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A volcanic activity alert-level system for aviation: review of its development and application in Alaska

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Abstract An alert-level system for communicating volcano hazard information to the aviation industry was devised by the Alaska Volcano Observatory (AVO) during the 1989–1990 eruption of Redoubt Volcano. The system uses a simple, color-coded ranking that focuses on volcanic ash emissions: Green—normal background; Yellow—signs of unrest; Orange—precursory unrest or minor ash eruption; Red—major ash eruption imminent or underway. The color code has been successfully applied on a regional scale in Alaska for a sustained period. During 2002–2011, elevated color codes were assigned by AVO to 13 volcanoes, eight of which erupted; for that decade, one or more Alaskan volcanoes were at Yellow on 67 % of days and at Orange or Red on 12 % of days. As evidence of its utility, the color code system is integrated into procedures of agencies responsible for air-traffic management and aviation meteorology in Alaska. Furthermore, it is endorsed as a key part of globally coordinated protocols established by the International Civil Aviation Organization to provide warnings of ash hazards to aviation worldwide. The color code and accompanying structured message (called a Volcano Observatory Notice for Aviation) comprise an effective early-warning message system according to the United Nations International Strategy for Disaster Reduction. The aviation color code system currently is used in the United States, Russia, New Zealand, Iceland, and partially in the Philippines, Papua New Guinea, and Indonesia. Although there are some barriers to implementation, with continued education and outreach to Volcano Observatories world-wide, greater use of the aviation color code system is achievable.

Keywords Aviation hazards · Hazard warning systems · Volcanic ash hazards

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1 Introduction

The hazard to safe and efficient air travel from airborne volcanic ash is widely recognized, and a global risk mitigation strategy is in place (Casadevall 1994; Miller and Casadevall 2000; Guffanti et al. 2010). Motivated by severely damaging encounters of passenger aircraft with volcanic ash clouds in the early 1980s, the International Civil Aviation Organization (ICAO)[1] established the International Airways Volcano Watch (IAVW) in 1987 as the basis for developing globally coordinated operational procedures to (a) report eruptions that are imminent or underway, (b) detect ash clouds in the atmosphere and forecast their expected movement hours into the future, and (c) issue special warning messages to aviation meteorological offices, airline operation centers, and air-traffic management centers. Together, these actions are aimed at ensuring that flights avoid potentially hazardous airspace (International Civil Aviation Organization 2007).

In this paper, we examine an aspect of aviation risk mitigation related to eruption reporting, specifically the development and use of a color-coded alert-level system to notify the aviation sector of activity at volcanoes. The alert-level system was devised in 1990 by the Alaska Volcano Observatory (AVO)[2] during the 1989–1990 eruption of Redoubt Volcano. A modified version subsequently was adopted by ICAO as the recommended guidance for volcano observatories worldwide, making it the only standardized international volcano alert system currently in effect (Fearnley et al. 2012). With the aim of increasing awareness of the system and establishing its utility, we review its evolution from a local solution to an international standard and analyze its application in the North Pacific where transoceanic air routes carry as many as 20,000 passengers and many millions of dollars of cargo daily over one of the most active volcanic regions of the world.

2 Development of the color code alert-level system for aviation

2.1 Initial development

The aviation color code grew out of the need to communicate more effectively to non-scientists about volcanic activity during the 1989–1990 eruption of Redoubt Volcano in Alaska, USA. Redoubt Volcano, located 180 km southwest of Anchorage on the west side of the Cook Inlet, began its third historical eruption on December 14, 1989 following 21 years of quiescence. The eruption lasted over 6 months as more than 20 major explosions and dome collapses produced volcanic tephra (fragmented particles of solidified magma; also often called "ash") that was deposited over thousands of square kilometers of southcentral Alaska or was dispersed by winds aloft as airborne ash clouds (Miller 1994).

Both aircraft in extended flight mode (at altitudes of ~9 km or more) and those in terminal flight mode (landing or taking off at Anchorage International Airport, a major air cargo and passenger hub) were adversely affected by Redoubt's activity through direct encounters with volcanic ash clouds, cancellations and re-routing of flights, and closure of airports due to ash fall (Casadevall 1994). The most severe aircraft encounter was related

[1] The International Civil Aviation Organization (ICAO) is a specialized agency within the Economic and Social Council of the United Nations charged with coordinating and regulating international air navigation.

[2] The Alaska Volcano Observatory (AVO) is operated jointly by the U.S. Geological Survey, Alaska Division of Geological and Geophysical Surveys, and the University of Alaska Fairbanks Geophysical Institute.

to an explosive event on December 15, 1989 when an ash column reached at least 12 km (~40,000 ft) above sea level (asl) and drifted northeast from the volcano. A Boeing 747–400 passenger jet nearing Anchorage International Airport encountered the ash cloud at ~7.5 km (~25,000 ft) asl, 90 min after the explosion and 280 km northeast of the volcano. About a minute and a half after entry into the ash cloud, all four of the aircraft's jet engines lost thrust power. For a few harrowing minutes, the aircraft fell more than 3.5 km (~12,000 ft) before engines could be restarted, narrowly averting a crash into mountainous terrain. The aircraft limped into Anchorage and landed safely, but it sustained more than $80 million (~$150 million in 2012 dollars) in damages (Tuck and Huskey 1992).

