MFE 659 Lecture 5b
Air Pollution

Air Pollution – Elevated levels of aerosols and harmful gases

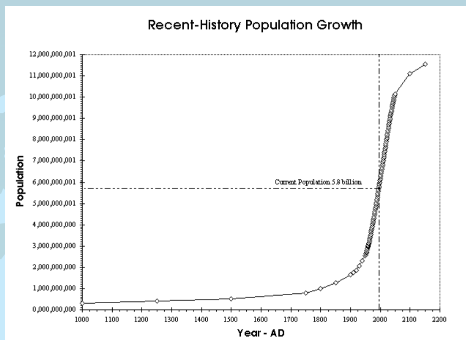
MFE 659 Lecture 5b Air Pollution

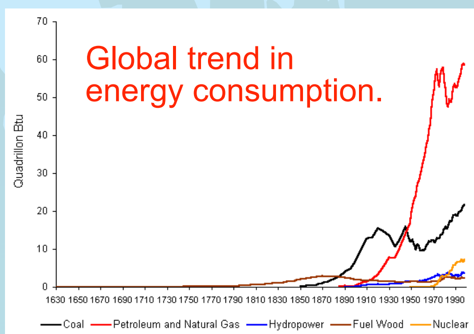
- A bit of history
- The planetary boundary layer
- Conditions that promote air pollution episodes
- Acid Rain
- Ozone Hole
- Volcanic smog or “vog”
- Monitoring vog
- Dispersion modeling of vog

Air Pollution – Elevated levels of aerosols and harmful gases

Air Pollution

Man-made pollution – related to population and industrialization.

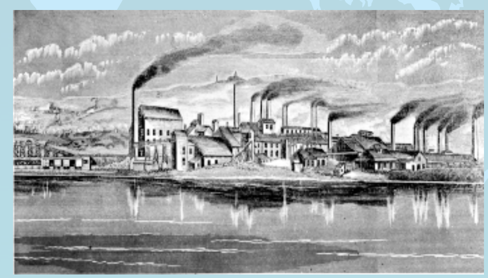




Historic Pollution Episodes

Many of the worst air pollution episodes occurred during the last two centuries in London, England.

- key ingredients - calm winds, fog, smoke from coal burning (thus the term smog)
- 1873 - 700 deaths
- 1911- 1150 deaths
- 1952 - over 4000 deaths
- this last event prompted the British parliament to pass a Clean Air Act in 1956



The Horse Problem

- Prior to the car, the horse was the dominant mode of transportation.
- Horse waste was a serious problem.
- In NYC 2.5 million tons of solid waste and 60,000 gallons of liquid waste had to be cleaned from the streets annually at the turn of the last century.
- 15,000 dead horses had to be removed from the city annually
- Odorous germ-laden street dust from dried waste caused disease.
- The car was considered the antiseptic solution,quieter, more comfortable, and cleaner.

US Pollution Episodes

- In the U.S., air quality degraded quickly shortly after the industrial revolution
- Problem was coal burning in the central and midwestern U.S.
- 1948 - Donora, PA in the Monongahela River Valley five-day episode - 1000's became ill, 20 were killed
- 1960s - NYC experience several dangerous episodes
- 1960s-70s - Los Angeles - increase in industry and automobile usage led to many pollution episodes
- The above events led to passing the Clean Air Act of 1970 (updated in 1977 and again in 1990) empowered the federal government to set emission standards that each state would have to meet.

Hazardous Pollutants

A particularly nasty bunch of pollutants

- Carbon Monoxide (CO) enters the bloodstream and causes cardiovascular damage and can lead to suffocation
- Ozone and Nitrogen Oxides (NO_2 and NO) damage the lungs, leading to asthma and other respiratory illnesses (especially in children)
- Particulate matter (PM_{10} and $PM_{2.5}$), especially from diesel trucks, is carcinogenic
- Sulfur Dioxide (SO_2) and NO_2 cause acid rain
- Lead (Pb) poisoning destroys the body's organs

National Ambient Air Quality Standards

The Clean Air Act requires Environmental Protection Agency (EPA) to set National Ambient Air Quality Standards for six common air pollutants.

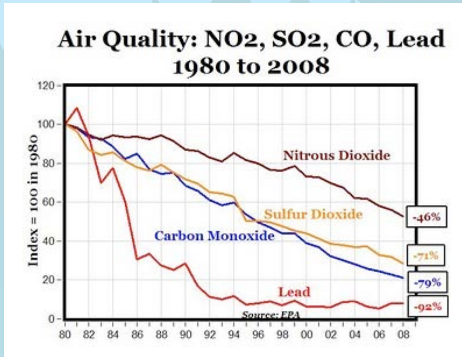
- Ozone
- Particulate Matter
- Carbon Monoxide
- Nitrogen Oxides
- Sulfur Dioxide
- Lead

Mexico City

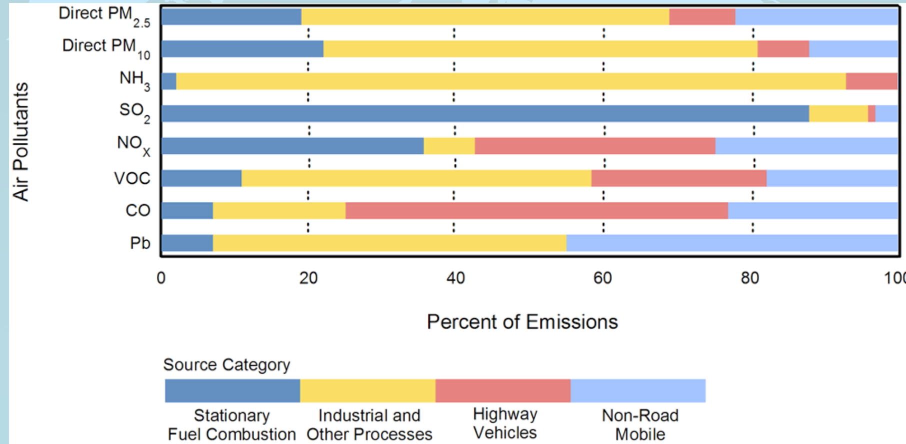
National Ambient Air Quality Standards

The Clean Air Act requires Environmental Protection Agency (EPA) to set National Ambient Air Quality Standards for seven common air pollutants.

