PROGRESS REPORT
and
INCREMENTAL FUNDING REQUEST
for
NSF PROPOSAL # ATM-9708314
entitled

A Lake-ICE Proposal: Operations Center and Multi-Scale Numerical Investigation

PI: G. J. Tripoli
Co-PI: J. A. Young

University of Wisconsin-Madison
Department of Meteorology
Madison, Wisconsin 53706

December 4, 1998

1 Progress Report

The first year's progress is described below. Work began before the acquisition of NSF funding in order to be prepared for the field phase. Early work included hosting a Lake-ICE Operations workshop in June, 1997, conducting a search for an airport facility at Madison (in anticipation of having the Operations Center in Madison), and rewriting the model code as parallel computer code. Below we describe the major components of the first year's accomplishments beginning with the model rewrite and computer acquisition, the field operations support, and finally the analysis and research phase ongoing since the field phase.

1.1 Model Rewrite

The first task of the project was to acquire the proposed computing platform, necessary to perform the large numerical experiments proposed. We needed a workstation with at least a factor of eight more computational power than our previous IBM RISC and Hewlett Packard single processor platforms. Our research of computer performances, led us to the the Silicon Graphics Inc. Origin 2000 workstation. We acquired half of the computer platform with our matching funds 4 months prior to the arrival of NSF funding so that we could begin the lengthy process of model recoding for the parallel platform in time for the model to be available in support of the field phase of Lake-ICE in December. We subsequently added the second two processors to the workstation in late November 1997, also before the arrival of NSF funding so the full computational configuration could be stabilized in time. Nevertheless, because of the extensive recoding of the model necessary, we were unable to have the model running with full efficiency during the December field phase, but we did have adequate performance, given the lack of suitable lake effect situations requiring high resolution simulation during that period.

We achieved much greater efficiency in support o the second phase of Lake-ICE, which began after the new year. During that time, we were able to operationally integrate a 10km resolution grid over the study area.

Further model refinements were made during the second field phase and into the summer months. When we attempted our first research CRM (cloud resolving model) simulation in late summer, we had achieved a model performance of 15-20 times greater than what we had with the IBM RISC, nearly double our expectations. This then enabled a more highly resolved CRM study than we originally anticipated in the proposal for the first year.

As part of the model rewrite, many of the dynamical schemes, physics packages, and boundary condition schemes of the model were improved, rewritten and even reformulated. There was extensive testing of the new model against analytical theory in order to validate the new formulations and code. A particularly significant achievement of the new NMS, was a new variable stepped topography scheme that eliminates many of the disadvantages of a stepped topography model while retaining all of the advantages of the stepped scheme. This eliminates a major concern expressed by the reviewers of this proposal and of the LES proposal. A paper describing the new model and the results of these tests was completed and will be submitted as a Journal Publication.

The model rewrite, although not fully complete by the field phase of Lake-ICE, were sufficient for us to deliver real time forecasts.. Their utility to field operations is described below.

1.2 Field Operations

As proposed in our original proposal, we provided significant forecast support for the field operations component of the Lake-ICE/SNOWBAND experiment. The operational support was supplied in two forms: forecast expertise and numerical model output from the University of Wisconsin Nonhydrostatic Modeling System (UW-NMS). Brad Hoggatt, lead project forecaster, and Bill Badini, assistant forecaster, worked with other forecasters from the University of Michigan and the National Weather Service to provide forecasts on a daily basis as to whether atmospheric conditions were favorable for the initiation of an intense observation period (IOP). Moreover, forecasters were responsible for advising the operations director and the flight crews of changing weather conditions which could adversely affect flight operations. The forecasters typically worked two shifts. The day shift began in the morning and included a presentation at the daily weather briefing and the composition of the project forecast discussion. The night shift typically began around 10-11 PM and included an early morning weather briefing focusing on specific scientific flight objectives, a pre-flight weather briefing, and a project forecast discussion. The ensuing paragraphs are included to provide additional insights into the operational requirements of the Lake-ICE/SNOWBAND projects and forecaster duties.

It is an irony of many field campaigns that the processes which the principal investigators (PIs) are trying to measure on any given mission, or in the case of Lake-ICE/SNOWBAND, IOP's, are the same processes that they have to be able to forecast accurately in order to place the observing platforms effectively. Forecast needs of the PIs were highly dependent on what the project's operating mode was at the given time (ie. current OP, potential IOP, and inactive). In the 12-48 hour period before a possible IOP, forecast needs focused on the timing and type of the event. The forecasters would attempt to identify windows in which the maximum allocation of resources, primarily the aircraft, could be most effectively deployed to attain the predetermined research goals. The forecast information the Lake-ICE PIs required was:

1) If and when (within a 4 hour window) will conditions for boundary layer based convection commence?

2 Where, within, a 50-100 km radius, will the convection develop?

3) What are the estimates of boundary layer depth, boundary layer lapse rates, cloud top temperature, band geometry, and sensible/latent fluxes?

The SNOWBAND PIs required different forecast information for their decision making:

1) If and when (again within a 4 hour window) will favorable conditions exist for the formation of significant snowfall forced by large scale ascent accompanying an extratropical cyclone?

2) Where, within a 400 km radius of the aircraft base, will the snowfall occur?

3 What were the likely primary forcing mechanisms responsible for the formation and structure of the significant snowfall (ie. slantwise convection, frontogenesis, etc.)?

Within 12 hours of IOP initiation, the forecast needs of the projects evolved into a "nowcast" mode. Forecasts of the aforementioned requirements were continuously updated. The timing and placement of the event were narrowed using recent numerical model output along with current satellite, radar, RAOB, and surface data as guidance. If the conditions for justifying an IOP were marginal, the forecast and current conditions were further scrutinized to make a decision as to whether or not to initiate the IOP. The final forecast and assessment of the IOP was performed approximately 4 hours before the scheduled aircraft deployment and included an informal presentation by the forecasters and subsequent decision by the PIs. If the IOP commenced, a final forecast product was developed and presented to the crew(s) of the aircraft at the airport. Short term forecasts for turbulence and icing were generated for the airspace through which the plane(s) would fly. Additionally, surface forecasts involving ceiling, visibility, precipitation, and wind for the base airport were provided in addition to the identification of alternate landing sites.

In order to generate the aforementioned forecasts and fulfill Lake-ICE/SNOWBAND operational requirements, project forecasters had access to a suite of products including: surface, RAOB, radar, GOES satellite, pilot reports, non-research numerical model, and research numerical model information. One of the research numerical models utilized was the UW-NMS. The UW-NMS employed a three grid configuration with the second grid covering all of the Upper Midwest and the inner grid encompassing a 400 km x 400 km domain centered on southern Lake Michigan. The horizontal resolutions of the three grids were 60, 20, and 10 km. The UW-NMS utilized a vertical grid spacing of 200 m for the first five grid boxes near the Earth's surface stretching gradually to a minimum resolution of 1000 m. A total of 35 levels were employed. Forty-eight hour forecasts were performed at 00/12 UTC with the forecasts available to project forecasters by 07/19 UTC. The timeliness of the simulations allowed the high spatial resolution output to be effectively incorporated into the daily forecast process. The ability to generate timely, high resolution forecasts was made possible through the acquisition of a SGI Origin 2000 using NSF funds. The UW-NMS demonstrated significant skill in predicting boundary layer depth, boundary layer lapse rates, cloud top temperature, and precipitation distribution. VIS5D loops of the 10 km inner grid provided information on the temporal fluctuations in lake-effect convection in addition to the location of initial cloud development within the convectively unstable boundary layer over Lake Michigan. The UW-NMS proved to be a valuable tool to the project forecasters and PIs.

The field operations were also supported by Tripoli and Lennartson who remained at Madison to oversee operations and maintain the model code. Their work included archiving

NCEP data streams, supervising model operations and making adjustments when interruptions in data acquisition from Washington occurred or were absent, and continuing to improve the model code, still under development in the conversion process.

Tripoli and Co-PI Young traveled to the Operations Center over the period of 8-13 January, 1998, when a major cold outbreak occurred setting up the only classic Lake Effect event of the experient. Young and Tripoli participated in Operations discussions and planning. In addition, Young, Tripoli and Hoggatt flew on research flights of both the Electra and Wyoming King Air. This provided the PIs with invaluable first hand observational experience with the Lake effects structures, that would henceforth be simulated in the numerical Laboratory.

In addition to forecasting and participating in research flights, the University of Wisconsin acted as the project's satellite data archive. Visible, infrared, and water vapor imagery was archived at 30 minute intervals except during IOPs when the imagery frequency was increased to 7.5 minutes or even 1 minute. The satellite imagery was archived on 4 mm DAT tapes and sent to UCAR for distribution upon the completion of the field phase of the project. Moreover, during the project, real-time satellite imagery including super rapid scan imagery (1 minute data) was made available via a home page.

1.3 CRM Research

Over the past year we have made good progress developing and implementing a cloud resolving model simulation of lake effect bands. As mentioned above, over the first half of the year, we directed all of out efforts toward rewriting our NMS model for optimal performance on the new parallel computer platform and toward improving the model code. The model improvements included development of an improved topography stepping system allowing for variable sized steps. This new system eliminates disadvantages of step topography in the vicinity of subtle slopes, which was a disadvantage of the NMS model criticized by reviewers of this project when proposed. Numerous improvements were made to the model's dynamics system and boundary conditions to better simulate classical small scale fluid flow problems in anticipation of performing the CRM simulations.

