

- We need comprehensive dual Doppler radar coverage. Both airborne and ground-based radars are needed to provide detailed flow fields for the entire life cycle of a MCS.

**N94-24400**

#### **4.6.2 Session on techniques and resources for storm-scale numerical weather prediction**

*Kelvin Droegemeier*

The recommendations of this group are broken down into three areas: modeling and prediction, data requirements in support of modeling and prediction, and data management. The format in this section differs somewhat from that used in the previous workshop session descriptions, due to the more technical nature of the material.

##### *I. Modeling and Prediction*

###### *a. Current Status*

This group worked under the assumption that the CME would run a realtime forecast model in support of field operations and to evaluate the model's predictive capabilities as applied to MCS's and related phenomena. Additionally, the model would provide assimilated datasets for post-analysis. It is unlikely that massively parallel processing (MPP) systems will be utilized effectively enough by mid 1995 to play a role in this program, and thus the group recommended that the model be used on a more conventional (e.g., Cray-type) platform. However, if significant strides are made in MPP utilization during the next two years, an MPP option should be left open, particularly in light of the extremely large memories available on such machines. The NOAA Forecast Systems Laboratory recently completed an evaluation of current mesoscale models, and an even more detailed study of this type is being performed by the Air Force. The choice of a model or models for CME should be carefully orchestrated, with consideration given to model capabilities, efficiency, flexibility, and appropriateness for the CME mission.

###### *b. Modeling and Technological Recommendations*

The principal unknowns at this point, apart from the model itself, concern data, initialization methods, validation techniques, computing facilities, and data storage and display strategies. It is likely that *special computing facilities will be required* to support model execution and output archival, as well as collection of raw input data. The CME should determine which group or groups will bear this responsibility, and assess the need

for upgraded telecommunications capabilities. In order for the model to be effective in realtime, *appropriate data displays must be available*. The CME should explore the accomplishments of various groups in this area (e.g., FSL, University of Illinois). A model forecast duration of 18 hours is deemed optimal for the goals of the CME.

*This group strongly endorses the use of adaptive grids in the realtime prediction support*, though it is less vocal about the role of adaptive grids in creating the assimilated datasets for post-analysis. The most plausible strategy for adaptive refinement is to allow the program to make a "first guess" on optimal grid placement, with augmentations allowed by the person coordinating the model runs. Although fully automated grid placement is not yet available, ongoing developments may provide this capability by the mid-1990s (e.g., work is being conducted in adaptive grid refinement by W. Skamarock at NCAR, L. Wicker and Texas A&M, M. Xue and K. Droegemeier at CAPS, W.-K. Tao at NASA GSFC). CME should encourage these groups to make intercomparison studies of the various available models, and re-evaluate the state-of-the-art in adaptive refinement at various times prior to the field experiment. Thus, the CME should re-evaluate this recommendation prior to the actual field program.

Finally, this group wishes to underscore the limitations of a realtime forecast model. The CME should view the model as a tool for providing statistical or probabilistic guidance, out to 18 or so hours, and avoid relying on it too heavily for detailed guidance (see discussion of model validation below). The model used should probably be configured with a simplified set of parameterizations appropriate for the scales and phenomena being studied. A mix of guidance products (radar, model, surface and upper air data) will be optimal supplements to the model.

## ***II. Data Requirements in Support of Modeling and Prediction***

We recommend that *all* available data be used to define the model's initial state. Techniques to assimilate radial velocity and reflectivity data from WSR-88D systems should be pursued aggressively; however, it is unclear whether single-Doppler techniques (apart from VAD) will be mature enough for use by 1995. The choice of a model for this program should be made carefully, and only after a number of candidate codes have been examined in light of program requirements. The FSL has already performed such an exercise for its FAA-related programs, and this information might prove useful to CME. Most mesoscale models are initialized using analyses based upon NMC gridded fields, perhaps augmented by available profiler and surface net data. The FSL LAPS analysis, by virtue of its combined

data types, represents a possible "melting pot" for observations and thus could serve as the initial state for the mesoscale model to be used.

*This group feels very strongly that moisture is the key to successful prediction, modeling, and data assimilation in support of CME.* In order to provide high-quality and spatially-dense measurements, the group recommends the use of rawinsondes, perhaps a few of which are high quality "reference sondes". Additionally, a few Raman lidars, co-located with the sondes, would provide important ground truth measurements. It was felt that the CASH program could be a critical element of CME, provided that it was in place by the time of the field experiment. Other airlines should be encouraged to participate.

*The importance of obtaining "raw" sonde data cannot be overemphasized.* Through the various stages of data processing, a considerable amount of useful information is discarded from the sondes, including moisture at high levels. Further, the sounding data are sometimes truncated at levels around 200 mb, thus deleting important information. This group strongly urges the CME to make provision for the availability of raw sonde data, and to examine special release strategies to minimize data contamination by nearby storms. In addition, the CME should consider using only one brand of rawinsonde to ensure consistency.

Cloud water/ice were identified as important missing parameters in conventional observations, not only with respect to model initialization, but also for radiation budgets. Although various assimilation schemes might provide decent estimates of this variable, *cloud water and ice might be the Achilles heel of the modeling effort*, particularly with regard to the upper levels, where stratiform clouds play such a major role in radiative processes. Satellite rain retrieval algorithms can provide some information associated with the horizontal distribution of cloud water content, though the vertical distribution is less certain with such methods. Quantitative precipitation measurements were deemed critical for a number of reasons, particularly because soil moisture depends upon an accurate assessment of antecedent precipitation.

### **III. Data Management**

Quite often in field programs, data management receives secondary consideration to science with regard to funding. A number of groups (e.g., FSL, UCAR Unidata) have developed sophisticated database archival systems, and thus the CME should avoid reinventing the wheel in this regard. It is not clear whether all data should be archived at a

single site, or whether multiple sites should be used. This group favors the single site strategy for the following reasons. First, a single large facility (e.g., NCAR) is more likely to be capable of handling large and multiple-type datasets. Second, such facilities have people dedicated to this task, whereas other options (e.g., universities) do not and would likely make data archival a secondary task. Finally, it would probably be easier to ensure consistency of formats and methods of access at a single facility.

*This group strongly urges the CME to put sufficient resources into data management since the effective usefulness of the data collected depends, to a large degree, on the scientist's ability to access it. Given the quantity of data to be collected and generated by the model, data management is a much bigger issue than in previous field programs. We propose a hierarchical strategy that provides a user with quick-look data (e.g., a GIF-formatted image of a few radar display sequences that can be displayed on any X-windows compatible system) as well as complete menu-driven or command-line-interface driven query capability over the NSF internet. The CME should stress the use of common and machine-independent data formats (e.g., netCDF, GRIB, BUFR), and should work with developers (e.g., FSL, NCAR, Unidata) to make available basic workstation software to the user community. We suggest that suspect data be flagged, but not changed, during the quality control process, and reiterate that raw, rather than averaged, raob data be made available.*

## 5. Summary

The Colloquium and Workshop on Multiscale Coupled Modeling was designed to bring together a diverse group of modelers, program managers, and other scientists to address modeling issues of importance to planning for the Cooperative Multiscale Experiment (CME). The primary purpose of the colloquium was to assess the current ability of numerical models to accurately simulate the development and evolution of mesoscale cloud and precipitation systems and their cycling of water substance, energy, and trace species. The primary purpose of the workshop was to make specific recommendations for the improvement of mesoscale models prior to the CME, their coupling with cloud, cumulus ensemble, hydrology, and air chemistry models, and the observational requirements to initialize and verify these models.

*Meteorological programs that could benefit from a multiscale MCS study*

Representatives from six meteorological programs each expressed a potential interest in collaborating together to achieve the unified purposes of the CME. In particular:

- (1) The USWRP will make an effort to synergize with other programs to address the need for conducting a large multiscale experiment, versus the benefits to be gained from more focussed objective experiments. The proposed CME would benefit the USWRP by providing high resolution data for improving forecasting of precipitation and severe weather, the basic understanding of the limits of predictability and the nature of interactions between processes at the mesoscale and at smaller and larger scales, and understanding of the impacts of mesoscale weather events on hydrology. The USWRP recommends conducting OSSE-type experiments to first determine the need for a large number of rawinsondes in such an experiment.
- (2) GCIP would benefit from a cooperative multiscale experiment by providing data for helping to provide closure on regional and mesoscale water and energy budgets, for initializing and verifying high resolution atmospheric models, land surface and convective parameterization schemes, and as input to hydrological models. GCIP is considering providing augmented observations in the form of additional soundings and surface energy budget stations for a 5-7 year period at some of the sites composing the profiler hexagonal array that surrounds the ARM/CART site.
- (3) The focus of GCSS is to develop parameterization schemes for mesoscale cloud systems, including precipitating convectively-driven cloud systems like MCSs, in large-scale models. Observations from field programs that can adequately measure scale interactive aspects are required for comparison with cloud-resolving model simulations.
- (4) The goal of GVap is to improve the understanding of water vapor and its variability on all scales, a goal that would benefit greatly from a multiscale observing strategy. An implementation plan has been developed for a pilot phase, which includes operation of a Water Vapor Reference Station at the ARM/CART site for a continuous period of 3 months in late spring of 1995 and intensive intercomparison of water vapor sensors during part of this period.
- (5) The ARM goals are to provide an experimental test bed for improving the treatment of radiative transfer in GCMs and to improve the parameterization and modeling of cloud formation, maintenance, dissipation, and related processes in GCMs. Some of the scientific issues that are critical to the ARM objectives require intensive measurements on a variety of temporal and physical scales. In addition to the regular measurements at the CART site, a series of intensive observational periods will be performed for short periods as well as participation in any cooperative field campaigns in the region.
- (6) The AWP aims to improve the weather information provided to the aviation community. This program would also benefit from participation in a cooperative multiscale experiment by obtaining data for evaluation of aviation weather forecast products and by making it possible to evaluate the added benefit of enhanced data sets collected during the experiment on those forecast and analysis products.

