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Automated forecasting of volcanic ash dispersion utilizing Virtual Globes

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Abstract There are over 100 active volcanoes in the North Pacific (NOPAC) region, most of which are located in sparsely populated areas. Dispersion models play an important role in forecasting the movement of volcanic ash clouds by complementing both remote sensing data and visual observations from the ground and aircraft. Puff is a three-dimensional dispersion model, primarily designed for forecasting volcanic ash dispersion, used by the Alaska Volcano Observatory and other agencies. Since early 2007, the model is in an automated mode to predict the movement of airborne volcanic ash at multiple elevated alert status volcanoes worldwide to provide immediate information when an eruption occurs. Twelve of the predictions are within the NOPAC region, nine more within the southern section of the Pacific ring of fire and the others are in Europe and the Caribbean. Model forecasts are made for initial ash plumes ranging from 4 to 20 km altitude above sea level and for a 24-h forecast period. This information is made available via the Puff model website. Model results can be displayed in Virtual Globes for three-dimensional visualization. Here, we show operational Puff predictions in two and three-dimensions in Google Earth®, both as iso-surfaces and particles, and study past eruptions to illustrate the capabilities that the Virtual Globes can provide. In addition, we show the opportunity that Google Maps® provides in displaying Puff operational predictions via an application programming web interface and how radiosonde data (vertical soundings) and numerical weather prediction vertical profiles can be displayed in Virtual Globes for assisting in estimating ash cloud heights.

Keywords Puff · Volcanic ash · Dispersion modelling and Virtual Globes

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Abbreviations

AFWA	Airforce Weather Agency
API	Application programming interface
ARSC	Arctic Region Supercomputing Center
ASL	Above sea level
AVHRR	Advanced very high resolution radiometer
AVN-GFS	Aviation model-global forecast system
AVO	Alaska Volcano Observatory
CanERM	Canadian emergency response model
DEM	Digital elevation model
GOES	Geostationary operational environmental satellite
HYSPLIT	Hybrid single-particle Lagrangian integrated trajectories
KVERT	Kamchatka Volcano Emergency Response Team
KML	Keyhole markup language
KMZ	Keyhole markup language zipped
MODIS	Moderate resolution imaging spectroradiometer
NAM	North American mesoscale model
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NOGAPS	Navy Operational Global Atmospheric Prediction System
NOPAC	North Pacific
NWP	Numerical weather prediction
NWS	National Weather Service
OMI	Ozone monitoring instrument
®	Registered trademark
UAF	University of Alaska Fairbanks
UMBC	University of Maryland – Baltimore County
USGS	United States Geological Survey
UTC	Coordinated universal time
VAAC	Volcanic Ash Advisory Centre
VATD	Volcanic ash transport and dispersion
WRF	Weather research and forecast

1 Introduction

There are numerous active volcanoes in the North Pacific (NOPAC) region, Fig. 1, most of which are located in uninhabited areas along the Aleutian Islands and Kamchatkan Peninsula, Russia, extending into the Kurile Islands. The region is remote and vast (5,000 km by 2,500 km) but sparsely populated. Some of these volcanoes erupt explosively, as frequently as several times per year, and have the capability of sending ash and aerosols up to altitudes greater than 10 km into air traffic routes, such as those in Fig. 1. From 1975–2006, there were well over 200 separate volcanic ash clouds reaching at least 6 km (20,000 ft) potentially jeopardizing aircraft safety (Webley et al. 2008a). Tracking and understanding the dispersion of young volcanic ash clouds is crucial because ash concentrations are at a maximum at the early stages of eruption (Rose et al. 1995). Ash clouds can cause severe damage to jet aircraft engines, fuel lines, abrade internal and external surfaces and shut down major airports (Blong 1984; Casadevall 1993; Casadevall and Krohn 1995; Miller and Casadevall 2000).

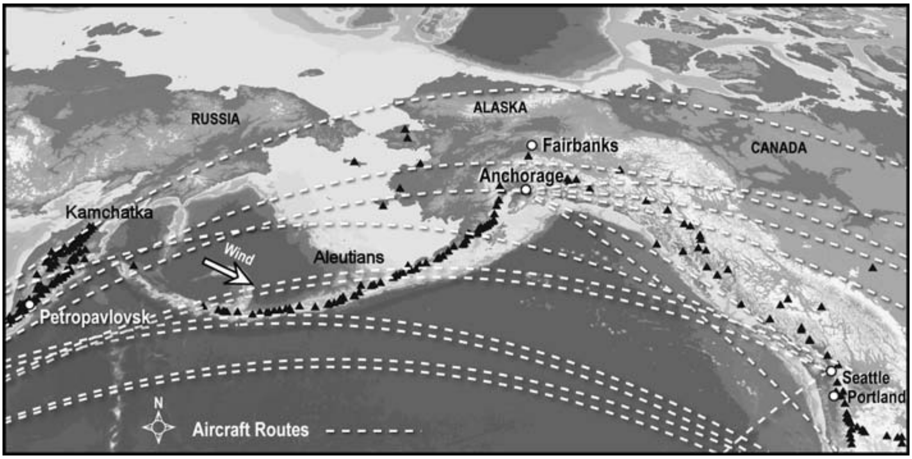

Fig. 1 Geographical map of the North Pacific (NOPAC) Region indicating the primary intercontinental flight routes (from Dean et al. 2008). The arrow represents the prevailing wind direction in the NOPAC region

Prior to, and in the initial stages of volcanic eruptions, volcanic ash transport and dispersion (VATD) models are invaluable in predicting the movement of volcanic ash clouds and ensuring aviation safety. Until visual or ground observations are available, VATD models provide the best quantitative means to predict the ash cloud trajectory. In addition, they complement remote sensing data and visual observations from the ground and aircraft, while providing unique information that is otherwise difficult or impossible to collect from these other data sources. There are three models often used for forecasting ash cloud motion in the NOPAC region: Canadian emergency response model (CanERM, Servranckx et al. 1996), Hybrid single-particle Lagrangian integrated trajectories (HYSPLIT, Draxler and Hess 1997, 1998) and Puff (Searcy et al. 1998). CanERM is the operational transport-dispersion model used for environmental emergency response at the Canadian Meteorological Centre (CMC). CanERM is a fully three-dimensional Eulerian grid model for medium and long range transport of pollutants in the atmosphere (Peterson et al. 2008). HYSPLIT, initially developed at NOAA Air Resources Laboratory, supports a wide range of simulations related to the transport, dispersion and deposition of substances in the air such as volcanic ash or radioactive species as well as dust storms (Draxler et al. 2001). Puff is primarily focused on forecasting volcanic ash transport and dispersion. Here, we show how the Puff model has been used to assist the Alaska Volcano Observatory (AVO) and agencies in NOPAC region for volcanic ash cloud predictions. Peterson et al. (2008) provide an interesting discussion and model comparison for the VATDs in the NOPAC and Witham et al. (2007) provide a model comparison for those used worldwide by the Volcanic Ash Advisory Centers (VAAC's) for Grimsvotn volcano.