- Volatile Organic Compounds
- Ozone
- Particulate Matter
- Carbon Monoxide
- Nitrogen Oxides
- Sulfur Dioxide
- Lead

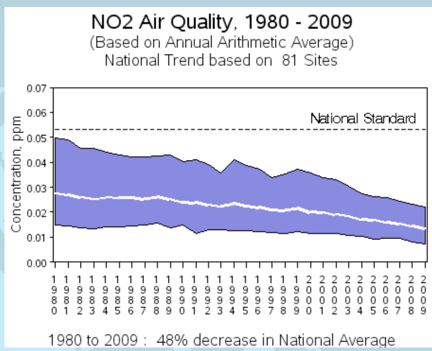


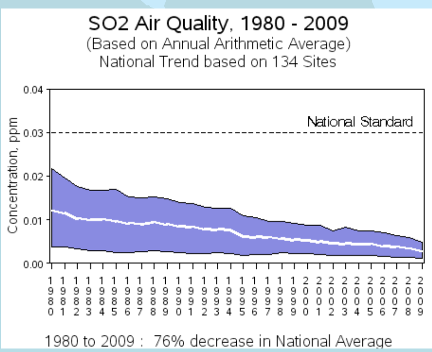
Sources of Pollution

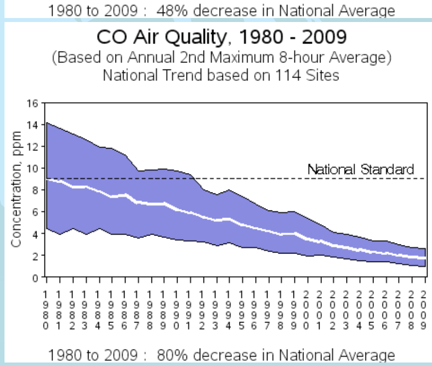


http://www.epa.gov/air/emissions/where.htm

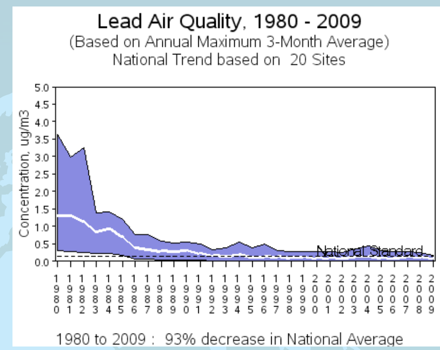
Pollution Trends 1980-2009

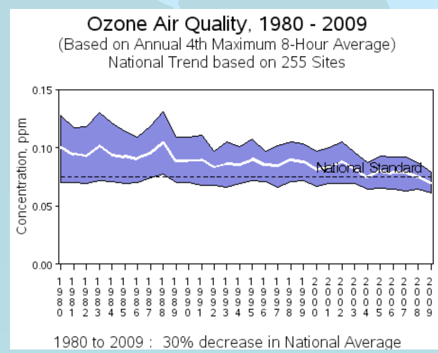


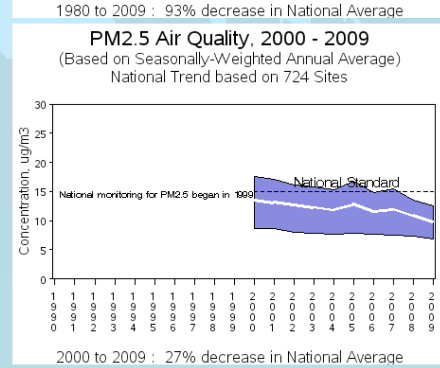




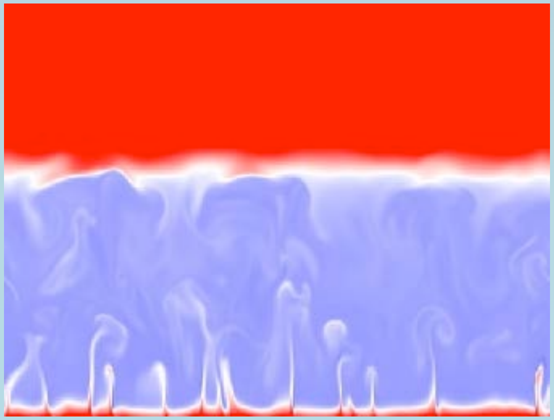
Pollution Trends 1980-2009





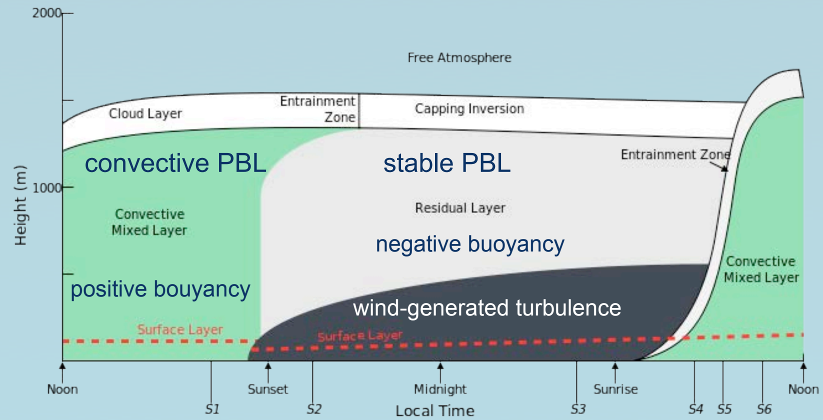


Planetary Boundary Layer (PBL) aka Atmospheric Boundary Layer



The planetary boundary layer (PBL), also known as the atmospheric boundary layer (ABL), is the lowest part of the atmosphere and its behavior is directly influenced by its contact with a planetary surface.

