Realtime Prediction System of Forest-Fire Smoke using Satellite Data and the PUFF Model

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1. INTRODUCTION

Natural and human-induced wildfires in the circum-polar region draws increasing attention in recent years in relation to the global carbon cycle. When a wildfire breaks up, the boreal forest becomes a large source of carbon dioxide rather than a sink of it. Therefore, the total area of the fire, the frequency, and the total amount of burned biomass are the great concern for the study of the global warming.

The realtime monitoring of the wildfire is also an important subject for the material transport of CO2 and aerosols. The realtime tracking of the smoke is now possible using the satellite data over the circum-polar region. Knowing where the burning wildfire is and where the fire smoke will go is an important information for the operational fire control as well as the public safety near the wildfire.

Recently, we have successfully modified the PUFF model for the purpose of the wildfire smoke prediction. The PUFF model is a realtime volcanic ash plume tracking model, developed for the purpose of realtime aviation safety in northeastern Pacific rim including Alaska volcanos, and is operational at the Japan Airlines (Akasofu and Tanaka 1993; Tanaka 1994; Tanaka et al. 2004).

The purpose of this study is to describe the realtime prediction system for the dispersal of the wildfire smoke coupled with the satellite images provided as the ground truth of the smoke. The smoke tracking model was applied to the actual fire event occurred in the Far East in May, 2003. The simulation results are presented with the NOAA satellite images at the International Review Meeting for the Arctic Climate Research at Sendai Japan for 15 to 17 March 2004. This report describes the result of the numerical simulation by the PUFF model.

2. PUFF MODEL AND DATA

The PUFF model was constructed in 1991 for the volcanic plume prediction and reported in detail by Tanaka (1994) and Searcy et al. (1998) as an application of pollutant dispersion models. The model is based on the three-dimensional (3-D) Lagrangian form of the transport-diffusion equation. In the Lagrangian framework, a realization of the stochastic process of plume particles may be described by a random walk process (e.g., Chatfield, 1975). Here, the diffusion is simulated by a sufficiently large number of random variables $r_i(t)$, $i = 1 \sim M$, representing position vectors of M particles from the source S of the wildfire. The diffusion is superimposed on convective transport and gravitational fallout. Refer to Tanaka et al. (2004) for the detail.

With a discrete time increment Δt (= 5 minutes), the Lagrangian form of the governing equation may be written as

$$\begin{cases} r_i(0) = S, \qquad for \quad t = 0, \\ r_i(t+\Delta t) = r_i(t) + V\Delta t + D\Delta t + G\Delta t, \\ \qquad for \quad t > 0, \quad i = 1 \sim M \end{cases} \tag{1}$$

Figure 1: NOAA satellite image of the wildfire in the Far East on May 23, 2004. The red spots marked by a circle are the locations of actual fire used for the numerical simulation of the PUFF model.

where $r_i(t)$ is a position vector of an i-th particle at time t, V is the local wind velocity to transport the particle, D is a vector containing three Gaussian random numbers for diffusion, and G is the gravitational fallout speed approximated by Stokes Law.

For the computation of convective transport, the wind velocity $V = (u, v, w)$ is obtained from the global Grid Point Values (GPV) provided by Japan Meteorological Agency (JMA). The gridded data are first interpolated in time onto the model's time steps of every 5 minute. A cubic spline method is used to interpolate the wind data from 6 hour interval to the model's time step. Then, the wind velocity at an arbitrary spatial point is evaluated using the 3-D cubic-splines from the nearby gridded data.

The diffusion of the smoke particles $D = (c_h, c_h, c_v)$ is parameterized by the random walk process, where the horizontal and vertical diffusion speeds c_h, c_v may be related to the horizontal and vertical diffusion coefficients K_h, K_v. We have repeated diffusion tests with various values of diffusion coefficients, and the resulting dispersals are compared with satellite images of actual dispersals for several volcanic eruptions in the past (Yamagata, 1993; Tanaka and Yamamoto 2002; Yamamoto 2000). With these diffusion tests, we find that the appropriate horizontal and vertical diffusion coefficients are K_h=150 and K_v=1.5 ($m^2\ s^{-1}$), respectively. Note that the values may be different for different locations and for different weather conditions.

The gravitational settling is based on Stokes Law as a function of the particle size r. The fallout velocity $G = (0, 0, -v_t)$ is approximated by the terminal speed v_t of plume particles. The actual smoke contains different size of particles around 1 μm. We have assumed that the initial particle size distribution obeys a logarithmic Gaussian distribution centered at 1 μm with its standard deviation 0.5. Thus, about 95% of particles are supposed to have their size between 0.1 μm and 10 μm.