2 The Puff model

Puff was developed into a powerful research and operational tool at the University of Alaska, Fairbanks (UAF), based on a model conceived by Dr. H. Tanaka at the University of Tsukuba (Searcy et al. 1998). Puff is a Lagrangian model that uses an adjustable number of tracer particles to represent a volcanic ash cloud. Model simulations place hypothetical particles above a selected volcano, release them into a gridded wind field and calculate their movement. For volcanic predictions, required eruption source parameters include start time, length of eruption, plume altitude, plume shape, particle size and duration of model prediction. Start time, eruption length and plume altitude are assumed from a default dataset unless there is information available from seismic monitoring or observations. Low altitude plumes commonly are linearly distributed, while more powerful events begin with some type of "umbrella" shape with a higher concentration of particles near the top (Peterson et al. 2008). Current numerical weather prediction (NWP) model forecasts are used for operational predictions and global reanalysis data sets are used for post-eruption simulations. The wind field model data are on a regular three-dimensional grid and are used to define the advective term (Table 1).

GFS, NAM, NOGAPS and WRF are all NWP data sets that are available for use with Puff, and are locally stored with a 1-week archive. Table 1 shows that for the Puff model, both regional and global NWP wind fields are available. For automated predictions, the best spatial resolution model is used. For example, the NAM model would be used for volcanoes in the Aleutian Islands, WRF for those on the Alaska mainland and the AVN-GFS for those volcanoes outside the NOPAC region. The choice of wind field models is an important factor for the Puff model simulations. The high spatial resolution wind fields from the WRF model ($\sim$10 km) would be better at representing the complex low altitude (boundary layer) winds within the Cook Inlet area of Alaska than the 45 km resolution of the NAM model due to the extreme topography. The Puff model will interpolate between each grid point to determine the wind fields in between; and therefore, the improved spatial resolution in the wind field will lead to more representative ash cloud predictions.

For model simulations 1-week or more after an eruption, NCEP reanalysis data is used. In the Puff model, the vertical distribution of the initial tracer particles can be adjusted depending on the strength of the eruption along with the number of particles and their vertical distribution as either linear, poisson or exponential. Particle size is specified using either a normal distribution with an adjustable mean value or user-specified φ-distribution. Tracer particle distributions can be displayed by height or concentration, and fallout by relative or absolute concentration. Relative ash concentration can be calculated on an adjustable grid and absolute values are possible if the total eruption mass or volume is known. Optional map projections include Polar Stereographic, Mercator or Lambert. Multiple eruptions can be tracked at the same time. There is no inherent limit to the number of events that can be simultaneously tracked (Peterson et al. 2008).

Table 1 Gridded wind-fields used by the Puff model in the NOPAC region

Wind field	Cell size	Max altitude (km)	Region
AVN-GFS	1.25 × 1.25°	20	Global
NOGAPS	1 × 1°	34	Global
NAM 216	45 × 45 km	22	Regional
WRF	10 × 10 km	16	Regional
Reanalysis	2.5 × 2.5°	34	Global

AVN-GFS: Aviation model, now known as the GFS (Global Forecast System) model from National Centers for Environmental Prediction (NCEP), NOGAPS: Navy Operational Global Atmospheric Prediction System, NAM: North American Mesoscale Model and WRF: Weather Research and Forecast Model (derivative of Mesoscale Model v.5; adapted from Peterson et al. 2008)

The Puff model has been used as a VATD model for numerous volcanic eruptions in the North Pacific. Searcy et al. (1998) demonstrated the accuracy of the model by comparing predictions to satellite images of the eruptions at Mount Spurr in 1992 and Kliuchevskoi Volcano in 1994. Dean et al. (2002) accurately predicted the movement of the ash cloud from the Cleveland Volcano 2001 eruption and Aloisi et al. (2002) used the model to analyze the ash cloud from the Mount Etna July 1998 eruption. Papp et al. (2005) investigated the probability of ash at aircraft cruising altitudes in the NOPAC based on multiple, hypothetical eruptions over several years. Peterson et al. (2008) compared model predictions from Puff, HYSPLIT and CaNERM for selected eruptions in the North Pacific. Webley et al. (2008b) used the model during the 2006 eruption of Augustine volcano. Recently, Webley et al. (2008c) and Sassen et al. (2007) showed how Puff model predictions were used to initiate Lidar measurements to validate the model predictions during the eruption of Augustine Volcano in 2006. The model is now used at AVO, United States National Weather Service (NWS), Anchorage VAAC, Washington VAAC, Airforce Weather Agency (AFWA), and other national agencies and universities world-wide, such as the Kamchatka Volcano Emergency Response Team (KVERT) in North Eastern Russia. AVO is a joint program of the United States Geological Survey (USGS), the Geophysical Institute of the UAF and the State of Alaska Division of Geological and Geophysical Surveys.

