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The Atmospheric Release Advisory Capability

This paper was prepared for presentation at the Workshop on
"Environmental Dimensions of the Gulf: Policy and Institutional Perspectives,"
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Abstract

The Atmospheric Release Advisory Capability modeled the wind flow in the Gulf Region in order to make projections of the Kuwait oil fires pollution dispersion. Extensive meteorological models incorporating explicit terrain influences to the flow fields were routinely employed through a six month international assessment support effort organized by the World Meteorological Organization and U.S. scientific research agencies. Results show generally close agreement with visible imagery of the smoke plumes as detected by meteorological satellites. However, there are some examples of significant disagreement or failure of the meteorological models. These failures are most likely directly linked to missing or unavailable weather observations.

Introduction

The Atmospheric Release Advisory Capability (ARAC) was originally conceived and developed at Lawrence Livermore National Laboratory as a nuclear accident emergency response service.[1] It's purpose is to provide near real-time dose assessment calculations for accident response decision makers. Based on operationally-robust three-dimensional atmospheric transport and dispersion models, extensive geophysical and dose factor databases, real-time meteorological data acquisition and highly experienced staff, ARAC responds to radiological accident events in the United States within 30-90 minutes. Through extensive research and experience, ARAC has demonstrated the capability to quickly adapt its modeling system to any accident location.[2]

Beginning with the Chernobyl accident, ARAC has, on several occasions, been requested to calculate the transport and dispersion of hazardous substances for accidents outside the United States.[3] One of the latest such requests was for support of the U.S. research aircraft flight programs measuring the pollutants from the Kuwait oil field fires (May 12 - June 15 and July 26 - August 20,1991). This was followed by a United Nations World Meteorological Organization (WMO) request for assistance to the Gulf region's environmental and meteorological services. Beginning on May 12, 1991 ARAC initiated calculations of the wind flow and pollutant dispersion conditions of the Gulf region which continued through October 31, 1991 just 6 days before the last well fire was extinguished. These calculations were produced for a 3200 kilometre square region using meteorological data sources from the U.S. Air Force Global Weather Central (AFGWC) in combination with the ARAC wind field and pollutant dispersion models which included effects of terrain. AFGWC provided both analysis and prognostic gridded datafields from a Relocatable Window Model (RWM) which produced wind component data on a 40 x 40 grid at 50 nautical mile spacing at 1,000 ft, 2,000 ft, 5,000 ft and every 5,000 ft up to 30,000 ft elevation and a surface level grid of 80 x 80 points at 25 nautical mile spacing. The analyses were received for every 6 hour period and the forecast periods were 6, 24 and 36 hours from 0000 and 1200 UTC. In general, there was/is insufficient observational data to support independent wind flow analyses for this region using the standard ARAC approach[4] based on observation data.

After ARAC completed the implementation of the data and modeling system for the 3200 km regional calculations, a northern hemisphere modeling system was activated using 381 km gridded analysis data at standard pressure levels. This is the methodology ARAC developed during the Chernobyl accident (1986) for assessment of long range transport and dispersion.[5] Using this modeling system, ARAC evaluated the long range transport, dispersion and deposition of fire generated soot particles at 12-hour intervals (0000 and 1200 UTC).

Description of Modeling System

ARAC's principal atmospheric transport and diffusion models are the Meteorological Data Interpolation Code (MEDIC), the Mass-Adjusted Three-dimensional Wind (MATHEW)[6] model and the Atmospheric Dispersion Particle-In-Cell (ADPIC)[7] model. The MEDIC code was substantially modified to ingest the new RWM data grids along with available observational data to initialize the three-dimensional modeling volume for the regional calculations. The processes involve $1/R^2$ weighted interpolation of the AFGWC data to the ARAC Universal Transverse Mercator (UTM) projection 3200 km grid and vertical interpolation to 15 evenly spaced levels from the surface to 6 km. A detailed regional terrain grid was inserted as the lower boundary of the initialized model volume prior to iterative adjustment by the calculus of variations encompassed in the MATHEW model to achieve a minimally-adjusted, mass-consistent (divergence free) wind field. This process was repeated for every analysis and prognostic data set. The most significant consequence of this MEDIC/MATHEW process appears to be the explicit topographic influence of the flow fields leading to enhanced channeling over the Gulf and delineation of vertical shear. ADPIC is a three-dimensional dispersion model that releases and tracks thousands of marker particles in the flow. These particles are then transported with the wind as they diffuse and are affected by size-dependent gravitational settling and dry deposition processes.

Marker particles from four oil field source regions (up to nine sources are possible) were simultaneously injected into the wind flow fields by ADPIC. Each source region had its own release rate, particle size distribution, mean deposition velocity, and plume rise characteristics. A total of (up to) 20,000 marker particles were used to represent all sources. The smoke particles were given a median diameter of 0.3 microns and a deposition velocity of 1.0 cm/sec. For the fires, 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 atmospheric boundary layer. We placed a maximum limit of plume rise at 2000 metres, based on early reports by the United Kingdom and U.S. flight programs. The boundary layer depth and stability were specified for each 6-hour period due to the lack of direct observational data. A diurnal cycle of mixing/boundary layer depth ranging from 500 metres during the nights to 1200 metres during the day, and stability class E (stable) at night to class B (moderately unstable) during the day was modeled.

The air concentration of the smoke was calculated in seven horizontal layers in the vertical, and deposition of the particles was computed at the ground. Contours of ground deposition and vertically integrated optical depth were generated in order to delineate the relatively dense smoke plume structure both for the research flight program and for comparison with available satellite visible imagery. The marker smoke particles serve as tracers for the depiction of the (modeled) flow regimes just as the real smoke particles serve the same function for the actual flow as evidenced by the smoke plumes observed in weather satellite imagery.

Development of the Wind Flow Regimes

Beginning with the commencement of combat by Coalition forces on January 17, 1991 ARAC archived all available meteorological data including the RWM analyses from AFGWC. In addition to employing these data for several special assessments during the Gulf war, ARAC staff attempted a simulation of an early oil storage area fire at Al Ahmadi. This initial work paved the way for subsequent contingency assessments. With the quick ending to the combat phase on February 28, all ARAC activities related to the war ceased except the data archival.

When the WMO called a meeting of experts for late April, ARAC evaluated the possible ways its modeling system could contribute to the scientific effort to collect data on the oil fire smoke plumes. It was determined that ARAC could model, both diagnostically and prognostically, the air flow throughout the Gulf region by a combination of the AFGWC RWM analysis and forecast wind components in conjunction with the terrain-influenced, mass-adjusted MATHEW wind flow model. The combined wind field provided the necessary transport input to the ADPIC pollutant dispersion model.

The terrain data used for these calculations was extracted from an online 10 km worldwide digital database ARAC maintains[8] (acquired from NOAA) known as ETOPO5. NOAA created the source database by merging several sets of the original five-minute resolution data. Figure 1 shows the terrain grid used to represent the topographic features of the region, features which proved very important in modeling the regional flow. A typical coverage of surface level meteorological data is shown in figure 2, clearly showing the large data deficient areas of the region. Figure 3 depicts the gridded data detail available to ARAC interpolated from the RWM model output. ARAC has high confidence in this data source because it incorporates the extensive USAF weather data capture resources, military data and weather-satellite-derived information such as cloud tracked winds and vertical thermal structure (over water). Figure 4 shows the terrain grid used to represent the topographic features on a 381 km northern hemisphere grid which ARAC uses for long range transport and dispersal calculations. Figure 5 depicts an example of the wind data and its spatial patterns typical of this scale.

Regional-Scale Air Flow Depiction

Two ARAC products useful for depicting air flow characteristics over a region are wind vector plots and particle position plots. Figures 3 and 5 are vector plots. The arrows show the direction of flow and the length of the arrows indicate the speed of the flow. Figure 6 a-c show three different levels of the atmosphere over the Gulf region on June 3, 1991 at 1200 UTC. Note the "typical" strong Shamal conditions in the lower levels directly over the Gulf and eastern Saudi Arabia on this date. Also note the blocking and deflection of this flow by the Zagros mountains along the western and southern parts of Iran. The missing and very light winds to the north and east of this boundary indicate the explicit effect of the terrain at the lower levels in this critical region of the model domain. The example wind field also reveals the diverse nature of the air flow over the modeled area on this particular date.

Figure 7 depicts a characteristic particle plot for the forecast of the oil fire smoke plume for June 3, 1991. The plot is an overhead, satellite-like view of the model domain. Since ARAC modeled the fires as continuous releases, the particles depict the resultant flow history for the period of time from when each particle was created until it exited the grid (sides or top) or was deposited on the ground or water. Such plots have proven extremely useful to the ARAC staff in verifying the temporal and spatial variations in changing flows of pollutant transport. Several validation studies[9,10,11] using mostly passive tracer gases have verified that the particle-in-cell modeling methodology in conjunction with terrain-influenced flow field adjustment is a highly successful technique. However, caution must be used when viewing particle position plots because one cannot directly infer pollutant concentrations from this visual presentation. This is so because the overhead view does not show of the vertical location of the particles or the mass of material represented by each individual particle. Particle mass can change due to a time-varying source strengths or because of the numerical computation and particle budget management.

