UCRL- JC-109830
PREPRINT

# Daily Dispersion Model Calculations of the Kuwait Oil Fire Smoke Plume


James S. Ellis, Connee S. Foster,
Kevin T. Foster, Thomas J. Sullivan
Lawrence Livermore National Laboratory

Ronald L. Baskett, John S. Nasstrom, Walter W. Schalk III
EG&G Energy Measurements, Inc.

George D. Greenly Jr., CCM
IT Corporation



This paper was prepared for Presentation at the
Air and Waste Management Association
85th Annual Meeting
Kansas City, Missouri
June 22-26, 1992

April 23, 1992


Lawrence Livermore National Laboratory

# Daily Dispersion Model Calculations of the Kuwait Oil Fire Smoke Plume

James S. Ellis, Connee S. Foster, Kevin T. Foster, Thomas J. Sullivan
Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, CA 94550

Ronald L. Baskett, John S. Nasstrom, Walter W. Schalk III
EG&G Energy Measurements, Inc.
5667 Gibraltar Drive
Pleasanton, CA 94588

George D. Greenly Jr., CCM
IT Corporation
2355 Main St., Suite 100
Irvine, CA 92714-5804

## ABSTRACT

The Atmospheric Release Advisory Capability (ARAC) provided daily forecasts of the position and spatial character of the Kuwait oil fire smoke plume to the NSF-coordinated research aircraft missions in the Persian Gulf. ARAC also provided daily plume dispersion products to various nations in the Persian Gulf region under the auspices of the World Meteorological Organization for a period of nearly 5 months. Forecasted three dimensional winds were provided to ARAC from the U.S. Air Force Global Weather Central's Relocatable Wind Model (RWM). The RWM winds were spaced approximately 90 km in the horizontal and were located at the surface, 1000 ft, 2000 ft, 5000 ft and every 5000 ft up to 30,000 ft elevation. The forecast periods were 0, 6, 24, and 36 hours from both 0000 and 1200 UTC. A wind field model (MATHEW) corrected for terrain influences on the wind. The smoke plume was dispersed using a three dimensional particle-in-cell code (ADPIC) with buoyant plume rise capability. Multiple source locations were used to represent the burning oil fields. Improved estimates of the source term and emission factors for the smoke were incorporated into the ADPIC calculations as the field measurement data were made available.

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract Numbers W-7405-ENG-48 and DE-AC08-88NV10617.

## INTRODUCTION

The Atmospheric Release Advisory Capability's (ARAC) primary mission is to provide in real-time dispersion estimates of the accidental releases of radioisotopes in the atmosphere. However, over the years the ARAC has been called to support a variety of other events such as volcanic ash clouds, toxic chemicals releases, and the spread of radioactive materials from the breakup of nuclear reactors onboard satellites during re-entry into the Earth's atmosphere.[1] The Kuwait oil fire smoke was one of the latest events for which ARAC provided dispersion calculations.

ARAC calculated the dispersion of the Kuwait oil fire smoke plumes initially for a few specific events during the Persian Gulf war (January - February 1991) and then daily from the middle of May 1991 until the last oil well fire was extinguished on November 6, 1991. Plume position analyses were distributed daily to various nations in the Persian Gulf region at the request of the World Meteorological Organization (WMO) from June 16 to November 6, 1991. During multiple U.S agency sponsored research aircraft missions in the Persian Gulf, ARAC calculated plume positions twice daily for 24-hour and 36-hour forecasts and telefaxed them to the research aircraft science teams in the Persian Gulf. Sponsoring agencies were the Departments of Energy (DOE) and Defense (DOD), the National Oceanic and Atmospheric Administration (NOAA), the Environmental Protection Agency (EPA), and the National Science Foundation (NSF). The effort was coordinated by the NSF.

The University of Washington and the National Center for Atmospheric Research (NCAR) flew aircraft from May 13 to June 11, 1991 and the DOE Battelle Pacific Northwest Laboratory (PNL) flew its aircraft from July 21 to August 18, 1991.

## MODELS

The ARAC's principle atmospheric transport and diffusion models are the Mass-Adjusted Three-dimensional Wind (MATHEW)[2] model and the Atmospheric Diffusion Particle-In-Cell (ADPIC) model.[3] MATHEW ingests three dimensional gridded wind data, places the terrain data into the wind field, and mass adjusts the wind to maintain continuity in incompressible flow. ADPIC is a three-dimensional dispersion model that releases thousands of marker particles into the wind field which are transported with the wind as they diffuse and are affected by gravitational settling and dry deposition processes.

Marker particles from up to nine different sources can be simultaneously injected into the flow field by ADPIC, with each source having its own release rate, particle size distribution, deposition velocity, and plume rise characteristic. Each marker particle carries information about its size and settling velocity. The plume rise is controlled by the amount of heat energy being released, the inversion height if present, the stability of the atmosphere and the speed of the wind in the boundary layer of the atmosphere. The planetary boundary layer depth and the stability can be specified as a function of time.

The air concentration of smoke in the horizontal plane was calculated at nine levels in the vertical. Deposition of the particles on the ground was also calculated and contours of ground deposition were generated. In addition, the loading of all nine vertical levels were combined to generate contours of optical depth.

