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A Real-Time Meteorological Analysis And Dispersion Prediction System For Emergency Preparedness

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ABSTRACT

Improvements in computational power in recent years have resulted in operational numerical weather prediction (NWP) models being run at increasingly higher resolution. Regional operational models used at the National Centers for Environmental Prediction (NCEP) are now run routinely at meso-beta and meso-gamma scale resolutions, multiple times per day. In addition, more advanced data assimilation techniques are now being employed at operational forecast centers resulting in improved high frequency mesoscale analyses.

The diagnostic meteorological model (CALMET) uses three-dimensional gridded data from prognostic meteorological models to develop fine-scale winds and other meteorological fields consistent with the terrain and land use on the fine-scale diagnostic grid and optionally assimilates meteorological observations into the analysis. Interfaces have been developed between CALMET and operational models such as the NCEP ETA model and the Forecast Systems Laboratory (FSL) Rapid Update Cycle (RUC2) model, as well as the Penn State/NCAR Fifth Generation Mesoscale Meteorological Model (MM5) and the Regional Atmospheric Modeling System (RAMS). Three-dimensional gridded analyses and forecasts are readily available from NCEP and other web sites in real-time. A demonstration is provided in this paper of the use of ETA model forecast fields around a hypothetical nuclear power plant to produce fine scale predictions of three-dimensional meteorological fields. The CALMET model has the advantage of being capable of running at higher resolutions than the dynamical models to improve the simulation of meteorological fields. This is especially relevant at coastal boundaries and in complex terrain. The non-steady-state CALPUFF dispersion model uses the three-dimensional meteorological fields from the CALMET model to simulate plume transport and diffusion within spatially and temporally varying flows. The CALPUFF modeling system is approved as a *Guideline Model* by the U.S. Environmental Protection Agency for long-range transport and on a case-by-case basis for near-field analyses involving complex or non-steady-state flows. Plume transport and diffusion are critical elements for dose assessment and radiation monitoring team dissemination during an accidental release. The ETA/CALMET/CALPUFF forecast/dispersion modeling system is currently operational at two industrial sites in North America providing routine real-time and forecast predictions of dispersion impacts to plant operators.

This paper provides a demonstration of the use of the CALMET/CALPUFF modeling system coupled with a forecast model (ETA) for a well-defined lake breeze event in the summer of 2003. The use of the system to support emergency response operations at nuclear power plants is discussed. The importance of characterizing spatial and temporal changes in the meteorological fields and treating the non-steady-state aspects of plume dispersion are also discussed.

INTRODUCTION

Real-time analysis and prediction of plume transport and diffusion during an accidental release at a nuclear power plant has been a challenging problem for many years. Many nuclear power plants are situated along coastlines or within river valleys; thus terrain forced mesoscale circulations are an important part of the climatology in the regions around these plants. The ability to resolve the spatial and temporal evolution of diurnal terrain forced flows are critical to simulations of plume transport and diffusion, and ultimately to the analysis and prediction of plume concentrations and deposition within both the 10-mile plume exposure pathway emergency planning zone (EPZ) and the 50-mile ingestion pathway EPZ. In many cases, meteorological observational networks around nuclear power plants are not of sufficient density to allow the mesoscale meteorological systems to be properly resolved. Additionally, straight line Gaussian dispersion models can not properly determine plume position and concentrations in such non-steady state flow situations.

In recent years, significant advances in prognostic meteorological models, and atmospheric dispersion models have been achieved. This has been facilitated by dramatic increases in computational power, which has allowed model simulations to be performed with increasingly higher resolutions and with improved physics and parameterization schemes. Regional operational models used at the National Centers for Environmental Prediction (NCEP) are now run routinely at meso-beta and meso-gamma scale resolutions, multiple times per day. The NCEP ETA model (Black, 1994) is now run four times per day at a horizontal spatial resolution of 12 kilometers (km) with 60 vertical levels while the operational RUC model (Benjamin et al, 2002) is run hourly at a horizontal spatial resolution of 20 km with 50 vertical levels. Recently, NCEP has implemented higher resolution ETA model runs at a horizontal spatial resolution of 8 km, four times per day for limited area domains covering the United States. In addition, more advanced data assimilation techniques are now being employed at operational forecast centers, such as the three-dimensional variational analysis technique (3DVAR). This technique has replaced the Optimum Interpolation technique used for many years at NCEP and other forecast centers. The primary advantage of the 3DVAR approach is that many different types of data can be assimilated more easily when compared to the Optimum Interpolation scheme. In the previously used Optimum Interpolation approach, newer remote sensing data such as GOES radiance measurements or radial winds derived from Doppler radars were subject to the constraint that each type of data must be assimilated separately. Thus it was not possible to incorporate a wide range of data types into an analysis. The more recently implemented 3DVAR technique solves this problem. The inclusion of more data, particularly the remote sensing data, into the model analysis has resulted in an overall improvement in high frequency mesoscale analysis.

The combination of higher spatial resolution and improved analysis has allowed the NCEP operational model's gridded data sets to be usable in variable trajectory atmospheric dispersion modeling systems such as the CALMET/CALPUFF modeling system (Scire et al 2000a,b). The prognostic models have the advantage of being able to realistically predict the evolution of mesoscale meteorological fields not completely resolved by observations alone. Diagnostic meteorological models like CALMET can further resolve the effects of smaller scale terrain features and sharp gradients in land surface characteristics that are not resolved by the prognostic models. This blend of prognostic and diagnostic meteorological models have shown to be a practical approach for producing high resolution three dimensional meteorological fields for non-steady state dispersion models such as CALPUFF. Experiments with MM5 and the CALMET model (Robe and Scire 1998) have demonstrated that improvements in meteorological fields are evident when using MM5 simulations as a first guess in the CALMET model.

Real-Time CALMET/CALPUFF Modeling System

A flow diagram showing the design of the real-time CALMET/CALPUFF modeling system is provided in Figure 1. This system consists of two components, the analysis subsystem and the prediction subsystem. Both the analysis and the prediction subsystems will execute simultaneously. The objective is to use the prediction subsystem to forecast meteorological fields and plume concentrations and use the analysis subsystem to track the predictions. The entire modeling system can be implemented on a standard personal computer and is fully automated so it can operate on a continuous basis unattended. The core of the system is the CALMET diagnostic meteorological model and the CALPUFF dispersion model.

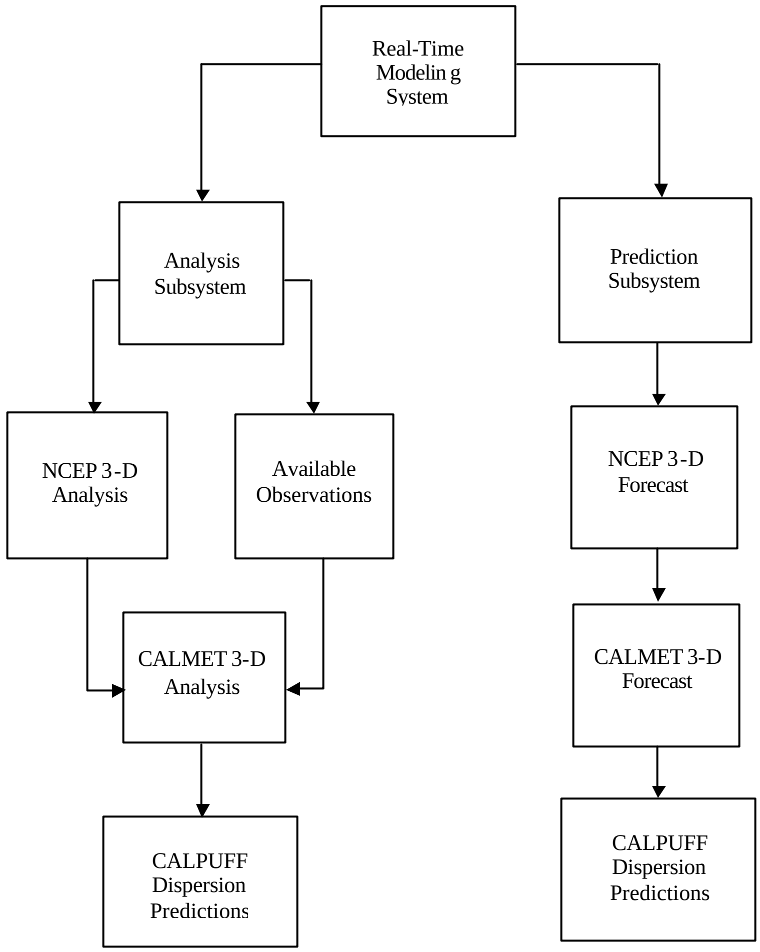


Figure 1. Flow chart depicting design of real-time CALMET/CALPUFF analysis and prediction system

