

## **Chapter 4**

### **Real time modeling and emergency response forecast**

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### **Abstract**

Given an actual release of hazardous material into the atmosphere, time is of the essence in the response to the emergency situation. Equally important, however, is accuracy, and the balance between these conflicting requirements is the challenge of emergency response teams. Instead of an idealized source, emergency response personnel must consider the detailed source configuration (spatial, temporal, and particle size distribution), the detailed dispersion in a potentially extremely complex urban terrain, and the human and health effects. The time required to obtain this information and to make it available to the analysis of the situation, however, reduces the time available to perform the actual analysis. Mesoscale dispersion modeling for emergency response thus consists of balancing the required level fidelity with timeliness of response.

# 1. Introduction

Emergency response to an atmospheric release of a hazardous material is an incredibly challenging problem. Some types of chemical releases may only be toxic in high concentrations and hence result in relatively short-range hazards under all atmospheric conditions; on the other hand, certain radiological releases may have nearly continental scale ramifications on human health and activity. This makes the problem of emergency response more encompassing than the already difficult issue of atmospheric dispersion, and a higher level of discussion is necessary.

An emergency response scenario begins with a **release**. This release may be natural (e.g., a volcanic eruption such as Monserrat), accidental (e.g., the Bhopal chemical disaster or the Chernobyl nuclear accident), or intentional (e.g., the releases of sarin in the Tokyo subway by the Aum Shinrikyo sect). The next phase in an emergency response scenario is **notification**. This may take the form of a detailed description of the release, or may be a sketchy news bulletin. At this point, a bifurcation takes place in the emergency response process. **First Responders** represent the first governmental agents on-scene, and may be police, fire department, or military personnel who have access to a certain amount of local information (e.g., which way the wind is blowing now), but who fundamentally are operating initially without detailed knowledge; the **analysis** team provides support to the first responders and has the mission of acquiring as much information as possible about the source details, the forcing meteorology, and the terrain, and determining the most likely dispersion of the released material *along with a measure of confidence in the final analysis*. The goal of the analysis team is to **disseminate** the results of their analysis forward to the first responders in as timely a fashion as possible.

In this chapter, we will explore each of the phases of an emergency response scenario in detail. We will discuss both the detailed scientific definition of each phase as well as the real-world requirements, which are often quite different.

## 2. Release

The scientific description of an atmospheric release involves quite a lot of detailed information about the spatial, temporal, and particle size distributions, the material physical and chemical properties, and any associated thermodynamic information that is source-specific. The *real-world* description may be limited to “something happened over there.” In the real-world, source information is typically described in terms of *where, when, what, and how much*.

### 2.1 Spatial, Temporal, and Particle Size Distribution

In the idealized world or research, atmospheric releases can be characterized as point sources, moving point sources, or areal releases. It is true that this does provide a rough representation of stack plumes, automobiles, boats, and planes, and urban pollution, but it is not nearly enough to describe the spectrum of scenarios required by the emergency responder. Idealized releases are also either instantaneous or continuous. The real world, however, includes both industrial explosions that provide a nearly instantaneous release of a hazardous material and transportation accidents involving a tank car where the exact amount released will depend on the pressure in the tank; as the pressure changes due to material release, so does the rate of release. Finally, ideal releases involve massless passive tracers, or (at worst) releases of inert particles of a uniform size. The real world includes volcanic eruptions with particle sizes ranging from microns to meters.

Any function can be de-composed into a series of weighted basis functions. In the idealized description of Lagrangian dispersion models, the basis functions are Gaussian “puffs,” hence it makes sense to use this as our frame of reference. In this framework, each puff  $i$  represents a specified mass of released material,  $m_i(t)$ , distributed over a spatial extent represented by a Gaussian distribution centered at the point  $(x_i(t), y_i(t), z_i(t))$  with spatial variance  $(\sigma_{x_i}(t), \sigma_{y_i}(t), \sigma_{z_i}(t))$  and all of the material having a single particle size  $a$ . This can be represented by:

$$c_i(x, y, z, t, a) = \frac{m_i(t)}{\sigma_{x_i}(t)\sigma_{y_i}(t)\sigma_{z_i}(t)\sqrt{(2\pi)^3}}\delta(r-a) \times \exp\left\{-\left[\frac{(x-x_i(t))^2}{2\sigma_{x_i}^2(t)} + \frac{(y-y_i(t))^2}{2\sigma_{y_i}^2(t)} + \frac{(z-z_i(t))^2}{2\sigma_{z_i}^2(t)}\right]\right\} \quad (1)$$

where  $c_i$  is the concentration associated with puff  $i$ .

Puffs are released at discrete points in time such that the released puff mass equals the amount of material that would have been released by the continuously varying source. In this fashion, a continuous process can be approximated by a series of discrete puff elements.

