Met.O.(PR) Turbulence and Diffusion Note No. 202

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18 th December 1992

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Note

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Summary

The UK Meteorological Office Nuclear Accident Dispersion Model (NAME) has been run in seven different configurations to produce hindcasts of the spread of the Kuwait smoke plume validating at 00Z 29th March 1991. This note discusses how the model results subtly differ when the model parameters, including release profile and horizontal and vertical turbulent diffusion, are changed. The results are compared with the plume observed by satellite photograph and with aircraft measurements made during a sortie by the MRF C130. Finally an intercomparison was made with another Lagrangian long range transport model developed by Imperial College, using identical input meteorology.

Introduction

In late February 1991 about six hundred Kuwaiti oil wells were set alight emitting very large quantities of smoke into the atmosphere. The resultant plumes travelled for considerable distances in the Gulf region. This incident provided a rare opportunity to test the UK Meteorological Office's Nuclear Accident Response Model (to be referred to by its acronym NAME) against such observations as are available. The model, being designed for long range transports (LRT), cannot be expected to reproduce the detailed structure of the visible plume (within a few hundred km of the source) with great accuracy, but the availability of satellite photographs and investigative flights by instrumented aircraft provided too good an opportunity to miss. In addition, the opportunity presented itself of carrying out intercomparisons with another, generically rather similar, LRT model, Imperial College's '3-DRAW', using the identical situation and data. This intercomparison was requested by Dr E H Holt as the final stage of a contract between the U.S.Army Research Office and the U.K Met Office.

Several runs were made where model parameters such as smoke release height and turbulent spread were varied. Model output included trajectory end-points (together these constitute an instantaneous 'visible plume'), computed boundary layer and elevated level concentrations of smoke, and the deposition of pollutant to the surface.

As a means of verification the model results were compared with photographs taken from the METEOSAT satellite in the visible part of the spectrum, and computed vertical profiles of smoke concentration were compared with airborne measurements collected by the C-130 aircraft of MRF [1].

The NAME Model

NAME is a 3-dimensional Lagrangian multi-level, multi-particle model used to compute instantaneous or time integrated air concentrations of atmospheric pollutants, together with accumulated wet and dry depositions to the surface. It is described fairly fully in Maryon et al (1992). Although designed as a nuclear accident response model, it is easily adaptable to other large pollutant releases. The version used to simulate the Gulf oil fire plume utilised archived meteorological fields from the Met. Office's former 'Fine Mesh' operational numerical weather prediction (NWP) model, resolved at approximately 95 by 80 km. Unlike later versions of NAME, which use NWP model terrain-following coordinates, the Gulf version used winds, etc, from standard pressure levels, which is less than ideal in some situations.

The model is of 'Monte Carlo' type, very large numbers of particles being released into the model atmosphere according to a prescribed source emission profile. Each particle represents a small quantity of the pollutant (here carbon) and is carried along in the model wind fields and with perturbations to take into account sub-grid scale diffusion. The Gulf version of NAME has a domain extending from 11.25^0 W to 109.69^0 E and from 4.5^0 N to 54.0^0 N; that is, 130 by 67 grid points at intervals of 0.9375 degrees longitude and 0.75 degrees latitude (Figure 1). The model has nine levels in the vertical, the highest being $100mb$. The particles are released in hourly batches and then advected using a 15 minute timestep, the model winds being interpolated in time and space from the archived, 3-hourly, wind fields. At each timestep a random perturbation is added to the horizontal displacements to account for eddy diffusion so that the solution for a position vector at time i+1 is given by :-

$$\mathbf{x}_{i+1} = \mathbf{x}_i + \mathbf{u}(\mathbf{x}_i)\Delta t + \mathbf{A}r \qquad (1)$$

where $\mathbf{x}$ is the position vector, $\mathbf{u}$ is the mean wind vector, Δt is the model time step, r is a random number from a suitable distribution and $\mathbf{A}$ is a length equivalent to the $\sqrt{2\Delta t K}$ of conventional parametrizations, in which K is the horizontal diffusivity. The diffusivity was held constant during these integrations. Above the ABL the horizontal diffusion was reduced to 25% of the ABL value.

It is assumed that the atmospheric boundary layer (ABL) is always well-mixed: particles within the ABL are randomly re-assigned vertically (within the ABL) at each 15 minute timestep (roughly an eddy turn-over time for the convective boundary layer), so that each particle experiences a mean boundary layer wind as time passes. Vertical diffusion above the ABL again takes the form of a random displacement. As this would result in a one-way feed of particles downwards into the ABL, which is not realistic, the random

[1]Meteorological Office Research Flight

vertical reassignment of ABL particles is spread over a distance slightly larger than the ABL depth, to compensate. This distance is calculated using the assumption that a uniform air concentration would be unchanging with time. This, then, is the parametrization of small-scale entrainment processes.

Large scale interchanges are dealt with very simply, by constantly re-diagnosing ABL depth at the particle position (and time) using the 'Fine Mesh' model vertical profiles of wind and temperature. Thus entrainments, etc, due to diurnal and large scale changes are automatically allowed for. In this way the model boundary layer evolves realistically with time, and the diffusion the individual particles experience depends upon their position above or below the inversion capping the ABL. To diagnose the ABL depth a Richardson Number formulation was used. The Richardson Number (R_i) is defined

$$R_i = \frac{g\delta\theta/\delta Z}{T(\delta u/\delta Z)^2} \tag{2}$$

where g is 9.81 ms^{-2}, T is the average temperature of the model layer, $\delta\theta/\delta Z$ is the potential temperature gradient within the layer and $\delta u/\delta Z$ is the wind shear. R_i is effectively a ratio of the work done against gravity by vertical motions to the shear-generated turbulent energy. When R_i is positive—or, to be more precise, when it increases beyond a critical value (here taken as 1.3)—turbulence tends to be suppressed, so that R_i is used to identify the stable inversion layer capping the ABL. The difficulty lies in estimating this height from rather coarsely resolved model profiles (the numerical problem is discussed in Maryon 1989 and an assessment of techniques used to determine ABL depth for the NAME model contained in Maryon and Best 1992). In the Gulf version of NAME linear profiles of $\delta T/\delta Z$ and $(\delta u/\delta z)^2$ were assumed to exist between consecutive grid points in the vertical and a simultaneous equation solved to obtain the height at which the Richardson number falls to the critical value.

During the period under study most of the carbon deposition to the surface occurred through dry deposition, as very little rainfall occurred in the region at that time. The loss of mass is expressed by :-

$$dM/dt = -V_d M/Z_i \tag{3}$$

where dM/dt is the rate of change of mass, V_d is the dry deposition velocity and Z_i is the boundary layer height. V_d for carbon was assumed to have a constant value of 0.0005 ms^{-1}. All of the particles in the ABL undergo a proportional loss of mass in this way; particles are never deposited to the surface and entirely lost to the integration. Air concentration is computed at each model analysis level simply by counting particles in each grid volume.

Plume lofting

It was realised at an early stage of the Gulf crisis that dense smoke from oil fires might absorb solar radiation and be lifted buoyantly to high levels. If it reached the stratosphere it would persist, with possible repercussions on the earth's climate. Parallels were drawn with the nuclear winter scenario. To investigate this, a parametrization for this effect was incorporated into various Met Office models, including NAME, used to simulate the spread of the Kuwait smoke. The effect proved to be unimportant on large scales (Browning et al 1991), but the parametrization was retained for one of the sensitivity studies carried out here.

The transmission of radiation by smoke is proportional to $\exp(-kc/\cos\zeta)$, where c is the smoke column density, k is the absorption coefficient, assumed to be $10m^2g^{-1}$, and ζ is the solar zenith angle. Thus the solar absorption in a layer N is from

$$\Delta S = S\left[\exp\left(-\Sigma_{i=1}^{N-1}\frac{kc_i}{\cos\zeta}\right) - \exp\left(-\Sigma_{i=1}^{N}\frac{kc_i}{\cos\zeta}\right)\right]$$

where S is the solar radiation at the top of the atmosphere (the normal attenuation is relatively unimportant and is neglected). The heating rate in the layer is then

$$C\frac{g}{c_p}\frac{\Delta S}{\Delta p}\text{K/unit time}$$

where Δp is the thickness of the layer in mb (C is a factor which simply allows for the units adopted). Integration is carried out downwards from the top of the model, layer by layer. Each particle thus contributes to the smoke column density via the concentration diagnostics; it is assumed to heat up with its ambient air, and then rises to its level of neutral buoyancy.

There is one distinct difficulty in applying this technique: the coarse resolution of the model means that the smoke density is greatly underestimated close to the point of release. A factor taking into account, approximately, the difference in area between the plume and the grid box was applied to increase the plume concentration solely for this parametrization.

Pollutant release

A single point source of smoke was placed at 29.25 N ; 47.40 E. This was derived from two major fires centred at 29.3 N ; 47.6 E and 29.2 N ; 47.2 E . Aircraft measurements indicated a release rate of 3.95 * 10^6 tons of carbon per year which was reduced to an hourly rate for input to the model, where it was represented by a continual emission of 500 particles per hr. Six 48 hr integrations commencing 00Z 27th March 1991 were made to test the sensitivity of the plume to different model configurations: details are all as Run 1 below except for the points of difference listed. The release height and period of integration were constrained to enable comparisons to be carried out with the 3-DRAW model. The seventh integration was released a day earlier with a more realistic initial distribution of particles.

- Run 1 ABL ($950mb$) release with no lofting scheme and a moderate value for K, the horizontal diffusivity, of $2500m^2s^{-1}$. Slight vertical diffusion above ABL: random particle displacements within $\pm 3mb$ approx., per timestep.

- Run 2 ABL ($950mb$) release incorporating the effects of lofting through the absorption of solar radiation.
- Run 3 ABL ($950mb$) release with double the vertical diffusion of run 1 above ABL—that is, a random particle displacement within $\pm 6mb$ per timestep.
- Run 4 ABL ($950mb$) release with no vertical diffusion within or above ABL.
- Run 5 ABL ($950mb$) release with a value of K of zero.
- Run 6 $850mb$ release (above ABL).
- Run 7 Release commencing 00Z 26th March 1991, extended uniformly from 950 to $650mb$; forecast for 72 hours to end at 00Z 29th March as before.

Material from the ABL releases would at once be mixed through the ABL depth by the diffusion parametrization. Material released above the ABL would undergo a relatively slower vertical diffusion, but any becoming entrained into the ABL would again be mixed at once through its depth.

Observation of the Plume

Figure 2 is a METEOSAT picture of the region at 07Z 29th March 1991. Careful examination suggests that the main part of the plume is drifting SE over the Persian Gulf and spreading S'wards towards Bahrain and Qatar, and thence SW. More diffuse material is moving NE over Iran, the extent of which was somewhat obscured by cloud. The nephanalysis for 13Z made by specialist Met Office staff at the time (Figure 3) was based upon high quality photographic sequences from which the movement of smoke could be ascertained even in areas of very poor contrast, and confirms the impression given by the 07Z photograph in Figure 2.

Some weeks after the Gulf conflict had ended, the C-130 aircraft of MRF was sent to the area to assess the environmental impact of the smoke from the Kuwaiti oil well fires. Although little information could be gleaned on the large-scale spread of the smoke, the MRF flight of the 28th March was used to estimate the source strengths of the plume (Johnson et al (1991)). Data from this flight has been used for comparisons with some of the model runs.

The synoptic situation during the release is illustrated in Figure 4—a weak high pressure system lay over W Saudi Arabia with relatively low pressure centred over SE Saudi Arabia with the few surface observations suggesting light winds between W and N over the Gulf itself. The model analyses suggest that the winds became more generally NW with increasing altitude. At the highest levels of interest here, towards $500mb$, a steady, stronger W to SW wind blew over the area of main interest (Kuwait and across central Iran). Thus there were significant wind shears in the vertical, and the structure of the plume was complex. Vertical velocities were rather variable, but subsidence was generally prevalent over the Gulf, and ascent nowhere very marked. The aircraft sortie of March 28th reported a very thick plume up to almost $5,000m$ with multiple layers in the vertical. The main body of the plume was capped by a thin layer of altocumulus in places.

Model Results

In the model output, analysis layer 1 is the ABL, which of course has a variable top. Layer 2 is from the ABL top to $950mb$ (if $950mb$ is above the ABL top, otherwise it does not exist). Layer 3 is from the higher of the ABL top or $950mb$ to $850mb$, layer 4 from the higher of the ABL top or $850mb$ to $700mb$, layer 5 from 700 to $500mb$. We are not concerned with higher levels, here. Figure 5 below shows the NAME diagnosis of ABL depths, in metres, for 00Z and 12Z, 27th March. At midnight (that is, 3AM local time) the heights are an almost uniform $200 - 250m$: these are, in fact, largely model default minimum values (25mb), as the ABL would be very shallow at midnight. By midday (3PM local) the depths have grown to between $1000 - 1500m$ overland whilst increasing only slightly over the sea. The evolution of the ABL depth thus appears quite realistic, and the land/sea difference is very pronounced. This contrasts with other studies in which NAME has been shown to underestimate daytime ABL depth quite seriously, and it may be that the Gulf ABL was in reality considerably deeper—Maryon and Best (1992) contains an account of the difficulties with the NAME ABL diagnosis, and the action since taken to improve the parametrization. The 'rogue' value in the SE corner at 12Z has not been investigated, but pressure was low over the adjacent mainland of Arabia (Figure 4), and it may well be that fresh onshore winds developed, accounting for the low ABL diagnosis.

The following account of the sensitivity studies is based upon the plume analysis at 00Z 29th March 1991.

- Run 1
  Figure 6 is a plot of the computed trajectory end points of each particle and shows that the main plume is situated over the Persian Gulf with a small part extending N over SW Iran. The trajectory end-points have been colour coded (in all figures) as follows:

  Release 00Z-12Z 27/3/91 blue
  Release 12Z-24Z 27/3/91 green
  Release 00Z-12Z 28/3/91 yellow
  Release 12Z-24Z 28/3/91 red

  Most of the plume is in layers 1 and 2 but much of the N'ly part, where the plume is being carried up the foothills of the Zagros, is in layer 3 (the model relief is plotted in Figure 7). The simulated plume thus remains closer to the surface than might be expected, a fact made more clear in the plume cross-section shown in Figure 8. This section is between model rows 32 and 33, just N of the marked strip in Figure 1. In Figure 8 the bold line is the line of surface pressure, which gives a close approximation to the actual surface. Figure 6 shows a distinct change of character in the way the particles of different ages spread. The older (green and blue) parts of the plume experienced greater turbulent diffusion (deeper ABL's) and more exposure to vertical shear as they moved into SW Iran; broadly W to SW winds at low levels gave way to more frequent NW'lies aloft, so that these older parts of the plume became sheared in the way shown.

  Neither the plan nor the cross-section exhibit much in the way of fine detail in the plume structure (the turbulence parametrization would obscure the small-scale features). A cross-section between rows 33 and 34, however, (Figure 9, corresponding to the marked strip in Figure 1), reveals some vertical structure. Such material of the yellow band as is present seems to be sitting above the Gulf ABL, which is fairly empty at this locality. The proximity of the $950mb$ source is apparent.