3 Puff online and automated operational forecasts

Recent developments have begun to dramatically expand the capabilities of the Puff model. For example, the recently developed multiple eruption capability provided critical information regarding ash location during the January 2006 eruption of Augustine volcano when it simultaneously tracked the movement of six volcanic clouds across the Gulf of Alaska (Webley et al. 2008b). The Puff model can be installed and run locally or simulations can be performed using the online interface. The Puff website, http://puff.images.alaska.edu, provides access to the online interface, as well as the automated predictions, with an option allowing users to display their results within Google Earth® (http://earth.google.com). There are several source parameters that can be specified for each eruption, such as eruption length, initial plume shape, size, width and height, initialization wind model, start time and length of simulation. These can all be defined through the online interface and are pre-defined for the automated predictions. The Puff model can be run with or without a digital elevation model (DEM) to define the ground surface elevation. The use of a DEM can significantly affect the forecast results, which is important for accurately tracking low altitude ash clouds and predicting ashfall. Without a DEM, all elevations are assumed to be sea level. To properly represent the ashfall on the local topography, a DEM is required. The results can be displayed on two-dimensional maps using different geographical projections, varying altitude ranges and geographical domain of interest as well as a three-dimensional ash cloud within Google Earth®. To assist in hazard mitigation, automated volcanic ash-cloud forecasts were developed for volcanoes at elevated alert within the NOPAC region. The Darwin VAAC, the Montserrat Volcano Observatory, the Instituto Geofisico in Ecuador and the Istituto Nazionale di Geofisica e Vulcanologia in Italy have requested automated runs for alert volcanoes in their regions as well. As a result, volcanoes outside the NOPAC region, such as Sangay, Tungurahua, Manam, Kelut, Etna, Stromboli, Reventador and Soufriere Hills to name a few, have been added to the automated Puff monitoring.

Automated VATD model simulations predict the location of a potential volcanic ash cloud, 24 h a day. When a volcano erupts, the first minutes are the most critical and automated VATD runs provide immediate predictions on the movement of the ash. This assessment provides the first indication of the potential area at risk from the eruption plume. Once more information is available on the eruption plume characteristics, such as height and start time, the Puff model can be re-run by updating the input parameters with the new information. This simulation can be compared to satellite remote sensing data, pilot reports and/or ground observations for verification when they are received. The automated Puff model predictions are generated every 3 hr for the NOPAC region and every 6 hr for other regions. Predictions are made for initial maximum plume heights ranging from 4 to 20 km ASL and for a 24-h forecast period. The information displayed on the Puff website will automatically update after each new model prediction. These forecasts are for potential eruptions and are used as a first assessment of the ash cloud's movement.

4 Virtual Globes

Virtual Globes, like Google Earth®, have become widely used for visualization in the scientific environment and they have become a tool for displaying three-dimensional geophysical data both operationally and retrospectively. In the recent past, Puff forecasts have been displayed as two-dimensional maps of ash location, colour coded by altitude and/or relative ash concentration. This is a useful tool for operational analysis but does not take full advantage of the three-dimensional nature of the data. Google Earth® is one of the many Virtual Globes available. Here, we show how we have used the Google Maps® application programming interface (API) [http://maps.google.com/] to centralize all the Puff model runs for the NOPAC region and how Google Earth® can be used to display VATD simulations in both two and three dimensions.

4.1 Google Maps and Puff predictions

Google Maps® provide a centralized interface that can be used to display the Puff model predictions for tracking potential ash clouds from the worldwide volcanoes. Through the Google Maps® API, a geographical map is embedded into a web browser, with a predefined area as the default region of interest. The API was added to the Puff website in 2007 and has been developed further since its initial installation. To access the Puff predictions, the user first selects the volcano icon and a 'text box' will appear identifying the volcano. Choosing the volcano icon again will result in a new 'text balloon' including the most recent Puff model forecast for a potential eruption, as shown for Shiveluch volcano in Kamchatka in Fig. 2. Because the Puff model is used to track potential eruptions from 21 volcanoes for plume heights from 4–16 km ASL and every 6 hr, Google Maps® has provided a useful centralized location for all the automated Puff model predictions. The results from any Puff model simulation/prediction is a three-dimensional data set of ash particle locations. Virtual Globes, such as Google Earth®, support the display of these results in three dimensions.

4.2 Puff simulations displayed in Google Earth

The Puff model is being used for (1) automated predictions, (2) during eruption response for actual eruption clouds, Webley et al. (2008a) for the Augustine 2006 eruption and

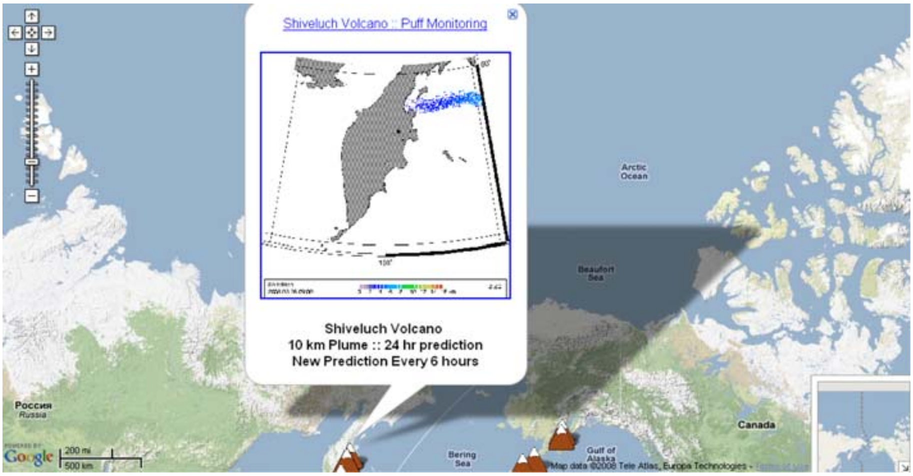

Fig. 2 Puff-Google Maps® API interface and automated Puff predictions of a potential eruption at Shiveluch volcano

(3) for post-event analysis, such as Dean et al. (2002) for Mount Cleveland's 2001 eruption. Virtual Globes, such as Google Earth®, allow all three forms of Puff model results to be displayed in their three-dimensional form. In addition, the two-dimensional maps of airborne ash cloud movement and ashfall, colour coded by altitude, can be displayed easily within Google Earth®. In this section, we illustrate how the automated predictions are displayed, how images can be displayed as overlays, how virtual globes are used for illustrating ashfall predictions and we show simulations from the 2006 Rabual eruption and a post-event analysis for the 1980 Mount St Helens eruptions.