Diurnal Evolution of the PBL

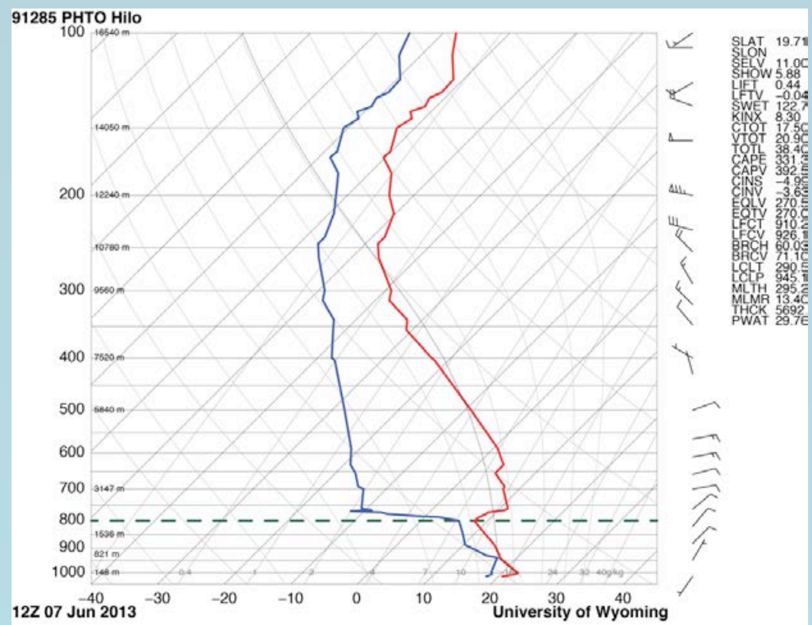


The PBL usually responds to changes in surface forcing in an hour or less. In this layer physical quantities such as flow velocity, temperature, moisture etc., display rapid fluctuations (turbulence) and vertical mixing is strong.

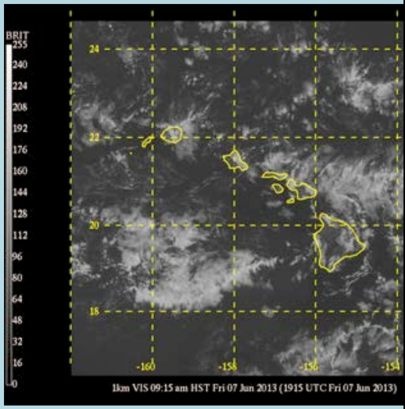
The Free Atmosphere

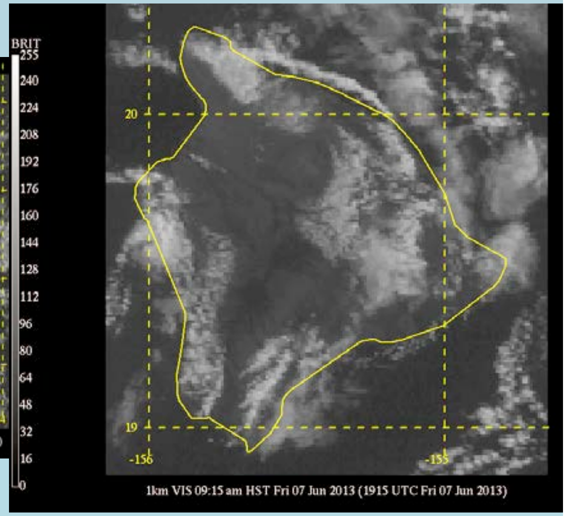
Above the PBL is the "free atmosphere" where the wind is approximately geostrophic (parallel to the isobars) while within the PBL the wind is affected by surface drag and turns across the isobars. The free atmosphere is usually nonturbulent, or only intermittently turbulent.

PBL in Hilo Today



PBL and Orographic Impact





Clean Boundary Layer

The atmospheric boundary layer is the lowest layer of the troposphere where friction is active. Most boundary layers are capped by a stable layer above.

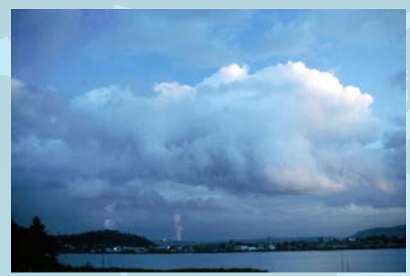
We live in and breathe the air of the boundary layer.

Clean Boundary Layer

It is more than a blessing to have clean air. It is essential for good health.

We live in and breathe the air of the boundary layer.

Pollution in the Boundary Layer



Most pollution enters the atmosphere near the surface.

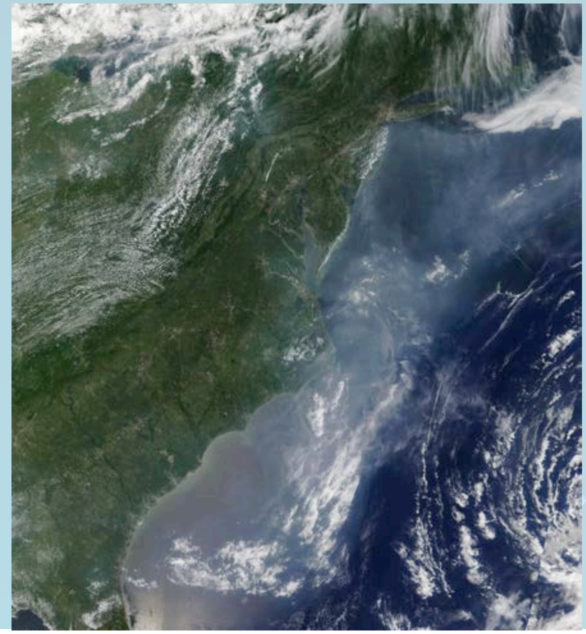
Conditions that Promote Pollution Episodes

Atmospheric conditions that limit horizontal and vertical mixing of the air result in high pollution concentrations.

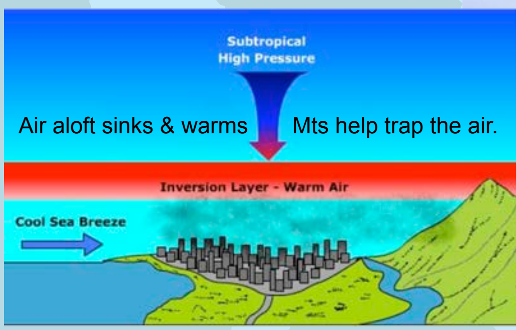
These conditions are found within areas of high surface pressure, especially in winter, when radiational cooling causes cold, stable air to collect near the surface.

Recent US Pollution Episode

High pressure with light winds and limited mixing lead to elevated levels of air pollution, visible along the East Coast in this satellite image.



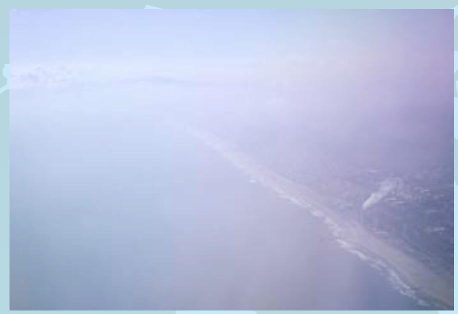
Pollution Episodes



Los Angeles from the air.