Examples of the output for carbon concentrations and depositions produced by NAME are given for this particular run in Figures 10 and 11. Figure 10 is a map of the grid box mean values of air concentration of carbon at 00Z on 29th March in the diagnosed ABL ranging from about 200 $\mu g m^{-3}$ in the source region (the release point is above the ABL at 00Z) to 1300 $\mu g\ m^{-3}$, the largest values being located at the NE end of the Gulf. Similar plots indicate a maximum concentration of 1300 $\mu g\ m^{-3}$ at source in layer 2. Layers 3 and 4 have maxima around 980 $\mu g\ m^{-3}$ and 30 $\mu g\ m^{-3}$ respectively, both over SW Iran. No material reached layer 5. Figure 11 is a plot of the accumulated carbon deposition and shows, unsurprisingly, that the highest values are over Kuwait with figures of 38 mg m^{-2}.

- Run 2

This model run (Figure 12) illustrates very well the complicated structure of the plume owing to the sheared winds. The figure shows that this run, which included plume lofting, has diffuse material absent from Run 1. Analysis of the various levels shows that changes were slight in layers 1 and 2. There was a decrease in maximum concentrations in layer 3 but a wider S'ward spread of diffuse smoke. Layer 4 had similar features, with a much wider spread (of very diffuse material), now more to the SE. This diffuse, lofted, material had also reached layer 5, where it was swept away in stronger SW'ly winds towards Afghanistan. Very small amounts of smoke were lofted to even higher levels. These features are reflected in Figure 12. The accumulated dry deposition showed little change from Run 1 other than a somewhat wider spread to the S, suggesting that some of the lofted material carried in that direction had found its way back into the ABL.

The plume cross-section in Figure 13 shows the lofted material, its relative density and its differential transport. Note that lofting was largely confined to the earliest period of release: this would have had the longest exposure to solar radiation, and some assistance was no doubt provided by the older smoke encountering the deeper ABL's over SW Iran: given the ABL diffusion parametrization, a significant amount of smoke would have to make its way above the ABL for the lofting to get under way, and a deep peak ABL depth would assist in this process. In addition, forced uplift over the Zagros may have had some effect in countering synoptic-scale subsidence often present over the Gulf. The concentration of material above $700mb$ is indeed very small, being 1-2 $\mu g\ m^{-3}$ at most. Although the lofting is of necessity parametrized rather crudely in the NAME model, the indications are qualitatively similar to those of the Met Office meso-scale Model (Browning et al, 1991) and with the 0.3 per cent of particles reaching the stratosphere in integrations by Bakan et al (1991).

This model plume shows interesting parallels with the satellite picture, which also shows smoke streaming away from the main body of the plume (the apparent difference in direction is partly accounted for by the map projection of the plot). Although there is no means of establishing beyond doubt the age or altitude of the smoke featured in the photograph, synoptic charts of the period do not support the idea that the smoke spreading NE over central Iran might consist of old plume residues at lower levels. It is almost certainly at relatively high level (as in the aircraft observations), and streaming away in the strong SW'ly flow aloft.

- Run 3

  In this run vertical mixing above the ABL was doubled to what is considered a moderate value of random displacement within $\pm 6mb$ per timestep, using a rectangular distribution. Figure 14 shows that this resulted in a slightly increased S'ward spread (compared with Figure 6). This occurred in the bottom 3 layers, but was particularly marked in layer 3: clearly more material was lifted to experience stronger winds. Some of this presumably returned to the ABL, hence the increased spread in layer 1. Maximum concentrations were reduced by over 20% in the 00Z ABL and smaller reductions occurred in layers 2 and 3. In part this was no doubt due to the wider spread and hence increased diffusion of the pollutant. However, some of the reduction was very likely due to changes in the small-scale entrainment parametrization corresponding to the increased vertical diffusion (see section 2 - description of NAME), associated with a smoke source in the ABL: leakage from the ABL would have increased. Changes at layer 4 were slight; a very small amount of pollutant reached layer 5 where the plume crossed into SW Iran.

  Peak values in time-integrated dry deposition and air concentration in the ABL showed slight increases. This is difficult to account for, although it was noted that the pattern of turbulent spread in the near-source grid-cells was somewhat different. The cross sections corresponding to Figures 8 and 9 show the increased vertical spread clearly, although they are otherwise very similar, and not reproduced here.

- Run 4

  The denser parts of the plume may well have suppressed convective motions in the ABL to a considerable extent, while mixing will have continued as a result of overturning processes in the plume itself. To reproduce this effect in a rather crude way, a run was made with no vertical mixing in the ABL, but with the vertical diffusion retained above the ABL. Horizontal spreading due to meandering was retained at all levels: this may have been a somewhat arguable procedure, but it was decided to look at the suppression of horizontal diffusion in isolation in a later run. In the present case the particles diffused slowly in the vertical when above the ABL, and (a much smaller effect) as a result of the horizontal diffusion and transports spreading them into areas of different vertical velocity. Much of the plume would have alternated between suppressed vertical diffusion in the ABL and weak vertical diffusion above the ABL in a way that was crudely representative of the suggested scenario.

  A comparison of Figure 15 with Figure 6 shows that the plume remained narrower near to the source, no doubt due to the reduction in shear experienced by individual particles as a result of the suppressed vertical diffusion, and the N'ward spread over SW Iran was lost. The older (green/blue) part of the plume was concentrated far more over SW Iran, and had lost a good part of the main S'ly drift of Run 1. These effects, of course, reflect the height, and hence winds, associated with the bulk of the particles. Maximum air concentrations showed a 6 - 8% increase in the lowest 2 levels, due to reduced shear spread, no doubt, but a 2/3 reduction in layer 3 due to the suppressed vertical mixing. Much less material reached layer 4. Accumulated depositions and time-integrated ABL concentrations were reduced.

  Run 4 very probably gave a better estimate than Run 1 of the E'ward movement of the low level material, but shear spread was lost due to the single-level release into a wind field without vertical diffusion, while the parametrization adopted did not handle the far field effectively. A deeper source would have given more realistic results (see Run 7).

- Run 5

As some long range dispersion models eschew turbulent mixing completely, it was of interest to carry out an integration with the horizontal diffusivity set to zero. The result, at Figure 16, should again be compared with Figure 6. As the particles are released in hourly batches, the spread due to wind-shear close to the source is characterised by a tendency for the particles to fan out in bands. With the horizontal diffusion removed the plume is only slightly narrower, which infers that most spread is indeed through wind shear rather than through turbulent mixing. However, there is *on average* a somewhat more S'ly track, for the younger particles and the northernmost green and blue, particularly over SW Iran, while the older have not spread so far S towards Qatar. At these ranges the omission of horizontal diffusion seems to have made only minor differences, and was possibly advantageous close to the source. It is easy to see, however, that time-integrated air concentrations and accumulated depositions would start to differ considerably with the passage of time, particularly close to the source, while the plume would no longer affect parts of the far field reached in the diffusive case, even in an attenuated form. It is likely then, that the simulation would eventually fail to reflect the spread comprehensively. The differences may have assumed more importance in cases where shear is less marked.

Maximum boundary layer concentrations of carbon are increased by about 11% due to the reduced diffusion, but the other layers, depositions and integrated ABL concentrations are little changed apart from the expected reduction in spread.

- Run 6

This run differed from all the foregoing in that the release was at $850mb$, that is, well above the ABL except occasionally when it is at its deepest. Here, the particles are subject to a more pronounced SE and later S'ly wind, carrying most of the particles to the W of Qatar (Figure 17). Of great interest is the thin trail of particles drifting NE: this must consist of near-source material entrained in the ABL when it is sufficiently deep, and then being well mixed and experiencing the mean ABL wind. The sharpness of the bifurcation is difficult to account for, but must be associated with the increased ABL depth N'ward from the release point (Figure 5). One wonders how realistic this representation of fumigation is. The observed plume provides no answer, as the smoke source was not a point at $850mb$, and the trapped material drifting NE, if it existed, would have been very diffuse. Note also that in this plume the green and blue particles have lost the characteristic banding (Figure 6, etc) which was no doubt associated with the ABL depth diagnosis and shears.

The cross section in Figure 18 (further S than previous cross sections) shows that the particles starting at $850mb$ descend below $900mb$ over the Gulf waters: the maximum ABL concentrations occur W of Qatar and are well under half the Run 1 maxima. The steadiness of descent implies large scale vertical motion rather than sub-grid diffusive effects. Indeed, the vertical velocity fields generally showed substantial descending motion over the Gulf, most frequently increasing E and S of the source. Differential vertical velocities of a few mb/hr account for the configuration of Figure 18. The diffusion parametrization would destroy these effects in the mixed boundary layer.

At layer 2 quite dense concentrations are spread down the W coast of the Gulf as far as Qatar, although at this level too the values are below half the peak concentrations (at source) in Run 1. Layer 3 exhibits much greater S'ly spread than Run 1 but, contrary to what might have been expected from the height of release, there is little spread away from the source in layer 4 (850 - 700mb): there is evidently a loss of material due to the descent illustrated in Figure 18. Accumulated dry deposition is, of course, greatly reduced in this run due to the smaller ABL residence times and concentrations. Peak values are about 1/4 of the Run 1 maxima, and situated to the W of Qatar. The Run 1 depositions *at that locality* were very small: below 1 mg m^{-2}.

- Run 7

In contrast to Runs 1 to 6, which were specifically designed to compare different configurations of the NAME model with Imperial College's 3-DRAW model, as well as the observed spread, Run 7 was designed to be as realistic a simulation as possible. The release was started a day earlier to allow wider spread of the material, and in view of the aircraft observations of smoke reaching to the mid-troposphere, a much deeper source was assumed, extending from 950 to 650mb. The colour coding for the particles is now extended to

Release 00Z-12Z 26/3/91 black
Release 12Z-24Z 26/3/91 purple,

otherwise they are coloured as before.

The analysis at 00Z on the 29th March, shown in Figure 19, compares quite creditably with the photograph in Figure 2. Most of the observable features of the plume are reproduced: the material fanning out over the Gulf and sweeping in a great arc around Qatar and SW over Arabia; the accumulations over the SW Iranian littoral and the Zagreb; the spread NE across central Iran. A good attempt seems to have been made at the thin streak of distinctly denser material sweeping E and SE of Qatar which the earlier runs were too brief to reproduce. The northernmost part of the 'green and blue plume' in Run 1 (Figure 6), which is unsupported by the photograph, is no longer in evidence: this must have resulted from excessive particles in the ABL in that run. There are two important points of difference from the observed plume, however. The photograph suggests that considerable material was carried directly SE over the coastal regions of Saudi Arabia, whereas the simulation has relatively little smoke inland from the Gulf; secondly the simulation produces a streak of older smoke spreading westwards to the N of Kuwait which is not visible in the photograph. It may be wrong, or it may be too diffuse or obscured to be noticeable in the picture. One also has the impression that some of the smoke fanning out over central southern Arabia (Figure 3) may have been older material released before the start of Run 7.

Most of the smoke spreading to the southern Gulf and SW over Arabia is below 850mb; most of the NE'ly spread across Iran is old smoke above 700mb, as is the questionable westward extension N of Kuwait. Indeed, the complexity of a plume evolving in four dimensions is well illustrated by the sequence of E-W cross sections (moving from N to S) in Figures 20 to 22. No attempt will be made here to account in detail for the many features shown, which are the result of strong shears, a wind-field changing with time, vertical motions and ABL turbulence. Features to note are probable subsidence over the Gulf, and the overhang, particularly of the green particles in Figures 21 and 22.

The fields of air concentration and deposition add little of interest: as the release was spread over great depth the concentrations are naturally much reduced at low levels and increased aloft. Relatively high concentrations occur in the vicinity of Qatar, as in Run 6.

Comparison of Aircraft Data With NAME Model Calculations

The C-130 sortie of March 28th made measurements of the horizontal and vertical structure of the plume at about 120 km from the fires (Figure 4 shows the aircraft track across the plume). One of the key instruments on board was a Passive Cavity Aerosol Sampling Probe (a laser scattering probe) which counts and sizes particles between 0.1 and 3 μm. Hence a smoke density was determined.

Cross-plume runs were made at heights of 1430, 1520, 1980, 2440 and 4420m and the smoke densities against along track distance are shown in Figure 23. The measured plume was typically about 50km wide, above the ABL. Peak and average smoke densities were calculated from the calibrated data between times when it was apparent that the aircraft was within the plume. The results are plotted on the top left in Figure 24 for comparison with the values extracted from model runs 1,6 and 7. The average and peak figures are calculated from model carbon concentrations in the lowest five layers approximately 120km from the model source. This is the most reasonable method of comparison, particularly for the 950mb run where the observed and modelled plumes did not coincide.

The profile from Run 1 (ABL release) compares very poorly with the measured profile with a disproportionate amount of material in the lowest part of the atmosphere and none above about 800mb. The simulated plume was also well to the N of the observed location. Run 6 (850mb release) however gives a much better comparison with the right order of smoke density between 1000 and 800mb, and, although insufficient, at least a little material up towards 600mb. However, it must be remembered that the modelled values are grid-cell means, so that the similarity in peak and mean values is fortuitous—the averages over the model grid-cells should be well below the aircraft observations. The Run 6 plume was correctly located. Evidently the 850mb run, although only a point release, was a far better approximation to the actual effective source for the dense plume traversed by the C-130. The initial buoyancy—possibly with some assistance from plume lofting—gave considerable vertical depth to the plume from the outset. The dense smoke of the plume would also have had the effect of suppressing ABL turbulence below and reducing mixing downwards: the NAME ABL diffusion parametrization would accordingly be inappropriate, close to the source, and the 950mb release, in particular, lead to quite unrealistic results. Indeed, the situation is one requiring a suitable interactive model, resolved to handle meso-scale motions.

There is no doubt that the Run 7 profiles are the best of the three. There is still relatively too much material at low levels, but the shape of the profile is more realistic, and the 3 - 5 fold (roughly) reductions in concentration only to be expected when they are computed as averages over large grid-volumes.

In comparing the observed and simulated cross-sections it should be borne in mind that the aircraft measurements are not coincident in time with the 48-hr hindcast result, and there is no way of determining the precise age or source of the smoke at the different levels in the observed cross-sections. Even the run using the $950mb$ point release *may* have reflected the path of some material not well observed by the aircraft or in the photograph.

Comparison With Imperial College Model

Imperial College's 3-DRAW (3-Dimensional Random Walk Model) was also developed to simulate the dispersal of an atmospheric release from a nuclear accident. The model represents the release as an assembly of particles which are transported by a three-dimensional windfield. Like NAME the model has a boundary layer that evolves with time and within which dispersion is controlled by advection and wind shear. Trajectory end points, integrated atmospheric concentrations and accumulated deposition are all computed by the model. Thus the model belongs to the same family as NAME. It has, however, important points of difference, so that a plume intercomparison using identical set-up and meteorology is of value, both to the respective groups of modellers, who can study the points of difference for clues to aspects of the parametrization which may need improvement, and to the modelling community at large, who will be interested in the variability (and hence reliability) of Lagrangian methods.