That near-tragic event demonstrated how quickly volcanic activity can imperil aircraft. The need to rapidly and clearly communicate information about volcanic activity to meteorological and aviation authorities and air carriers prompted U.S. Geological Survey (USGS) scientists at AVO to develop a simple alert scheme to describe changing hazards and conditions at the volcano in a manner understandable by non-scientists. The colors Green, Yellow, Orange, and Red were chosen because they represent low-to-high levels of concern that could be grasped quickly and intuitively by a variety of users. Initially, the levels were defined as:

- Green — Volcano is in its normal dormant state (normal seismicity and fumarolic activity is occurring).
- Yellow — Volcano is restless. Seismic activity is elevated. Potential for eruptive activity is increased. A plume of gas and steam may rise several thousand feet above the volcano, which may contain minor amounts of ash.
- Orange — Small ash eruption expected or confirmed. Plume(s) not likely to rise above 25,000 ft asl. Seismic disturbance recorded on local seismic stations, but not recorded at more distant locations.
- Red — Large ash eruptions expected or confirmed. Plume likely to rise above 25,000 ft asl. Strong seismic signal recorded on all local and commonly on more distant stations.

Volcanological details of little significance to decision-making by pilots, dispatchers, and meteorologists were purposely excluded. The plume height threshold of 25,000 ft (7.6 km) in the Orange and Red levels was chosen because most flights in the North Pacific are carried out above that altitude.

Alaska Volcano Observatory (AVO) instituted the Level of Concern Color Code for Redoubt Volcano on February 8, 1990. "Level of Concern" referred to scientists' assessment of the severity of the immediate to near-term hazard to aviation based on activity at the vent (Brantley 1990). It is important to note that the levels were *not* defined to characterize downwind hazards posed over time by the drifting ash cloud or to represent the hazards posed on the ground as those might be quite different from aviation hazards. In practice, color code levels were assigned to Redoubt Volcano by the USGS Scientist-in-Charge of AVO after discussion with the Observatory's scientific staff about the significance of seismic data, visual observations, and other relevant evidence. During the rest of the eruption and for several months following the end of the eruption in June 1990, written updates stating the color code and summarizing current observations and activity were distributed by AVO via fax to the Federal Aviation Administration (FAA), Anchorage International Airport, the Anchorage office of the National Weather Service (NWS), and Alaska Division of Emergency Services at least once a day on a routine basis and immediately after any significant event occurred or was forecast.

The next volcano monitored by AVO to erupt after Redoubt Volcano was Mount Spurr in June 1992, and the color code system was applied with slight modifications to the initial version (see Eichelberger et al. 1995 for a detailed chronology of color code assignments during Mount Spurr's 1992 activity). The Redoubt eruption had increased industry and regulator awareness of the extensive damage that could result from aircraft encounters with ash. In the aftermath of that eruption, AVO had worked with other agencies (most notably the NWS and FAA) and the air carriers to improve coordination and messaging. Mount Spurr provided an opportunity to test those improvements through its months-long period of developing unrest and three explosive, ash-producing events in the summer of 1992. Although ash clouds from the Mount Spurr explosions drifted over Alaska, Western Canada, and the north-central United States (Schneider et al. 1995) and caused a day-long disruption of flights in the eastern United States, no damaging encounters of aircraft with that ash cloud occurred (Casadevall and Krohn 1995).

Early use of the aviation color code was not limited to the United States. The Russian volcano monitoring group Kamchatkan Volcanic Eruption Response Team (KVERT) adopted AVO's color code at the outset of its operations in 1993. Klyuchevskoy volcano on the Kamchatka Peninsula erupted explosively in October 1994, sending ash to an altitude of more than 15 km where a strong jet stream rapidly spread the ash into and across North Pacific air routes (Kirianov et al. 2002). With effective monitoring and information dissemination by KVERT, the National Oceanic and Atmospheric Administration (NOAA), and AVO, no damaging aircraft encounters occurred. Because of the high frequency of eruptions in Kamchatka, KVERT subsequently has had extensive practice changing color codes for multiple volcanoes in the Russian Far East (see Neal et al. 2009a and Rybin et al. 2011 for discussion of the Russian use of the color code and its impact on aviation in the North Pacific).

2.2 Subsequent modifications

Awareness of the color code alert system received a substantial boost when it was endorsed by ICAO in 1997 as a means to assist the IAVW's global standardization of information provided by volcanological agencies to aviation users. Also, by 1997 as part of the IAVW, a worldwide system of nine Volcanic Ash Advisory Centers (VAACs) had been established to detect ash clouds in the atmosphere and issue advisories describing current and expected locations of ash clouds based on satellite data, volcano observatory notifications, pilot reports, and atmospheric dispersion modeling. AVO, meanwhile, modified the color code definitions to introduce specific forecast time frames for expected eruptive activity (within weeks for Yellow, within a few days for Orange, within 24 h for Red; Neal et al. 1997). However, ICAO did not include such specific time frames in the definitions it adopted for worldwide use, in recognition that such specific forecast windows were unlikely to apply consistently to diverse volcanic behavior globally.

