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DEVELOPMENT OF A PREDICTION SCHEME FOR VOLCANIC ASH FALL FROM REDOUBT VOLCANO, ALASKA

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ABSTRACT

The purpose of this project is to develop a volcanic plume prediction model for volcanoes located in the Cook Inlet area, Alaska. Knowing where the ash plume is and predicting where it will go are important for public health and safety, as well as for flight operations and mitigating economic damage. For near-real-time plume prediction, acquisition of upper-air wind data is the essential part of the prediction scheme.

In this project, near-real-time meteorological data are provided by the National Meteorological Center, transmitted via Unidata. Reading the real-time and forecast wind data, the prediction model computes advection, diffusion, and gravitational fallout for the plume particles from the vertical column over the volcano. Three-dimensional dispersal of plume particles are displayed on the computerized graphic display as a function of time following the eruption. The model predictions appear on the screen about 15 minutes after the eruption report, showing the geographical distributions of plume dispersal for the following several hours. Although the model simulation inevitably has forecast errors owing largely to errors in the forecast wind input, the prediction product offers a useful guide for public safety, especially for the Cook Inlet area, Alaska.

INTRODUCTION

Anchorage, Alaska is one of the focal points of international aviation activities. The city lies close to several active and potentially active volcanoes including Hayes, Spurr, Redoubt, Iliamna, Augustine, and Douglas along the west shore of Cook Inlet, and Wrangell Volcano to the east. In this century Spurr, Redoubt, and Augustine together have had eight significant eruptions that have spread ash over a broad area of south-central Alaska. It is necessary to establish a reliable scheme for predicting the distribution of volcanic ash fall after an eruption in order to avoid unnecessary disruptions of aircraft operations. For the plume prediction to be operational, an immediate eruption report and real-time upper-air data must be available. A quick response is one of the priorities of the plume-prediction system.

The Alaska Volcano Observatory (AVO) at the Geophysical Institute, University of Alaska, Fairbanks, has direct access to near-real-time satellite imagery and upper-air weather data (Dean and others, this volume). By combining this information with the established eruption-monitoring network provided by AVO, we have established a volcanic plume prediction model that predicts volcanic ash dispersal as a function of time immediately after the eruption. The upper-air wind data are the fundamental input to the plume-prediction model. The National Meteorological Center (NMC), in Washington, D.C., offers daily weather predictions as well as analyzed and initialized meteorological data on three-dimensional (3-D) gridded mesh. Recently, a national program in atmospheric sciences, referred to as Unidata, enables university researchers to use the real-time NMC data through a satellite downlink (Sherretz and Fulker, 1988; Tanaka, 1991a, 1991b). Therefore, the real-time upper-air wind data are available at AVO.

In response to the eruption of Redoubt Volcano at the end of 1989, a volcanic plume prediction model has been developed within the AVO (Tanaka, 1990). This project incorporates wind data from Unidata for predicting the distribution of volcanic ash plumes on a real-time basis after an eruption is reported. Using the real-time and predicted upper-air data, the model computes advection, diffusion, and gravitational fallout of the ash particles. Three-dimensional distributions of the ash plume are displayed on the computerized graphic display, predicting the direction and dispersion of ash clouds for the first several hours after eruption. This report describes the algorithm of the present particle-tracking model in a Lagrangian framework. The results of the demonstrations and the procedure of the information-transfer network are presented.

UNIDATA

Unidata (University data) is a national program for providing near-real-time meteorological data to university