## WIND DATA

The atmospheric wind forecast and analysis data were provided to ARAC by the United States Air Force Global Weather Central (AFGWC). These data were generated by the AFGWC Relocatable Window (RWM) model on a horizontal grid at approximately 90 km horizontal grid point spacing with vertical levels at the surface, 1,000, 2,000, 5,000 ft and every 5,000 ft to 30,000 ft elevation. Forecasted wind data were valid 0, 6, 24 and 36 hours from both 0000 and 1200 UTC. ARAC interpolated the data to a 3200 km x 3200 km horizontal, 6 km vertical regional grid with 40 x 40 horizontal grid points and 14 vertical levels. This intermediate wind set and the detailed regional terrain were processed by MATHEW at 6-hour intervals prior to being input to the ADPIC model.

Figure 1 shows an example of a MATHEW-processed lower level wind field over the 3200 km region selected for the oil fire smoke dispersion calculations. Kuwait is near the center of the grid with Iraq and Iran to the north and the Arabian Peninsula and the Arabian Sea to the south. The horizontal wind field shown at 1700 m above sea level is bounded on the east side of the Persian Gulf by the higher terrain in western Iran. The higher speed winds, represented by longer vectors, coming from the northwest direction and traveling along the eastern side of the Arabian Peninsula and over the Persian Gulf are known as the "Summer Shamal" winds. These winds, which are quite persistent from late spring to late summer, loft silt into the air from the Tigris-Euphrates river valley and loft sand from the desert. The wind flow pattern over the entire region is quite complex as there is often a flow in the northerly direction over the Red Sea region and flow towards the east over the Arabian Sea to the south. The southwest summer monsoon frequently contributes to a flow toward the northeast along the southern coast of the Arabian Peninsula.

## INPUT PARAMETERS

An estimated 605 wells were initially ignited within Kuwait, spewing 6.2 million barrels of oil per day. By early May, 50 well fires had been extinguished and by early June, 100 were extinguished.[4] Approximately 4.3 million barrels of oil per day were burning from these well heads in early June 1991.[5] Eight oil fields were grouped into three source regions: the south field (Burgan, Ahmadi, and Magwa) with 89.1%, the north field (Raudhatain, Sabriya, and Bahrah) with 8.1%, and a third source region called the 'other' field (Minagish and Umm Gudair) with 2.8% of the 4.3 million barrels per day. The fraction of the combusted oil that went into particulate smoke (the smoke emission factor) was taken to be 2.0%.[5] The specific extinction factor used to calculate the optical depth of the smoke was estimated from measurements to be 6.0 $m^2/g$.[6]

The smoke particle size distribution was assumed to be log-normal with a 0.3 μm mean diameter and maximum and minimum diameters of 10.0 μm and 0.02 μm, respectively. This size distribution will be modified when measurement data from both the small-mode and large-mode particles become available.

Atmospheric stability, the boundary layer depth, and the mixed layer depth were varied diurnally using the rawinsonde temperature profiles in the region.

## DISPERSION MODEL RESULTS

Dispersion model results, discussed below, are examples from three days out of the nearly 180 consecutive days that ARAC did dispersion modeling of the Kuwait smoke plume.

### May 8, 1991

ARAC began doing dispersion calculations prior to the first NSF coordinated aircraft measurements mission to the Persian Gulf region. Smoke particles were injected into the model atmosphere beginning on May 1 in order to generate a time history of the smoke plume. After seven days of simulation, the winds had sufficient time to carry the earliest released smoke particles that had not deposited on the ground out of the model atmosphere domain, thus creating a continuous plume from the source. The plume from the ADPIC-generated marker particles on May 8, 1991 at 0600 UTC (9:00 am Kuwait local time) is shown in Figure 2. The plume extends along the Persian Gulf from Kuwait to the southeast beyond Oman over the Arabian Sea. A Defense Meteorological Satellite Program (DMSP) image in the visible spectral channel was provided to ARAC by the AFGWC for the same UTC time. Figure 3 shows the actual position of the plume as seen from space. Only the portion of the plume in which the optical depth is above an undetermined threshold value can be seen from space. The actual plume position shown in the satellite image is 100 to 200 km to the west of the model calculation. This position is within the limits of the uncertainty in the input wind data, which have a spatial resolution of 90 km.

### June 3, 1991

ARAC supported the NSF coordinated aircraft measurement missions in the Persian Gulf by twice daily telefaxing 24 and 36 hour forecasts of the plume position to their operations center in Bahrain. Figure 4 shows the 24 hour "forecast" plume valid for 1200 UTC (3:00 pm local) on June 3, 1991. The plume is inland just north of Qatar extending to the southwest across Saudi Arabia. A somewhat detached remnant of the plume to the south, caused by horizontal and vertical wind shear, extended back toward the northeast over the United Arab Emirates (UAE) into the Persian Gulf.

