LARGE-SCALE WEATHER PATTERNS FAVORABLE FOR VOG OCCURRENCES ON OAHU, HAWAII

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Abstract

Kilauea Volcano is one of the most active volcanoes in the world, and its two vents (Halemaumau and Puu Oo) release more sulfur dioxide (SO$_2$) than major power plants. During the time of this study (April 2009 – December 2014), the two vents released approximately 3,700 tons of SO$_2$ per day. Within the atmosphere, the SO$_2$ is oxidized and converted to sulfuric acid aerosols through reactions with OH radicals and H$_2$O molecules in clear sky and cloud reactions. This sulfuric aerosol is commonly referred to as volcanic smog (vog) in Hawai'i. During prevailing trade winds conditions, the vog emitted from Kilauea volcano is advected towards the southwest of the Big Island of Hawai'i. However, when winds shift to a southeast or southwest direction, then vog can be carried up the island chain affecting all the Hawaiian Islands. This study focuses on the large-scale weather patterns that cause this wind shift and specifically, on conditions that bring the vog to the island of Oahu, the most heavily populated island. In order to identify large-scale weather patterns that bring vog to Oahu, two datasets were used.

Firstly, the Hawai'i Department of Health maintains a record of hourly aerosol mass concentrations in size ranges below 10 µm (PM$_{10}$) and below 2.5 µm (PM$_{2.5}$). The volcanic plume consists of accumulation mode sulfuric acid aerosols below 1µm in diameter and therefore, the PM$_{2.5}$ measurements will capture information about vog concentrations. As part of this study, Hawai'i Department of Health PM$_{2.5}$ measurements were used to identify elevated vog conditions.
Secondly, European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis data were used to determine weather patterns occurring prior and during Oahu vog events. As part of this effort, the ERA-Interim reanalysis data, for different weather patterns, were downscaled to a resolution of 3.3 km using the Weather Research and Forecasting (WRF) model. The WRF output was run in the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model to produce both trajectory and concentration plots. The HYSPLIT model allowed for a visual representation of how the vog plume follows the large-scale wind patterns. Data from April 2009 throughout 2014 were analyzed and the total number of vog days was found to be 101. These 101 vog days were the result of 57 distinct vog events lasting from hours up to four days. The 57 events were further categorized into three large-scale weather patterns: pre-cold fronts (37 cases), upper-level disturbances (17 cases) and Kona lows (3 cases). The pre-cold front events had variable duration lasting up to four days and it was found that the largest vog concentrations (PM$_{2.5}$ values) occurred during long duration pre-cold front events.
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1. INTRODUCTION

1.1 The Hawaiian Islands

The pristine Hawaiian archipelago is located in between the latitudes of 19-22° N and longitude 154-160° W in the middle of the Pacific Ocean. The islands should have one of the cleanest air qualities in the world; however, the air quality is not always what most people would consider good. The poor air quality is not mainly because of common mobile sources of pollution such as cars, buses, planes, and trucks, nor the stationary sources such as power plants, industrial facilities, and factories. These sources do affect the air quality, but one of the major concerns here in Hawaii is from a natural source, which is the Kilauea Volcano.

Hawaii has eight main islands (Fig. 1), which are Niilau, Kauai, Oahu, Molokai, Lanai, Kahoolawe, Maui, and the largest island, which is Hawaii (the Big Island) where the Kilauea Volcano is located. The subtropical high-pressure system located to the north or northeast of the Hawaiian Islands, depending on the time of year, generates trade winds that are present about 90% of the time in summer, and about 65% of the time in winter (Garza, 2012). When the northeast trade winds blow, the plume from the active volcano is sent offshore and along the Kona side of the Big Island, but when the winds become light and variable, or come from the south, the exhaust plume can affect the air quality of almost anywhere in the archipelago.

1.2 The Kilauea Volcano

In the early 1800s through 1954, Kilauea erupted mainly from the volcano summit. Since 1955, most eruptions have occurred along the East Rift Zone. The
volcano started erupting continuously in 1983, mainly from the Puu Oo vent located on the East Rift Zone. In March 2008, an additional vent opened in the Halemaumau crater at the volcano’s summit (Fig. 2). The gases being emitted from the two vents are comprised of mainly water vapor (H₂O), carbon dioxide (CO₂), and sulfur dioxide (SO₂) along with some other minor trace gases. The main gas of interest being released from the vents is SO₂. During the time from January 2009 to January 2015, the two vents released an average value of 3,700 ± 1,400 tons of SO₂ every day. The daily flux ranged from about 500 – 12,000 tons of SO₂ (personal communications, J. Sutton, United States Geology Survey (USGS), Hawaiian Volcano Observatory (HVO). SO₂ is a problem near Kilauea’s active vents, but when SO₂ is released into the atmosphere, the gas reacts with sunlight, dust, and moisture to create sulfuric aerosols (SO₄) or what most people in Hawaii know as vog. The SO₂ oxidation half-life is estimated to be about 6 ± 4 hours (Porter, 2002). Therefore, SO₂ is a pollution problem closer to the vents, however, minutes to hours later it will oxidize into SO₄, which is the problem further away from the vents. It is assumed that the particulate SO₄ consists of sulfuric acid (H₂SO₄), ammonium sulfate ((NH₄)₂SO₄) and ammonium bisulfate ((NH₄)HSO₄), where the former is more acidic and the latter is partially neutralized.

The prevailing trade winds usually blow the SO₂ from Puu Oo out to sea while the SO₂ from Halemaumau creates vog in the Kau communities from Pahala to Ocean View. Some of the vog is also advected and trapped along the Kona coast as well because of strong localized sea breezes, and the Big Island wake. The wake is created by island blocking, which initiates a clock-wise eddy to the west of South Point,
shifting the flow towards the Kona coast. Sea breezes usually occur in the afternoon after solar heating has produced a large pressure difference over land and ocean.

1.3 Health risks associated with vog

Vog or volcanic smog is a visible haze, which has a unique mixture of gaseous SO$_2$ and particulate SO$_4$ that is more harmful than either constituent alone. The amount of SO$_2$ is higher closer to the vents, which will make individuals experience a dry cough and hay fever symptoms. The further away from the vents, the higher the SO$_4$ values, which will give individuals sinus congestion and bronchitis-like symptoms (Longo, 2009). These highly acidic sulfuric aerosols of SO$_4$ are small enough to penetrate deep into the human lung. When SO$_4$ is inhaled into the lungs, it can irritate the lungs and the mucus membranes. This has an effect on how well the lungs work and also the immune system. The people who are especially sensitive to SO$_4$ are children, individuals with chronic asthma or other respiratory impairments, or individuals with circulatory problems. Symptoms may include breathing difficulties, coughing, sore throat, flu-like symptoms, headaches, eye irritation, lack of energy and more mucus production.

Studies on the Big Island found statistically significant positive associations between chronic exposure and increased prevalence of cough, phlegm, rhinorrhea, sore/dry throat, sinus congestion, wheezing, eye irritation, and bronchitis resulting from the SO$_2$ and SO$_4$ exposure (Longo, 2007).

The sulfuric aerosols can also form acid rain, which affects various sectors of agriculture, including crops and nursery industries, forests and lakes. Acid rain can leach lead from rainwater catchment systems into the water supply. Vog can, in
addition, reduce visibility and create a potential hazard for drivers, as well as for marine and aviation interests (Sutton et al., 2000).

