- Our knowledge of the optical properties of clouds related to MCSs is incomplete.
- Very importantly, no consistent radiation-microphysical coupling exists in current mesoscale radiative transfer schemes.

c. *Specific recommendations*

The recommended activities by this group consist of the needs to:

- Develop and validate a community radiative transfer code suitable for use with mesoscale models, and establish an intercomparison project to isolate and understand radiative processes in mesoscale models.
- Encourage work on the sensitivity of long-term mesoscale model integrations to changes in radiative transfer parameterizations.
- Assess which measurement strategies are needed for remote active and passive sensors, radiometers, and microphysics probes.
- Develop field strategies to study climatic influence of MCSs; these may include long level flight legs in stratiform region "debris" downwind of dissipative stage of MCS (in contrast to step legs in the region of active MCS), and measurements of upper level humidity increase due to MCSs.

d. *Implications for observing system strategies*

The foregoing concerns indicate the need for these observational approaches:

- Measure moisture, cloud cover, microphysical properties on large spatial and temporal scales. Combine in situ, active and passive remote sensors, and satellite data.
- Determine MCS related cloud optical properties such as optical thickness, their morphology, and microphysical composition.
- Provide observations to establish the radiative budgets of different kinds of MCSs throughout their entire life cycle.
- Collaborate with other radiation field campaigns and projects.

4.5 Session on coupled atmospheric/chemistry coupled models

Anne Thompson

a. *Current model limitations*

- *Current coupled regional meteorological/chemical models have fairly crude parameterizations of surface and boundary layer processes.* For example, 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. One of the most critical boundary layer meteorological parameters is the depth of the mixed layer. The simulated diurnal variation of this depth needs to better follow observations.

- *Parameterizations of convective clouds also need to be more realistic.* Convective clouds on all scales from small fair-weather cumulus to well organized MCSs need to be considered. Upward transport of trace gases is typically simulated, but downward motions within the cloud are not always considered. Very little data are available to validate schemes developed to simulate boundary layer venting by non precipitating cumulus clouds.

- Other limitations of current models include radiative effects, heterogeneous chemistry, and production of NO_x by lightning. Production of aerosol has generally been neglected in regional models. 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..*

b. Current issues and critical unknowns

The most crucial scientific issues and problems that this workshop defined are these:

- *Obtain field validation of model-predicted cloud dynamics.* Model simulations reveal very complex dynamics for which almost no observational verification exists. Fortunately, several trace gases of interest to chemists are also excellent tracers of cloud dynamics.

- *Determine the role of convection in stratosphere-troposphere exchange.* Upward and downward motions affect O_3, NO_x, and other trace gases.

- *Verify ozone production enhancement following convective transport of precursors* shown by tandem cumulus/chemical modeling approach. In particular, confirmation of the predicted magnitudes of cloud outflow and downstream photochemical ozone production is needed in a concerted chemical-mesoscale field program. The magnitude of these processes must be determined on a global scale; this requires better parameterizations of convection and chemical reactions.

- Determine the role of cloud microphysical processes in chemical scavenging and the role of lightning in NO formation.

- Further work is needed on the role of heterogeneous processes in altering ozone and sulfate production in clouds; NO is a key trace gas in the troposphere and lower stratosphere.

c. Modeling Activity to be Completed Prior to the CME

Some model improvements are currently underway. For example, the transilient matrix method of parameterizing convective transport of trace gases in a regional model has been tested in a version of RADM (Walcek 1993). A Regional Particulate Model, based on RADM, is being developed at EPA to simulate the production and transport of sulfate aerosol. The GCEM has recently been improved with a new cloud microphysics scheme, and transport of trace gases using GCEM winds has been improved with a new numerical advection scheme. Hydrometeor data from GCEM will be used to better estimate heterogeneous losses of trace gases in the Goddard 1-D photochemical model. All of these activities will likely be completed before the CME is conducted. However, the CME will provide data that will be useful in validating these new model formulations. The experiment (data collection strategies described in the next section) will stimulate further model improvements, particularly addressing the limitations listed above. Of great importance with respect to the CME will be the planned linkage between the GCEM and the NCAR/Penn State mesoscale model.

d. Specific recommendations and experimental strategies

Multiscale surface layer - PBL - chemical flux measurements

Surface hydrology and meteorology field studies in CME should be supplemented with chemical flux measurements to enhance the data base for deposition and emissions for use in regional modeling. Fluxes of CO_2, O_3, NO_x, and NO_y 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. For example, measurements should be made to determine how point source fluxes of trace species aggregate to form a grid cell size emission. The importance of subgrid fluxes due to subgrid circulations over regions of heterogeneous land use should also be assessed.

Eulerian budget study

Parameterizations of cloud-scale processes are usually based on a number of empirical observations or conceptual models of the nature of cumulus convection, and there is an ongoing need to validate and reaffirm the accuracy of these models with observations. Over the past 20 years, meteorologists have evaluated cumulus parameterizations using measurements of heat, moisture, and momentum. By carefully measuring the time rate of change of potential temperature, water vapor, or momentum, and also monitoring the inflow, outflow (and wet deposition) of these variables, it is possible to "measure" the integrated effects of cumulus clouds on the budgets of these parameters within an isolated atmospheric column containing clouds. These meteorological tracers (heat and moisture) undergo both convective transport and diabatic effects as they are acted upon by an ensemble of cumulus clouds, and as a result, it is often difficult to directly distinguish these two effects.