Using this paradigm, the release of sarin in a subway may involve, initially, a single spheroidal puff, while a volcanic eruption such as Monserrat may involve the specification of hundreds or thousands of puffs from the surface up to tens of kilometers and over an area of many square kilometers. The goal of the emergency response system, then is to take a limited amount of information (“something happened over there”) and to turn it into a set of puff specifications. This is in general a nearly impossible task due to the limited information available to the emergency response center and the time criticality of the analysis, and so it is necessary to have previously developed relocatable source models for certain baseline scenarios that take a limited amount of input and provide the detailed source puff specification.

## 2.2 Material and Chemical Properties

A tremendous amount of effort has been expended over the past five decades in studying the dispersion of passive, neutrally buoyant tracer gases. Real problems, often involve volatile particulates; hence the density of the material as well as its temperature dependent vapor pressure are important physical parameters. Another important parameter is the solubility in water; this impacts on the ability of the material to be scavenged by precipitation or absorbed on wet surfaces and bodies of water. Unfortunately, it is often true that the details of the released material are some of the last pieces of information available to

the analyst; hence most initial analyses must be performed assuming passive gas or particulate releases.

### **2.3 Thermodynamic Source Considerations**

One of the hardest issues to insert into the real-time response to an emergency is the thermodynamic forcing of the source. Chernobyl, for example, presented a massive thermal energy source such that the radiation was released in a strongly buoyant plume. In addition, the thermal output of the crippled reactor went through several surges creating an extremely complex source. At the other end of the spectrum, many hazardous materials, such as liquefied natural gas (LNG), may be strongly cooled in a tank rupture event due to the latent heat required for vaporization, resulting in an overdense plume.

Another, more unusual, source term is a momentum jet. Pyroclastic eruptions (*c.f.* Figure 1) such as occurred on May 18, 1980 at Mt. St. Helens can eject material at almost sonic velocities. These types of source terms, when coupled with broad particle size distributions, create a nearly impossible problem to approximate under the time constraints of a real emergency. The usual solution methodology is to estimate the initial stabilized plume height and then to develop an elevated source release at that altitude.

### **2.4 First Approximation Source Terms**

Given the range of complexity of real source terms, how does the emergency planner develop a system for building a suitable *representative* source term that incorporates the *known* information, *approximates* the unknown information, and guesses at the *unknowable* information? An example is provided by the National Atmospheric Release Advisory Center (NARAC) of the US Department of Energy (DOE) [2].

On the morning of July 26, 1993, NARAC responded quickly to requests from the State of California and San Francisco Bay Area agencies to provide needed guidance during a sulfuric acid gas leak from a rail tank car at the General Chemical plant in Richmond, California. In this case, the material released was *known* (sulfuric acid gas), the total



Figure 1. On May 18, 1980, Mt. St. Helens underwent a pyroclastic explosion that sent ash and rock over 10 miles into the sky (from [1]).

amount released was *unknown*, but could be estimated from the total capacity of the tank car, but the time history of the release was *unknowable*. Since 1979, NARAC has responded to over 70 alerts, accidents, and disasters; based on these experiences, NARAC has developed a hierarchical questionnaire-based system for providing information on the source of a release (*c.f.* Figure 2).

Other emergency response systems have also developed menu based source information systems, often with intelligent defaults. One of the most extensive is the Hazard Prediction and Assessment