The SO$_4^-$ particles go under the category PM$_{2.5}$, which is particulate matter smaller than 2.5 µm in diameter. The second type of particulate matter is PM, which has a size of 2.5-10 µm. There are state and federal regulations for particulate matter.

### 1.4 The Air Quality Index (AQI)

A standard measurement of how clean or polluted the air is, and also the associated health effects, is the Air Quality Index (AQI). The Environmental Protection Agency (EPA) calculates the AQI for five major air pollutants: ozone, carbon monoxide, sulfur dioxide, nitrogen dioxide, and particulate matter. The air quality is satisfactory for particulate matter or PM$_{2.5}$ when the AQI is between 0-50 (0-12 µg/m$^3$). At these low values PM$_{2.5}$ poses little or no risk. When the AQI is between 51-100 (13-35.4 µg/m$^3$), the air quality is moderate; this means that sensitive people may need to take precautions. The other levels of particle pollution are found in Table 1 along with their associated AQI.

### 1.5 Goals

The main goal of this study is to find the large-scale weather patterns that cause vog to reach the island of Oahu. Oahu is chosen because the majority of people in Hawaii live on Oahu, and the fact that volcanic smog or vog is a health problem for many people living in Hawaii. There are about one million people living on Oahu. Vog can also have a negative affect on the tourism industry, where people with
sensitive airways might choose another destination for their vacation. According to Hawaii Tourism Authority, Oahu has about five million visitors every year.

This study uses the limited amount of Department of Health (DOH) PM$_{2.5}$ data, the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis data, Service Records Retention System (SRRS) ocean analysis charts, and the Weather Research and Forecasting (WRF) model and Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model to address the following questions:

- When do vog events occur on Oahu?
- How frequent are vog events?
- What concentrations of vog do Oahu usually experience?
- What is the typical duration of a vog event?
- What types of large-scale weather patterns are associated with vog events?
2. DATA AND METHODOLOGY

2.1 Data

In this section, different types of data sets will be discussed, as well as the methodology. The data vary from local air quality measurements to the ERA-Interim reanalysis data set. There will also be a section about the types of models used.

2.1.1 DOH data

The DOH, Clean Air Branch (CAB), monitors the ambient air in the State of Hawaii (State of Hawaii Department of Health, 2014). There are stations on the four main islands: Kauai, Oahu, Maui and the Big Island, which measure various gaseous and particulate air pollutants. The main pollutants of interest are SO\textsubscript{2} and fine particulate matter (PM\textsubscript{2.5}), but this study focuses on PM\textsubscript{2.5} on Oahu where the stations are Kapolei, Pearl City, Sand Island and Honolulu. The first three stations are unfortunately subject to background pollution from industrial areas and power plants, so the station in Honolulu is our main source. The station is located on the roof of the DOH in downtown Honolulu, more precisely at 21.30758° N and 157.85542°W. The area includes a major hospital (Queen’s Medical Center), the state capitol, other state, county, commercial and business buildings as well as residential condominiums. The station has been operating since 1972; however, it did not start monitoring PM\textsubscript{2.5} until April 2009.

PM\textsubscript{2.5} refers to tiny particles or droplets in the air that are 2.5 microns or less in diameter; SO\textsubscript{4} go under this category of particles. The PM\textsubscript{2.5} measurements are taken using the beta-attenuation particulate monitor BAM-1020, which automatically
measures and records airborne particulate concentration levels using the industry-proven principle of beta ray attenuation. The hourly PM$_{2.5}$ data set start April 2009 for station Honolulu and for this study lasts until December 2014. Data from the year 2015 will not be available until summer 2016 after the preliminary data has been validated. Outliers in the data set that are removed include New Years Eve day and also the day after due to extreme firework activity. For example, measurements of hourly PM$_{2.5}$ at 0000 HST 1 January 2010 were as high as 366 µg/m$^3$. PM$_{2.5}$ levels around New Years Eve were very high prior to the firework ban in 2011, but even after the ban there are still noticeably higher values of PM$_{2.5}$ (e.g., 44 µg/m$^3$ at 0100 HST 1 January 2014). There was a total of 53 missing days, and the total of 3498 hours from the study period. The years with the most missing data were 2013 and 2014.

The EPA has set state and federal ambient air quality standards for PM$_{2.5}$, where the federal primary standard states that the 24-hour average should not exceed 35 µg/m$^3$ and the annual average should not exceed 12 µg/m$^3$ (Table 2). There are currently no standards for the state of Hawaii. One concern about the lack of a state standard for PM$_{2.5}$ in Hawaii is the background pollution of sea salt, which can influence the measurement of PM$_{2.5}$. Fig. 3 shows vog and sea salt plotted according to their diameter size versus their typical distribution in the atmosphere here in Hawaii. This is for aerosols in equilibrium at a relative humidity of 75%. The figure shows how the left tail of the sea salt distribution could potentially slightly contaminate the PM$_{2.5}$ measurements. The values are fairly low and not considered a problem for days with elevated PM$_{2.5}$ values, like in this study. However, during
summertime, when the surf along the south-facing shores is elevated, that is when the measurements could have been contaminated with sea spray.

### 2.1.2 ERA-interim data

The ERA-Interim data set is from the ECMWF. ERA-Interim covers the period from 1 January 1979 onwards, and continues to be extended forward in near-real time (Dee et al., 2011). The data set uses a spectral model integrated at a T225 (80 km) horizontal resolution with 60 vertical hybrid levels. ECMWF’s high-resolution upper air datasets use a hybrid system for specifying the levels of the data, where they combine the constant pressure level system with the sigma level system based on surface pressure. The prognostic equations are solved using the semi-Lagrangian method with a finite element method in the vertical. A four-dimensional variational data assimilation system with 12-hour cycling is used with output every six hours (Hodges, 2011).

The ERA-Interim used an assimilation of humidity observations from satellites to produce a new humidity analysis that reduced the problems found in ERA-40. A full range of observations is bias corrected before assimilation, where one example is the variational scheme that is used for satellite radiance. The period used in this study was from April 2009 through 2014, consistent with the PM$_{2.5}$ data. Geopotential heights at different levels were used to study the different large-scale patterns that caused vog to reach Oahu.

### 2.1.3 Pacific East Surface Analysis
The National Oceanic and Atmospheric Administration (NOAA) offers ocean analysis products through the Service Records Retention System (SRRS). SRRS stores weather observations, summaries, forecasts, warnings, and advisories provided by the U.S. National Weather Service (NWS). There are three broad categories of SRRS data, which are observations, forecasts, and graphics. The graphics contains images of surface analysis, standard layer upper air analyses, weather depictions, radar summaries, and ocean products. The ocean products or more specifically the ocean analysis of the Pacific East Surface Analysis are available for download through the NOAA Operational Model Archive and Distribution System (NOMADS): http://nomads.ncdc.noaa.gov (Rutledge et al., 2006). The ocean analysis products were used to verify the ERA-Interim reanalysis data.

### 2.1.4 Surface Integrated Data

The NOAA offers the Integrated Surface Database (ISD). The global data set that consists of hourly and synoptic observations compiled from numerous sources into a single common ASCII format and common data model (Lott et al. 2001). The data set was developed by Asheville’s Federal Climate Complex, and includes over 35,000 stations worldwide. ISD covers the period from 1901 to present, but the volume increases substantially in the 1940s and in the early 1970s. ISD Version 1 was released in 2001 and ISD Version 2, with an additional quality control applied, was released in 2003.

