking difficulties.

2) Interpolating: This level-2 linearly interpolates the clean rawinsonde profiles to 6 s time intervals. Six seconds represents the sample rate of the rawinsonde.

3) Above-ground-level to above-sea-level conversion of rawinsonde heights is performed on the interpolated profiles.

4) Block-averaging: Low (+/- 200 m) and high (+/- 50 m) resolution block-averaging on wind speed, wind direction, and meteorological U and V wind components are calculated at this stage. These block-averages are equivalent to the wind profiler range gates, allowing a direct comparison of the profiler and rawinsonde data.

5) Other final routines combine processed rawinsonde and profiler components U and V for comparison, separates data into low and high resolution/ night and day categories, and calculates the root-mean-square (RMSE) for data under 3000 m.

6.1.1.2 Graphical Displays

We developed scatter plots that summarize graphically the statistical comparison between the rawinsonde standard U and V and the profiler for each site. Eight graphical displays were created for each site and are categorized into nighttime (1900 - 0800 PDT), daytime (0800 - 1900 PDT), low and high resolution, thresholded and non-thresholded. These data are contained in Appendix B.

6.1.1.3 Audited sites

1) Arbuckle (ARB)
2) Delta Island (DEL)
3) Oroville (ORO)
4) Pleasant Grove (PLG)
5) Rancho Seco (RAN)
6) Travis North (TRN)
7) Travis South (TRS)
8) U.C. Davis (UCD)

6.1.1.4 Missing Data

1) There are no nighttime rawinsonde data for Travis North.
2) There are no non-thresholded radar data for Travis South.
3) There are no thresholded data for Pleasant Grove.

6.1.1.5 Statistics

The graphs in Appendix B display both a scatter plot and a summary table of the quantitative statistics for each comparison:

- **Var:** The variable RU stands for Rawinsonde U, RV stands for Rawinsonde V. The variable PU stands for wind profiling radar U, PV for wind profiling radar V. Both U and V are the meteorological components of the wind.
- **n:** The sample population.
- **min:** The minimum data point for the variable.
- **max:** The maximum data point for the variable.
- **Mean:** The measure of central tendency of the sample.
- **SD:** The standard deviation measures the average absolute deviation of the sample population from the mean.
- **r**: The correlation coefficient between RU and PU and RV and PV. It quantifies how well the two variables correlate with each other, a value of 1.00 being a perfect linear correlation.
- **r^2:** The coefficient of determination which is a measure of the strength of the straight-line relationship.
- **SE:** The standard error of the estimate is the square root of the residual mean square. It is an overall indication of the accuracy with which the fitted regression function predicts the dependency of Y on X.
- **RMSE:** The root mean square error is an average absolute error for data expressed on a continuous numerical scale. The RMSE for RU and PU is the square root of the sum of $(RU - PU)^2$ divided by n.

It is important to note that in these data sets, RMSE is a statistic calculated for data below 3000 m. All the other calculated statistics in the tables represent the entire sample of data taken at all heights.

6.2 Comparison Of RMSE Differences Using Non-Thresholded And Thresholded Data Sets

Tables 1 and 2 are summary tables of the RMSE for non-thresholded/thresholded U and V at each site. Table 1 shows how the RMSE generally improves after thresholding, indicating an improvement in wind profiler and rawinsonde correlation. But are these improvements statistically significant? To answer this question a 1-tailed t test was performed on the RMSE at the .05 (5%) significance level. In this case the hypothesis H_0 represents a RMSE increasing or remaining the same after thresholding, and the alternative hypothesis H_A represents a RMSE decreasing after thresholding. The 5% significance level means that H_A is so far from H_0 that its occurrence by chance alone is less than 5%. Thus it is assumed that its occurrence happens because H_O is in fact false, and H_A is accepted as the rule.

The t test results show that a significant decrease in RMSE occurred at the following locations and under the specified conditions:

- Oroville: nighttime high resolution in the V component; low resolution in the U and V component.
- Rancho Seco: nighttime low-resolution in the U and V component.

A t-test was not possible in the following cases because of insufficient or corrupted comparison data:

- Plesant Grove (neither daytime nor nighttime periods).
- Travis South (neither daytime nor nighttime periods).
- Travis North (no nighttime period).

Our investigation suggested that during this time, bird migration patterns tracked from the north-northwest to the south-southeast along the Sierra Nevada mountain range, where birds migrated only at night. Because birds typically fly closer to the Sierras than farther west along the plains, the most likley profiler sites with bird-contaminated data were Oroville, Pleasant Grove, and Rancho Seco. The above analyses from Oroville and Rancho Seco show that thresholding significantly reduces the bird contamination problem in these data. All other RMSE improvements were insignificant at the 5% level, supporting the hypothesis that heavy bird contamination did not occur at the sites further from the mountains.

Table 1 Summary of RMSE for ***non-thresholded*** low/high resolution data below 3000 m.

NCT91	Low Res Night		Low Res Day		High Res Night		High Res Day	
SITE	**U**	**V**	**U**	**V**	**U**	**V**	**U**	**V**
ARB	2.1	2.7	1.3	1.8	1.7	2.0	1.2	1.6
DEL	1.5	2.5	2.1	2.3	2.0	1.8	2.1	2.4
ORO	2.9	4.9	0.8	1.1	2.5	4.2	1.1	1.2
PLG	3.7	4.6	1.0	1.6	2.6	3.5	1.1	1.6
RAN	2.3	4.2	1.6	1.1	1.4	3.2	1.3	0.8
TRN	ND	ND	2.1	2.2	ND	ND	2.4	2.1
TRS	ND	ND	ND	ND	ND	ND	ND	ND
UCD	1.2	1.5	1.7	2.6	3.3	3.0	1.8	1.8

* ND: no data

Table 2 Summary table of RMSE for ***thresholded*** low/high resolution data below 3000 m.

NCT91	Low Res Night		Low Res Day		High Res Night		High Res Day	
SITE	**U**	**V**	**U**	**V**	**U**	**V**	**U**	**V**
ARB	1.6	2.3	1.0	1.6	1.4	1.7	1.0	1.7
DEL	1.4*	1.0*	2.1	2.3	1.4	1.4	2.2	2.3
ORO	1.1	1.5	1.6	1.1	1.2	1.7	1.1	1.2
PLG	ND	ND	ND	ND	ND	ND	ND	ND
RAN	1.1*	1.2*	1.6	1.6	0.8	2.5	1.8	1.6
TRN	ND	ND	2.4	2.6	ND	ND	2.5	2.1
TRS	ND	ND	2.0	1.7	ND	ND	2.5	2.4
UCD	1.4*	2.0*	1.7	2.5	3.4	3.2	1.5	1.4

* n samples less than 10.
* ND: no data

6.3 **Representativeness: Collocated profilers**

Past discussions within ARB have examined the optimum spatial distribution of upper air soundings. However, little quantitative guidance has been available. To assist in the analysis of this problem we deployed two wind profilers within about 10 km of each other southwest of Sacramento in a north-south line near Travis Air Force Base.