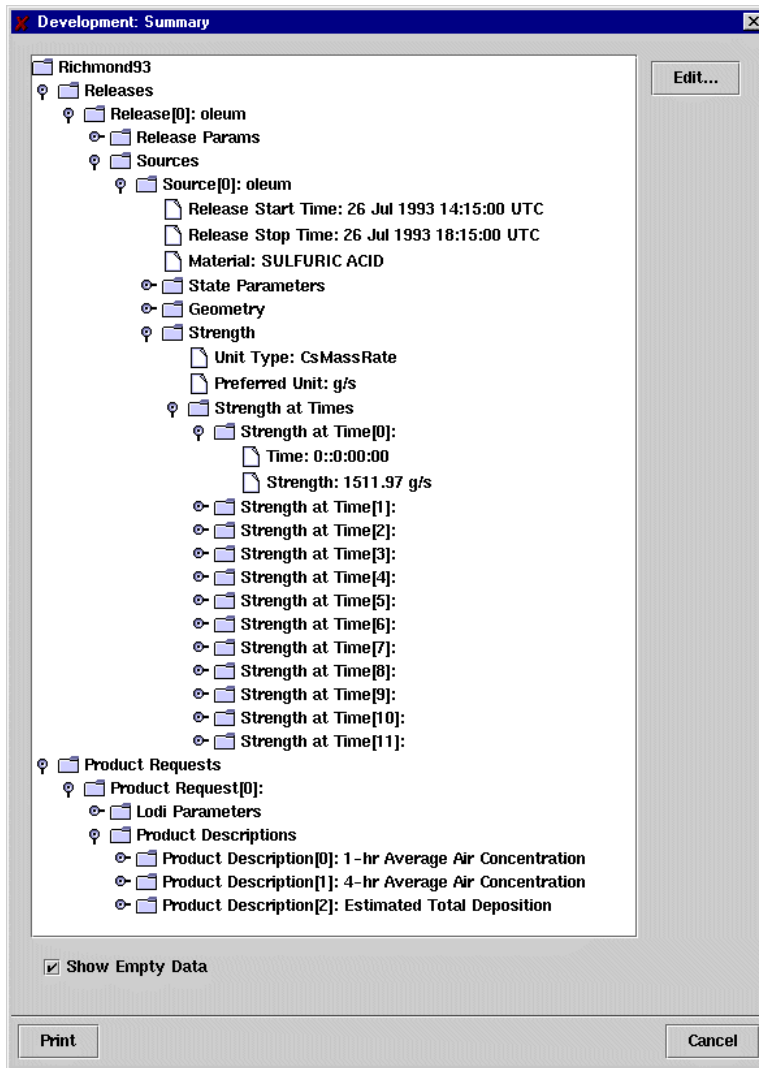


Figure 2. Hierarchical source question developed by NARAC.

Capability (HPAC) developed by the US Defense Threat Reduction Agency (DTRA) [3]. HPAC has developed rapid source determination models with intelligent defaults for nuclear, biological, and chemical releases.

### 3. Notification

The first notice is obviously the most important, but often conveys the least quantitative information. This is the reason why the analysis team is often faced with conflicting courses of action - to begin the analysis in advance of complete information, or to wait until additional information is forthcoming. As we mentioned in the previous section, the real-world notification is rarely in scientific terms; it is more often couched in terms of *where*, *when*, *what*, and *how much*. In an emergency situation, however, time is of the essence and therefore, most action begins once the *where* has been determined - even roughly.

Given a rough location, the first response team can start moving towards the area affected, and the analysis team can start acquiring whatever meteorological observations, analyses, and forecasts (in that order) are available for the release point and its environs. The missing *when*, *what*, and *how much* information can initially be overcome by using a continuous release and assuming a neutrally buoyant trace gas.

### 4. First Responders

As we just mentioned, once the release location is known, even roughly, the first response team can begin to move towards the release point. The next critical pieces of information for them is the exact nature of the release - the *what* and *how much*.

Almost any substance is toxic if the concentration is high enough. Even oxygen, without which human life is impossible, is toxic at high concentration for extended periods of time leading to pulmonary oxygen toxicity and oxygen convulsions (Council for National Cooperation in Aquatics, [4]). Dealing with the plethora of potential material spills would be nearly impossible without computer-based tools. One of the most commonly used is the Computer Aided Management of Emergency Operations (CAMEO) system developed jointly by the US National Oceanographic and Atmospheric Administration (NOAA) and the US Environmental Protection Agency (EPA). CAMEO's chemical database provides ready access to response recommendation for over 4,000 chemicals, including fire fighting, physical properties, health

hazards, and first aid guidance. The system contains over 60,000 chemical synonyms and identification numbers in a searchable format so that unknown substances can be quickly identified during an incident.

The CAMEO system also includes the Areal Location Of Hazardous Atmospheres (ALOHA) straight-line dispersion model [5]. ALOHA uses current local wind information, assumes that it is horizontally uniform and constant, and predicts a simple downwind dispersion hazard. CAMEO and ALOHA were designed to be fast-running on PC-based systems and are valid for ranges from a few tens of meters to a few kilometers. Fortunately this covers the bulk of the small-scale industrial accidents such as an accidental spill or small tank rupture. So great is the need of the first responders, however, that it is often used for problems with much greater ranges and hence a more detailed analysis team is needed to back up the quick simple answer with something more substantial.

## **5. Analysis**

In the world of emergency response, the great bulk of events are the accidental spill of a limited quantity of a hazardous chemical which results in a hazardous area of a kilometer or less. A large number of models have been designed to handle this type of accident. A recent compendium of models by the Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM) [6] listed over 60 atmospheric transport and diffusion models, the great majority of which were simple puff dispersion models such as ALOHA.

Rapidly changing meteorological conditions or regions of complex terrain cannot be handled by such systems. In addition, the potential consequences of a major release of nuclear, biological, or chemical material with hazardous footprints of tens to hundreds of kilometers are so severe that they must also be considered. Finally, a release in an urban environment with the dispersion dominated by the urban canyon flow and thermally driven circulations poses its own set of problems (see Chapters 12 and 13).