There has been a continuous effort in the improvement of automated quality control software. Additional quality control software has been developed and applied to the entire ISD archive, which includes algorithms checking for proper data format
for each field, extreme values and limits, consistency between parameters, and continuity between observations. In this study, only the period between April 2009 through 2014 was used for consistency with our PM$_{2.5}$ data. The stations used were the main airports at Lihue, Honolulu, Kahului, Kona and Hilo, which form a transect through the Hawaiian Islands. The temperature, dew point temperature, and pressure data were used to detect the strength of cold fronts near the island chain.

### 2.2 Model

#### 2.2.1 Weather Research and Forecasting (WRF) model

The WRF model is a mesoscale numerical weather prediction system for atmospheric research (Skamarock, 2008). The model is computationally efficient, and its two-way nesting capabilities allow fine grid resolution. Version 3.5 of the Advanced Research WRF (WRFV3.5) was downloaded and used through the Computational and Information Systems Laboratory (CISL), and more specifically Yellowstone. Yellowstone is a high-performance computing resource that consists of a 1.5-petaflops HPC system in an IBM iDataPlex cluster with 72,576 Intel Sandy Bridge processors.

The ERA-Interim reanalysis data was dynamically downscaled from the coarse resolution of 80 km to 10 km and eventually down to 3.3 km. The outer domain has the coordinates (166°W - 147°W, 29°N - 13°N), and the inner domain has the coordinates: (161°W - 154°W, 17°N - 23°N). Both domains cover the main Hawaiian Islands and surrounding ocean (Fig. 4). The WRF Preprocessing System (WPS) allows various resolutions of terrain and land data sets to be used. The horizontal resolution spacing of the outer domain is 10 km and the inner domain is 3.3 km,
correspond to a time step of 30 seconds for both. The WRF is a sigma-level model where 38 levels were used in the vertical. The physics schemes used are found in Table 3. The main reason for dynamically downscaling the ERA-Interim data was to include more local-scale effects when running the HYSPLIT model. One event from each category was dynamically downscaled, with the exception of the pre-cold front that had two events.

2.2.2 The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model

The HYSPLIT model was developed by NOAA’s Air Resources Laboratory (ARL) (Draxler and Hess, 1998). HYSPLIT is one of the most widely used models for atmospheric trajectory and dispersion calculations. The most popular model application is back trajectory analysis to determine the source of air mass or pollutants (Fleming et al, 2012). HYSPLIT is available for the public as well as for registered users through http://ready.arl.noaa.gov/HYSPLIT.php. The LINUX version was also downloaded at CISL, and more specifically Yellowstone. This gave easy access to HYSPLIT through the program terminal from any LINUX or Mac platform.

The model can compute trajectories, complex dispersion, and deposition simulations using either puff or particle approaches. In the puff approach, the puffs expand until they exceed the size of the meteorological grid cell, which could be either horizontally or vertically, and then split into several newer puffs. The particle approach releases a certain amount of particles within the domain, which is advected by the mean wind field and spread by a turbulent component. The default configuration assumes a 3-dimensional particle distribution, both horizontally and
vertically. The HYSPLIT model can be used either through a graphical interface or the command line. The trajectory setup menu is fairly simple and requires a starting time, starting location(s), total run time direction, top of model and the meteorology file. The concentration plot, on the other hand, requires all the above and also the pollutant, deposition and grid setup.

2.3 Methodology

The DOH hourly PM$_{2.5}$ data were used to find vog days. One vog day was defined by finding at least three consecutive hours of PM$_{2.5}$ greater than or equal to 13 µg/m$^3$. The threshold of 13 µg/m$^3$ was set according to the AQI for particulate matter. Once the air quality has the value of 13 µg/m$^3$, it is considered moderate. A script was written and executed to find the total of 101 vog days for station Honolulu. An attempt to use daily PM$_{2.5}$ proved that the daily averages had a tendency to remove details about the vog days.

The second step was to analyze the 101 vog days by using the ERA-Interim data, available every six hours, as well as the surface analysis maps over the East Pacific from SRRS. Mean Sea-Level (MSL) pressure, 850-, 500-, and 250-geopotential heights were extracted from the ERA-Interim data set to study the synoptic patterns of the vog days. When studying the synoptic settings along with elevated hourly PM$_{2.5}$, it is obvious to conclude that the 101 vog days are actually a part of 57 vog events with varying duration from one to four days. The 57 vog events can also be categorized into a total of three large-scale weather patterns: pre-cold fronts, Kona lows, and upper-level disturbances (Table 4). The three different types of weather patterns are described in more detail in section 3.3. But for a brief introduction, the pre-cold front
events had a low-pressure with its associated cold front moving in from the west while the subtropical high was being pushed to the east. The category is called pre-cold front because the vog reached Oahu before the front had passed over the Island. For the pre-cold front cases, ISD data variables including temperature, dew point temperature and pressure, were used to identify the strength of the cold fronts. The pre-cold front category had event duration varying from one to four days, and certain differences between the short and the long events were noted. As a result, these are two sub-categories of the pre-cold front pattern.

The Kona low has a surface circulation for more than 24 hours, and the circulation extended all the way up to 250 hPa (O’Connor, 2013). The upper-level low was a cut-off low from the westerlies, and the surface low had to pass south of 35°N. The upper-level disturbance pattern had a low-pressure center or a low-pressure trough in the upper levels, however, with no closed circulation at the surface unlike the Kona low.

In the last step, the WRF model was used to dynamically downscale the ERA-Interim reanalysis data for the four case studies down to a resolution of 3.3 km. The reanalysis data has a resolution of 80 km, and is therefore too coarse to be used directly in the HYSPLIT model. It is more desirable to downscale the data to a higher resolution to include local island circulation. The four case studies included one prefrontal event with elevated PM$_{2.5}$ for one day, one prefrontal event with elevated PM$_{2.5}$ for four days, one Kona low event and one upper-level disturbance event. The total period for each event was two days prior to the vog day starting at 0000 UTC, the time during the event, and one day after the vog event. The WRF were initialized two days prior to the vog event to allow the model to spin up and include the large-
scale pattern before the vog plume reached Oahu. WRF is divided into two sections, the WRF Preprocessing System (WPS) and the actual WRF. WPS consists of three programs that collect and prepare the input data before running the actual WRF model. The three programs are geogrid, ungrib and metgrid. Geogrid defines the model domain and interpolates static geographical data to the grid (e.g. terrain, surface albedo), ungrib extracts the meteorological fields, and metgrid horizontally interpolates the meteorological fields to the model grid (Skamarock, 2008). Once the metgrid-files are created from metgrid, they are run in WRF by using real.exe and wrf.exe after changing the namelist.input file. The namelist has the option of setting the length of the integration, frequency of output, size of domain, timestep, physics option, and other parameters. Each run took about 10 hours depending on how long the vog event lasted. Only four case studies were chosen because running the WRF model with a high resolution can be computationally expensive.

The WRF output was then converted into HYSPLIT format through the script called wrf2arl. The HYSPLIT model was used to create ensemble trajectory and concentration plots for each of the four case studies. The ensemble trajectory automatically starts multiple trajectories from one selected starting point. There are 27 trajectories, and each trajectory is offset by one meteorological grid point in the horizontal and 0.01 sigma units in the vertical.