### *The Cooperative Multiscale Experiment*

The scientific objectives of the CME include increasing the understanding of: (1) how scale-interactive processes generate and maintain MCSs; (2) the relative roles of balanced and unbalanced circulations in MCS dynamics; (3) the predictability of MCSs; (4) the role of MCSs in large-scale atmospheric circulations and the relationship of MCS occurrence to

variations in large-scale flow; (5) what data bases are required to initialize and validate coupled cloud-resolving/mesoscale models, that may be further coupled with hydrological or chemical models; and (6) the optimal use of four-dimensional data assimilation to retrieve cloud and state parameters from remote sensing instrumentation. Bill Cotton's presentation on the CME emphasized the manifold reasons for why a multiscale experiment is required to understand MCSs and their interactions with other scales. The CME scientific steering committee has chosen the central United States as the location for study of mesoscale convective systems, because of a high frequency of MCS activity in the spring and summer months, the ability to transfer research results to the data-sparse tropical environment, and the availability of frequent, high density operational measurement systems in the central U. S. A cooperative experiment is needed, because even though the costs of implementing a multiscale experiment is reduced by the considerable observations already available there, the total additional observing systems needed to provide the necessary multiscale measurements is still quite expensive (\$2-6M). A cooperative program is a wise investment of resources, so it is important that the above six programs join forces to implement such a multiscale experiment. Ideally, running the field experiment from mid-April to mid-August in 1995 would allow sampling both spring storms residing in a rather baroclinic environment and mid-summer storms which reside in a more barotropic, tropical-like environment.

### *Grand scientific challenges*

Steve Koch highlighted differences between past convective field experiments and the present opportunity for a truly multiscale field experiment. Most convective field experiments in the past have attempted to resolve only the immediate scales of moist convection using network arrays that spanned two or three atmospheric scales at most, which has precluded a description of the entire life cycle of MCSs and their interaction with larger scale systems, the land surface, and trace species. Fortunately, observational, computer, and data assimilation advances now make it possible to simulate scale contraction processes from the synoptic scale down to the cloud scale, and interactions between complex meteorological, land surface, precipitation, chemical, and hydrologic processes with coupled, multiscale models. Thus, the time is finally right from a technical and observational perspective to conduct a multiscale, multi-disciplinary field experiment focused on the mesoscale convection problem. Since numerical models now have the capability to explicitly resolve mesoscale gravity waves, slantwise convection resulting from conditional symmetric instability, density current-like microstructures at the leading edge of cold fronts, mesoscale tropopause folds, detailed land surface characteristics, and many other

features which are inherently scale-interactive, it is extremely important to muster all the scientific forces which have an interest in these problems to develop a multiscale field experiment that contains meaningful meteorological, hydrological, and chemical observing and modeling elements.

### *Data assimilation and model initialization techniques*

This session covered both current-generation approaches (intermittent and continuous data assimilation, and physical initialization) and next-generation (variational, adjoint) techniques. A major issue concerns precipitation data assimilation, in that there are serious problems in both assimilating techniques and the sources of hydrologic data. *The quality and interpretation of indirectly measured hydrologic cycle data need to be improved*, in conjunction with the development of techniques to retrieve hydrometeors, which are needed to infer latent heating profiles from satellites and WSR-88D radars. In addition, techniques need to be developed to insert information about fluxes, transports, and other process rates (e.g., evapotranspiration, rainfall rates, and TOA radiative fluxes) into analyses in a consistent fashion.

At the convective scale, since the primary observing tool will be Doppler radars, the key issue is the determination of initial conditions for all model variables from measurements of radial velocity and reflectivity in combination with other larger-scale data. Many questions remain on the types of data needed, the spatial density and temporal frequency required and the amount of error the techniques will tolerate. Much work remains to incorporate adjoint methods into a data assimilation system for real time prediction of storm-scale flows. Specification of the initial conditions in regions where no radar data are available remains an unsolved problem. The use of multi-parameter radar to initialize microphysical processes in coupled models should be investigated further.

Critical areas for research with variational (or Kalman filter) approaches to data assimilation include the needs to treat discontinuous processes (e.g., cumulus convection), reduce the huge computational requirements, and obtain meso- and cloud-scale error covariance statistics (*which can only be obtained from multiscale measurements*). Nudging approaches that employ variational techniques to define relaxation coefficients need to be further developed and tested to determine their usefulness in mesoscale models.

### *Measurement and modeling of moist processes*

Excellent results have been obtained with coupled meso/cloudscale models when simulating squall line or other convective systems that are strongly forced by fronts or other lifting mechanisms. Less highly forced systems are difficult to model, particularly in nearly barotropic environments. In such cases, accurate predictions of MCSs may require: details about soil moisture, vegetation, outflow boundaries, and gravity waves triggered by earlier convection; either improved cumulus parameterization schemes or explicit simulation of deep convection over large domains; and increased upper air sampling to capture weak short-waves and jet streaks.

*Knowledge of the three-dimensional mesoscale structure of the moisture field at frequent time intervals was echoed by this group, in addition to most of the other groups at the workshop, as the most crucial required measurement for CME. Concerning the measurement of water vapor, cloudy conditions compromise the measurements of most remote sensing systems, although use can be made of satellite cloud classification schemes to provide three-dimensional relative humidity fields in cloudy conditions. MCS measurement strategies must extend well beyond the "visible" cloud boundaries, and must not be limited to the dynamically active stages of MCSs, but also include observations of "fossil" MCS residue. In fact, all the important sources and sinks of moisture associated with MCS genesis and evolution (e.g., large-scale advection, evapotranspiration, precipitation) must be identified in three dimensions and with sufficient temporal resolution to be useful for developing, improving, and verifying sub-grid scale parameterization schemes. Additional needs exist to: couple aerosol and cloud microphysics models, obtain measurements of aerosols and hydrometeor spectra for radiation calculations, and provide soundings over the eastern Pacific to identify subtropical jets and jet streaks entering the southwest and impacting the MCS genesis region. An urgent need exists to integrate satellite, surface and radiosonde data to provide mesoscale analysis of moisture required for further development and validation of coupled multiscale models. Hydrological cycle improvements are critically needed to not only produce accurate precipitation in all kinds of situations, but also to transport moisture vertically and to improve upon model treatments of clouds as they relate to the radiative budgets by using explicit prediction of condensate fields and knowledge in the initial state of the models of the cloud bases, tops, and optical properties.*

### ***Parameterization of sub-grid scale convection***

The relative importance of convective heat and moisture processes is scale-dependent: whereas in climate models it is crucial that the parameterization predict the proper



evolution of the moisture field, at the mesoscale it becomes extremely important to predict the location and rate of convective latent heat release, as the evolution of mesoscale systems is highly dependent upon the diabatic heating. Most current cumulus parameterizations do not appear to be valid when applied on grid meshes smaller than about 20 km, but when the grid mesh becomes greater than about 2 km, explicit moisture schemes tend to produce unrealistically large vertical drafts. Research is needed to determine the best methods of simulating convection for grid meshes between 2 - 20 km. There are *no existing data sets* with sufficient temporal and spatial resolution to verify closure hypotheses contained in cumulus parameterization schemes. The data must be able to separate the convective response to grid-scale changes from the grid-scale response to convection. This will require very high temporal resolution data over multiple scales to analyze complex interactions between clouds and the mass field, as well as in-situ measurements of thermodynamic properties and hydrometeors. Rather than direct tests between existing parameterizations, what is needed is to isolate the major assumptions used in each scheme and test these assumptions within carefully controlled experiments in which all other components of the scheme are similar.

Effects of the moisture field on convection and vice-versa need to be better understood. Further research is needed to develop cumulus parameterization approaches that predict convection in terms of the physical processes that directly cause clouds to form. In addition, development of MCS momentum-exchange parameterization techniques is badly needed, particularly for climate models and other coarse-grid models. However, the *most critical process that needs to be determined to improve cumulus parameterizations is the rapid interaction between the clouds and the mass field on meso-beta through synoptic scales.* The best way to infer these interactions is by observing the divergent component of the winds. It should be possible to use wind profilers to interpolate in time between rawinsonde sampling times. In addition, high temporal and spatial resolution measurements of the three-dimensional atmospheric winds on the scale of 2-20 km need to be obtained using doppler radar. *Convection is much more of a multi-scale phenomenon than is commonly realized; experiments that have focused only on the structure of individual clouds or MCSs have not been able to resolve the nature of the processes that cause convection or to document the complete effects of convection upon larger scales.*

### ***Coupled land surface/hydrologic/atmospheric models***

*Evapotranspiration modeling presents the most serious challenge in these coupled models, because of its complexity, yet its importance to the development of convection.*

Soil-water content is the single most important land-surface variable in atmospheric prediction models. There is *a critical need for time-series measurements of soil moisture profiles* to complement other mesoscale data, particularly in the dryline-prone regions of the High Plains contained within the CME enhanced observational area. Explicit modeling of the fully interactive relationship between the heterogeneous surface, boundary layer and clouds can lead to more accurate predictions of cloud onset and amount over land surfaces. The CME presents opportunities to expand upon our present inadequate knowledge of mesoscale circulations forced by inhomogeneous land surface characteristics, and to develop approaches for parameterizing their effects in mesoscale and larger-scale models. The linkage between boundary-layer thermals and the characteristics of the underlying surface also should be investigated in CME. The influence of spatially coherent fluxes that result from landscape heterogeneity are not included in current models. Fortunately, valuable representations of several aspects of the landscape pattern currently exist, including digital elevation data and measures of the leaf area index (i.e., NDVI from AVHRR data). *A major deficiency*, however, is the lack of an ability to sample spatially representative shallow and (especially) deep soil moisture. Numerous mesoscale modeling and observational studies have demonstrated the sensitivity of planetary boundary layer structure and deep cumulonimbus convection to the magnitude of the surface moisture flux.

Latent heat, sensible heat and net radiative fluxes are needed at enough sites to characterize means and variability in order to scale up from the hydrology catchment scale to the MCS scale. It was recommended that high-resolution OSSEs should be conducted to examine sensitivity of the atmosphere to the quality, distribution, and sampling of various land surface and vegetation parameters prior to CME. Specific measurements that may be needed include vegetation cover, soil characteristics, and terrain data on 1 km scales, recording and archiving of WSR-88D data, automated soil moisture profiles by neutron probe, dual ground based Doppler lidar to characterize boundaries, and new types of measurement platforms for economical boundary layer measurements such as instrumented radio-controlled aircraft. The CME planning committee should also incorporate satellite remote sensing technologies, especially FIFE results, into the project design and operation.