This report presents a statistical comparison of the 915 MHz wind profiler performance between Travis North and Travis South during the 1991 Northern California Transport (NCT) experiment. The wind profiler site Travis South was located approximately ten km south of the Travis North wind profiler site. The two sites were chosen in close proximity to compare radar performance while operating under predominantly similar atmospheric conditions within the strong flow region east of the San Francisco Bay Area. During a two-month period (July and August), the wind profilers were operating simultaneously for fifty-three days. The data used in this analysis were processed using the 1993 version of the Weber-Wuertz wind profiler editing including bird contamination and C_n^2 thresholding.

The purpose of this analysis is to present these comparisons in a format that is easily referenced for further study. The following text is a brief explanation of the:

- methodology in processing the data for comparison.
- summary table of the root mean square error (RMSE) for specific height categories.
- statistical conclusions based on the change in RMSE between specific height categories.

6.3.1 Categories

Meteorological U and V components from profiler winds at both sites are analyzed according to the following categories:

1) Low and high resolution.
2) Afternoon/nighttime period: 1300 - 0100 PDT.
3) Morning/daytime period: 0100 - 1300 PDT.
4) Six height levels:
   a) 0.0 - 0.75 km
   b) 0.75 - 1.5 km
   c) 1.5 - 3.0 km
   d) 3.0 km and above
   e) 0.0 - 1.5 km (high resolution data only)
   f) 0.0 - 3.0+ km (low resolution data only)

A total of sixteen graphs (Appendix C) and Table 3 present these comparisons.

6.3.2 Data processing

Between the Travis North and South sites, the profiler range gates differed by 15 m for low resolution data and 43 m for high resolution data. A cubic spline technique was used on the high resolution data from both Travis North and South, interpolating data to 100 m range gates up to 1500 m before analysis. The spline technique was very restrictive, rejecting any cases with less than 40% of valid data points in an hour, and rejecting any height levels where an extrapolation was required. The 15 m range gate height difference in the low resolution data was considered to be insignificant. The afternoon/nighttime and morning/daytime periods correspond to well-established marine flow and weak or variable flow, respectively.

6.3.3 Analysis of RMSE at specific height levels

Table 3 summarizes the RMSE for each flow regime at the specified height category, resolution, and time period. The lower RMSE for flow regimes between .75 and 3 km suggest that there is more meteorological variability within the lowest .75 km than at higher heights. The increased RMSE above 3 km raises questions. An increase in RMSE at a height level characterized by uniform flow suggests, but does not prove, low signal to noise ratios for these profilers at this height level.

6.3.4 Discussion

The graphs show a strong correlation between the two wind profilers suggesting a common wind flow at both sites during this time period. This is indeed the case where troughs were dominant (19 cases of 24-hour periods) opposed to ridges (3 cases of 24-hour periods). Ridges indicate greater wind variability because of greater subsidence, lighter wind speeds, and a shallower marine layer. It was observed during one comparative ridge case, correlation between the two wind profilers was poor. Unfortunately, the occurrence of ridges during the comparison period was minimal, and thus the results of comparisons under these conditions inconclusive.

It is possible to achieve representative wind profiles with a single radar in areas located within homogeneous wind flow regimes: such homogeneity might result from strong, uniform forcing such as that associated with the seabreeze or because of well-defined topopgraphic constraints. However, the small scale meteorological variability within the lowest 0.75 km may require several radars to fully assess local boundary layer variability in critical regions or more adequate boundary layer parameterizations in numerical models.

Table 3 Summary table of RMSE for thresholded low/high resolution data for each specific height category.

NCT91	Low Res AN*		Low Res MD**		High Res AN		High Res MD	
HT km	U	V	U	V	U	V	U	V
0.-.75	2.6	2.1	2.3	2.4	2.6	2.1	2.6	2.5
.75-1.5	2.2	1.9	1.8	1.8	2.3	1.9	1.7	1.6
1.5-3.0	2.2	2.1	1.6	1.7	NA***	NA	NA	NA
3.0 +	2.8	2.3	2.2	2.2	NA	NA	NA	NA
0.- 1.5	NA	NA	NA	NA	2.4	2.0	2.1	2.0
0.- 3.0	2.3	2.0	1.8	1.9	NA	NA	NA	NA

* AN: (afternoon/nighttime) = 1300 - 0100 PDT.
** MD: (morning/daytime) = 0100 - 1300 PDT.
*** NA: not applicable for this specific data set.

6.4 **Analysis Of Spatial Patterns And Representativeness**

The measurement of meteorological parameters in support of regional air quality field studies has always been a challenge, particularly when the region is in complex terrain such as that of California. As radar wind profiler use increases, especially for regional air quality work, methods of analysis of wind data from arrays of these instruments become increasingly important. The methods should be designed to enhance the information provided to air quality specialists concerning the horizontal and vertical transport processes of the atmosphere. Here, we concentrate on the horizontal transport. A simple spatially gridded model is used that displays wind profiler observations classified by synoptic categories. This information can also be displayed by height. Directly related to the issue of transport is the issue of spatial representativeness of the wind profiler data. This becomes very important because arrays of wind profiler data are used in air quality models in complex terrain. In this report, we introduce a technique that helps determine spatial representativeness. It uses the results of the simple grided model to calculate two-dimensional correlations between grid points to provide information on the representativeness of the observations. As above, this information can be displayed by height. The data used in this analysis were from the Northern California Transport (NCT) study during the summer of 1991.

6.4.1 Wind profiler instrumentation and data characteristics

The 915-MHz boundary layer wind profilers use scattering from radar refractive index in clear air to measure the Doppler shift of the scatter and hence the wind speed along each radial. For the NCT study, each profiler had three antennas to measure the three components of the wind. In each case, one antenna was vertical to directly measure the vertical velocity. During this study, the profilers operated in two simultaneous pulse-width modes representing 100-m and 400-m range gates. The 100-m gate is used for the lower-level winds (250 m and 500 m) presented here, and the 400-m range gate is used for the higher-level winds (2000 m).

The maximum range of usable data from the wind profilers depends on the magnitude of small-scale moisture fluctuations. The moisture fluctuations create the radar refractive index irregularities from which the radar waves are scattered. Generally, the higher the background absolute humidity gradients and turbulence intensities, the larger the refractive index fluctuations and the greater the radar range. During the NCT study, the daytime ocean onshore air flow through San Francisco Bay into the Sacramento Valley results in a more humid boundary layer. However, above this moist layer, it can be very dry, limiting the performance of the wind profilers. The layer of increased moisture may be 1 to 2 km deep, and maximum ranges of the radars for the 400-m range resolution were between 3 and 4 km.

The full three components of the winds for the entire profile are calculated every 3 min. Each profile used in this analysis represents a 1-h average. Prior to the calculation of this average, the winds from each radial are edited for consistency in both time and height (Weber *et al.*, 1993). The same editing is applied over 24-h blocks using the hourly data. This eliminates most of the inconsistent winds caused by low signal-to-noise ratios or by non-meteorological targets (e.g., aircraft, biological targets, intermittent precipitation). This discussion is limited to daytime data to avoid contamination caused by nighttime bird migration.

Figure 1 showed the locations of the wind profilers and also the contours of the rather complex terrain on either side of the valley. The channel from the ocean through San Francisco Bay into the large opening to the valley obviously has a significant effect on the boundary layer flows within the Sacramento Valley. The wind profilers were strategically located to help delineate this flow. The profiler data from selected sites used for this analysis were taken from the period from 9 July through 26 August. All eight profilers operated concurrently during that time.