Finally, the CRM simulation was performed on a five grid system having a horizontal resolution of 500m across Lake Michigan over the Lake-ICE observation region. The model did an excellent job of capturing a variety of observed cloud structures including not only the wind and shear parallel rolls, but also shear perpendicular shoreline parallel gravity wave bands driven by frictional differences between land and water. This work led to the conference preprint paper (Adams, *et al* , 1999. A journal publication based on this work is also in progress.

In addition to the CRM, there was significant participation from members of this project with the Large Eddy Simulation project for Lake effects whose PIs include Ed Eloranta and G. Tripoli. Since Tripoli and Hoggatt were funded by the CRM Lake Ice project, no seperate funding from the LES project with Eloranta was requested although both investigators worked closely with the LIDAR group using the NMS model to perform Large Eddy simulations of the Lidar observed Lake-ICE boundary layer. The model was able to simulate observed cellular structures of shallow "steam fog" flow just off the windward shore of Lake Michigan in the Lake Ice observation region. A second Boundary Layer Conference paper by Mayor *et al* 1999, has already resulted from this work and an journal publication is planned based on this work for next year.

Also as part of this project, a Masters thesis by Dan Lennartson was completed addressing the coupling between a major lake effect circulation and a passing synoptic scale weather system occurring on 18 December 1996. The Lake-Effect Snow Project team at the National Weather Service Forecast Office (NWSFO) in Duluth, Minnesota observed and collected data for this unusual lake effect snow case. Although the event took place over Lake Superior, the the concepts developed from this investigation also aid in the understanding of lake effect structures that occur over the Lake-ICE study area.

2 Research Plans

Our Research Plans for the next year include the following:

1. Complete and submit to Boundary Layer Meteor. paper on CRM study.
2. Submit Model description paper to Mon. Wea. Rev.
3. Submit paper describing Field forecasting operations in collaboration with University of Michigan and Pennsylvania State University.
4. Perform sensitivity studies to CRM simulation, with the goal of showing what environmental features control the observed and simulated 6.5 km spacing of cloud bands. This is the basis for a Masters thesis and possible PhD for Amanda Adams, who joined the project beginning in the 1998-1999 academic year.
5. Simulate a contrasting shear parallel roll case observed during Lake Ice, possibly the January 13 case.
6. Begin development of theoretical treatment to CRM study.
7. Continue close collaboration with the ongoing LES research.

3 Project Personnel Changes

There were no changes among senior personnel in the first year.

4 Publications and Reports

Masters Theses:

1. **Lennartson, D., 1998: A Detailed Analysis of Multi-Scale Interaction Within a Storm System Approaching Lake Superior.**

Publications:

1. Forecasting during the Lake-ICE Field Experiment: A Recipe for Success. Peter J. Sousounis, George Young, Greg Mann, Brad Hoggatt, Dick Wagenmaker, and Bill Badini. (To be submitted January 1999 to Weather and Forecasting)

2. The University of Wisconsin Nonhydrostatic Modeling System: Use of a variable stepped topography. (In final preparation, to be submitted to Mon. Wea. Rev.

Conference Presentations

1. Tripoli, G., A. Adams, and B. Hoggatt, 1999: Cloud Resolving Model Simulation of the Convective Boundary Layer Observed by Lake-ICE. 13th Symposium on Boundary Layers and Turbulence, 10-15 January 199, Dallas Texas.(see attachment)

2. Lennartson, D., G. Tripoli and B. Hoggatt, 1999: A Detailed Analysis of Multi-Scale Interaction Within a Storm System Approaching Lake Superior. 13th Symposium on Boundary Layers and Turbulence, 10-15 January 199, Dallas Texas.(see attachment)

3. Mayor, s., G. Tripoli and e. Eloranta, 1999: Comparison of Microscale Convection Patterns seen in Lidar Data and Large Eddy Simulations.13th Symposium on Boundary Layers and Turbulence, 10-15 January 199, Dallas Texas. (see attachment)

5 Additional PI and Co-PI Funding Support since Proposal

1. Improvement of QPF of Land Falling Atlantic Hurricanes using Remote Sensing. PI: G. Tripoli ATM- 9714354.

2. The Use of 4-Dimensional Lidar Data to Evaluate Large Eddy Simulations: A Lake-ICE Project. Co-PIs: E. Eloranta and G. Tripoli NSF project ATM-9707165 . (Tripoli and Hoggatt receive no salary support from this grant)

6 Attachments

4.3

CLOUD RESOLVING MODEL SIMULATION OF THE CONVECTIVE BOUNDARY LAYER OBSERVED BY LAKE-ICE

by
Gregory J. Tripoli
Amanda Adams
Bradley Hoggatt

Department of Atmospheric and Oceanic Sciences
University of Wisconsin – Madison
Madison, WI 53706

1. INTRODUCTION

On 10 January 1998 a massive arctic air outbreak moved across an anomalously warm Lake Michigan. The strong cold and dry westerly winds impinging on the western lakeshore produced an exceptionally unstable convective boundary layer that resulted in precipitating convective snow bands on the lee side of the lake. The Lake-ICE (Lake Induced Convection Experiment) was operating on this day and sent both the Wyoming King Air and NCAR Electra equipped with Eudora Doppler to observe the evolving structure of the convective boundary layer and the evolution of heat and moisture fluxes across the lake.

The setup for this case provided an exceptionally ideal laboratory for the evaluation of a numerical simulation of the convective boundary layer. Meso-β scale model predictions made in real time using the University of Wisconsin Nonhydrostatic Modeling System (UW-NMS), featured a horizontal resolution of only 20 km, but provided excellent predictions of the air mass evolution across the lake and of the resulting lake-effect snowfall on the lee side. Subsequent experiments with 10-km resolution revealed important links between the efficiency of convective overturning and large scale forcing resulting from the passage of a vorticity center aloft. More recently, in a research mode, a system of five two-way nested grids was employed to grid down to a cloud-resolving grid resolution of 550 m over a limited region across the Lake where the Lake-ICE experimental observations were collected. This report will focus on the results of the numerical experiment and its comparison to observations.

2. EXPERIMENTAL DESIGN

The UW-NMS is a nonhydrostatic quasi-compressible, and enstrophy conserving model formulated in a non-Boussinesq framework. The governing equations are cast on a rotated spherical grid. Topography is represented by a variably stepped topography (Tripoli and Hoggatt, 1999). Predictive variables include the three components of velocity, exner function, ice-liquid water potential temperature, total water specific humidity, and five categories of precipitating hydrometeors. These include rain, pristine crystals, rimed mature crystals (snow), aggregated crystals and graupel. The specific concentration of the snow crystal ice category is also predicted. Cloud droplet specific humidity, vapor specific humidity, and air temperatures are diagnosed from the predicted variables.

The turbulence closure used was a simple first order scheme where eddy viscosity was diagnosed from turbulent kinetic energy, under the assumption of a balance between its production and dissipation. The vertical surface fluxes were calculated using the Louis (1979) surface layer scheme. Surface land temperature were based on a surface energy budget between five layers of predicted snow temperature (soil south of the snow cover) , turbulent latent and sensible heat upward, and radiative incoming and outgoing energy fluxes. Over the water, a constant lake temperature was used, set to 5C over Lake Michigan. A newly developed long and short-wave radiative transfer model developed by Pannegrossi , et al (1999) was used to model radiative transfer in the atmosphere.

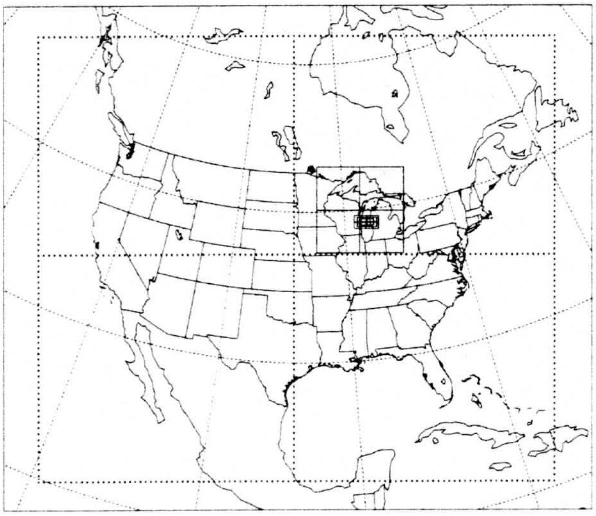


Figure 1. Depiction of grid locations for five-nested grid system employed by the cloud-resolving model. Centers of outer grid boxes for each grid are represented by dots.

The five-nest grid configuration used is depicted in figure 1. The outer grid features 60 km resolution and spans a domain 6000 by 5000 km. The second grid centered over the western Great Lakes has a resolution of 10 km and spans a distance of about 1000 km in each direction. The third grid begins to focus over the Lake-ICE area, having a resolution of 3.3 km, spanning a domain 250 km parallel to the wind and 133 km normal to the north-south direction. The outer grid was nested one-way wind (north-south). The fourth grid has a resolution of 1.1 km, and spans a distance of 210 km in the east-west direction and 105 km in the north-south direction. Finally the fifth grid features a cloud resolving spacing of 550m and spans a distance of 140 km in the east-west direction and 70 km in the within the operational NCEP ETA analysis and prediction of 00UTC, 10 January 1998.

The simulation was integrated from 0000 UTC until 1400 UTC at which time the three inner-most grids were added. The Lake-ICE IOP Electra flight began flight legs across the lake about this time. The five grid system was integrated for 4 hours, approximately the time scale for an air parcel to traverse the lake.