The CALMET meteorological model is used to generate the analysis and forecasts of three-dimensional meteorological fields, which are then used as input for a CALPUFF simulations. The CALPUFF simulation will estimate both predicted and current analyzed plume location, downwind concentration and deposition. The prediction subsystem typically uses real-time gridded forecasts and analysis from either the NCEP ETA or RUC models, available online through NCEP's public FTP server. However, it can easily use other mesoscale models such as MM5 (Grell et al, 1994), if required. The analysis subsystem uses a blend of both three-dimensional analysis fields from the NCEP regional models and data from observation stations around the source. The CALMET model interpolates the NCEP gridded data (either analysis or forecast fields) onto the CALMET higher resolution grid and uses these data as a "first guess". It will then adjust the meteorological fields accounting for terrain effects such as slope flows, channeling and blocking. In the case of the analysis subsystem, the CALMET model will interpolate available observational data onto the CALMET grid after any terrain adjustments are complete.

The CALMET model is typically configured using a much higher spatial resolution, typically around 1-2 km compared to the operational models (i.e.8 km or 12 km). It uses high-resolution United States Geologic Survey (USGS) digital terrain data and land use data, including the Composite Theme Grid land use data at 200-meter resolution. In addition to terrain adjustments, the CALMET model will compute mixing depth and turbulence parameters on a grid cell by grid cell basis using both an over-land and over-water boundary layer module. The final product is a three-dimensional fine scale analysis or forecast of wind, mixing depth, turbulence parameters that can be used to drive the dispersion calculations in CALPUFF.

The CALPUFF model is a non-steady-state Gaussian puff model that can account for multiple processes such as building downwash, terrain-plume interactions, dry and wet deposition, and over-water dispersion. In addition, CALPUFF can model emissions from a wide range of source types (e.g. point, line, and volume sources). Using three-dimensional meteorological fields from the CALMET model, the CALPUFF model can simulate plume transport and diffusion within regions with spatially and temporally varying meteorological fields. Dispersion coefficients can be determined using Pasquill-Gifford or Mcelroy-Pooler curves, or using similarity theory with heat and momentum fluxes provided by CALMET. The model includes algorithms for handling overwater dispersion and coastal interaction effects (e.g. thermal internal boundary layers and plume fumigation). The model uses the probability density function approach during convective conditions. The CALMET/CALPUFF modeling system is highly modularized, such that new modules, such as a dose assessment module, can easily be implemented. Thus, the state-of-the-art dispersion modeling techniques and resulting plume transport and diffusion parameters of CALPUFF can be easily combined with a dose conversion module to generate necessary results for dose assessment. The CALPUFF modeling system has been approved by the U.S. Environmental Protection Agency as a *Guideline Model* (Federal Register, April 15, 2003) suitable for regulatory use for long range transport and on a case-by-case basis for short-range applications involving complex and non-steady-state flows such as in complex terrain, coastal situations, and where flow stagnation and flow reversals are important.

The real-time ETA/CALMET/CALPUFF system has been running successfully for nearly two years at an industrial facility in Texas (Robe et al., 2002) and for 9 months at a second facility, located in Ontario, Canada (Morrison et al., 2003). These systems are operating in real-time and are fully automated, yielding customized output four times per for use by plant personnel. As described in the references, comparisons of CALPUFF predictions with observations at both sites showed the ETA/CALMET/CALPUFF modeling system has performed very well.

Lake Breeze Episode of July 29, 2003

In order to illustrate the capabilities of the real-time CALMET/CALPUFF modeling system, a simulation was performed of a lake breeze event that occurred along the western coastline of Lake Michigan on July 29, 2003. The synoptic conditions on this day are shown by the surface and 500 millibars (mb) analysis given in Figure 2. The surface analysis for 1200 Coordinated Universal Time (UTC) on July 29, 2003 prepared by the Hydrometeorological Prediction Center, shows a surface anticyclone oriented from west to east across the Midwest with the ridge axis situated just south of Lake Michigan. The NCEP 500 mb analysis shows a northwest flow across the western Great Lakes on the east side of a large scale ridge over the western United States. These synoptic conditions support clear conditions with weak surface winds over the western Great Lakes, an environment suitable for lake breeze development.

CALMET and CALPUFF model forecast simulations based on the ETA model forecast fields are conducted for a 12-hour period to illustrate how CALMET/CALPUFF modeling system predicts pollutant dispersion within complex mesoscale flows such as a lake breeze. The modeling domain chosen for these simulations is located along the western coastline of Lake Michigan in the vicinity of Sheboygan, Michigan. The CALMET meteorological model is configured for a 55 × 55 km modeling domain with a horizontal spatial resolution of 1 km. Ten vertical layers are used to resolve the vertical wind structure from the surface up to a height of 3000 meters. The meteorological fields are driven by the NCEP ETA model forecast fields from the 1200 UTC, July 29, 2003 operational ETA run. These fields are treated in the CALMET model as first guess winds and interpolated to a 1-kilometer resolution using CALMET's diagnostic wind field algorithms.

Figure 3 shows some wind field plots from the CALMET meteorological model simulations. The 1-hour, 3-hour, and 6-hour predicted wind fields at 10-meters above ground are shown. The green circle on the plots depicts the 10-mile plume exposure EPZ for a hypothetical nuclear power plant located at Universal Transverse Mercator (UTM) coordinate 440.000 km East, 4850.000 km North. The 1-hour predicted wind field (8 a.m. local standard time [LST]) shows a very weak northwest flow across the domain with wind speeds generally less than 1 meter per second (m/s) over the east portion of the domain to about 2 m/s over the western sections. At this time the lake breeze had not begun. By 10 a.m. LST (3-hour forecast) it is clear the lake breeze is starting to develop. The wind field shows very light winds, on the order of 1 m/s across the modeling domain with northwesterly winds over the western portion of the domain. However, a southeasterly flow is beginning to develop within a few km of the coast and over the open waters of Lake Michigan. This results in a sharp convergence zone just a few kilometers inland from the lake, with a band of nearly calm winds where the two opposing flows converge. At 1 p.m. LST (6-hour forecast) the lake breeze has strengthened and pushed deeper inland. Winds are mostly southeasterly at this time within most of the CALMET domain. The strongest winds (about 3-4 m/s) are predicted to be within about 5 km of the coastline and offshore. Much weaker winds are shown over the western part of the domain with wind speeds about 1 m/s. Hourly wind observations at the National Weather Service station at Sheboygan, support these predicted winds, with northwesterly winds of 2 m/s reported around 9 a.m. LST, variable winds reported from 11 a.m. to 12 p.m. LST, and winds shifting to southeast by 1 p.m. LST. Further, the Sheboygan NWS station observed wind speeds increasing to near 5 m/s consistent with the predicted inland penetration of the onshore flow. Later in the afternoon winds at Sheboygan became southerly and then southwesterly.

Figure 4 presents the predicted wind field (4-hour forecast) valid at 11 a.m. LST at three separate vertical levels (10 meters, 120 meters, and 450 meters) in order to show how the winds change with height. At 10 meters above ground, the winds over the western part of the CALMET domain, shows very light west-northwest flow, while near the coast and offshore winds are stronger and southeasterly, consistent with the developing lake breeze. Note that at 10-meters above ground the onshore flow has penetrated about 10 km inland. At the 120-meter level, the onshore flow is just reaching the coast with the convergence zone situated further east than at 10 meters. Again, the overall winds are weak and are on the order of 1-2 m/s. Along the convergence zone axis winds are nearly calm. Finally, at 450 meters above ground the winds are shown to be from the northwest at about 2 m/s across the entire CALMET modeling domain. These wind patterns suggest a shallow and weak lake breeze at this time, with the onshore flow confined to a shallow layer, of a couple of hundred meters above the ground. These features illustrate the wind field complexity that can arise during the development phase of lake breeze circulations. These patterns are also shown in Figure 5, which provides a time-height section of predicted wind vectors from the CALMET model. This plot clearly shows the development of the onshore lake breeze flow that increases in depth through the day.