As the color code system received more exposure worldwide, a standing group of experts established by ICAO in 2002 to evaluate and improve the operation of the IAVW—the International Airways Volcano Watch Operations Group (IAVWOPSG)—revised the definitions of the levels in 2004, for inclusion in an amendment to Annex 15 (Aeronautical Information Services) of the Convention of International Civil Aviation.[3]

[3] Current standards and recommended practices for international air transport are published by ICAO as Annexes to the Convention on International Civil Aviation which was established in 1944; changes to the Annexes are made through a regular amendment process.

The current definitions of the color codes (Table 1) vary from the original and 1997 versions in several ways. (1) The 25,000 ft threshold differentiating Orange and Red levels was dropped because it was recognized that ash can be hazardous at any altitude, and the distinction was changed to minor versus major ash emission occurring or expected. (2) Yellow still indicates elevated unrest but does not explicitly state that the potential for eruption is increased, in recognition that a restless volcano may well return to Green status. (3) Orange is used for both heightened precursory unrest and minor eruptive activity because both conditions provoke essentially the same reaction—a high degree of watchfulness for increased activity; moreover, a volcano can shift between heightened unrest and minor eruptive activity without much warning, or minor activity can be obscured by weather clouds. (4) Language was added to make it clear that the levels work for both increasing and decreasing volcanic activity. (5) No specific forecast time frames are indicated.

To further improve how volcanic information is provided to aviation users, the IAVWOPSG developed a structured message format—called a Volcano Observatory Notice for Aviation (VONA)—to deliver the color code and critical observations in a concise manner easily understood by non-volcanologists (Albersheim and Guffanti 2009). Beginning in 2007, AVO tested a prototype VONA for ICAO for 2 years with users that included dispatchers, pilots, aviation meteorologists, and air-traffic controllers. That testing identified some needed changes in format, and a revised version (Table 2) was accepted by ICAO in 2010. ICAO's recommended guidance is that a Volcano Observatory (or equivalent scientific agency) issue a VONA when the aviation color code at a volcano is changed up or down or within a color code level when an ash-producing event or other significant change in volcanic behavior occurs. Dissemination of the VONA to the appropriate aviation weather office (called a Meteorological Watch Office), VAAC, and Air Route Traffic Control Center is by email, fax, and/or posting on a public website. A proposed 2013 amendment to Annex 3 (Meteorological Service for International Air Navigation) of the Convention of International Civil Aviation includes a reference to the VONA.

Explanations of the use of the aviation color code and VONA are given in ICAO's Handbook on the IAVW (Document 9766; http://www2.icao.int/en/anb/met/iavwopsg/IAV%20Handbook/Forms/AllItems.aspx/). In the United States, the aviation color code

Table 1 Definitions of aviation color code levels of volcanic activity

Level	Activity
Green	Volcano is in normal, non-eruptive state *or, after a change from a higher level*: Volcanic activity considered to have ceased, and volcano reverted to its normal, non-eruptive state
Yellow	Volcano is exhibiting signs of elevated unrest above known background levels *or, after a change from higher level*: Volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase
Orange	Volcano is exhibiting heightened unrest with increased likelihood of eruption *or,* Volcanic eruption is underway with no or minor ash emission
Red	Eruption is forecast to be imminent with significant emission of ash into the atmosphere likely *or,* Eruption is underway with significant emission of ash into the atmosphere

Table 2 Format of a Volcano Observatory Notice for Aviation (VONA), as recommended by the International Civil Aviation Organization

(1) Volcano Observatory Notice for Aviation—VONA	
(2) Issued	Universal (Z) date and time (YYYYMMDD/HHMMZ)
(3) Volcano	Name and number (per Smithsonian database at http://www.volcano.si.edu/)
(4) Current aviation color code	**GREEN, YELLOW, ORANGE**, or **RED** in uppercase bold font
(5) Previous aviation color code	Lowercase font, not bold
(6) Source	Name of Volcano Observatory (volcanological agency)
(7) Notice number	Create unique number that includes year
(8) Volcano location	Latitude, longitude in NOTAM format (N or S deg min W or E deg min)
(9) Area	Regional descriptor
(10) Summit elevation	nnnn FT (nnnn M)
(11) Volcanic activity summary	Concise statement that describes activity at the volcano. If known, specify time of onset and duration (local and UTC) of eruptive activity
(12) Volcanic cloud height	Best estimate of ash cloud top in nnnn FT (nnnnn M) above summit or AMSL (specify which). Give source of height data (ground observer, pilot report, radar, etc.). "UNKNOWN" if no data available or "NO ASH CLOUD PRODUCED" if applicable
(13) Other volcanic cloud information	Brief summary of relevant cloud characteristics such as color of cloud, shape of cloud, and direction of movement, etc. Specify if cloud height is obscured or suspected to be higher than what can be observed clearly. "UNKNOWN" if no data available or "NO ASH CLOUD PRODUCED" if applicable
(14) Remarks	Optional. Brief comments on related topics such as monitoring data, observatory actions, volcano's previous activity, etc
(15) Contacts	Names, phone numbers (voice and fax), email addresses
(16) Next notice	''A new VONA will be issued if conditions change significantly or the color code is changed." Indicate URL of Web site where latest volcanic information is posted