Satellite pictures or imagery of the visible light reflection during daytime can reveal flow patterns if either natural moisture (in the form of clouds) or an absorbing or highly reflective pollutant is in the field of view. In the case of the Kuwait oil fires, weather satellite visible imagery readily detected and revealed the highly absorbent smoke particle plume(s). This has provided a unique opportunity for direct comparison between the actual particles (smoke) and their dispersal by the real atmospheric flow and modeled tracer particles in synthesized model flow regimes derived from limited observational data and mass conservation algorithms. Figure 8 is a copy of the NOAA-11 visible channel image for June 3, 1991 at 1105 UTC. The nearest ARAC particle position plots are for 1200 UTC. The example displayed in Figure 7 shows our 24 hour forecast for June 3rd. Figure 9 depicts the same plume position based completely on a series of analysis data and valid at the same time as Figures 7 and 8. Note that the overall structure of all three depictions is very similar; the plume derived completely from analysis data more closely agrees with the satellite picture in some details and the forecast derived plume agrees equally well in other areas. Overall the essence of the time-integrated flow is well modeled. Figures 10 and 11 similarly compare favorably for May 8, 1991 although it is apparent that the model missed the small, but important differences near the release point. The model maintained the plume immediately on the gulf coast rather than move it a small distance onshore as was detected from the satellite imagery.

Every day was not modeled as well as May 8th. Our forcasts, Figures 12a and b, and the NOAA-11 satellite images, Figure 13, show one day, May 17, when there was a significant problem with the modeled wind flow and subsequent plume position simulation.

Preliminary investigation of the disparity in the calculated versus real plume location points to a lag in detection and analysis of a cold front moving southeastward through the region. Figure 12a is a 36 hour forecast and Figure 12b is a 24 hour forecast. There is some evidence that the latter forecast reflects more of the frontal "push" but it still misses the strong inland penetration of the smoke plume flow over Saudi Arabia. In conjunction with the cold front there was a distinct change in airmass characteristics including a more stable boundary layer and lower and stronger inversion, particularly during the day. An upper air sounding indicated a capping inversion at about 1000 m at 1200 UTC 17 May 1991. Figures 14a, b and c show improved agreement that we were able to achieve by changing our specified diurnal cycle to match the characteristics just discussed. This is another example of the urgent need for reliable and timely meteorological observations which form the basis of regional flow modeling.

For long term continuous plumes, an error in modeled particle positions is propagated until it leaves the model domain. ARAC is attempting to validate its entire modeling effort for the smoke plume transport and dispersal from May 8 to Nov 6, 1991 by means of satellite data intercomparison.

Hemispheric-Scale Air Flow Depiction

In addition, ARAC also has begun using hemispheric-scale winds to simulate the long range transport and dispersion of the oil fire plumes. We started with releases beginning on February 21, 1991 and have completed through July 1, 1991 as of this writing. The long range model does not exhibit the details evident in the 3200 km regional model, but the overall patterns based entirely on analyzed wind fields, show strong similarity to the regional results. Thus we are confident that this model represents the plume reasonably well over longer ranges where the smoke particles are too widely dispersed or removed so as not to be visible in the satellite imagery. Figure 15 shows an example of long range plume simulation for May 8 which reveals a very complex and widespread transport and dispersal history for the smoke plume soot particles. Note that since the present version of the ARAC models cannot remove smoke particles by cloud/precipitation processes the modeled plumes are far more extensive than one would anticipate based on the measured hygroscopic nature of the soot particles.

Some further examples of successful wind flow modeling in the Gulf region are found in Figures 16, 17 and 18 for July 1, 1991. Figure 16 shows our ARAC model particle plot valid for 1200 UTC and Figure 17 is the NOAA-11 satellite visible imagery for just a few hours prior. Note the generally close agreement between these two figures including the thinned smoke veil over Qatar. Figure 18 provides a view of the modeled long range dispersion of the fire soot particles. It is noteworthy to see the basic comparability of these model results and the satellite "truth" data.

Another, and final, example is shown in Figures 19 and 20 depicting the modeled and real plume dispersal for July 25, 1991. Once again there is evidence of substantive modeling skill, both in transport and diffusion. Specifically, the modeling system has very accurately carried the recent plume nearly straight along the western shore of the Gulf and then across the western portion of the United Arab Emirates. A separate, older, sheared segment of the plume is positioned across the southern part of the Gulf and extends well into southern Iran. This provides a very clear example of the three dimensional nature of atmospheric flow (in the Gulf region) and the absolute necessity to utilize three-dimensional atmospheric models to assess the transport and dispersion of pollutant emissions throughout the region.

Recommendations

The enormous environmental impacts of the Kuwait oil field fires should be studied and evaluated to the maximum extent possible. Unknown human and ecological consequences should be evaluated and bounded by careful assessment of the pollutant dispersal throughout the Gulf region and beyond. To have confidence in such an approach, the model systems to be used must be evaluated against all available data. The WMO's Background Air Pollution Monitoring Network data must be screened for confirmation (or refutation) of the long range transport of the pollutants out of the Gulf region. Studies should be initiated and supported to determine the human population exposure to hazardous pollutants from the oil fires and also possible impacts or links to precipitation anomalies across South Asia during the period of smoke/soot particle dispersion.

Despite the catastrophic nature of the oil fires, they provided an opportunity to observe and assess the long range widespread dispersion of pollutant emissions. Environmental scientists/scientific teams should be supported in their endeavors to thoroughly research this event with the aim to specifically improve humanity's knowledge of the consequences of inadvertent, accidental and known/planned emissions into the atmosphere.

Summary

ARAC responded to a U.S. government request to support scientific research flights with forecast Kuwait oil fire plume positions on a daily basis mid-May to mid-June and mid-July to mid-August 1991. Review of the ARAC plume analyses and forecasts by the WMO resulted in an official request from the WMO to the U.S.

Department of Energy to have ARAC provide the plume calculations to the Gulf region countries from early June until cessation of the fires.

Both regional and hemispheric modeling systems (and data sources) were employed. A 3200 km regional system, with explicit terrain influenced flow, provided the operational analyses and forecast plume positions. The hemispheric modeling system has been used to study long range aspects of the plume dispersion.

From a limited set of satellite data we see a generally favorable comparison between the ARAC modeled flow and satellite plume imagery. We have found a few occasions with disparate results, most probably a consequence of inadequate input (or availability) of observational weather data to initialize the models. It is strongly recommended that all available data be collected and models be validated and possibly modified to incorporate new knowledge acquired from the study of this major environmental event.

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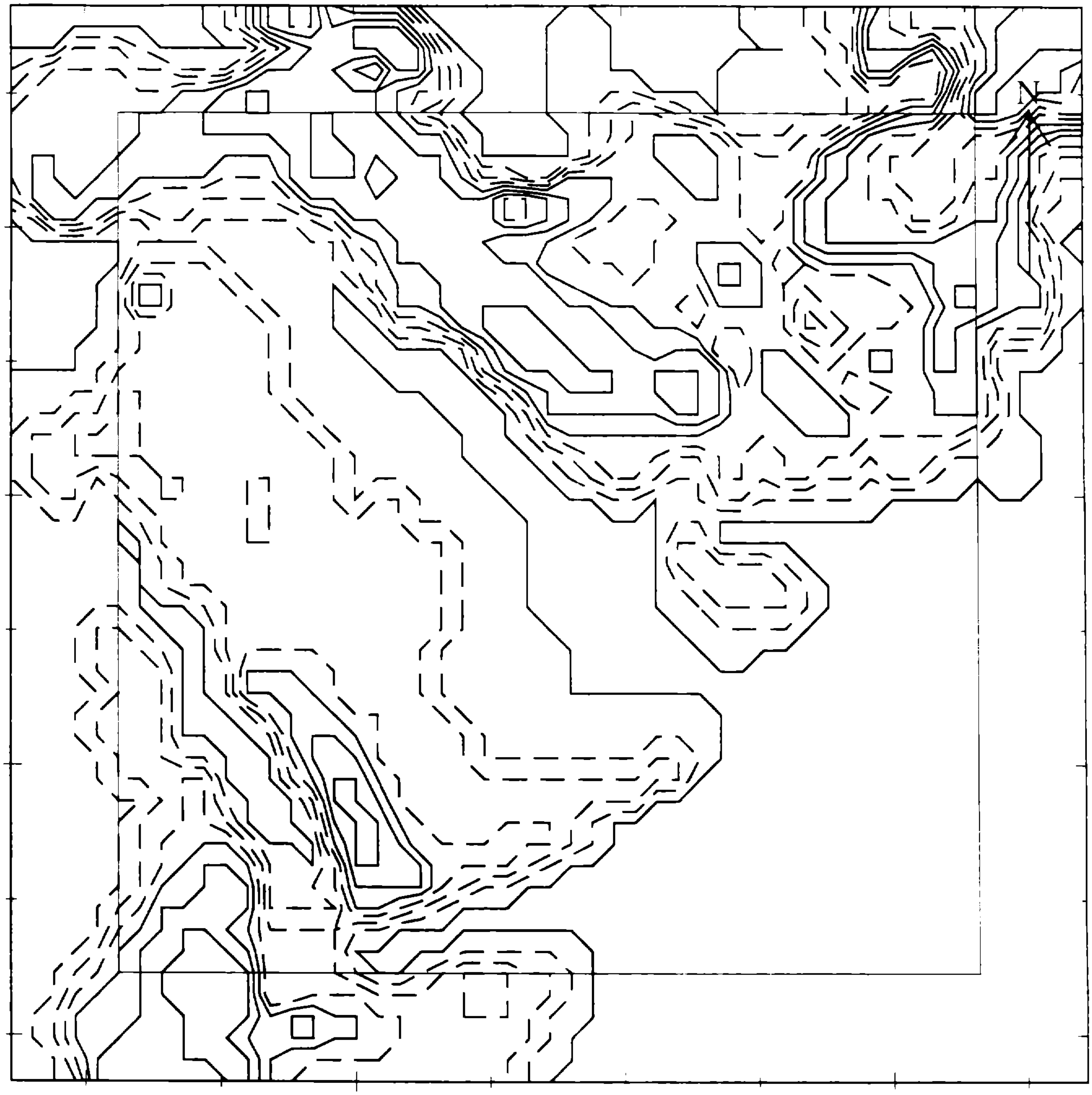


Figure 1. The 40 x 40 terrain grid used in the regional model calculations. Each grid cell is 80 km in the horizontal and the elevation is contoured at ~ 430 m intervals.