Halemaumau is located 1247 m above mean sea level (msl) with coordinates (19.4100°N, 155.2864°W), and Puu Oo is 698 m above msl with coordinates (19.3864°N, 155.1050°W). The plume height is assumed to be 500 m above the vent locations. It was also assumed that all the gaseous SO₂ were converted immediately to particulate SO₄ after being released. Wet and dry depositions were included in the
calculations to represent a more viable deposition mechanism for the vog particles. The emission rate was set to continuous to release the average value of 150 tons of SO$_2$ per hour. This value was set according to the mean daily release of 3,700 tons of SO$_2$ every day. The starting time for each case study varied depending on event type due to varying wind strength and wind direction. The one-day cold front was initialized at 0200 HST (1200 UTC), two days prior to the event, and the four-day cold front was initialized at 0200 HST (1200 UTC) one day prior to the event. The local standard time is Hawaiian Standard Time (HST). The Kona low and upper-level disturbance events were both initialized at 0200 HST (1200 UTC), one day prior to the event. The time it takes for the vog plume from the Big Island to reach Oahu varies according to wind strength and direction. The straight-line distance from the vents on the Big Island to Honolulu on Oahu is about 350 km. If the wind strength were between 4 to 10 m/s, at least 10-24 hours would be a good estimate of how much time the vog plume is expected to reach Oahu. All the case studies were simulated for 72 hours.
3. RESULTS

In the following section, the research questions raised in the introduction under goals will be answered. The last question also includes four different case studies discussed in further detail. The pre-cold front events were chosen to represent the typical conditions but also according to duration length, one short event and one long event were selected. A sample Kona low and an upper-level disturbance were chosen to better understand the typical conditions for these event types as well.

3.1 When do vog events occur on Oahu?

The entire DOH hourly PM$_{2.5}$ dataset from April 2009 through 2014 from station Honolulu is shown in Fig. 5. The red line in the figures shows the 13 µg/m$^3$ threshold set by the EPA for moderate air quality. The figures give a good indication of how the PM$_{2.5}$ data varied from year to year. Days and events above the threshold are clearly seen in the time series. Fig. 5a shows two events in May, two events in October, two events in November and two events in December. Single one-hour spikes do not count as a vog day, because they do not meet the definition for a vog day, which is at least three consecutive hours of elevated PM$_{2.5}$.

Fig. 5b has a total of 11 vog events, and the three black arrows indicate events of interest. The first arrow is indicative of a pre-cold front on 22-25 January; the second arrow is for a pre-cold front on 2 February, and the third arrow is from a Kona low on 2-3 May. These events will be discussed in further detail in section 3.3.3. Fig. 5c shows multiple single-hour spikes from February through mid-September. One single-hour spike is not enough to yield a vog day; however, ten vog events were
found in 2011. There was one event in January, one in February, four events in March, two in April, one in September and one short event at the end of November.

The following year, 2012, has a total number of 12 vog events where two of the events lasted four days. There are two major spikes, one in March and one in July, but neither last for longer than one hour and are therefore not counted as vog days. There are unfortunately some smaller gaps of missing data in Fig. 5e, but mainly in summer time when vog is usually brought out to sea and along the Kona side of the Big Island.

The year of 2013 has a total of 14 vog events, and the bulk of the events are in March and April. The black arrow indicates area of interest, in this case it is an upper-level disturbance on 22-23 May, 2013. The last year, 2014, in Fig. 5f has the least amount of five vog events compared to the other years.

Fig. 5 also shows evidence of an annual cycle with higher values in winter months than in summer months. The PM$_{2.5}$ values during summertime never fully reach zero, because the samples can get contaminated with sea spray. Summertime has the biggest surf along south facing shores. Both the mean and median value of PM$_{2.5}$ from station Honolulu from April 2009 through December 2014, was 5 $\mu$g/m$^3$, and the standard deviation was 5.1 $\mu$g/m$^3$. These mean and median values fall into the good air quality category.

Fig. 6, the monthly mean of the 101 vog days from station Honolulu, shows that most of the vog days occur during winter. The exception is several vog days in May and one vog day in September. January has the highest amount with 27 vog days, and the second highest is December with 25 days. There is a small bump in May, which could be due to an increase in upper-level disturbances, and this will be discussed further in section 3.3. The months June, July and August have no vog events, and the month of September has only one vog day.
3.2 How often do vog events occur every year?

The annual variations in vog days from April 2009 through 2014 are shown in Fig. 7. The years 2012 and 2013 show the highest number with 24 and 23 vog days, and year 2014 the lowest with only seven vog days. The cause of the low value of in 2014 are still unknown, but it could be related to the emission rate from the Kilauea Volcano, calibration error from the BAM-1020, and/or a change in the large-scale weather patterns favorable to bring vog to Oahu in that year. El Nino Southern Oscillation (ENSO) was considered to be a likely trigger for vog occurrences. ENSO is marked by a warm-phase (El Nino) and a cold-phase (La Nina). The year 2009 was under a warm phase during the latter half of the year, 2010 was under a warm-phase during the first half of the year and a cold-phase during the second half, 2011 was mostly cold phase and the remaining years were neutral. Based on the limited data, there are no clear links between vog events and ENSO.

The annual mean number of vog days is about 16.8 days every year. The 95% bootstrap confidence interval for the mean is (12.2, 21.2). The bootstrap estimates any function of the underlying distribution by using the same function, but using the empirical distribution, which puts probability 1/n on each side of n observed PM$_{2.5}$ measurements. The method treats the finite sample at hand as similarly as possible to the unknown distribution from which it was drawn. The main idea behind the method is re-sampling with replacement, and is often used to estimate confidence intervals around observed values of a test statistic, such as the mean and the variance (Wilks, 2011).
3.3 What synoptic-scale patterns bring vog to Oahu?

This is a major part of the study and will be answered using mainly ERA-Interim reanalysis data, and the ocean analysis charts for extra guidance. The ERA-Interim’s six-hour output was studied two days prior to the vog day(s), during the vog day(s), and one day after to subjectively determine the type of weather pattern. This is where the 101 vog days were studied in detail and successfully divided into the three large-scale weather patterns: pre-cold fronts, Kona lows, and upper-level disturbances. Under the section entitled “case studies”, one event from each weather pattern will be discussed in more detail, and the HYSPLIT model will show ensemble trajectory and concentration plots of each event.

3.3.1 Large-scale weather pattern 1: Pre-cold fronts

In winter, the trade winds are frequently disrupted by the passage of cold fronts that penetrate into the subtropics. The most common way to recognize a cold front on a weather map is by the sharp change in temperature, humidity, and wind direction. But these cold fronts are often slow moving and modified by the underlying warm ocean water, and are sometimes called shear lines because of the contrast in wind fields rather than a distinct temperature gradient (Larson, 1976). Cold fronts may usually bring light to moderate rainfall to the Hawaiian Islands, but heavy rain can occur in the prefrontal zone (Blumenstock, 1967). Most cold fronts dissipate or pass to the north of the islands before crossing the entire island chain. The mean number of frontal passages at Kauai per winter season is about 16, but only about nine frontal passages will make it all the way down to the Big Island (Worthley, 1967).
In this study, a cold front was defined as when 1) a low-pressure system with its associated frontal boundary builds in closer to the islands, and 2) the subtropical high is being pushed farther to the east. The vog is brought to Oahu before the cold front has passed the islands while the low-level winds are still coming out of the south and southwest, so the cold front category will be referred to as pre-frontal. After the passing, the winds turn to the north and northwest.