The main points of difference between the NAME and 3-DRAW models are:

- The wind profile is treated differently below $950mb$. Whereas NAME utilizes an NWP model $10m$ wind based upon similarity profiles, 3-DRAW uses a power law relationship.
- The random horizontal displacement is not a constant, but a variable depending on the ABL height and wind shear within the ABL. The spread above the ABL has a fixed, reduced diffusivity.
- There is no vertical diffusion above the ABL, and no small scale interchanges of material across the capping inversion. Thus for a fixed ABL (used below) there is no loss of material from the ABL.
- The ABL depth is diagnosed following an entirely different strategy. This would almost certainly lead to very significant differences in the integrations, as this depth influences the turbulent spread and transports, as well as the dry deposition to the surface. However, it was decided to exclude this source of model variation in this study by using fixed ABL depths.

Both models used identical analysed winds and meteorology from the Fine Mesh NWP model. The initial conditions used for the NAME and 3-DRAW integrations were:

1. The ABL depth was set at $1000m$ across the entire model domain for the complete duration of the model run.
2. Release of carbon was as before at 29.25^0N, 47.4^0E.
3. In the first run the release height was $925mb$ or approximately $750m$ above ground level. In the second run the release height was $850mb$ or approximately $1500m$ above ground level. (NAME release height is input in millibars whilst 3-DRAW is input in metres.)
4. No lofting scheme was used.
5. Dry deposition velocity of carbon in NAME was 0.0005 ms^{-1} whilst the Imperial College model used a value of 0.001 ms^{-1}.
6. 500 particles/hr were released from the point sources.

The integrations made by Imperial College are described in Lowles and ApSimon (1992), which carries out its own comparisons of the 3-DRAW and NAME integrations.

Figures 25 and 26 are the trajectory end points for the NAME and 3-DRAW model runs (respectively) for the $925mb$ release heights. The results are very similar on the broad scale, but have some points of difference. The most obvious is that the variable diffusivity of 3-DRAW leads to a great deal of fine structure in the plume which may or may not be of value. A more critical difference is the presence in NAME of the N'ward extension of blue—the oldest—particles over extreme SW Iran which is much less marked in 3-DRAW, and in the NAME Runs 4 and 7. This feature may then have been associated with ABL diffusion at an early stage after release. It is difficult to determine to what extent the feature is reproduced in the photograph—certainly there is some NW-SE striated smoke (parallel to the grain of the country) in the upslope region over SW Iran, which may be associated with the similarly directed shear of the green and blue particles of the NAME integrations. If the photographed smoke was at high level, however, the suggestion is that the modelled feature results from an excessive fixed ABL diffusivity in NAME, at least for the early stages of plume growth (this is thought to be likely in any case). Neither run aligns the plume across the aircraft flight path. The S'ly parts of the plumes are very similar to each other. The yellow particles seem to have spread a little further E in the NAME run; this may reflect the different low-level wind profiles used.

The $850mb$ runs (Figures 27 and 28) are very similar in their basic alignments, but with large differences of diffusive spread. In the case of NAME this will have been accentuated by the vertical diffusion scheme, which would expose the particles to greater shear, and by the constant ABL depth, which would have enhanced turbulent spread given NAME's diffusion parametrization. One has the feeling reality might lie between the two solutions. There is no means of validation since the release height was fixed and arbitrary. It is not clear that the dog-legged plume of 3-DRAW actually had material on the flight path; the diffusion in this run was very slight until considerable S'ward transport had taken place, when presumably material was becoming entrained into the ABL.

In each run the grid-cell values of deposition and integrated concentration were summed to give areally integrated figures: for a fixed ABL depth and deposition velocity, and with no loss processes apart from dry deposition, it is easy to show that the total deposition to the surface is equal to the deposition velocity times the time-integrated air concentration summed over all the grid-cells. This was confirmed for both models. The NAME figures for integrated concentration are greater by about 30% whereas 3-DRAW's total deposition values are greater by 50%. The differences are quite compatible with the different dry deposition velocities. A grid-cell to grid-cell comparison of deposition and integrated concentration is difficult, as the exposure grids are not located in the same position and do not have the same resolution: it is not attempted here.

Discussion and Conclusions.

The NAME model has been run using six different model configurations to produce 48 hr hindcasts of the spread of the Gulf plume, validating at 00Z 29th March 1991. A 7th, 72 hour run was given a more realistic source profile for validation at the same time. The situation was one in which the wind profiles were characterised by strong vertical shears. Validation was against a METEOSAT photograph of 07Z 29th March and the MRF C-130 plume cross-sections of around midday on 28th. A successful 48 hr *forecast* by NAME of a rather similar situation is described in Browning et al (1991).

In each run a plume was simulated which was broadly similar to the satellite photograph, although where the release was confined to the ABL the spread seems to have been somewhat too far to the N, and the transport possibly a little too far E. The satellite picture cannot be interpreted with complete unambiguity, however. The 950mb release was in a sense inappropriate, given the ABL and diffusion parametrization of NAME, as the real plume probably tended to suppress ABL turbulence in the source region. Run 4, intended to reflect these effects in a crude way, gave less dispersion to the N. The initial plume buoyancy accentuated (to some extent) by plume lofting resulted in a deep source cloud, much of which sat above the ABL. Thus the 850mb release gave a better approximation to the path (and concentration profile) of the dense part of the plume as observed by the aircraft, although as the source was in reality complex, extended over considerable depth, and wind shears were marked, both 950 and 850mb releases should have reflected different features of the spread. The 72 hr Run 7 did utilize a deep source, and yielded by far the most realistic simulation with the possible exception of a streak of smoke to the N of Kuwait, for which there is no evidence. A meso-scale model able to handle plume/ABL turbulence interactions is required, ideally, to model the near-source plume, although LRT models such as NAME are more appropriate for the far field, of course.

The effect of the plume lofting parametrization (Run 2) was to transport diffuse material to upper levels, where it was carried rapidly NE in the strong upper winds. This resembles Run 7 and the METEOSAT picture, which, it is argued in the discussion of Run 2, most likely shows high level smoke in this region. In reality, the deeper source would have provided most of the smoke at this level, although lofting may have played a part during the initial buoyant phase. The lofting is largely confined to the earliest smoke released, for the reasons put forward in the earlier discussion. A deeper initial release profile would no doubt have accentuated the lofting somewhat by taking smoke clear of the ABL turbulence parametrization. The very small amounts of material reaching high altitudes are conformable with other investigations.

Due to the diurnal changes in ABL depth, material at upper levels was sometimes re-entrained and mixed through the ABL. Doubling the vertical diffusion above the ABL spread material further afield by this mechanism—some smoke diffused to higher levels, travelled further in the stronger winds, but was later 'fumigated' to the surface as it was intercepted by a deep ABL. A rather subtle interaction between ABL depth and the upper level plume is discussed under Run 6.

Although the bulk of the plume spread in these integrations was due to vertical wind shear, it was apparent from Run 5 that removing turbulent spread completely would make a significant difference, which with the passage of time would no doubt lead to an inferior representation of the plume. However, as discussed above, the simulated near-source turbulent spread is likely to have been excessive, and may have contributed to an unrealistic drift of smoke ENE in the early stages. This is an area where the diffusion parametrization requires improvement. The plume also displayed a marked response to the vertical velocity field as long as it lay above the ABL (in which material is kept well mixed).

Imperial College's 3-DRAW model gave broadly similar results. The different diffusion parametrization produced a more detailed plume structure, although it is uncertain to what extent this constituted an improvement. It certainly resulted in less spread than NAME close to the source, and this seems to have repercussions later over SW Iran. These differences may also owe something to the different profiles of low level wind in the two models. The photograph, taken some 7 hr after the validation time, is not easy to interpret in the area without knowledge of the levels reached by the smoke, but the smaller near-source ABL diffusion of 3-DRAW and Runs 4 and 7 seems preferable.

The horizontal and vertical diffusion above the ABL was also treated differently, and was again much less in 3-DRAW than in NAME. 3-DRAW shows little spread for the 850*mb* release until smoke is entrained into the ABL towards Qatar. On the whole, however, both models simulated the plume reasonably well, and the longer Run 7 gave a very creditable reproduction of the observed plume. The intercomparison was invaluable for pointing to areas of the parametrization that led to slight differences, and may need review. Either model could be used with confidence if a similar situation were to arise in the future.

Acknowledgments

We would like to thank G.E. Holpin and R.J. Allam of the Image Processing Group of FR Division for providing the satellite picture, and H.M. Apsimon and I. Lowles of Imperial College for the 3-DRAW model results.

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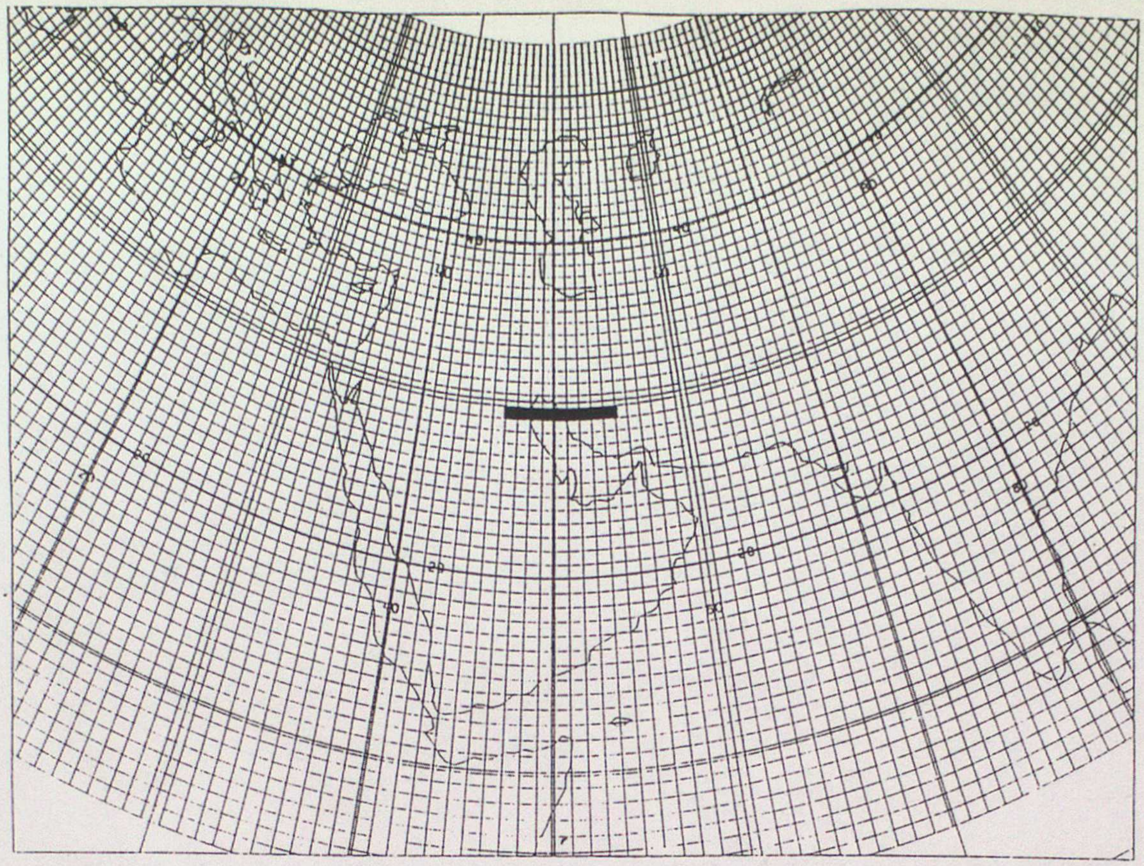