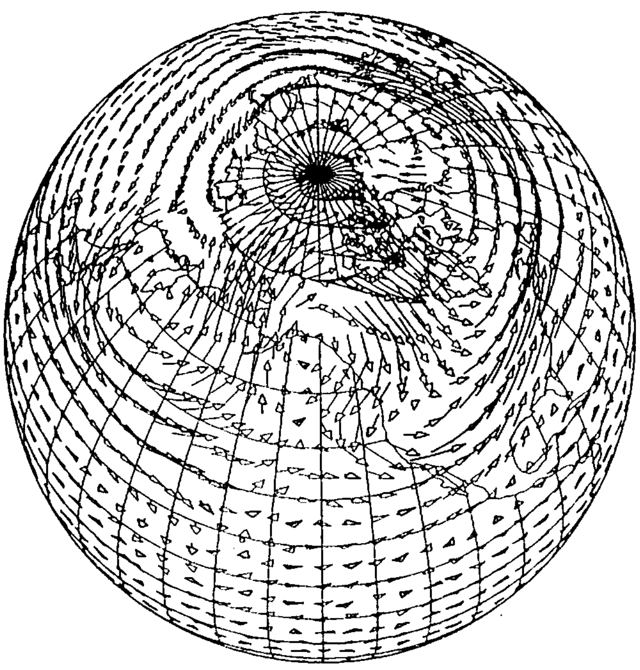

Figure 1. Example of NMC data received at the Alaska Climate Research Center via Unidata showing the global distribution of wind vectors at the 500-mb level, February 3–7, 1989. Length of staff indicates wind speed; pointer indicates wind direction. The horizontal grid interval available for Unidata is 5° for longitude and 2.5° for latitude.

users. The Unidata program center is located in Boulder, Colo., and it is managed by the University Corporation for Atmospheric Research (UCAR). The Unidata program established its own data feed from the National Weather Service operational circuit to distribute the near-real-time and forecast meteorological data for university users. Among the service programs, the NMC provides global analysis data and forecast gridded data. The meteorological data are transmitted by satellite downlink under a contract with Zephyr Weather Information Service.

The NMC meteorological variables of zonal and meridional wind speeds, u and v (m/s); temperature, T (K); geopotential height, ϕ (m); and relative humidity, R (percent) are given at 2.5° latitude and 5.0° longitude grids at 10 mandatory vertical levels of 1,000, 850, 700, 500, 400, 300, 250, 200, 150, and 100 mb over the whole global domain (fig. 1). Those basic meteorological variables are transmitted twice a day, for 00:00 and 12:00 UTC. In every data transmission, the global gridded data include not only the initial conditions for the weather-prediction model (plus 0-hour NMC initial data) but also the data for the forecasting time of 6, 12, 18, 24, 30, 36, 48, and 60 hours, provided by the NMC numerical weather-prediction model. The initialized global data at forecasting time 00:00 may be regarded as observed data.

Figure 2 illustrates a relation between NMC data transmission and the volcanic plume prediction. The twice daily NMC data, including the forecast data, are stored and continuously updated in the computerized database. The database always consists of past observed data and forecast data for 2 to 3 days ahead. Therefore, when an eruption is reported, the prediction model can use the present and future upper-air data for the computation of plume advection. The forecast upper-air wind data for a 1-day prediction are typically as good as the analyzed wind data (Kalnay and others, 1990), even though the analysis data often contain considerable discrepancy from the real upper-air wind.

As an example, figure 3 compares the analyzed wind field (solid arrows) at the 500-mb level with the corresponding wind field for the 24-hour forecast from 1 day before (dashed arrows). The differences appear to be minor for this example, suggesting that the forecast wind field is useful for real-time plume prediction. However, the accuracy of the predicted wind depends on the weather situation. For example, the prediction is generally good when a persistent, blocking, high-pressure system stays near Alaska, but the prediction is poor when a low-pressure system is passing the Cook Inlet. Moreover, the analyzed wind field, interpolated from the upper-air observations onto the longitude-latitude grids, often contains considerable errors due to the imperfect interpolation technique. Yet, knowing the degree of the analysis error, the NMC upper-air data is still useful for plume prediction when no alternative exists.

DESCRIPTION OF THE MODEL

The volcanic plume prediction model is constructed by an application of pollutant dispersion models (e.g., Praham and Christensen, 1977; Suck and others, 1978; Kai and oth-

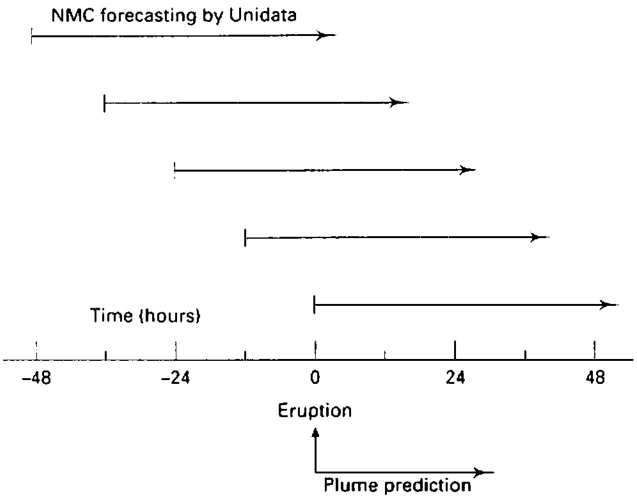

Figure 2. Schematic diagram showing the relation between the twice-daily NMC data transmitted by Unidata and the volcanic plume prediction. Arrow for NMC data describes a data span for the forecasting time from 0 to 48 hours. In response to an eruption report, the volcanic plume prediction model reads the archived NMC database to run the model using real-time wind data.