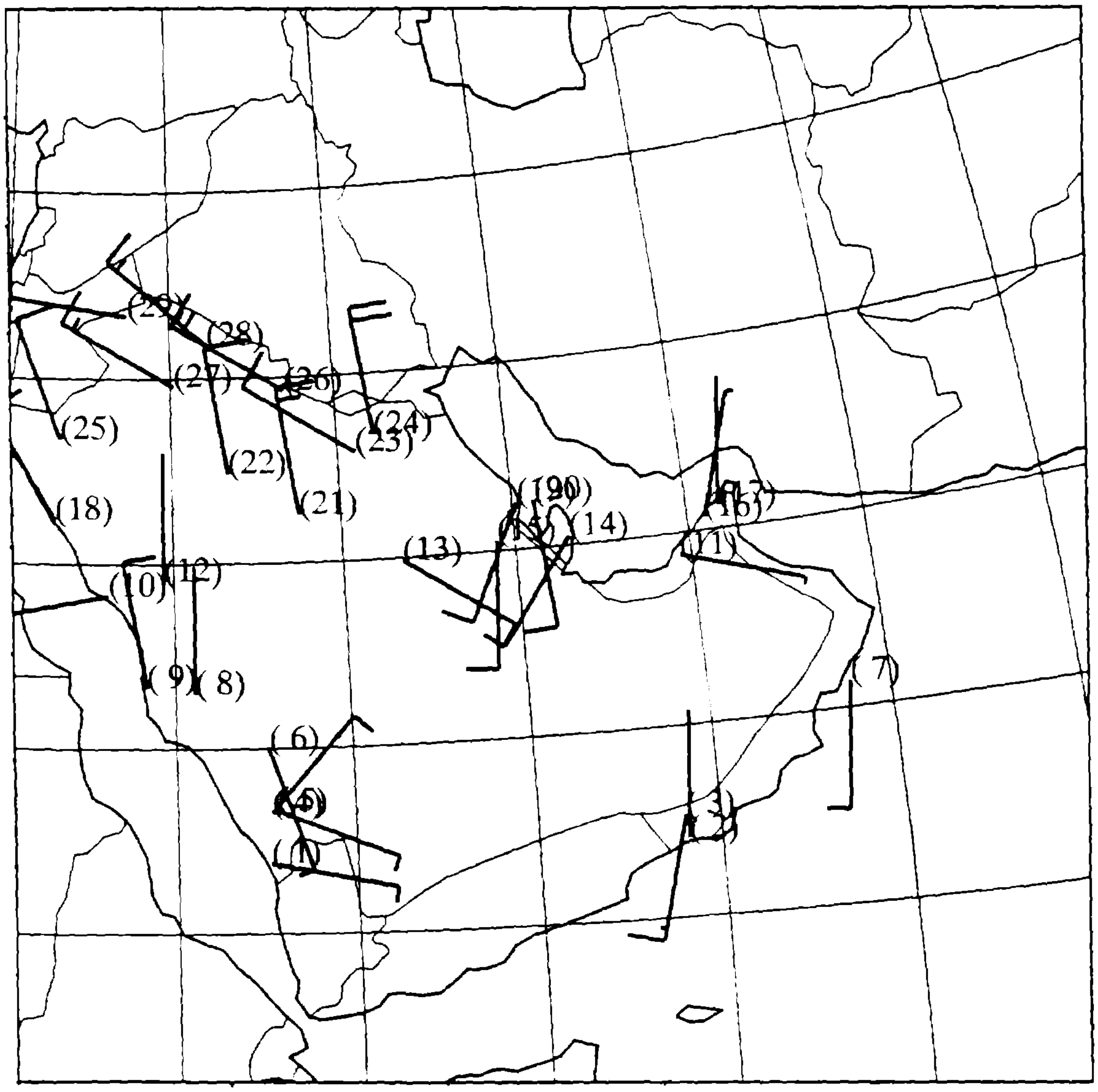


Figure 2. The surface observation data available for a typical primary data period at 0000 UTC, 17 May 1991. Only 29 stations were reported before the meteorological analysis commenced.

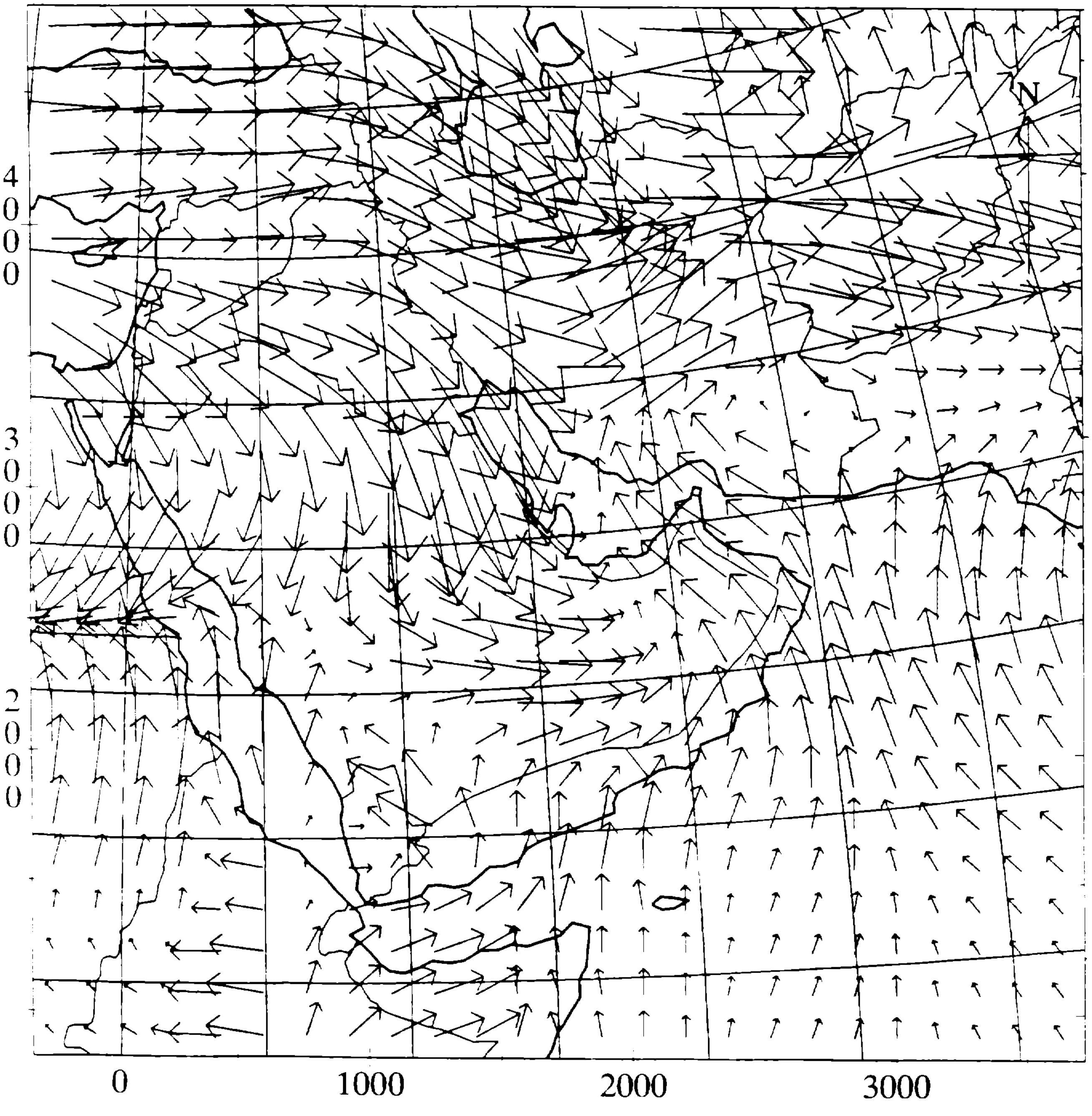


Figure 3. Interpolated wind vectors (for every 2 grid points) at 6 m elevations prepared from the surface observations and AFGWC Relocatable Window Model (RWM) forecast grid. After this data was mass-adjusted, including terrain influence, then the resulting flow field was used for a six hour period centered on 0000 UTC, 17 May 1991.