There is a need to permit two-way interactions between the atmosphere, and biophysical and hydrologic processes. This feedback is essential in order to properly represent the control on transpiration of water into the boundary layer environment. These interactions point to the necessity for interdisciplinary activities in the CME. Involvement by the hydrology, ecology, and chemistry communities would be mutually

beneficial. For example, since stomatal conductance of water is directly related to carbon dioxide fluxes, these models must also influence dry deposition of other chemical species, particularly hygroscopic aerosols and gases. Likewise, meteorological models require knowledge of soil hydraulic properties for input to surface layer parameterizations. Correspondingly, an accurate characterization of precipitation, evapotranspiration, and landscape structure is necessary for input to hydrology models. A similar relationship exists with the ecological modeling community. Atmospheric models are strongly affected by vegetation processes, while the ecological community needs atmospheric information to properly simulate soil and vegetation biophysics (e.g., the soil carbon budget).

### *Incorporation of the planetary boundary layer in atmospheric models*

The planetary boundary layer (PBL) plays a crucial role in coupled mesoscale systems, because of its importance in transporting momentum, heat, and moisture from the surface into the systems. Despite major progress over the last two decades in modeling the PBL, *very little is known about the influence of mesoscale variability on PBL and turbulence statistics*, since the parameterization of boundary layer processes for use in larger scale models has been based almost exclusively on observations collected for horizontally homogeneous surface conditions under simple, slowly time-varying synoptic weather conditions.

Another issue concerns how cumulus-induced subgrid-scale effects should be included. Mesoscale cloud systems strongly modify the underlying PBL structures due to the effects of detraining cumulus downdrafts, cumulus-induced subsidence, cloud cover modulation of radiation inputs into the PBL, and rain evaporation. Since these modifications often change the subsequent mesoscale system development, it is important to incorporate these modifications into PBL parameterizations. For example, it is not clear how to incorporate the formation and dissipation of PBL stratiform clouds in models, yet frontal systems are typically associated with such clouds. Often too thin to be resolved in the vertical grid, these stratiform clouds need to be included in the PBL parameterization. Stratus-type clouds and their effects on mesoscale systems are deserving of much study, since not only do these clouds play an important role in the climate-radiation budget, but they may also be important for the development of mesoscale frontal system circulations. A stratus-topped PBL is much more complicated and less understood than clear PBLs, because its structure is strongly affected by many additional physical processes.

In order to better understand the underlying PBL effects on MCSs, we need to learn first how the PBL structure evolves along with the overlying convection and how it varies spatially within the system. For this purpose, *we need to design field experiments that can simultaneously measure the PBL and the overlying convection.* This may require using aircraft, acoustic sounders, wind profilers, lidars, and radars simultaneously. *The use of chemical species as tracers* in observing the transport properties of PBL turbulence and clouds was highly recommended. Before the CME takes place, we need to gather information on what prior field experiments have and have not learned.

Funds should be provided not only for carrying out field programs, but also for their design and for the analysis of their data. *Formation of a working group to evaluate and develop PBL models in the mesoscale context would be highly beneficial to CME.* Although large-eddy simulations (LES) should play a major part in such an evaluation, the LES database is limited to horizontally homogeneous PBL types. We must depend on observations for more complicated PBL cases. We may also want to apply this evaluation process to coupled land process-PBL models, coupled cumulus parameterization-PBL models, and coupled air chemistry-PBL models.

#### *The role of radiation in mesoscale flows: physics, parameterizations, codes*

It is vitally important to expand our basic knowledge of how MCSs influence climate through their extensive cloud shields and increase of humidity in the upper troposphere. In order to accomplish this task, it will be necessary to improve radiation parameterizations used in mesoscale and GCM models. One of the most critical problems facing modelers presently is that no consistent radiation-microphysical coupling exists in current mesoscale radiative transfer schemes. *It will be extremely helpful to develop and validate a community radiative transfer code suitable for use with mesoscale models, and to establish an intercomparison project to isolate and understand radiative processes in mesoscale models.*

Equally important is the need to improve our understanding of the influence of radiation and cloud microphysical properties on MCS dynamics due to diabatic heating, production of condensate, and vertical and horizontal heat fluxes. Observational requirements concern the needs to determine MCS related cloud optical properties, such as optical thickness, their morphology, and microphysical composition. It should be a *major* scientific objective of CME to provide observations to establish the radiative budgets of different kinds of MCSs *throughout* their entire life cycle. It is also essential to consider

how to convincingly present results from mesoscale models and field studies in their more global climate context, and how experiences in other radiation and climate related projects (ARM, FIRE, etc.) could contribute to the design of the CME field project.

### *Chemistry on the mesoscale: modeling and measurement issues*

This session reviewed the current knowledge and research needs for chemistry on the meso and cloud scales. First, tropospheric ozone is a multiscale problem (urban, regional, global). Treatments of surface and boundary layer processes (including natural HC emissions from vegetation) and cloud venting are required for understanding the production and distribution of ozone in the troposphere. Uncertainties that exist in many modules of regional and cloud-scale chemical models could be reduced by incorporating chemical measurements and modeling into the CME. Conversely, the use of chemical tracers in a CME can help define air motions on both cloud and mesoscale. A major model limitation is that deposition of trace gases to the surface and emission of other species from the soil and from vegetation need to be better specified in the models. In addition, the simulated diurnal variation of the boundary layer depth needs to better follow observations. Cloud microphysical schemes and treatment of radiational characteristics within and surrounding a cloud remain the largest uncertainties of cloud-scale models. When photochemical models are run in conjunction with cloud models, there are large uncertainties in the photolysis rates within and above the cloud. *These models are limited by a lack of observational data to verify convective transport of ozone precursor gases and subsequent ozone production.* In particular, confirmation of the predicted magnitudes of cloud outflow and downstream photochemical ozone production is needed in a concerted chemical-mesoscale field program. Also needed is *vastly* improved information on the role of cloud microphysical processes in chemical scavenging and the role of lightning in NO formation.

Specific observational requirements consist, first of all, of the need to supplement surface hydrology and meteorology field studies in CME with chemical flux measurements to enhance the data base for deposition and emissions for use in regional modeling. Fluxes of CO<sub>2</sub>, O<sub>3</sub>, NO<sub>x</sub>, and NO<sub>y</sub> should be measured in conjunction with fluxes of sensible heat, latent heat, soil heat, as well as albedo and vegetation characteristics. Profiles of these species should be measured simultaneously with those of temperature, humidity, and winds. Scale issues should be addressed over heterogeneous land use and terrain. Using measurements of chemical species concentrations as passive tracers in the vicinity of convective storms, it is possible to directly assess the dynamic exchange of air within an

atmospheric column. This group proposed that carbon monoxide and ozone budgets be defined and used to assess the vertical exchange of air during conditionally unstable conditions. *These chemical measurements will provide a valuable additional set of observations that can be used to assess the performance of cumulus parameterization schemes.* Furthermore, inert tracers like SF<sub>6</sub> and perfluorocarbons can be released by aircraft, both above and within the mixed layer, during episodes of deep, penetrative cumulus convection to determine the overall transport due to an ensemble of nonprecipitating cumuli. Concerning the need to determine the degree of deep convective enhancement of ozone production, the CME must acquire sufficient data over thousands of square kilometers with a ground-based network of soundings, profilers, at least two Doppler radars and aircraft flying in and near convective cells. Characterization of the chemical environment can be done with two aircraft and minimal surface instrumentation; however, a third aircraft with limited chemical instrumentation is strongly preferable.

### *Validation of mesoscale models*

Recent numerical simulation of ocean cyclones and mesoscale convective systems using nonhydrostatic coupled cloud/mesoscale models with a grid size as small as 2-km have demonstrated the potential of these models for predicting MCSs, squall lines, hurricane rainbands, mesoscale gravity waves, and mesoscale frontal structures embedded within an extratropical cyclone. Although these models have demonstrated strong potential for use in operational forecasting, very limited quantitative evaluation (and verification) of the models has been performed. As a result, the accuracy, the systematic biases, and the useful forecast limits have not been properly defined for these models. It has been shown that systematic errors in predicted synoptic-scale fields adversely affect a model's ability to predict MCSs. No serious attempts have yet been made to use such models for operational prediction of mesoscale convective systems.

*The key element in verifying mesoscale forecasts is the availability of mesoscale observations.* In order to perform a comprehensive verification of mesoscale prediction, high quality "assimilated fields" are needed. Therefore, it is *essential* to develop a "state-of-the-art" mesoscale data assimilation system to produce IIIb analysis for CME, with a horizontal resolution of ~10 km. Broad rawinsonde coverage at a variety of scales is needed if we are to capture the genesis, development and dissipation stages of the MCS. This is *essential* if we are going to advance cloud/mesoscale models for predicting the initiation and organization of mesoscale convective systems. High resolution, high quality moisture measurements (including precipitation) are required to validate model hydrological

processes. Finally, *comprehensive dual Doppler radar coverage is required to validate couple meso/cloudscale model simulations of MCS circulations.* The scientific steering committee for CME should also consider collaborating with the COMPARE project by providing a set of scientific hypotheses to be verified by coordinated numerical experimentation using data and analyses drawn from a CME event.

### ***Techniques and resources for storm-scale numerical weather prediction***

*This group recommended that the CME define a model (s) to be used for both real-time forecast assistance in the field operations, as well as for assimilating the observations and to evaluate the model's predictive capabilities.* The choice should be carefully made, with consideration given to model capabilities, efficiency, flexibility, and appropriateness for the CME mission. The model should probably be configured with a simplified set of parameterizations appropriate for the scales and phenomena being studied. The CME also needs to determine which groups will bear the responsibility of providing special computing facilities to support model execution and output archival.

Other principal unknowns at this point concern data, initialization methods, validation techniques, computing facilities, and data storage and display strategies. It will be necessary to assess the need for upgraded telecommunications capabilities. In order for the model to be effective in realtime, appropriate data displays must be available. The CME should explore the accomplishments of various groups in this area. *The use of adaptive grids was strongly endorsed in the realtime prediction support,* though the role of adaptive grids in creating the assimilated datasets for post-analysis is not so strongly advocated. CME should encourage groups to re-evaluate the state-of-the-art in adaptive refinement at various times prior to the field experiment.