In order to illustrate how the CALPUFF non-steady state model will handle plume transport within such a meteorological regime, a CALPUFF simulation was conducted using the predicted winds from the CALMET model. The CALPUFF simulation assumed an accidental release from a hypothetical 100-meter stack, as might be found with a boiling water reactor (BWR). The simulation started at 7 a.m. LST and lasted for 12 hours (i.e. about the duration of the lake breeze event). Figure 5 shows a plot of a puff trajectory from the CALPUFF model simulation. This figure shows the puff is initially transported toward the southeast crossing the coast just before 9 a.m. LST, and then proceeding to move over Lake Michigan. From 10 a.m. LST to 11 a.m. LST the puff turns sharply toward the west and northwest; crossing the coastline around 15 km (about 9 miles) south-southeast of the hypothetical stack location, in response to the developing onshore flow. The puff is then transported northward back toward the hypothetical stack, moving parallel to the coastline and only about 1 km inland. Eventually, the puff turns toward the northeast and again crossing the coastline northeast of the hypothetical stack just prior to 4 p.m. LST. The puff then moves out over Lake Michigan and continues north-northeastward for the remainder of the simulation. This trajectory is consistent with the developing onshore lake breeze flow, which gradually turns clockwise during the day due to the Coriolis effect. Here, only one puff was tracked for simplicity, but CALPUFF will use numerous puffs to simulate the plume. Steady-state dispersion models cannot capture complex trajectories involving flow reversals such as this.

Figure 7 shows contour plots of predicted 1-hour average ground level concentration of radionuclides at four different times based on an instantaneous release at 7 a.m. LST, July 29, 2003 from a hypothetical 100 meter tall stack. Contour plots showing hourly average concentrations from 8:00 a.m. – 9:00 a.m. LST, 10:00 a.m. - 11:00 a.m. LST, 2:00 p.m. – 3:00 p.m. LST, and 4:00 p.m.- 5:00 p.m. LST are shown. At 8:00-9:00 a.m. LST, the ground level concentrations are relatively high and the plume has been transported toward the southeast, extending out a distance of about 15 km from the stack. At 10:00-11:00 a.m. LST, the plume is being transported back towards the coast by the developing onshore lake breeze flow. At this time, the concentrations are significantly less than at the previous period due to puff diffusion. The ground level concentrations at 2:00 –3:00 p.m. LST clearly show the plume transport now is northward as the southeast flow turns more southerly. By 4:00 – 5:00 p.m. the plume is now located north of the hypothetical stack with further reductions in ground level concentration evident. Note that this northerly transport would not have been simulated if only observations at 8 a.m. LST were used. The CALMET predicted winds being driven by the NCEP ETA model winds allow these shifting trajectories to be anticipated several hours in advance.

CONCLUSIONS

A real-time meteorological analysis and dispersion prediction system based on the ETA NWP model, the CALMET diagnostic model and the CALPUFF dispersion model has been developed for operational use on a desktop PC. The CALMET diagnostic meteorological model is coupled to the NCEP ETA prognostic model to produce high-resolution forecasts of three-dimensional meteorological fields. These meteorological fields are then used to drive the non-steady state CALPUFF dispersion model. The entire modeling system is designed to be implemented on a personal computer with a high-speed Internet connection to obtain NCEP forecast fields. The system is fully automated so it typically operates unattended. Output from this system can be fully customized to meet specific emergency preparedness needs. The real-time/forecast ETA/CALMET/CALPUFF system for one industrial facility has been running successfully for nearly two years, and at a second site for 9 months.

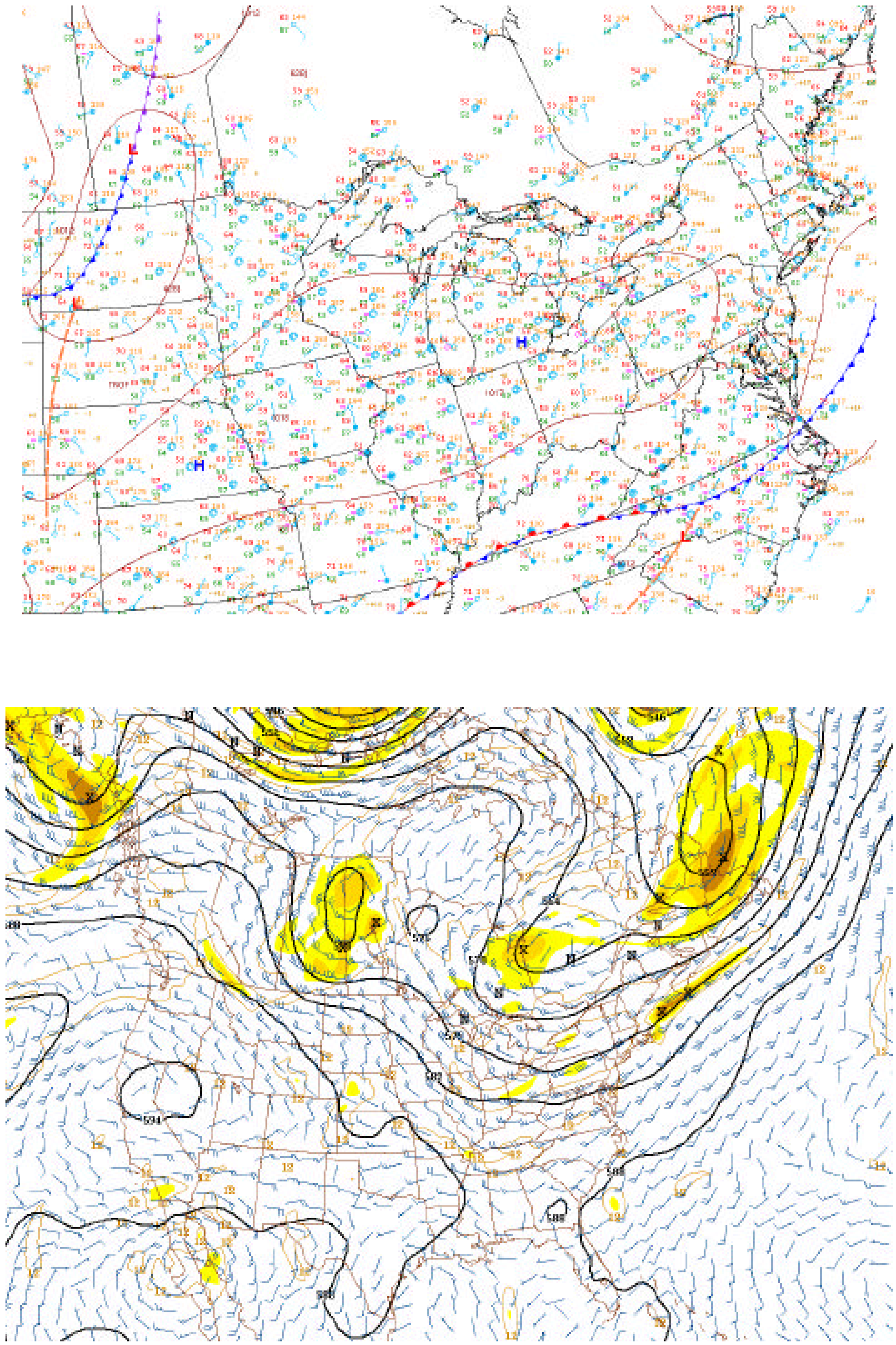


Figure 2. Hydrometeorological Prediction Center surface analysis for 1200 UTC, July 29, 2003 (top) and the NCEP 500 mb Analysis for the operational ETA model valid at 1200 UTC, July 29, 2003 (bottom)