Figure 1 Model Area
Dark Strip Is Between Rows 33 And 34 And Columns 62 To 71

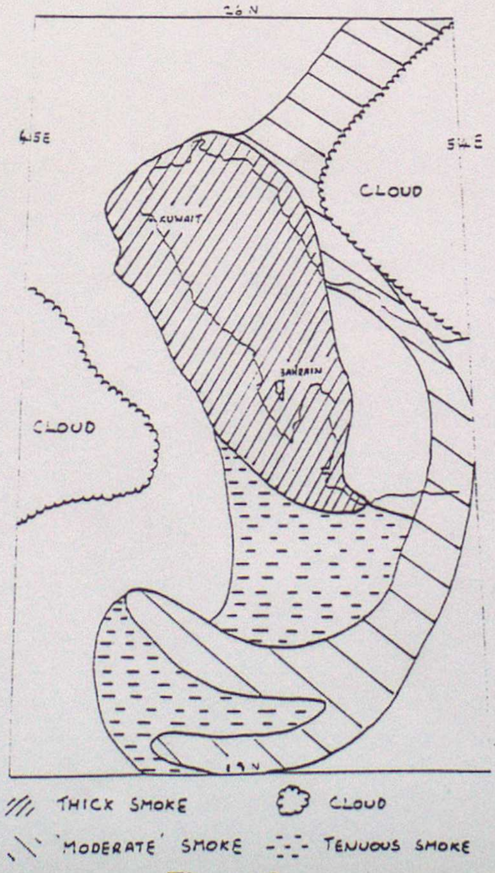


Figure 3
Nephanalysis At 13:00 Z 29th March 1991

Figure 2 METEOSAT Visible Picture At 07:00Z 29th March 1991

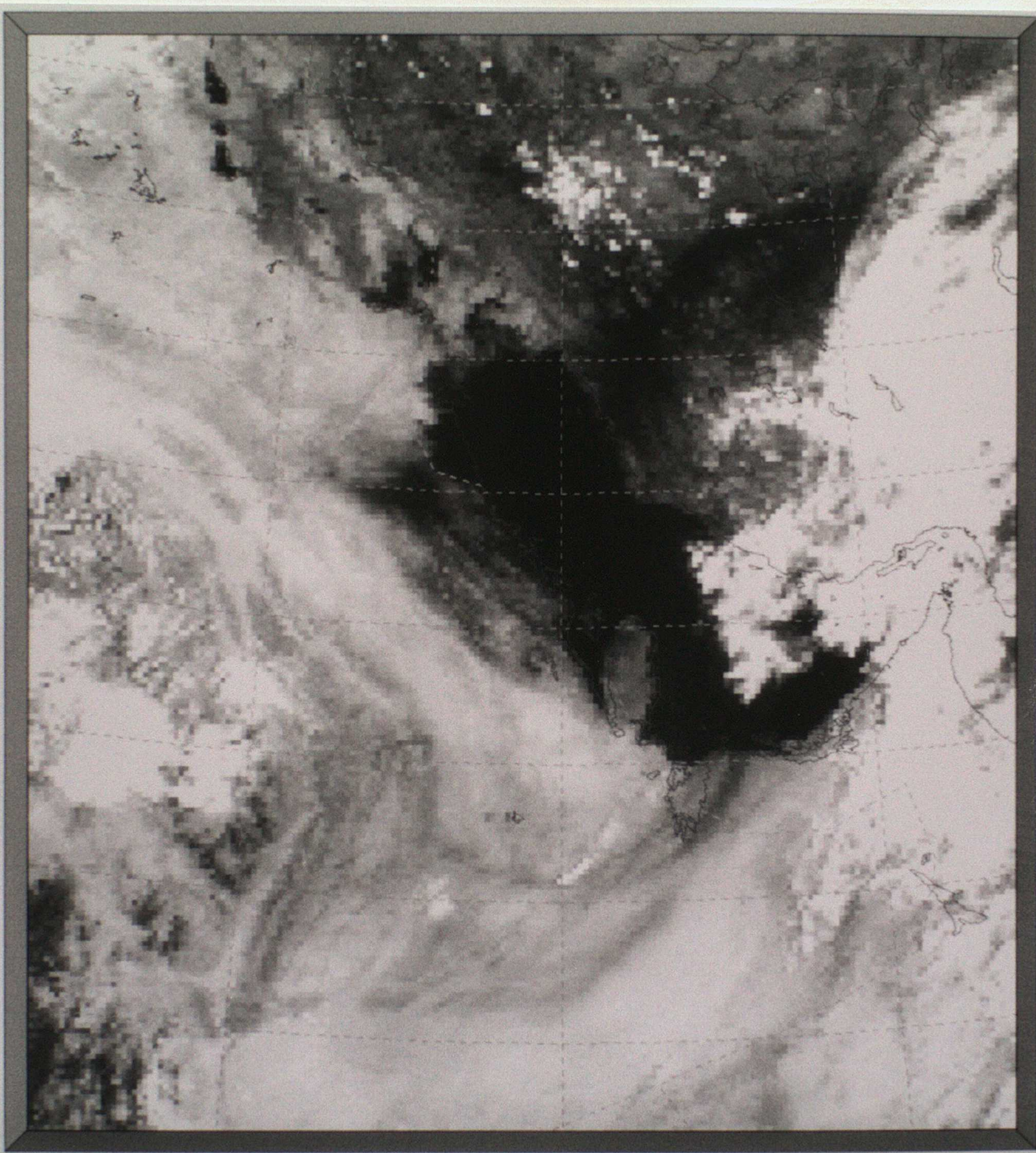
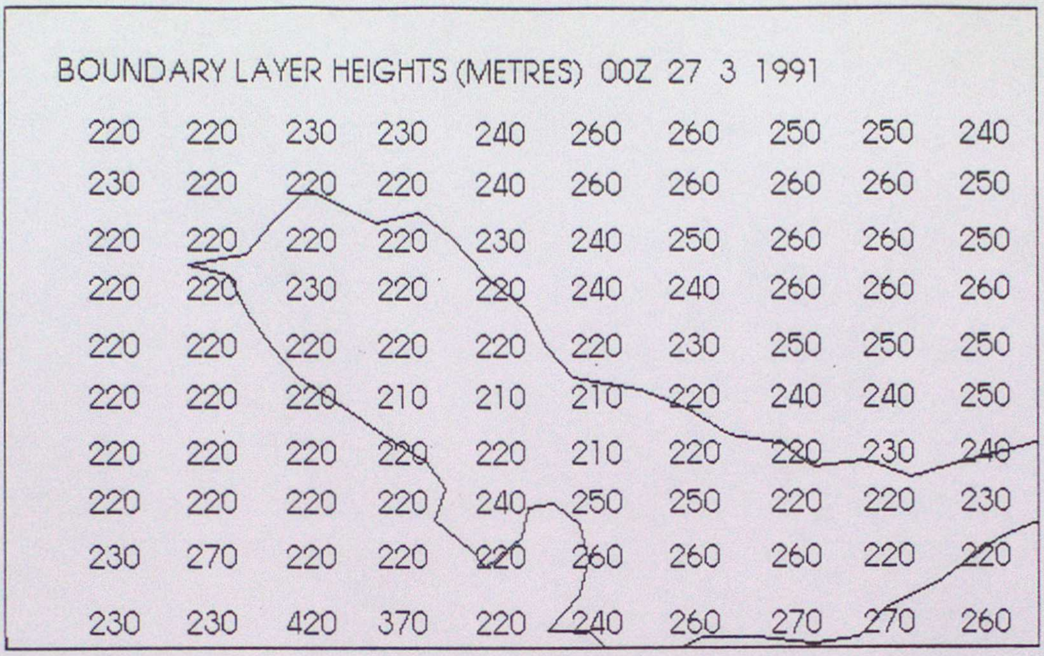


FIGURE 4 SYNOPTIC CHART AT 00Z 28/3/1991

A TO B REPRESENTS AIRCRAFT TRACK FOR THE CROSS PLUME RUNS


BOUNDARY LAYER HEIGHTS (METRES) 00Z 27 3 1991
220 220 230 230 240 260 260 250 250 240
230 220 220 220 240 260 260 260 260 250
220 220 220 220 230 240 250 260 260 250
220 220 230 220 220 240 240 260 260 260
220 220 220 220 220 220 230 250 250 250
220 220 220 210 210 210 220 240 240 250
220 220 220 220 220 210 220 220 230 240
220 220 220 220 240 250 250 220 220 230
230 270 220 220 220 260 260 260 220 220
230 230 420 370 220 240 260 270 270 260

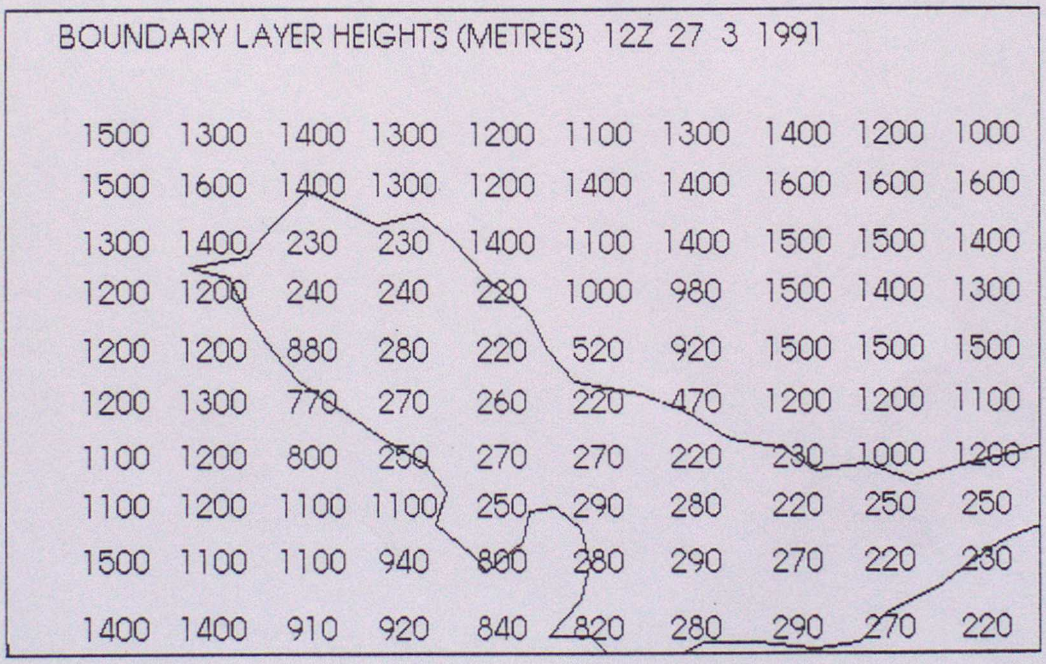

BOUNDARY LAYER HEIGHTS (METRES) 12Z 27 3 1991
1500 1300 1400 1300 1200 1100 1300 1400 1200 1000
1500 1600 1400 1300 1200 1400 1400 1600 1600 1600
1300 1400 230 230 1400 1100 1400 1500 1500 1400
1200 1200 240 240 220 1000 980 1500 1400 1300
1200 1200 880 280 220 520 920 1500 1500 1500
1200 1300 770 270 260 220 470 1200 1200 1100
1100 1200 800 250 270 270 220 230 1000 1200
1100 1200 1100 1100 250 290 280 220 250 250
1500 1100 1100 940 800 280 290 270 220 230
1400 1400 910 920 840 820 280 290 270 220

Figure 5

FIGURE 6 – RUN 1
950 MB RELEASE AT 0Z 27/3/91

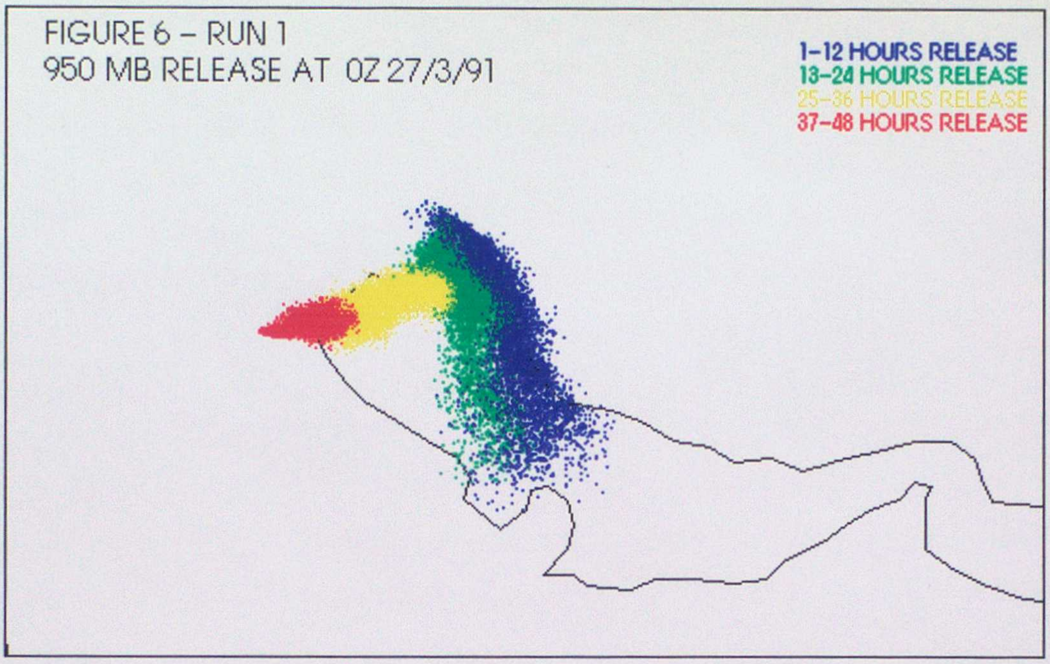


FIGURE 7 – RELIEF MAP OF REGION (IN METRES ABOVE SEA LEVEL)