*This group felt very strongly that moisture is the key to successful prediction, modeling, and data assimilation in support of CME.* In order to provide high-quality and spatially-dense measurements, the group recommends the use of rawinsondes, perhaps a few of which are high quality "reference sondes". Additionally, a few Raman lidars, co-located with the sondes, would provide important ground truth measurements. It was felt that the CASH program could be a critical element of CME, provided that it was in place by the time of the field experiment. The CME should make provision for the availability of raw sonde data, and examine special release strategies to minimize data contamination by nearby storms. In addition, only one brand of rawinsonde should be used to ensure consistency. *Cloud water/ice were identified as important missing parameters in*

conventional observations, not only with respect to model initialization, but also for radiation budgets. Although various assimilation schemes might provide decent estimates of this variable, it might be the Achilles heel of the modeling effort, particularly with regard to the upper levels, where stratiform clouds play such a major role in radiative processes.

Finally, from both political and scientific viewpoints, it would be wise to emphasize linkages between CME and climate. For example, medium-range prediction experiments could be conducted to assess the impact on their accuracy of CME data. Further, the CME data could be used to validate parameterizations used in global models, and to make assessments regarding the impact of orphan MCS cloud residue on medium- and long-term predictions and climate change. Finally, most cloud-impact climate studies have been focused on the tropics, where the moisture content at mid- and upper-levels is a key element in cloud-radiative forcing. The CME could uniquely provide information on moisture transports from the tropics to mid-latitudes, with emphasis on global responses.



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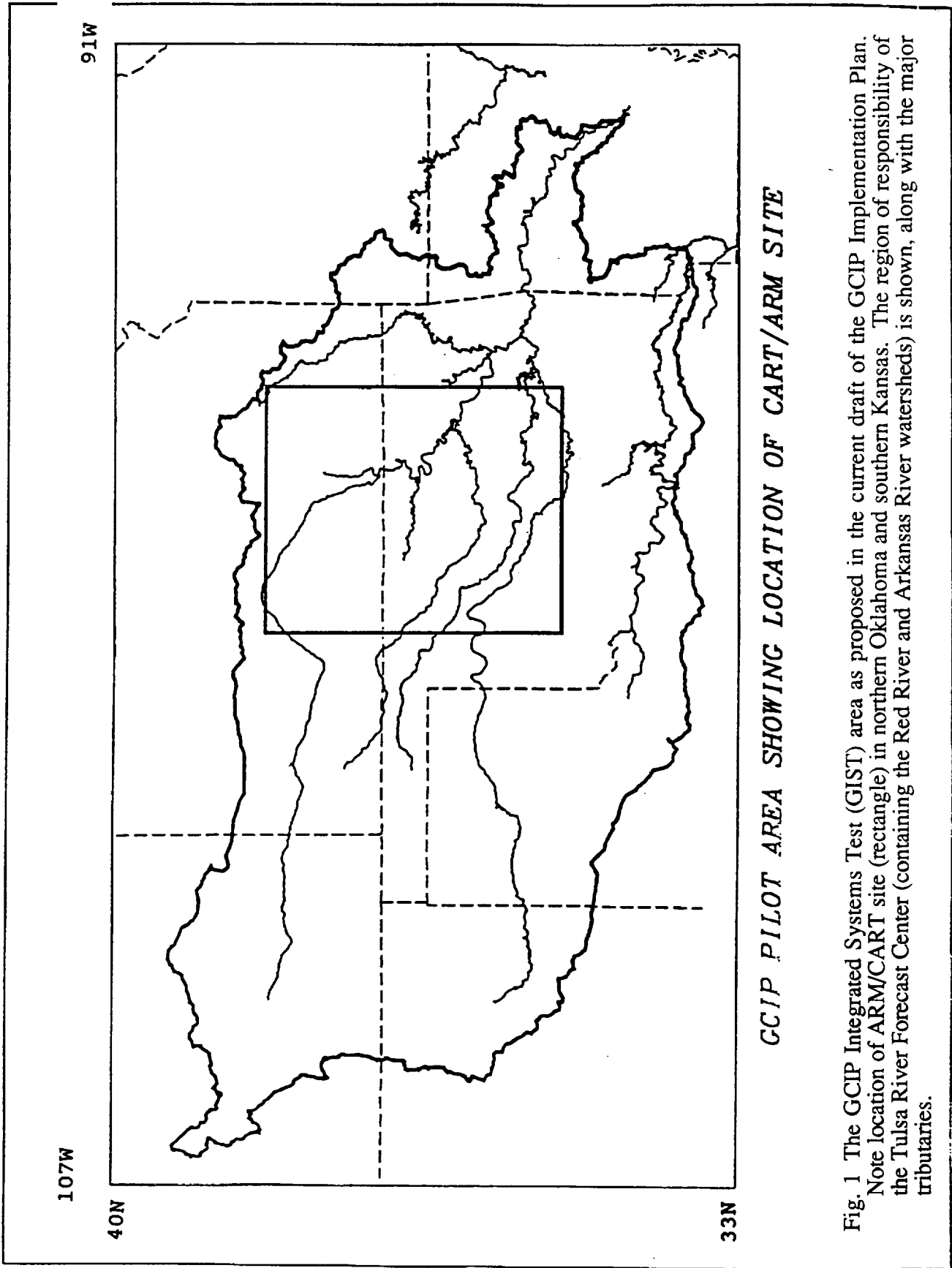
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*GCIIP PILOT AREA SHOWING LOCATION OF CART/ARM SITE*

Fig. 1 The GCIIP Integrated Systems Test (GIST) area as proposed in the current draft of the GCIIP Implementation Plan. Note location of ARM/CART site (rectangle) in northern Oklahoma and southern Kansas. The region of responsibility of the Tulsa River Forecast Center (containing the Red River and Arkansas River watersheds) is shown, along with the major tributaries.

# GCIP MEASUREMENT SUPPORT

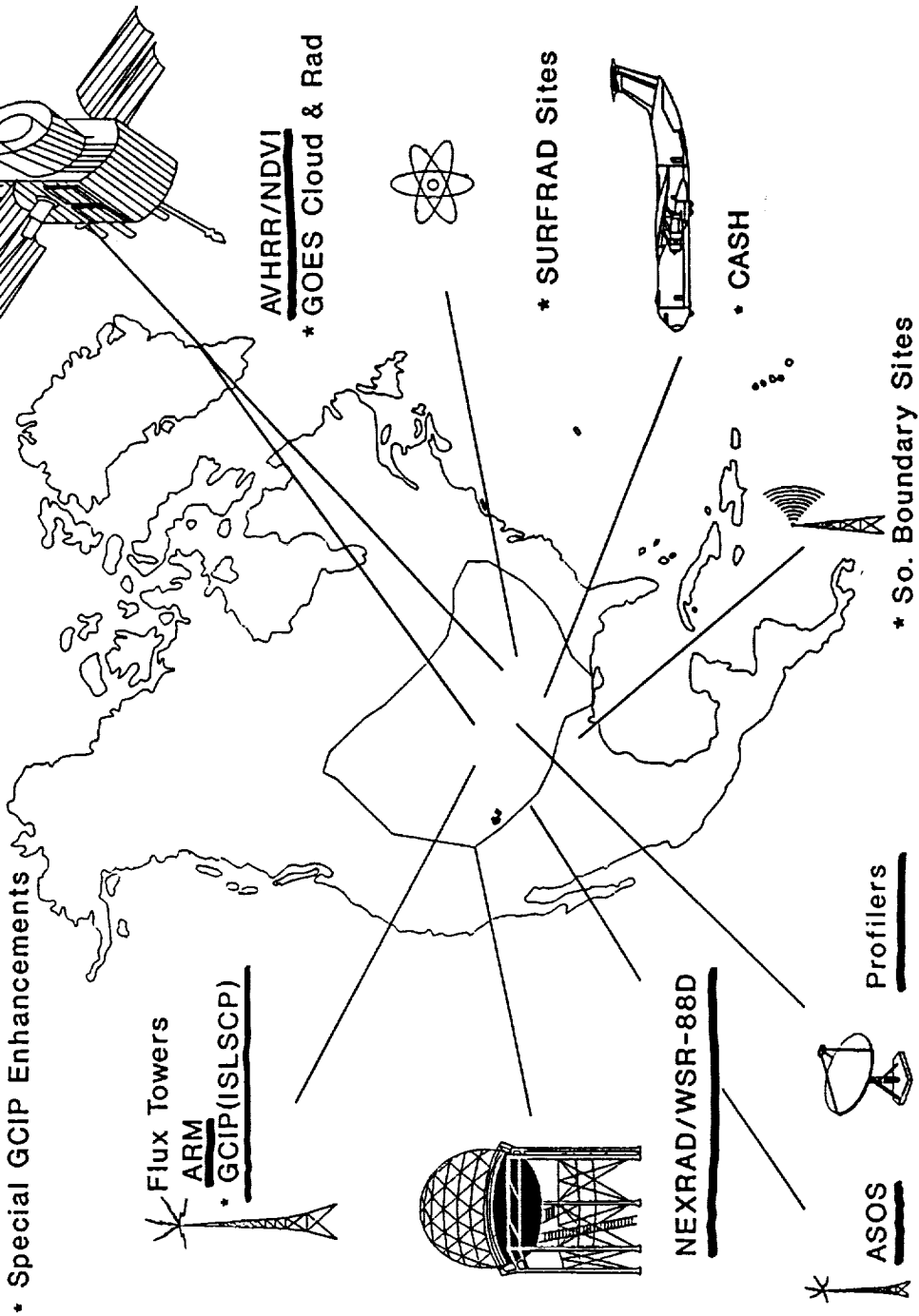


Fig. 2 The GCIP supporting measurement systems within the GCIP observing region (the Mississippi River Basin). Currently proposed augmentations to the nation's present or planned observing systems are noted with an asterisk (\*), and include a network of 10-15 radiative flux towers (some of which may be located in the inner "hexagon" of wind profilers), boundary layer wind profilers located along the southern boundary of the U.S. and perhaps in the wind profiler hexagonal network, additional soundings at the "hexagon" sites, surface energy balance (SURFRAD) sites, and new cloud products derived from satellites and ASOS, and calibrated with the SURFRAD data.