For the automated predictions, the Puff model provides information on the ash clouds location every hour for a 24 h time period. The automated model predictions include information on the eruption source parameters, Fig. 3a, two-dimensional maps of the ash clouds location, Fig. 3b, and three-dimensional ash clouds, Fig. 3c and d. Within Google Earth®, each volcanic ash particle is defined by a separate placemarker, where a semi-transparent image represents the ash particle. A placemarker is a point within Google Earth®, with an associated latitude, longitude and altitude. For each model time interval, there is a placemarker for each ash particle which combine to represent the ash cloud's location and shape, Fig. 3c. Using the 'animation' options within Google Earth®, the model forecasts can be 'time stamped'. That is, for each time interval, the data is provided in a Google Earth® kmz file, which when displayed together show the location of ash clouds and movement as an animation. A KMZ file is a KML zipped format that allows the geographical information and ash images to be stored together. More information on KMZ files and the KML format types can be found at http://code.google.com/apis/kml/documentation/.

For the two-dimensional maps of ash colour coded by altitude, Google Earth® can be used to display these as static images or as 'time stamped' datasets. Figure 3a shows the airborne ash image overlay, colour coded by altitude, for Augustine volcanoes continuous eruptive period at the end of January 2006. Power et al. (2006) provide a description of the 2006 Augustine eruption, Webley et al. (2008b) provide a detailed description of the use of the models during the eruption response and Wallace et al. (2008) provide a description of the ashfall during the Augustine eruption, such as ashfall at Kodiak City (shown in Fig. 4)

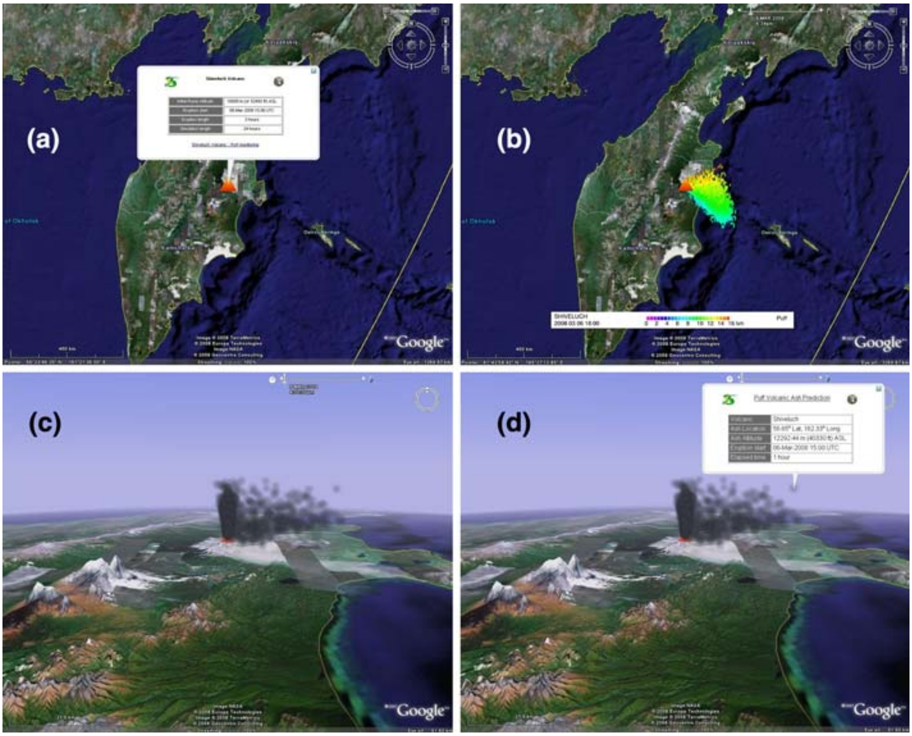

Fig. 3 Automated Puff model predictions displayed in Google Earth®. (**a**) Eruption source parameters providing start time, plume altitude and simulation length, (**b**) two-dimensional maps of ash, colour coded by altitude, as time stamped overlays, (**c**) three-dimensional ash cloud and (**d**) how, by selecting each ash particle, the user can view its location, volcanic origin, time since eruption start and altitude in km and feet ASL

on 29 January 2006 during the continuous phase. Figure 4b illustrates the Puff-predicted ash deposits colour coded by elevation, south of the volcano illustrating the transparent overlay option, which allows the base topographic imagery to be viewed through the overlay. This option is a very useful tool as the region of predicted ash fallout can then be mapped directly onto any affected populated areas, as highlighted in Fig. 4.

For simulations of past eruptive events, NCEP reanalysis wind fields are used. Figure 5 shows Puff model simulations for the Mount St Helens eruption from 18 May 1980. Here, a 9-h eruption is modelled to represent the plinian phase of the eruption (Christiansen and Peterson 1981) using a plume height of 20 km. The maximum height of the ash cloud did reach higher than 20 km, but the NCEP reanalysis wind field data only has a few model levels above this altitude; therefore, Puff would not be able to resolve the wind fields at significantly higher altitudes. In addition, Harris et al. (1981) show that apart from the initial minutes of the May 18 eruption, the plume height ranged from 16–20 km for the majority of the 9-h event. The Puff model results show the eruption column and ash dispersion to the east of the volcano 2 h after the start of the eruption, (Fig. 5a), with the aerial view (Fig. 5b) showing the horizontal extent of the ash cloud with the local population centers highlighted, which closely matches the mapped airborne ash movement, shown in the insert in Fig. 5b from Sarna-Wojcicki et al. (1981). The insert shows the maximum downwind extent of the airborne ash cloud and is compiled from National Oceanic and Atmospheric Administration (NOAA)