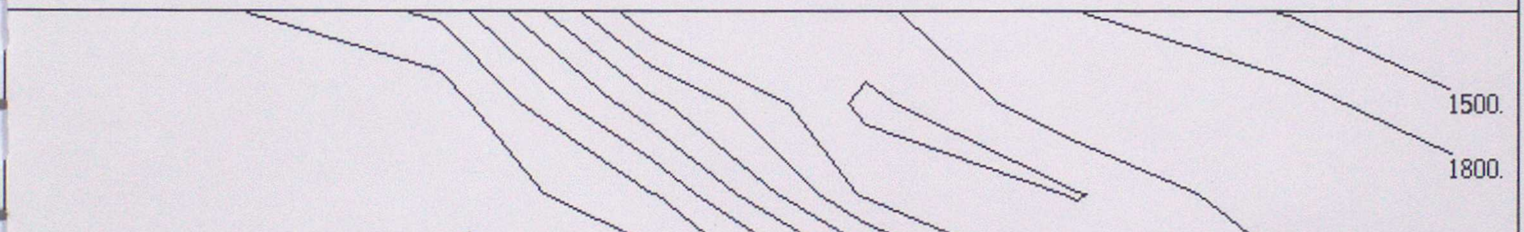


FIGURE 8
PLUME X-SECTION FOR STRIP 32 TO 33
950 MB RUN - NO LOFTING SCHEME

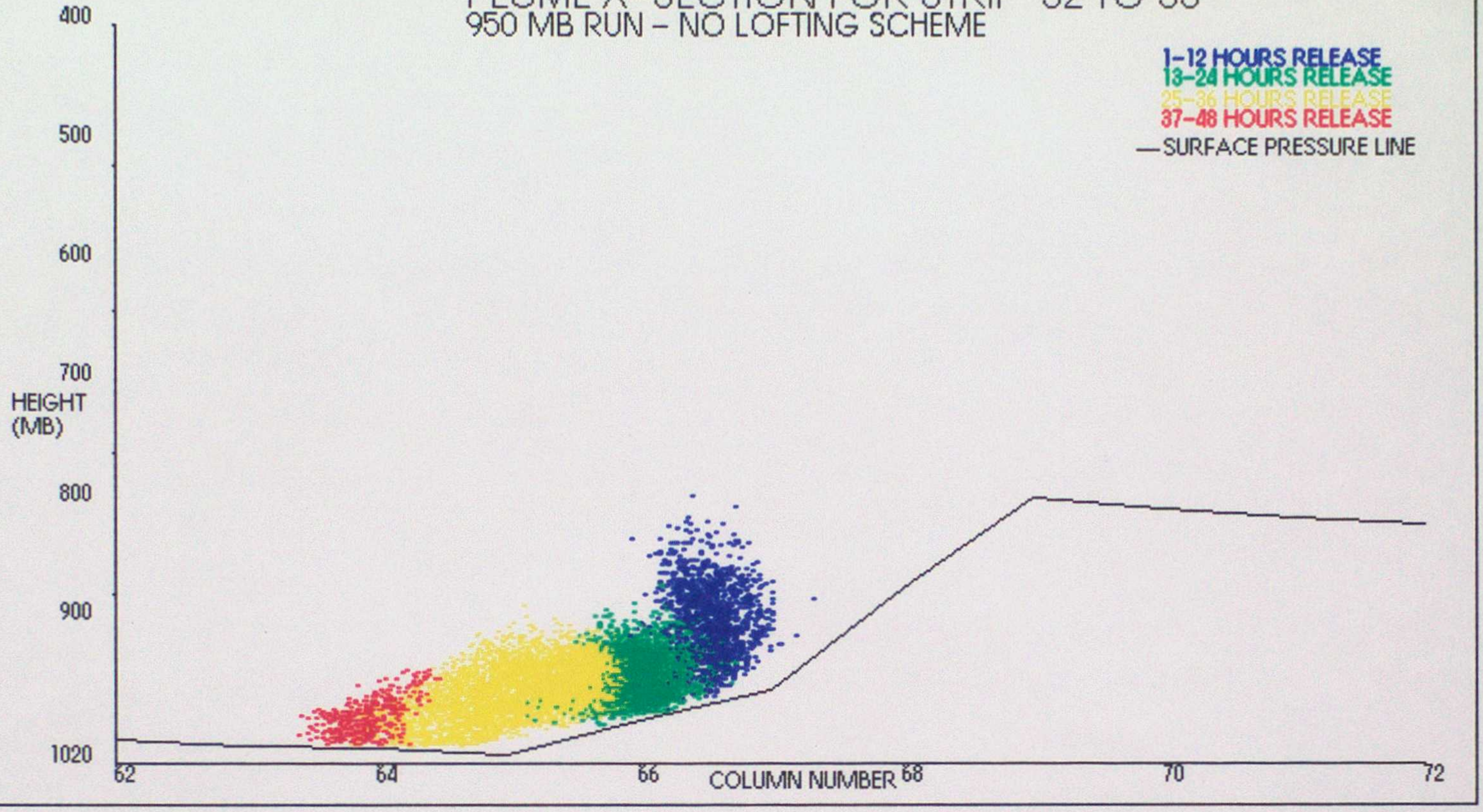
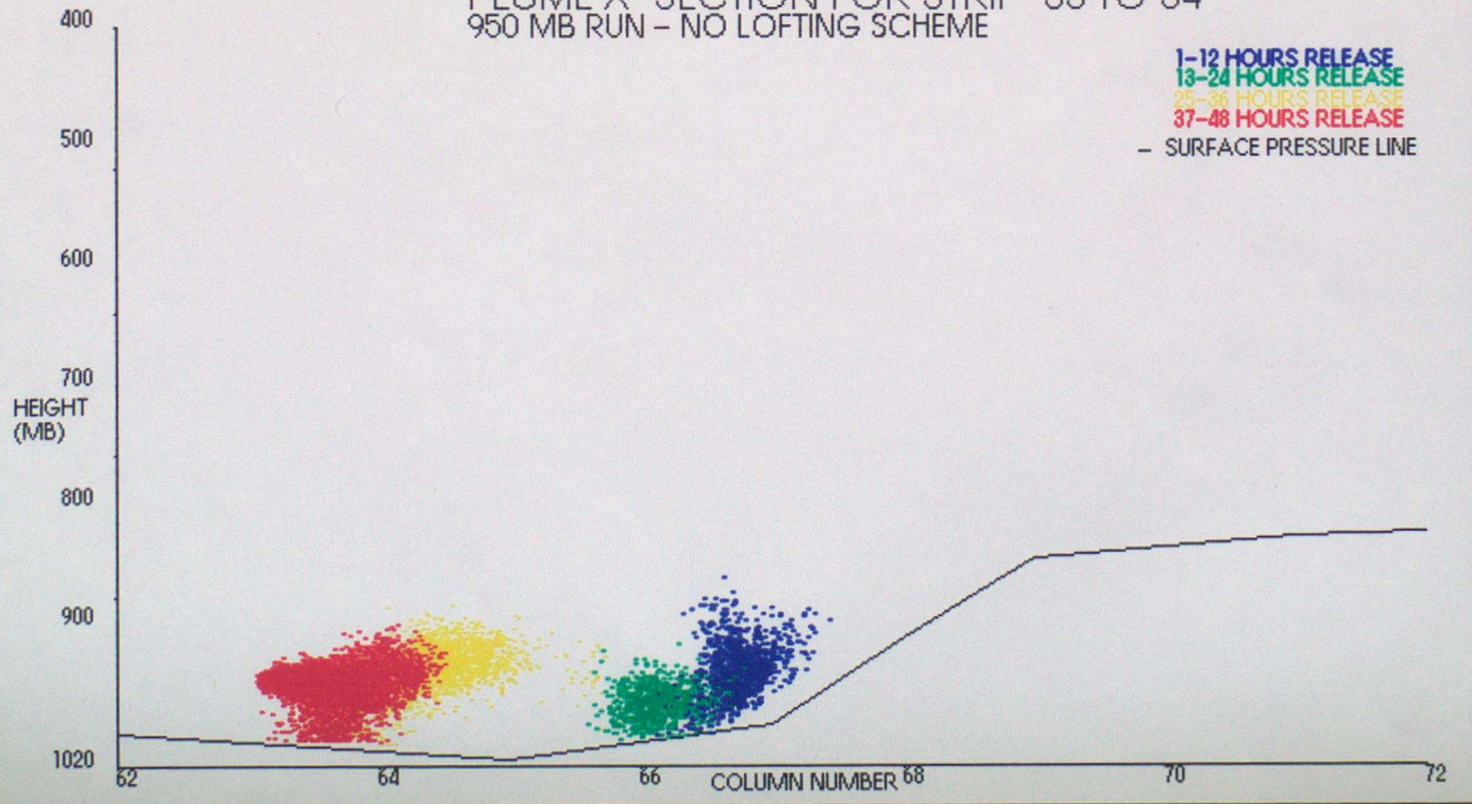


FIGURE 9
PLUME X-SECTION FOR STRIP 33 TO 34
950 MB RUN - NO LOFTING SCHEME



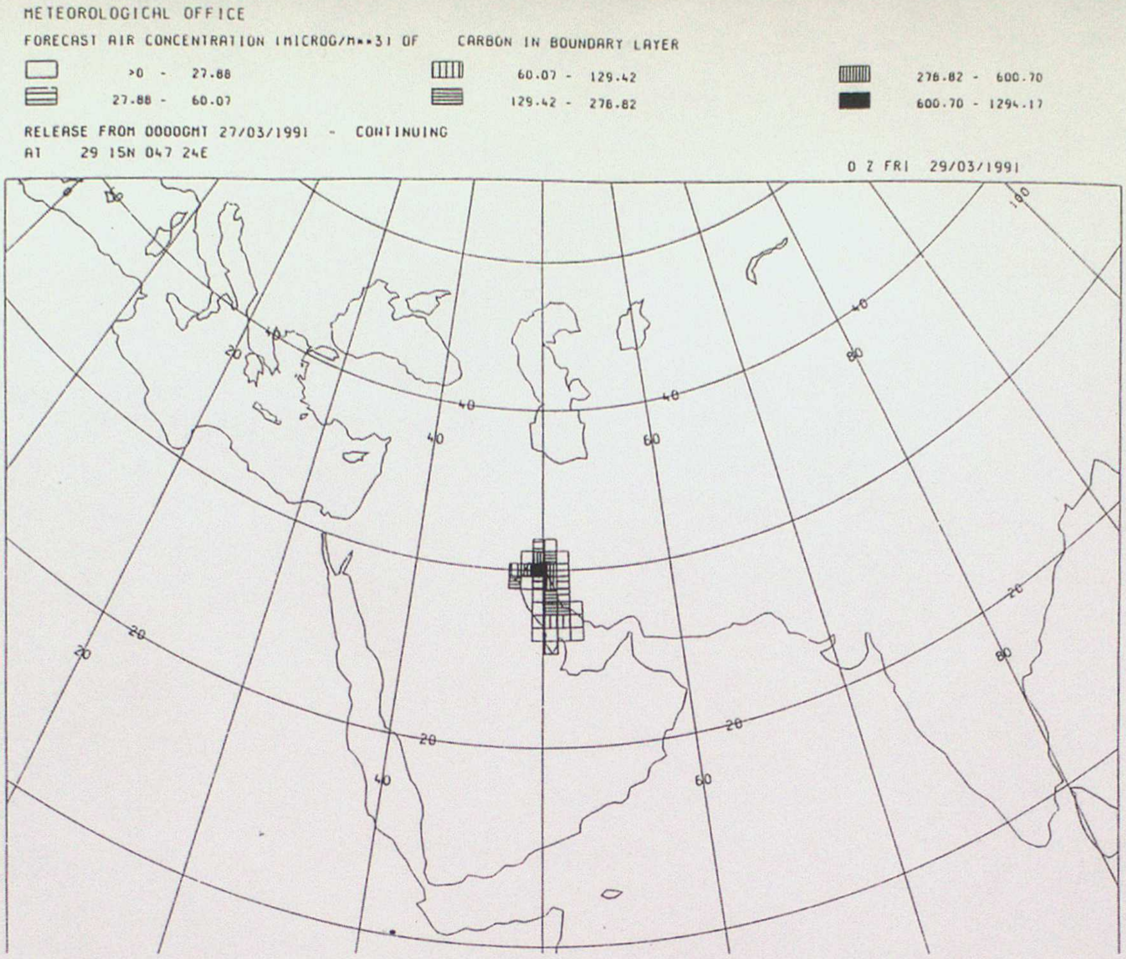


Figure 10 Air Concentration For Run 1

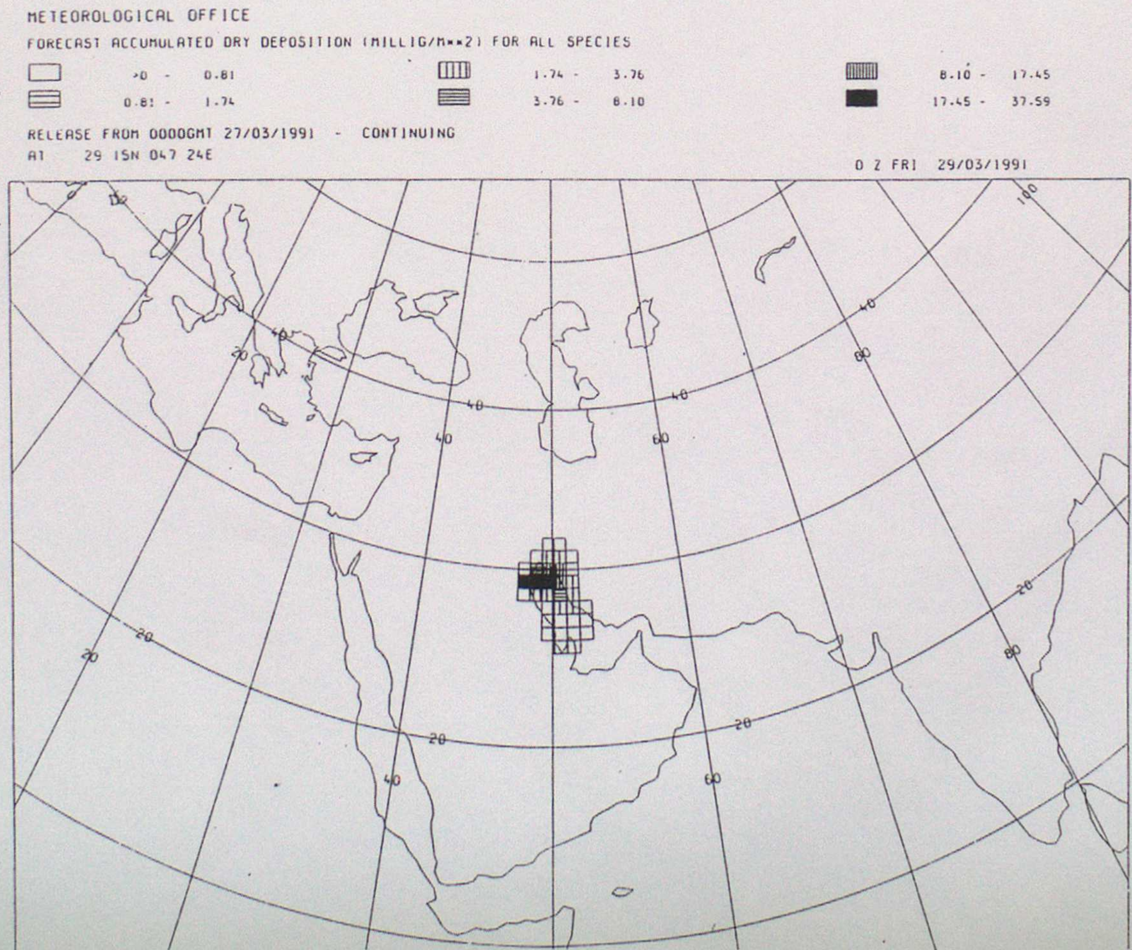


Figure 11 Dry Deposition For Run 1

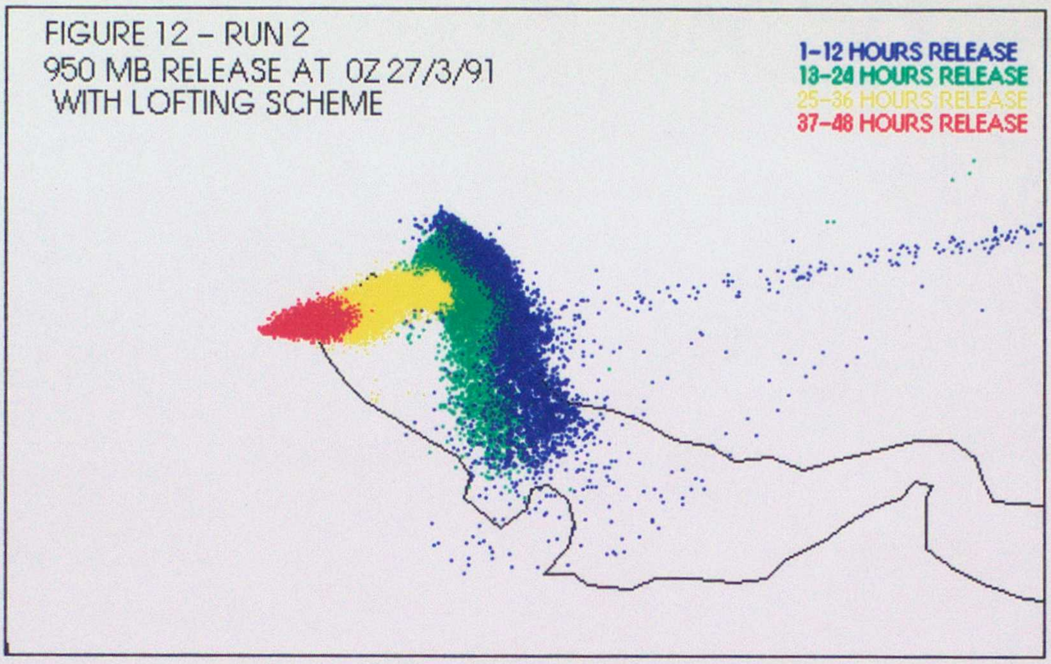


FIGURE 12 – RUN 2
950 MB RELEASE AT 0Z 27/3/91
WITH LOFTING SCHEME
1-12 HOURS RELEASE
13-24 HOURS RELEASE
25-36 HOURS RELEASE
37-48 HOURS RELEASE