# CONTRIBUTION OF PRINCIPAL PROGRAMS TO GCSS

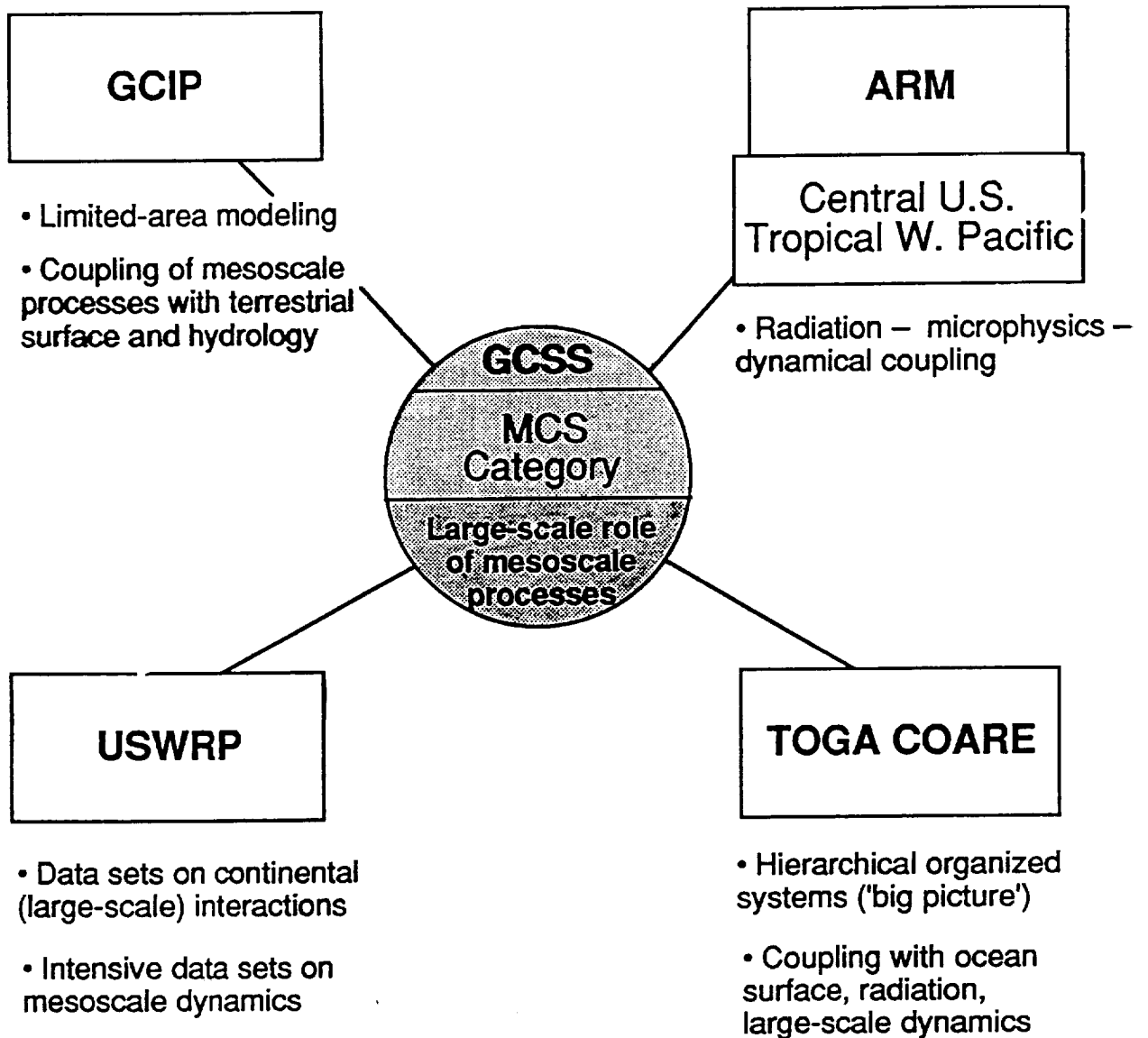


Fig. 3 The relationship of GCSS to other principal programs.

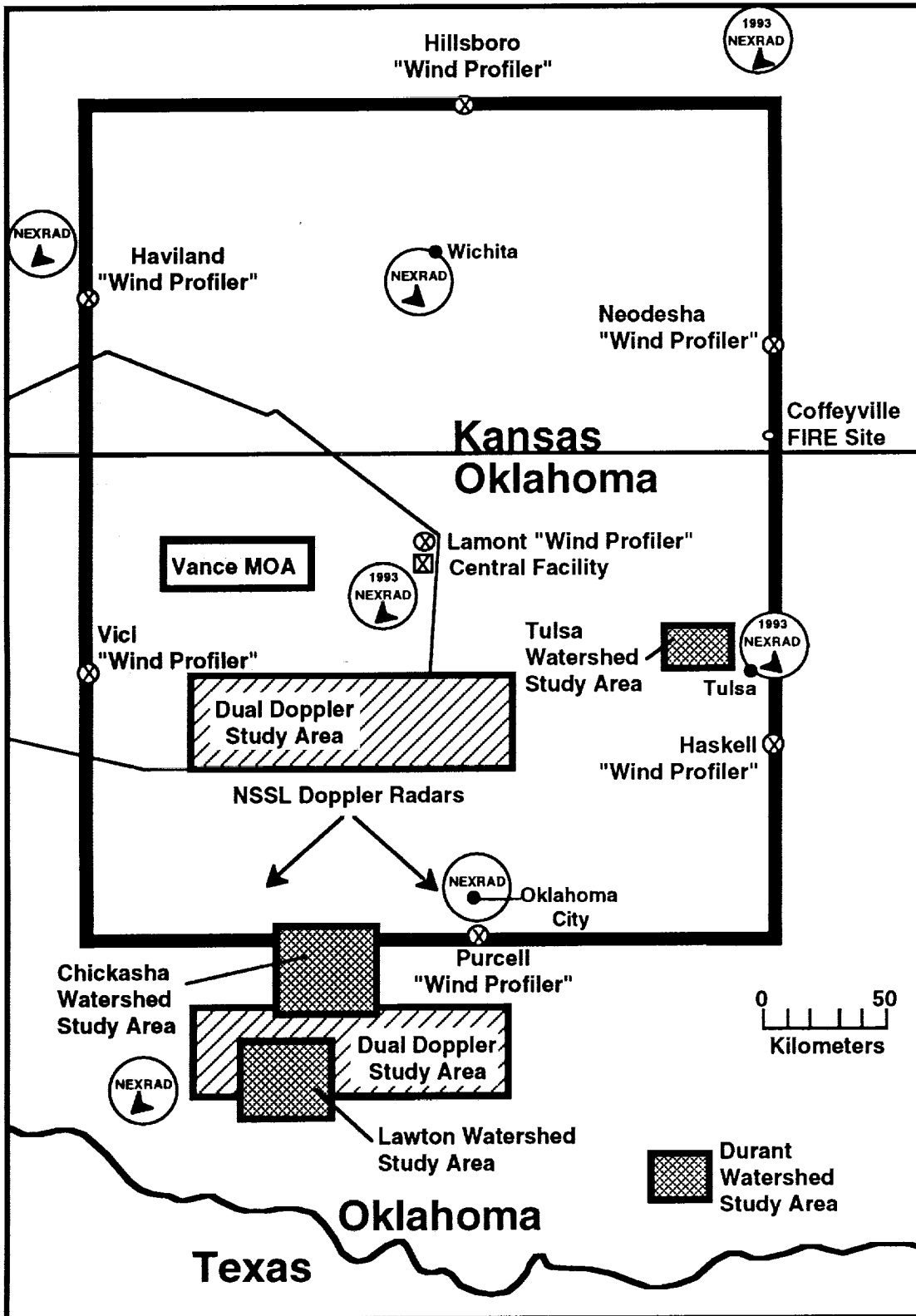


Fig. 4 The ARM/CART site and its relationship to other nearby observing systems, including the NEXRAD facilities, the inner hexagon of wind profilers, various watersheds, and the National Severe Storms Laboratory dual Doppler radars.