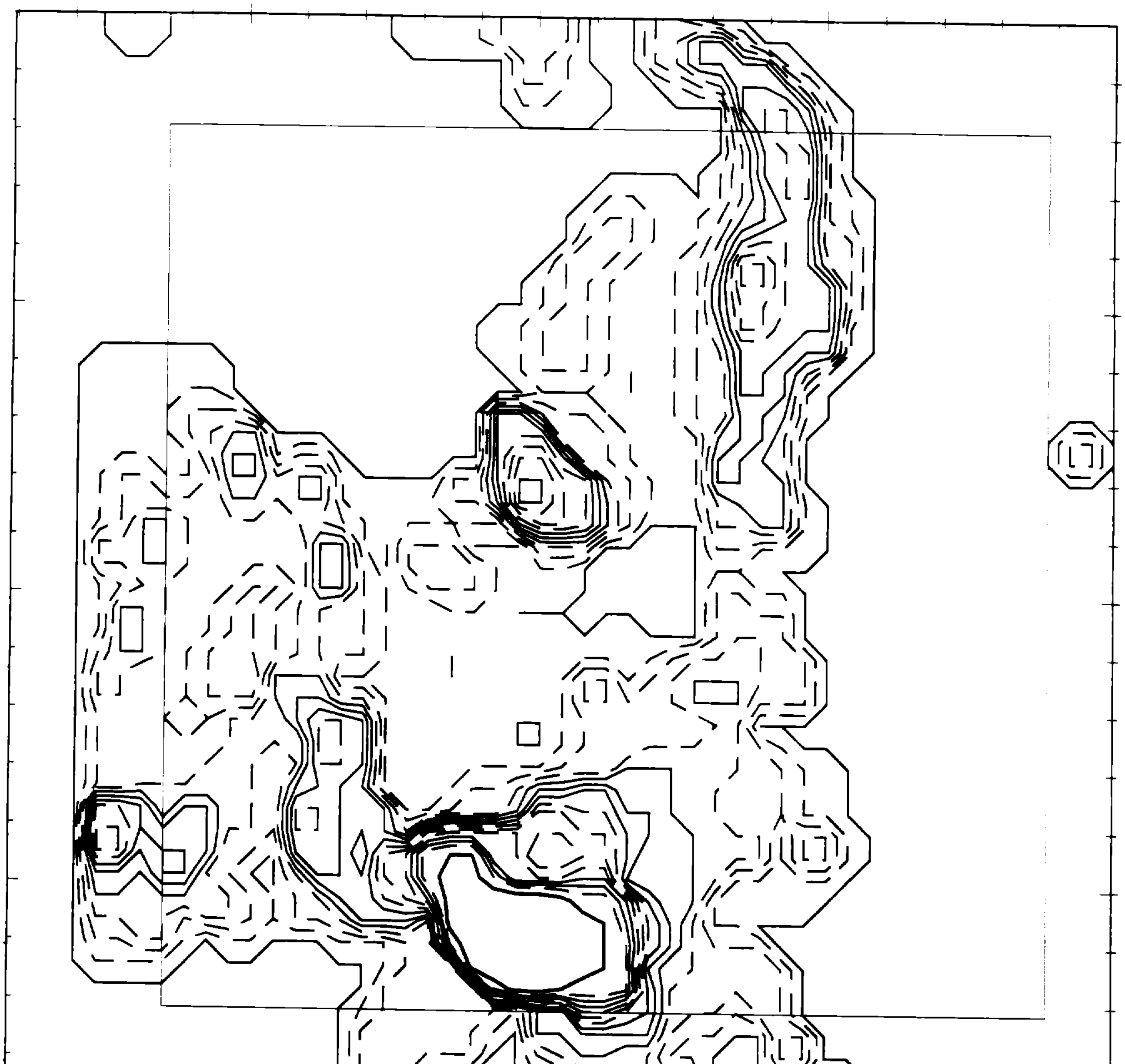


Figure 4. Comparable to Figure 1, this depicts the 47 X 51 381 km terrain grid used with the hemispheric modeling system. The elevation contour interval is 350 m.

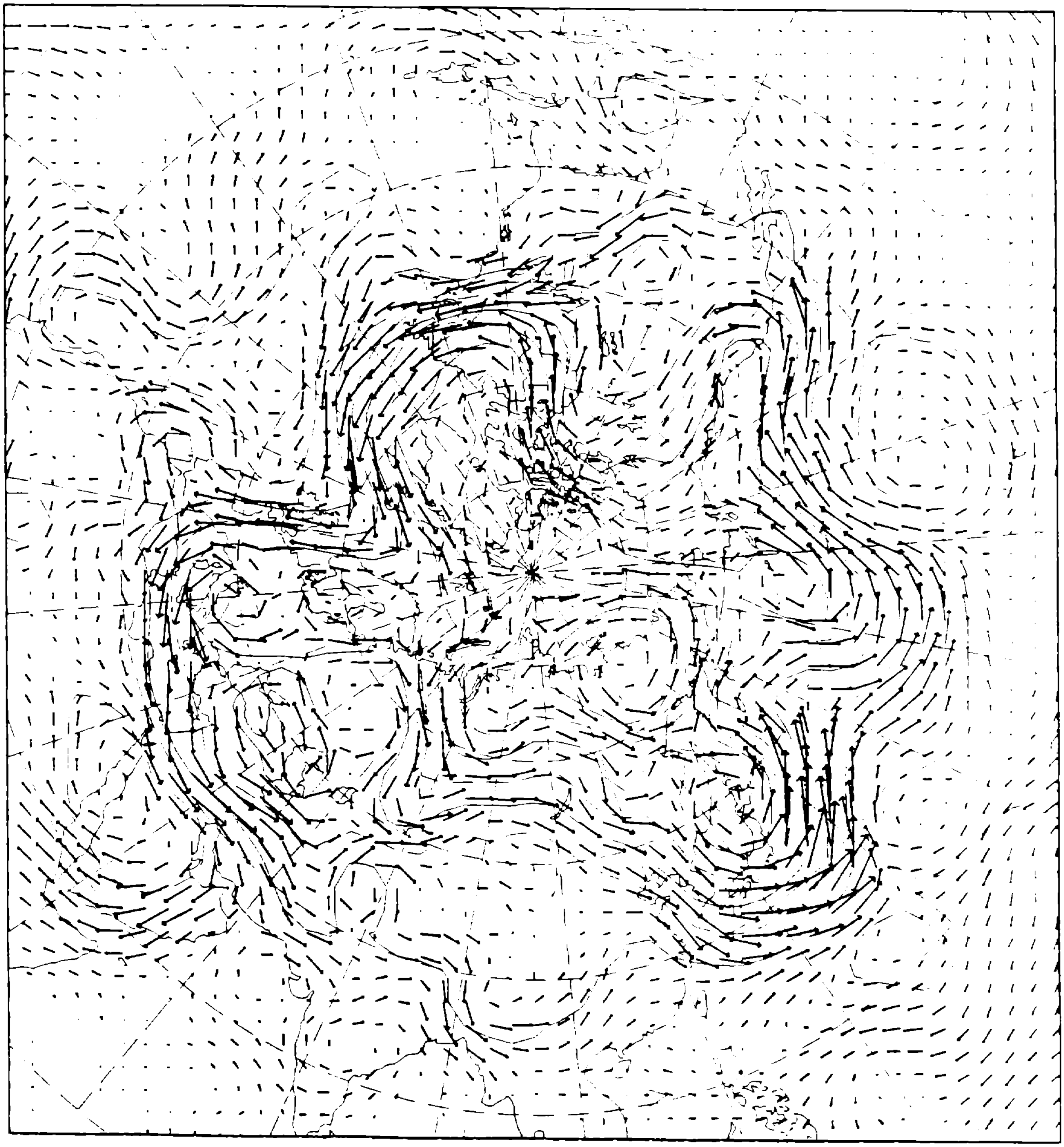
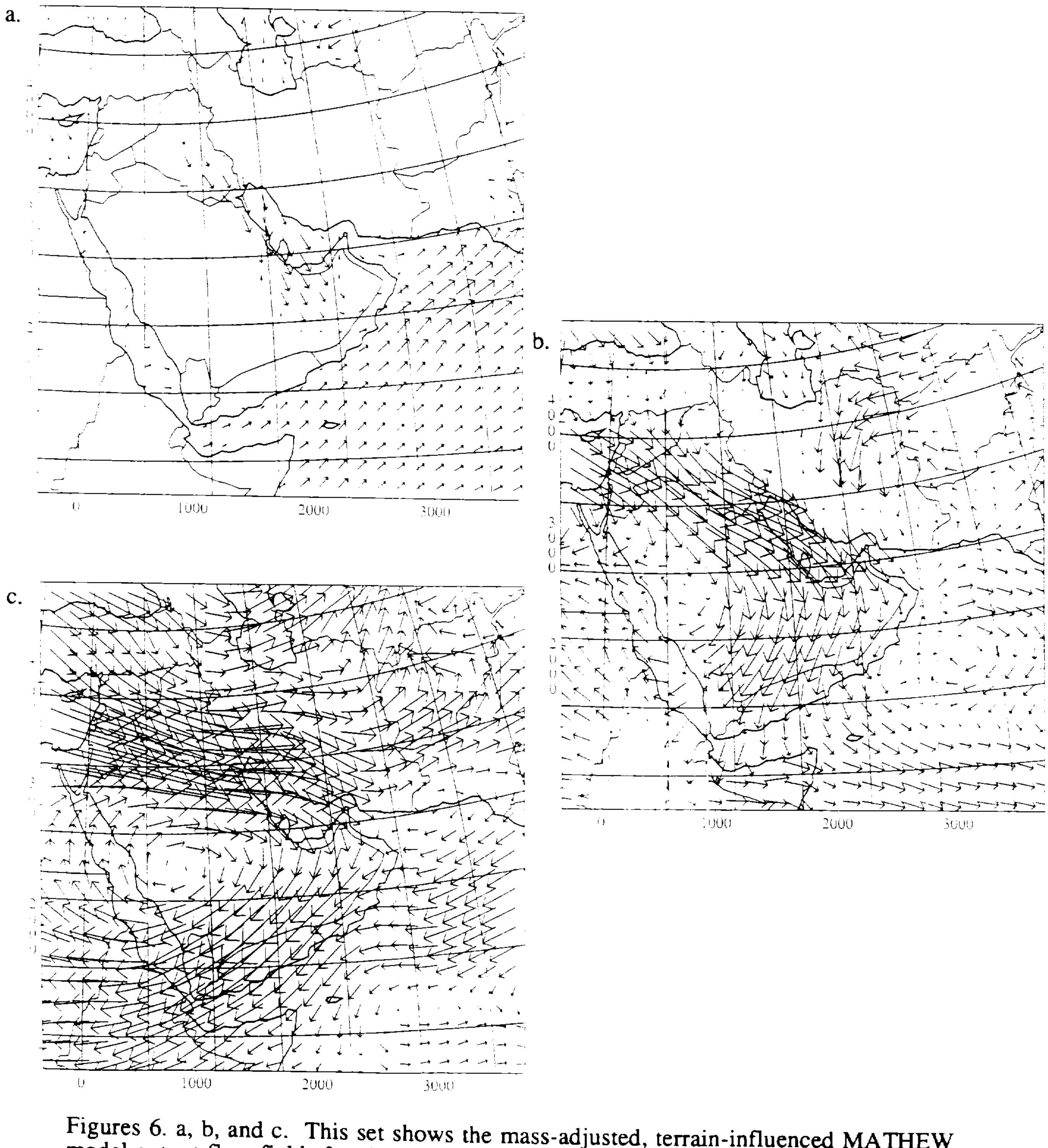


Figure 5. The hemispheric scale wind vector data provided by AFGWC for long range transport and diffusion assessments. This data is for the 700 mb (~ 3,300 m) level; at 0000 UTC, 17 May 1991. The vector lengths are proportional to speed. Note the 381 km spacing of the grid points.