Sufficiently large number of particles are released within the initial vertical column above the area of the wildfire. We assume a circle with the radius of 100 km. During the 5 min of a time step, the particles are released constantly in time from the source area in the model. A simple buoyancy model is considered with initial upward motion w_0 and a constant damping rate λ (=1/60s). When the equilibrium top height z_2 is given, the initial speed w_0 may be evaluated from z_2, and the vertical smoke distribution z may be calculated for a given time t. Random numbers are generated uniformly in time t for the time step of 5 min, which produces dense smoke particles near the top of the smoke. We set z_2=2000 m in this study based on a Lidar observation in Japan. The gravitational fallout and convective transport during the 5 min are calculated for a given time t superimposed on the vertical distribution to generate the smoke source $S = (x, y, z)$.

The wildfire continues for certain period of time. The model generates new particles over the same vertical column for every time step during the specified period. For a steady case, the particle number tends to increase in the model atmosphere before the particles have

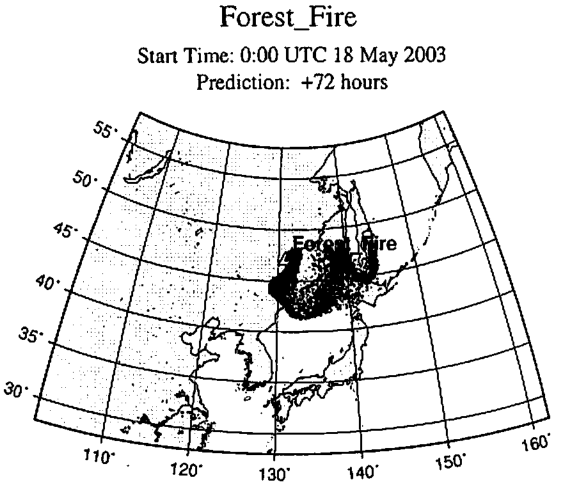

Figure 2: Distribution of smoke on 21 May 2003.

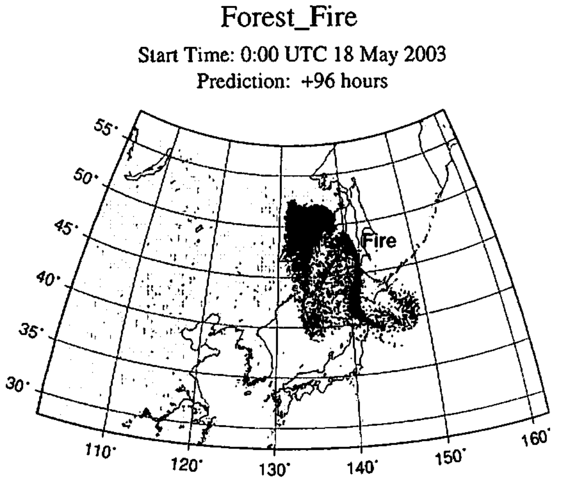

Figure 3: Distribution of smoke on 22 May 2003.

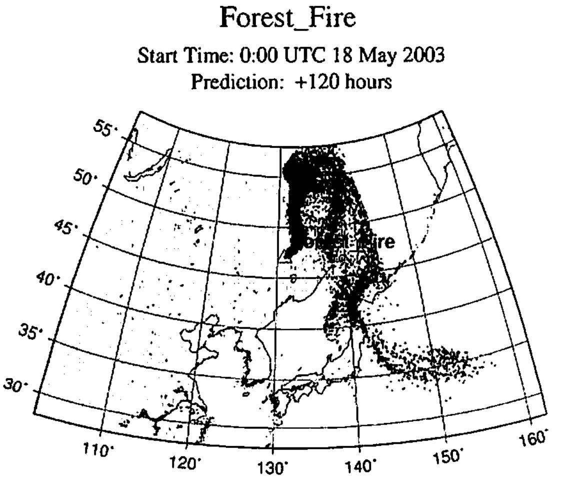

Figure 4: Distribution of smoke on 23 May 2003.

dropped or crossed the vertical wall of the model domain. Therefore, the number of particles released at every time step is adjusted in order to draw optimal statistical information from the model products. For this reason, we set the number of the particles released for a time step as 10 in this study. Although it is possible to increase the number toward the limit of the computer capability, the time integration will then be considerably slower, which is a disadvantage for the urgent case. An excessive complication and sophistication are not recommended in the application to the realtime operational prediction.