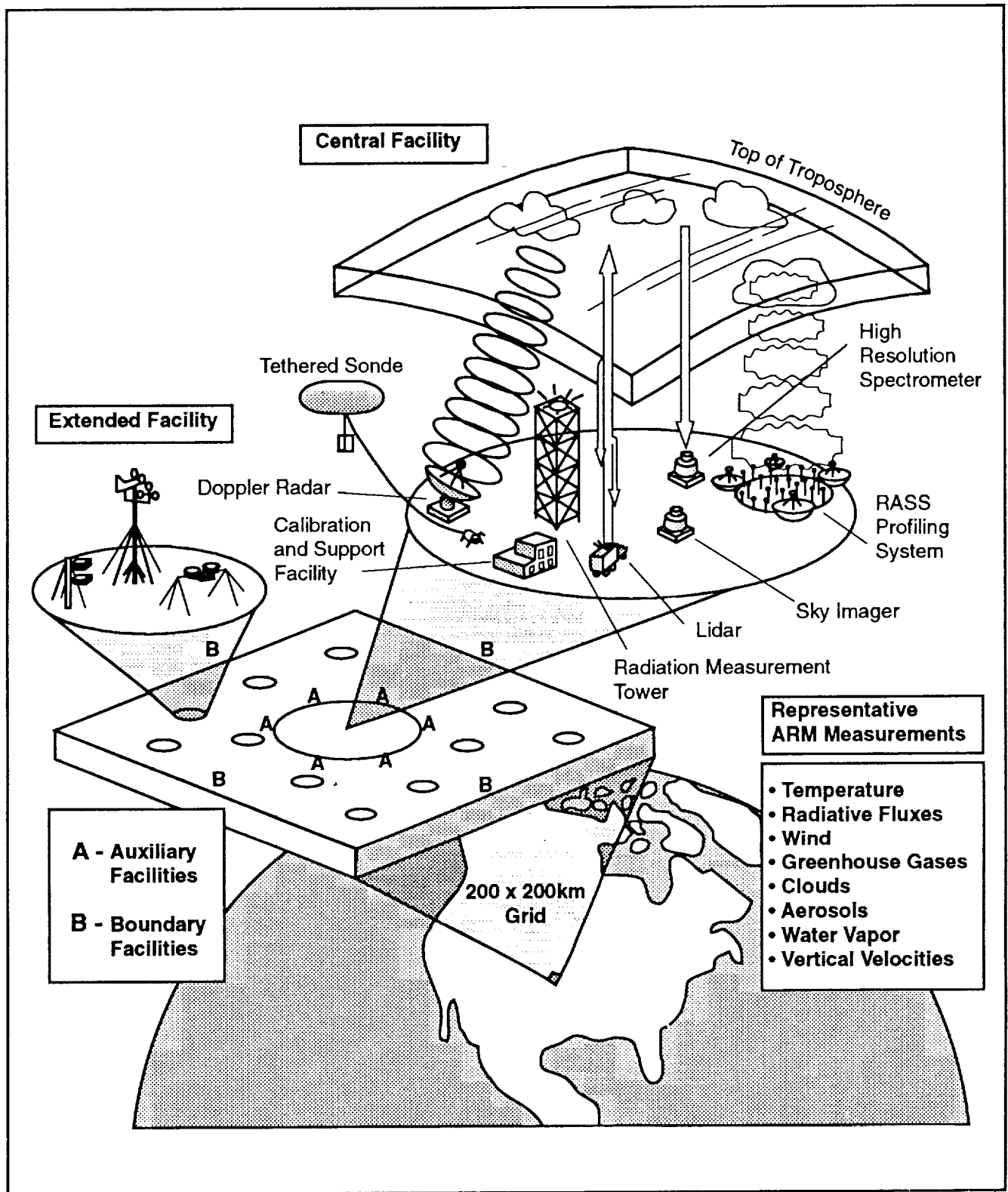


Fig. 5 The sensor components of the CART central facility and extended (auxiliary and boundary) facilities.

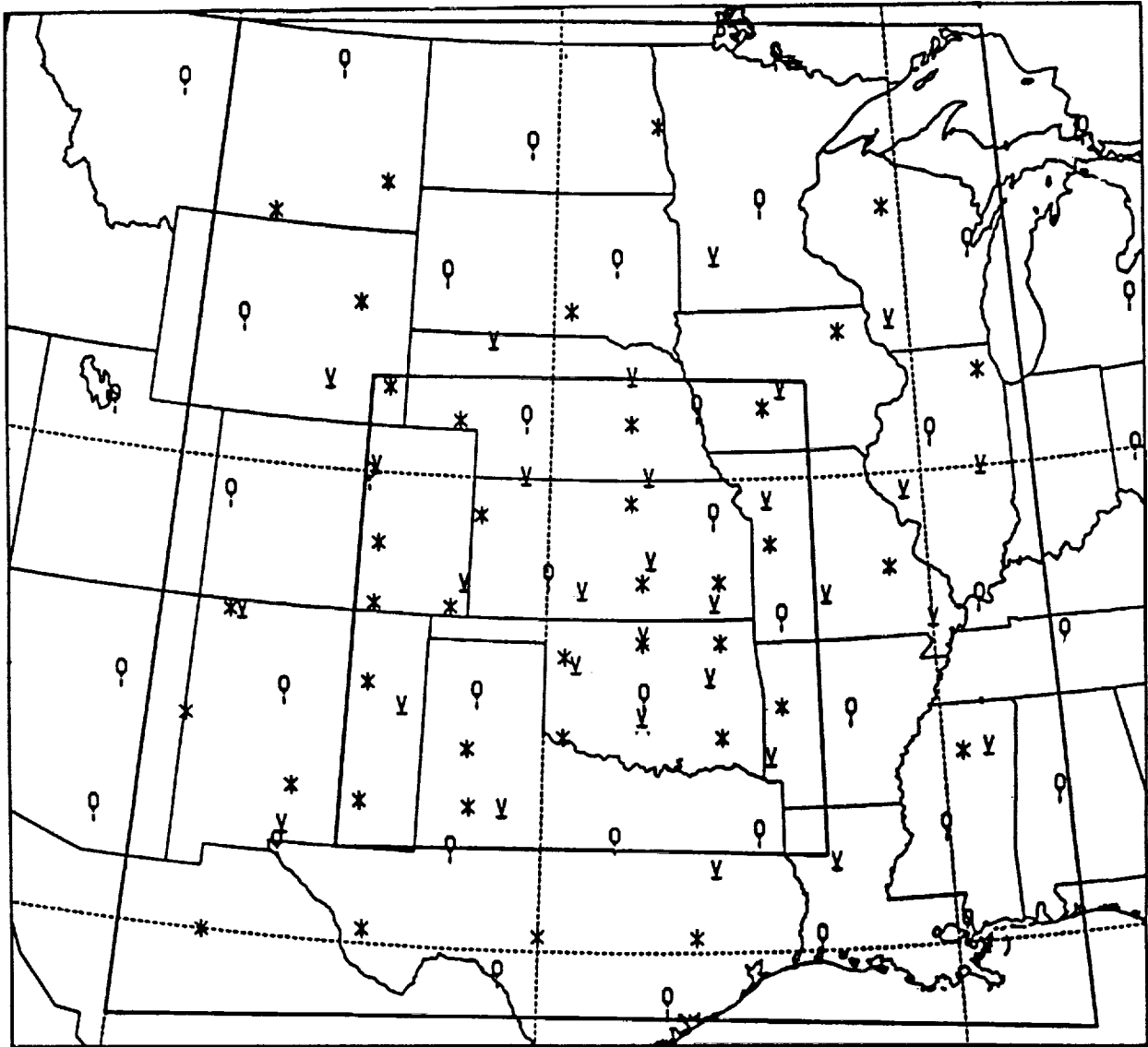


Fig. 6 The meso-alpha and meso-beta scale National Weather Service and supplemental sounding sites proposed for the Cooperative Multiscale Experiment.

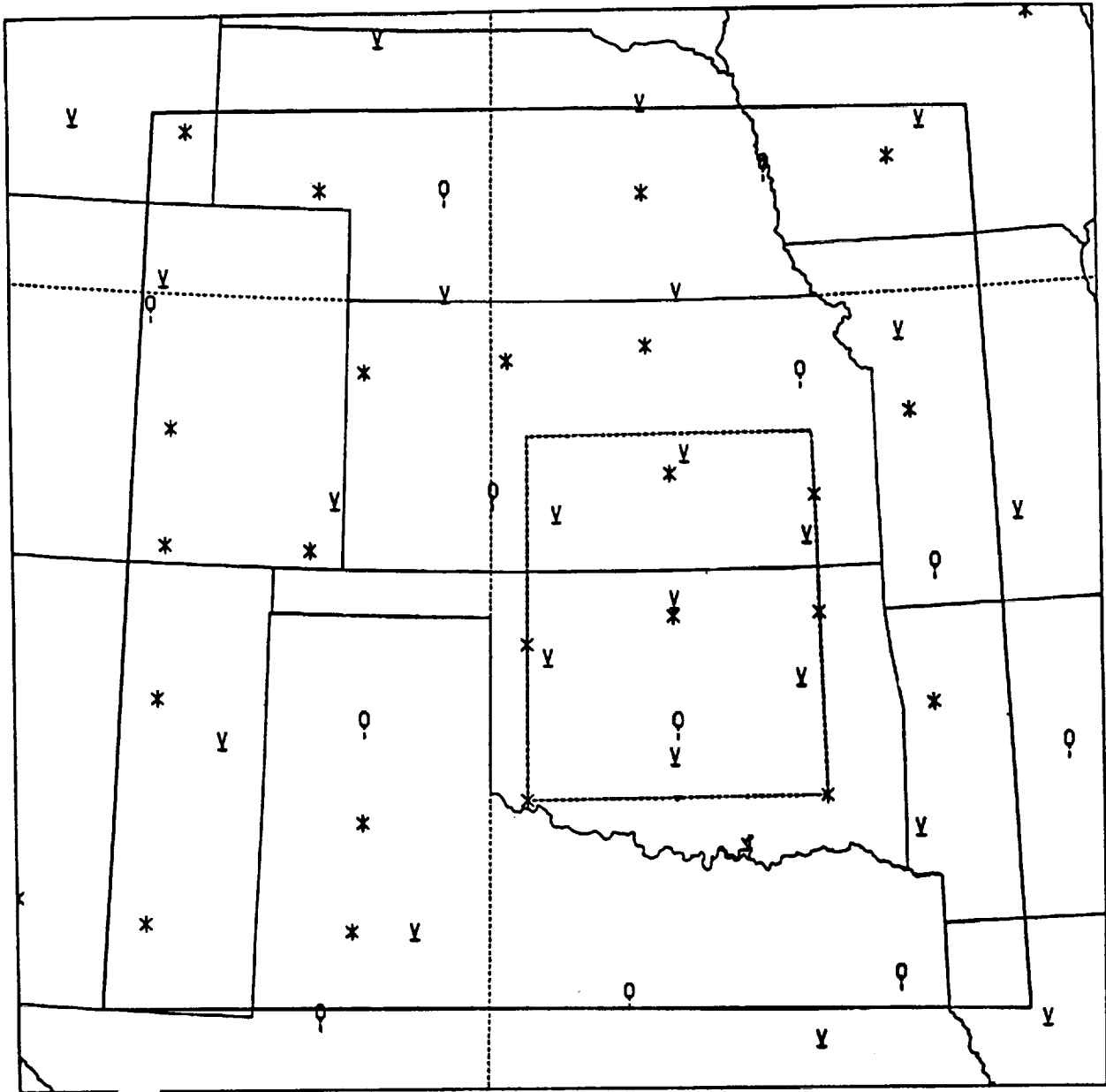


Fig. 7 The meso-beta scale National Weather Service (0) and supplemental (\*) sounding sites proposed for the Cooperative Multiscale Experiment. Also shown are the Demonstration Wind Profiler locations and the ARM/CART site.