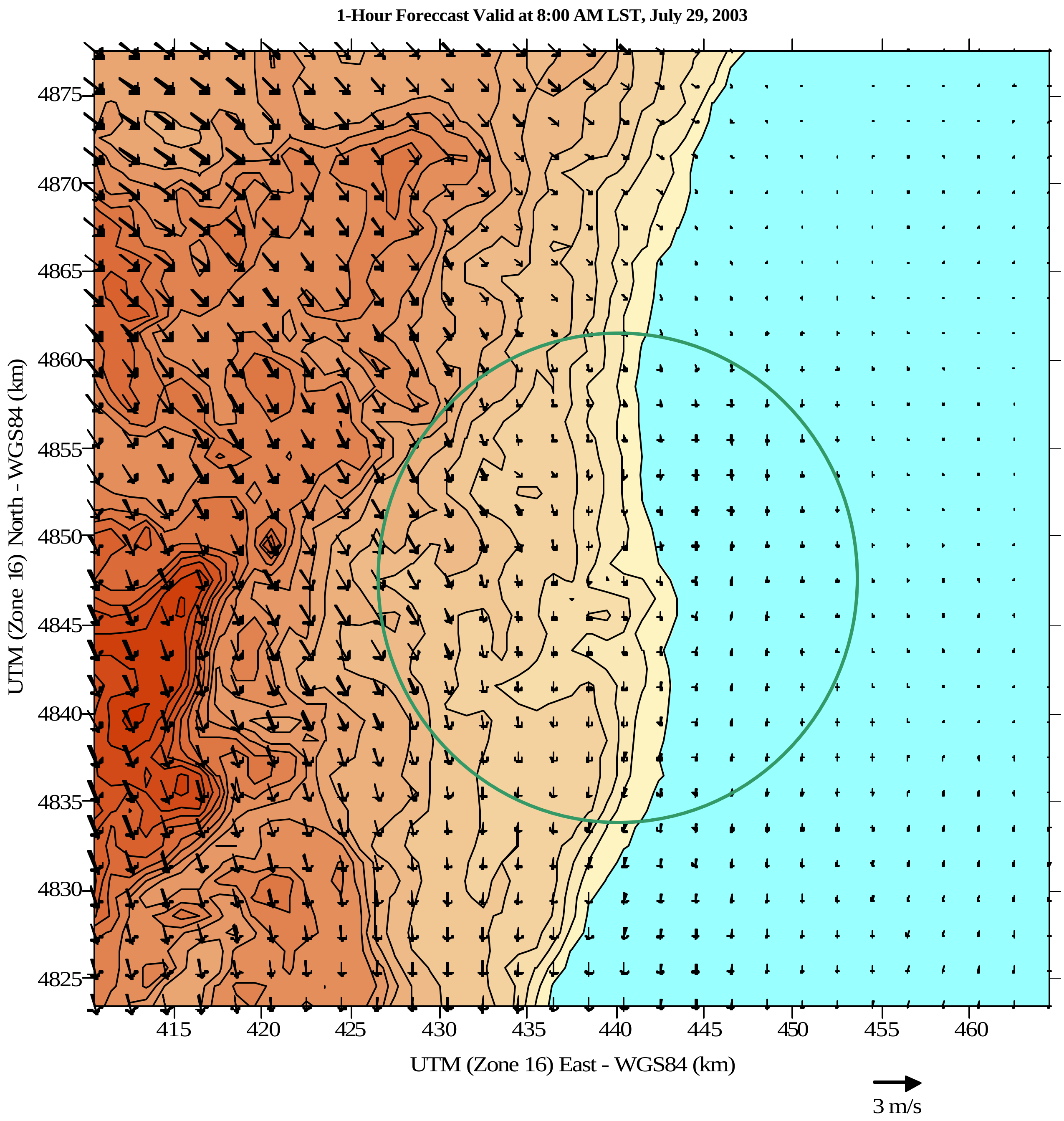


Figure 3. Plot of 1-hour, 3-hour, and 6-hour predicted wind fields from the ETA/CALMET models for July 29, 2003 (Sheet 1 of 3)

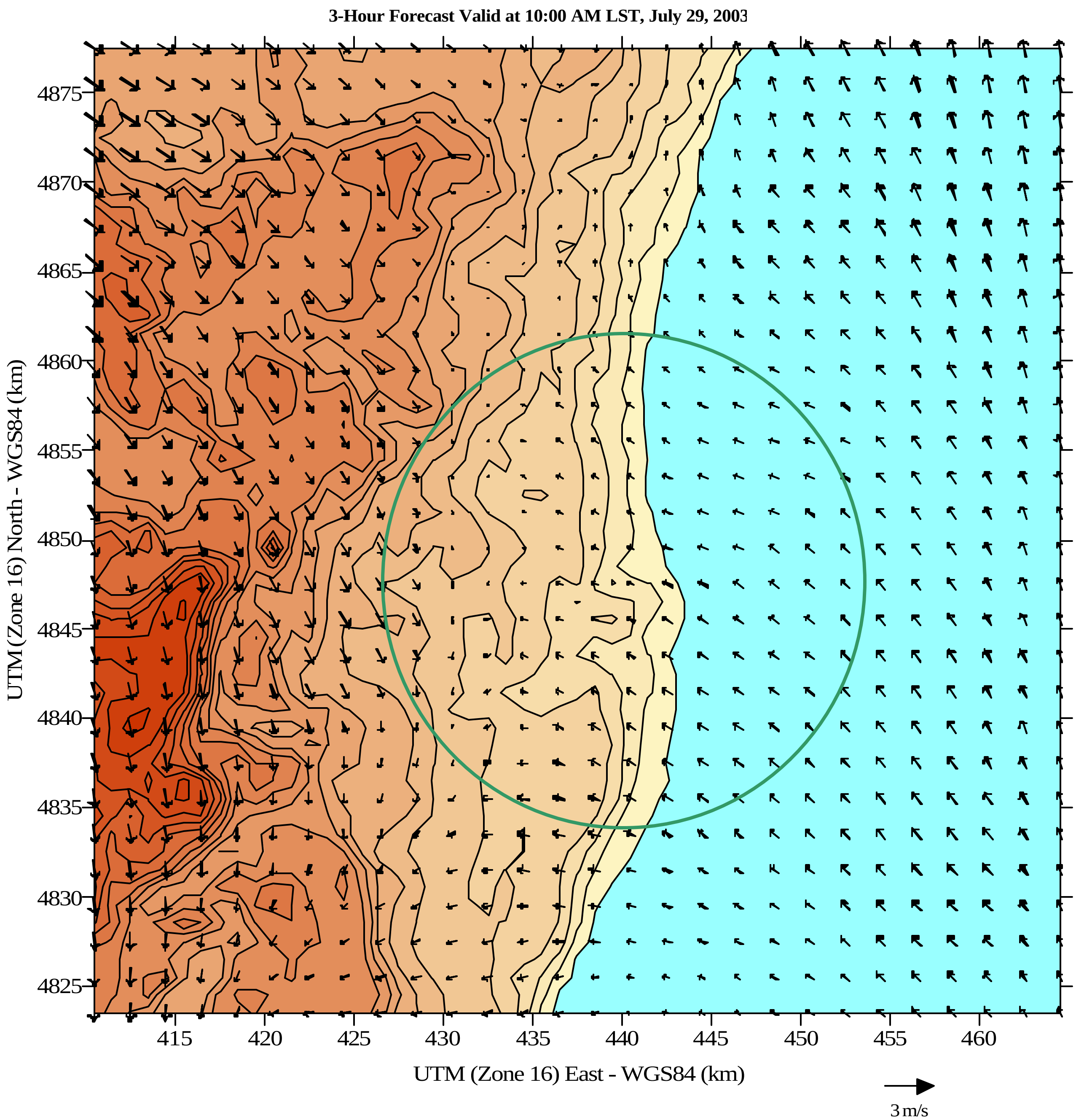


Figure 3. Plot of 1-hour, 3-hour, and 6-hour predicted wind fields from the ETA/CALMET models for July 29, 2003 (Sheet 2 of 3)