The structured format is intended to help non-volcanologists more easily understand and use volcanological information. Volcano Observatories are urged to issue a VONA when the aviation color code at a volcano is changed up or down or within a color code level when an ash-producing or other significant change in volcanic behavior occurs and VONA are part of the National Volcanic Ash Operational Plan for Aviation (http://www.ofcm.gov/p35-nvaopa/pdf/FCM-P35-2007-NVAOPA.pdf) and associated regional plans such as the Alaska Interagency Operating Plan for Volcanic Ash Episodes (http://www.avo.alaska.edu/pdfs/cit3996_2011.pdf). Current color codes assigned by the USGS to U.S. volcanoes are displayed for the public on an automatically updated map at http://volcanoes.usgs.gov/, and current and past VONA issued by U.S. Volcano Observatories are posted at http://volcanoes.usgs.gov/activity/vonainfo.php/.

Gardner and Guffanti (2006) explain how the aviation color code system is coordinated with notifications about ground-based volcanic hazards, as part of the overall alert-level system for volcanic activity used by the USGS. A key feature of the overall USGS system is that it employs the terms "Normal, Advisory, Watch, and Warning" to inform people about volcanic conditions they face on the ground. Usually the assigned terms for ground hazards and colors for aviation hazards will move together during activity at a volcano (i.e., Normal/Green, Advisory/Yellow, Watch/Orange, Warning/Red), but they may move independently in some cases such as the occurrence of a large fast-moving volcanic debris flow (Warning) with minimal ash production (Orange). This use of terms and colors, with the option of decoupling them, allows ground and aviation hazards to be evaluated and communicated separately as needed.

3 Recent application of the color code to volcanic activity in Alaska

In addition to AVO, the other U.S. Volcano Observatories (California, Cascades, Hawaiian, and Yellowstone) have adopted the aviation color code, but with Alaska having more than 50 volcanoes that have erupted in the past historical 250 years, AVO has the most experience in assigning color codes. In doing so, AVO relies on data from its extensive monitoring infrastructure of seismic networks, webcams, GPS arrays, infrasound sensors, and a portable weather radar, as well as from airborne gas, thermal, and visual surveys. AVO also has rapid access to multispectral satellite data from a variety of space agencies, occasional space-based radar for imagery and deformation analysis, and access to a network of three FAA weather radars.

To evaluate the application of the color code in Alaska, we examined the archive of Volcanic Activity Notifications on the AVO website (www.avo.alaska.edu/activity/avoreport.php) and counted the number of days Alaskan volcanoes were at elevated colors (Yellow, Orange, or Red). We chose the 10-year-time period 2002–2011 mainly because by 2002, many new seismic networks had been installed at Alaskan volcanoes in the Aleutian Islands, thus minimizing the possibility of apparent volcanic quiet actually being an artifact of non-detection. Some volcanoes, however, still remain unmonitored by ground-based instrumentation, which has led AVO to deem the status of such volcanoes as "Unassigned" rather than Green because background states cannot be confidently assessed or determined; these volcanoes are considered "Unassigned" until some evidence is obtained such as pilot observation or satellite data to warrant assigning an elevated color code.

Bar graphs of the frequency of elevated color codes at each volcano are given in Fig. 1. During 2002–2011, AVO assigned elevated color codes to 13 Alaskan volcanoes, eight of which erupted with five cases of unrest that did not end in eruption. Eruptions with significant ash emission (Red) occurred at Augustine (in 2006), Kasatochi (in 2008), Okmok (in 2008), and Redoubt (in 2009); eruptions with chronic minor ash emission (Orange) occurred at Cleveland (in 2005–2009, 2011), Pavlof (in 2007), and Veniaminoff