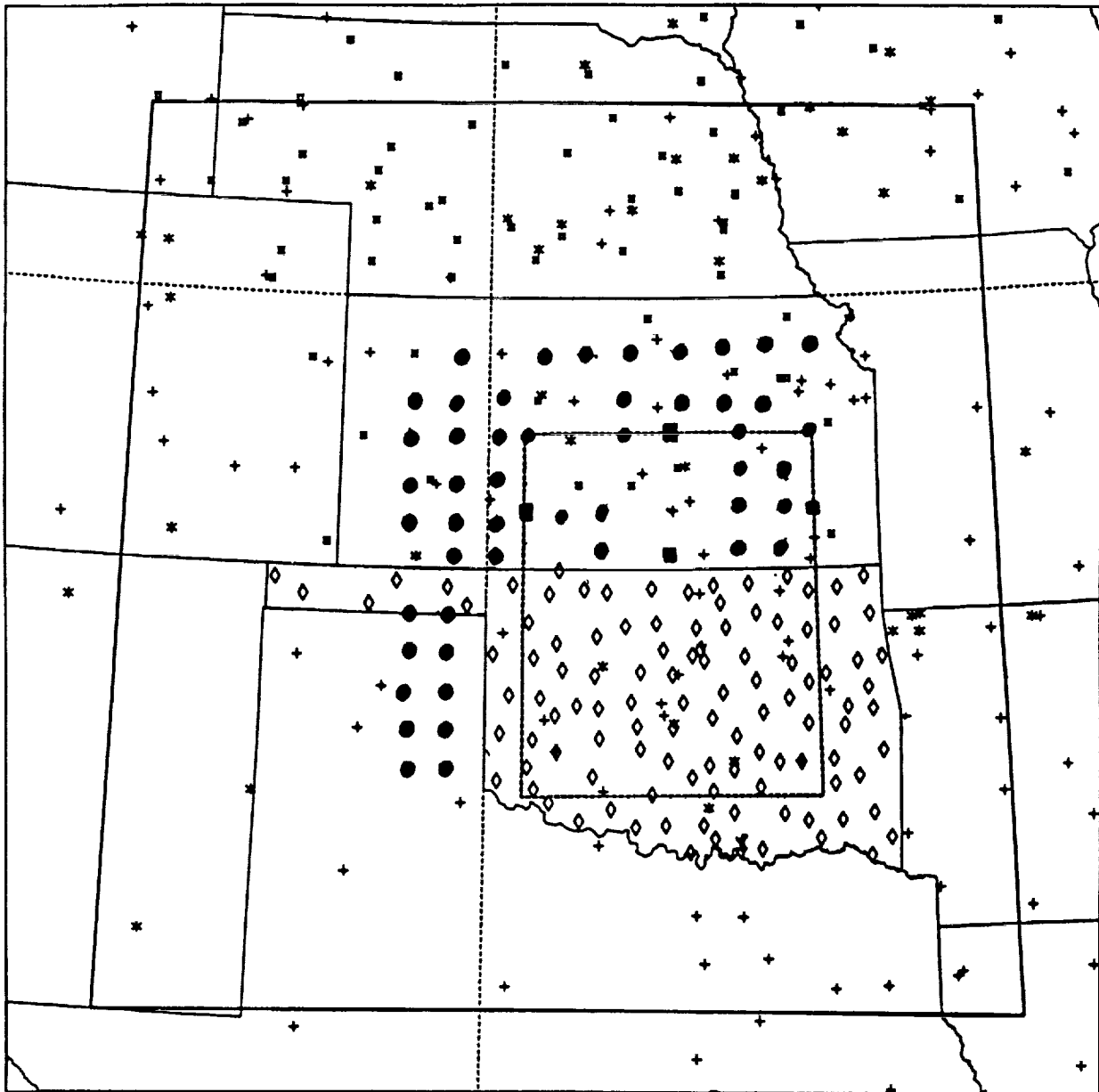


Fig. 8 The surface networks proposed for the Cooperative Multiscale Experiment, consisting of proposed PAM II sites (dots), and expected ASOS (+), AWOS (\*), High Plains Cooperative Network (small boxes), and Oklahoma mesonetwork (diamond) sites.

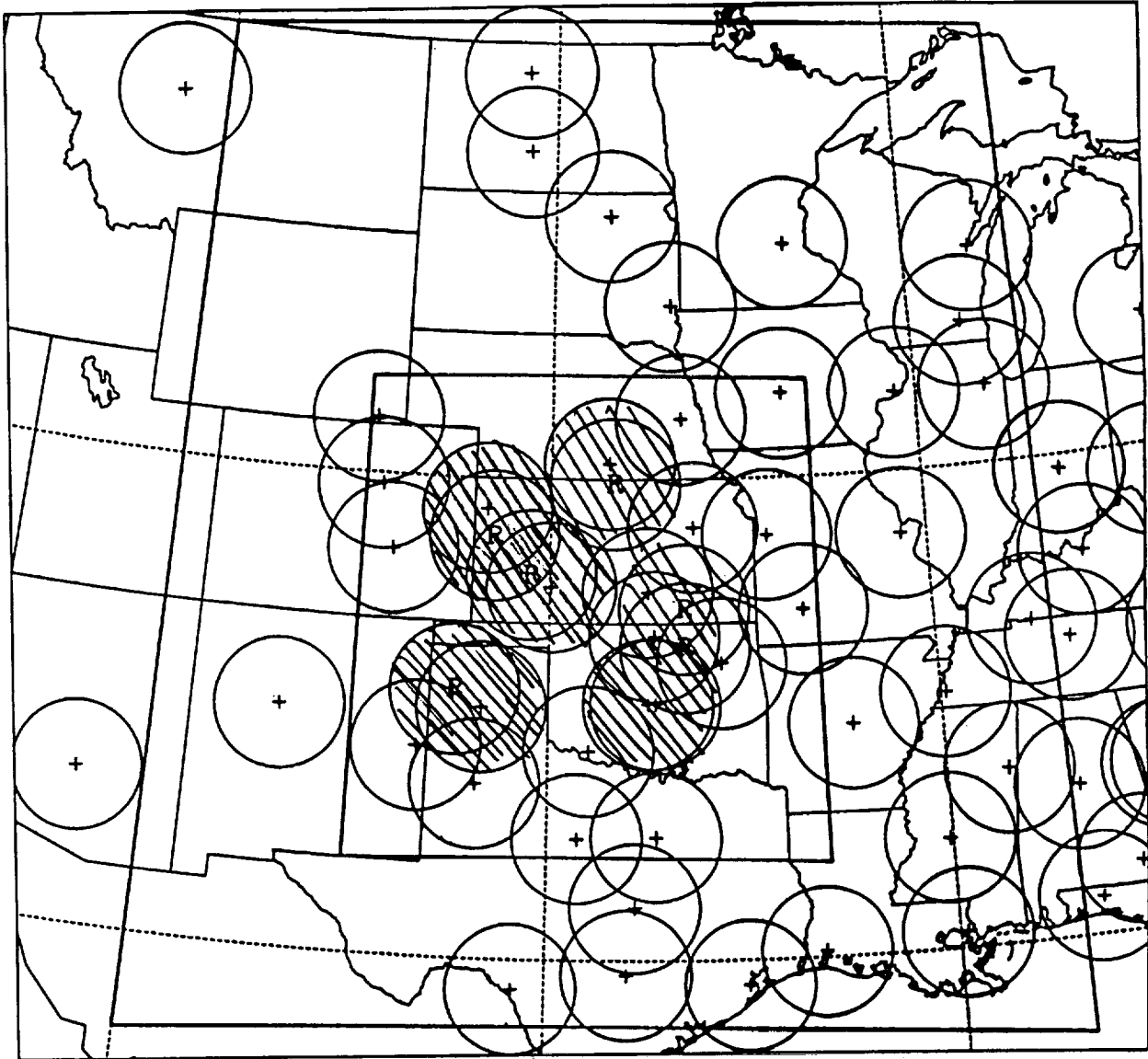


Fig. 9 The NEXRAD radar sites (open circles) and proposed research Doppler radar sites (hatched circles) proposed for the Cooperative Multiscale Experiment. Range circles are 100 km radius.