High resolution weather forecasting is the key to accurate dispersion modeling; neither single point surface data nor large scale

analysis information is sufficient. To improve the fidelity of hazardous dispersion models, it is essential that the meteorological forecast itself be improved. This is because the modeling of atmospheric dispersion involves virtually all scales of atmospheric motion from microscale turbulence to planetary scale waves. The Operational Multiscale Environment model with Grid Adaptivity (OMEGA) was designed to improve the state-of-the-art in atmospheric dispersion. OMEGA is a multiscale simulation tool, which simulates fine scale flows without the need for multiple nested grids, that incorporates an embedded dispersion model [7]. An example of an OMEGA simulation in a data sparse region is shown in Figure 3. This figure shows the predicted plume from the Kuwait oil fires for a specific data in March 1991 and the actual observation.

In this section we explore the determination of the weather conditions for an emergency response situation, including the level of confidence therein, and discuss high resolution dispersion modeling, including the estimate of uncertainty.

### **5.1 The Need for Analysis – Bhopal**

A classic example of the need for rapid analysis is seen in the events that occurred in Bhopal, India in the early morning of December 2, 1984. At 12:20 local time, a pressure relief valve on a storage tank opened venting 20 tons of methylisocyanate (MIC) to the atmosphere.

The fate of this heavier-than-air gas has been the subject of many studies including one by Boybeyi *et al.* [8]. Bhopal was a city of several hundred thousand and at the time of the release, the mesoscale circulation was dominated by the stable air mass caused by a large lake in the area and the urban heat island that ducted the light winds over and around the city. Within two hours, those closest to the release were affected with eye and lung irritation, but no general alert had gone out. During this time the dense MIC pooled, increasing its concentration above the lethal threshold. As the urban heat island dissipated, and the winds picked up, the now lethal plume moved over the city killing 5,000 people.

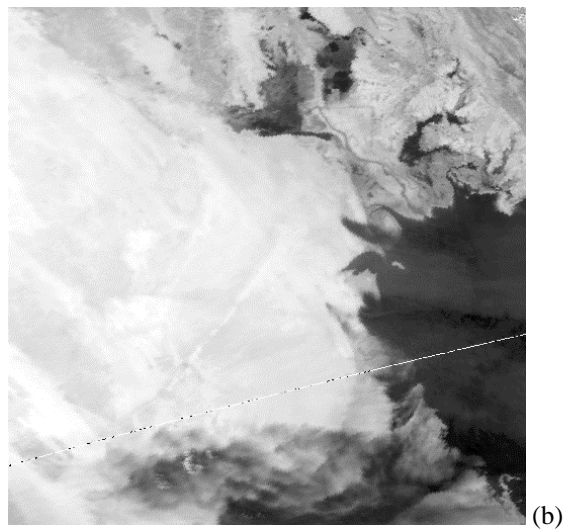
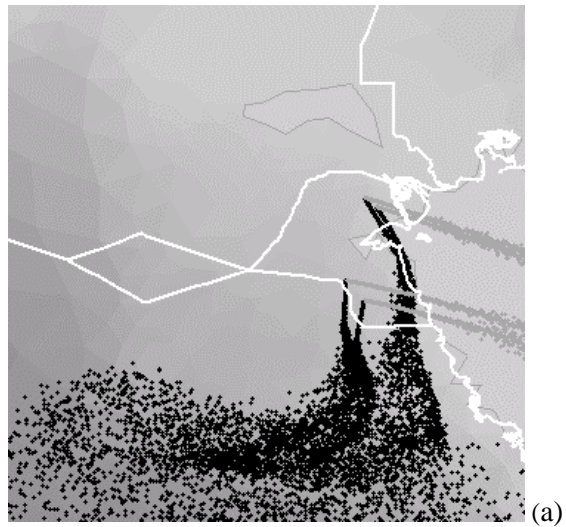


Figure 3. A comparison of (a) OMEGA simulated oil-field fire plumes and (b) AVHRR image data. The OMEGA simulation is valid at 1030Z on March 11, 1991; AVHRR image was taken at 1020Z.

## 5.1 Weather Analysis

The amount of global *in situ* weather data is abysmally small –roughly 25 MB of data in total per day for both the world-wide surface and upper air data. The surface observations are taken hourly at roughly 8000 points on the globe; the upper air observations are sampled from less than 1000 locations twice a day. Given this limited amount of data, the probability that an observation will be close to a random release point is extremely small – *unless the site has been instrumented prior to the release*. This latter approach was the basis of the NARAC system previously mentioned.

NARAC was created to serve as an emergency management tool for releases at nuclear facilities. Since the facilities were known, it was possible to instrument each site with a local mesonet. While this approach has many advantages (*e.g.*, high quality local data, known calibration of the instrumentation), it obviously is not appropriate for the general case.

In the general case, the data is just a starting point. If raw data is obtained, it must undergo quality control prior to use due to the large number of observations that possess instrument, transcription, or transmission errors. The raw data is processed by the national weather services of the various countries to create gridded *analyses* and *forecasts*. Unfortunately for many dispersion problems, the spatial and temporal resolution of these analyses are not sufficient.