We limit the discussion to three critical measurement levels, 250 m, 500 m, and 2000 m above sea level (ASL). The 250-m level is nearly always within the daytime boundary (or mixed layer). The 500-m level is not always within the morning mixed layer (probably in transition), but is within the afternoon mixed layer. The 2000-m level is always above the mixed layer.

6.4.2 Data analyses

There are two questions to answer from this work: (1) What are the transport patterns in the Sacramento Valley? (2) How spatially representative are the wind profiler observations? The first question is very important during the high-ozone season in the valley to assist interpretation of surface ozone and ozone precursor measurements made during the NCT study. The two questions are strongly related and, in fact, are interdependent; therefore, the results of the two analyses will be presented together in the next section. The answer to the first question is needed to interpret the answer to the second question. This section discusses the analysis methodology used to address both concerns.

To determine the transport patterns, we use a simple and fairly standard two-dimensional interpolation model that grids the array in the horizontal at selected vertical levels. The model is given by

$$\phi_d = \Sigma \omega_s \phi_s$$

where

$$\omega_s = D^{-E}$$

ϕ_d is the interpolated data, and ω_s is the weight; D is the distance between the source point and its neighbor, and $E = 3.5$, an adjustable constant. This method provides a user-controlled interpolation weighting and smoothing. The smoothing is performed once over the neighboring points. This technique, or usually a variant thereof, is often used for regional boundary layer meteorological model data initialization. The grid size used here is approximately 10 km in the east-west direction and 11.2 km in the north-south direction.

A somewhat more sophisticated technique includes the terrain and uses a mass-conserving model. This technique is important when data are sparse temporally and/or spatially and/or when vertical profiles are not available. If properly located, the wind profiler data implicitly include the terrain effects in the flow because of the profilers' strategic locations relative to important terrain features, their relatively high time resolution (1-h averages), and the fact that they provide high-vertical-resolution profiles. In the future objective analysis techniques used in the initialization of more sophisticated numerical models may prove appropriate.

A measure of the representativeness comes from Eckman *et al.* (1992) who suggest, for regional application in complex terrain, the geophysical "correlation,"

$$\gamma(r) = 1 - \frac{D(r)}{(\overline{u_1^2}+\overline{u_2^2})}$$

where $D(r) = \overline{(u_1 - u_2)^2}$ is the structure function and u_1 and u_2 are wind components measured simultaneously in time at two different locations. This method is based on a variogram defined by Isaaks and Srivastava (1989). We apply the technique in a different manner from that of Eckman *et al.* (1992). We present the results as two-dimensional contours in space by correlating a particular, selected wind profiler site with all other grid points in the domain. The contours in the complex-terrain environment of the NCT study are often very spatially asymmetric. The regions within the higher correlation contours are those for which the measurement may be considered representative. The correlations provide a quantitative measure of the representativeness.

Both the transport measurements and the spatial correlations are classified according to the following synoptic categories, representing three (1-3) cases:

- Case 1: 500-hPa ridge (inland thermal low)
- Case 2: 500-hPa trough off the coast (approaching surface front)
- Case 3: 500-hPa trough nearly over the Sacramento Valley (dynamic trough at the surface).

These categories provide a link between the synoptic-scale forcing and the regional patterns. We discover in the next section that there are, in some situations, significant differences between these cases. The number of days and percentage of total days in each category are Case 1, 19 (39%); Case 2, 15 (31%); and Case 3, 15 (31%). It is interesting that during the period of this study, the synoptic patterns were so evenly distributed.

6.4.3 Results

The wind patterns are divided by synoptic cases, by morning and afternoon, and then stratified by height. For brevity, we present only results from three levels ASL: 250 m, almost entirely in the daytime mixed layer; 500 m, transition as the mixed-layer cap moves through it; 2000 m, well above the mixed layer. The 2000-m ASL level, although above the level of daytime surface heating effects, may still be affected by the higher terrain on each side of the valley (Fig. 1). In fact, we show here that there are some terrain effects at this level.

Figures 6.1, 6.2, and 6.3 present the wind patterns for synoptic Cases 1, 2, and 3 within the inner rectangle in Fig. 1, at the three levels. A predominant feature in all three cases is the inflow of marine air in the lower levels from the Pacific Ocean through the San Francisco Bay area. Case 1 (Fig. 6.1) shows the weakest flow of the three cases, especially at 2000 m. This is, of course, the ridging case, and perhaps the situation with the most significant chance of higher ozone concentrations. Although there are small differences between the three cases at the 250-m level, the most significant differences occur at the 2000-m level. The 500-m level indicates the most difference between Cases 1 and 2 during the morning. It appears that the differences in synoptic forcing between the three cases are most pronounced at the 2000-m level. There is relatively strong southerly flow ahead of the front in Case 2 at this level. Even Case 3 shows southerly flow, although weaker. For both Case 2 and Case 3, the terrain influences appear to be small at 2000 m; they are much more pronounced in Case 1 at this level.

In each synoptic category in the morning, a northwesterly flow is indicated on the west side of the Sacramento Valley, suggesting drainage from the higher ground to the north and west (see Fig. 1). By afternoon, this flow pattern shifts to easterly, suggesting an upslope forcing due to solar heating. Also, in each classification there is a suggestion of the terrain-forced cyclonic Shultz eddy (Fitzwater, 1981) at the two lowest levels. The wind patterns in Figs. 6.1-3 illustrate the complexities of the transport processes. It is widely assumed that the major source of ozone precursors into the Sacramento Valley is the San Francisco Bay area. There is strong flow into the valley from the Bay Area, but there is also opposing flow apparently from drainage in the morning between the 250-m and 500-m levels. By afternoon, the air from the Bay Area has moved well into the valley and there is possible horizontal eddy formation in the mixed layer, creating a suggestion of recirculation of the pollution. Remember that these results are not from a model, but from actual interpolated, smoothed, and gridded wind profiler measurements.

Figures 6.4 through 6.9 present the correlations as found from the equation for $\gamma(r)$ and in the same domain as Figs. 6.1-6.3. Figures 6.4-6.6 provide examples of the differences between levels at three selected sites, and Figs. 6.7-6.9 provide examples of the differences between synoptic cases at the same three sites. The sites selected are Travis North (TRN), Pleasant Grove (PLG), and Arbuckle (ARB). They were selected because TRN is representative of the inflow into the Sacramento Valley from the Pacific Coast, PLG is representative of the center of the valley, and ARB is representative of a region of strong influence of the nearby mountains. Correlations are performed on the east-west wind component (u) and the north-south wind component (v) separately. The morning represents an average between 0900 and 1100 PDT, and the afternoon, between 1300 and 1700 PDT.

The results indicate how the flow patterns shown in Figs. 6.1-6.3 affect the corresponding spatial correlations of the wind components. In general, as expected, the correlations are high over a broad region in situations in which the winds are predominantly east-west, in u over a large area (e.g., TRN, 250 m, morning, Fig. 6.4). Where the winds are mainly north-south, the correlations are high over a large area (e.g., all three sites, Case 2, afternoon, Figs. 6.7-6.9). Figures 6.4-6.6 show that as the wind patterns change with height, the spatial correlation patterns in u and v change significantly. This spatial correlation change also occurs as the wind patterns change synoptically (Figs. 6.7-6.9), particularly between Case 1 and the other two classifications.