The "analysis" position of the plume (Figure 5) derived from the historical RWM analyzed winds, rather than from the forecast RWM winds, shows the plume covering most of the northern Persian Gulf and coming inland over and to the south of Qatar. It differs from the 24-hour forecast position in several ways. The 24-hour forecast position of the plume does not extend to the east across the central Gulf as does the analysis. The plume also comes inland north of Qatar, whereas the analysis has the plume mostly south of Qatar as it bends inland. The 24-hour forecast position of the plume on many occasions was observed to be drawn farther inland than on the analysis position due to higher wind speeds and more curvature to the southwest in the 24 hour forecast RWM winds. The southern edge of the analysis plume is not as far south as in the 24-forecast plume, but still depicts the inland extent of the plume over Saudi Arabia. A satellite image in the visible channel 2 of the NOAA 11 satellite (Figure 6) shows that the plume comes far inland over Saudi Arabia, as indicated also in the ADPIC results. The plume was also visible over most of the northern Persian Gulf in the original copy of the satellite image, as indicated also in the ADPIC analysis results of Figure 5. The major difference between the ADPIC results and the satellite image is the north-to-south extent of the plume along the Persian Gulf as it comes inland. The position difference is about 200 km.

The optical depth of the plume was also calculated and sent along with the marker particle plots to the aircraft teams. The optical depth was calculated by multiplying the specific extinction factor by the vertical integral of the smoke concentration. Source term information, the smoke emission factor, and the specific extinction factor, as determined by the aircraft measurement teams, were applied to update optical depth plots in Figures 7 and 8 for May 8 and June 3, respectively. Optical depths are 0.1 or greater over the 2000 km length of ADPIC-generated plume for both days. A 0.1 optical depth is equivalent to 10% light attenuation through the plume from a directly overhead sun. Within 200 km of the greater Burgan Field, the optical depth is 1.0 or greater, or 63% or more light attenuation from an overhead sun as seen on an enlarged close up view of the plume on May 8, 1991 (Figure 9). Within 150 km of the source, the optical depth is greater than 2.0 but less than 3.0, or 86% or more light attenuation; and within 100 km of the source, the optical depth is greater than 3.0, or more than 95% solar attenuation. Values of optical depth near the source on June 3 (Figure 10) are not as large as on May 8. This is most likely due to the increased width of the plume and, consequently, reduced smoke concentrations on June 3.

Thin veils of smoke were detected in visible data of the METEOSAT geosynchronous satellite as far away as 2000 km east of Kuwait in southwestern Pakistan.[7] The average optical depth was estimated from the METEOSAT data to be about 2.0 in the 0.6 μm wavelength band over the darkest parts of the plume. The NSF aircraft missions in the Persian Gulf reported optical depths between 2.0 and 3.0 in the thicker regions of the plume 60 to 100 km downwind from the source after individual well fire plumes had merged.[8] These measurements agree with the ADPIC-calculated plume optical depths on May 8 but are larger than the model results on June 3.

Flight crew members could routinely see the plume from the aircraft. However, on several occasions the flight crew could not see the plume because of reduced visibility from blowing dust and sand suspended at and below flight altitude.[9]

**August 10, 1991**

The PNL aircraft was in the Persian Gulf from July 29 to August 19, 1991. The researchers of this team asked that ARAC provide them with plots showing the age of smoke particles at various elevations above ground. The ARAC computer software was modified to display the age of the ADPIC particles at 2100 m and 3800 m elevations in 12-hour intervals out to 48 hours (Figure 11) and 24-hour intervals from 48 hours to 144 hours or 6 days (Figure 12). As expected, the older particles, with ages greater than 48 hours, are at greater distances from the sources in Figure 11. However, the older particles over the southern Persian Gulf with ages greater than 6 days are closest to the sources in Figure 12. This pattern indicates that there was a circulation bringing the older particles back toward the source region. This phenomenon was displayed by the ADPIC model on a number of occasions during the PNL aircraft sampling period. Validation of this phenomenon awaits PNL aircraft measurement data.

## CONCLUSIONS

ARAC provided dispersion calculations of the Kuwait oil fire smoke continuously to the NSF coordinated measurement aircraft deployed to the Persian Gulf and to various nations in the vicinity of the Persian Gulf at the request of the WMO for a combined effort of over 6 months. Sample ARAC-calculated plumes for two days showed close agreement with the plume position from satellite images. The optical depth of the ARAC-calculated smoke plume was quantitatively similar to that determined both from satellites and in situ measurements.

ARAC will continue to refine the ADPIC dispersion calculations as data from the measurements of the smoke properties are made available. More comparisons with satellite data will be made to assess the model's plume location and shape accuracy. Of particular interest in future work will be to compare the ADPIC plume properties with simultaneous measurements.

## REFERENCES


1. R.L. Baskett, J.S. Nasstrom, J.J. Watkins et al., "Atmospheric Modeling of the July 1991 Metam Sodium Spill into the California Upper Sacramento River," 2-155.01, Air & Waste Management Association, Pittsburgh, 1992.

2. C.S. Sherman, "A Mass-Consistent Model for Wind Fields over Complex Terrain," J. Appl. Meteor. 17 (3): 312 (1978).

3. R. Lange, "ADPIC - A Three-Dimensional Particle-In-Cell Model for the Dispersion of Atmospheric Pollutants and Its Comparison to Regional Tracer Studies," J. Appl. Meteor. 17 (3): 320 (1978).

4. B. Bailey, Kuwait Oil Fire Extinguishing Chronology, compiled by the Gulf Program Office, Office of the Chief Scientist, National Oceanic and Atmospheric Administration, Washington, D.C., 1991.