3. OBSERVATIONS

The predicted synoptic situation at the surface is given in fig. 2. Note the passage of the arctic air had just taken place and a strong pressure gradient was creating strong surface winds.

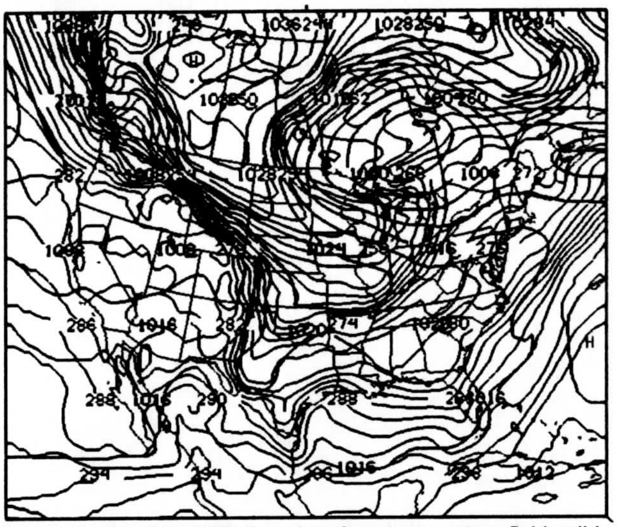


Figure 2. Predicted MSLP and surface temperature field valid at 1700 UTC 10 January 1998. Isotherms are every 2C and isobars are at 4 kPa intervals.

As the arctic air moved across the Lake, shear parallel bands quickly developed. The super rapid scan GOES-8 1 km imagery revealed the roll cloud pattern (Fig 3.):

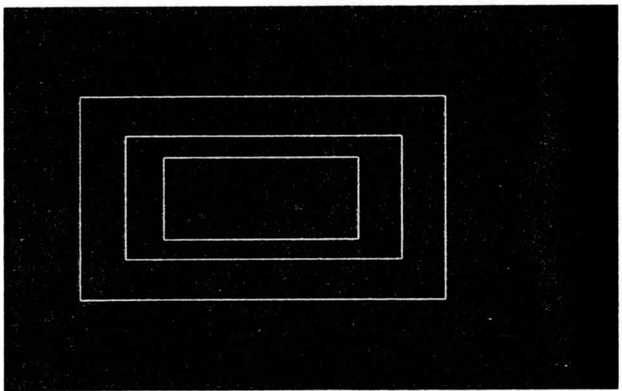


Figure 3. One km super rapid scan visible imagery at 1730 UTC 10 January 1998 over central Lake Michigan. Boxes outlined in white depict of locations of model grids 3,4 and 5.

From Figure 3, it is readily apparent that there are two distinct linear organizations. First, the shear or wind parallel bands are most visible over the land regions downwind of the Lake, but extend over the lake. They were less visible over the lake because the lateral mixing of thin cirrus blurs the spaces between the bands. Nevertheless, it can be seen that the approximate spacing of the bands was similar to the more visible spacing over the land, which were about 6-7 km.

A second distinct organization is noticeable in Figure 3 are waves oriented perpendicular to the flow beginning on the western shore and weakening in strength as one moves eastward across the lake. That wavelength was about 14 km.

NEXRAD radar from the Green Bay and Milwaukee/Sullivan sites west of the Lake were too distant to capture the shallow mid and eastern lake cloud bands. The Eudora radar was not available at the time of this writing. Radar coverage over the land immediately east of the lake is given in fig. 4., shown below:

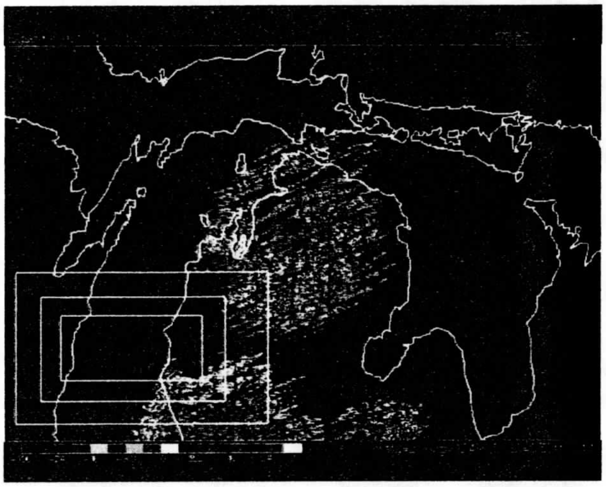


Figure 4. NEXRAD reflectivity composite consisting of 1730 UTC scans from Grand Rapids, Muskegon and Detroit. Note again the location of the inner three grids of the simulation.

The above radar clearly displays the 6-7 km spacing of the cloud bands to the west of the simulation site. Note the patches of higher reflectivity within individual bands, suggesting perhaps larger or wetted crystals.

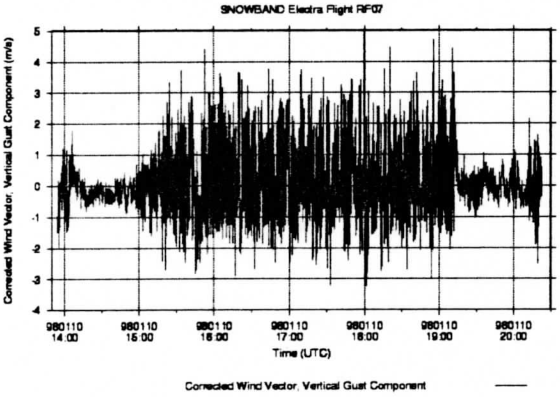


Figure 5. Vertical velocity from Electra Gust Probe.

The Electra observed , among other things, peak vertical motions across the lake at the flight level of 350 m. MSL. These observations are summarized above in Fig 5:

4. RESULTS OF SIMULATION

We will examine the results at approximately 3.5 hours after the inner most grids were added. Below is a depiction of the cloud field of grid 5 visualized as a three dimensional surface from above and from the south:

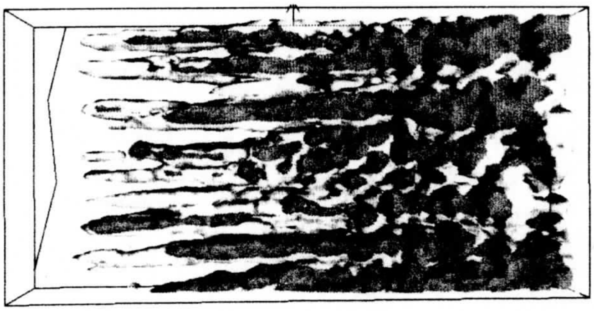


Figure 6a. Grid 5 cloud field viewed from above. The lighter transparent surfaces are the .01 g/kg pristine crystal surface. The darker shaded surfaces represent the .01 g/kg aggregate crystals. Integration time is 17:40 UTC.

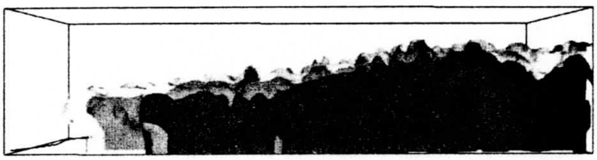


Figure 6b. Same as figure 6a, except view from South. The dark color is because the aggregate field is not behind the semitransparent pristine crystal surface. The depth of this figure is 2km, hence the highest cloud band reaches to about 1.3 km.

These figures show that the NMS successfully simulated the correct scale of 6-7 km spacing across the bands The intermittent aggregate field within the bands would be realized as the patches of high reflectivity viewed by the NEXRAD. Note the loss of distinction of the bands immediately on shore of the lee side of the lake. This seems to be an effect of surface friction and perhaps the land breeze which augments the cloud growth on the eastern shore of the lake giving rise to greater instability and hence stronger more cellular convection near the lee shore.

It is also interesting to examine the vertical velocity field predicted by the model. The vertical velocity fields at 300m and 1200m MSL are given in figure 7. Note the structure at 300 m strongly reflects the cloud rolls, even before condensed clouds are formed. The braiding of the vertical motion bands are interesting and have also been noted in our large eddy simulations of the cloud rolls (Shane, et al, 1999). These braided structures become the hexagonal–like cellular structures as the wind speed is diminished. Note the more cellular structure evolving on the lee side of the lake.

Note that the magnitude of vertical motion simulated, and displayed in figure 7a-b, simulated to be between –3 and +7 m/s is very close to the vertical motion observed by the Electra gust probe, and also from the King Air gust probe (not shown).

Of particular interest was the vertical motion pattern simulated just above the convective mixed layer at 1.2 km MSL shown in figure 7b. Here waves normal to the flow were found with a wavelength of 10-15 km. In was shown, in the previous section, that such wave structures were indeed visible in the

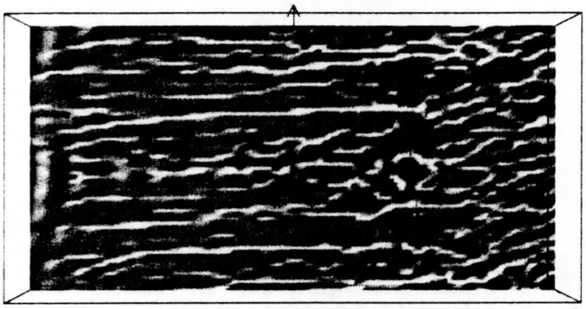
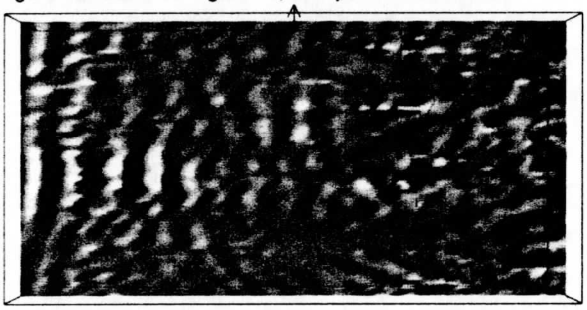


Figure 7a. Grid 5 vertical motion at 500m AGL. Upward vertical motion ranging from 0-5 m/s in light shading, downward vertical motion ranging fro 0 to –3.5 m/s in darker shading.