6.4.4 Summary and conclusions

The results presented here illustrate a method by which wind profile data from regional arrays can be represented, analyzed, and understood in a complex-terrain area. These depictions can be used to understand air pollution transport patterns as they are influenced by terrain and larger-scale synoptic forcing. The spatial correlations quantify the transport regions and can be used to aid in siting of instrumentation prior to deployment by employing the results of a three-dimensional complex-terrain model.

The terrain influence is implicitly included in the wind patterns and correlations by using the observed measured wind profiles, which, one assumes, are affected by the terrain. However, a significant improvement, leading to explicit inclusion of the terrain influence, is to use a mass-conserving model or the initialization procedure for a numerical predictive model, including the terrain.

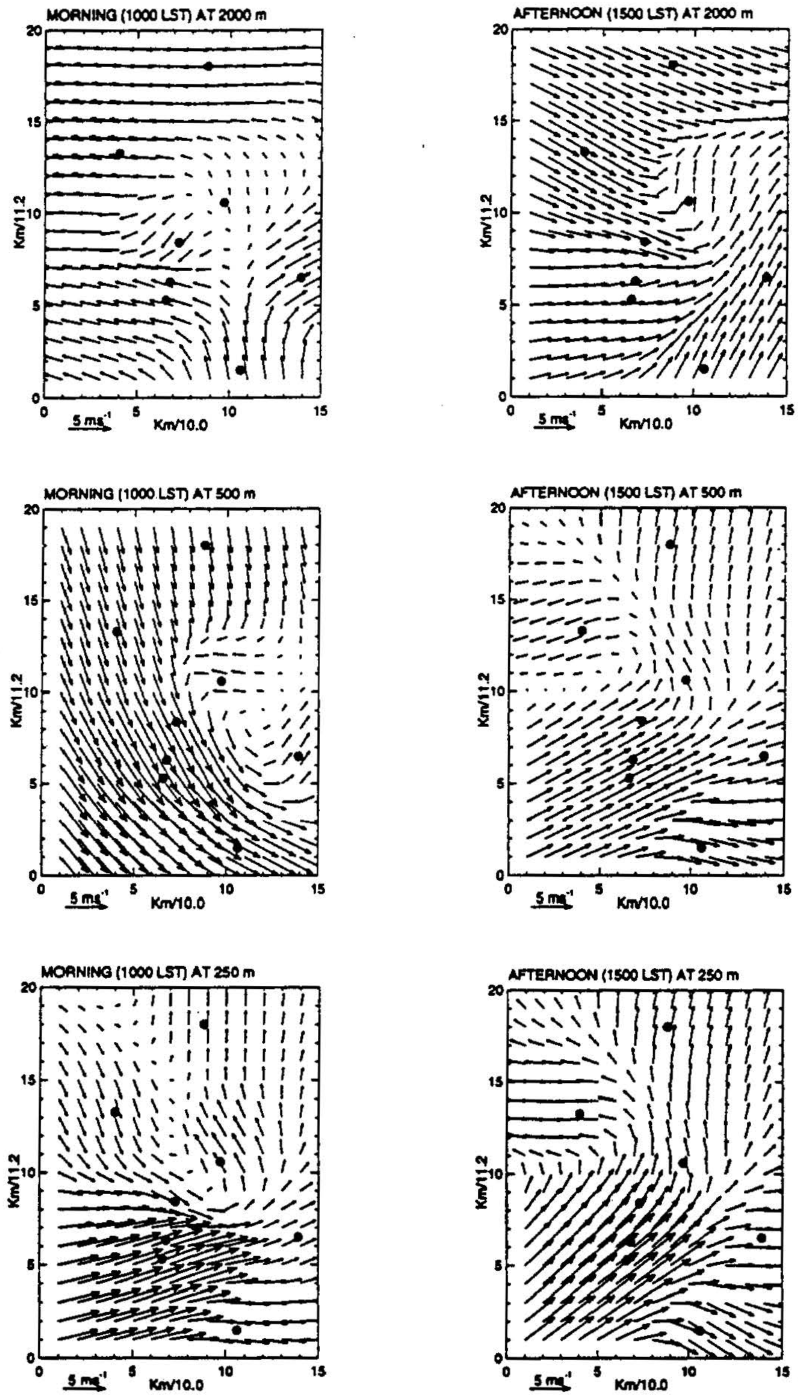

Figure 6.1 Wind speed and direction at three levels, for 1000 PDT (left panels) and 1500 PDT (right panels) for synoptic Case 1. The dots locate the wind profiler sites shown in Fig. 1. The east-west grid should be multiplied by 10 to scale in kilometers and the north-south axis by 11.2.