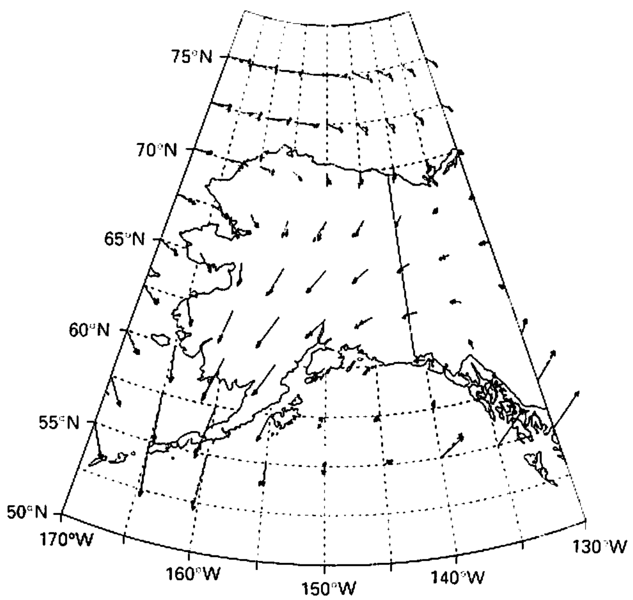

Figure 3. Comparison of analyzed wind vectors (solid arrows) at the 500-mb level and corresponding wind vector of the 24-hour forecast from 1 day before (dashed arrows), the State of Alaska, November 11, 1990. This example indicates the usefulness of the 1-day forecast data, although the wind error can be large depending on the weather situation (see text).

ers, 1988). The model is based on the three-dimensional (3-D) Lagrangian form of the diffusion equation. We assume a vertical column of pollutant source that diffuses along with the Gaussian distribution in the 3-D space. A diffusion approximation of the pollutant turbulent mixing is used with 3-D diffusion coefficients to evaluate the dispersion of pollutant concentration. In the Lagrangian framework, diffusion of plume particles may be described by a random walk process (Chatfield, 1984). Here, the diffusion is simulated by a sufficiently large number of random variables $r_i(t)$, ($i = 1 \cong M$), representing position vectors of M particles from the origin (the volcanic crater). The diffusion is superimposed on advection and gravitational fallout.

With a discrete time increment, Δt, the Lagrangian form of the governing equation may be written as:

$$r_i(t+\Delta t) = r_i(t) + V\Delta t + Z\Delta t + G\Delta t, \quad i = 1 \cong M \qquad (1)$$

where

$r_i(t)$ is a position vector of an ith particle at time t,

V is the local wind velocity to advect the particle,

$Z = (z_h, z_h, z_v)$ is a vector containing three Gaussian random numbers with its standard deviation (c_h, c_h, c_v) for horizontal and vertical directions, and

G is the gravitational fallout speed approximated by Stokes' law.

Note that the diffusion, $Z\Delta t$, is direction dependent, and the gravity settling, $G\Delta t$, depends on particle size.

For the computation of advection, the wind velocity, V, is obtained from NMC via Unidata. The gridded data are first interpolated in time onto the model's time step. The cubic spline method (Burden and others, 1981) is used up to the 3-hour interval, then a linear interpolation is applied for the 5-minute time steps. The wind velocity at an arbitrary spatial point is evaluated using the 3-D B-splines (Burden and others, 1981) from the nearby gridded data.

For the computation of diffusion, we consider the following diffusion equation in Eulerian form:

$$\frac{\partial q}{\partial t} = K\nabla^2 q \qquad (2)$$

where

q is the plume mass density,

∇^2 denotes a Laplacian operator, and

K denotes the diffusion coefficient.

For simplicity in derivation and for uncertainty in the magnitude of K, we consider a one-dimensional case in space along the x-axis. The solution of the diffusion equation for a point source at the origin is given by:

$$q(x, t) = \frac{1}{2\sqrt{\pi K t}} \exp\left(-\frac{x^2}{4Kt}\right) \qquad (3)$$

which may be regarded as a Gaussian distribution with its standard deviation

$$\sigma = \sqrt{2Kt} \qquad (4)$$

It is found that the plume dispersal, represented by σ, expands in proportion to $\sqrt{t}$.