Most global weather forecast models are run at a spatial resolution of 50-100 km. In addition, most are spectral models that assume a spherical Earth and thus possess extremely limited information about the local terrain. For a dispersion problem near a coastal region or in complex terrain, this lack of spatial resolution is intolerable. Many operational forecast centers are now running regional or mesoscale models down to resolutions of 30-50 km. Although these models have more terrain information, even this resolution is not sufficient for the detailed dispersion analysis necessary in an emergency response situation. This is part of the reason that even finer scale models with grid resolution down to 1 km (*e.g.*, OMEGA) have been developed.

Resolution alone is not the answer. Increased resolution permits the resolution of fine scale atmospheric features that are important for

dispersion. But the physics that drives these fine scale features must be modeled. In addition, these fine scale features must also be allowed to affect the larger scale circulation. Thus a model such as OMEGA can resolve microscale events while being fully consistent and providing the large scale forcing which is required to ensure the proper simulation of the atmosphere. In order to accomplish this, however, it is necessary to include all of the physical parameters and processes which affect the local flows. These include not only the topography, but also the land use, the land/water composition, the vegetation, the soil moisture, the snow cover (if appropriate), and the surface moisture and energy budgets. Much of this additional physics is only appropriate because of the increased spatial resolution.

## **5.2 Weather Uncertainty**

Given a weather observation, analysis, or forecast, how sure are we of the validity of that data to the problem at hand? Rarely, if ever, will the data be at the precise time and location of the actual event, hence we have to make assumptions as to the representativeness of the observation some distance removed from the event. For example, if a *perfect* observation is taken in the Midwestern US with relatively flat terrain and a meteorological condition that is relatively constant, then the observation may be valid for some considerable distance and time. On the other hand, if it was taken in mountainous terrain with a front moving through, then the observation may be immaterial to the problem at hand. The same can be said for analyses and forecasts. Their representativeness for dispersion studies depends on their own spatial resolution and that of the databases that support them. A grid point analysis or forecast at 100 km spacing is a useful qualitative tool, but it may result in an incorrect dispersion analysis.

The errors in these systems can be grouped into observation, analysis, or forecast errors, any of which can lead to errors in calculating the dispersion of a hazardous aerosol or gas. Quality control can eliminate bad observations prior to use leaving analysis and forecast errors. Of these, given equivalent surface information and grid resolution, the latter is the more significant.

Forecast errors can be *estimated* by a variety of validation runs. Unfortunately, numerical weather prediction (NWP) models cannot be validated in the mathematical sense. In mathematical terms, NWP is plagued by a lack of data (data sparse), has poorly defined lateral and top boundary conditions, has incomplete surface boundary conditions, and contains motions spanning many temporal and spatial scales. For this reason, while parts of NWP models may be rigorously validated (in the mathematical sense), the only true test is by comparison with observations.

Forecast errors arise from a combination of limited grid resolution and the approximations that resolution imposes, actual errors in model physics, and in the initial and boundary conditions of the model. The errors in the initial conditions are often termed the “butterfly effect”, but this is more true of synoptic motion than local terrain forced flow. Many operational forecast centers have developed *ensemble* forecast systems for their global forecast models. Typically this involves running a degraded resolution model with slightly differing initial conditions or with particular spectral components (the “breeding” modes) enhanced. By running a set of variations, they can determine whether the baseline forecast of the large scale flow of the atmosphere is robust – and for how long it will continue to be robust. An example is given in Figure 4 which shows the results of just 5 of 12 runs of the Medium Range Forecast (MRF) model used at the National Centers for Environmental Prediction [9]. This figure shows the intersection of the 500 mb pressure level with the 5640 m geopotential height. The figure indicates that the 3 day forecast is relatively robust for North America (top) while the 5 day forecast has considerably more scatter.

A very real question is the validity of this analysis as a basis for quantifying the forecast error. The 12 standard MRF runs used for the NCEP ensemble are the baseline MRF forecast result (T126), a control run at degraded resolution (T62), and five (5) pairs (plus / minus) of perturbations with different breeding modes run at the degraded resolution. The result is an exercise in *model* variability, not true forecastability. For those cases where agreement exists, however, some level of robustness can be assumed.