Figures 6. a, b, and c. This set shows the mass-adjusted, terrain-influenced MATHEW model output flow fields for a) the surface level, b) the 1714 m level and c) the 3857 m level. Complex, sheared flow environments are evident in several parts of the grid as is the terrain-influence.

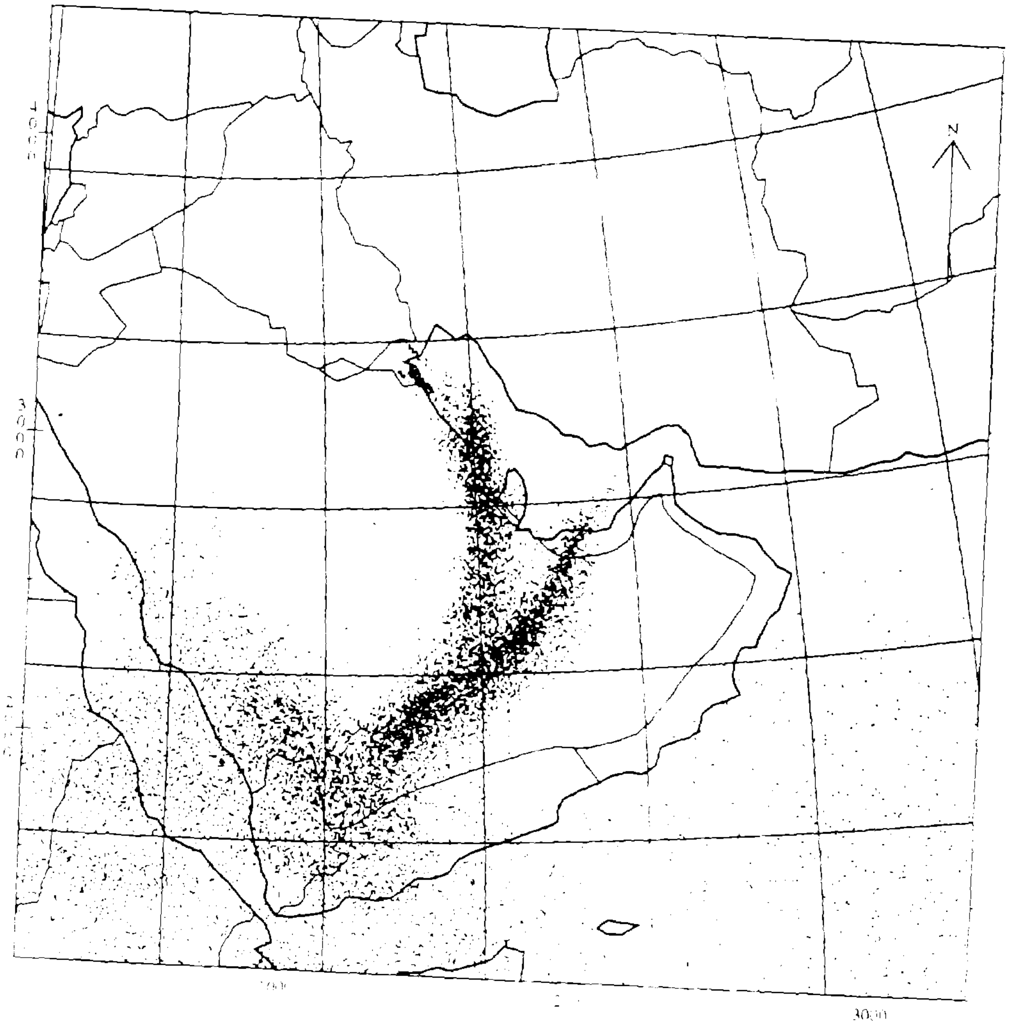


Figure 7. ADPIC marker particles, 24 hour forecast, valid 1200 UTC 3 June 1991.

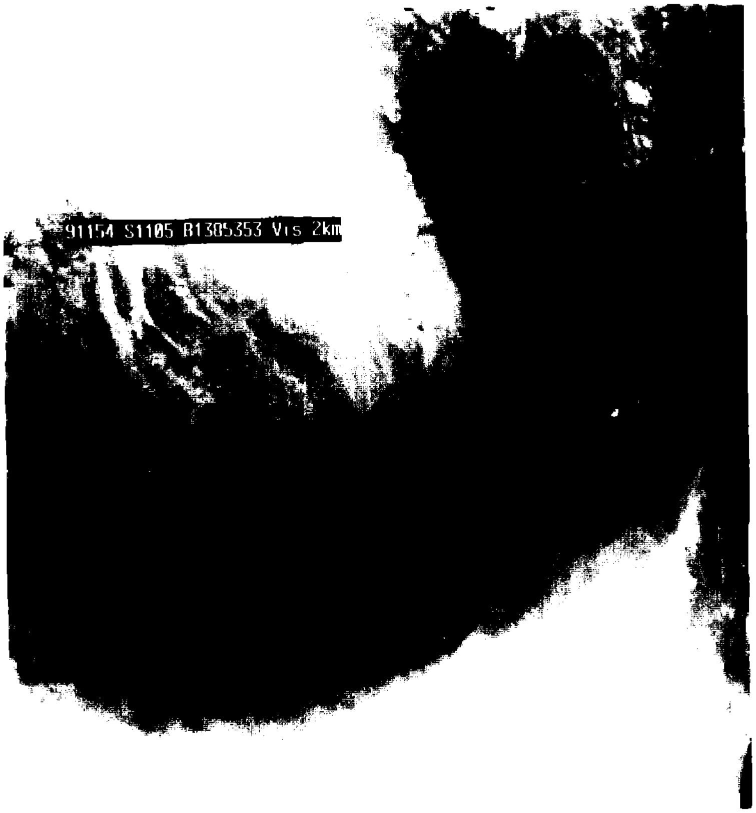


Figure 8. NOAA-11 satellite visible channel image, 1105 UTC 3 June 1991 showing the smoke plume extending deep into Saudi Arabia.

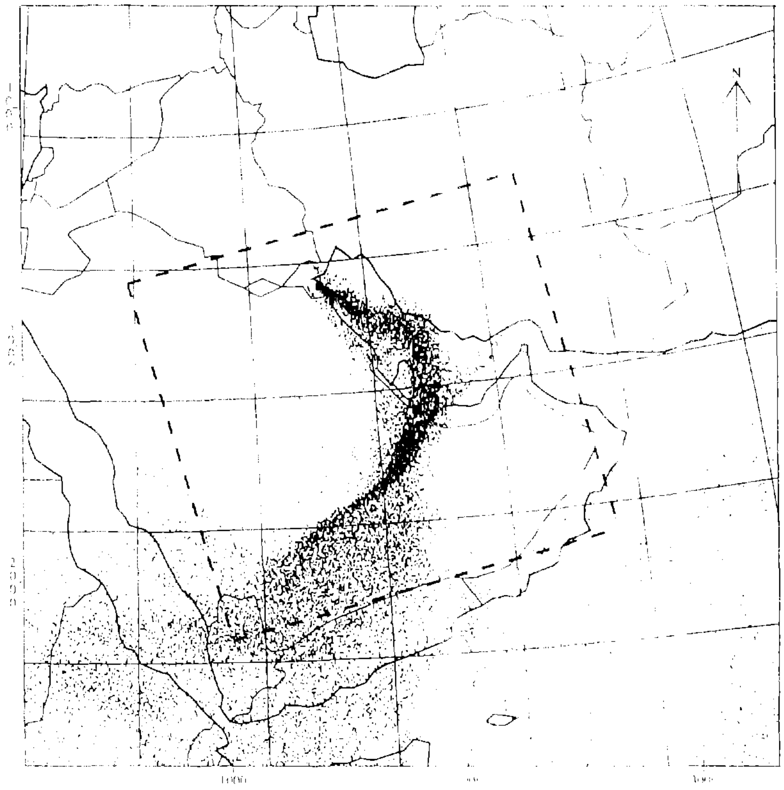


Figure 9. ADPIC marker particles for a refined, analyzed data only plume projection. This shows subtle improvements in the final plume agreement with the satellite image in Figure 8.