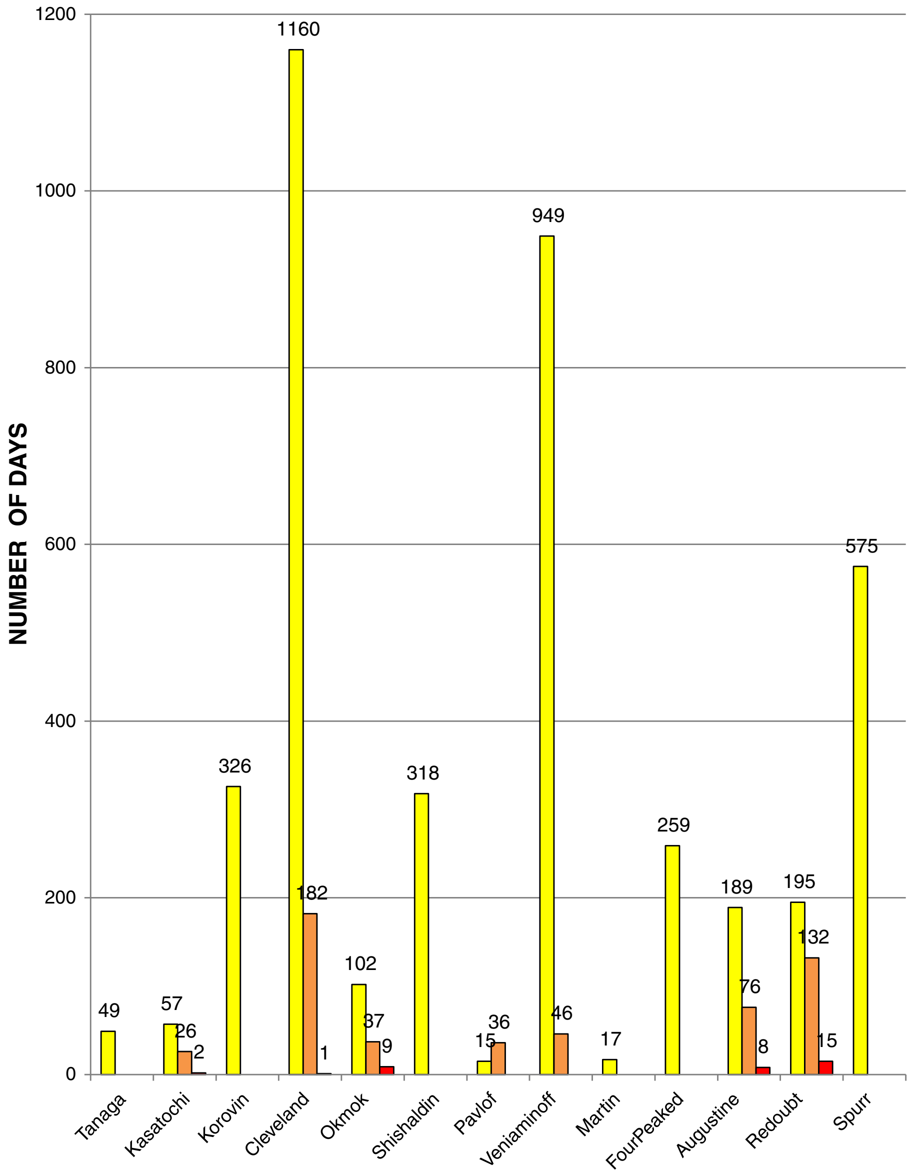

Fig. 1 *Bar graphs* showing number of days that Alaskan volcanoes were at elevated aviation color codes, 2002–2011. Volcanoes arranged from west to east on *horizontal axis*

(in 2005). During the time period examined, Fourpeaked mountain is notable as having produced the only phreatic eruption, a steam-driven explosion in 2006 in which no new magma was ejected, but volcanic gas was emitted (Neal et al. 2009b). Korovin, Veniaminof, and Spurr are notable for exhibiting unrest for long periods of time (months) without culminating in eruption.

Figure 2 shows the percentage of each year that Alaskan volcanoes were at elevated levels during the past decade. Overall, one or more Alaskan volcanoes were at Yellow on

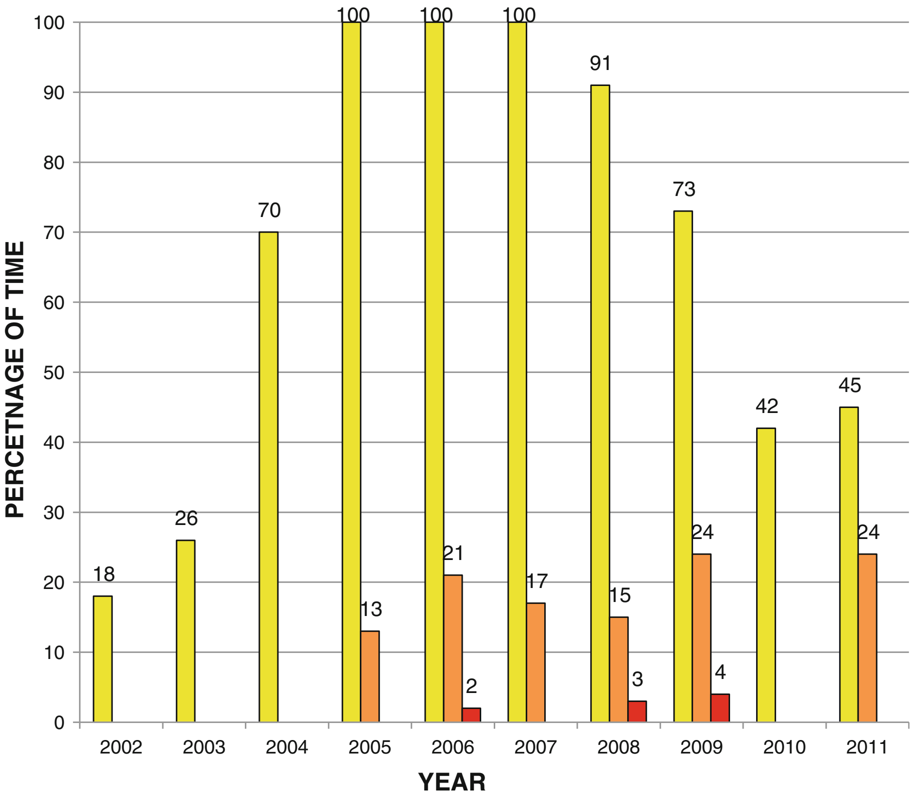

Fig. 2 *Bar graphs* showing percentage of time by year that 13 Alaskan volcanoes were at elevated aviation color codes, 2002–2011