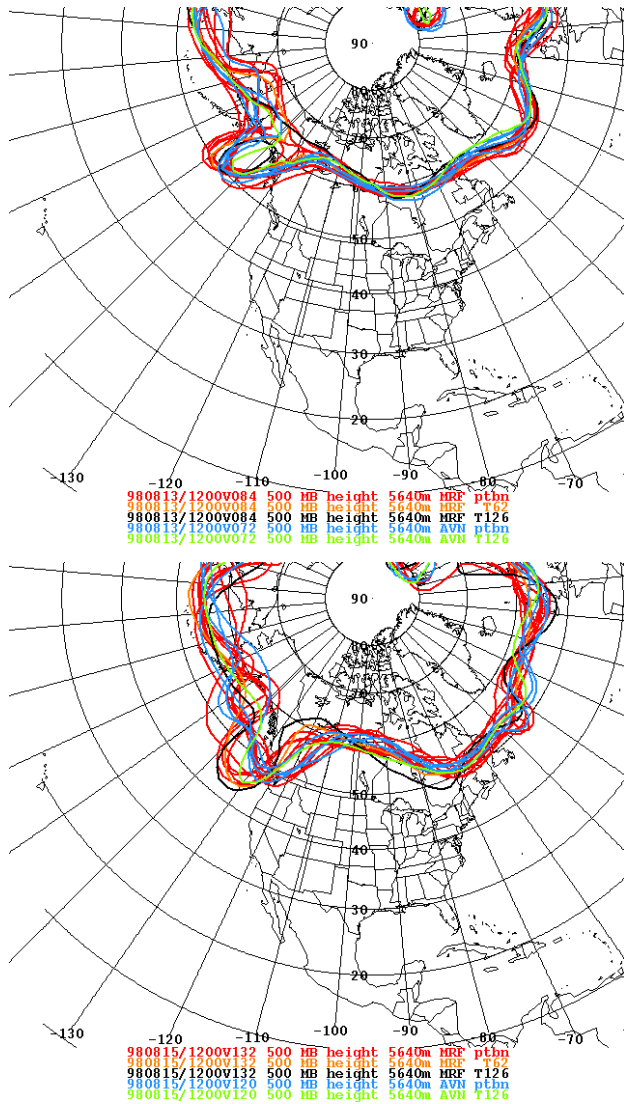


Figure 4. Ensemble forecast products produced by NCEP showing the increase in forecast variability from 3 to 5 days. The top panel shows a collection of simulation results for a 3 day forecast; the bottom panel for a 5 day forecast. (Courtesy of NOAA / NCEP.)

Another valid question is the impact of these synoptic forecast errors on dispersion calculations. Ensemble forecasts are produced for only a very few products due to the high computational cost of production. Wind speed and direction, typically are not driving needs for most operational weather forecast centers, hence this is not a high priority for ensemble forecasting. (This is another example of why it is necessary to improve the state of weather forecasting to improve the state of dispersion forecasting.) But even if it was, it is valid to ask if this is a reasonable methodology for dispersion purposes.

Ensemble forecasts rely on multiple forecasts at degraded spatial resolution. The resolution **must** be degraded due to the large amount of computational cycles that must be spent on these multiple forecasts. But dispersion is a problem that is critically dependent on the *details* of the atmospheric circulation. In addition, most dispersion problems occur in the planetary boundary layer where they are forced by fixed surface features that may be quite small (terrain, coastlines, vegetation or land use variations). Thus an argument can be made that it is preferable to utilize all the available computational cycles to create a *single, high fidelity* forecast than multiple low fidelity ones.

Figure 5 shows a situation that demonstrates the problems of ensembles of low resolution simulations. This figure shows a part of the terrain of southeastern New Mexico. As can be seen at the top of the figure, some of this terrain is extremely complex with many features at the few kilometer scale. If this terrain is resolved only at 10-30 km resolution, then all of the critically important terrain features will be missed by the NWP simulations. Hence any ensemble of these results will be worthless as they **all** would have failed to resolve the critical feature – the terrain.

Situations such as this demonstrate the natural separation of operational weather forecasting and high resolution forecasting for dispersion. The low resolution ensembles currently in vogue at national and regional forecast centers provide a means of measuring the synoptic forecastability but provide no guidance for dispersion. Since dispersion simulations *require* the highest possible resolution of surface feature, all available computational cycles should be devoted to a single, high resolution simulation.