On the other hand, a random walk process in Lagrangian form is defined as:

$$\begin{cases} r(0) = 0, \\ r(t+\Delta t) = r(t) + z(t)\Delta t \end{cases} \qquad (5)$$

where

$r(t)$ is the position of a particle along the x-axis,

$t = n\Delta t$, ($n = 0, 1, 2, \ldots N$), and

$z(t)$ is the zero-mean Gaussian random number with its standard deviation, c.

For this random walk process, the standard deviation of $r(t)$ is given by:

$$\sigma = c\sqrt{t\Delta t} \qquad (6)$$

Comparing these standard deviations in Eulerian form and in Lagrangian form, we obtain a relation between the diffusion coefficient, K, and the diffusion speed, c, as:

$$c = \sqrt{\frac{2k}{\Delta t}} \qquad (7)$$

The diffusion velocity depends on the time increment of the discrete time integration. We use $\Delta t = 5$ minutes in this study. We have repeated diffusion tests with various values of K, and the resulting dispersals are compared with satellite images of actual dispersals from Redoubt Volcano. With these diffusion tests, we find that the appropriate diffusion coefficients are $K_h=10^4$ (m^2/s) and $K_v=10$ (m^2/s) for the horizontal and vertical directions, respectively. Note that values may be different for other volcanoes.

The diffusion speed may be sensitive to the scale in consideration. For example, the present value of the diffusion coefficient varies as the horizontal scale, which ranges from several hundreds of kilometers to 1,000 km in length. Figure 4 illustrates a result of the diffusion test. The steady plume at the origin spreads downstream of the source under the influence of constant wind. The theoretical standard deviation of the plume dispersal is indicated by the parabolic solid line in the figure.

The gravitational settling is based on Stokes' law as a function of the particle size, d_i. The fallout speed $|G|$ is approximated by the terminal velocity below:

$$|G| = \frac{2\rho g d_i^2}{9\eta} \qquad (8)$$

where

ρ is the density of plume particles,

η is the dynamic viscosity coefficient, and

g is the acceleration due to gravity.

We have assumed a constant for $\rho g/\eta = 1.08\times10^9$ m^{-1}s^{-1} for simplicity. The actual eruption contains large fragments, up to few centimeters in diameter, as well as fine ash, which occupies a continuous particle-size range to less than 1 µm. Large particles typically settle out within a short time, and the particle-size spectrum in the air shifts toward smaller particles. Because we are interested in particles that can travel for several hours, we have assumed that the initial particle-size distribution is centered at 100 µm. It is assumed that the size distribution in logarithmic axis has a Gaussian distribution. Thus, about 95 percent of the particles are supposed to have diameters between 1 µm and 1 cm. Using Gaussian random numbers, every particle is assigned with its own diameter, between 1 µm and 1 cm, when it appears at the volcanic crater. In practice, particles larger than 100 µm drop quickly, within a few steps of time integration. Particles that are less than 100 µm in diameter can travel far from the source, providing important information on plume dispersion.

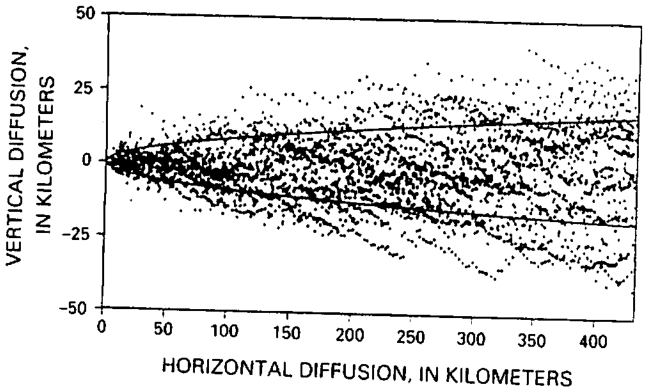

Figure 4. Plan view showing a 12-hour particle diffusion test for a steady plume at a constant zonal wind of 10 m/s. The parabolic line in the figure indicates a theoretical standard deviation of the plume distribution.