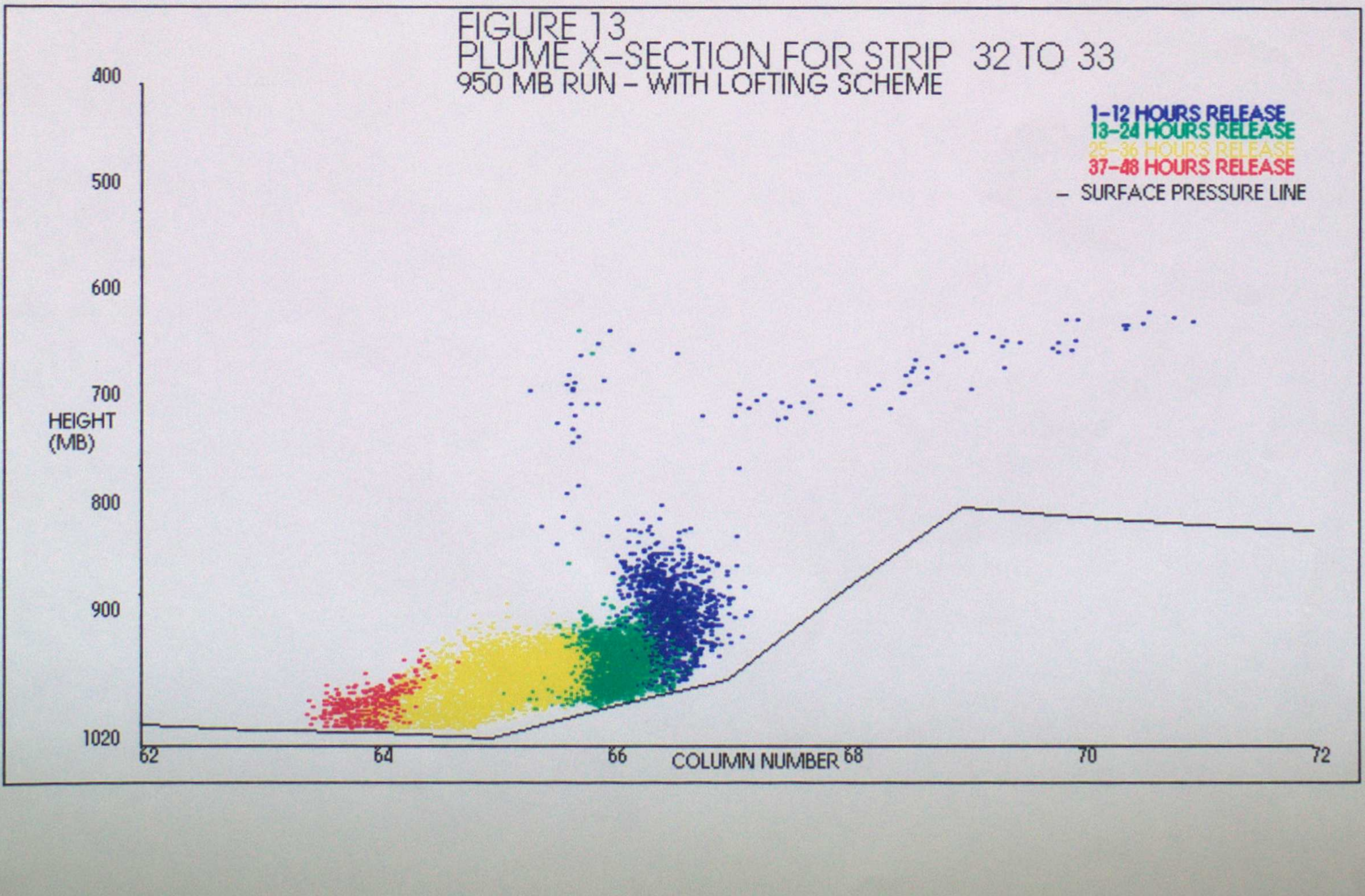


FIGURE 13
PLUME X-SECTION FOR STRIP 32 TO 33
950 MB RUN – WITH LOFTING SCHEME
1-12 HOURS RELEASE
13-24 HOURS RELEASE
25-36 HOURS RELEASE
37-48 HOURS RELEASE
– SURFACE PRESSURE LINE
400
500
600
700
HEIGHT (MB)
800
900
1020
62
64
66
COLUMN NUMBER
68
70
72

FIGURE 14 – RUN 3
950 MB RELEASE AT 0Z 27/3/91
ENHANCED VERTICAL MIXING

1-12 HOURS RELEASE
13-24 HOURS RELEASE
25-36 HOURS RELEASE
37-48 HOURS RELEASE

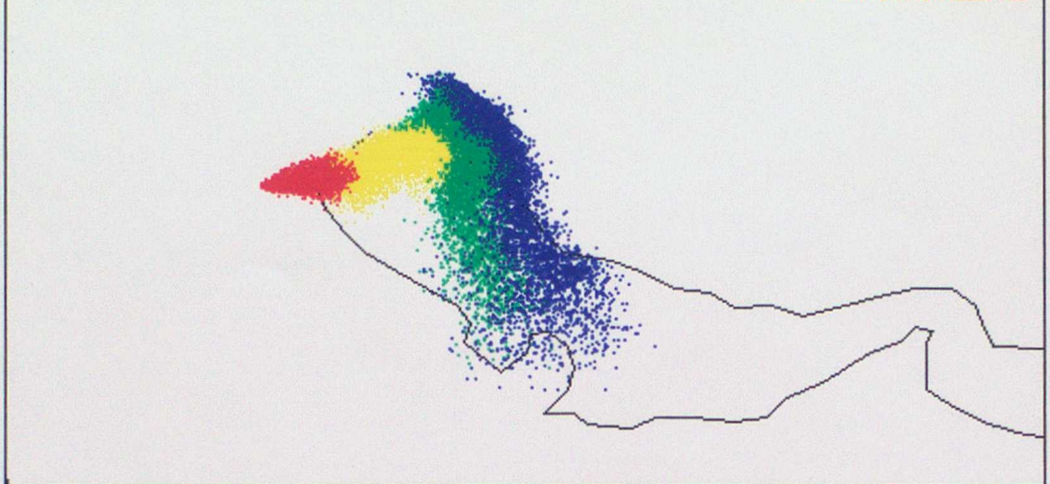


FIGURE 15 –RUN 4
950 MB RELEASE AT 0Z 27/3/91
NO VERTICAL MIXING

1-12 HOURS RELEASE
13-24 HOURS RELEASE
25-36 HOURS RELEASE
37-48 HOURS RELEASE

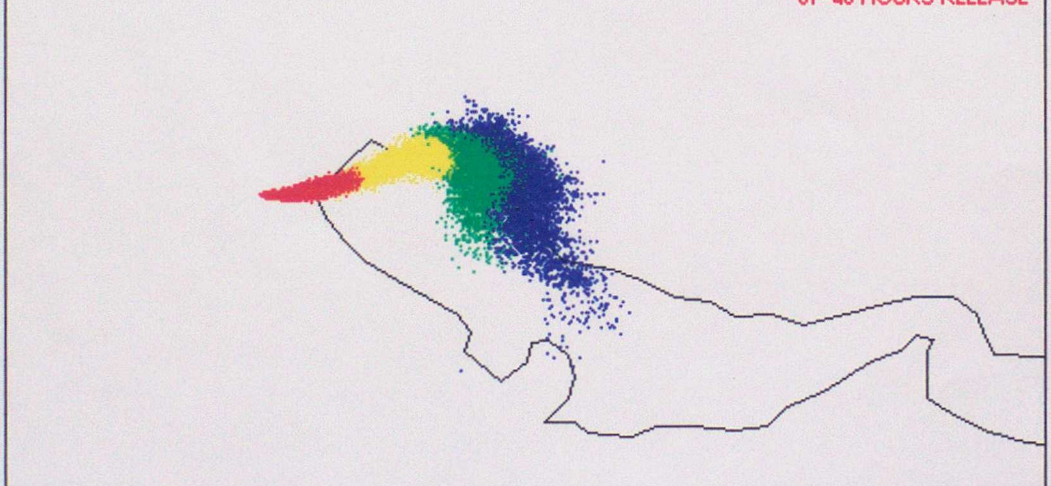
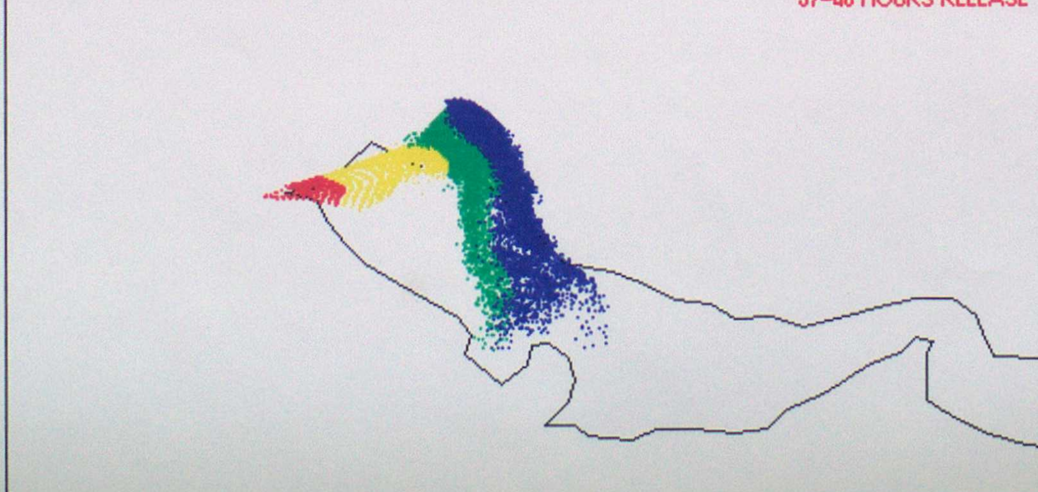