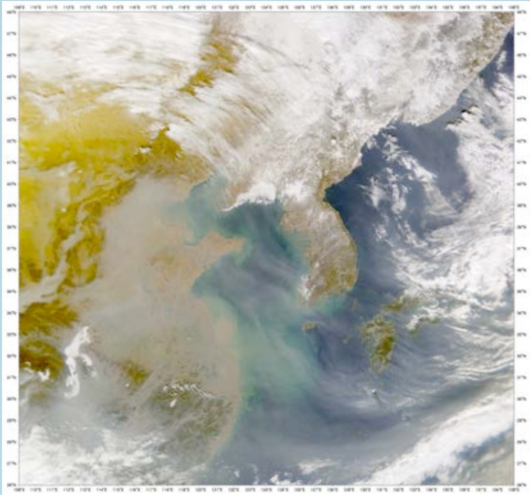
Pollution episodes occur in areas of high surface pressure resulting in stable air (temperature inversions) and light winds.

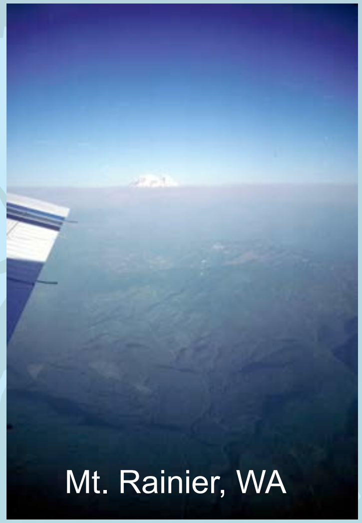
Polluted Boundary Layer



LA and Denver “brown clouds” primarily caused by automobile exhaust plus sunlight. Altitude and thin air exacerbates the problem in Denver.

Polluted Boundary Layer

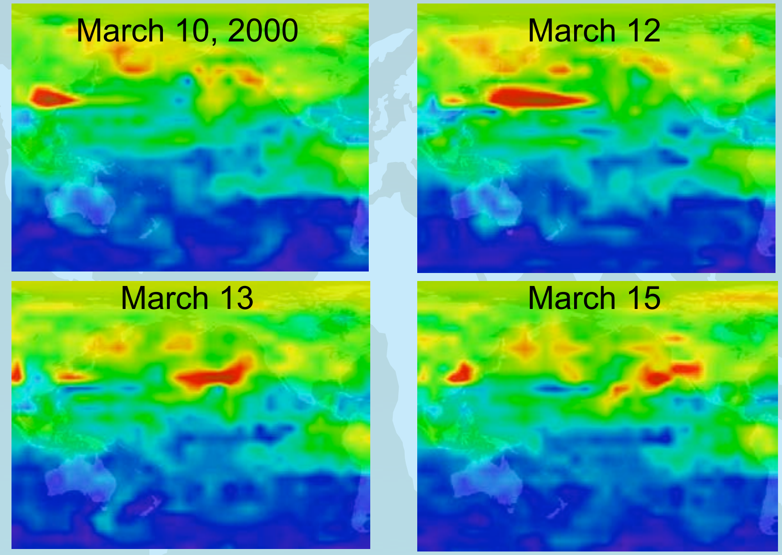




China from space.

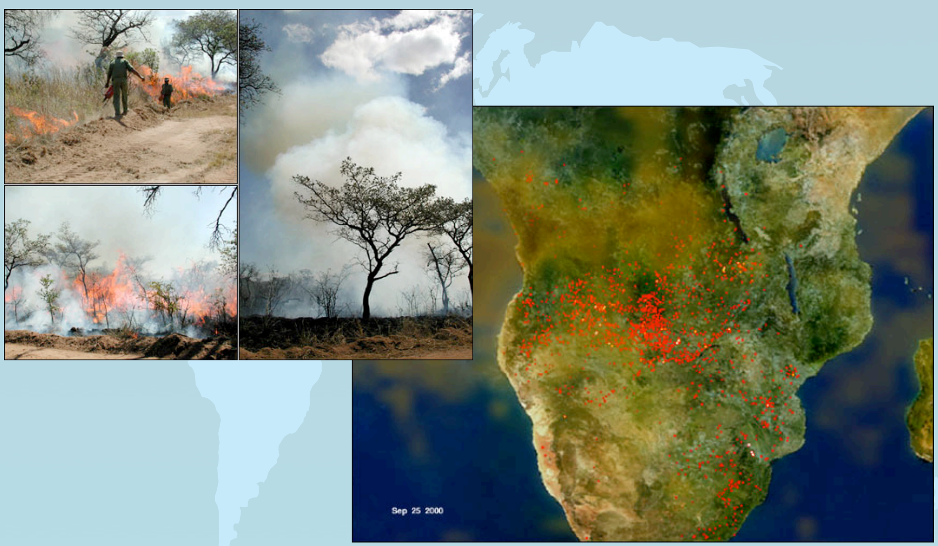
Pollution in the atmosphere can travel great distances.

CO concentration from Satellite



Carbon Monoxide (CO) at 15,000 ft traced from China to USA.
CO in the lungs prevents the uptake of oxygen!

Anthropogenic Sources of Air Pollution

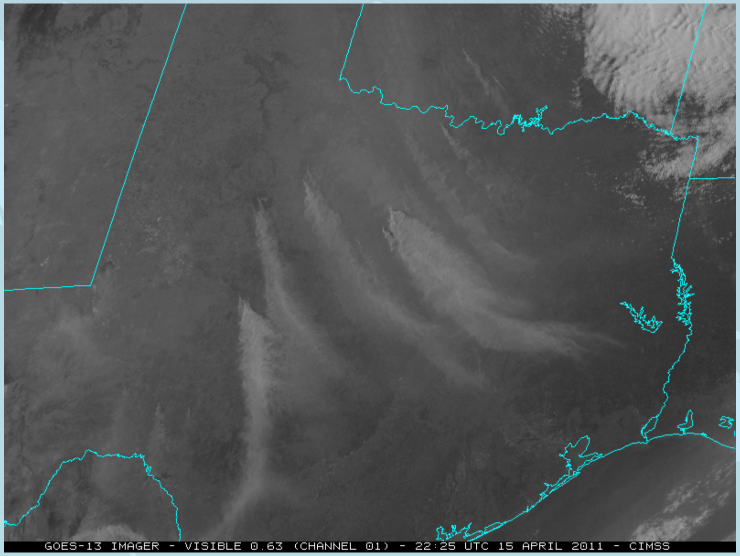


Intentionally set fires are a large source of pollution and CO_2

Fires are Promoted by Droughts

Texas wildfires fanned by high winds in April 2011.