Figure 7b. Same as Figure 7a, except for 1200 m AGL.



satellite image depicted in Figure 3. The origin of these waves seems to be rooted in the off shore acceleration of the flow, resulting from a combination of the downslope flow on the windward shore, the tendency for a land breeze, and the sudden reduction of friction as air passed onto the water. This acceleration resulted in a locally strong subsidence, which warmed the air. Figure 8 depicts this acceleration from the perspective of Grid 4:

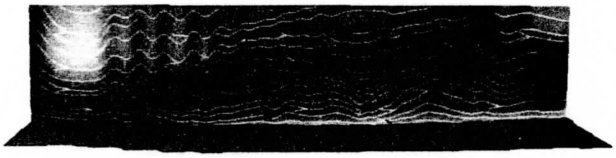


Figure 8. East-west cross section through center of grid 4 to a height of 2 km showing stream lines (white) and temperature(dark shading colder and lighter shading is warmer). The underlying medium gray surface represents the topography.

Note the strong subsidence selectively forms a lee wave that is apparently trapped in a wave duct formed by the frontal layer bounded below by the convective boundary layer and above by the upper frontal surface (above and out of the picture). In Fig. 8 one can also see the enhanced uplifting on the lee shore evidenced by the deep cool anomaly formed above the advected convective boundary layer and the resulting reduction of stability. It is here that the more cellular convection erupts.

The structure of the simulated convective rolls is depicted with a trajectory analysis displayed in Figure 9. Note that trajectories released at the surface on the up-wind (western) side of the subdomain converge into 5 lines of convection, all of one of which forms a cloud on the western side of the subdomain. As the trajectories move westward across the subdomain, the quickly collapse into a narrow line of uplift, rise to about 800-1000 m MSL (600-600 AGL) and then spread laterally (preferentially toward the south, but also to the north less often) and then turn downward. After traveling downward they eventually curve back toward the line at lower levels and again move upward forming a helical pattern with a vertical circulation period of roughly 20-30 minutes over a distance of approximately 40-50 km.

Figure 9. Visualization of trajectories moving through convective rolls viewed within a 35 km by 35 km subdomain of grid 5 over the east-central zone of Lake Michigan. Trajectories were calculated over a 2000 s period beginning at 17:30 UTC (3.5 hours since introduction of the inner 3 grids). Trajectories are shaded by the value of vertical thermal flux, with lightest shading representing 800 W/m2 and the darkest shading –800 W/m2 flux. Trajectories were released at 17:30 UTC from each of the grid points along the intersection of the western and surface boundary of the subdomain. The boundary of the pristine crystal and aggregate crystal ice field forming the predicted convective roll clouds at the final trajectory time is depicted by the semi-transparent surface. The top figure is the view of the subdomain from the west to a height of 1.2 km MSL. The bottom portion shows the same sub-domain from above.

Analysis of the vertical eddy heat flux relative to a meridional average ov vertical velocity and temperature across grid 5, demonstrate that as the trajectories start up they are warm anomalies, but become cold anomalies very rapidly at the highest point of their rise. This cooling is largely a relult of turbulent mixing with the top of the boundary layer, as evidenced by the fact that these trajectories remain cold as they move downward. They tend no be less cold than they were warm however, and many of the trajectories fail to sink all of the way back to the surface. It was found that some of the air reaching the surface actually originates above the convective layer, keeping the surface from substantial warming over the period.

5. CONCLUSION AND FUTURE RESEARCH

The multiple nested CRM of Lake effect convective rolls observed during Lake-ICE has successfully simulated many of the characteristics of the convective boundary layer observed by Lake-ICE and conventional observation platforms. Examination of the verified simulated structures has provided new insights and verified some accepted conceptual models of the convective roll structures. The robustness of the model, simulating complex scale interactions of the convection, including its microphysical and dynamical structure, with the mesoscale structures of the Lake Michigan land breeze system have already led to new hypotheses concerning how roll structures evolve and are maintained.

Planned future experimentation with the CRM investigating the sensitivity of the predicted structures to hypothesized environmental influences on roll structure promises to definitively verify hypotheses formulated here and many yet to formulated.

6. ACKNOWLEDGEMENTS

The authors wish to acknowledge Mr. Pete Pokrandt and Mr, Johan Kellum for their assistance in technical aspects of preparing this manuscript. Special thanks also to Dr. Paul Menzel and the UW Center for Meteorological Satellite Studies for their contribution to our acquisition of a computing platform sufficient to carry out these large experiments. This work was supported by a Lake-ICE research grant from the National Science Foundation (ATM9707165).

8. References

Louis, J. F. 1979: A Parametric Model of Vertical Eddy Fluxes in the Atmosphere. Boundary Layer Meteor. , 17, 187-202

Mayor, S. G. Tripoli. E. Eloranta and B. Hoggatt, 1999: Comparison of Microscale Convection Patterns Seen In Lidar Data and Large Eddy Simulations. Conference on Boundary Layer Meteorology.

Pannegrossi, G., S. Ackerman and G. J. Tripoli, 1999: A New Radiative Transfer Model Designed to Capture Effects of Ice Crystals. (In preparation)

Tripoli, G. J. and B. Hoggatt, 1999: The University of Wisconsin Nonhydrostatic Modeling System. To be submitted to Mon. Wea. Rev.

P 1.3

A DETAILED ANALYSIS OF MULTI-SCALE INTERACTION WITHIN A STORM SYSTEM APPROACHING LAKE SUPERIOR

Daniel Lennartson*, Greg Tripoli, Brad Hoggatt

The University of Wisconsin-Madison
Department of Atmospheric and Oceanic Sciences
Madison, WI 53706

Gary Austin and Brad Bramer

The National Weather Service Forecast Office
Duluth, MN 55811

1. INTRODUCTION

During the winter, Lake Superior regularly endures more unmodified arctic air masses than any other Great Lake. Consequently, the most abrupt changes to the planetary boundary layer (PBL) occur when these unmodified cold air masses advect over Lake Superior. The heating and moistening of the PBL results in various forms of lake-effect precipitation patterns such as wind parallel bands, shore parallel bands, mid-lake bands, and meso-β scale lake vortices (Hjelmfelt 1990). Larger scale lake-effect disturbances such as meso-α scale lake aggregate vortices are also known to develop and generally form several hours after the onset of the individual lake-effect storms (Sousounis 1997).

The Great Lakes also impact wintertime synoptic scale weather systems that migrate through the Great Lakes Region. For example, Petterssen and Calabrese (1959) noted that pressure perturbations induced by the Great Lakes tend to deter surface high pressure systems from propagating over the Lakes. Moreover, Fritsch and Sousounis (1994) showed that the track and intensity of approaching weak cyclones are significantly affected by the Great Lakes.

This paper will present an unusual southward propagating lake-effect snow band observed to extend far inland southwest of Lake Superior. Although the snow band appeared to be an anamalous extension of a shore parallel lake-effect band, modeling experiments to be presented show the feature to be a Lake Superior modified synoptic structure.

2. MESOSCALE/SYNOPTIC ANALYSIS

From 1400 to 1800 UTC 18 December 1996, the National Weather Service Forecasting Office (NWSFO) in Duluth, MN observed an intense lake-effect snow band on their WSR-88D Doppler radar display (Figure 1). Based on other numerous lake-effect snow bands observed by their WSR-88D, the forecaster's intuitive response would have been that it was a form of lake-effect shore parallel band. The peculiar part of this lake-effect snow band, however, was its deep 80km inland penetration. In fact, the effects of the band were felt as far to the southwest as Hinckley, MN where an inch and a half of snow fell in a little more than an hour. Another bizarre aspect of the snow band, was its steady southward propagation away from Duluth. The methodical movement is unlike ordinary lake-effect bands that are generally quasi-stationary. These unique characteristics of the Duluth snow band prompted the examination of the 0000 and 1200 UTC analyses for some clues on the band's development and evolution. For instance, the 1000 hPa temperature analyses from

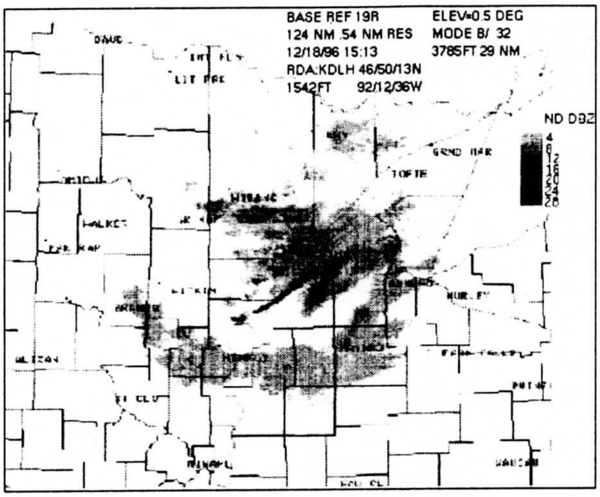


Figure 1 Radar reflectivity from Duluth, MN NWS at 1513 UTC.