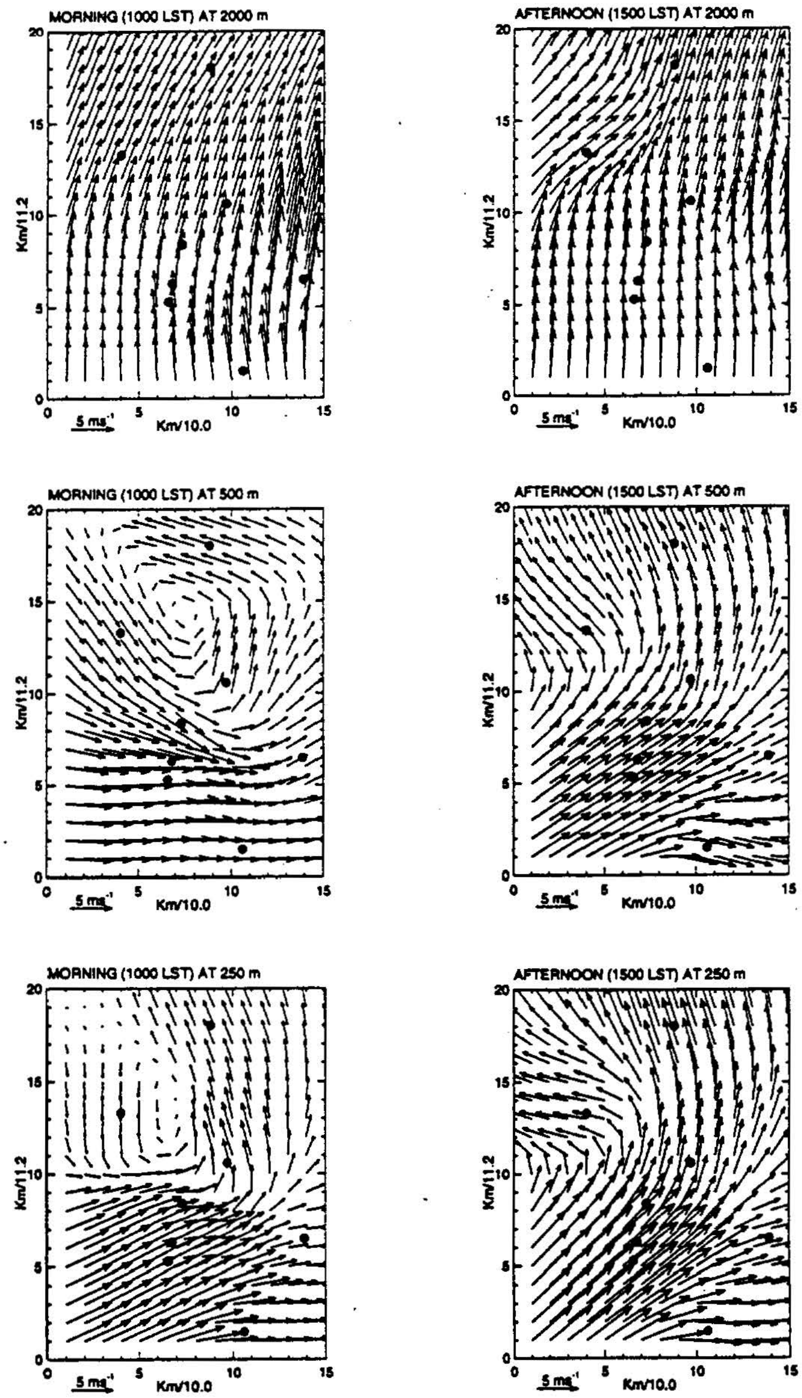

Figure 6.2. Same as Fig. 6.1, except for Case 2.

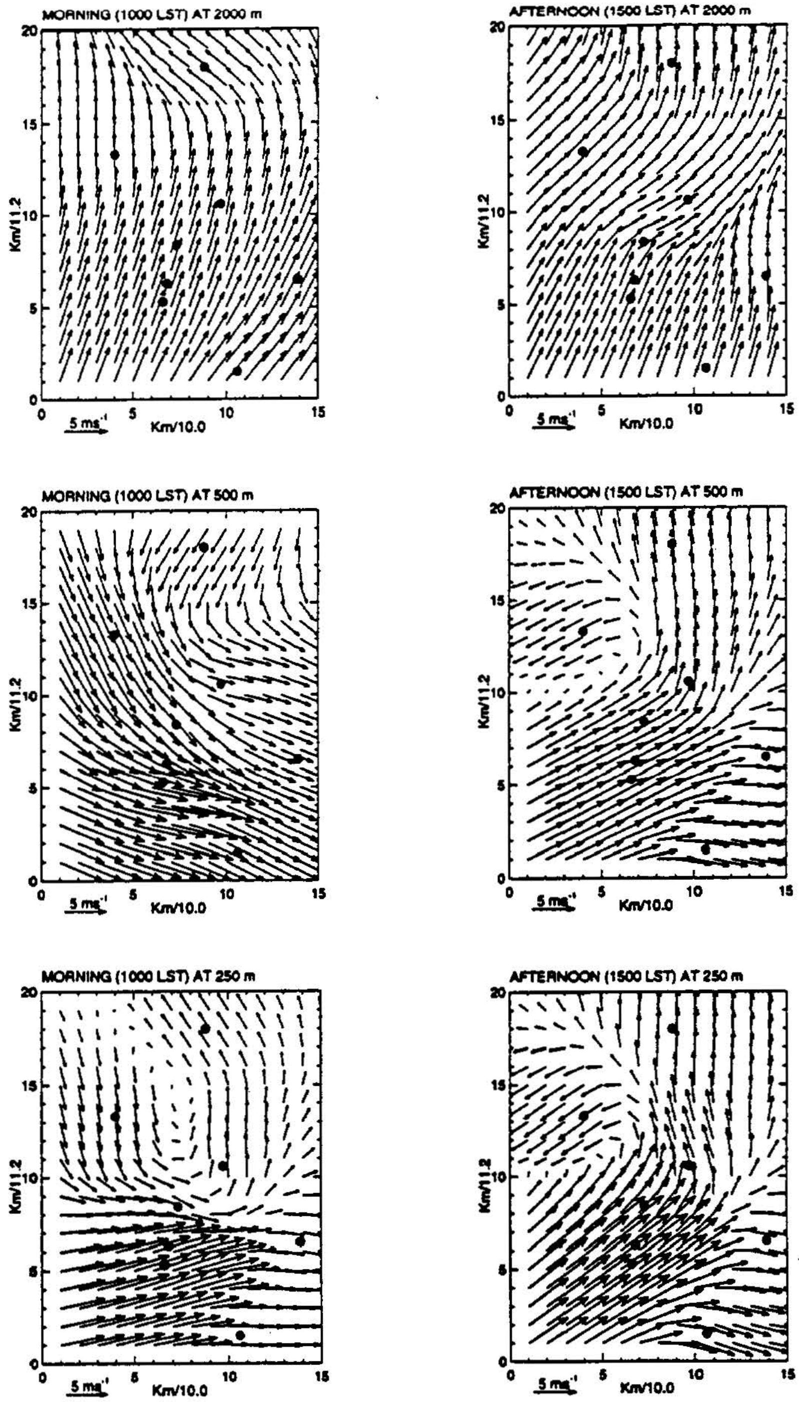

Figure 6.3. Same as Fig. 6.1, except for Case 3.