Texas Wildfires Fanned by High Winds



Most pollution enters the atmosphere near the surface.

Wildfires

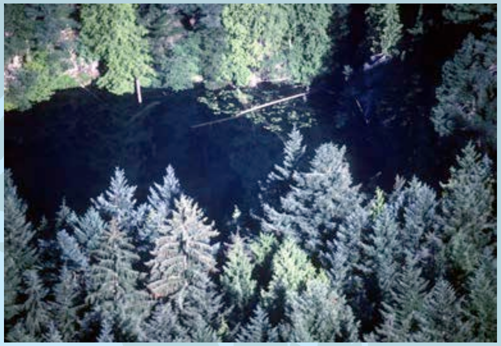
Big Meadow controlled burn --> Wild fire

Yosemite NP, August 2009

Acid Rain

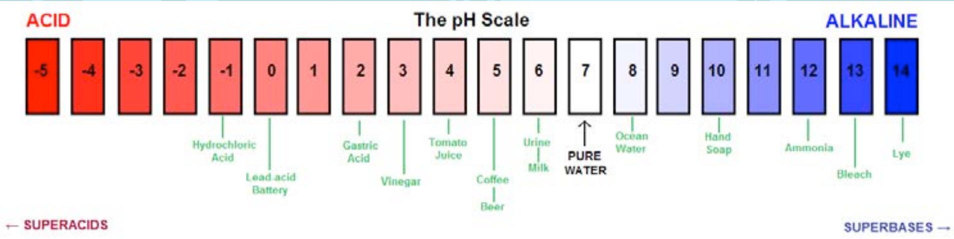
Acid rain is caused by sulfur dioxide (SO_2) and nitrogen oxides (NO_x) being released into the atmosphere and producing sulfuric acid and nitric acid.

Sources of SO_2 and NO_x include factories, power plants, automobiles, trucks.



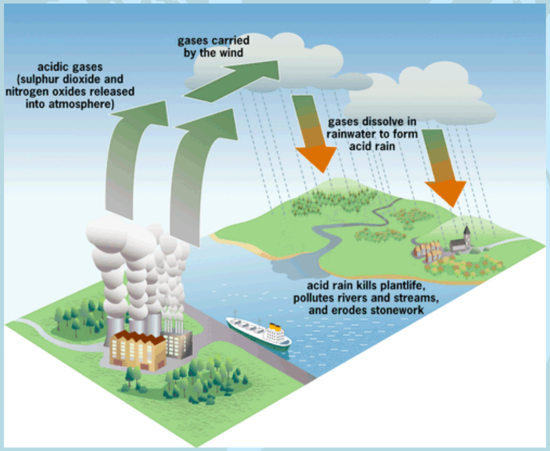
Acid Rain

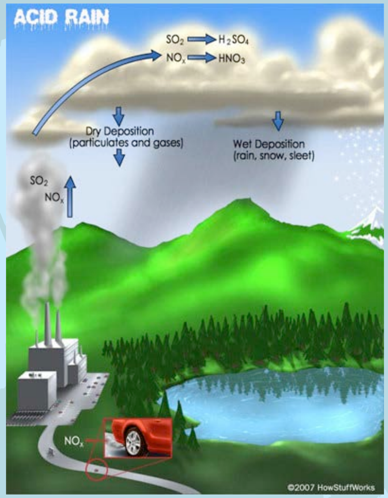
The pH scale measures how acidic or basic a substance is.



Acidic and basic are two extremes that describe chemicals, just like hot and cold are two extremes that describe temperature. Mixing acids and bases can cancel out their extreme effects, much like mixing hot and cold water can even out the water temperature. A substance that is neither acidic nor basic is neutral (e.g., pure water with a pH of 7).

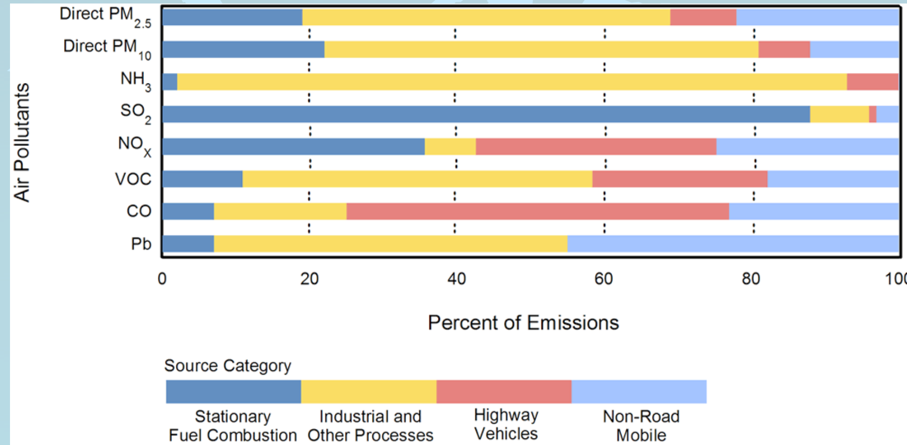
Acid Rain





Sources of SO_2 and NO_x include factories, power plants, automobiles, trucks and even pine forests.

Acid Rain



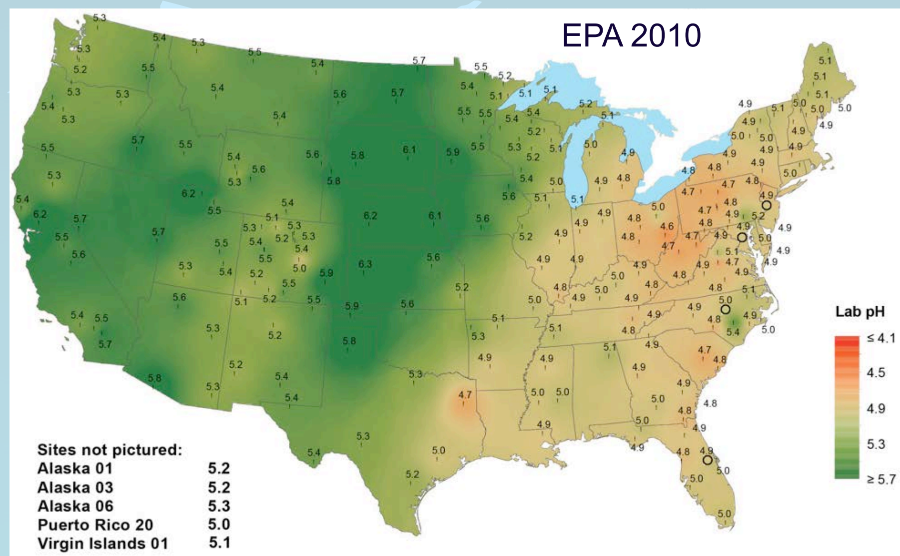
Sources of SO_2 and NO_x include factories, power plants, automobiles and trucks.