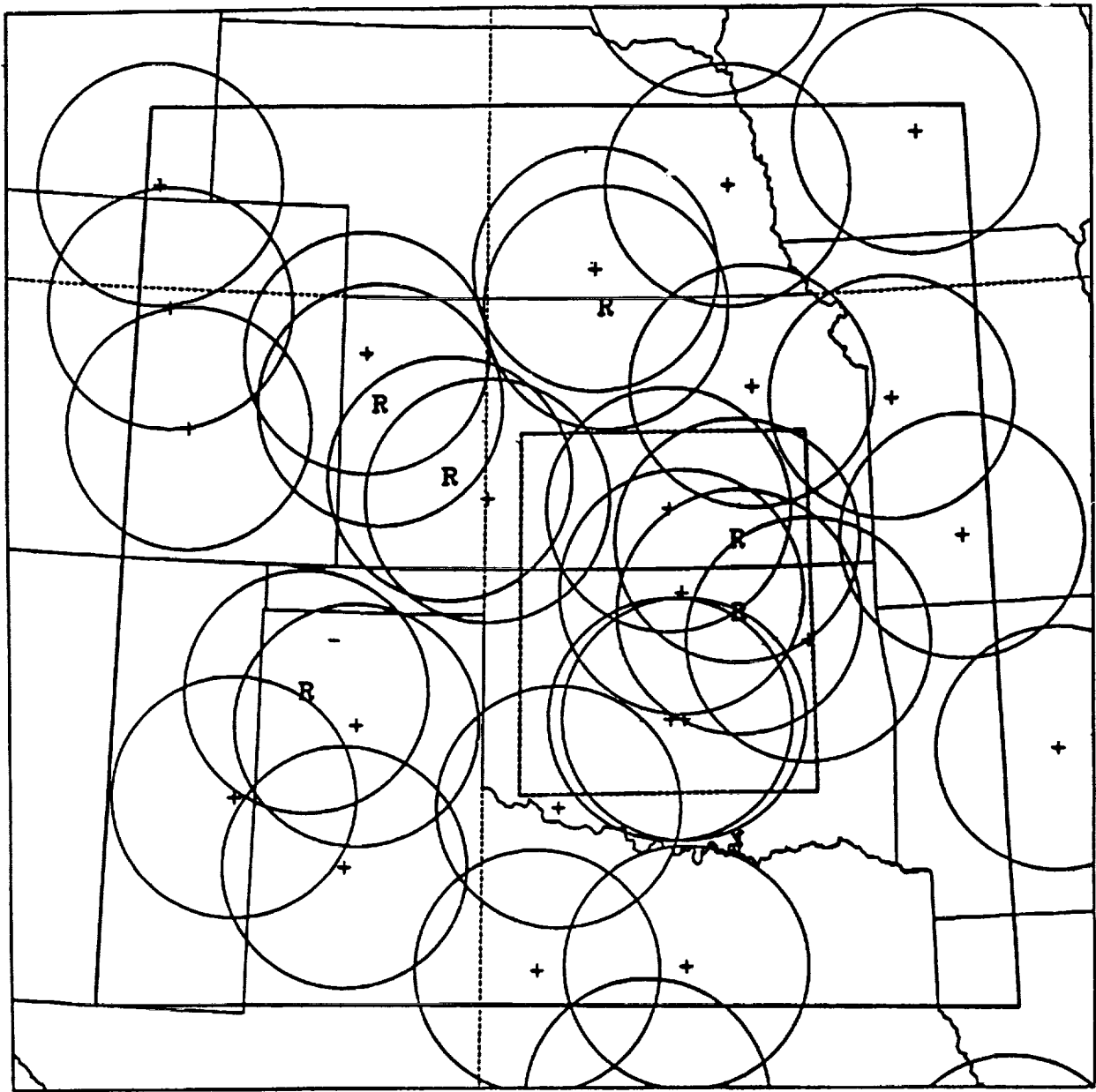
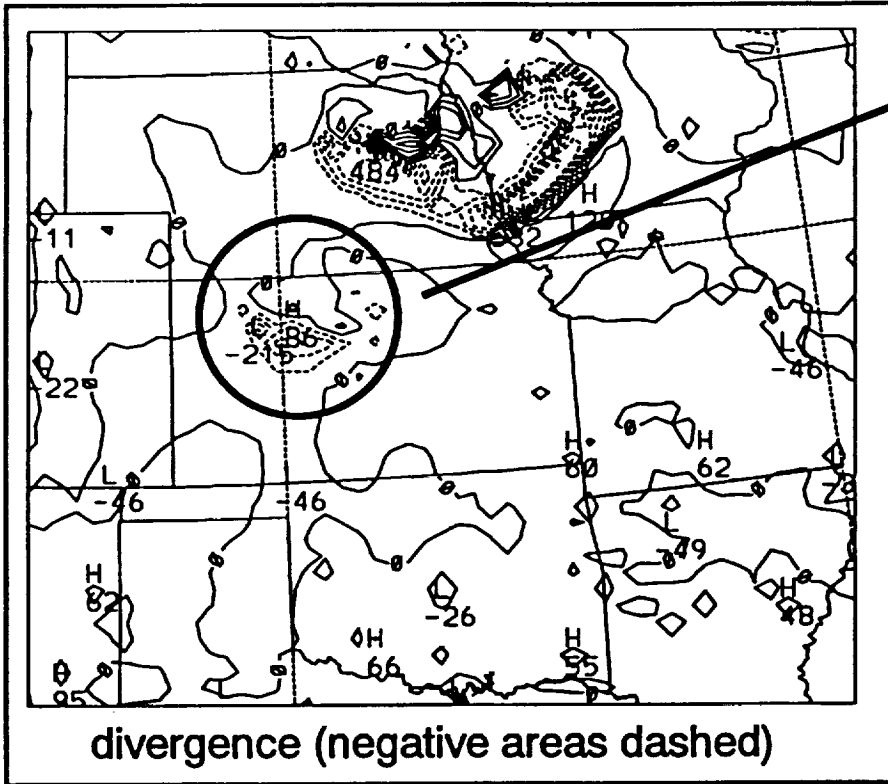


Fig. 10 The proposed beta-network radar sites proposed for the Cooperative Multiscale Experiment, consisting of NEXRAD (+) and research Doppler radars (R).

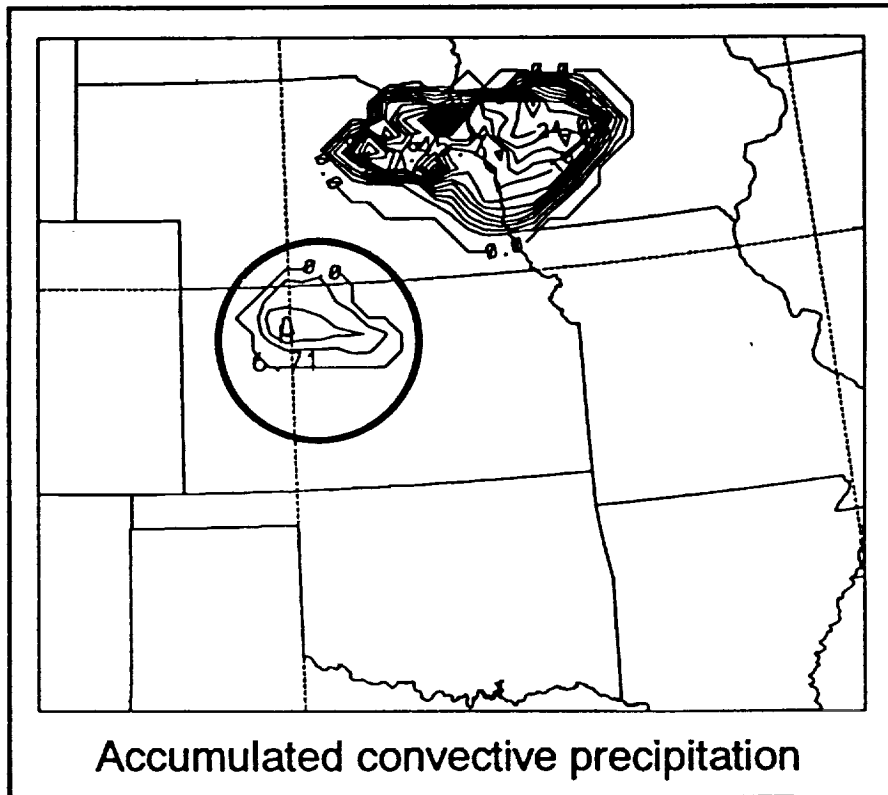


**Example of convergent initial wind field at the surface triggering premature convection in the PRE-STORM area**



Note the strong convergence here due to convergent initial wind fields

The "bogus" convection in the prestorm area raised the soil moisture, inhibiting the diurnal heating in the PRE-STORM area. No MCS formed in this simulation



The contouring here shows where the parameterization has been active. Note the circled region of convective activity in the PRE-STORM region.

**These plots are at 2.5 hours of simulation time, 8:30 AM local time**

Fig. 11 2.5-hr RAMS model forecasts of surface divergence and convective precipitation fields for the 23-24 June 1985 PRE-STORM case.

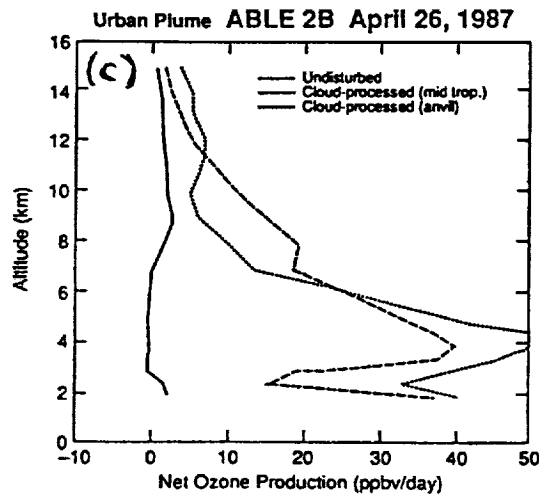
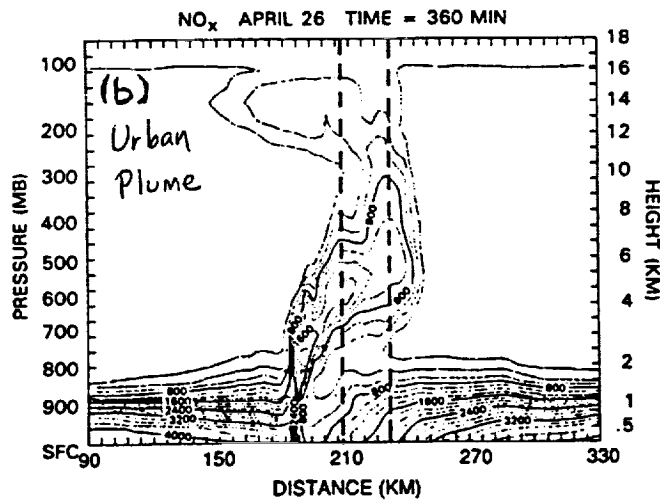
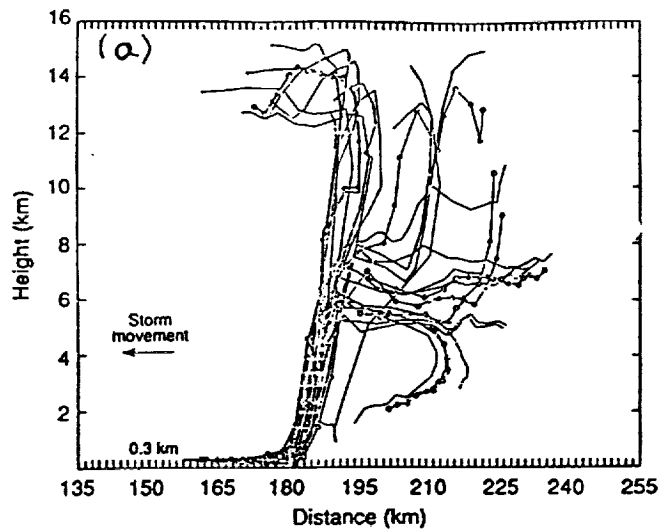


Fig. 12 Interaction of convection and trace gases from the 26 April 1987 convective squall line from GTE/ABLE 2B. (a) Forward trajectories from 0.3 km level show where air is transported and detrained during convection; (b) convective redistribution of NO<sub>x</sub> from Manaus, Brazil, plume at end of 4 hours simulation with 2D cloud tracer model; (c) Effect of convection on O<sub>3</sub> photochemical production rate (24-hour integrated rate of O<sub>3</sub> formation) due to convection. Solid line represents O<sub>3</sub> formation in "undisturbed" air; dashed lines refer to O<sub>3</sub> formation based on cloud-processed NO<sub>x</sub> profiles shown in (b). After Pickering et al. (1992c).

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