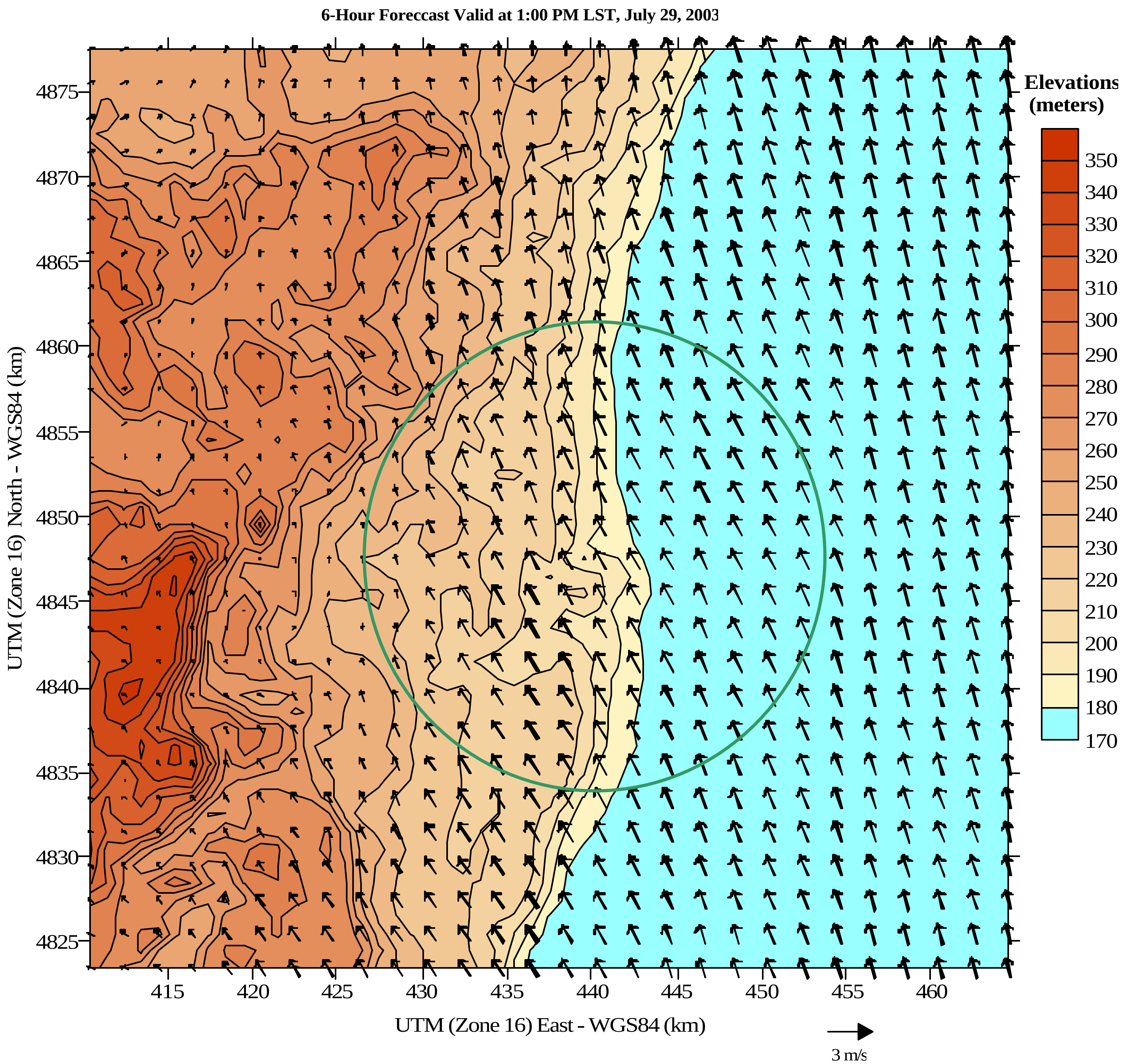


Figure 3. Plot of 1-hour, 3-hour, and 6-hour predicted wind fields from the ETA/CALMET models for July 29, 2003 (Sheet 3 of 3)

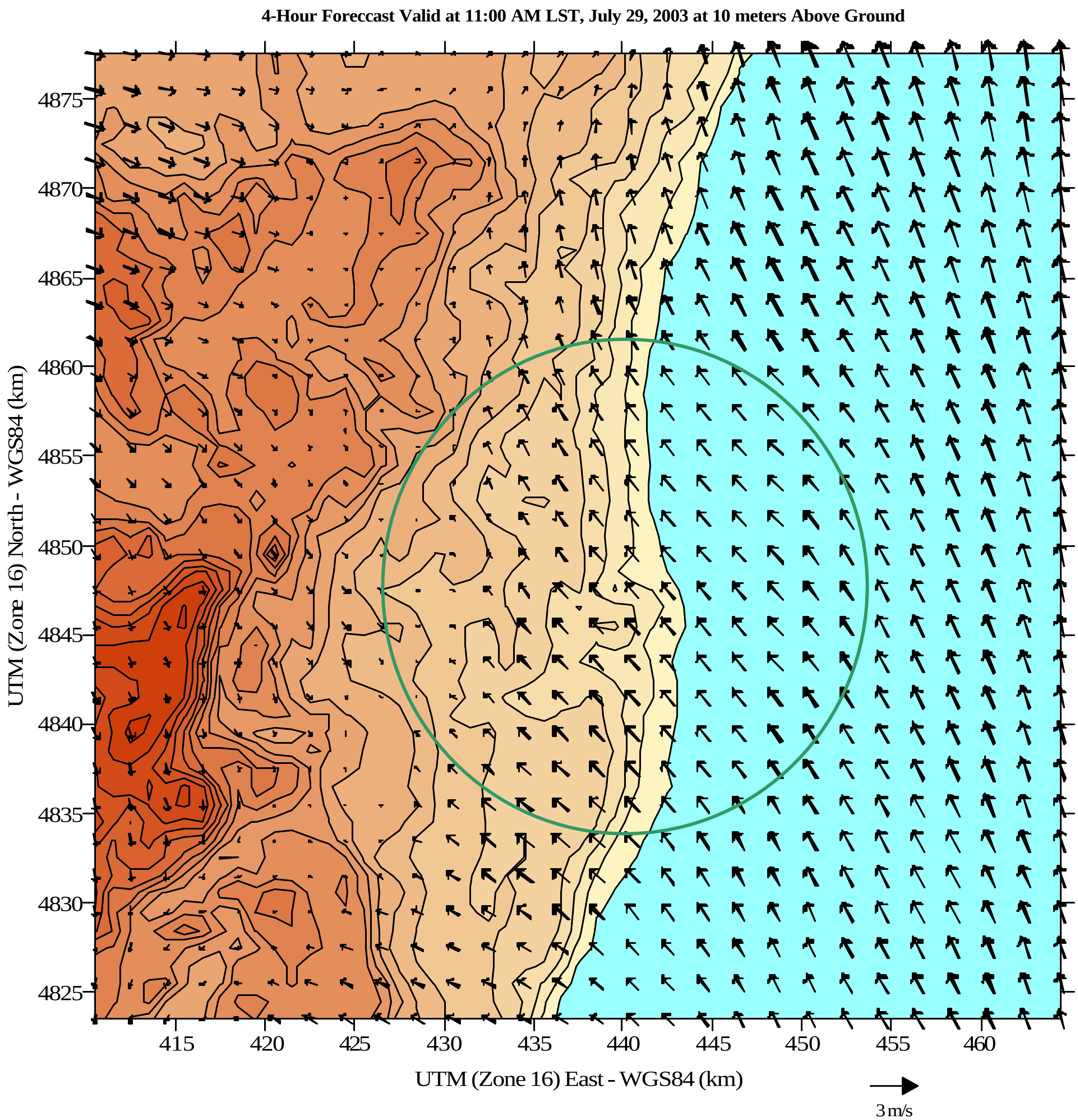
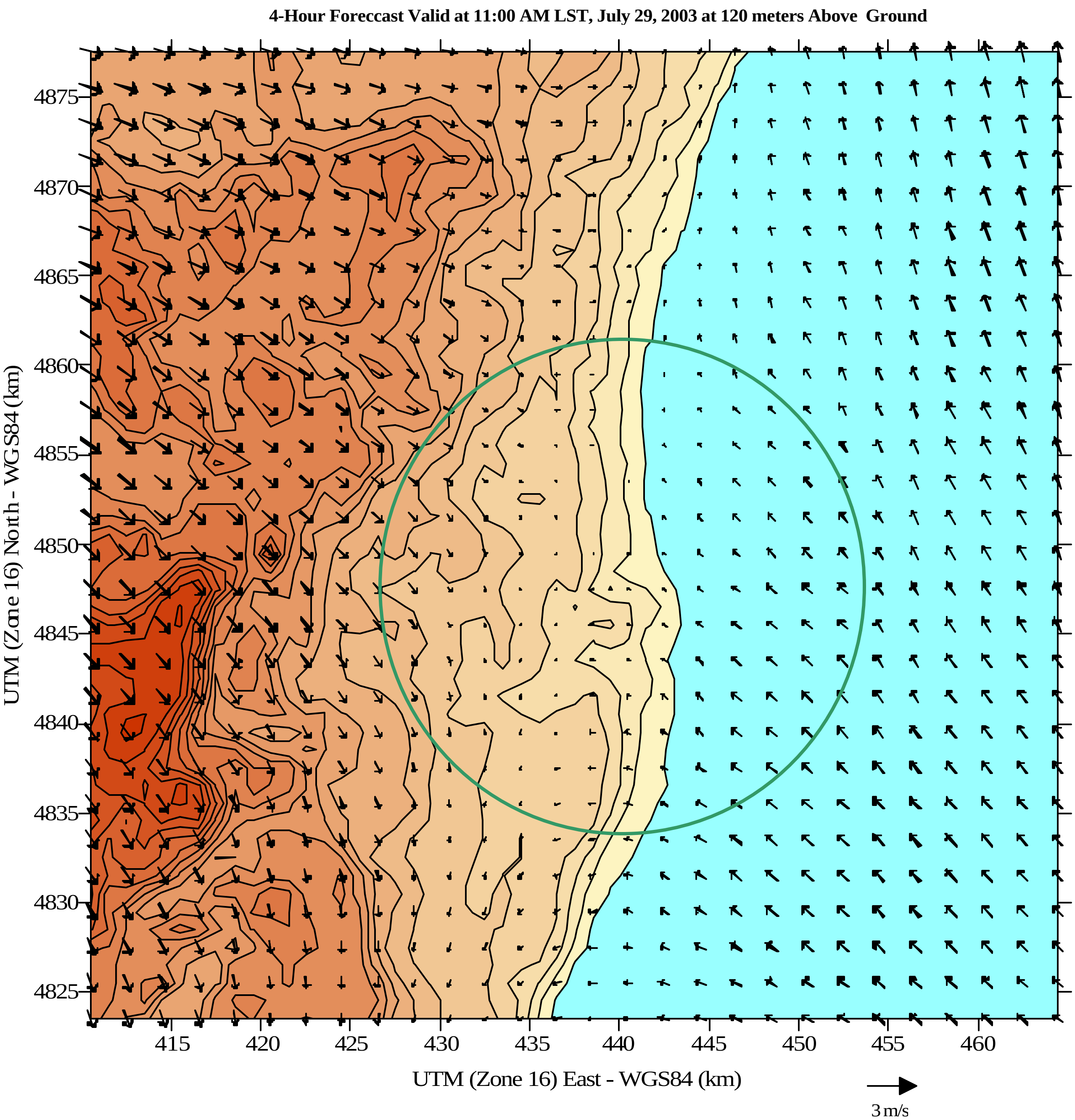