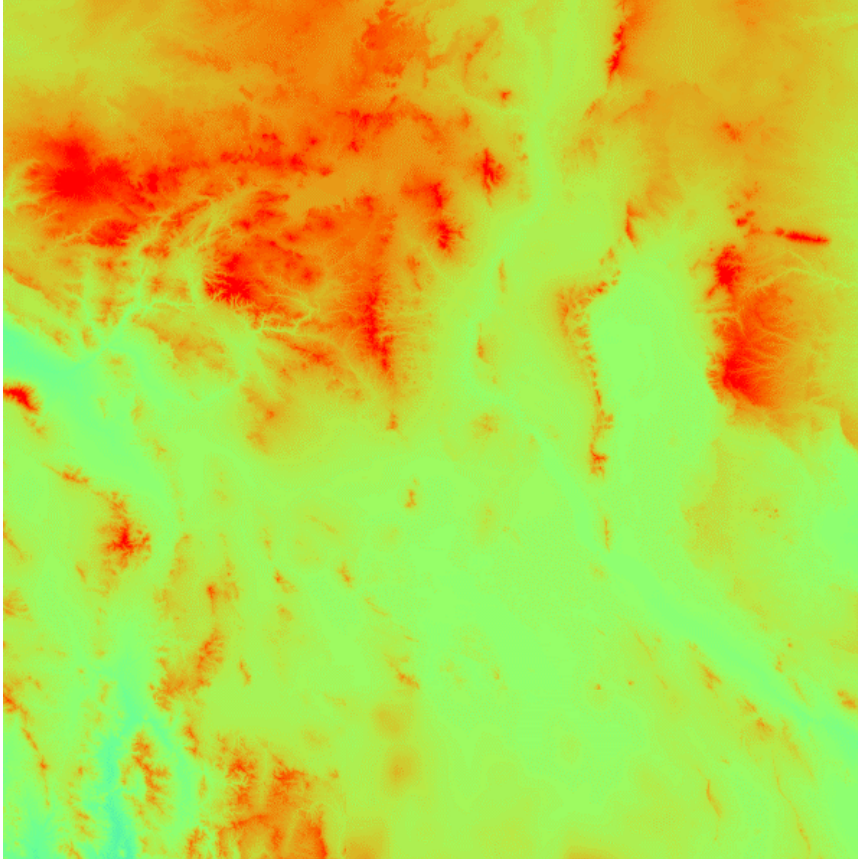


Figure 5. The terrain in southeastern New Mexico. Near the top of the figure the terrain is quite complex with many features on the order of a few kilometers.

The use of a single high resolution simulation, however, does not eliminate the need to understand the limitations of the model and to try to quantify the forecast error. Without a true mathematical means of establishing the accuracy of an NWP model, the best that can be done is to develop model output statistics (MOS) for the model by comparing the forecasts against the observations or the analyses. Comparing against the observations is preferable, but only allows MOS development for the observation locations; analysis derived MOS have

the advantage of total coverage (over the forecasted domain), but are removed somewhat from a direct comparison with the data. Whichever method is used, the MOS can then be utilized to provide the dispersion calculation with a measure of the uncertainty in the forecasted products directly applicable to dispersion: temperature, dewpoint, wind speed, and wind direction.

### **5.3 High Fidelity Dispersion Modeling**

Improving the forecast of the weather is only the first step in improving the forecast of dispersion. A critical step is providing this weather information to the dispersion model. Most dispersion models are designed to ingest weather information produced at some spatial and temporal resolution and to then calculate the dispersion. (*e.g.*, the EPA Models-3 program has designed their air quality modeling system around this paradigm.) Unfortunately, as the NWP model resolution increases, the input / output (I/O) requirements of the dispersion model increases as the *cube* of the NWP model resolution. Increasing the resolution from 100 km (the norm at the beginning of this decade), to 1 km increases the data handling requirement by  $10^6$ . The alternative to this is to embed the dispersion model into the NWP model; this is the paradigm used by OMEGA.

OMEGA contains both puff and particle dispersion models as part of its embedded Atmospheric Dispersion Model (ADM) routines [7]. These models are run as part of the overall simulation and have access to the full NWP model results at each timestep. Since the ADM routines are embedded inside OMEGA, there is no additional I/O constraint. An example of the ADM particle output is shown in Figure 3.

While the use of embedded transport is ideal for high fidelity simulations, it has a significant drawback for emergency response support: the lack of ability to change source location and characteristics and/or aerosol or gas characteristics. For this reason, it is still necessary to provide a means to export the NWP output for use in post-processed dispersion models. The embedded transport results, however, can significantly improve the data export by providing guidance on the exact domain for which the NWP results are required.

## 5.4 Mean and Variance

Turbulence in the atmosphere produces fluctuations in measured concentration *even if the source is absolutely constant*. Most dispersion models were developed to simulate just such a situation: stack emissions from power plants or chemical facilities. The data taken from situations such as this is typically reduced to provide the mean value of the effluent concentration as a function of range and atmospheric conditions and this is the standard against which most dispersion models are judged. Emergency response situations, however, often involve chemicals for which the *peak* rather than the mean concentration is the critical value. This requires understanding the variance associated with the mean concentration.

Several variance models have been developed over the years. The first is due to Wilson *et al.* [10,11] and uses conventional first-order turbulence closure; the second has been developed by Sykes *et al.* [12] and is based on a second-order closure turbulence model. Both have their strengths and weaknesses. Upon initial inspection, the Second-Order Closure Integrated PUFF (SCIPUFF) model appears to have an edge due to its higher order closure of the turbulence terms in the Navier-Stokes equations; however, it relies on knowledge of the initial and boundary conditions for the Reynolds stresses, which are not standard observations. SCIPUFF gets around this limitation using a climatological database for Reynolds stresses. Hence what should be a clear advantage becomes a philosophical issue as to the benefit of using current observations with a lower order closure scheme (as in Wilson), or a high order closure scheme with climatological initial and boundary conditions (as in SCIPUFF).

Regardless of the approach, for emergency response it is the availability of a quantitative measure of the variance that is critical to the response teams.