The initial particles are modeled to be uniformly distributed in the vertical column, between the top of the erupting volcano and the specified plume top, using a uniform random-number generator. The altitude of the plume top is assumed to have been reported to AVO by visual observers, which may include pilot reports and reports from ground-based observers. In a case of a short-lived explosive eruption, ash particles are generated only for the initial time of the time integration. When the eruption continues for a period of more than a few minutes, the model generates new particles over the same vertical column for every time step during the specified eruption period. For a steady eruption, the particle number tends to increase in the model atmosphere before the plume particles have dropped out. Therefore, the number of particles released at every time step is adjusted to draw optimal statistical information from the model products.

The total number of particles in the model atmosphere is kept at less than 1,000. Although it is possible to increase the number toward the limit of computer capability, the time integration will then be considerably slower, which is a disadvantage for the urgent prediction requirement. Likewise, excessive complication and sophistication are not recommended in the present application for urgent operational prediction. For comprehensive numerical predictions, refer to Sullivan and Ellis (this volume), Heffter and others (1990), Kai and others (1988), and Draxler (1988).

The plume-prediction model is tested first with a sheared flow in the vertical. Advective wind in the atmosphere has vertical shear with larger velocity, in general, at higher altitude. Figure 5 illustrates the result of the vertical cross sections of a plume-puff simulation for 1 through 6 hours after the eruption. Concentrated ash particles are released uniformly over the vertical column up to an altitude of 10 km at the origin. The plume clouds drift downstream by sheared flow. They diffuse and become thinner due to removal of larger particles. The result simulates reasonably well the transport of the ash plume.

The plume-prediction model is tuned by comparison with actual eruption records of Redoubt Volcano (Brantley, 1990). Model simulations are conducted for about 30 major and minor eruptions during December 1989 through April

1990, and the resulting plume-cloud distributions are compared with satellite images (K. Dean, University of Alaska, oral commun., 1991). Unfortunately, for this period, the Cook Inlet area is mostly covered by dense weather clouds, and there were not many satellite images that captured the ash plume immediately after the eruption.

Figure 6 illustrates a steady plume cloud for December 16, 1989, simulated by this model. Because Redoubt was in near-continuous ash emission on this date, we started the simulation assuming the eruption occurred at 10:00 UTC. A linear cloud extends from Redoubt Volcano toward the northern part of the Kenai Peninsula at 12:30 UTC. In the figure, open circles represent particles higher than 1,800 ft and solid circles represent particles lower than 1,800 ft. The simulation result is compared with satellite images from the NOAA-11 advanced very high resolution radiometer (AVHRR) at 12:18 UTC (see fig. 7). In figure 7, the black area over Cook Inlet describes a relatively dense ash cloud and the shaded area over the Kenai Peninsula represents a thin ash cloud. The satellite image describes the detailed structure of the cloud, which is beyond the model's resolution. Nevertheless, the overall agreement between the simulated and observed plume distributions is encouraging.

Figure 8 (*A–D*) illustrates a sequence of graphic products simulated for the eruption on January 8, 1990. The eruption started at 19:09 UTC and continued for 30 minutes. At 20:00, a cellular ash cloud is located near Redoubt Volcano (fig. 8*A*). The cloud crossed over the Cook Inlet and reached