Acid Rain

Impacts of Acid Rain

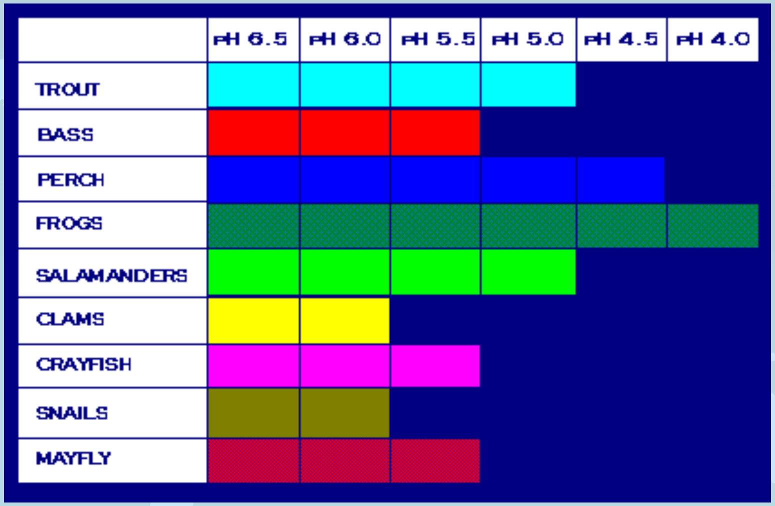
- Lakes and Streams
- Forests
- Human health: asthma, bronchitis, heart failure…
- Materials: Car coatings, roofing,…

pH of US Rain



Acid rain leeches heavy metals into lakes and streams.

Acid Rain



Animals are very sensitive to pH. Acid rain also leeches heavy metals, like mercury, into lakes, streams, and drinking water.

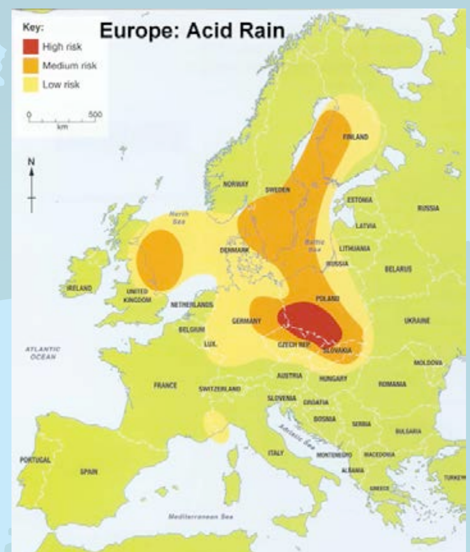
Acid Rain

Needles collect cloud water, which is more acid than rainwater.

Acid Rain

Spruce Forest in North Carolina impacted by Acid Rain

Acid Rain

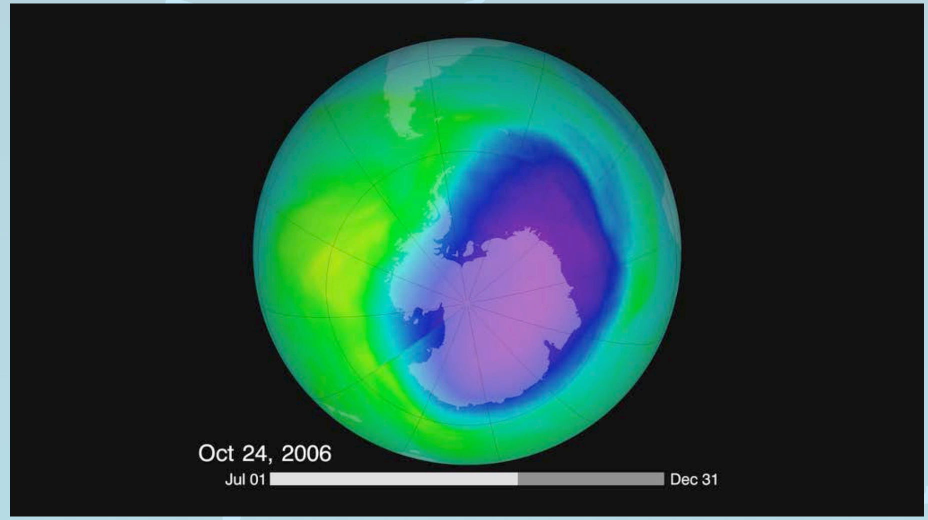


Spruce Forest in Europe impacted by Acid Rain

Costs of Acid Rain

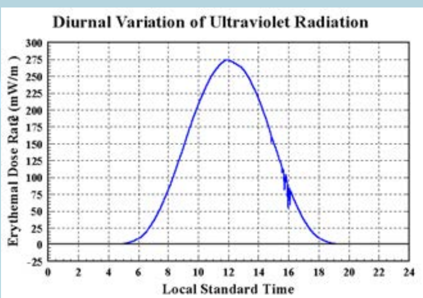
- Buildings: Marble and Limestone are dissolved by acid rain.
- Road way life is shortened.
- Metals on cars, bridges, tools, etc. are affected.
- Agricultural productivity reduced.

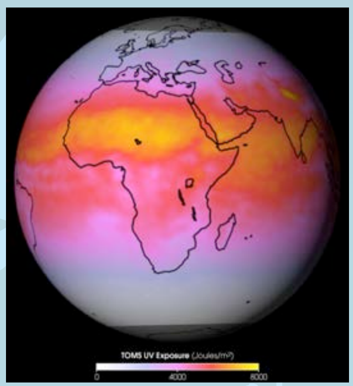
Global Ozone Depletion



The ozone hole reached its maximum extent in 2006.