A keynote about the pre-cold front events was the duration. Some events only lasted a couple of hours while other events lasted up till four days. One argument is that the stronger cold fronts moved through much faster than the weaker cold fronts or shear lines. The longer duration events could also have a stalled front that dissipated before even reaching Oahu, and the event were also longer if there were multiple fronts involved.

**Case study I: A short-duration pre-cold front event**

The first case study was for a short-duration pre-cold front event. The event occurred on 2 February, 2010, and there were two peaks in PM$_{2.5}$ that day. One peak is from 0800 - 1100 HST where the values range from 10 - 16 µg/m$^3$, and the second peak is from 1600 - 1900 HST where the values are about 10-15 µg/m$^3$ (Fig. 8). Fig. 9 shows the low-pressure system with its frontal boundary and the subtropical high pushed to east at 0200 HST 2 February 2010. The cold front moved rather quickly and passed Oahu by 0500 HST 3 February 2010 (Fig. 10). The PM$_{2.5}$ values are high on 2 February because the winds are still coming out of the southeast. At 1400 HST on 2 February the cold front is over Kauai, and around 0100 HST the next day the cold front passes Oahu and is located over Maui County. The synoptic maps are
consistent with the changes in PM$_{2.5}$ values, as the cold front is approaching we have higher vog values and once the front passes the values drop.

The ERA-Interim reanalysis data for this one-day cold front event was dynamically downscaled to a resolution of 3.3 km. The simulation was conducted from two days before the first appearance of moderate PM$_{2.5}$ values until one day after the event ended. The data were then run in HYSPLIT to produce an ensemble trajectory plot and concentration plots (Fig. 11). The ensemble trajectory (Fig. 11a) plot shows the trade winds are first blowing the vog plume from the Big Island out to sea. Some of the trajectories continue westward and a couple of the trajectories get caught in the Big Island wake. Most of the plume is blown from the south and northwestern towards Oahu and Maui County. When the cold front passes over Oahu, the winds shift to northwesterly. The subtropical high pressure builds back in and the trade winds reappear. This type of wind pattern associated with a cold front gives the trajectories a U-shaped path.

The concentration plots are run for 24-, 48-, and 72-hours. Fig. 11b and Fig. 11c shows the vog plume still affected by the trade winds, while Fig. 11d shows the wind shift as the front passes through the island chain. The highest concentration is to the west of the Big Island and Maui County, and to the east of the island chain. There are only a couple of areas of vog over Oahu. This figure is consistent with the DOH data that shows elevated but not too extreme values.

**Case study II: A long-duration pre-cold front event**

The second case study is a long pre-cold front event. The PM$_{2.5}$ values were elevated up to four days. The levels started to increase 0800 HST 22 January 2010,
and peaked around 2000 HST with 25 µg/m³ on the same day (Fig. 12). The next day the values were higher throughout the day ranging from 15 - 43 µg/m³, slightly lower on 24 January with values from 8 - 24 µg/m³, and higher again on 25 January with values around 11 - 35 µg/m³. The values went back down to normal on 26 January. This case study had the highest measured PM$_{2.5}$ values of the four case studies.

Fig. 13 shows the subtropical high being pushed to the east by the low-pressure system moving in from the west at 0200 HST 22 January. The cold front is approaching the island chain in Fig. 14a and 14b from the ocean analysis figure, but in Fig. 14c the front becomes stationary right to the north of Oahu. This front never reaches Oahu and moves to the east while remaining north of the island chain. A second cold front moves in closer on the early morning of 24 January. This cold front has more momentum than the previous front and passes Oahu around 0200 HST 27 January. One major feature to note is the much higher values of PM$_{2.5}$ during a long-duration event. The stalled front to the north of the island along with a second front moving in allows the vog to accumulate and remain high over Oahu for four days.

The ERA-Interim was again dynamically downscaled by using WRF. The ensemble trajectory plot and concentration plots from the HYSPLIT model are found in Fig. 15. In the ensemble trajectory plot (Fig. 15a), the wind initially blows from the northeast carrying the plume into the Big Island wake. The wind then turns southerly and heads to the northwest. This time the wind blows from the south much longer than by the previous discussed case study, and turns northwesterly on 23 January. All the trajectories show a similar trajectory path. Both the cold front cases have a similar U-shaped pattern in the trajectory plots.
Fig. 15b show the vog plume still being affected by the trade winds, and Fig. 15c shows how the vog plume is being affected by southerly winds and starting to cover the entire island chain. Fig. 15d shows a much higher concentration than the previous event, covering the entire island chain and surrounding water.

3.3.2 Large-scale weather pattern 2: Kona lows

The second type of synoptic pattern that brings vog to Oahu is a Kona low, also known as a subtropical cyclone. The word Kona is Hawaiian and is translated as leeward. During Kona lows, the winds shift to come out of the south instead of normal trades that come from the northeast or east. The Kona low can last for days or weeks without weakening and is associated with a variety of weather-related hazards including heavy rains, hailstorms, flash floods, landslides, high winds, large surf and swell, waterspouts, and thunderstorms (Morrison and Businger, 2000). They are cold core systems with the strongest circulation in the middle and upper troposphere, and are usually cutoffs from the upper-level subtropical westerlies. Kona lows are usually hard to forecast due to their erratic track, and they can propagate westward for long distances.

The criteria for a low to be categorized as a Kona low following Caruso and Businger (2005) are: 1) the upper-level low must remain cut off from the midlatitude westerlies for at least 24 hours, 2) the upper-level low’s center must pass south of 30°N, and 3) the low must occur during the cool season which is defined as from the beginning of October through April. In this study, the definition of a Kona low is similar but with two minor adjustments. The upper-level low’s center must pass south
of 35°N, and the period is from October through May. This definition found three Kona lows among the 101 vog days. The location of the Kona low was usually to the north of the islands, and the duration of the vog event is one or two days.

**Case study III: A Kona low event**

The third case study is of a Kona low from 2-3 May, 2010. The PM$_{2.5}$ values start to increase 1600 HST 2 May, and stay high the next day with levels at 8 - 18 µg/m$^3$ (Fig. 16).

The reanalysis data for (a) MSL, (b) 850-hPa, (c) 500-hPa, and (d) 250-hPa from 0200 HST 2 May are shown in Fig. 17. Fig. 17a shows the subtropical high to the northeast of the state, and a surface low immediately to the north-northwest. The circulation at the surface is present for more than 24 hours, and the cut-off low is evident at all the different levels up to 250-hPa (Fig. 17b, c, d). Fig. 18a shows the subtropical high pushed to the east and a low-pressure center with a stationary front extending from the north of the islands and all the way to the mainland U.S. Fig. 18b shows the subtropical high and the low-pressure deepening and moving slightly northwest. Fig. 18c shows a further deepening of the low-pressure with a cold front located above Kauai. The Kona low gradually weakens and moves northwestward by 4 May 2010 (Fig. 18d).