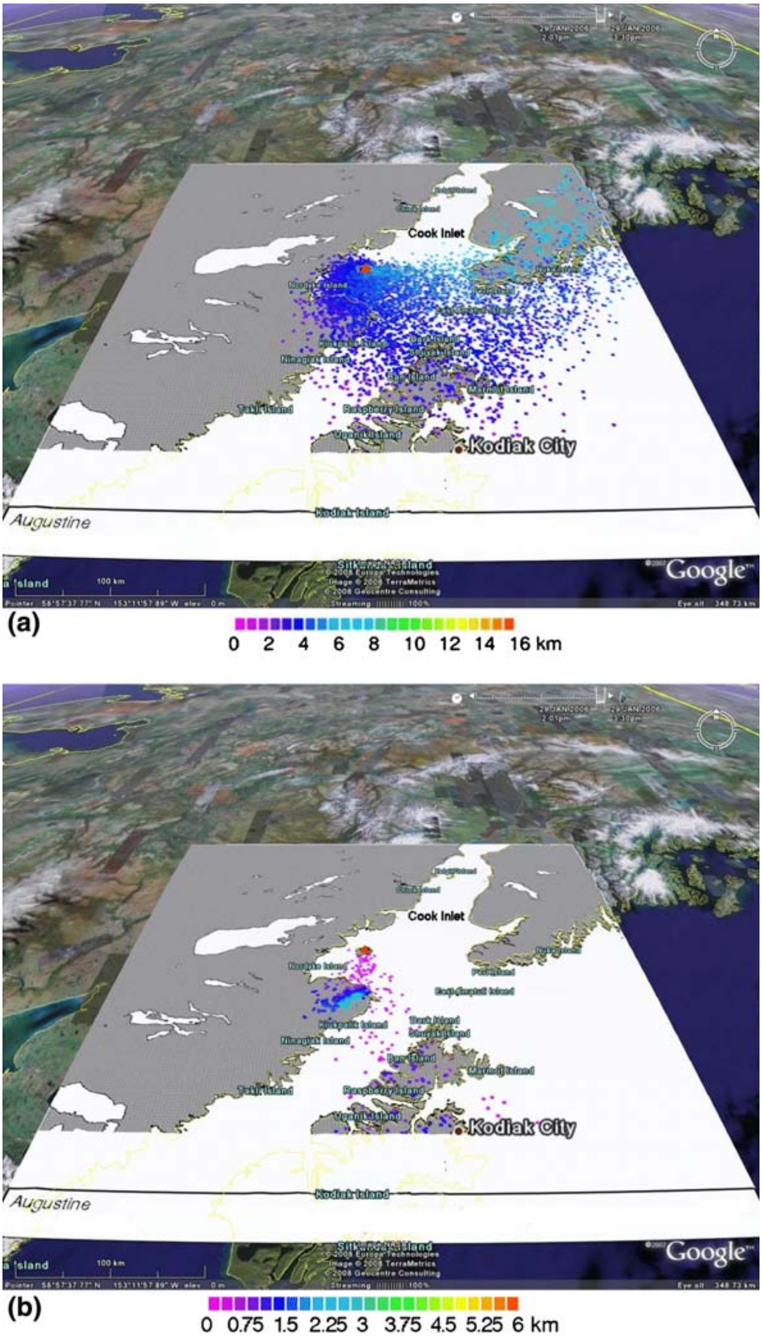

Fig. 4 Oblique view looking north up Cook Inlet showing Puff predictions for an eruption of Mount Augustine (location: red triangle), 28 January 2006. (**a**) Airborne ash colour coded by altitude is moving south of the volcano and (**b**) ash fallout prediction from the drifting cloud on a map as semi-transparent overlay over a Google Earth® image of topography. Altitude scale bars for airborne ash and ashfall are included

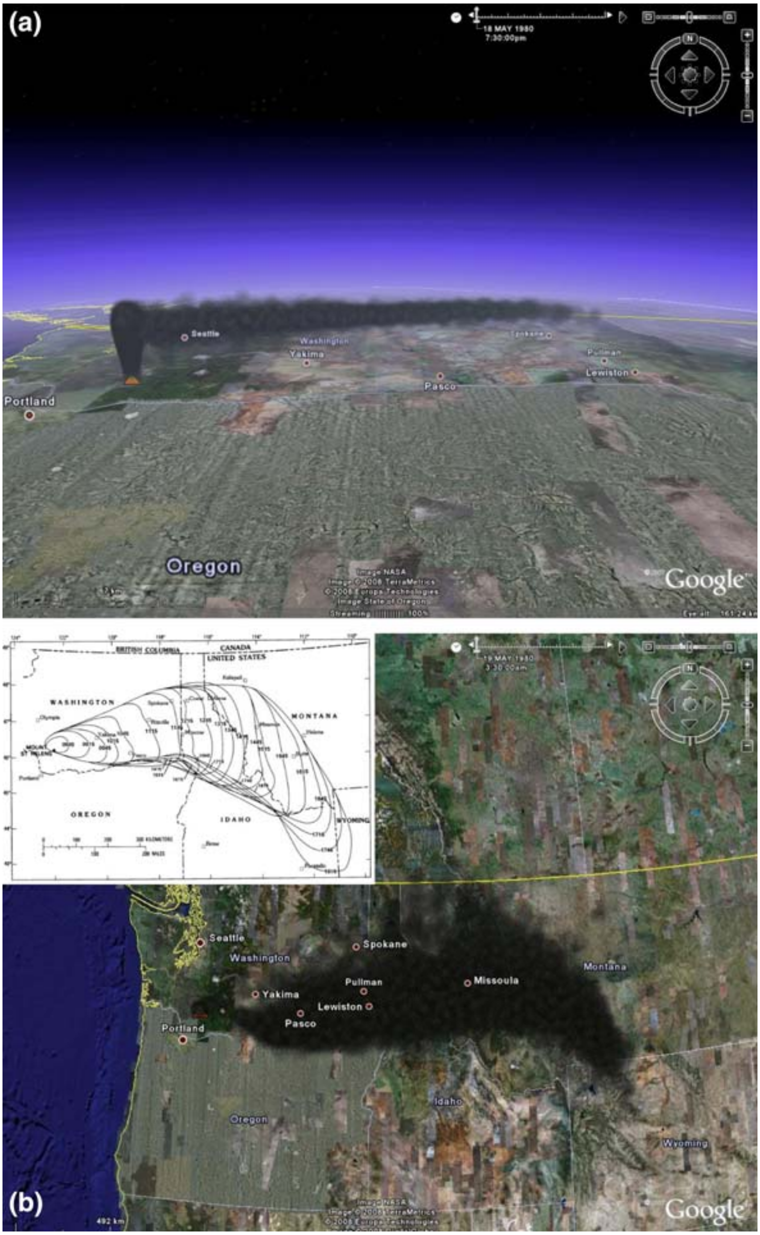

Fig. 5 A three-dimensional Google Earth® view of Puff simulations of Mount St. Helens May 1980 eruption using reanalysis data. (**a**) As the cloud develops and spreads east across northwestern USA and towards Southern Canada and (**b**) aerial view of eruption cloud at 03:35 UTC on 19 May, with the insert from Sarna-Wojcicki et al. (1981) showing the actual maximum airborne distribution

Geostationary Operational Environmental Satellite (GOES) images recorded every 30 min. With Google Earth®, it is easily possible to display the location of the affected population centers, airports and even the timing of ashfall.