*Coresponding author address: Daniel W. Lennartson, Univ. of Wisconsin-Madison, Dept. of Atmospheric and Oceanic Sciences, Madison, WI 53706; e-mail: dlennart@meteor.wisc.edu.

0000 to 1200 UTC showed a broad thermal ridge initially located along the Minnesota-Ontario border (Figure 2a). This thermal ridge seemed to narrow and intensify as it advected southward. By 1200 UTC, the thermal ridge extended down the major axis of Lake Superior to the

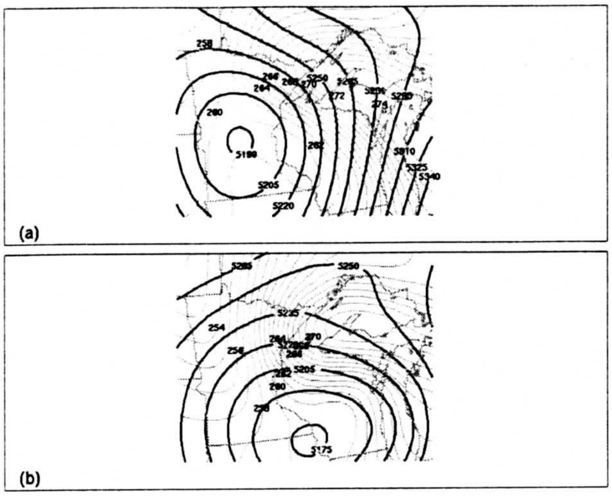


Figure 2 The 500 hPa geopotential heights contoured every 15 m and 1000 hPa potential temperatures contoured every 1 K from the ETA analysis for (a) 0000 UTC and (b) 1200 UTC 18 December 1996.

Twin Cities (Minneapolis/St. Paul, MN) (Figure 2b). It appeared that this ridge was spiraling towards the cyclone located to the southeast of the Twin Cities (Figure 2a-b). Also worth noting was the intensification of the thermal ridge upon the superpositioning of the ridge with the major axis of Lake Superior.

The apparent complexity of the multiple scale interaction involved in the development of the inland penetrating snow band encouraged the attempt to numerically simulate the storm. If the numerical simulation could successfully reproduce the snow band, then valuable information regarding the structural evolution of the band could be ascertained.

3. EXPERIMENTAL DESIGN

The University of Wisconsin Non-hydrostatic Modeling System (UW-NMS) (Hoggatt 1996) was employed to simulate the inland penetrating snow band observed from 1400 and 1800 UTC 18 December 1996. The UW-NMS has proven to be very skillful at predicting meso-β scale lake-effect precipitation patterns over the Great Lakes (Hoggatt 1996). A two way nested grid configuration was utilized with horizontal resolution of the outer and inner grids equal to 84 and 21 km respectively with vertical resolution of 100 m in the lowest levels gradually stretched to 1000 m at the model top of 16km.

4. RESULTS OF THE SIMULATION

The model simulated the development of a band of rising air just south of Duluth by 1300 UTC (Figure 3). This band propagated slowly southward decaying as it moved farther from Lake Superior perhaps showing the band's dependence on the Lake's heating. The simulated band seemed to coincide with a southward moving synoptic scale thermal ridge (Figures 2b and 3) and developed when the thermal ridge superimposed itself with the stationary mesoscale thermal ridge associated with the diabatic heating provided by Lake Superior. The superposition of the thermal ridges

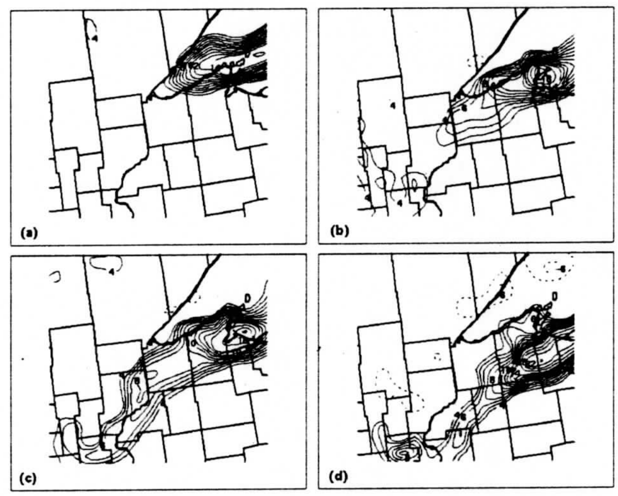


Figure 3 The 21 km UW-NMS forecasted vertical velocity contoured every 1 cm s^{-1} at (a) 1100 UTC, (b) 1300 UTC, (c) 1500 UTC, and (d) 1700 UTC.

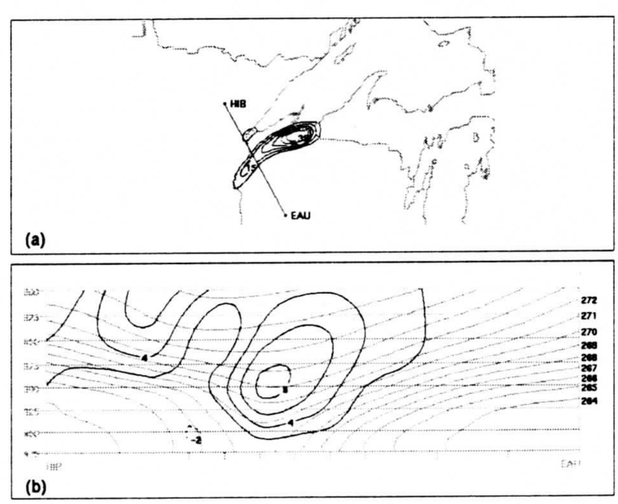


Figure 4 The 21 km UW-NMS 15 h forecasted (a) 950 hPa frontogenesis contoured every 5 K 100 km^{-1} 3 h^{-1} above 10 K 100 km^{-1} 3 h^{-1} and (b)cross section of potential temperatures contoured every 1 K and vertical motion contoured every 2 cm s^{-1}.

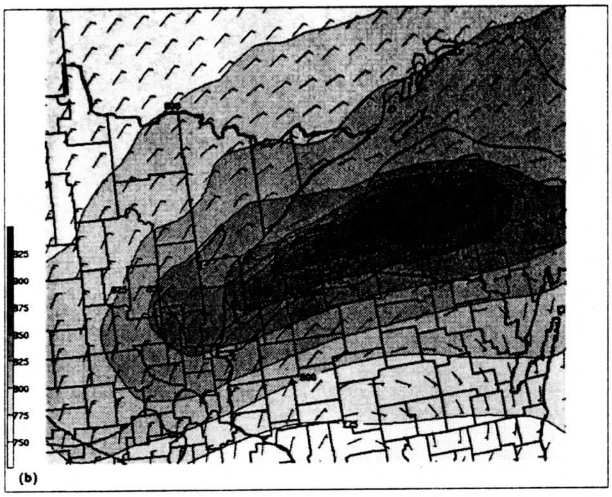


Figure 5 The 21 km UW-NMS 15 h 274 K isentropic surface contoured and shaded every 25 hPa with the darkest shading representing the highest pressure (lowest surface).

effectively promoted active diabatically generated frontogenesis resulting in upward vertical motion shown in Figure 4.

The band's behavior seemed to discount any notion that the snow band was purely lake-effect phenomenon. Instead, the snow band behaved more like a lake-enhanced snow band interacting in some way with the synoptic scale occluded cyclone. The analysis of observations and the numerical simulation suggested that the cyclone southeast of the Twin Cites was a weak occluded cyclone. The three dimensional structure of the cyclone could be visualized by inspecting an isentropic surface as suggested by Martin (1998) (Figure 5). The "sloping valley" on the isentropic surface shown in Figure 5 suggests the existence of a TROWAL (TROugh of Warm air ALoft) structure in the vicinity of the lake-effect snow band. Examination of the numerical simulated evolving structure suggested that the TROWAL spiraled into the cyclone and created a unique phasing of Lake Superior with the TROWAL. The phasing allowed the cyclone to tap the thermal energy of the Lake as the TROWAL became superpositioned over the major axis of the Lake. Some of the kinetic energy converted from this tapped thermal energy resulted in the thermally direct vertical circulation associated with active diabatic frontogenesis (Figure 4).

5. RESULTS OF THE FROZEN LAKE SIMULATION

In the above section, an explanation of the development and evolution of the snow band was proposed. In this section, the impact of Lake Superior's sensible and latent heat fluxes will be assessed. This was achieved by running the original simulation used above (CNTL) with Lake Superior completely frozen over (FZLK).
The FZLK simulation had far less precipitation than the CNTL simulation revealing the strong influence Lake Superior had on the precipitation pattern in the vicinity of the Lake (Figure 6). With Lake Superior frozen, the simulation (FZLK) failed to reproduce the snow band present in the CNTL simulation (Figure 7). The thermal ridge associated with the cyclone, however, was still present in the FZLK simulation but was far less robust than the thermal ridge in the CNTL simulation (Figure 7b). The deamplification of the thermal ridge apparent in the FZLK simulation would consequently weaken the frontogenetical forcing created by the thermal ridge. Hence, the snow band that was present in the CNTL simulation was not present in the FZLK simulation.