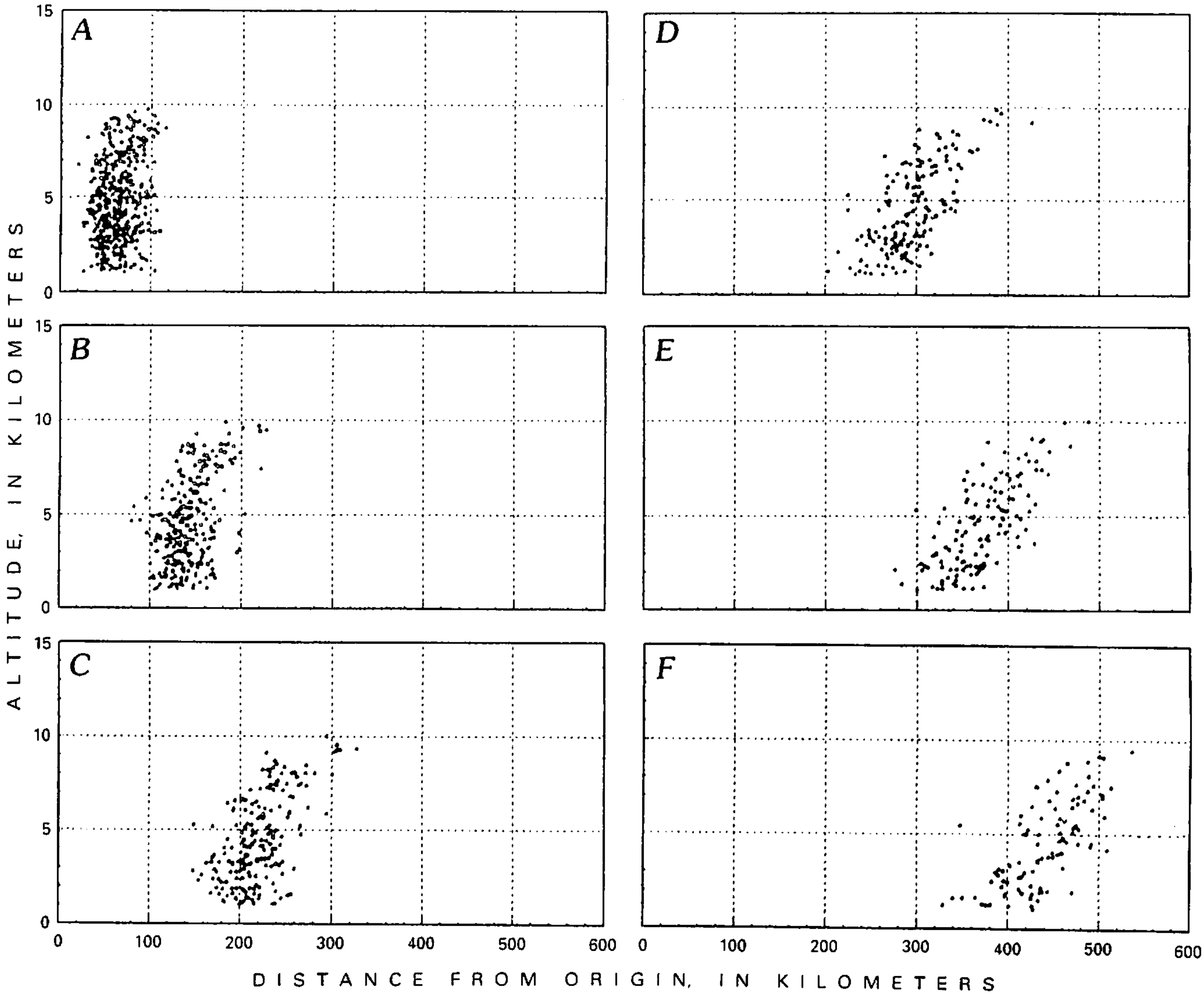

Figure 5. Vertical cross sections of a puff plume simulated for 1 through 6 hours after an eruption. In this test run, the initial ash particles are released uniformly over the vertical column up to an altitude of 10 km at the origin. *A*, plume simulation 1 hour after eruption; *B*, plume simulation 2 hours after eruption; *C*, plume simulation 3 hours after eruption; *D*, plume simulation 4 hours after eruption; *E*, plume simulation 5 hours after eruption; *F*, plume simulation 6 hours after eruption.

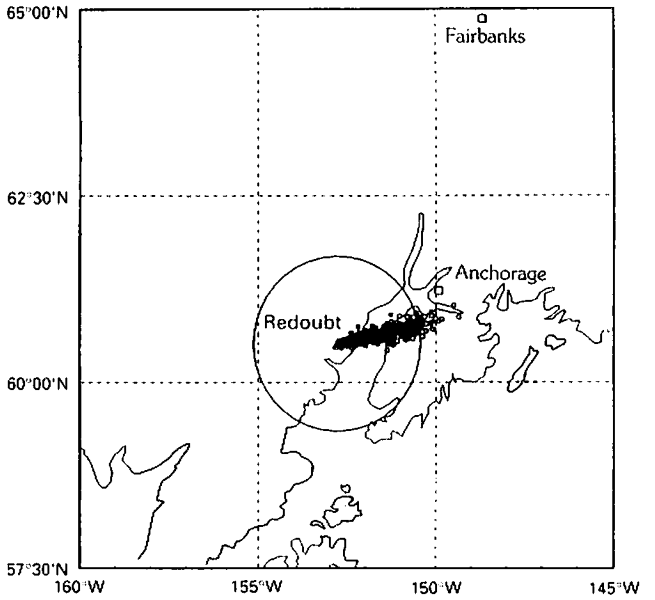

Figure 6. Simulated geographical distribution of particles from a steady plume for eruption of Redoubt Volcano, which started at 10:00 UTC, December 16, 1989. Illustration shows the model result at 12:30 UTC. Open circles, particles higher than 1,800 ft; solid circles, particles lower than 1,800 ft.