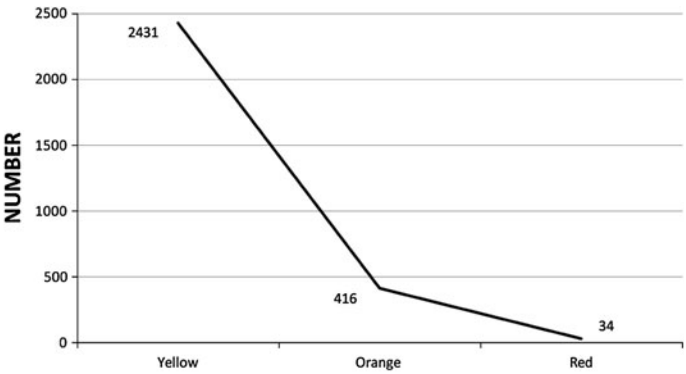

Fig. 3 Plot of total number of days at elevated aviation color codes for Alaskan volcanoes, 2002–2011

67 % of days and at Orange and Red on 12 % of days. Activity during 2005–2009 was particularly intense, with all Red days and most Orange days occurring within that period, as well as unrest (Yellow) occurring nearly year-round somewhere in Alaska. For the

decade as a whole, the total number of days at each elevated color (Fig. 3) decreases by an order of magnitude from Yellow to Orange and Orange to Red, following a general power law—consistent with the observation by Siebert et al. (2010) that on a global basis, small-to-moderate eruptions are an order of magnitude more common than large eruptions, as indicated by assignment of the Volcanic Explosivity Index.

The color code record for AVO clearly documents that unrest is a frequent phenomenon at Alaskan volcanoes, which is not surprising given their association with a major subduction zone. We note that assignment of Yellow (from Green) by AVO did not necessarily forecast impending eruption. In some cases (Augustine, Kasatochi, and Redoubt), unrest did progress directly to significant eruptive activity. But in other cases, unrest either did not culminate in eruption (Tanaga, Korovin, Shishaldin, Martin, Spurr) or usually did not culminate in eruption (most of the time at Veniaminof). And of course, Yellow (from Orange) also was used for periods of waning activity following heightened unrest or eruption.

Orange was used both for what turned out to be precursory unrest at Augustine, Kasatochi, and Redoubt and for minor eruptive activity at Cleveland, Veniaminoff, and Pavlof. Some volcanoes moved directly into Orange or Red without being assigned to Yellow, either because pre-eruptive unrest or minor eruptive activity was not detected at volcanoes lacking ground-based networks (e.g., unmonitored Cleveland in 2005–2006) or because the premonitory period was extremely brief and went undetected by AVO (e.g., less than 5 h at Okmok in 2008; Haney et al. 2008).

The assignment of Red to a volcano in Alaska generally was of brief duration, sometimes for just a few hours at a time to be followed by downgrade to Orange until another large explosive (Red) event was identified. During 2002–2011, the longest consecutive period at Red was 8 days leading up to and during a series of explosive events at Redoubt in 2009. AVO's experience has been that quick shifts between Orange and Red are accepted by aviation users who are familiar with rapidly changing meteorological hazards and, moreover, that long periods of Red in the absence of actual ash production can unduly prompt costly operational reactions on the part of airlines and government agencies (D. Bensimon written communication 2012). However, a particular complication with using the Red level too briefly occurred in 1992 during the August 18 eruption of Mount Spurr, as discussed by Eichelberger et al. (1995). AVO downgraded the color code from Red to Orange at the end of an explosive event but 3 h before ash stopped falling on Anchorage; although the color code change appropriately alerted the aviation sector about the end of explosive activity at the volcano, the discrepancy between the color code change and falling ash confused the city's citizens.

As an example of the progression among color codes during an eruptive episode, Table 3 shows the chronology of color code levels at Redoubt (modified from Table 1 of Schaefer 2011, to include the number of days at each step). Over a period of 302 days, from November 5, 2008 to September 28, 2009, AVO changed the color code 13 times. Months-long periods at Yellow and Orange preceded and followed the 12 days of main eruptive activity, during which 19 explosive ash-producing events occurred and the color code was alternated between Orange and Red. The Redoubt activity also posed mudflow hazards to an oil terminal at the base of the volcano (Schaefer 2011). Following the overall USGS alert-level system described by Gardner and Guffanti (2006), AVO issued Advisory, Watch and Warning notifications for ground hazards that moved in concert with Yellow, Orange, and Red aviation alerts.

Table 3 Chronology of color code levels at Redoubt Volcano, November 2008–September 2009 (modified from Schaefer 2011)

Dates	Color code	No. of days at that color
November 5, 2008–January 24, 2009	Y	57
January 25–March 9, 2009	O	44
March 10–14, 2009	Y	5
March 15–17, 2009	O	3
March 18–20, 2009	Y	3
March 21, 2009	O	1
March 22–24, 2009	R	3
March 25, 2009	O	1
March 26–April 2, 2009	R	8
April 3, 2009	O	1
April 4–5, 2009	R	2
April 6–June 29, 2009	O	83
June 30–September 28, 2009	Y	91

4 Discussion

The above analysis indicates that the color code has been successfully applied on a regional scale in Alaska for a sustained time period. Application of color codes to specific events is not without complexities however. For example, the distinction between Yellow (unrest) and Orange (heightened unrest with expectation of eruption) is a judgment call on the part of the Observatory scientists involved, and criteria may vary from volcano to volcano. Also, the color code definitions do not imply a risk outcome—i.e., that encounters of aircraft with ash clouds are more or less likely to happen—nor do they specify mitigation actions to be taken (Fearnley et al. 2012). Thus, for example, two volcanoes exhibiting persistent low-level ash emissions, but one located near an airport and one located far from air routes, nevertheless would both be at Orange, appropriately leaving it to the aviation sector to evaluate risk potential and identify needed mitigation actions.