One feature to note about the Kona low is that the location is very important for vog to reach Oahu. Not all Kona lows bring vog to Oahu, only the Kona lows that are located in a favorable location, for example, to the north of the island chain.

ERA-Interim data were dynamically downscaled to 3.3 km by using the WRF model. The output was then used to produce an ensemble trajectory and concentration
plots (Fig. 19). The ensemble trajectory-plot (Fig. 19a) shows that most of the ensemble trajectories travels a curved path towards northwest, and a couple of the trajectories get caught in the Big Island wake. Fig. 19b shows that the plume is starting to follow the same curved northwestward track, and also higher concentrations appear along the Kona coast. Fig. 19c and Fig. 19d show the vog plume covering the entire island chain. The direction of the plume is from the southeast pulling the higher concentrations of the vog plume over all the islands except Kauai. This pattern is different compared to the two prefrontal cases, where the vog plume followed a U-shaped path. In this case, the vog plume is going directly over the islands with the highest concentrations over the Big Island, Maui County and Oahu.

3.3.3 Large-scale weather pattern 3: Upper-level disturbances

The upper-level disturbance pattern can occur any time of year. The upper-level disturbance has the strongest circulation in the upper levels, and when the circulation penetrates downward it can affect the winds at the surface. One consequence can be the possibility of deep convection and heavy rain. The upper-level disturbance is similar to a Kona low when it comes to the downward development but the difference is that a Kona low has a closed surface circulation while the upper-level disturbance does not.

One type of an upper-level disturbance is the Tropical Upper Tropospheric Trough (TUTT) cell. The TUTT cell forms during summer over the ocean, and moves west-southwest. These cells have a favored updraft and rainfall on their south and east sides, and they have sinking on the north and west sides (Kelley and Mock, 1982).
The TUTT has a synoptic scale of about 3000 km in diameter. As mentioned, the TUTT is weaker in lower levels, and usually harder to find below 500 hPa. They can still de-stabilize the upper atmosphere, eliminate subsidence and cause heavy rainfall. In this study, the definition of an upper-level disturbance is fairly simple and includes a trough or a center of low pressure in the upper levels. This upper-level feature is the cause of a more southerly component at the surface. There were a total of 17 events that had an upper-level disturbance that brought vog to Oahu.

**Case study IV: An upper-level disturbance event**

The fourth case study is of an upper-level disturbance that occurred on 22 May, 2013 and the elevated PM$_{2.5}$ values last two days. The values are high from 1000-1700 HST 22 May ranging from 11-22 µg/m$^3$, and high all day 23 May ranging from 6-26 µg/m$^3$ (Fig. 20).

Fig. 21, the reanalysis data from 0200 HST May 22 2013, shows the broad subtropical high to the northeast of the state at the surface. This large-scale pattern would normally bring trade winds to the island chain, but there is a surface trough over the islands so it did affect the surface flow. The surface trough is a result of an upper-level low that is clearly seen at the 250-hPa level (Fig. 21d) and down to the 850-hPa level (Fig. 21b). The surface trough is easily observed in the synoptic map from 0400 HST 21 May, shows the subtropical high far to the north-northeast and an inverted trough located above the islands (Fig. 22a). An inverted trough bulges to the north, while still having cyclonic circulation. Twenty-four hours later (Fig. 22b), the inverted trough is less significant but still enough to keep the winds coming form the southeast. The inverted trough weakens more on 23 May (Fig. 22d), and becomes
slightly more pronounced on 24 May in Fig. 22d. The inverted trough is what causes the winds to turn southeasterly at the surface, which then bring the vog to Oahu.

The upper-level event was dynamically downscaled to a resolution of 3.3 km by using the WRF model. The run in WRF was started on 20 May and included two days prior to the event, the two days during the event, and one day after, which was 25 May. The ensemble trajectory plot in Fig. 23a shows how the wind shifts from southerly to easterly. The wind shift allows the vog plume to travel over the island chain. Fig. 23b shows the southerly wind taking the vog plume toward the north, and Fig. 23c shows the wind direction is shifting and coming from the southeast at this point. Fig. 23d has the highest concentration to the west of the Hawaiian Islands, and only a couple of patches of vog over Oahu.
4. CONCLUSION AND DISCUSSION

I have used the DOH PM$_{2.5}$ measurements from Honolulu to identify 101 vog days over a five year and nine month period. One vog day was defined by finding at least three consecutive hours of PM$_{2.5}$ greater than or equal to 13 $\mu$g/m$^3$. Vog days represent 4.8% of the period from April 2009 through 2014. ERA-Interim data were examined along with ocean products from SRRS to determine the large-scale weather patterns associated with each vog day. The results showed that the 101 vog days were actually associated with 57 vog events lasting in duration from one to four days. Vog does not reach Oahu during regular trade wind days; instead all the vog events occurred under the influence of one of three different synoptic-scale disturbances. These are 1) pre-cold fronts, 2) Kona lows, and 3) upper-level disturbances. The majority of the event types were prefrontal, which were responsible for 65% of the total number of vog events, another 30% were upper-level disturbances, and only 5% were Kona low events.

It is rare to experience vog events during summertime, and most of the events happen during wintertime from October through May. The typical duration of an event depends on the synoptic phenomena involved. The Kona low events lasted from one to two days, the upper-level disturbance events lasted from one to three days, and the prefrontal events lasted up to four days. During the vog events, the PM$_{2.5}$ measurements have an oscillating behavior and are not continually high throughout the event period.

The ERA-Interim reanalysis data from four case studies were dynamically downscaled in WRF, and run in HYSPLIT to demonstrate how the vog plume
behaved in each type of synoptic pattern. The two prefrontal cases showed a U-shaped ensemble trajectory path from Big Island to Oahu. The Kona low to the north of the Hawaiian Island allowed the vog plume to be pulled across the state by the southeasterly winds. The upper-level disturbance altered the trade wind flow to create southerly winds at the surface.

4.1 Interpretation of the Results

Previous studies found that approximately nine cold fronts per year pass through Hilo (Worthley, 1967). However, Kauai usually experiences a few more cold fronts than does Oahu and the other islands, because of its location at the northwestern end of the island chain. Sometimes the southernmost edge of a cool air mass will barely reach Kauai and then move eastward without reaching as far as Oahu. Other times, cold fronts may pass Oahu but will dissipate before reaching the remaining islands (Blumenstock, 1967). It is believed that this type of stalled prefrontal event brings in the highest levels of vog, allowing weak southerly winds to persist while the vog is accumulating over the island chain. According to the HYSPLIT model, both ensemble trajectory plots for the prefrontal cases showed a U-shaped path with vog first moving in a southwestward direction then re-curving and moving towards the northeast east to Oahu.

The annual number of Kona lows vary from year to year; however, the center needs to pass to the north of the Hawaiian Islands in order for the vog to reach Oahu. During the Kona low case study, the vog plume was transported across the entire
island chain from the southeast towards the northwest with a slight arc in the trajectories.

The upper-level disturbances can occur any time of year but during this study vog events were only found during wintertime. The upper-level disturbance is strongest in the upper troposphere, however, the circulation can penetrates downward and alters the trade wind layer flow. Knowledge about each of the three synoptic patterns and how they affect the vog plume can be a useful tool to help predict future vog events. This will allow the NWS to issue advisories so that people sensitive to vog can have time to plan and prepare before a vog event will occur.