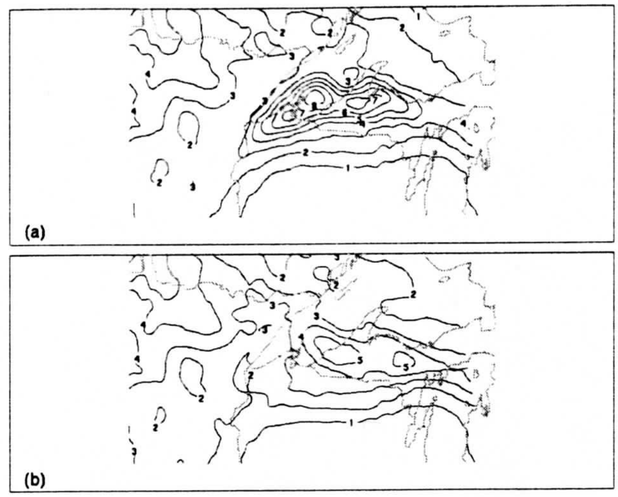


Figure 6 The 21 km UW-NMS 15 h forecasted precipitation contoured every 1mm for (a) CNTL and (b) FZLK.

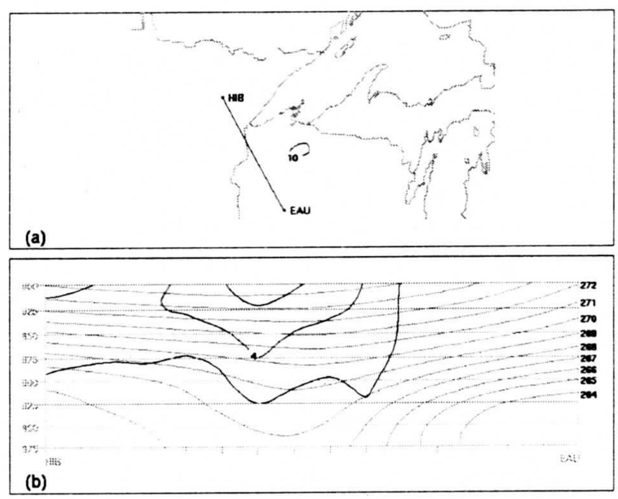


Figure 7 The 21 km UW-NMS FZLK 15 h forecasted (a) 950 hPa frontogenesis contoured every 5 K 100km^{-1} 3 h^{-1} above 10 K 100 km^{-1} 3 h^{-1} and (b) cross section of potential temperatures contoured every 1 K and vertical motion contoured every 2 cm s^{-1}.

6. SUMMARY AND CONCLUSIONS

A lake-enhanced snow band was featured exhibiting characteristics of both a lake-effect shore parallel band and a synoptic scale frontal precipitation pattern. It was shown from a numerical simulation that this peculiar snow band developed as a result of a Lake Superior modified synoptic scale structure. The sensible and latent heat fluxes off Lake Superior acted to intensify a synoptic scale thermal ridge associated with the TROWAL of an occluded cyclone located south of the region. The diabatic frontogenesis that resulted from the thermal ridge amplification produced a robust thermally direct vertical circulation that manifested itself as a thin line of strong upward vertical motion along the southern edge of the ridge forming the inland penetrating snow band observed on radar.

Without the Lake's heating (FZLK), the thermal ridge proved to be far less robust than in the CNTL simulation. Therefore, the diabatic frontogenesis accompanying the thermal ridge and its associated inland penetrating snow band virtually disappeared in the FZLK simulation showing the crucial importance of Lake Superior's thermal influence on creating the observed snow band.

The complex structure of the inland penetrating snow band has been shown though the use of numerical simulation. The results led to the hypothesis that the snow band resulted from a coupling of the mesoscale thermal forcing of Lake Superior and the TROWAL structure of an approaching occluded cyclone. The skill the UW-NMS displayed reproducing the snow band also demonstrated the utility of mesoscale models in forecasting complicated multiple scale weather systems that frequent the Great Lakes Region. As faster computers become affordable, mesoscale models such as UW-NMS can be used so that the behavior of complex weather systems like the featured inland penetrating snow band will not come as such a surprise.

7. ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation through Grant No. ATM9707165 and by NOAA contract No. UCAR S98-93861. Thanks to Ed Shimon and Ed Flenz at the National Weather Service Forecasting Office in Duluth, MN and to Pete Pokrant at the University of Wisconsin-Madison.

8. REFERENCES

Hjelmfelt, M. R., 1990: Numerical Study of the influence of environmental conditions on lake-effect snowstorms over Lake Michigan. *Mon. Wea. Rev.*, **118**, 138-150.

Hoggatt, B. D., 1996: Origins of temporal and spatial variability found within lake-effect snowstorms: A numerical investigation. *M.S. Thesis*, The University of Wisconsin-Madison, pp.131.

Martin, J. E., 1998: Quasi-geostrophic forcing of ascent in the occluded sector of cyclones and the TROWAL airstream. *Mon. Wea. Rev.*, in press.

Petterssen, S., and P. A. Calabrese, 1959: On some weather influences due to warming of the air by the Great Lakes in winter. *J. Meteor.*, **16**, 646-652.

Sousounis, P. J., and H. N. Shirer, 1992: Lake aggregate mesoscale disturbances. Part I: Linear analysis. *J. Atmos. Sci.*, **49**, 78-94.

Comparison of microscale convection patterns seen in lidar data and large-eddy simulations

Shane D. Mayor, Gregory J. Tripoli, Edwin W. Eloranta, and Bradley D. Hoggatt
Department of Atmospheric and Oceanic Sciences, University of Wisconsin
1225 W. Dayton St., Madison, Wisconsin, 53706, USA
phone: 608-263-6847, fax: 608-262-5974, e-mail: shane@lidar.ssec.wisc.edu

Introduction

Large eddy simulations (LESs) provide an attractive way of developing parameterizations for large-scale models such as global climate and weather forecast models. This is because they provide 4-D information which can potentially be used to compute fluxes with sampling errors that are much smaller than those made from in situ measurements. LESs, however, are only viable if we have confidence in their solutions. In particular, high resolution 4-D measurements are needed to test the LESs ability to accurately simulate the organization of convection such as linear and cellular boundary layer circulations. The objective of our research is to demonstrate the usefulness of volume imaging lidar data in LES validation.

To do this, we deployed the University of Wisconsin Volume Imaging Lidar (UW-VIL) at a site on the western edge of Lake Michigan and observed the growth of the convective boundary layer (CBL) over the water during cold-air outbreaks. We also ran the University of Wisconsin nonhydrostatic modeling system (UW-NMS) with microscale grid spacing to simulate lake-induced CBLs. This nonhomogeneous environment offers the advantages of a wide range of CBL depths and convective organization patterns within a simulation domain and requires substantially less computer time when compared to homogeneous CBL simulations that must be run for a large part of the diurnal cycle before several large-eddy turn-overs are obtained.

Previous work using VIL data to validate LES can be found in Avissar *et al.* 1998.

Observations

The UW-VIL was deployed in Sheboygan, Wisconsin, for the Lake-Induced Convection Experiment (Lake-ICE) during December of 1997 and January of 1998. The site (43°44'N, 87°42'W, 176 m ASL) was located within 10 m of the western shore of Lake Michigan. The VIL's beam-steering-unit (the point at which lidar beam is transmitted from) was located approximately 5 m above the lake surface. Thus, horizontal scans (PPIs) at 0° elevation allowed us to map the horizontal distribution of aerosol and steam-fog in a plane approximately 5 m above and parallel to the surface of the lake. Figure 1 is a PPI scan of this type. Steam-fog and hygroscopic aerosol produced a high-scattering tracer near the lake surface.

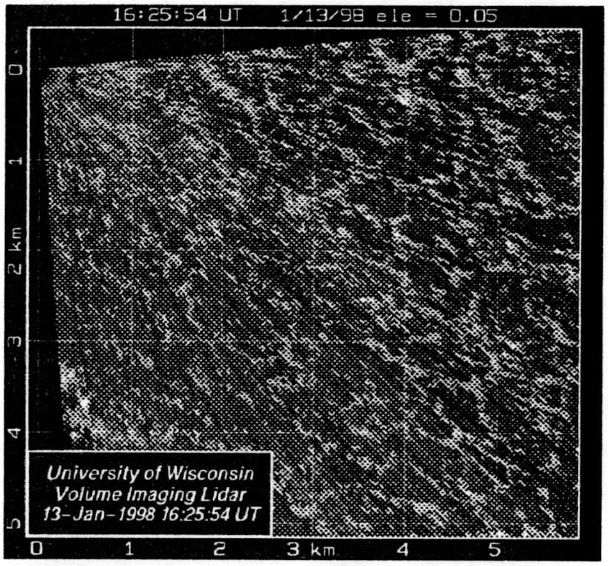


Figure 1. PPI of range-corrected backscatter intensity showing the organization of the steam-fog on 13 January 1998 from a few hundred meters to 5.9 km offshore. At the shore the mean wind during this time was from 280-290° at 5-10 m s^{-1} and the air temperature was -20° C. The open-cells range in horizontal size from about 100 m at 1 km offshore to about 500 m at 5.9 km offshore.