5. R.J. Ferek, P.V. Hobbs, and R.E. Weiss, "Fluxes and Compositions of Emissions from the Kuwait Oil Fires," A11A-10, AGU 1991 Fall Meeting, San Francisco, CA.

6. R.E. Weiss and P.V. Hobbs, "Optical Extinction Properties of Smoke from the Kuwait Oil Fires," A21A-4, AGU 1991 Fall Meeting, San Francisco, CA.

7. S.S. Limaye, V.E. Suomi, C. Velden et al.,"Satellite Observations of Smoke from Oil Fires in Kuwait," Science 252 (5012): 1536 (1991).

8. P. Pilewskie and F.P. Valero, "The Smoke Cloud from the Kuwait Oil Fires: Its Effects on Solar Radiation," A21A-5, AGU Fall Meeting, San Francisco, CA.

9. P.V. Hobbs, Atmospheric Sciences Department, University of Washington, Seattle, WA, personal communication, 1991.

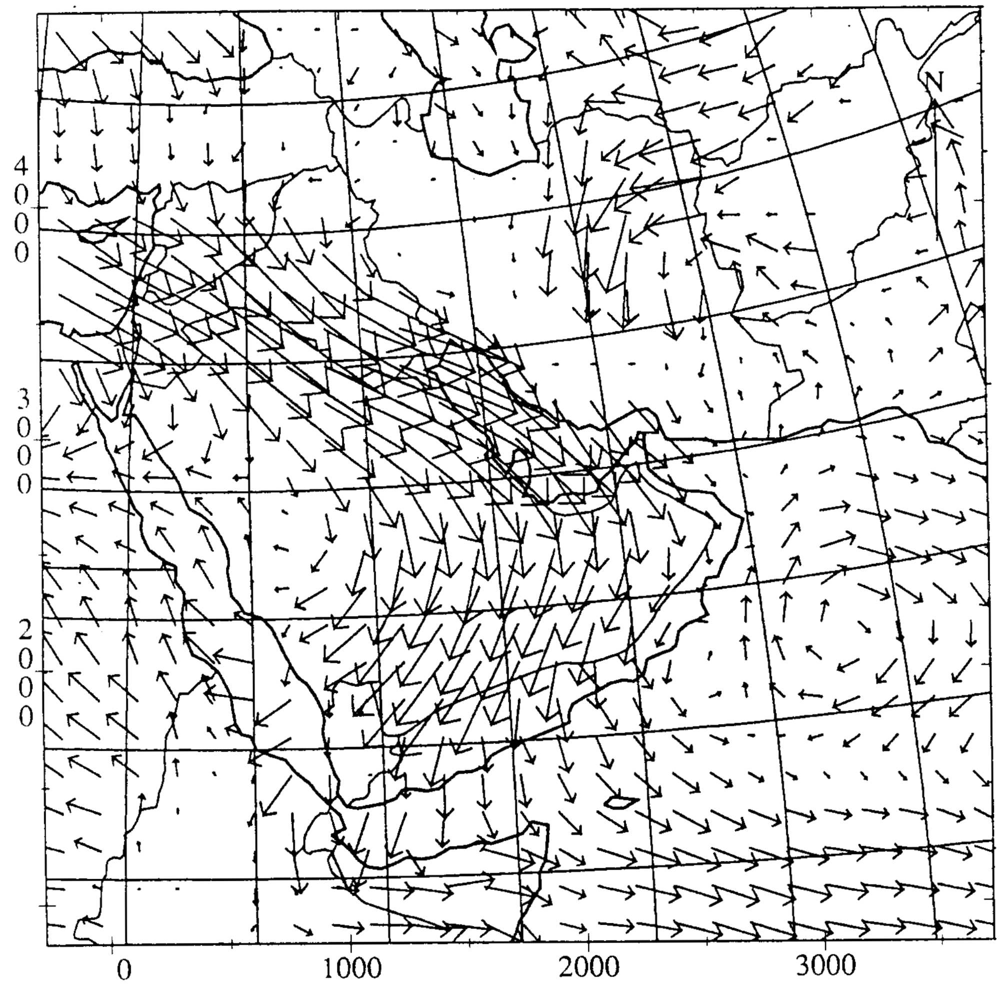



Figure 1. MATHEW wind field, 1700 m elevation, 1200 UTC, June 3, 1991.