FIGURE 16 –RUN 5
950 MB RELEASE AT 0Z 27/3/91
ZERO HORIZONTAL DIFFUSION

1-12 HOURS RELEASE
13-24 HOURS RELEASE
25-36 HOURS RELEASE
37-48 HOURS RELEASE



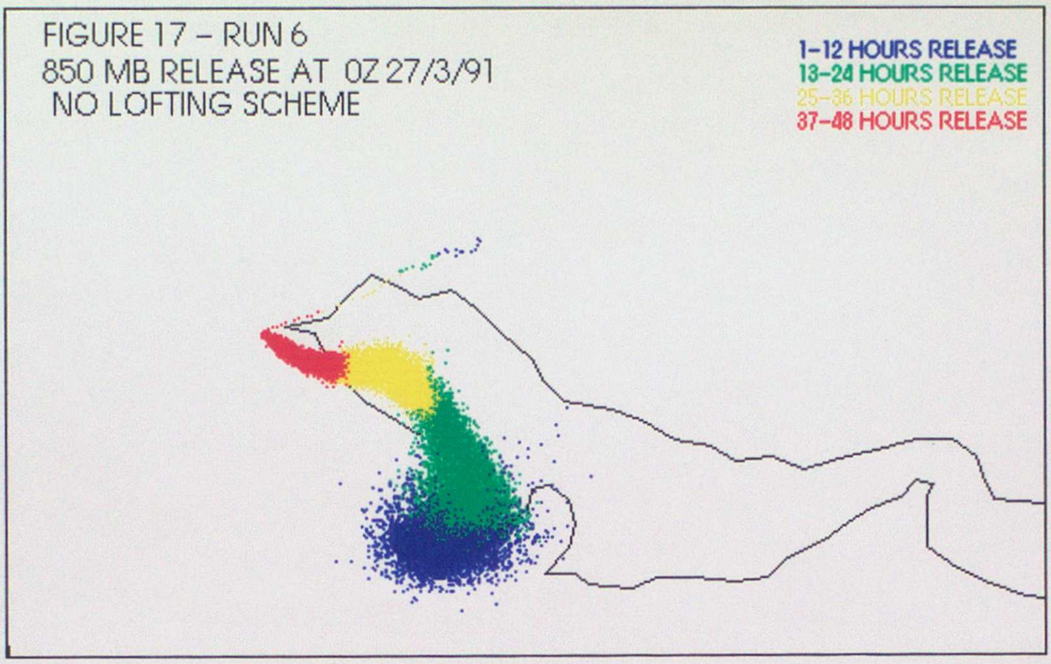


FIGURE 17 – RUN 6
850 MB RELEASE AT 0Z 27/3/91
NO LOFTING SCHEME

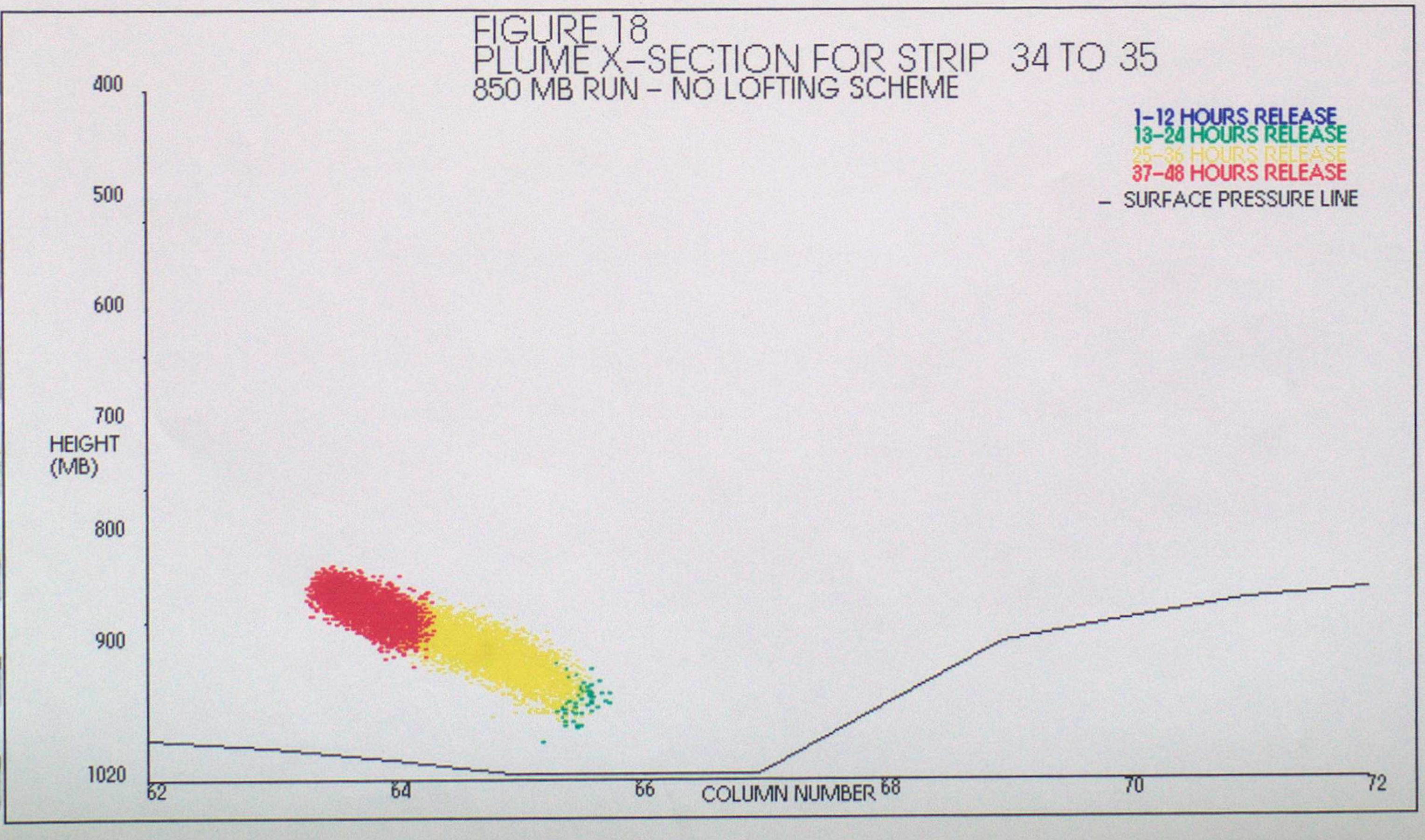


FIGURE 18
PLUME X-SECTION FOR STRIP 34 TO 35
850 MB RUN – NO LOFTING SCHEME

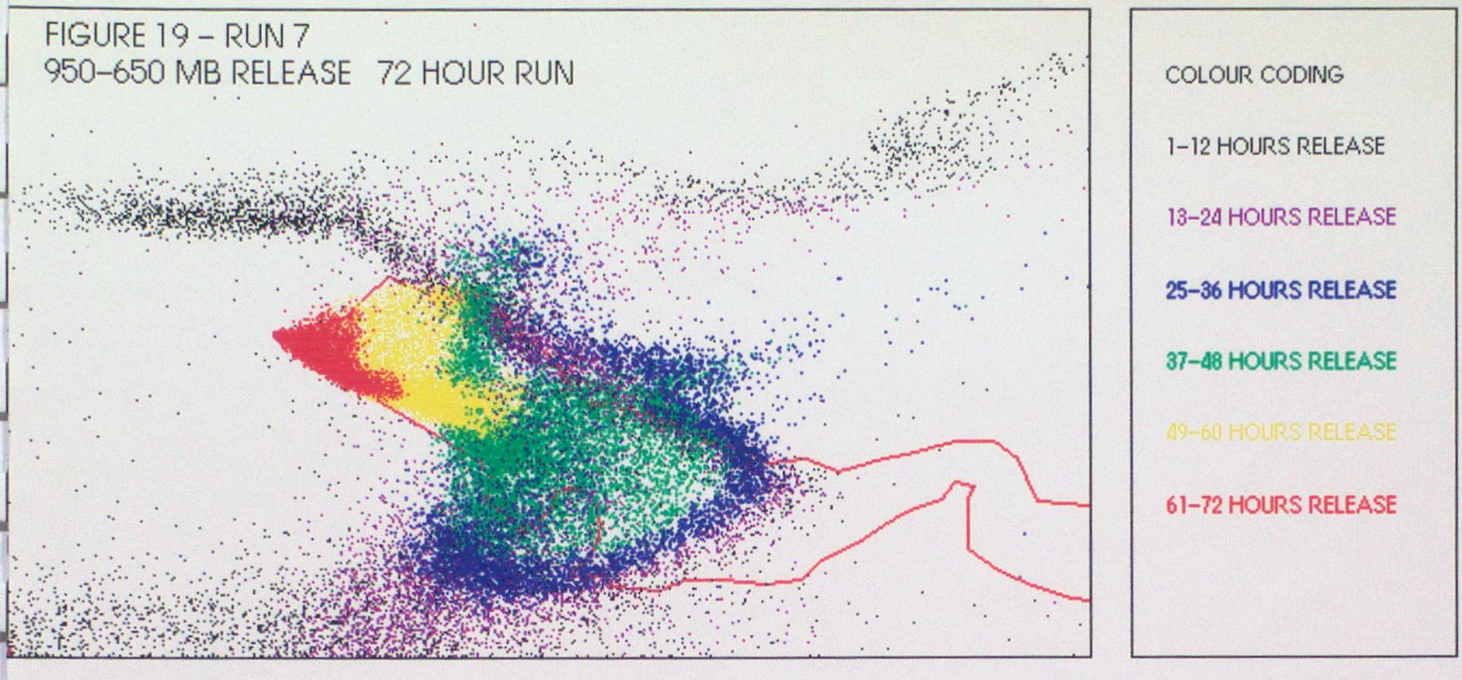


FIGURE 19 – RUN 7
950–650 MB RELEASE 72 HOUR RUN

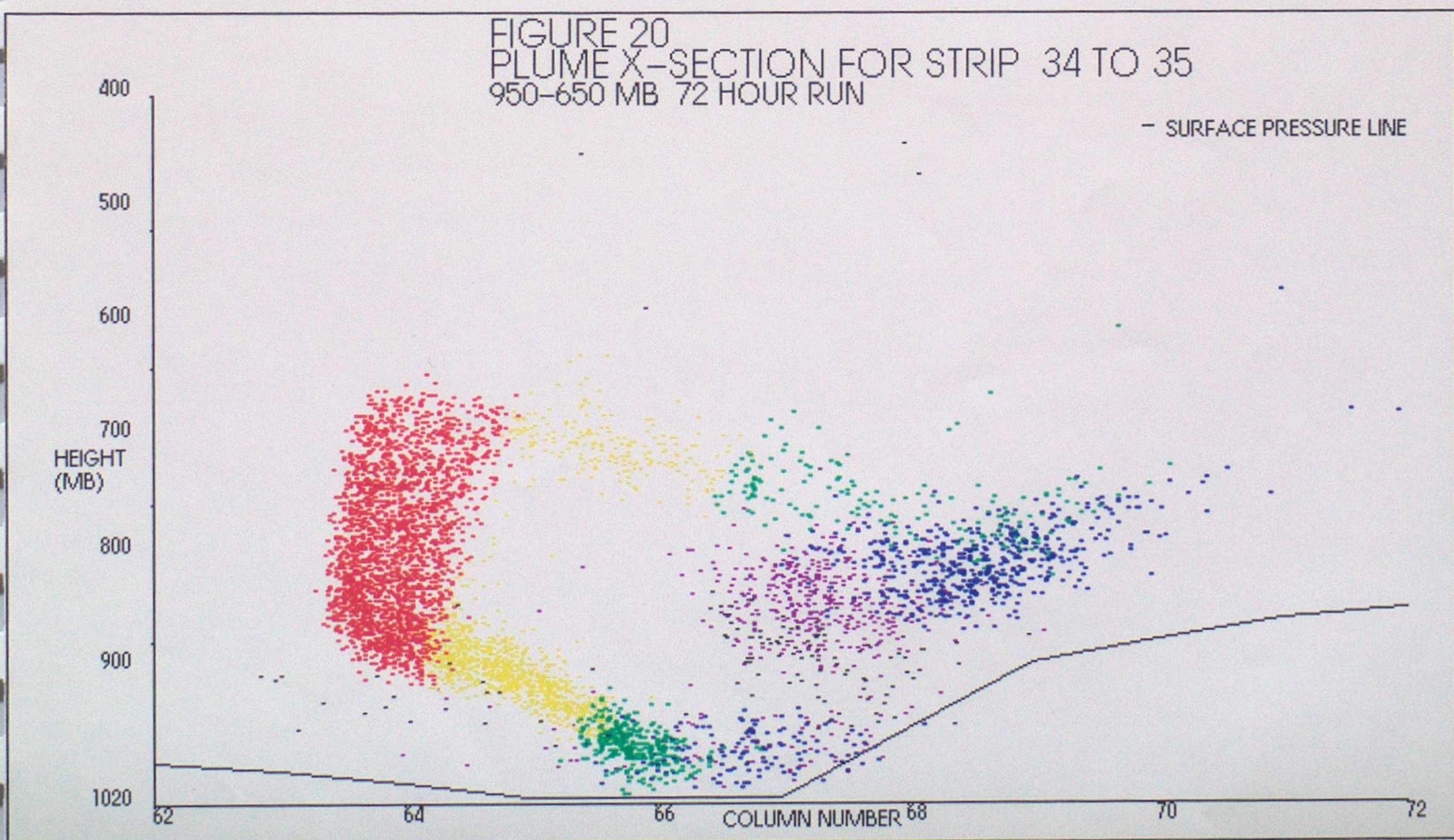


FIGURE 20
PLUME X–SECTION FOR STRIP 34 TO 35
950–650 MB 72 HOUR RUN

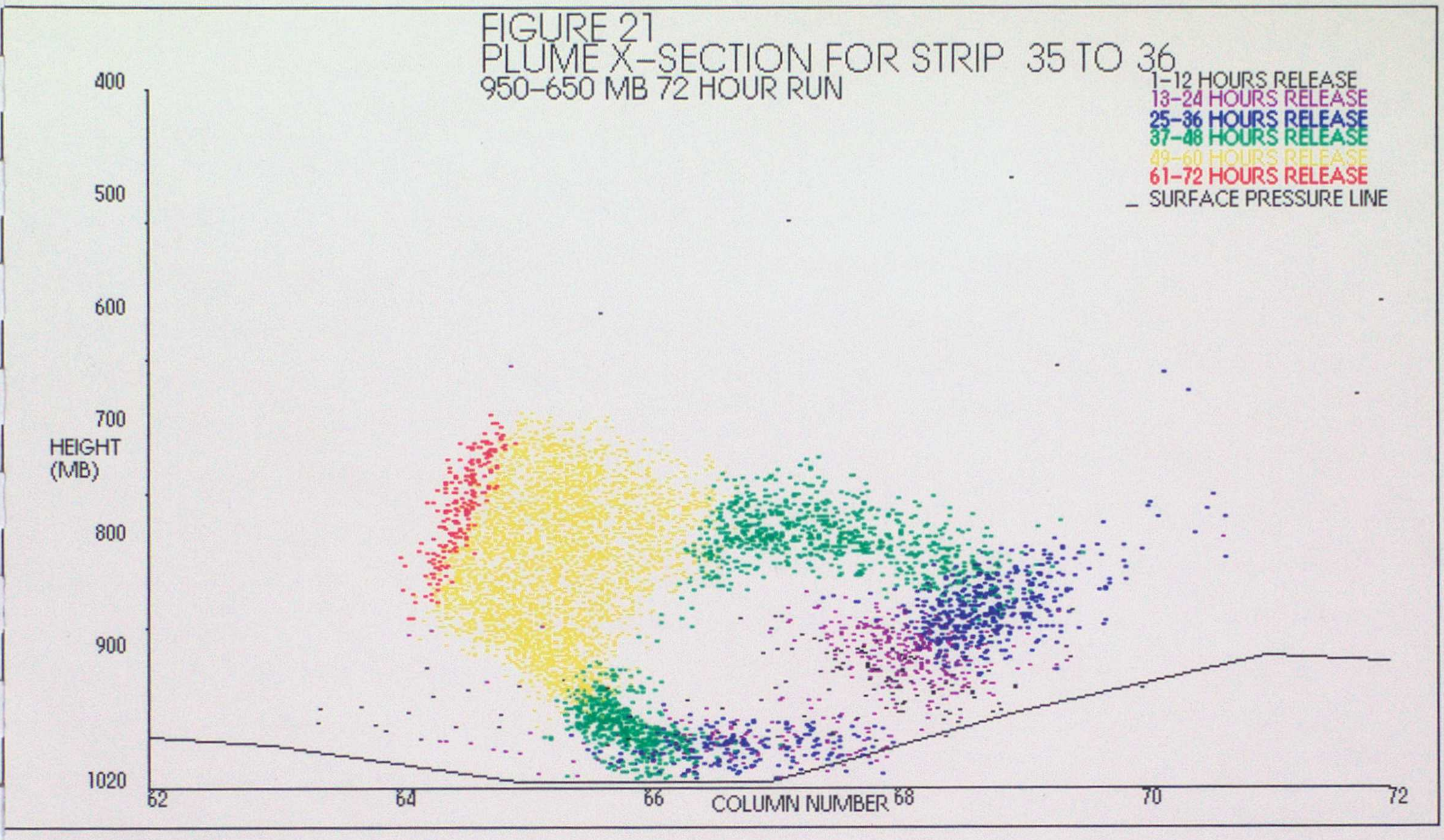


FIGURE 21
PLUME X-SECTION FOR STRIP 35 TO 36
950-650 MB 72 HOUR RUN
1-12 HOURS RELEASE
13-24 HOURS RELEASE
25-36 HOURS RELEASE
37-48 HOURS RELEASE
49-60 HOURS RELEASE
61-72 HOURS RELEASE
SURFACE PRESSURE LINE
HEIGHT (MB)
400
500
600
700
800
900
1020
62
64
66
68
70
72
COLUMN NUMBER

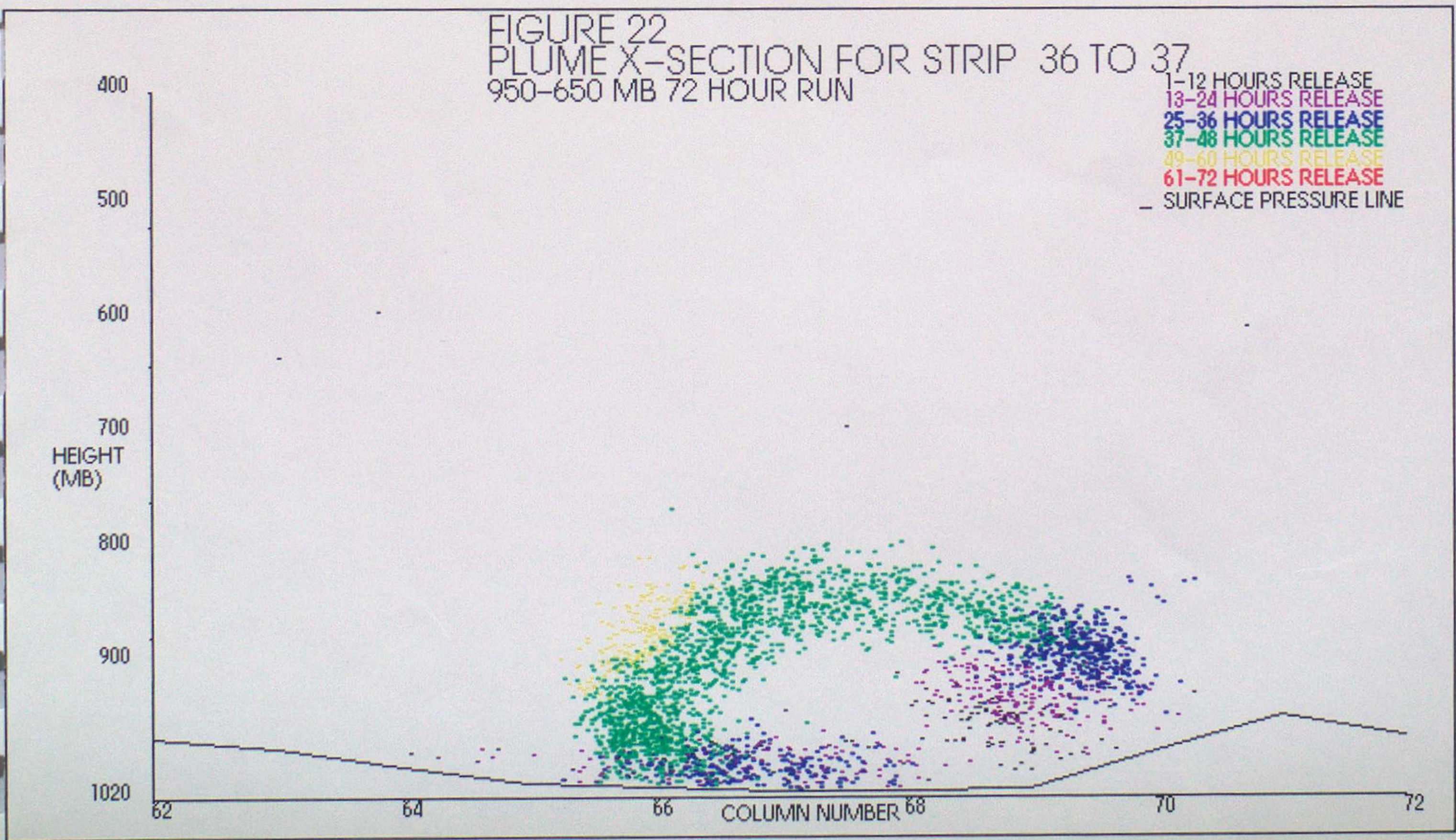


FIGURE 22
PLUME X-SECTION FOR STRIP 36 TO 37
950-650 MB 72 HOUR RUN
1-12 HOURS RELEASE
13-24 HOURS RELEASE
25-36 HOURS RELEASE
37-48 HOURS RELEASE
49-60 HOURS RELEASE
61-72 HOURS RELEASE
SURFACE PRESSURE LINE
HEIGHT (MB)
400
500
600
700
800
900
1020
62
64
66
68
70
72
COLUMN NUMBER