Beyond the NOPAC region, correspondence between the Darwin VAAC and AVO-UAF occurred during the Rabaul 7 October 2006 eruption. As a result, Puff model predictions were generated, Fig. 6. Fine tuning of the model initialization parameters was possible once more information was made available on the eruption start time and plume height. Correspondence between AVO and Darwin VAAC provided up to date initialization parameters. Figure 6 shows snapshots of the Puff simulation during 7–9 October 2006. In this example, NCEP reanalysis wind fields were used with a 20-km high ash plume and a 9-h eruption (the latter being the standard default parameter). Figure 6d shows sulphur dioxide (SO_2) images from the Ozone mapping instrument (OMI) instrument during 7–9 October. This data was provided by the University of Maryland – Baltimore

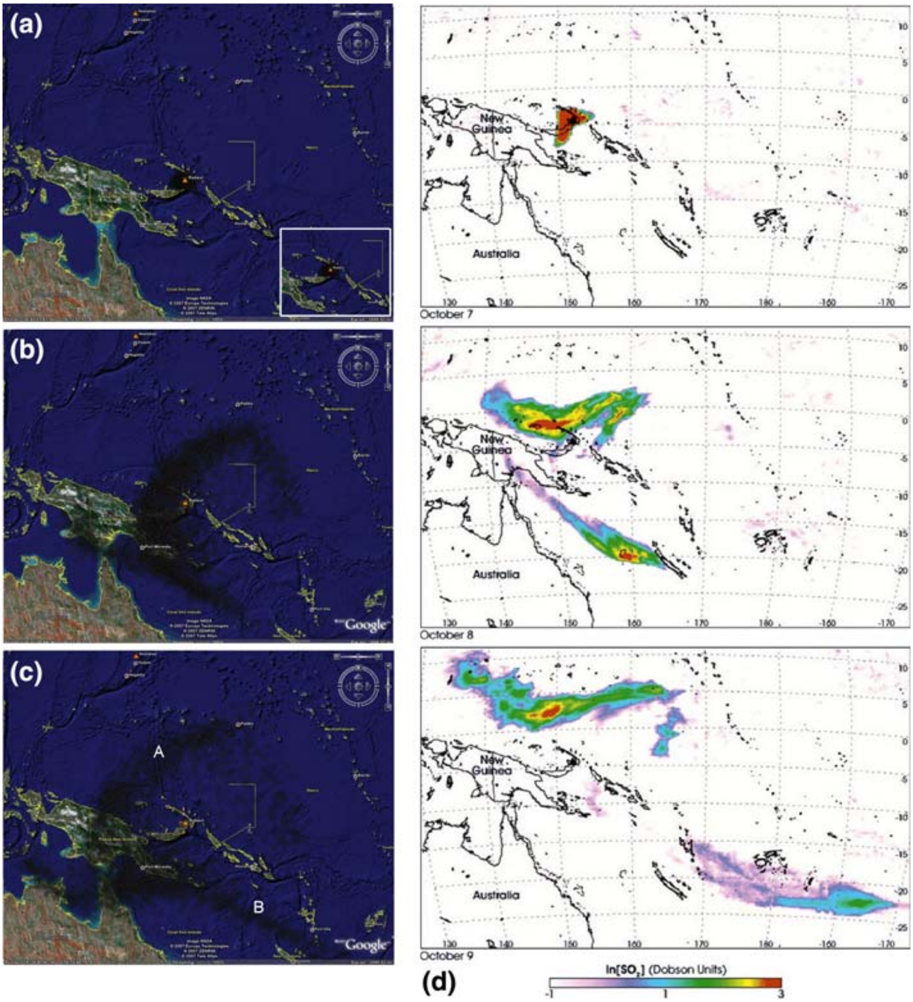

Fig. 6 Puff simulations of Rabual Volcano eruption, 22:45 UTC on 6 October 2006, as displayed in Google Earth®, along with OMI SO_2 data from 7–9 October 2007. (**a**) At 02:00 UTC on 7 October a plan view later as the ash cloud develops, (**b**) at 20:00 UTC on 8 October, (**c**) at 12:00 UTC on 9 October and (**d**) three panels from OMI SO_2 data from 7–9 October. A and B in (**c**) illustrate the location of two clouds seen in OMI SO_2 on 9 October

County (UMBC) sulphur dioxide group (http://so2.umbc.edu/omi). The SO_2 images show a good agreement with the Puff predictions. The OMI data show that by 8 October, the original plume has split into two clouds and by 9 October, these two have moved northwesterly and southeasterly, respectively. Puff indicates a similar movement of the ash cloud and shows the higher concentration of ash particles in the same geographical regions as the OMI data (labelled as A and B in Fig. 6c). OMI data detects the SO_2 component of the volcanic cloud and the Puff model predicts the movement of particles representing the ash component of the cloud. Puff can also be used to track volcanic aerosols, like SO_2. Sometimes, these show an agreement, as seen here. Using this example for Rabaul volcano, we can use the Google Earth® displays to estimate the altitude of the two components of the SO_2 cloud. In Fig. 6c, the ash cloud at location A is below 10 km and the ash cloud at location B is above 10 km. For an example where the ash and SO_2 component of a volcanic cloud did not match, see the El Chichon eruption in 1982 (Schneider et al. 1999). In this example, the ash-rich cloud and SO_2-rich cloud separated as a result of wind shear. The SO_2-rich cloud reached the stratosphere and the ash-rich cloud was transported to the troposphere. In this and other high altitude cases, the Puff model can be used but is limited by the resolution of the NWP wind field data at its upper boundary near the stratosphere.