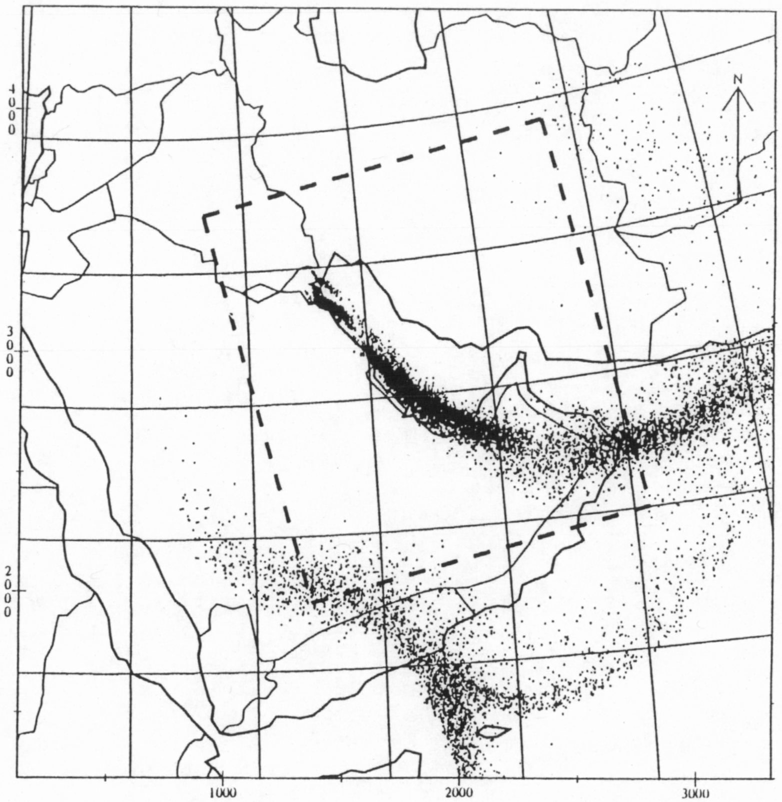



Figure 2. ADPIC marker particles, 0600 UTC, May 8, 1991.

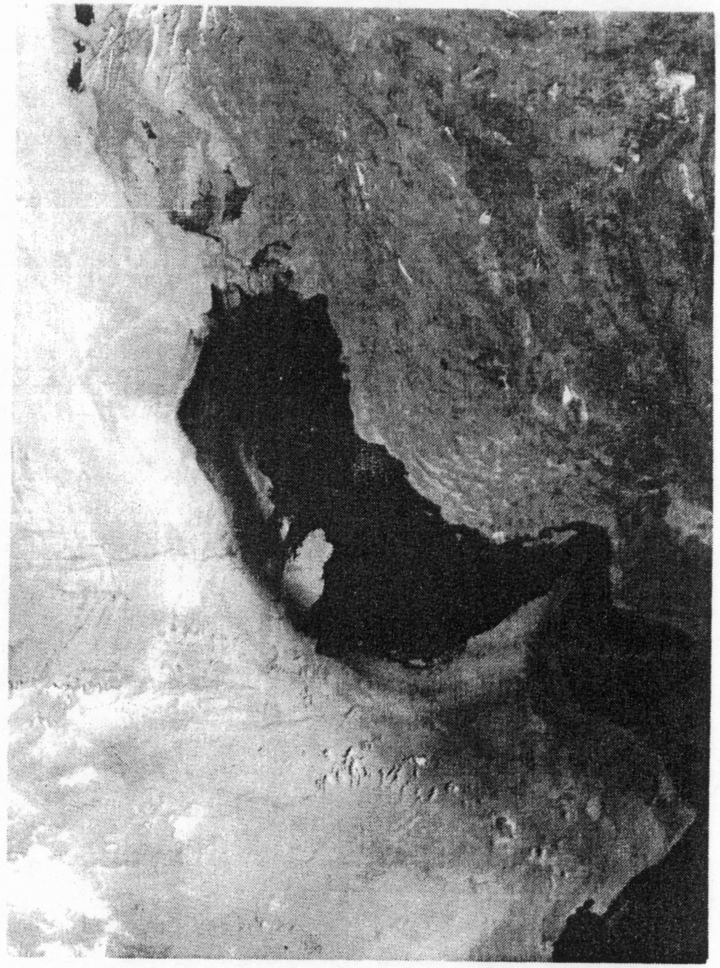


Figure 3. DMSP satellite visible channel image, 0518 UTC, May 8, 1991.