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. Carbon monoxide (CO) and ozone (O_3) are two chemical tracers that do not undergo physical or chemical transformations on the time scale of convective processes, and therefore can be used as a complement to the existing meteorological tracers. *We recommend that CO and ozone be measured* in the same manner that temperature and moisture have been measured in past meteorological experiments to extrapolate Q1 (heat), Q2 (moisture), momentum (Q3) tendencies due to cloud-scale processes. We propose that a "Q4" for CO and "Q5" for ozone be defined and used to assess the vertical exchange of air during conditionally unstable conditions. These measurements will provide a valuable additional set of observations that can be used to assess the performance of cumulus parameterization schemes.

Lagrangian experiment

A Lagrangian chemical experiment should be conducted as part of the CME. It would have as its objective investigations of pollutant transport and transformation through convective cloud systems using natural and artificial tracers. *This study will provide the basis for testing hypotheses and parametric schemes for convection-induced vertical exchange.* It should be possible to cover scales from penetrative nonprecipitating cumulus to well-organized mesoscale convective systems. Penetrative convection includes contributions of both the up and downdrafts to vertical exchange, as well as the products of cloud-induced aqueous-phase reactions. Outflow from organized convective clouds will provide information on venting of boundary layer pollutants into the free troposphere and lower stratosphere. Integration of nonprecipitating cloud and organized convection studies into the CME is envisioned. Descriptions of these two types of studies follow.

Nonprecipitating Cloud Studies

Inert tracers, SF_6 and perfluorocarbons can be released by aircraft, both above and within the mixed layer, during episodes of deep, penetrative cumulus convection. Mixtures of tracers from both mixed and cloud layers are subsequently sampled in mixed and cloud layers and also at the surface. Ratios of pollutant to tracer provide data on both mixing and aqueous transformation rates. Results are used to determine the overall transport due to an ensemble of nonprecipitating cumuli. Two sampling aircraft, as well as a tracer release aircraft and ground-based samplers are required. Sampling should also include natural tracers such as CO and O_3, as well as O_3 precursors NO_x and NMHC. Other CME studies will provide ancillary information to facilitate the interpretation of the cloud studies and strengthen the evidence and conclusions to be drawn about vertical exchange processes.

Organized Convective Systems

To determine the degree of convective enhancement of O_3 production, an experiment must acquire sufficient data for accurate model verification. *The cloud-dynamical model requires observations 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. One aircraft must have altitude coverage and range to encompass a mesoscale convective system with anvil outflow at 10-12 km. As far as we know, only the DC-8 meets these requirements and can cover both cloud-disturbed and undisturbed air masses. A second plane is required to concentrate on measurements in anvil outflow, including flights downwind and in the initially perturbed region both early in the storm and for a number of hours after the convective event. This is the most critical element for verifying post-storm O_3 production. A third aircraft would be deployed in the lower and middle troposphere. One role of this aircraft would be to make measurements in the undisturbed boundary layer just ahead of the convective cell(s) for complete characterization of boundary-layer transport and chemistry in pre-convective conditions.

During a mesoscale convective experiment the focus of the meteorological community may be on one particular scale of convective phenomena, e.g. mesoscale convective complexes (MCCs), but nature may not cooperate and a different type of convection may predominate (such as squall lines and air mass thunderstorms). Measurements of the following species are considered critical to meet the objectives: CO, O_3, H_2O, NO, NO_2, NO_y, and NMHC. In addition, UV-DIAL O_3 and aerosol measurements would also be required for assessing redistribution and ouflow from a convective system.

Aerosols - heterogeneous chemistry

Aerosols and gases associated with heterogeneous cloud chemistry should be sampled according to the flight scenarios described for nonprecipitating cumulus and for organized convective systems. High-volume samples taken over constant-altitude flight legs should be analyzed for NH_4^+, SO_4^{--} and other species. Shorter-time interval sampling should also be conducted and the samples analyzed for critical species. Cloud condensation nuclei (CCN) should be sampled both by aircraft and at the surface. The gases SO_2 and NH_3 should also be sampled from the aircraft and at the surface. These data will aid in understanding the behavior of sulfates and their relationship to CCN.

4.6 Joint sessions on validation of coupled models and techniques/resources for storm-scale numerical weather prediction

Bill Kuo and Kelvin Droegemeier

This joint session considered the recent modeling successes made with high resolution models which may be either nested within coarser mesh models or which may employ adaptive grid stategies. Suggestions for future multiscale model verification needs considered the special quality of these kinds of models. In addition, the requirements of coupled chemistry, land surface, hydrological, etc. models were considered by this group in making its recommendations.

4.6.1 Session on validation of coupled models

Bill Kuo

N94-24399

a. Current status

The use of a mesoscale model with a grid size of 20-km during STORM-FEST in 1992 has proven to be extremely valuable. The availability of forecast products at a much higher temporal and spatial resolution was very helpful for mesoscale forecasting, mission planning, and the guidance of research aircraft. Recent numerical simulation of ocean cyclones and mesoscale convective systems using nonhydrostatic cloud/mesoscale models with a grid size as small as 2-km have demonstrated the potential of these models for predicting mesoscale convective systems, squall lines, hurricane rainbands, mesoscale gravity waves, and mesoscale frontal structures embedded within an extratropical cyclone. Although mesoscale/cloud scale models have demonstrated strong potential for use in operational forecasting, very limited quantitative evaluation (and verification) of these models have been performed. As a result, the accuracy, the systematic biases, and the useful forecast limits have not been properly defined for these models. Also, no serious attempts were made to use these models for operational prediction of mesoscale convective systems.