4.3 Assisting in estimating altitudes of volcanic ash clouds

During operational monitoring, satellite remote sensing data can be used in conjunction with atmospheric temperature profiles (such as from radiosonde data) to estimate the altitude of ash clouds (Holasek et al. 1996). First, the cloud-top temperature is measured using a thermal infrared band in satellite data. Then, this temperature is compared to the radiosonde vertical temperature profile to estimate cloud height, at the altitude where the radiosonde temperature equals the satellite derived temperature. The height estimate of a volcanic cloud often requires the use of radiosonde data that are possibly 100s of km from the volcano and which may not accurately represent the atmospheric temperature profile at the volcano. To solve this problem, atmospheric-temperature-profiles are derived at AVO from NWP model forecast data at any volcano location worldwide. This information can be accessed via the Puff website or through a Google Earth® KML file, as shown in Fig. 7. This shows the NWP model profile for Cleveland volcano and both NWP model and radiosonde profiles at Cold Bay, the nearest radiosonde data profile to the volcano (400 km northeast of the volcano) as placemarkers within Google Earth®. These profiles will automatically update with the most recent profile, every 12 h for the radiosonde data and every 6 h for the atmospheric profile. Therefore, access to this data is possible as soon as it is available, without having to download any data. The match between the NWP model and radiosonde profiles at Cold Bay show the accuracy of the model method for this given period. Good agreement may not always occur, but the profile from the NWP data at Cleveland would generally be an improved representation of the conditions at the volcano over using the Cold Bay radiosonde. Additionally, the radiosonde data updates every 12 h and the NWP profiles every 6 h. This can cause discrepancies between each data set when one compares the 12:00 UTC radiosonde with the 18:00 UTC NWP profile. Further analysis is required to determine the impact this has on cloud height estimates. The profiles from the NWP modelled data are automatically generated for all of the volcanoes in the NOPAC region. These can then be used for plume height estimates and compared with satellite remote sensing data.

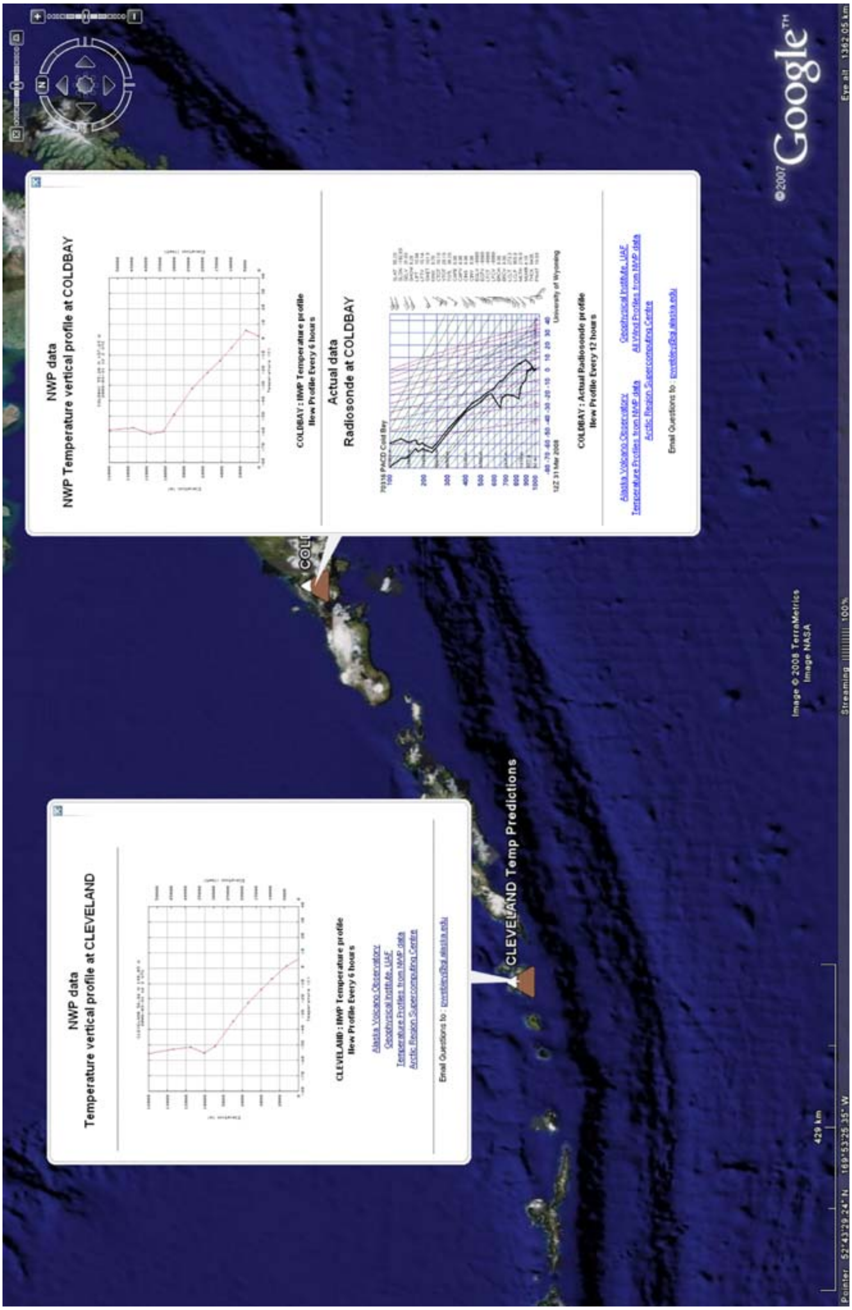

Fig. 7 **(a)** NWP profile for Cleveland volcano and **(b)** radiosonde and NWP profile for Cold Bay Radiosonde station