Figure 4. Four-hour forecast of the wind field from the ETA/CALMET models at 10 meters, 120 meters, and 450 meters above ground, valid at 11 a.m. LST on July 29, 2003 (Sheet 1 of 3)



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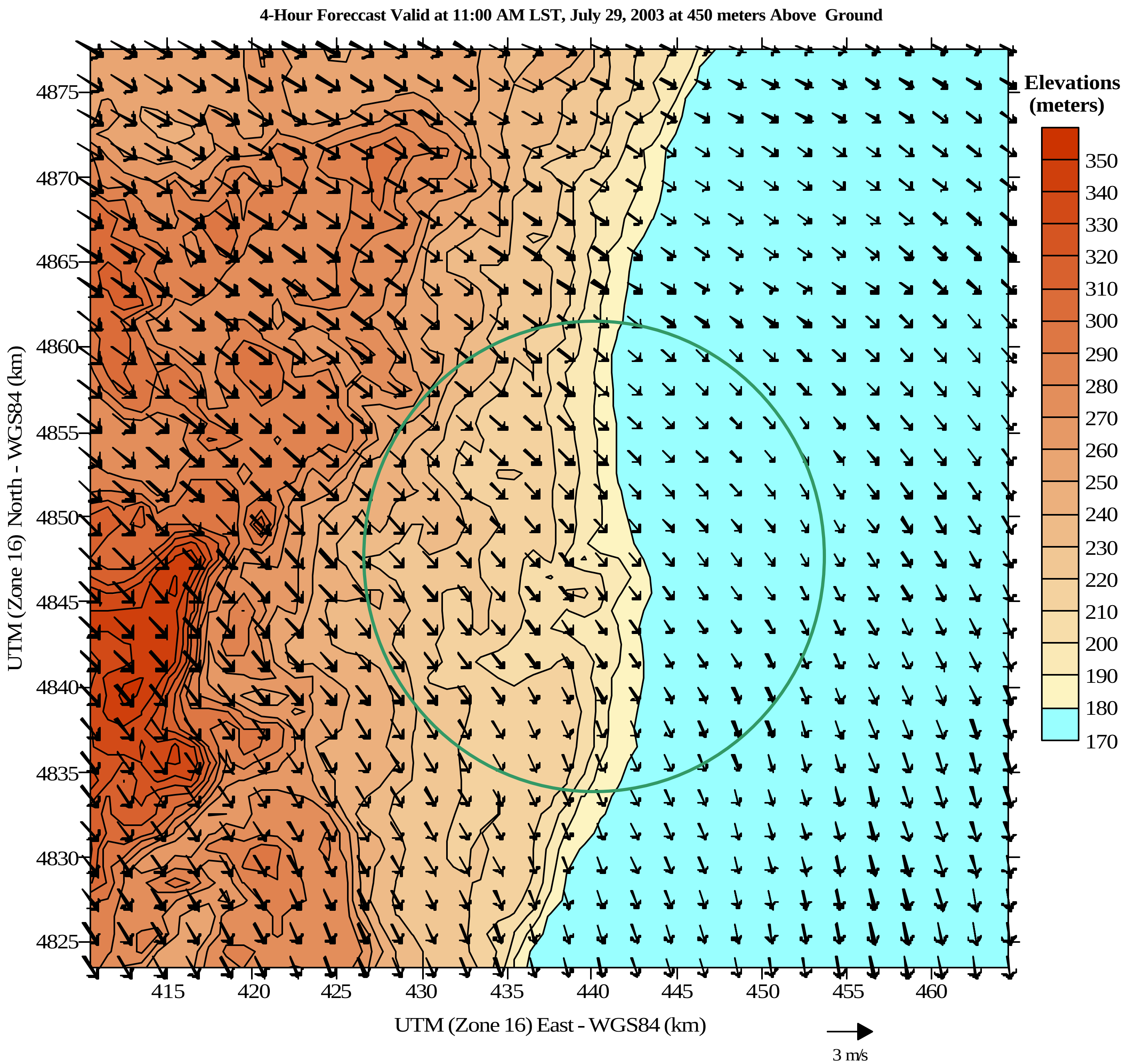