the Kenai Peninsula at 21:00 (fig. 8*B*). The cloud traveled over the Kenai Peninsula, indicating north-south elongation at 22:00 UTC (fig. 8*C*). A witness report describes that a dense volcanic ash cloud passed the western shore of the Kenai Peninsula at this time (Brantley, 1990), and, in downtown Soldotna, day time turned into darkness during the passage of the dense ash cloud. At 23:00, the northern edge of the elongated cloud reached just the south of Anchorage, and the southern edge of the cloud passed the Alaska coastline (fig. 8*D*). The simulation results are compared with a satellite image at 23:13 (fig. 9), which clearly shows a linear plume extending from the northern Kenai Peninsula to the Pacific coast near Seward. The satellite observation agrees well with the model simulation.

The graphic outputs (fig. 8) are stored in computer memory, which is connected with other systems through computer networks. The final stage of plume prediction is to distribute the graphic product to various users, including the Federal Aviation Administration (FAA), the National Weather Service (NWS), and the response center of the Alaska Volcano Observatory in Anchorage. In principle, any system connected with the ethernet electronic mail network can receive the graphic product through the network, and users in Anchorage can access the graphic product by telephone modem. For users without any computer facility, the graphic product is distributed by telephone facsimile.

This study demonstrates that the prediction model can provide useful information when it is applied for a real eruption. We have repeated similar demonstrations for each of the eruptions of Redoubt Volcano in 1989–90 and for Mt. Spurr in 1992. The results are compared with available satellite observations in order to increase the reliability of the prediction model. The model output will be especially useful when Cook Inlet is covered by dense cloud when neither satellite observations nor pilot's visual reports are available.

SUMMARY AND REMARKS

A volcanic plume prediction model has been developed for Cook Inlet volcanoes in Alaska. Reading the real-time upper-air data provided by NMC via Unidata, the prediction model computes advection, diffusion, and gravitational settling for plume particles released from the vertical column over the volcano. Three-dimensional distributions of the simulated plume particles are displayed on computerized graphic display. Hence, we can have important information on the predicted location of the ash plume in a real-time basis.

The model predictions, showing the projected geographical location of the plume clouds for several hours after the eruption, can appear on the computer screen about 15 minutes after eruption reports are received. This prediction is immediately available for users through existing computer networks. The graphical model output is distributed to related organizations using ordinary telephone facsimile. The present model simulation will have forecast errors owing, in part, to the errors in the forecast wind input.

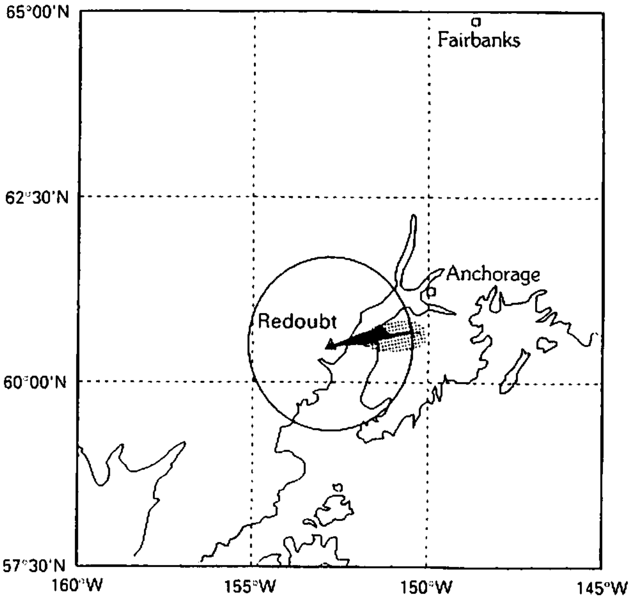

Figure 7. Sketch of satellite image of the steady plume at 12:18 UTC, December 16, 1989, derived by analysis of NOAA-11 data. Figure has been scaled to permit comparison with figure 6. Black area shows dense core of the ash cloud. Stippled area shows diffuse margin of the ash cloud (Kienle and others, 1990).