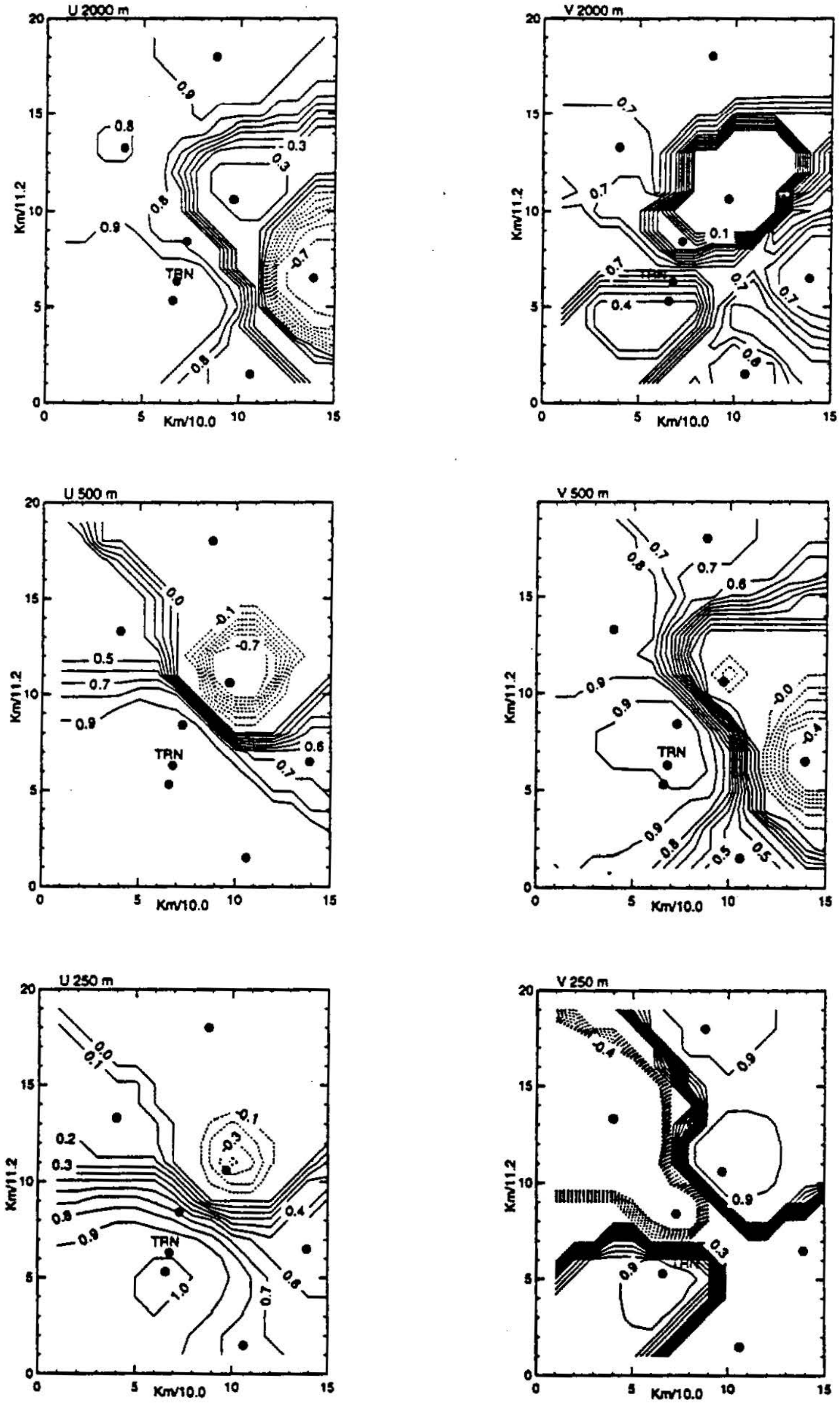

Figure 6.4. Spatial correlations between the TRN site and other grid points for *u*, (left panels) and v, (right panels) wind components. The correlations are for the morning average (0900-1100 PDT), for synoptic Case 1 at three levels. The dots show the profiler sites. The axes are multiplied by the same factors as in Fig. 6.1 to scale in kilometers.

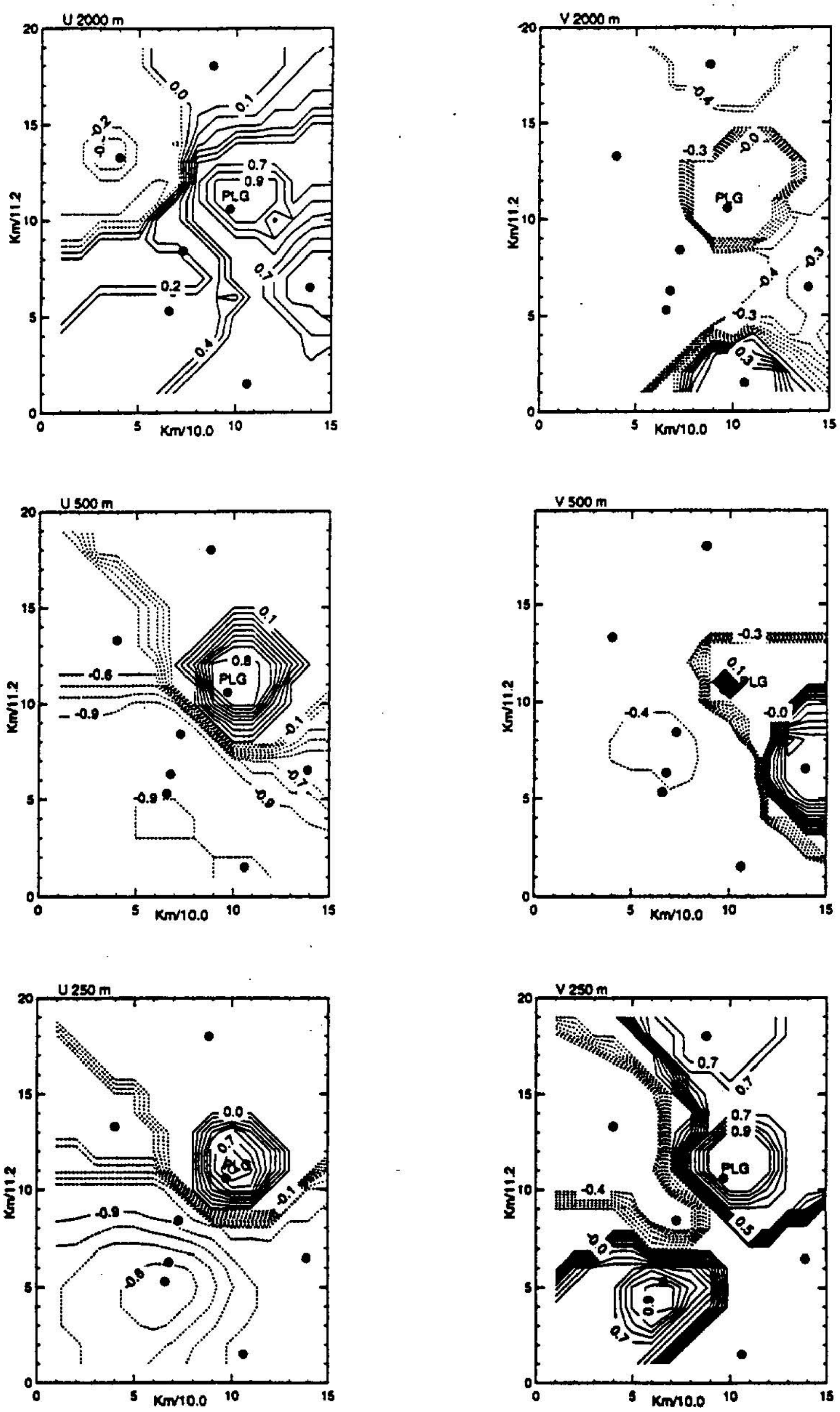

Figure 6.5. Same as Fig. 6.4, except that the correlations are for the PLG site.