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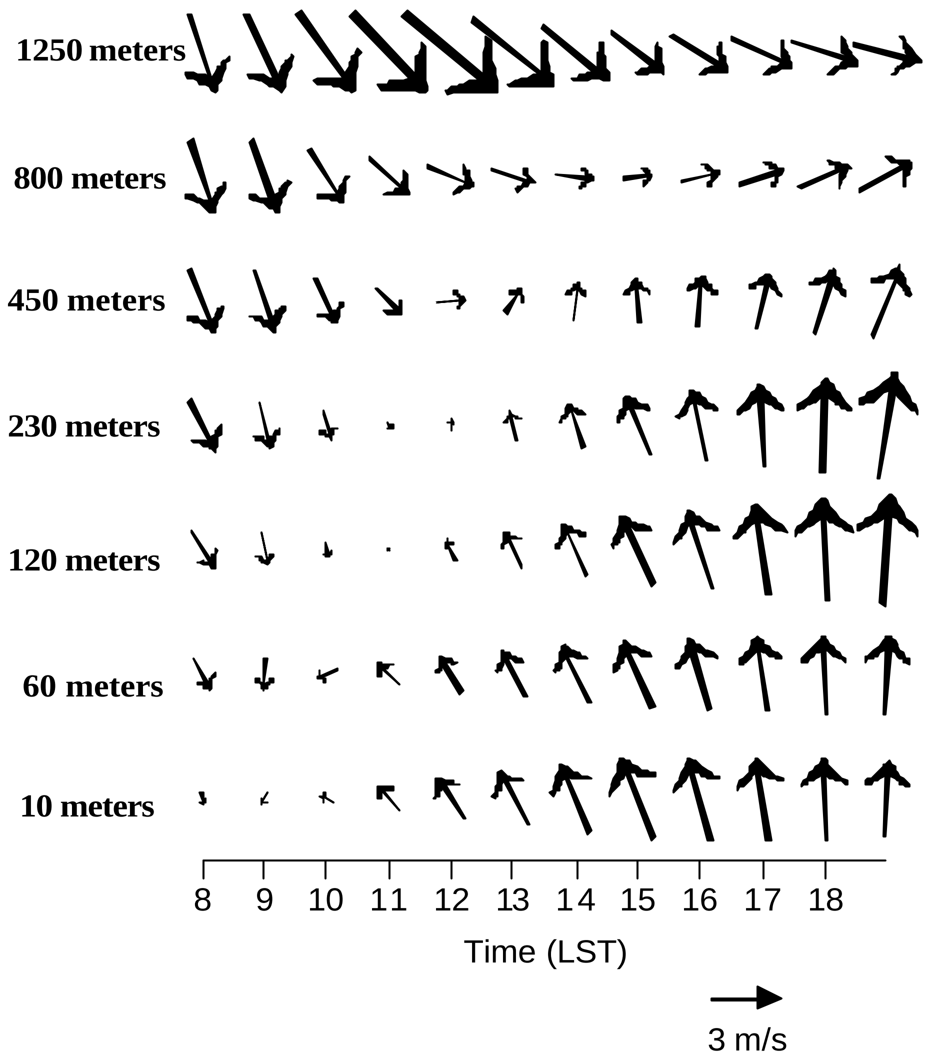


Figure 5: Time-height section of CALMET predicted wind vectors at the location of a hypothetical 100-meter tall stack. The stack location is at the UTM coordinate, 440.000 km East and 4850.000 km North

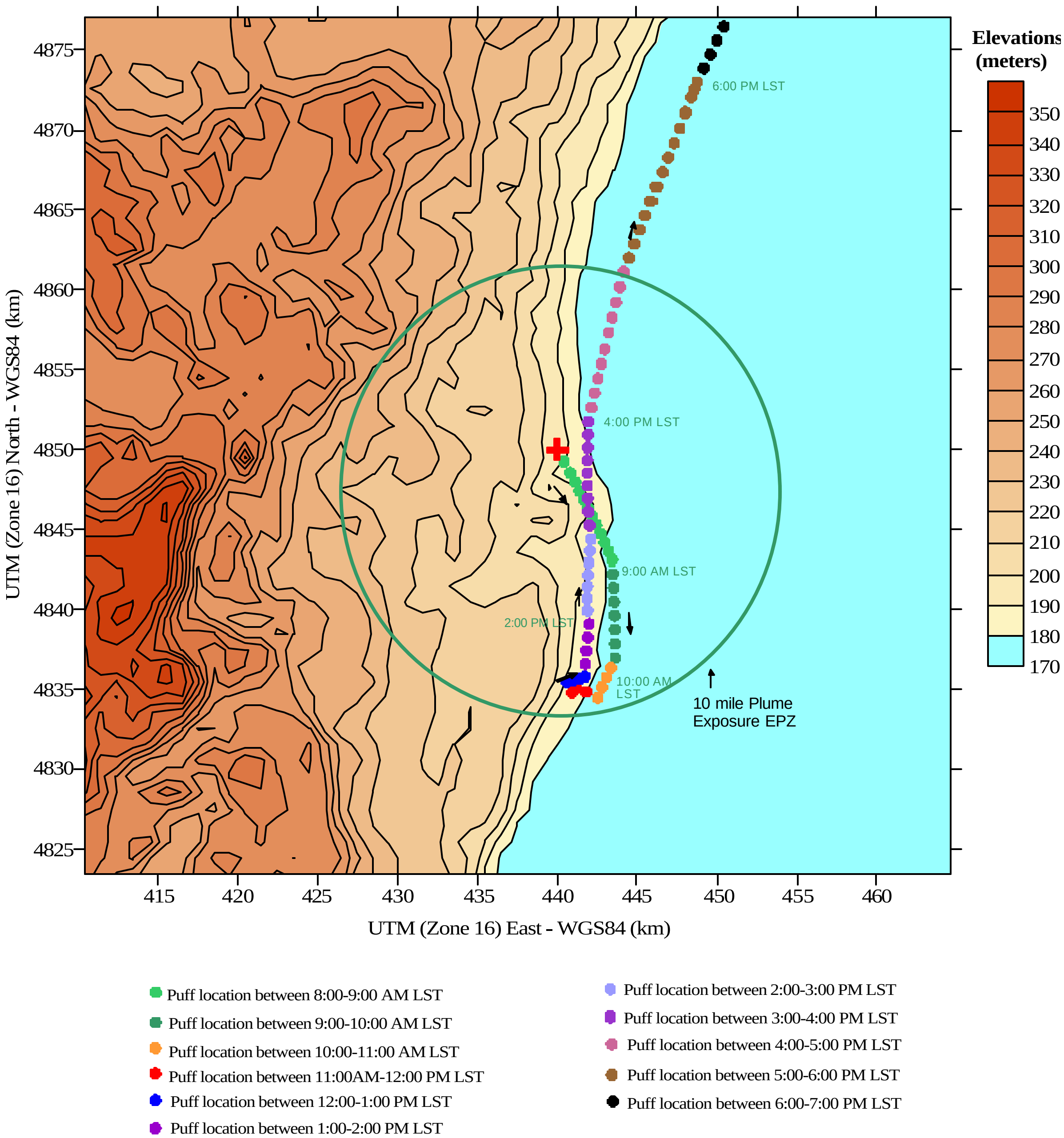
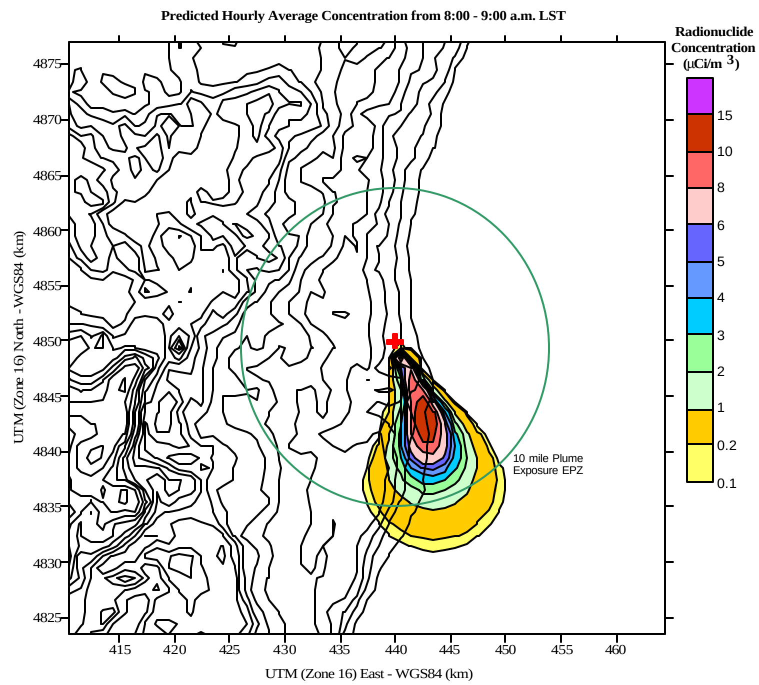


Figure 6: Plot of a single puff trajectory during a 12-hour CALPUFF simulation starting at 8 a.m. LST on July 29, 2003. Release is from a hypothetical 100-meter stack located at 440.000 km East and 4850.000 km North. Black arrows show the direction of puff transport.