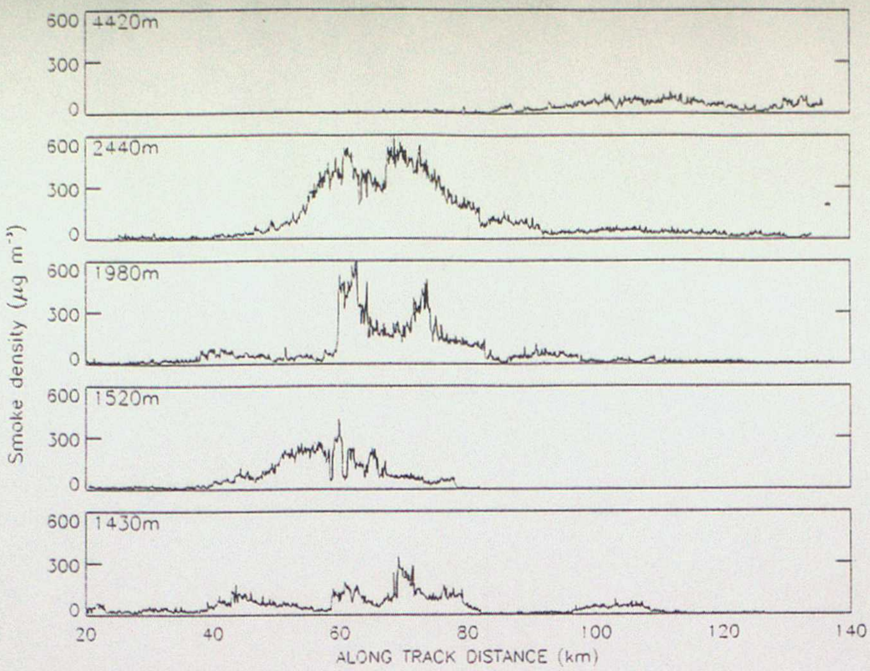


Figure 23 Horizontal Cross Sections of Smoke Density Made at Several Heights on 28 March 1991. From Jenkins et al *Weather* 47 212-220 (1992)

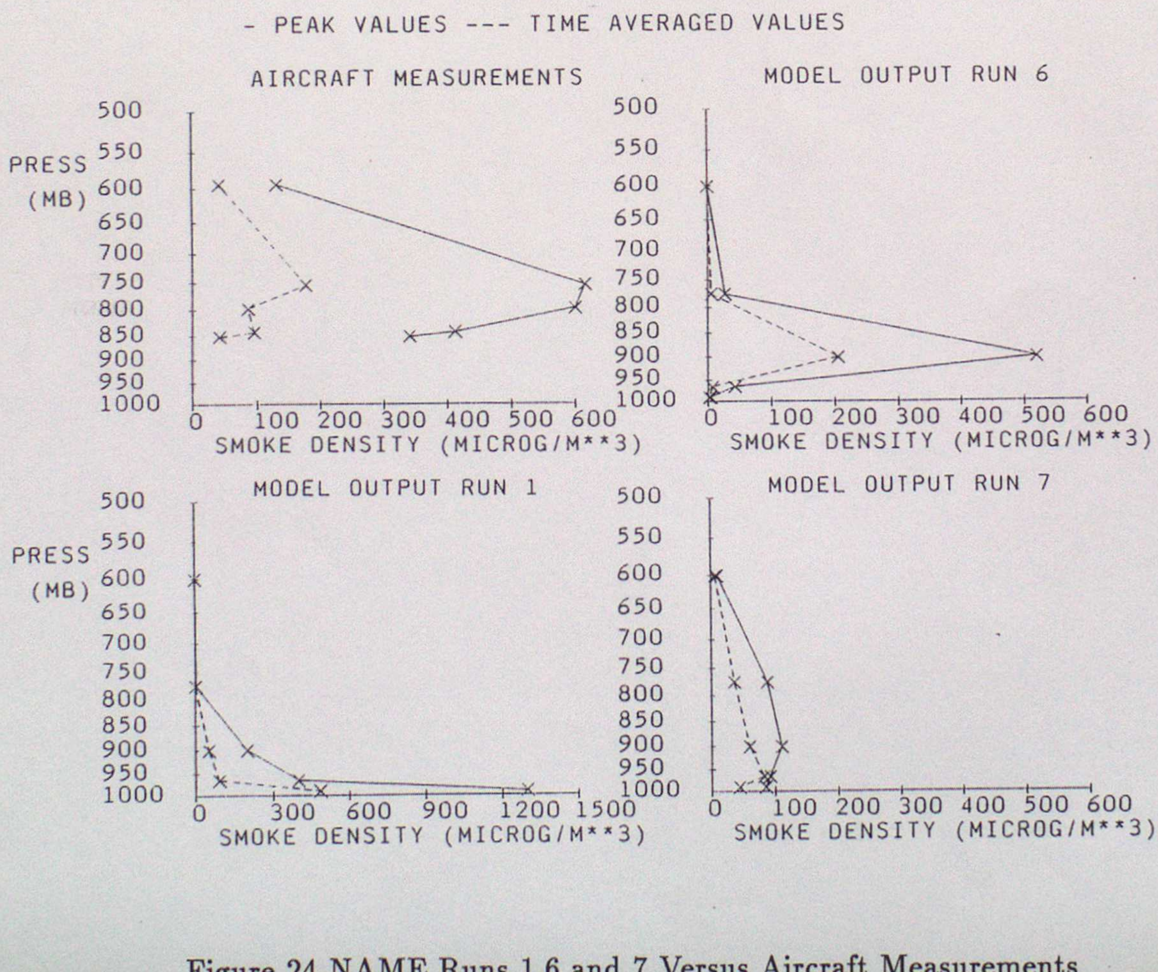


Figure 24 NAME Runs 1,6 and 7 Versus Aircraft Measurements

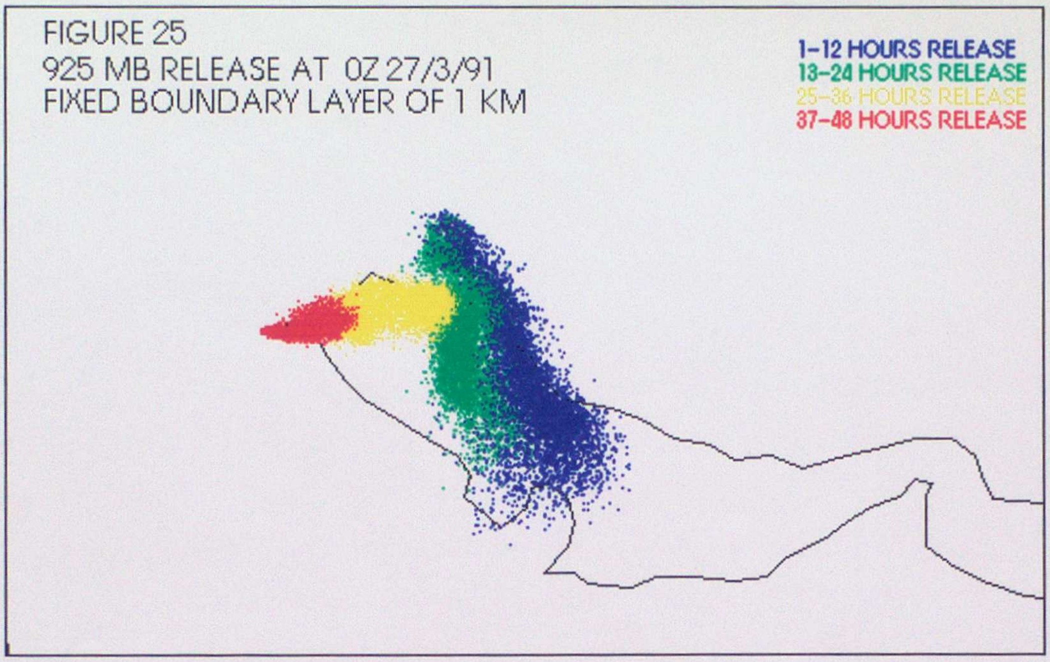


FIGURE 25
925 MB RELEASE AT 0Z 27/3/91
FIXED BOUNDARY LAYER OF 1 KM
1-12 HOURS RELEASE
13-24 HOURS RELEASE
25-36 HOURS RELEASE
37-48 HOURS RELEASE

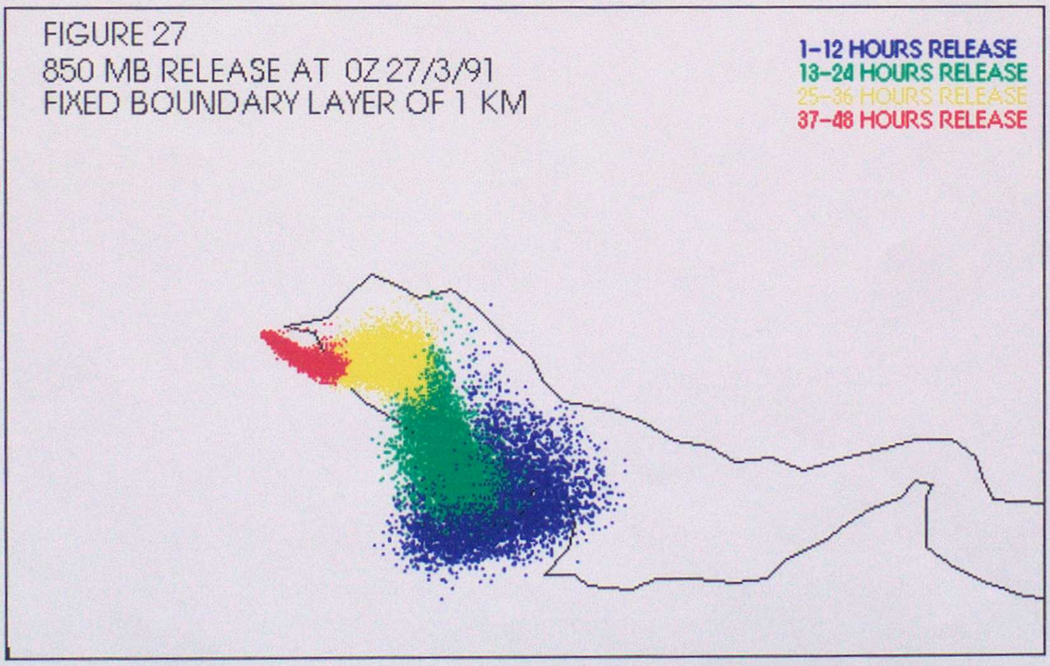


FIGURE 27
850 MB RELEASE AT 0Z 27/3/91
FIXED BOUNDARY LAYER OF 1 KM
1-12 HOURS RELEASE
13-24 HOURS RELEASE
25-36 HOURS RELEASE
37-48 HOURS RELEASE

Figure 26 3-DRAW 750m / 925mb release at 00Z 27/3/1991

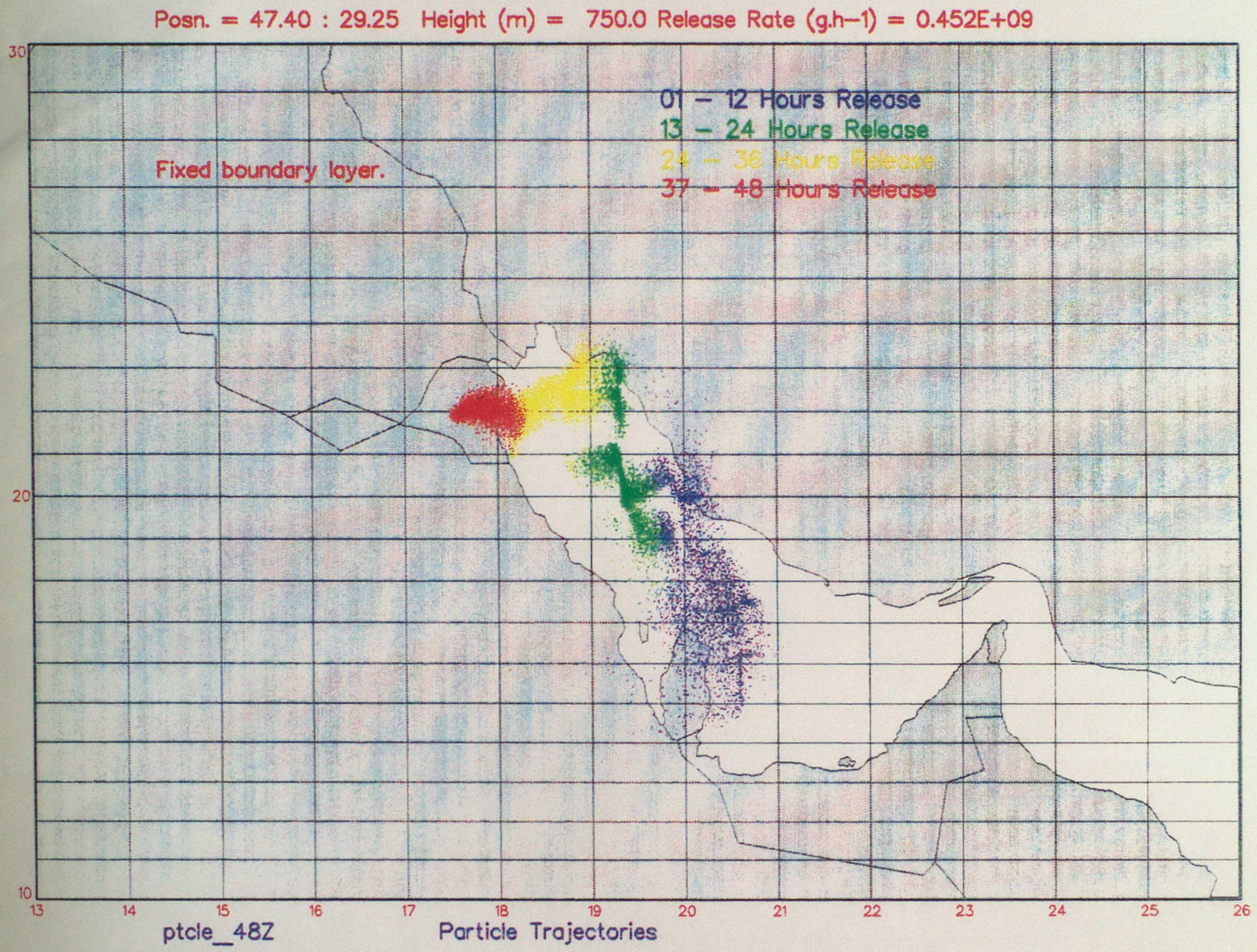


Figure 28 3-DRAW 1500m / 850mb release at 00Z 27/3/1991