92-76.05

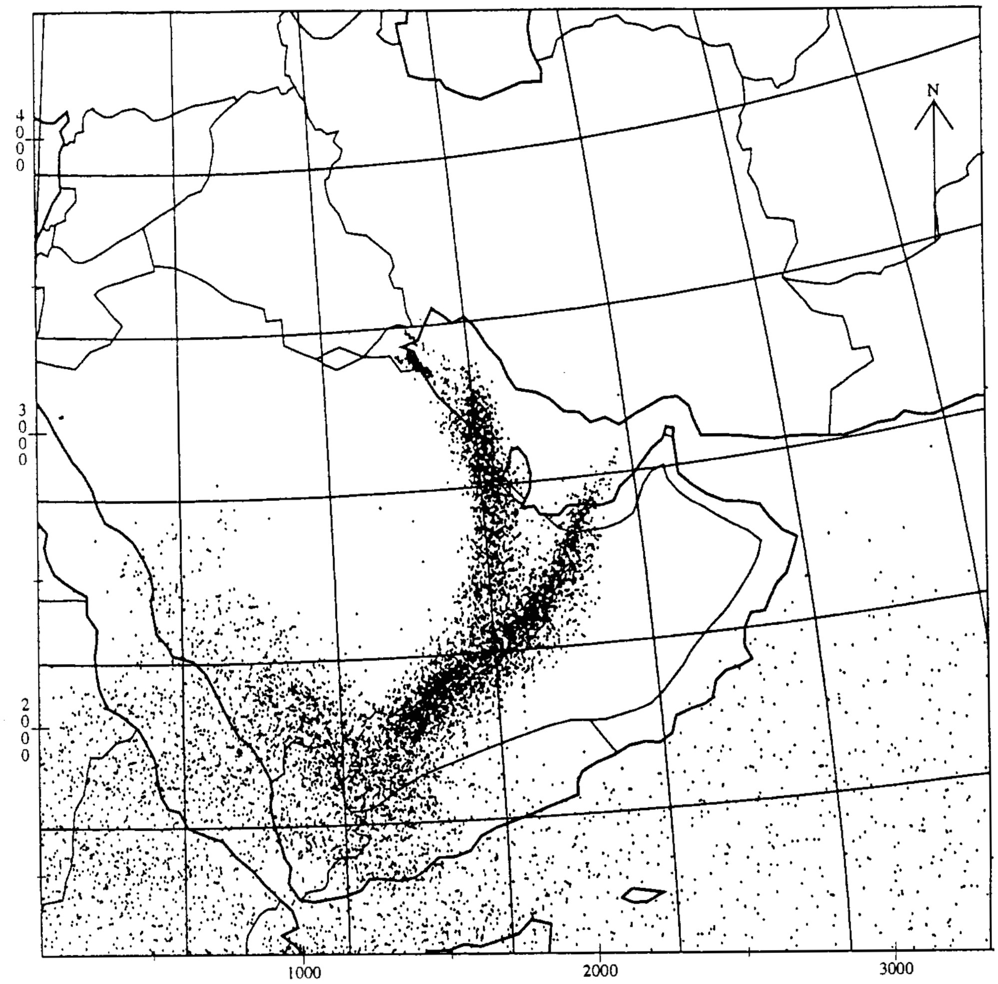



Figure 4. ADPIC marker particles, 24 hour forecast, valid 1200 UTC, June 3, 1991.

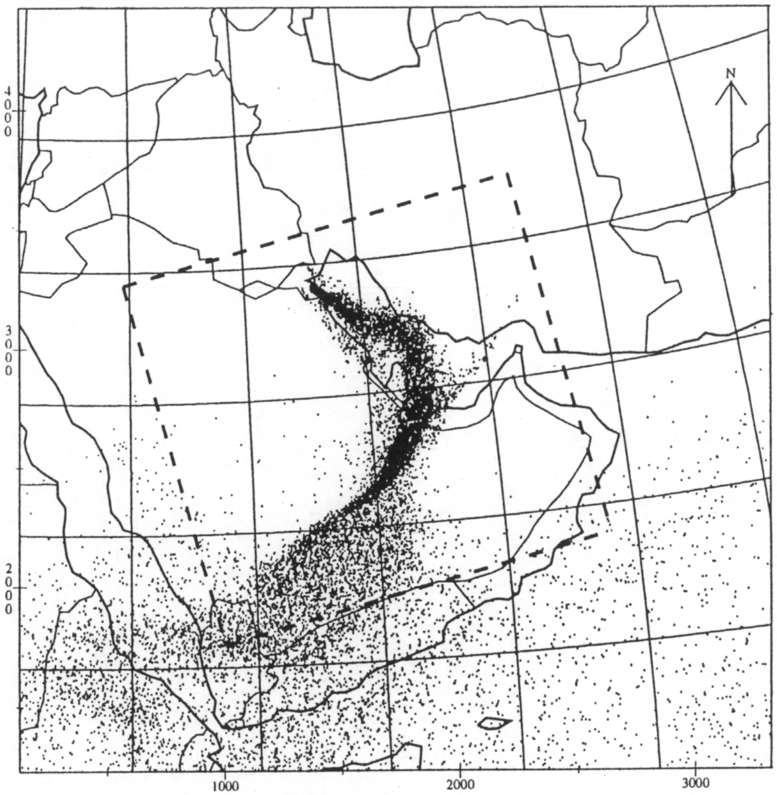



Figure 5. ADPIC marker particles, 1200 UTC, June 3, 1991.


Figure 6. NOAA-11 satellite solar channel image, 1105 UTC, June 3, 1991.

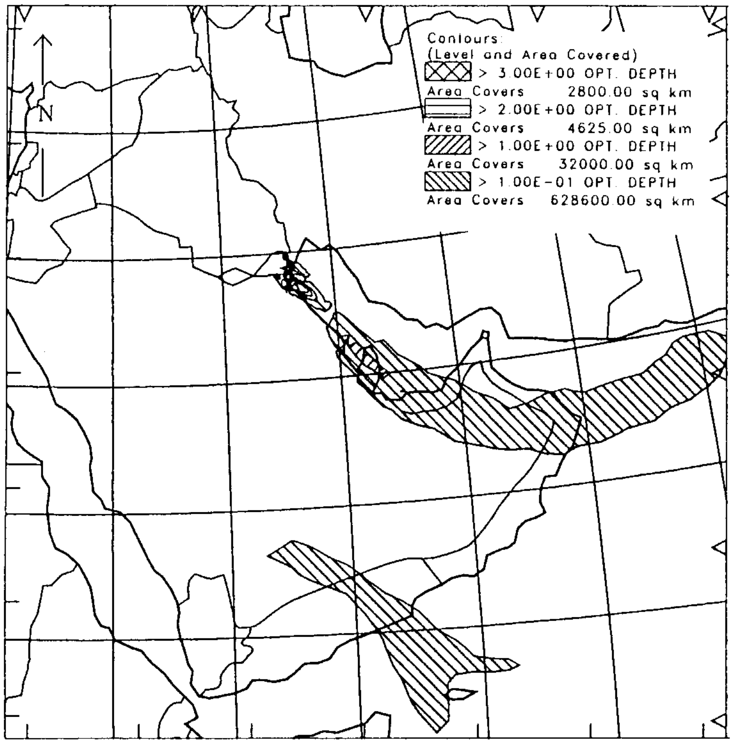



Figure 7. Optical Depth, 0600 UTC, May 8, 1991.