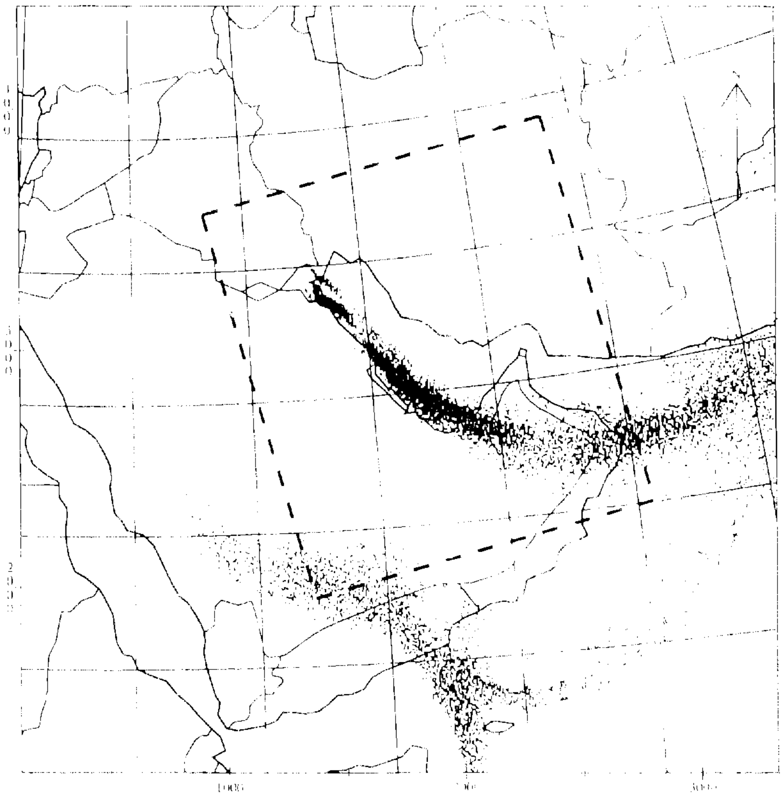


Figure 10. ADPIC marker particles, 0600 UTC 8 May 1991 with a box outlined to match the area covered by the satellite image in figure 11.

Figure 11. US/DoD Defense Meteorological Satellite Program satellite visible channel image for 0518 UTC 8 May 1991.

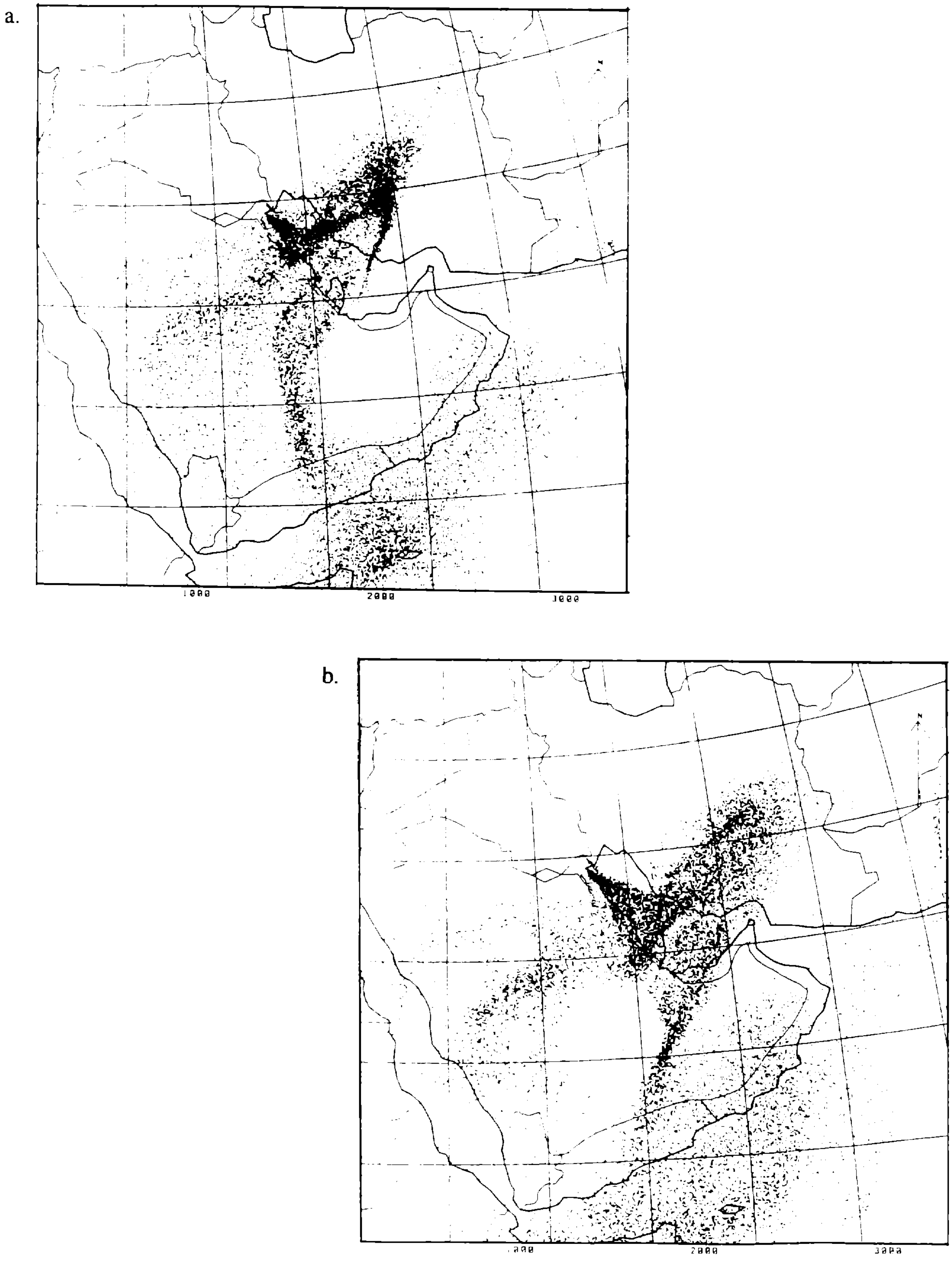


Figure 12. a) ADPIC marker particles, 36 hour plume position forecast valid 1200 UTC 17 May 1991; b) is the same based on a 24 hour forecast.

Figure 13. NOAA-11 Satellite visible channel image for 1058 UTC 17 May 1991.

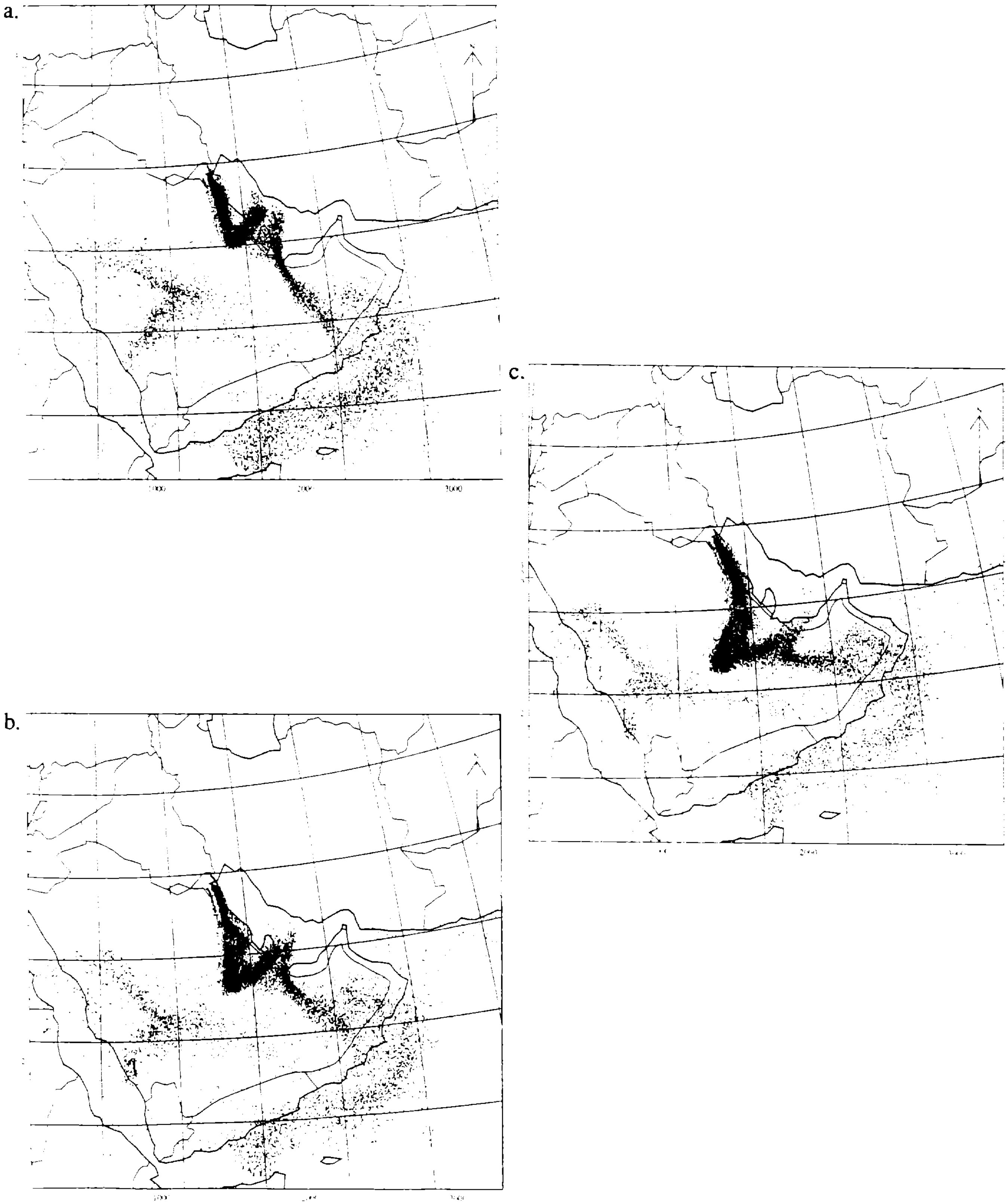


Figure 14 a, b and c. Improved ADPIC plume position and shape, based upon analyzed windflow data and strongly confined mixing layer depth for a) 1200 UTC 17 May 1991, b) 0000 UTC, 18 May 1991 c) 1200 UTC 18 May 1991.