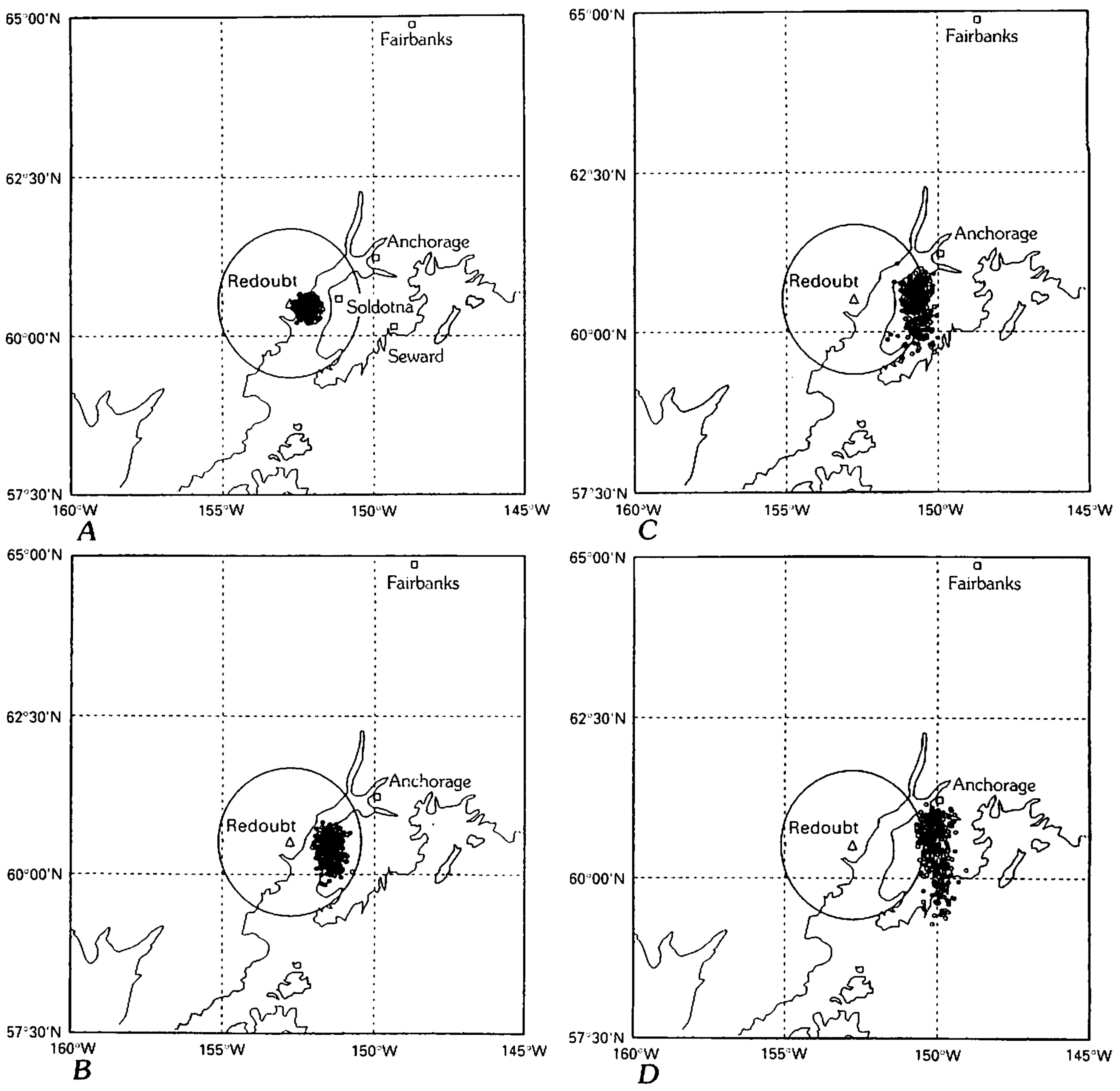

Figure 8. Simulated geographical distribution of a puff plume for the eruption of Redoubt Volcano on January 8, 1990, at 19:09 UTC. Model results are shown for *A*, 20:00 UTC; *B*, 21:00 UTC; *C*, 22:00 UTC; *D*, 23:00 UTC.

According to the latest statistics, upper-air wind has about 8 m/s root-mean-square (RMS) error on average for the Northern Hemisphere (Kalnay and others, 1990). Nevertheless, the prediction product, knowing the possible prediction errors, can offer a useful guide for public safety. The use of gridded data from a finer mesh weather prediction model would improve the advection computation. Because the NMC gridded data used in this project cover the whole globe, this prediction model can be applied for other volcanoes around the world.

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