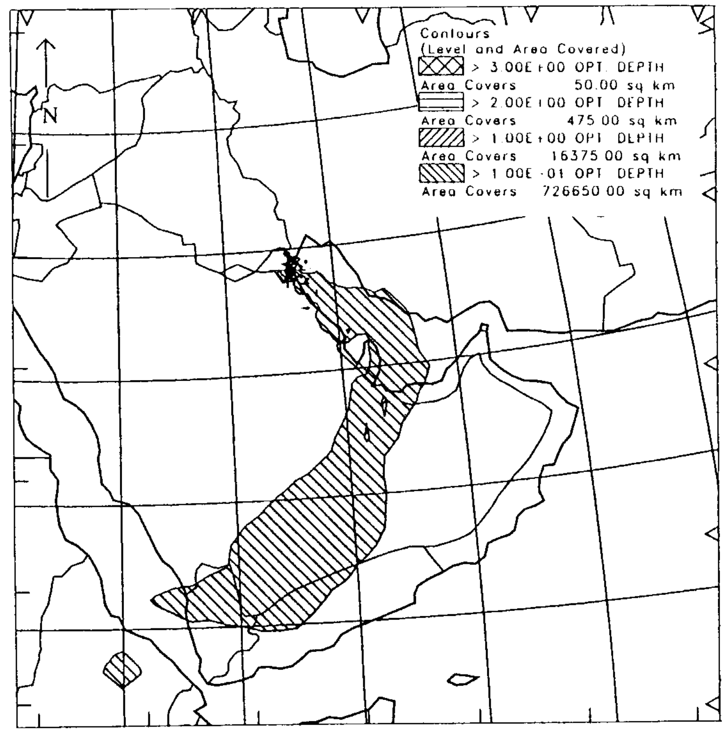



Figure 8. Optical Depth, 1200 UTC, June 3, 1991.



92-76.05

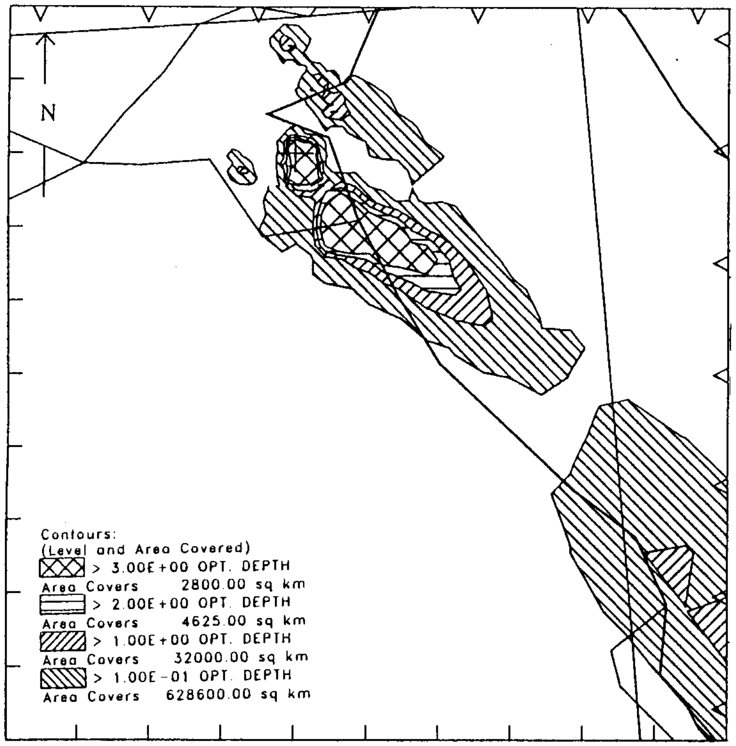



Figure 9. Optical Depth, 0600 UTC, May 8, 1991; an expanded view, 500 km on a side.