No formal user survey of the aviation color code has been conducted. However, as evidence of its utility, the color code has been integrated into operational procedures of the FAA and NOAA in Alaska and various airlines operating in the North Pacific. At the FAA's Air Route Traffic Control Center in Anchorage, meteorologists consult a map posted online by AVO that displays current color codes of Alaskan and Russian volcanoes (Fig. 4) to brief air-traffic managers and controllers on volcanic activity that they need to be aware of (C. Neal personal communication 2012). When AVO assigns the Orange or Red level to a volcano, NOAA's Anchorage VAAC increases the frequency of its satellite surveillance of that volcano and the FAA issues an international Notice to Airmen (NOTAM) that is read by pilots and dispatchers. As an example, on January 25, 2009, a NOTAM was issued that read "…Alaska Volcano Observatory has reported increased seismic activity in the vicinity of Redoubt Volcano which indicates the precursory activity to the possibility of a volcanic eruption. (Aviation alert color code ORANGE is in effect). Aircraft should remain alert for possible eruption, steam or ash clouds and report any sightings to ATC [Air-Traffic Control] immediately…" This kind of forewarning is the only official aviation-warning product that indicates impending ash hazards; other products

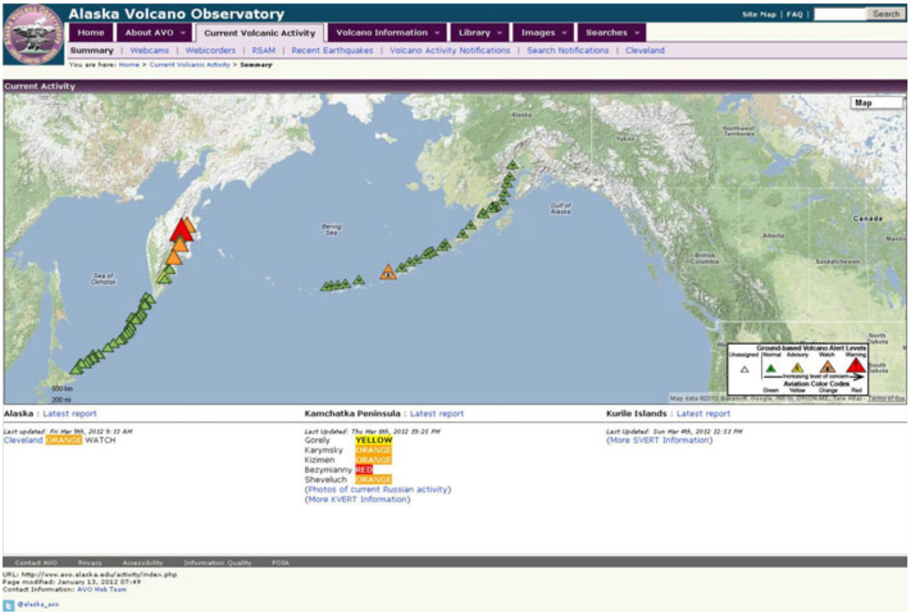

Fig. 4 Example of a map from the website of the Alaska Volcano Observatory showing current color codes at Alaskan and Russian volcanoes with links to the corresponding text updates (from http://www.avo.alaska.edu/activity/ on March 9, 2012)

such as VAAC advisories and associated warnings of significant meteorological events are based on the presence of ash already in the atmosphere. Use of Orange for eruption forewarning allows for preparations to be made during flight planning, such as adding more fuel or arranging for access to alternate airports in case flight diversions are needed. At Red, all parties (operators, regulators, and scientists) remain acutely focused on the high hazard potential of ongoing or imminent ash emission, working together to execute safe and efficient flights by planning avoid hazardous airspace, canceling and diverting flights in dire cases, or, as during the 2009 Redoubt and 2006 Augustine eruptions, by restricting flights to and from Anchorage Airport to daylight hours.

The use of the aviation color code and VONA by AVO conforms to the recommended elements of a "people-centered early-warning system" as defined by the United Nations International Strategy for Disaster Reduction (2006):