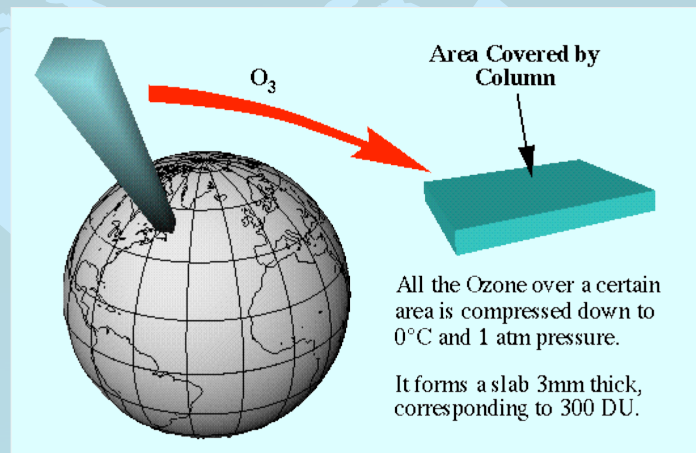
Hazards of Ozone Loss





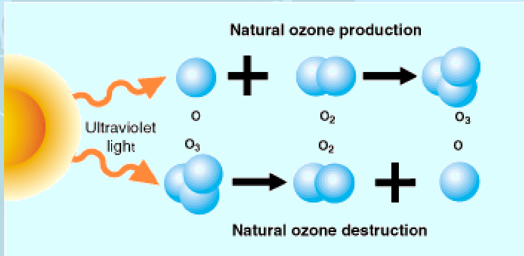
- Consequences of ozone loss
  - radiation reaching the ground
  - increase in skin cancer cases
  - increase in eye cataracts and sun burns
  - suppression of the human immune system
  - adverse impact on crops and animals due to increased UV
  - reduction in the growth of ocean phytoplankton
  - cooling of the stratosphere that could alter stratospheric wind patterns, possibly affecting the production (and destruction) of ozone.

Ozone Measurement

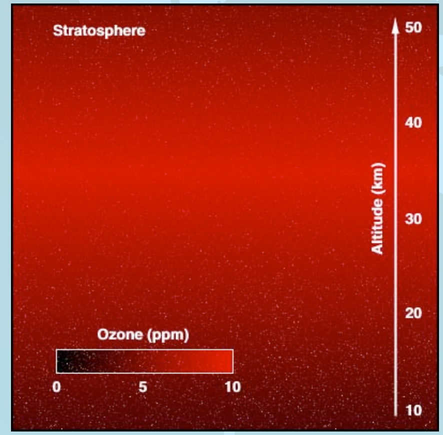


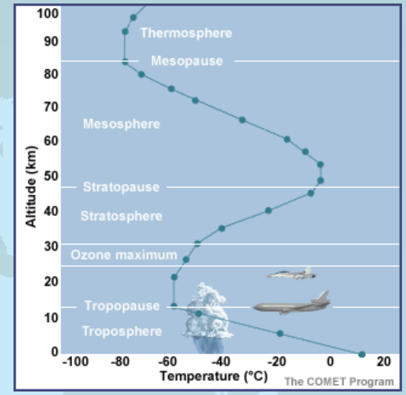
Atmospheric ozone is measured by satellite instrument in Dobson Units.