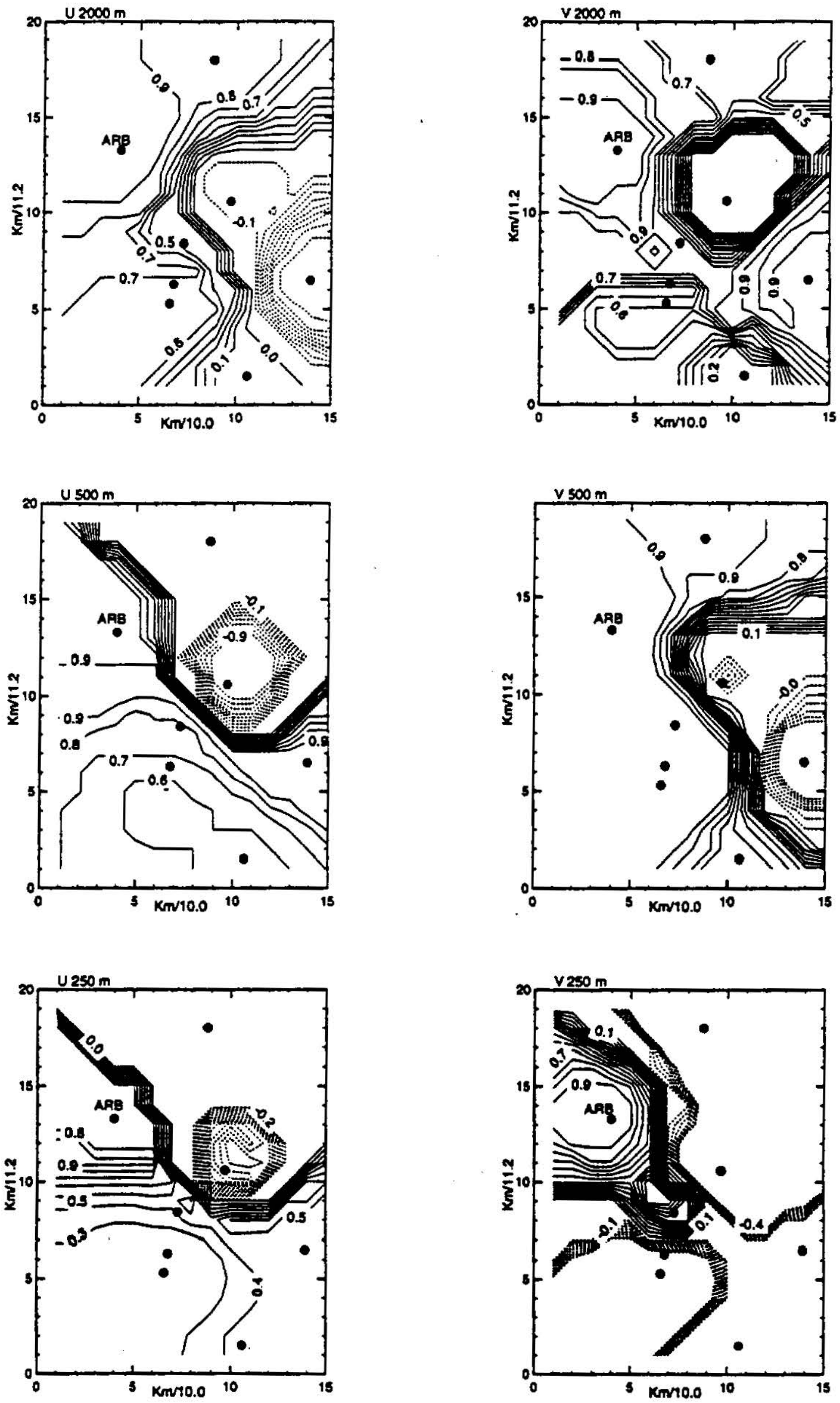

Figure 6.6. Same as Fig. 6.5, except that the correlations are for the ARB site.

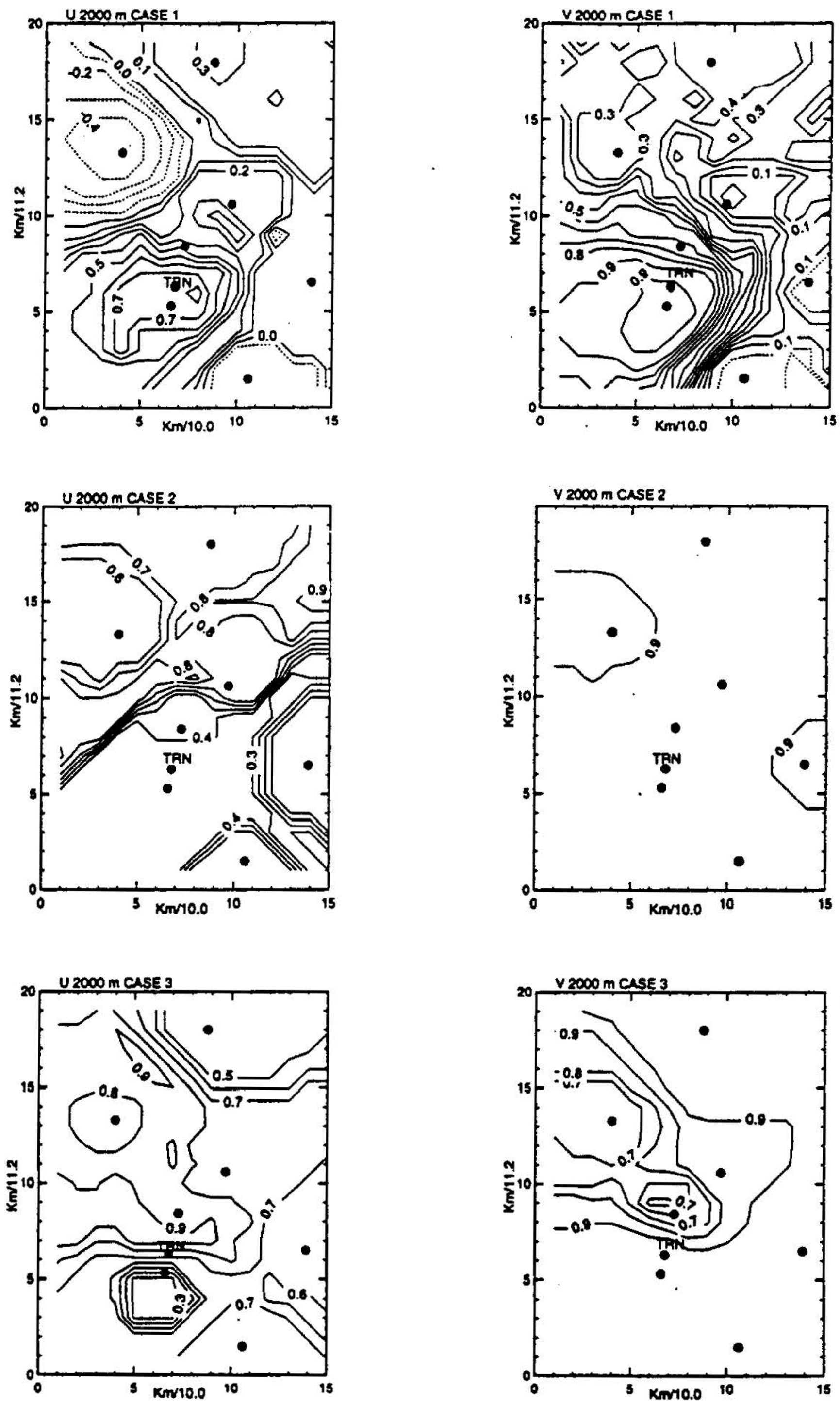

Figure 6.7. Spatial correlations between the TRN site and other grid points for the *u* (left panels) and *v* (right panels) wind components. The correlations are for the afternoon average (1300-1700 PDT) at the 2000-m level for three synoptic cases. The dots show the profiler sites.