Figure 8 shows an example of plume height estimates for a volcanic cloud for an eruption at Augustine volcano on 11 January 2006. Figure 8a shows the temperature of the initial opaque plume to be −55°C (blue) in AVHRR satellite data. Here, anything warmer than −40°C is omitted to emphasize the ash cloud's location. Using the closest radiosonde site (Fig. 8b at Anchorage at 12:00 UTC, 2 h before the satellite data was collected, over 250 km from Augustine volcano), the cloud height was determined to be approximately 8.7 km or 30,000 ft ASL. This information is helpful for hazard mitigation and can be useful in assisting in the Puff model initialization parameters, such as plume height, start

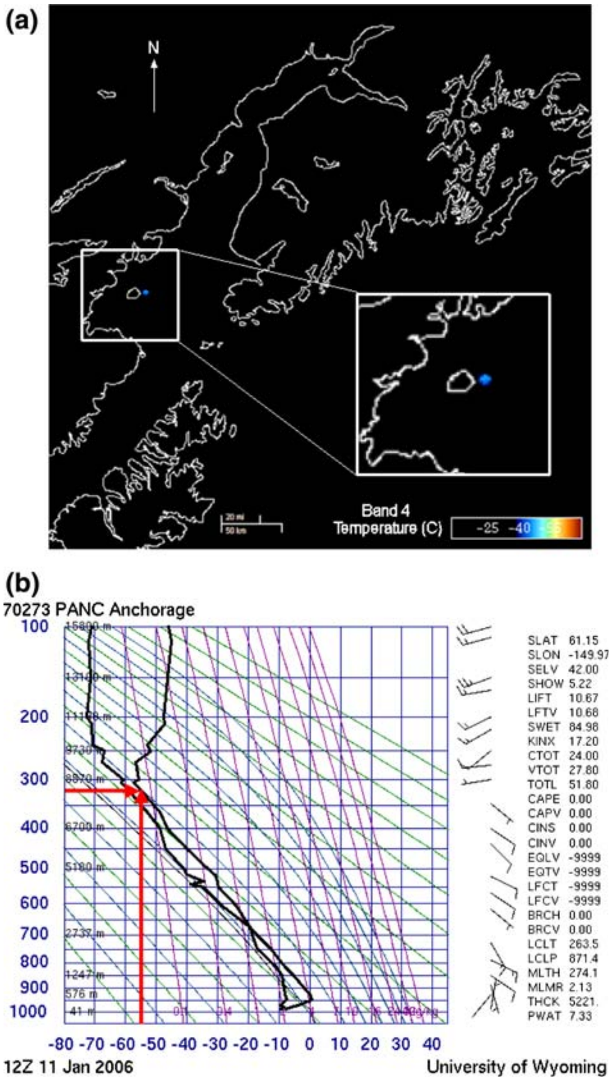

Fig. 8 (**a**) Thermal infrared (band 4) AVHRR image of Mount Augustine 11 January 2006 eruption, with zoomed in insert. The opaque plume (blue) has a temperature of −55°C derived from the satellite image and (**b**) Anchorage radiosonde (12:00 UTC 11 January 2006) from University of Wyoming showing −55°C temperature equates to 8.7 km ASL

time and duration. This technique works for ‘spectrally opaque’ ash clouds, but once an ash cloud is ‘spectrally translucent’, dispersion models, such as Puff, can be used to estimate ash clouds heights based on wind shears. Webley et al. (2008a) provide an example of this for the Augustine volcanoes eruptions in January 2006, where a full column eruption was used. Presently, with the automated runs described in this paper, we have ash columns from different starting heights of 4 to 16 km, which allow rapid assessment for a multitude of eruption plumes. This method of ash cloud detection using radiosonde profiles works well, provided the cloud behaves as a blackbody and the radiosonde profile is representative (Prata and Grant 2001). For high clouds near the tropopause, the method is prone to error because the rate of change of temperature with height is small, which leads to indeterminacy in the height assignment. Here, evidence of wind shear is needed to determine heights (Dean et al. 2004). If the satellite derived cloud top temperatures exist at multiple altitudes in the temperature profile, then the direction of the plume in the satellite data is compared to the wind direction in the profile. Where these match, the radiosondes altitude is used to determine the ash clouds altitude. For VATD models to be used for determination of ash cloud heights, the eruption column height in the model is critical to capture the correct wind direction within the shear.

5 Conclusions

Dispersion model predictions are used by AVO, NWS in Anchorage, AFWA and KVERT to assess the transport and dispersion of volcanic ash clouds. Here, we use the Puff dispersion model to show examples of their use for hazard mitigation and assessment. As the Puff model can be used with global NWP data sets, it is not limited to volcanoes in the NOPAC. Within the NOPAC region, volcanic ash clouds occur regularly (200+ separate events from 1975–2006). This level of activity poses many hazards, especially if data from ground or satellite based platforms are not available to track the movement of the clouds. Volcanic ash transport and dispersion models are used to forecast the movement of these ash clouds and to integrate with the ground-based and satellite-based data for validation when available. Here, we have shown how the Puff model is being used as an early warning prediction tool for potential eruptions and in retrospect to analyze past events. Also, automated atmospheric temperature profiles are generated at each volcano in the NOPAC region to improve the accuracy of plume height estimates. Accurate heights are critical for model predictions and hazard assessments. To assist in operational monitoring, automated Puff model forecasts are being used as ‘first’ assessment of the potential location of eruption clouds. Once more definitive information is available concerning the eruption, such as plume height, eruption duration and an accurate start time, more accurate forecasts of the ash cloud movement can be made.

The application of Virtual Globes has provided an interface to display and assess natural hazards. Here, we use Google Earth® as an example. Google Earth® is used to display Puff model runs in three dimensions and as a geographic frame of reference for the location of ash clouds. In addition, the Google Maps® API provides a centralized interface to the Puff model forecasts and makes the Puff predictions more user friendly. We have shown how both operational predictions and the analysis of past events can be displayed with Google Earth®. Many different datasets can be displayed in Google Earth® at any one time, such as seismic data, geological maps and satellite derived volcanic ash clouds during a volcanic eruption. Within a Virtual Globe, additional information is available at the users’ fingertips, such as the location of the populated areas, airports and road networks. Such information is valuable for hazards assessment during a volcanic crisis. The Virtual Globe interface can then be used to show the data to non-experts, such as students, teachers and the general public, and can be used to provide assistance in eruption crises.

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