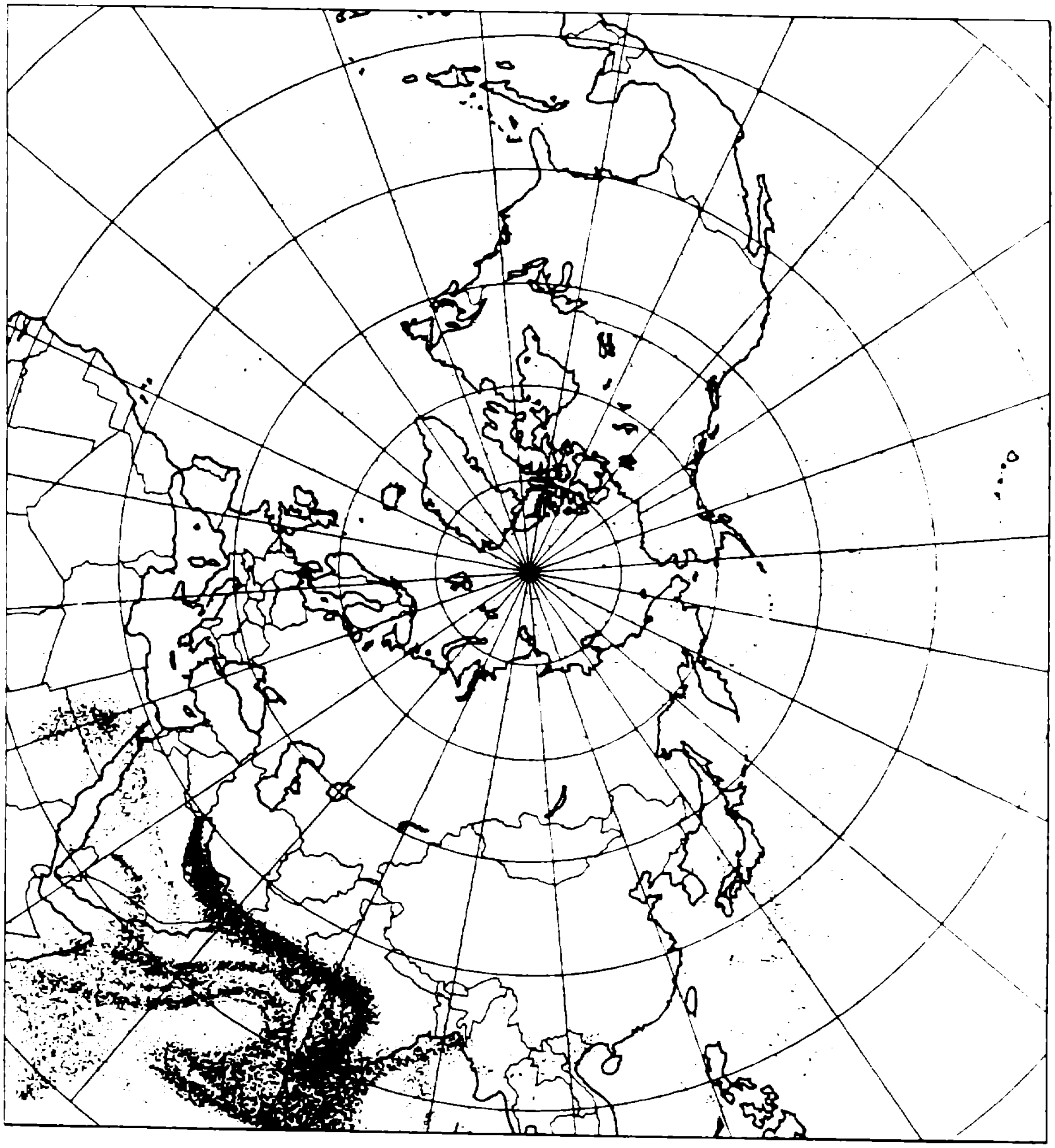


Figure 15. Hemispheric scale ADPIC marker particles valid for 1200 UTC 8 May 1991 based on continuous particle release from 21 February 1991.

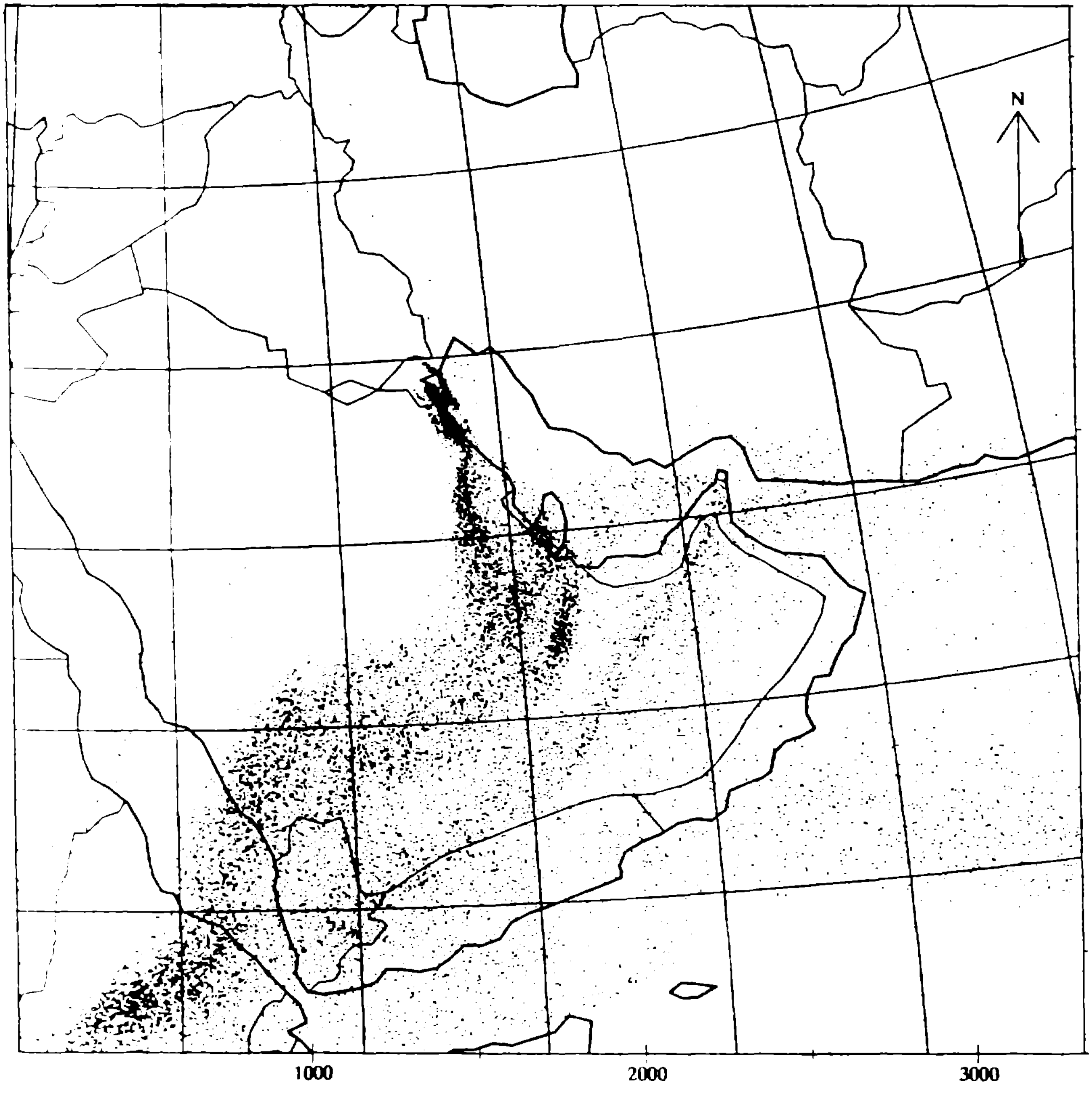


Figure 16. ADPIC marker particles, 1200 UTC 1 July 1991.

Figure 17. NOAA-11 satellite visible channel image, 1046 UTC 1 July 1991.