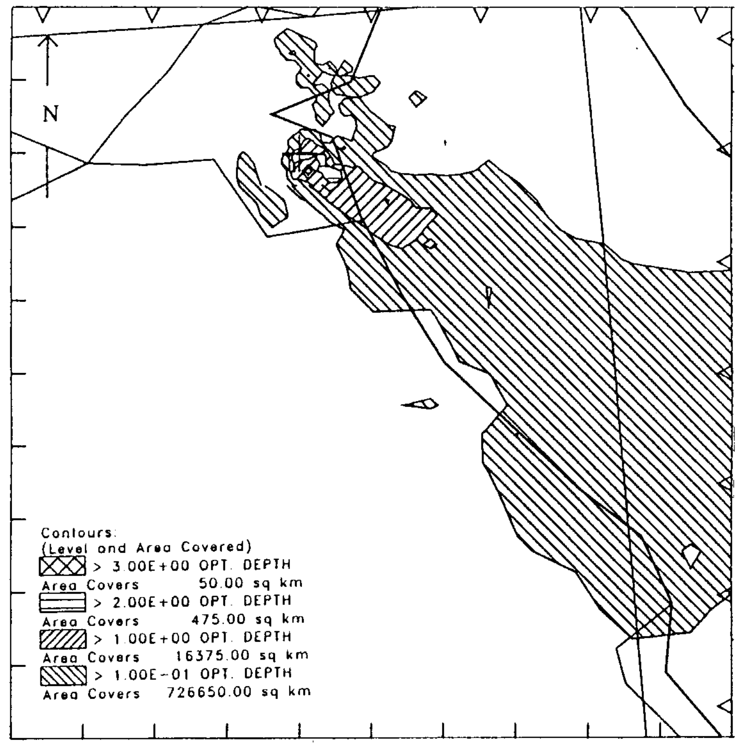
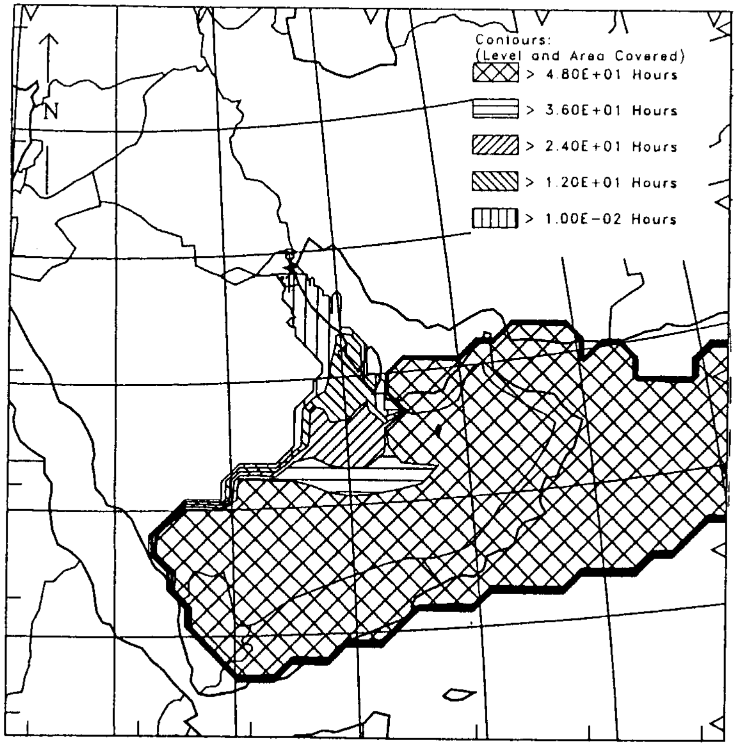



Figure 10. Optical Depth, 1200 UTC, June 3, 1991; an expanded view, 500 km on a side.



92-76.05



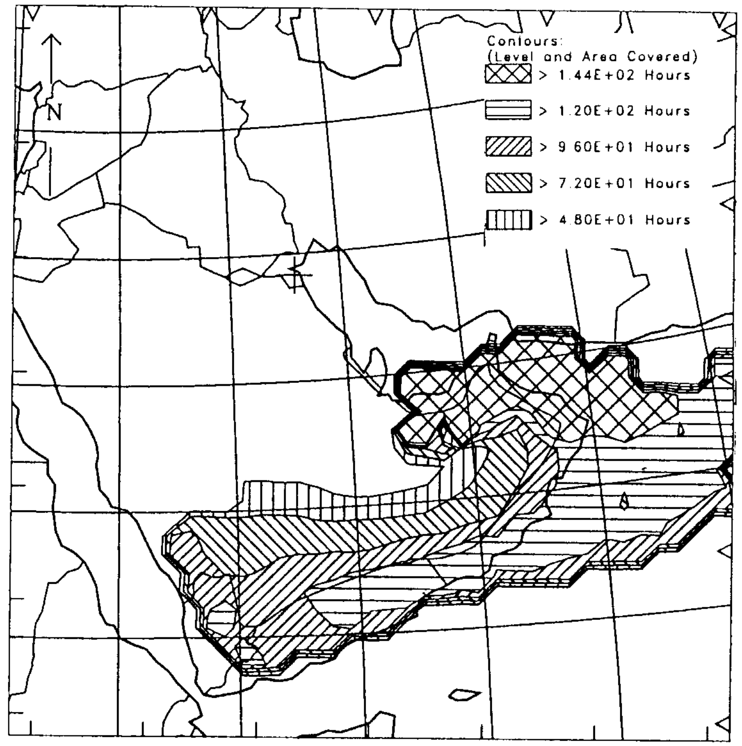




Figure 11. ADPIC particle age 0 to 48 h at 2100 m elevation; 1200 UTC, August 10, 1991.

Figure 12. ADPIC particle age 48 to 144 h at 2100 m elevation; 1200 UTC, August 10, 1991.

*Technical Information Department* • Lawrence Livermore National Laboratory
University of California • Livermore, California 94550