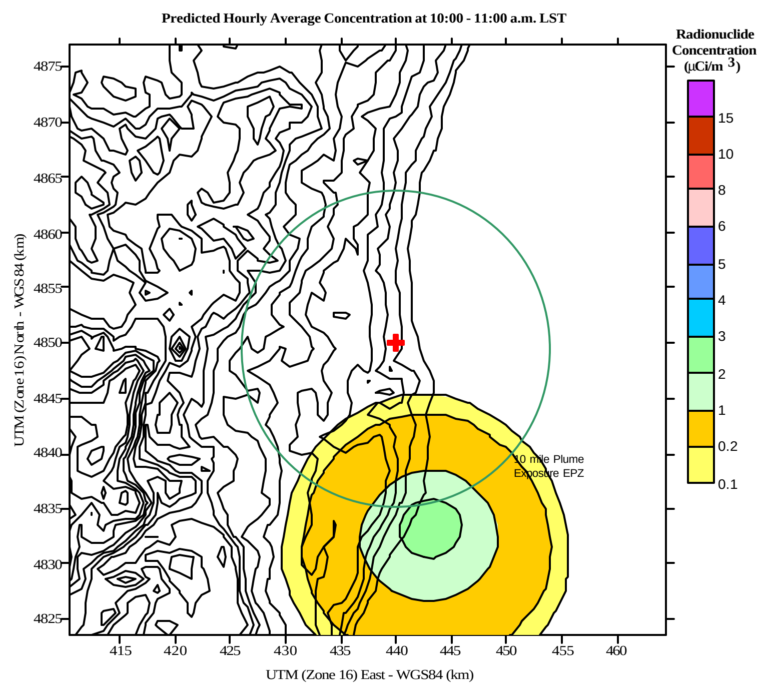
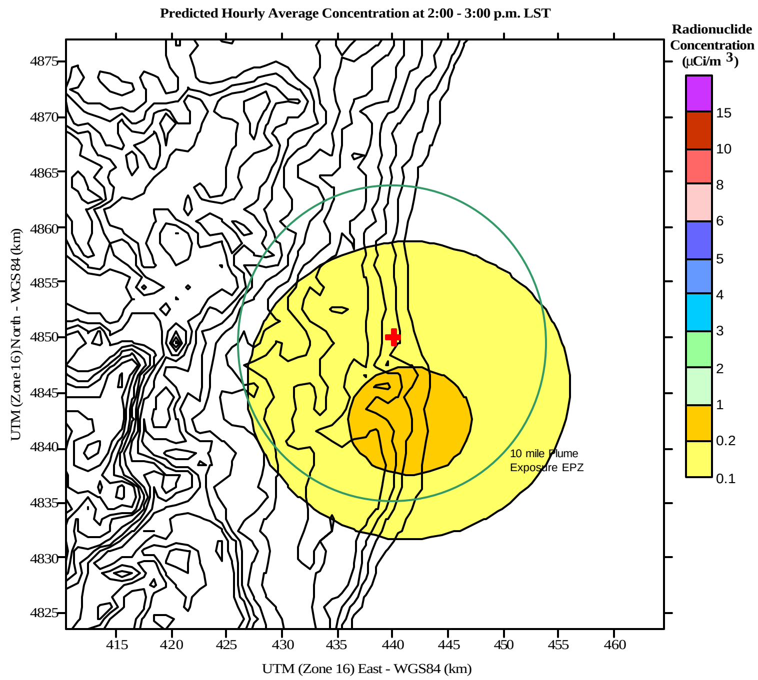
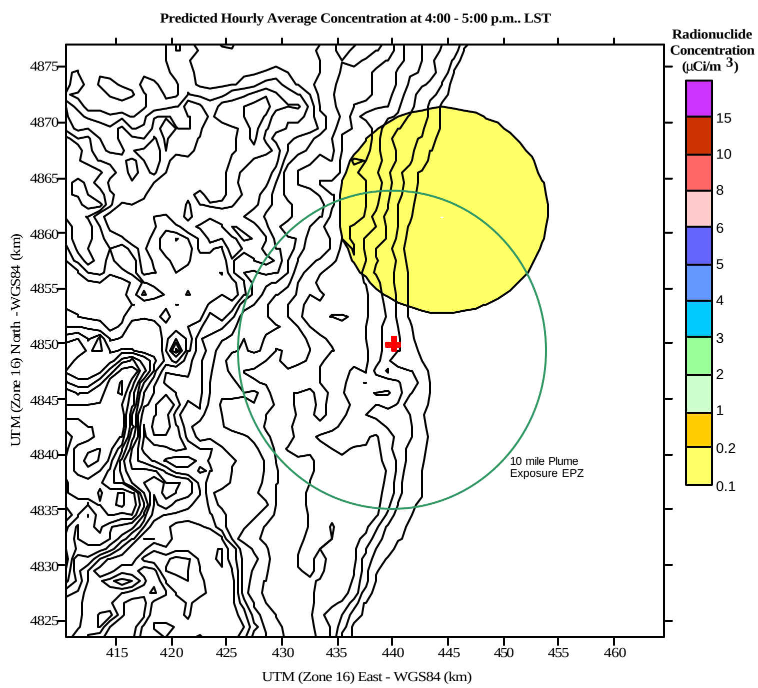


Figure 7: Contour plot of predicted hourly average ground level concentrations at each receptor at 8 a.m. –9:00 a.m. LST, 10:00 a.m. – 11:00 a.m. LST, 2:00 p.m. – 3:00 p.m. LST, and 4:00 p.m. – 5:00 p.m. LST on July 29, 2003. The hypothetical 100-meter tall stack location is shown by the red cross. The simulation assumed a 50 Ci/s release of radionuclides at 7 a.m. LST (Sheet 1 of 2)





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REFERENCES

Benjamin, S.G., G. Grell, J.M. Brown, K. J. Brundage, D. Devenyi, D. Kim, B. Schwartz, T. G. Smirnova, T. L. Smith, S. S. Weygandt, G. Manikin, 2000: The 20-km Version of the Rapid Update Cycle, Preprints, 9th Conference on Aviation, Range, and Aerospace Meteorology, American Meteorological Society, Orlando Florida, September 2000.

Black, Thomas L., 1994: The New NMC Mesoscale ETA Model: Description and Forecast Examples, Weather and Forecasting, 9, 265-278.

Grell, G.A., J, Dudhia, and D.R. Stauffer, 1994: A description of the Fifth Generation Penn State/NCAR Mesoscale Model (MM5), NCAR TN-398-STR, NCAR Technical Note.

Morrison, K. Z. Wu, J. Scire, J. Chenier, and T. Jeffs-Schonewille, 2003: CALPUFF-Based Predictive and Reactive Emission Control System, Abstract No. 70038. Presented at AWMA Annual Meeting.

Robe, F.R., and J.S. Scire, 1998: Combining Mesoscale Prognostic and Diagnostic Wind Models: A Practical Approach for Air Quality Applications in Complex Terrain, Preprints, 10th Conference on the Applications of Air Pollution Meteorology, 11-16 January 1998, Phoenix, Arizona.

Robe, F.R., Z. Wu, and J.S. Scire, 2002: Real-Time SO_2 Forecasting System with Combined ETA Analysis and CALPUFF Modeling; Proceedings of the Eighth International Conference on Harmonization within Atmospheric Dispersion Modeling for Regulatory Purposes, Sofia, Bulgaria, 14-17 October 2002.

Scire, J.S., F.R. Robe, M.E. Fernau, and R.J. Yamartino, 2000a: A User's Guide for the CALMET Meteorological Model (Version 5), Earth Tech, Concord, Massachusetts.

Scire, J.S., D.G. Strimaitis, R.J. Yamartino, and X. Zhang, 2000b: A User's Guide for the CALPUFF Dispersion Model (Version 5), Earth Tech, Concord, Massachusetts.