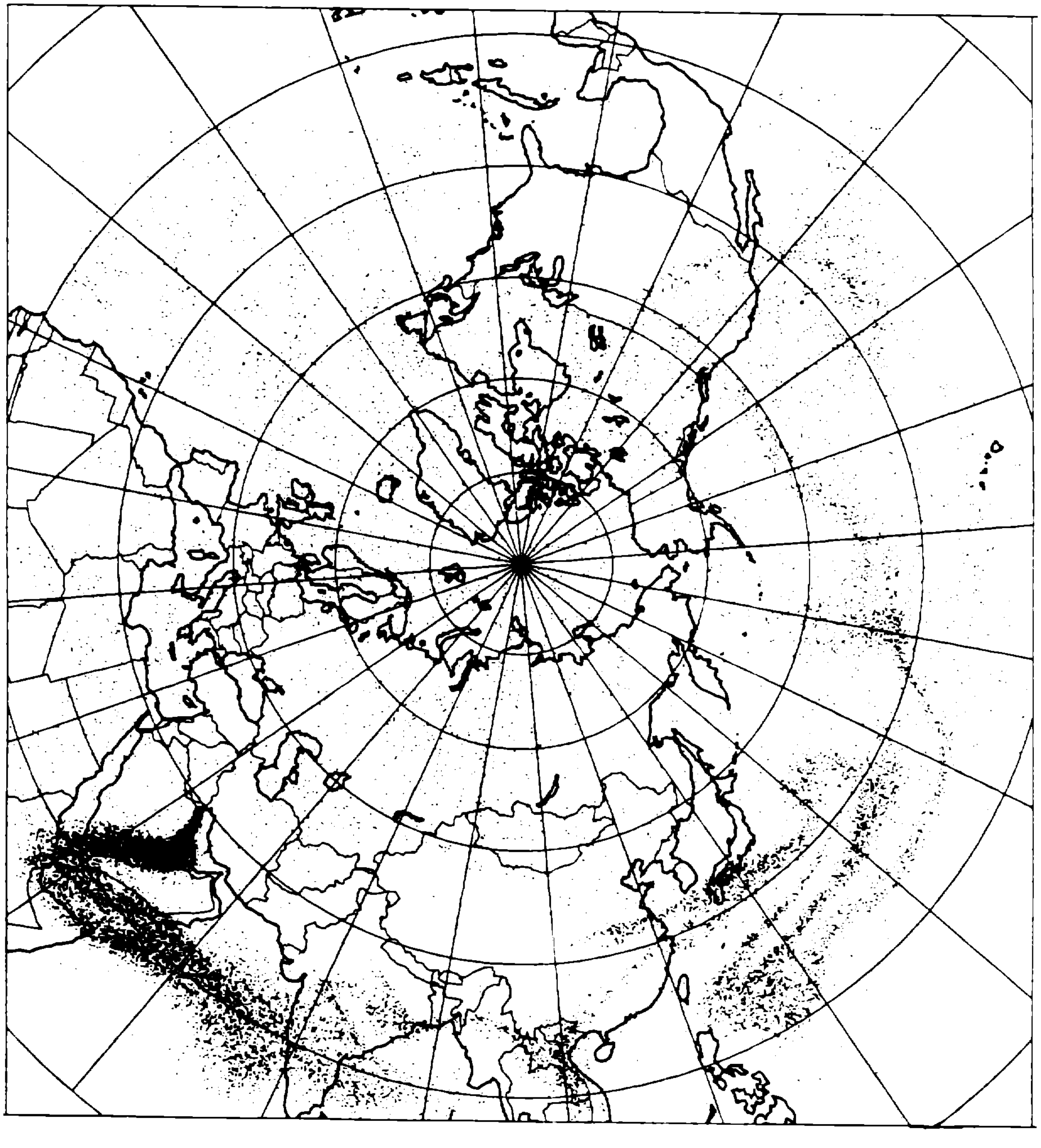


Figure 18. Hemispheric scale ADPIC marker particles, 0000 UTC 1 July 1991.

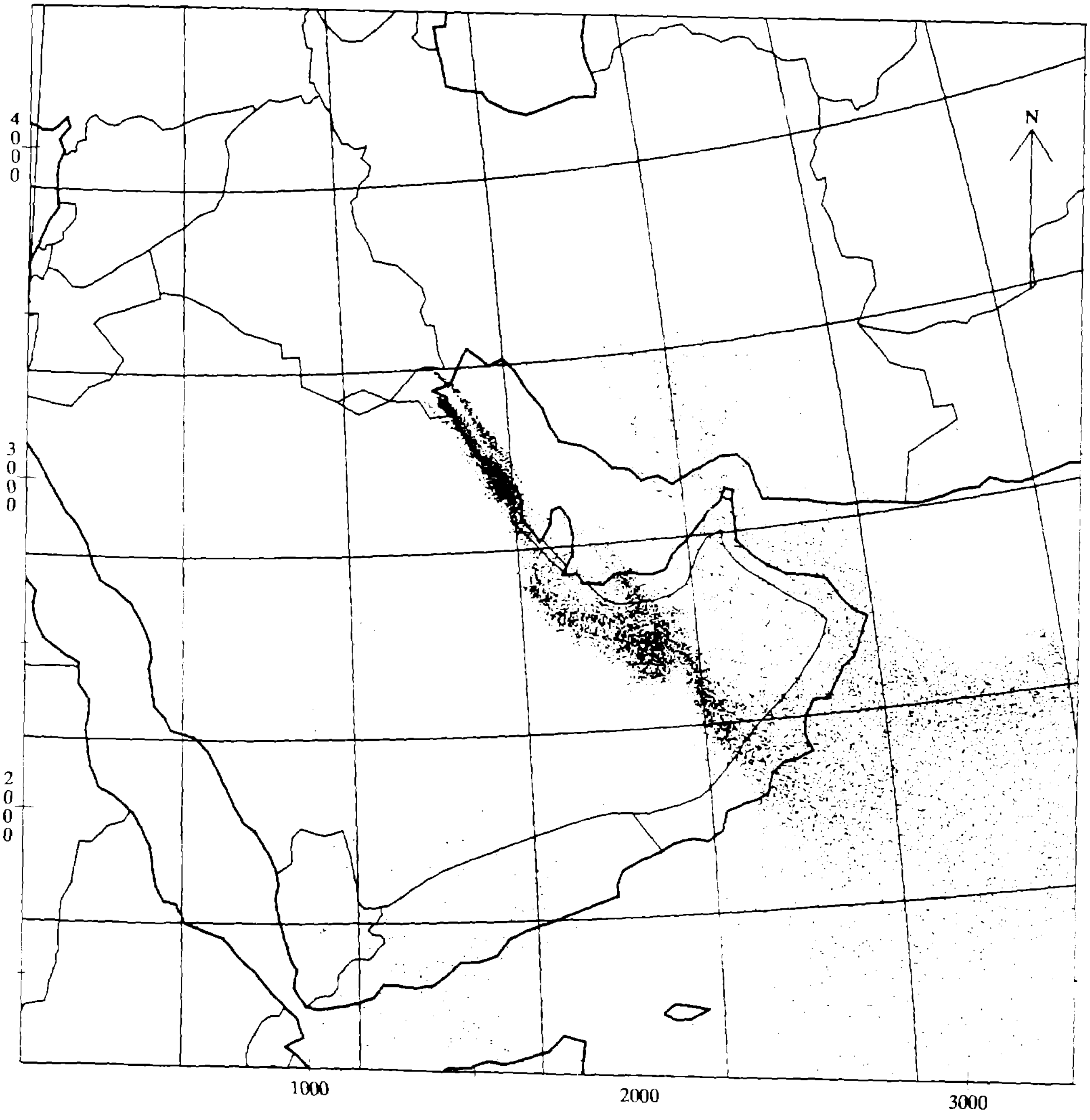


Figure 19. ADPIC marker particles, 1200 UTC 25 July 1991.

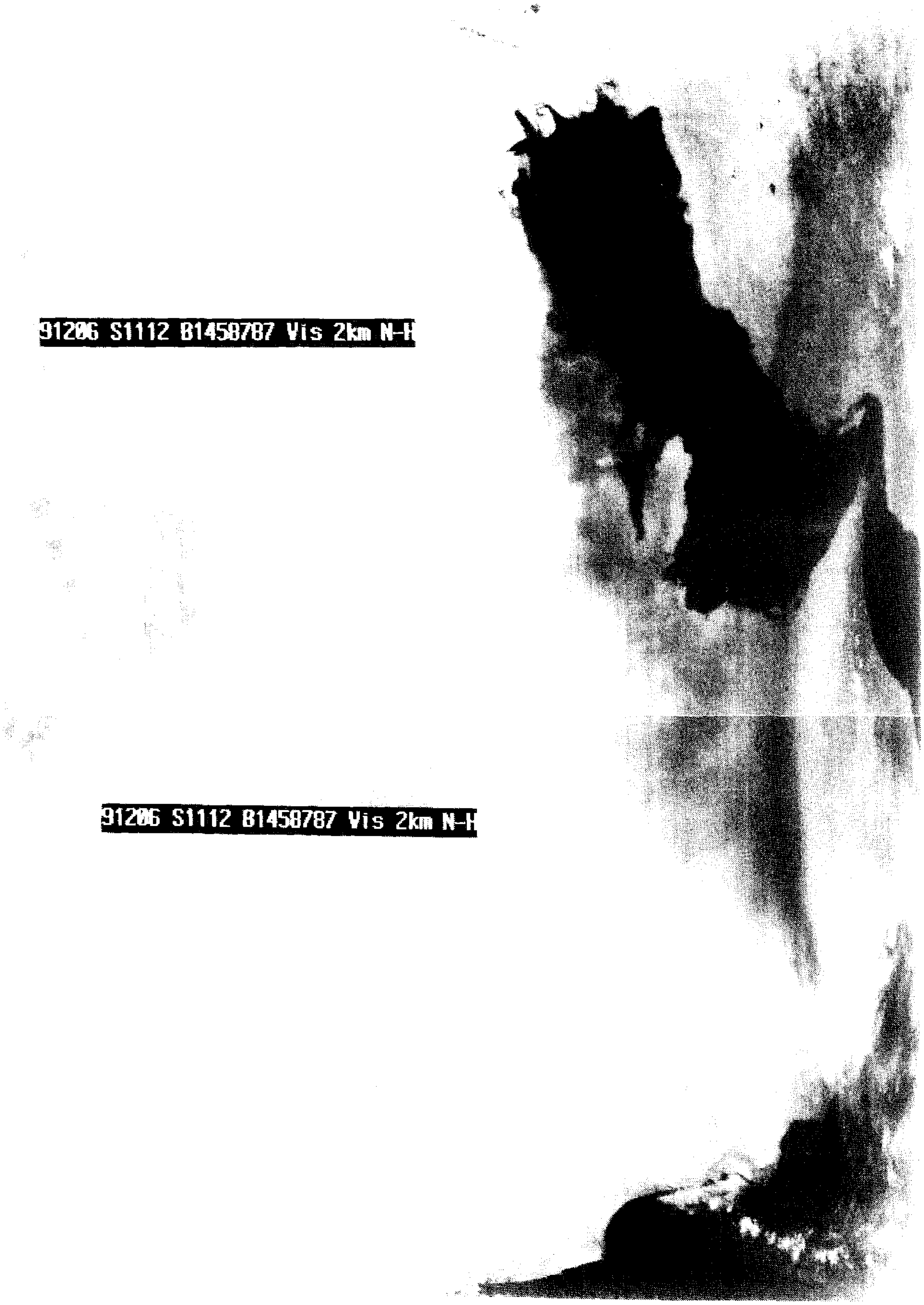


Figure 20. NOAA-11 satellite visible channel image, 1112 UTC 25 July 1991