4.2 Caveats

The threshold of 13 µg/m³ was chosen according to the AQI set by the EPA, where the air quality is considered moderate according to the federal standards. A problem with this is that the pollution on the mainland is different from the natural pollution from the Kilauea Volcanco. The volcano is very sulfur rich compared to man-made pollution so this might not be the correct standard for the state of Hawaii.

The DOH hourly PM₂.₅ data from Oahu is less than six years long. Only one station was used, which does not allow for any estimate of the spatial coverage of the vog. The data set also has missing days that could potentially have contained more vog events.

The reanalysis dataset chosen has a resolution of 0.75° by 0.75°. However, even with this resolution, the reanalysis data are not perfect, and especially not over the Central North Pacific Ocean where there are limited observations. According to Dee et al. (2011), there are limited observations of humidity, wind, and the distribution of
aerosols and greenhouse gases in large parts of the atmosphere. The gaps are filled by data assimilations by using physically meaningful information from forecast models, but this gap filling will always lead to uncertainties in the dataset.

When it comes to the HYSPLIT model, the first assumption converts all the SO$_2$ from the vents into SO$_4$ immediately after being released. The SO$_2$ has an actual conversion rate of 6 ± 4 hours, so the immediate conversion is a simplification. The emission rate in HYSPLIT is set to continuously release 3,700 tons of SO$_2$ per day, while the actual value fluctuates much more.

The WRF model requires several parameterization schemes including those for cumulus convection, surface fluxes of heat and moisture, and fluxes of momentum and vertical mixing in the planetary boundary layer. These are all crude approximations of the true physics and can thus affect the results.

There is speculation that pollution from far away can affect the vog measurements in Hawaii. This type of pollution would be long-range transport of anthropogenic or natural acidic material from major sources of continental origin. One example is Asian dust, which is transported into the mid-troposphere and then moved across the Pacific by the prevailing winds at levels above 2000 m (Miller, 1981). To be certain, case studies would have to be chosen and simulated in HYSPLIT along with back-trajectories to trace back the source.

There could potentially be a fourth synoptic pattern, where tropical cyclones would bring up vog from the Big Island. However, due to lack of observations this cannot be confirmed or denied. The hypothesis is that a tropical cyclone either passes in proximity to the islands bringing up the vog or that the trade winds flow gets
disrupted and winds turn southerly. Tropical cyclones usually bring heavy rainfall, so wet deposition could play a part in lowering the vog concentrations.

### 4.3 Future work

In this study, only four events were dynamically downscaled and simulated in the HYSPLIT model. These four events gave insight to the specific characteristics of each vog category, but one way to improve the study would be to dynamically downscale and run all the 57 vog events in HYSPLIT. Having more trajectory and concentration plots would allow a greater understanding for each type of synoptic-scale disturbance. If each category has a distinct path and concentration level associated with it, then knowing this in advance will allow for a better forecast of future vog events.

The other way to improve the study would be to count all the cold fronts that approached the Hawaiian Island. The total amount of cold fronts could then be compared to the cold fronts that brought vog to Oahu. This would allow insight in how many cold fronts actually bring vog to the station in Honolulu. The total number of Kona lows could also be compared to the three Kona lows found by station Honolulu. A comparison of the total amount of Kona lows with the three Kona lows that did bring vog to Oahu, would give characteristics of the Kona lows that actually will bring vog to the Island and aiding in future vog forecasting.

A final desirable condition would be the establishment of more vog monitoring stations on the island of Oahu, and eventually a longer period of PM$_{2.5}$ measurements. New stations should be placed away from industrial areas and highways, and be
placed from the Westside of Oahu to Hawaii Kai. More stations would allow for improved spatial coverage during vog events.
5. References


Table 1. The air quality guide for particle pollution. Figure taken from the website: www.airnow.gov.

### Air Quality Guide for Particle Pollution

Harmful particle pollution is one of our nation’s most common air pollutants. Use the chart below to help reduce your exposure and protect your health. For your local air quality forecast, visit [www.airnow.gov](http://www.airnow.gov).

<table>
<thead>
<tr>
<th>Air Quality Index</th>
<th>Who Needs to Be Concerned?</th>
<th>What Should I Do?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good (0-50)</td>
<td>No one. Air quality is good for everyone.</td>
<td>It’s a great day to be active outside!</td>
</tr>
<tr>
<td>Moderate (51-100)</td>
<td>Some people may be unusually sensitive to particle pollution and may need to take precautions.</td>
<td>Unusually sensitive people: Consider reducing prolonged or heavy exertion. Watch for symptoms such as coughing or shortness of breath. These are signs to take it a little easier. Everyone else: It’s a good day to be active outside!</td>
</tr>
<tr>
<td>Unhealthy for Sensitive Groups (101-150)</td>
<td>Sensitive groups include people with heart or lung disease, older adults, children and teenagers.</td>
<td>Sensitive groups: Reduce prolonged or heavy exertion. It’s OK to be active outside, but take more breaks and do less intense activities. Watch for symptoms such as coughing or shortness of breath. People with asthma should follow their asthma action plans and keep quick relief medicine handy. If you have heart disease: Symptoms such as palpitations, shortness of breath, or unusual fatigue may indicate a serious problem. If you have any of these, contact your health care provider.</td>
</tr>
<tr>
<td>Unhealthy (151-200)</td>
<td>Everyone can be affected.</td>
<td>Sensitive groups: Avoid prolonged or heavy exertion. Consider moving activities indoors or rescheduling. Everyone else: Reduce prolonged or heavy exertion. Take more breaks during all outdoor activities.</td>
</tr>
<tr>
<td>Very Unhealthy (201-300)</td>
<td>Everyone</td>
<td>Sensitive groups: Avoid all physical activity outdoors. Move activities indoors or reschedule to a time when air quality is better. Everyone else: Avoid prolonged or heavy exertion. Consider moving activities indoors or rescheduling to a time when air quality is better.</td>
</tr>
<tr>
<td>Hazardous (301-500)</td>
<td>Everyone</td>
<td>Everyone: Avoid all physical activity outdoors. Sensitive groups: Remain indoors and keep activity levels low. Follow tips for keeping particle levels low indoors.</td>
</tr>
</tbody>
</table>
Table 2. The state and federal standards for certain air pollutants in the U.S.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Monoxide (CO)</td>
<td>1-hour</td>
<td>9 ppm</td>
<td>35 ppm</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>8-hour</td>
<td>4.4 ppm</td>
<td>9 ppm</td>
<td></td>
</tr>
<tr>
<td>Nitrogen Dioxide (NO₂)</td>
<td>1-hour</td>
<td>---</td>
<td>0.100 ppm</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
<td>0.04 ppm</td>
<td>0.053 ppm</td>
<td>0.053 ppm</td>
</tr>
<tr>
<td>PM₁₀</td>
<td>24-hour</td>
<td>150 μg/m³</td>
<td>150 μg/m³</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
<td>50 μg/m³</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>PM₂.₅</td>
<td>24-hour</td>
<td>---</td>
<td>35 μg/m³</td>
<td>55 μg/m³</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
<td>---</td>
<td>12 μg/m³</td>
<td>15 μg/m³</td>
</tr>
<tr>
<td>Ozone (O₃)</td>
<td>8-hour</td>
<td>0.08 ppm</td>
<td>0.075 ppm</td>
<td>0.075 ppm</td>
</tr>
<tr>
<td>Sulfur Dioxide (SO₂)</td>
<td>1-hour</td>
<td>---</td>
<td>0.075 ppm</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>3-hour</td>
<td>0.5 ppm</td>
<td>---</td>
<td>0.5 ppm</td>
</tr>
<tr>
<td></td>
<td>24-hour</td>
<td>0.14 ppm</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
<td>0.03 ppm</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>Rolling 3-month</td>
<td>1.5 μg/m³⁴</td>
<td>0.15 μg/m³</td>
<td>0.15 μg/m³</td>
</tr>
<tr>
<td>Hydrogen Sulfide</td>
<td>1-hour</td>
<td>0.025 ppm</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>