## 5.5 Operational Considerations

The ideal situation aside, the real-time operational constraints of an emergency response center lead to a fine balance between what *should* be done and what *can* be done. (Remember, the analysis team is often

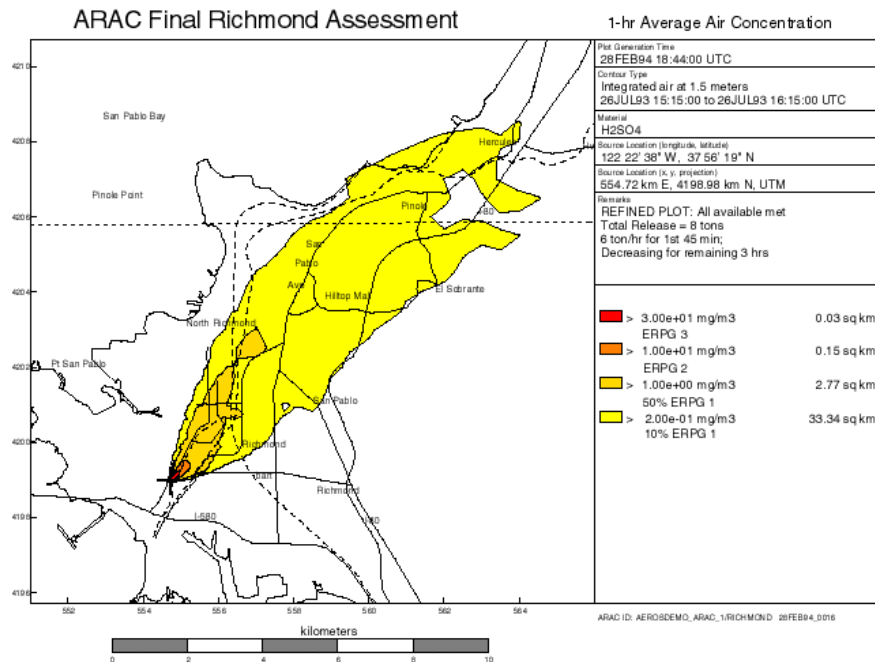


Figure 6. The 1-hour average air concentration for the second hour after release for the event described in Section 2.4. (Courtesy of NARAC.)

forming as the first responders are en-route; time is critical.) Retrieving the closest observations and the most recent large scale analysis is often the best that can be done before the first responders have arrived on site. This information can then be compared with their on-site observation. At this time, it may also be possible to make a first estimate of the hazard given the meteorological observations since the release and assuming that the current or on-site meteorological observations hold constant (*c.f.*, Figure 6). This is the most current methodology, and while it works under many situations, it is extremely dangerous in coastal situations or changing weather conditions. In these situations, it is necessary to access the operational forecast products and to generate a high resolution forecast to support further analysis.

Once the analysis has reached this point, a great deal of judgement comes into play. If a high resolution forecast is planned, then the model domain, resolution, and physics must be balanced against the

available computational resources in order to achieve a sufficient time compression for the operational need.

## **6. Results Dissemination**

The best possible analysis is worthless unless it can be transmitted to those making decisions. In the past, this data dissemination was achieved via dedicated circuits to central command facilities; today's mobile communications are rapidly placing the ability to provide graphical products to First Responders on-site. Cellular phones would appear to be ideal for this purpose, but in fact tend to saturate in emergency situations and may not be available in remote locations. Satellite based communication, on the other hand, is ideal for this purpose.

Satellite communication bandwidth depends primarily on the power of the transmission unit. This leads to a natural asymmetry in the communications path with higher bandwidth available *from* the analysis cell to the field and lower bandwidth available *from* the field to the analysis cell. Fortunately, the amount of information that needs to be passed back to the analysis cell from the field is primarily text based information while the analysis cell is primarily sending graphical products to the field so this natural asymmetry does not have negative implications.

As the power of mobile communications and computing increase, we will see an increasing move towards on-demand graphical distribution of dispersion analysis products to the first responders.

## **7. Summary**

Emergency response is a problem that requires a delicate balance between accuracy and timeliness. The most accurate dispersion forecast possible is useless if it cannot be delivered in time to save lives or prevent injury. A timely forecast that is incorrect, however, because it failed to consider important details in the source, the terrain, or in the ambient meteorology can be worse than no answer, however, as it may guide emergency personnel and the local populace into harms way.

In any application of numerical methods to solve a physical problem, it is of paramount importance that sufficient spatial and temporal resolution is provided to resolve the dominant physical processes. Dispersion, especially mesoscale dispersion, is a problem that depends critically on *details*. Modeling mesoscale dispersion requires the resolution of all the significant local terrain features (coastlines, elevation, land use, vegetation, *etc.*) as well as the details of the ambient meteorology (horizontal and vertical). All of this attention to detail comes at the cost of *time*, and the key to dispersion analysis for emergency response is to understand those features that **must** be included and those that can be left to later analysis.

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