In addition to measuring aerosol scattering on horizontal slices through the surface layer, the VIL is capable of making vertical slices (RHIs) through the entire mixed layer and mapping the 3-D structure of aerosol scattering in the boundary layer. By rapidly moving the laser beam in a series of RHIs, each with a slightly increased azimuth angle, we can measure the 3-D structure. For example, a volume scan spanning 40° in azimuth and 15° in elevation angle requires about 2 minutes. A typical change in elevation angle between two laser pulses during an RHI is 0.23°. By repeating such volume scans, we can also monitor the temporal evolution of the structures.

Perhaps the most interesting VIL observations during Lake-ICE were open-cell patterns in the steam-fog about 5 meters above the surface of the lake on 10 and 13 January 1998. Cold air advection was occurring on both of these days and visual observations confirmed clear skies over the lidar site and steam fog on the surface of the lake. On 10 January the minimum temperature reached -16.7° C at 14 UTC with the wind from 236° at 6.5 m s^{-1}. On 13 January the air temperature dropped to -20° C and the wind was from 280-290° at 5-10 m s^{-1}. The lake water temperature on these days ranged from 3 to 5° C. In this paper we focus on the 13 January case, but we intend to present other cases at the poster.

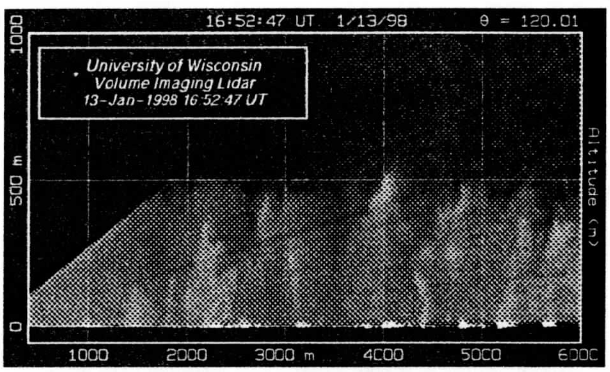


Figure 2. RHI of range-corrected backscatter intensity showing the vertical structure of steam-fog on 13 January 1998 from a couple hundred meters to 6 km offshore. Narrow columns of steam-fog and aerosol can be seen above the lake surface. A 500-m deep mixed layer formed over land appears to be advecting offshore which is also indicated in the upwind radiosonde sounding in figure 3.

The horizontal cell dimensions increase with increasing offshore distance and appear to be slightly elongated in the direction of the wind. Their somewhat hexagonal shape allows any one cell to share most of its walls with neighboring cells. Cell widths on the left side of figure 1 range from approximately 100 to 500 m while cell widths on the right range from 500 to 1000 m. The streaks across the image are caused by attenuation from the steam fog.

While the steam on the 10th did not appear to rise more than about 50-m above the lake, RHI scans from 13 January, such as figure 2, reveal narrow rising columns of steam which sometimes extend to the top of a 500-m deep mixed-layer. The columns are very bright near the surface and decrease in intensity with altitude. In figure 2, there is one such feature at about 4.4 km range that extends from the surface up to about 200 m. Some of these features may be steam devils and we hope that the VIL observations of them will enable us to quantify their size and number density.

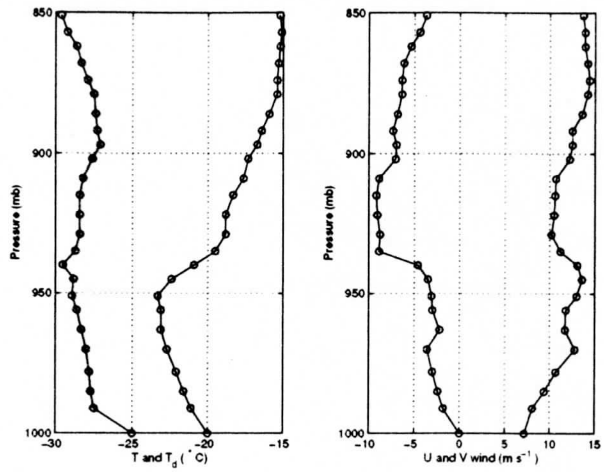


Figure 3. NCAR ISS CLASS sounding from 13 January 1998 at 16:30 GMT was used to initialize our model. The VIL also indicates a mixed layer extending up to about 500 m (about 950 mb) at the coast which is being advected over the lake by the larger scale flow. The wind profile shown here has been rotated so that the surface wind vector is normal to the north-south shoreline in the model.

Modeling

We are running the University of Wisconsin's scalable non-hydrostatic modeling system (Tripoli 1992) to simulate the leading edge of a lake-induced CBL. The model is a computationally efficient, elastic, fully non-Boussinesq grid-point model which includes enstrophy conservation.

For the work presented here, which represents our first attempts to simulate the lake-induced CBL, the model was run three times with horizontal resolutions of 10, 25 and 50 m. All of the simulations used a 0.25 s time-step and a vertical resolution of 1 m at the surface which increased at a rate of 1.1*dz until a resolution of 50 m was obtained (at about 450 m.) All simulations used 140x70x80 grid-points. The surface of the western 40 grid-points of each domain was snow-covered at air-temperature and the remaining surface was water at a temperature of 279 K.

The model was initialized with horizontally homogeneous initial conditions as prescribed by a radiosonde sounding 10 km upwind (figure 3). This profile of temperature, dew point and wind is maintained along the upwind (inflow at western wall) of the domain. Cyclic (periodic) boundary conditions are implemented along the northern and southern walls of the domain. An open boundary condition is maintained along the eastern wall (outflow). A Rayleigh absorbing layer of 16-points with a minimum dissipation time of 10 s was used at the top of the model. For these runs a geostrophic and hydrostatic reference state is assumed. Subgrid-scale turbulence parameterization is a buoyancy enhanced eddy-viscosity closure similar to that of Tripoli and Cotton (1982). Heat, moisture and momentum are transferred from the surface to the lowest layer of the model using standard bulk mixing theory. The model solves for saturation and cloud water diagnostically and the steam fog is produced as the result of supersaturation assuming conservation of total water mixing ratio and entropy.

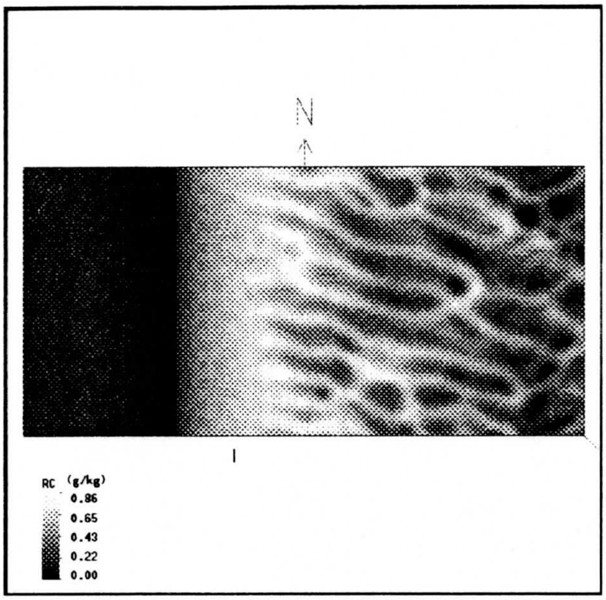


Figure 4. Horizontal distribution of condensed water (steam-fog in g/kg) at the lowest level of the model (1 m) at 30 minutes into simulation. The horizontal grid resolution was 50 m for this run. The size of the domain is 7 km (east-west) by 3.75 km (north-south).

The simulation with 50-m horizontal resolution, which has a horizontal domain of 7.0 by 3.5 km, produces a homogeneous region of steam-fog along the coastline out to approximately 1.5 km offshore where linear rolls form. The image shown in figure 4 is from 30 minutes after the beginning of the simulation—long after parcels entering the upwind edge of the domain would have traversed the full east-west distance of the domain. The flow near the surface veers with increasing offshore distance. At the downwind edge of the domain, the CBL depth has grown to approximately 600 m. When streamlines of the horizontal flow (such as those in figure 6) are superimposed on the condensed water field, the bands of steam-fog lie in regions of convergence and upward motion.

Figure 5 shows an east-west vertical slice of the lowest 15 grid-points at 30 minutes in the simulation. This image ranges from the surface to 26.2 m above the lake and is 7 km wide. The image shows the upward-sloping leading edge of the homogeneous band of steam-fog shown in figure 4 and some narrow columns of steam-fog rising from the surface of the lake. These features, which would be visible wisps of steam fog in reality, can be compared to the very bright spots along the bottom edge of the RHI shown in figure 2. The narrow columns of scattering which sometimes extend to the top of the 500-m deep mixed layer in figure 2 are composed of visible steam fog just above the surface and hygroscopically swollen aerosols at the remaining levels.

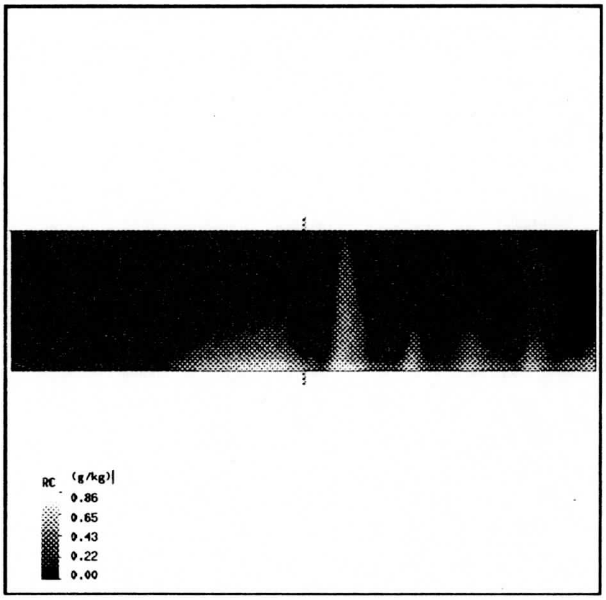


Figure 5. East-west vertical slice through the lowest 15 grid-points of the model domain showing condensed water (steam-fog in g/kg) at 30.0 minutes into simulation. The horizontal grid resolution was 50 m for this run. The image is 7 km wide by 26.2 m tall.