- *Risk Knowledge*—i.e., the hazards and vulnerabilities are well known:
  The capability of ash clouds to damage aircraft is well known within the aviation and scientific communities as a result of many well-publicized encounters over the years (Guffanti et al. 2010). However, the extremely disruptive eruption of Iceland's Eyjafjallajökull volcano in 2010 raised the issue of whether flight through airspace with very low concentrations of ash can be conducted safely. Better understanding of the risks of flight through aged, dilute ash clouds is needed.
- *Monitoring and Warning Service*—i.e., there is a sound scientific basis for hazard warnings and the ability to generate them 24 h a day in a timely fashion:
  Color codes are assigned by AVO on the basis of data from its monitoring networks and geological understanding of the volcano in question, a combination that provides a

sound scientific basis for volcanic warnings. The issue of timeliness of warnings for aviation is a constant concern, given the fact that explosive eruptive columns can reach cruise altitudes in a few minutes and that aircraft flying in same airspace where ash disperses can approach ash clouds at $\sim$800 km/h. AVO is not normally a 24/7 operation but moves to around-the-clock shifts when volcanoes are at Red and sometimes when at Orange. At all times, computerized alarms are used to alert on-call scientific staff of changes in key data streams. In the United States, a VONA is written by Volcano Observatory scientists and disseminated usually within tens of minutes after detection of an explosive eruption or ash in the atmosphere. To ensure immediate aviation authority and industry awareness in the wake of a confirmed ash cloud, AVO conducts a rapid telephone call-down to the FAA, NWS, and others as the VONA is being written.

- *Dissemination and Communication*—i.e., clear messages contain simple and useful information that reliably reaches those at risk and enables proper responses:
  The color code and VONA distill technical volcanological information into a readily understood language for non-volcanologists. Messages are distributed by telephone call-down to a specific list of key responders, by fax and email to the key group plus a larger group of interested parties, and publically through the Internet. A public online service introduced by the USGS in 2012 allows individuals to subscribe (with no fees) to receive automatic email notifications of volcanic activity, choosing the message types and U.S. volcanic regions of interest. (http://volcanoes.usgs.gov/vns/).
- *Response Capability*—i.e., people are prepared and ready to react to warnings:
  Overall, the response strategy for ash cloud hazards is well-organized and practiced. The aviation sector by its nature is highly structured, and the roles of various parties in avoiding hazardous ash clouds are spelled out in ICAO protocols and guidelines and in national and regional operational plans. In the North Pacific, eruptions occur frequently enough that people and organizations remain well-versed in what to do. In northern Europe, which is infrequently affected by widespread volcanic activity, the impacts of the 2010 eruption of Eyjafjallajökull exposed the need for a coordinated response across numerous national boundaries, and a more unified response capability is now being developed through multinational contingency plans and practical exercises involving regulators, aviation weather offices, airlines, and Volcano Observatories (see http://www.icao.int/safety/meteorology/ivatf/Pages/default.aspx).

The color code system for aviation is growing in use around the world. New Zealand, Australia, and Iceland have adopted it, as well as the United States and Russia. In the case of Australia, the Darwin VAAC as part of its Ash Advisories provisionally assigns aviation color codes to volcanoes in its jurisdiction in Indonesia, Papua New Guinea, and the southern Philippines, when possible from available data and cross-checking with the pertinent Volcano Observatories as needed. Following the 2010 eruption of Eyjafjallajökull Volcano, the Iceland Meteorological Office was motivated to start using the aviation color code. To foster wider implementation through education and outreach to other Volcano Observatories, the World Organization of Volcano Observatories is posting information about use of the aviation color code and VONA on its Web site at http://www.wovo.org/aviation-colour-codes.html/.

However, barriers to implementation remain. Many Volcano Observatories are focused on hazards to local ground populations and do not view international air transport as their primary responsibility (Ewert and Newhall 2004). Also, if a color code system is used for ground hazards, there is the possibility of confusion with respect to aviation colors.

Furthermore, in some countries real-time seismic monitoring is not extensive, and limited resources at many of these Volcano Observatories makes assigning color codes more difficult.

5 Conclusions

Designed by volcanologists in Alaska as a local solution to improve hazard communication with nonscientists, the color-coded volcanic alert-level system for aviation has evolved into a global standard through the endorsement of ICAO. The color code is now a key component of ICAO's global risk mitigation system for aviation hazards and has been adopted for use in the United States, Russia, New Zealand, Iceland, and partially in the Philippines, Papua New Guinea, and Indonesia.

Many years of use of the color code in Alaska have demonstrated that the ranked color codes can be matched to the changing conditions at the region's active subduction zone volcanoes as they move from normal background states through waxing and waning unrest or eruptive events and return to background. The Yellow category accommodates the fact that eruptive activity usually is preceded by signs of magma movement that can be detected with monitoring networks in place, but that not all unrest leads to eruption. The Orange and Red categories provide for the important distinction between minor and major ash-producing eruptive events, as well as an increasing likelihood of an eruptive event. The absence of predefined forecast times frames for expected eruptive activity at each level has facilitated the application of the color code by allowing scientists to evaluate each volcano's behavior on a case-by-case basis. As evidence of its utility, the color code has been integrated into operational procedures of NOAA and the FAA in Alaska and various airlines operating in the North Pacific.

Counting the number of days that volcanoes are at elevated colors is a measure of a region's volcanic vigor. In the case of Alaska during 2002–2011, elevated color codes were assigned to 13 volcanoes, eight of which erupted; for that decade, one or more volcanoes were at Yellow on 67 % of days and at Orange or Red on 12 % of days. This kind of analysis in other regions where the color code is used might provide a means of comparing activity across volcanic environments.

There are barriers to implementation to further use of the aviation color code, including that ground hazards are usually the highest priority of Volcano Observatories. However, substantial progress already has been made under the aegis of ICAO; with continued education and outreach to Volcano Observatories worldwide, greater use is achievable.

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