*a Primary Standards set limits to protect public health, including the health of "sensitive" populations such as asthmatics, children and the elderly.
*b Secondary Standards set limits to protect public welfare, including protection against decreased visibility, damage to animals, crops, vegetation, and buildings.
*c Due to a lack of evidence linking health problems to long-term exposure to coarse particle pollution, EPA revoked the annual PM₁₀ standard effective December 17, 2006. However, the state still has an annual standard.
*d The state standard is based on calendar quarter.
Table 3. The physics schemes chosen for the WRF model.

<table>
<thead>
<tr>
<th>Physics</th>
<th>Scheme</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud Microphysics</td>
<td>WRF Single-Moment 3-class</td>
<td>A simple, efficient scheme with ice and snow processes suitable for mesoscale grid sizes.</td>
</tr>
<tr>
<td>Shortwave Radiation</td>
<td>Dudhia</td>
<td>Simple downward integration allowing efficiently for clouds and clear-sky absorption and scattering.</td>
</tr>
<tr>
<td>Boundary Layer Physics</td>
<td>Yonsei University</td>
<td>Non-local-K scheme with explicit entrainment layer and parabolic K profile in unstable mixed layer.</td>
</tr>
<tr>
<td>Land Surface Processes</td>
<td>Noah Land Surface Model scheme: Unified NCEP/NCAR/AFWA</td>
<td>Soil temperature and moisture in four layers, fractional snow and frozen soil physics.</td>
</tr>
<tr>
<td>Cumulus Convection</td>
<td>Tiedtke scheme</td>
<td>Mass-flux type scheme with CAPE-removal time scale, shallow component and momentum transport.</td>
</tr>
</tbody>
</table>
Table 4. The total number of 57 vog events divided into three categories.

<table>
<thead>
<tr>
<th>Event:</th>
<th>Number:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-cold front</td>
<td>37</td>
</tr>
<tr>
<td>Upper-level disturbance</td>
<td>17</td>
</tr>
<tr>
<td>Kona low</td>
<td>3</td>
</tr>
</tbody>
</table>
Figure 1. The main Hawaiian Islands where the red dots indicate DOH measuring stations, the blue triangles are gas plant stations, and the two black stars are the vents on top of the Kilauea Volcano. The Puu Oo vent at the East Rift Zone is located closer to the ocean, and the Halema‘uma‘u vent at the summit is located further inland. Figure taken from the 2015 State of Hawaii Network Assessment.
Figure 2. The Halemaʻumaʻu vent located at the summit releasing water vapor (H₂O), sulfur dioxide (SO₂), and carbon dioxide (CO₂) along with other minor trace gases.
Figure 3. An example of typical aerosol size distributions near Hawaii for aerosols in equilibrium at a relative humidity of 75%. The red line depicts the accumulation mode concentration. Figure taken from Dr. John Porter’s website: www.soest.Hawaii.edu/porter.
Figure 4. The WPS domain configuration where in the outer domain is 10 km, and the inner domain is 3.3 km.
Figure 5. Showing hourly PM2.5 data from station Honolulu for (a) 2009, (b), 2010, (c) 2011, (d) 2012, (e) 2013, and (f) 2013. The red line indicates the threshold set by the AQI Index. The black arrows indicate areas of interest that will be discussed later.
Figure 6. Monthly mean of the vog days from station Honolulu with the time period from April 2009 through 2014.
Figure 7. Histogram of (top) the annual number of vog days and (bottom) the annual number of each synoptic-scale pattern at station Honolulu.
Figure 8. Time series of the hourly DOH PM$_{2.5}$ data for the pre-cold front (a) case on February 2$^{nd}$, 2010.
Figure 9. ERA-Interim reanalysis data from (a) Mean sea level (MSL) and geopotential height at (b) 850 hPa, (c) 500 hPa, and (d) 250 hPa (bottom right) for the short-duration pre-cold front event.
Figure 10. Ocean analysis product from the short-duration event on (a) February 1st, 2010, (b) February 2nd, 2010, and (c) February 3rd, 2010.
Figure 11. (a) Ensemble trajectory, (b) 24-, (c) 48- and (d) 72-hour concentration plots for the pre-cold front case on 2 February, 2010. The simulation starts on 31 January at 0200 HST, and runs for 72 hours.
Figure 12. Time series of the hourly DOH PM$_{2.5}$ data for the pre-cold front (a) case on January 22-24$^{th}$, 2010.
Figure 13. ERA-Interim reanalysis data at (a) Mean sea level (MSL), and geopotential height at (b) 850 hPa, (c) 500 hPa, and (d) 250 hPa for the long-duration pre-cold front event.
Figure 14. Ocean analysis from the long-duration cold front event on (a) January 22, (b) January 23rd, (c) January 24th, (d) January 25th, (e) January (f) January 26th, and (g) January 27th, 2010.
Figure 15. (a) Ensemble trajectory, (b) 24-hour, (c) 48-hour, and (d) 72-hour concentration plots from the pre-cold front on January 22-24\textsuperscript{th}, 2010. The simulation starts on January 21\textsuperscript{st} and runs for 72 hours.
Figure 16. Time series of the hourly DOH PM$_{2.5}$ data of (a) the Kona low case on May 2-3$^{rd}$, 2010.
Figure 17. ERA-Interim reanalysis data from (a) Mean sea level (MSL) in the top left panel, and geopotential height at (b) 850 hPa, (c) 500 hPa, and (d) 250 hPa for the Kona low event.
Figure 18. The ocean product from the Kona low event on (a) May 1st, (b) May 2nd, (c) May 3rd, and (d) May 4th, 2010.
Figure 19. (a) Ensemble trajectory, (b) 24-hour, (c) 48-hour, and (d) 72-hour concentration plots from Kona low case, 2-3 May, 2010. Simulations start 1 May and runs for 72 hours.
Figure 20. Time series of the hourly DOH PM$_{2.5}$ data of (a) the upper-level disturbance on May 22-23$^{rd}$, 2013.
Figure 21. ERA-Interim reanalysis data from (a) Mean sea level (MSL) in the top left panel, and geopotential height at (b) 850 hPa, (c) 500 hPa, and 250 hPa for the upper-level disturbance type of event.
Figure 22. The ocean product for the upper-level disturbance case from (a) May 21st, (b) May 22nd, (c) May 23rd, and (d) May 24th, 2013.
Figure 23. (a) Ensemble trajectory, (b) 24-hour concentration plot, (c) 48-hour concentration plot, and (d) 72-hour concentrations plot from the upper-level disturbance case on May 22-23rd, 2013. The simulation starts on 21 May and runs for 72 hours.