3. FOREST FIRE IN MAY 2003

The year of 2003 appeared to be the worst year in that the wildfire in Siberia was the record widest in the history. Recent warming in Siberia results in recent tendency of drying which creates a positive feed back for the wildfire and global warming.

Figure 1 illustrates the NOAA satellite image of the wildfire in the Far East on May 23, 2003. The red spots marked by a circle near the Lake Khanka at the Far East (131°E, 47°N) is the area of actual fire. Since the fire is mostly hidden by ordinary clouds, this fire was not detected until the PUFF model simulation speculated that the fire smoke must come from this area.

Figures 2 to 4 illustrates the model simulation of the forest-fire smoke from the Lake Khanka on 21, 22, and 23 May, respectively, started from 18 May based on the NOAA image in Fig. 1. After three days of the model run, the smoke front reaches Sapporo on 21 May by the northerly wind blowing over Sakhalin. On 22 May, a dense smoke travels to Ryori Observatory in Iwate Prefecture and Sendai in Miyagi Prefecture. On 23 May, the smoke near the source now travels toward north. A stretched smoke area extends from the Sea of Okhotsk to the Pacific across the northern Japan. We are convinced that the red sun at Sapporo reported by several news papers is brought by the wildfire near the Lake Khanka.

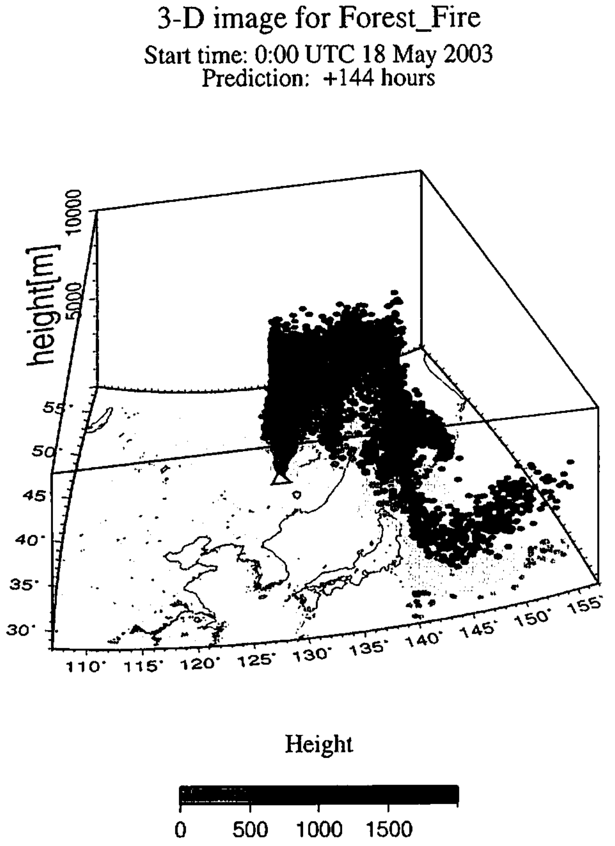

Figure 5: The 3-D perspective image of the fire smoke on 24 May 2003 started from 18 May 2003. Particles in different heights are designated by different colors, and the shadow represents the projection onto the ground.

Figure 5 shows the 3-D perspective image of the smoke on 24 May 2003 with the shadow representing the projection onto the ground. The PUFF model is capable of viewing the particle distribution from any angle. The smoke particles over the Ryori Observatory in Iwate Prefecture show the smoke height about 3000 m as observed by Lidar vertical sounding.

5. CONCLUSION

Dense aerosols were observed in the northern Japan on 23 May 2003. Yet, there was no information where the aerosols came from although it is likely to be the smoke from wildfire somewhere in Siberia.

The result in this study demonstrates that the wildfire smoke observed in northern Japan came from the wildfire near the Lake Khanka at the Far East (131°E, 47°N) released around May 18, 2004. There was a huge wildfire near the Lake Baykal reported spontaneously by the NOAA satellite. However, it is found by the PUFF model simulation that the smoke from the Lake Baykal can not reach to Japan by the upper air wind condition.

As demonstrated by this report, the realtime PUFF model simulation of the wildfire smoke is useful for the operational fire control as well as the public safety near the wildfire. We plan to accumulate the simulation experiments for many fire events compared with many satellite observations in order to increase the credibility of the PUFF model.

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