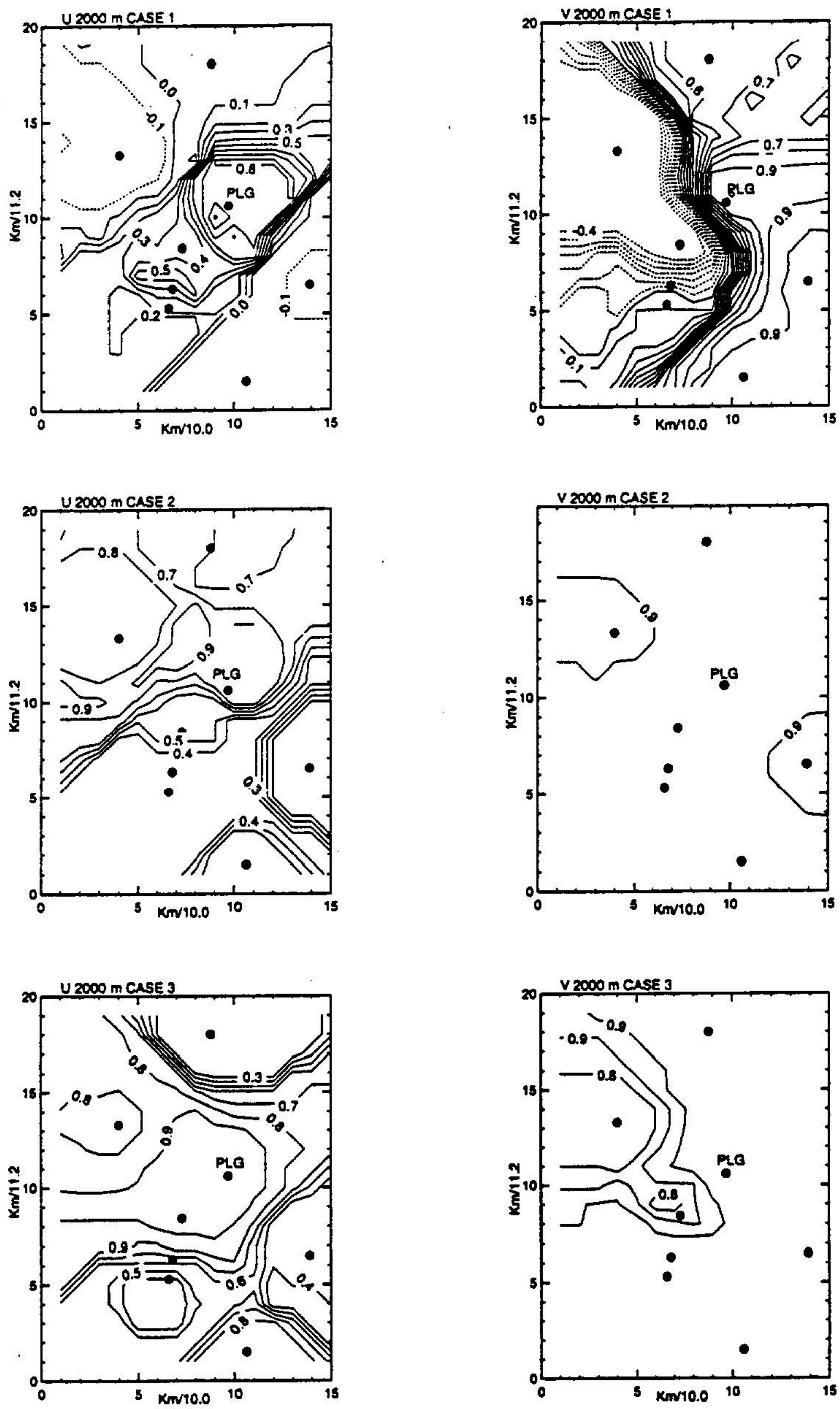

Figure 6.8. Same as Fig. 6.7, except that the correlations are for the PLG site.

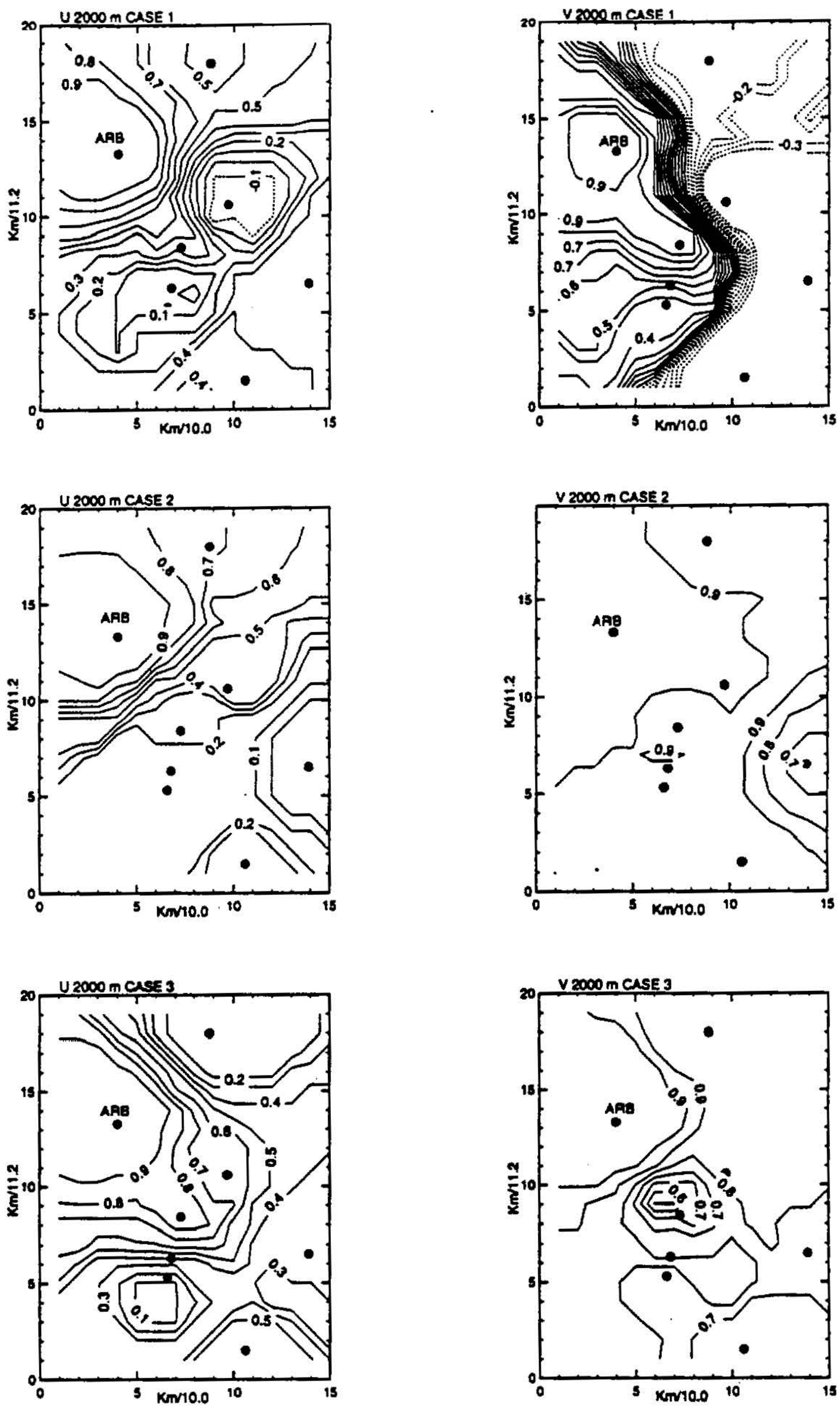

Figure 6.9. Same as Fig. 6.7, except that the correlations are for the ARB site.