The 25 m and 10 m horizontal resolution simulations also use domains with 140x70x80 grid-points, and thus cover less area than the 50 m grid. The 25 m grid covers 3.5 by 1.75 km and the 10 m grid covers 1.4 km by 700 m. Both of these simulations produce a homogeneous region of steam-fog immediately downwind of the shoreline followed by linear rolls. Nine roll circulations set up in the 50 m grid (λ = 420 m); approximately 12 in the 25 m grid (λ=160 m), and 18 in the 10 m grid (λ = 40 m). The 50 m grid appears to preserve these roll structures downstream for a much greater proportion of the grid. Downstream of the rolls, a braided or more cellular appearing pattern, can be seen in all three simulations. The dependence of the structure on resolution warrants further investigation.

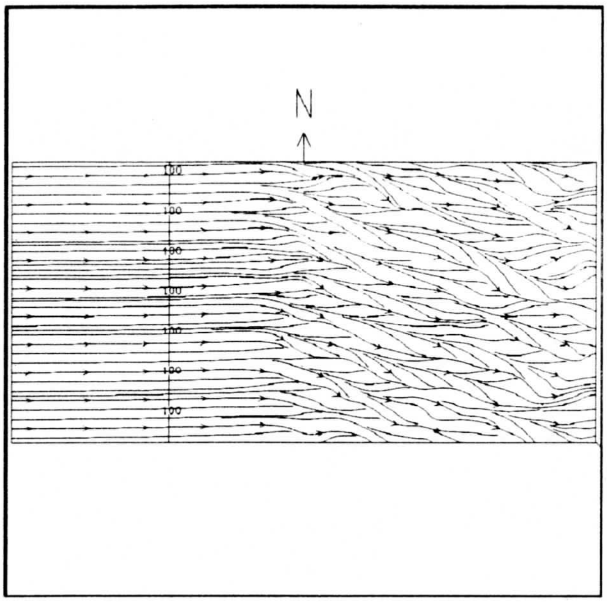


Figure 6. Streamlines of surface wind at 30 minutes into simulation. Grid resolution was 50 m for this run. The vertical line labeled 100 indicates the position of the coastline. This domain is 7 km (east-west) by 3.75 km (north-south).

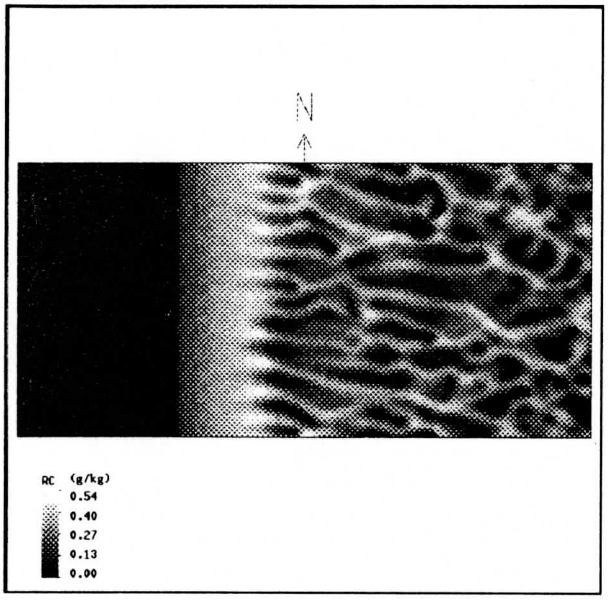


Figure 7. Same as in Figure 4 except with 25 m horizontal resolution and a 3.5 by 1.75 km domain.

All the images shown here are frames extracted from high-resolution color animations. These MPEG movies can be downloaded from our website at http://lidar.ssec.wisc.edu.

Summary

We have begun qualitative comparisons of VIL observations and LES of the lake-induced convective boundary layers. Our next steps include running

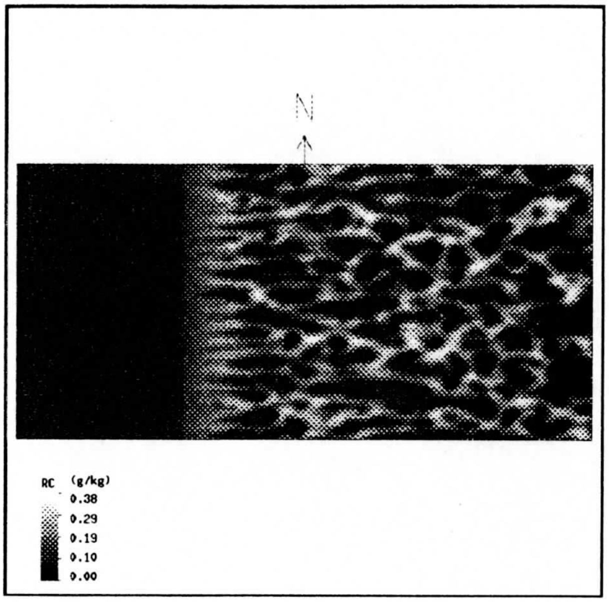


Figure 8. Same as in Figure 4 except with 10 m horizontal resolution and a 1.4 by 0.7 km domain.

simulations with high spatial resolution grids and very large domains. We will also perform quantitative comparison of wind fields; boundary layer depth; shapes, sizes and correlation times of the structures in both the observations and model output as a function of offshore distance.

Acknowledgements

This work was made possible by NSF grant number ATM9707165 and ARO grant number ARO DAAH-04-94-G-0195. The calculations were performed on an 8-processor J50 computer furnished by IBM Corporation.

References

Avissar, R., E. W. Eloranta, K. Gurer, G. J. Tripoli, 1998: An Evaluation of the Large-Eddy Simulation Option of the Regional Atmospheric Modeling System in Simulating a Convective Boundary Layer: A FIFE Case Study, *J. Atmos. Sci.*, **55**, 1109–1130.

Eloranta, E. W., 1988: Volume imaging lidar observations of the convective structure surrounding the flight path of a flux-measuring aircraft. *J. Geophys. Res.*, **97**, 18383–18393.

Tripoli, G. J. and W. R. Cotton, 1982: The use of ice-liquid water potential temperature as a thermodynamic variable in deep atmospheric models. *Mon. Wea. Rev.*, **109**, 1094–1102.

Tripoli, G. J., 1992: A nonhydrostatic mesoscale model designed to simulate scale interaction, *Mon. Wea. Rev.*, **120**, 1342–1359.

1 Dec 98 - 30 Nov 99

PROPOSAL BUDGET

FOR NSF USE ONLY

ORGANIZATION University of Wisconsin Space Science and Engineering Center	PROPOSAL NO.	DURATION (MONTHS) Proposed	Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR Gregory Tripoli	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.7. show number in brackets)	NSF Funded Person-mos. CAL	ACAD	SUMR	Funds Requested By Proposer	Funds Granted By NSF (If Different)
1 PI - G. Tripoli	2			$ 11,136	$
2 Co-PI - J. A. Young	1			9,797	
3 Co-I - B.Hogatt	6			17,579	
4	0			0	
5	0			0	
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (3) TOTAL SENIOR PERSONNEL (1-6)	9			$ 38,512	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( ) POST DOCTORAL ASSOCIATES	0			0	
2. ( ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0			0	
3. (1) GRADUATE STUDENTS				18,351	
4. ( ) UNDERGRADUATE STUDENTS				0	
5. ( ) SECRETARIAL-CLERICAL				0	
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				56,863	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COST)				12,853	
TOTAL SALARIES. WAGES AND FRINGE BENEFITS (A+B+C)				69,716	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $1,000.)					
TOTAL PERMANENT EQUIPMENT				0	
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				0	
2. FOREIGN				3,030	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 2. TRAVEL 3. SUBSISTENCE 4. OTHER					
TOTAL PARTICIPANTS COSTS					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				1,500	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				3,000	
3. CONSULTANT SERVICES				0	
4. COMPUTER (ADPE) SERVICES				2,000	
5. SUBCONTRACTS				0	
6. OTHER				0	
TOTAL OTHER DIRECT COSTS				6,500	
H. TOTAL DIRECT COSTS (A THROUGH G)				79,246	
I. INDIRECT COSTS (SPECIFY) 44% of A, B, C, E, F and G1-G4					
TOTAL INDIRECT COSTS				34,868	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				114,114	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPM 252 AND 253)				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 114,114	$

M. COST SHARING: PROPOSED LEVEL $	AGREED LEVEL IF DIFFERENT $			
PI/PD TYPED NAME & SIGNATURE* Gregory Tripoli [signature]	DATE	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
INST. REP. TYPED NAME & SIGNATURE* Cheryl E. Gest [signature: Cheryl E. Gest]	DATE OCT 2 0 1997	Date Checked	Date of Rate Sheet	Initials-ORG

NSF FORM 1030 (1/94) *Supersedes All Previous Editions* *SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPM233)