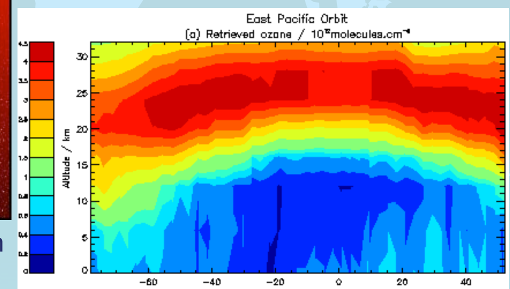
Natural Ozone Cycle



Ozone Distribution

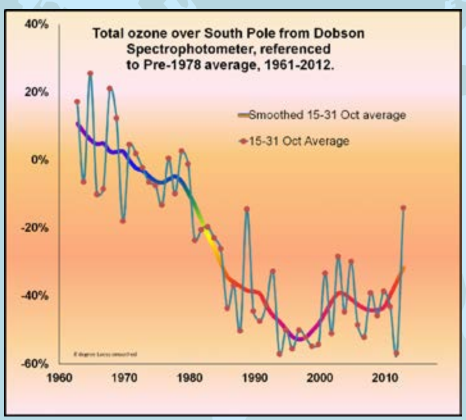


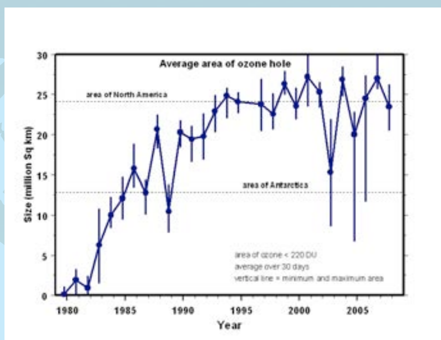




Ozone concentration is a maximum in the lower stratosphere

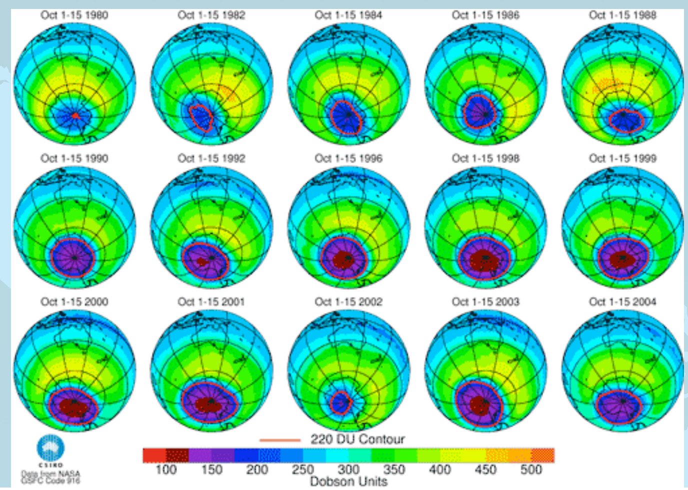
Ozone Hole

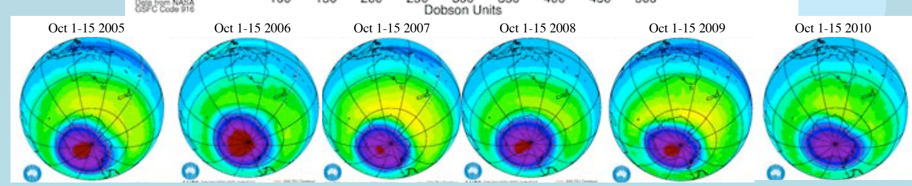




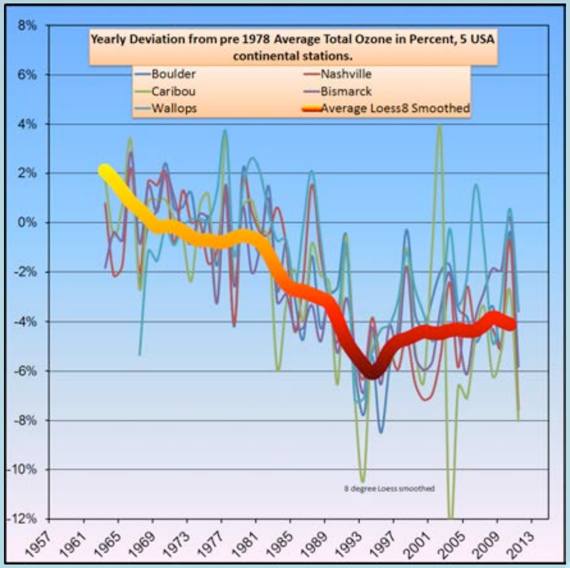
The decrease in ozone over the South Pole was first observed in the 1970's. It is linked to an increase in man made chemicals entering the atmosphere.

Ozone Hole



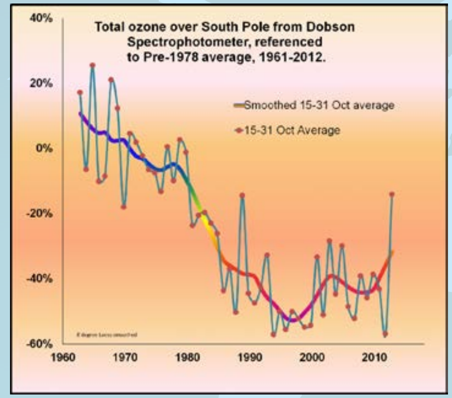


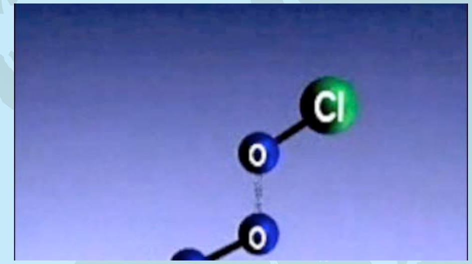
Ozone Declines



The decrease in ozone also observed at lower latitudes.

Causes for Stratospheric Ozone Depletion



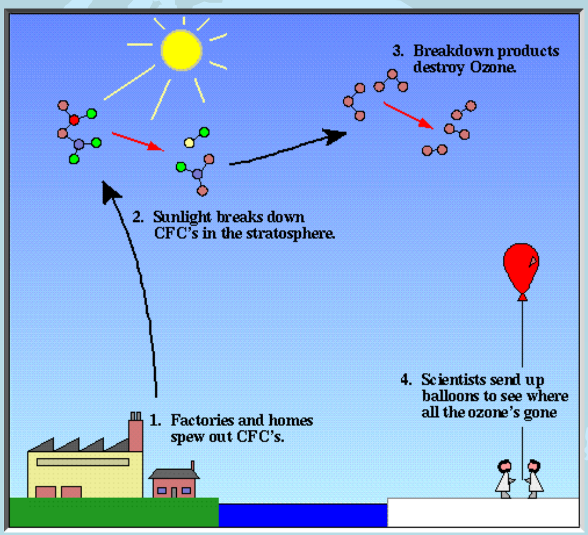


Chlorine and Bromine atoms result in global ozone depletion. CFCs release chlorine and halons release bromine. The most rapid breakdown of ozone occurs on the surface of polar stratospheric clouds.

Causes for Stratospheric Ozone Depletion

CFCs release chlorine atoms, and halons release bromine atoms

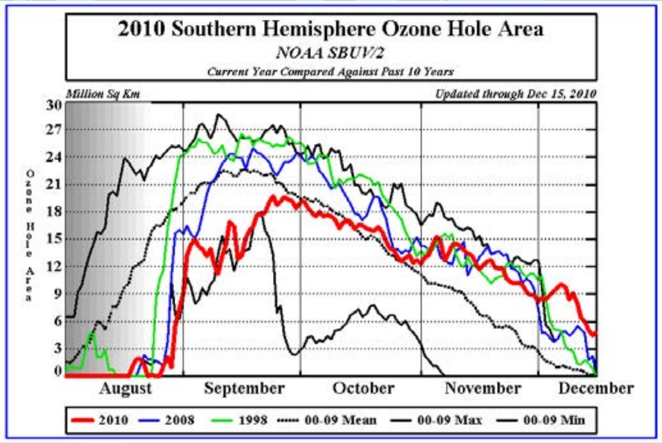
Chlorine and Bromine atoms result in ozone depletion.



Ozone Hole and Clouds

- Chlorine and Bromine compounds result in ozone depletion.
- Most rapid breakdown of ozone occurs on the surface of polar stratospheric clouds.

Changes in the Area of the Ozone Hole

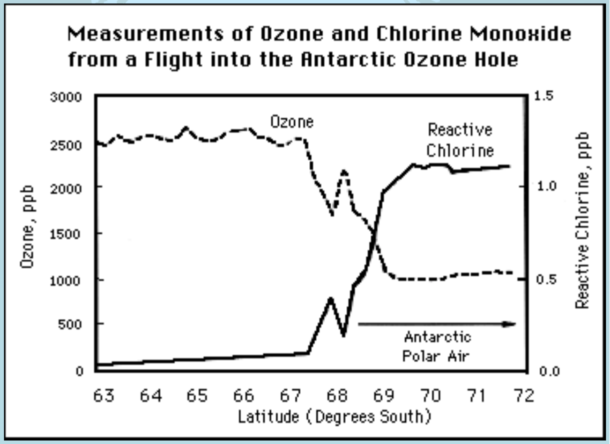


Most rapid breakdown of ozone occurs on the surface of polar stratospheric clouds, which are most prevalent at the end of winter in the SH (i.e., August and September).

Causes for Stratospheric Ozone Depletion

Chlorine and Bromine compounds result in ozone depletion.

Most rapid breakdown of ozone occurs on the surface of polar stratospheric clouds.

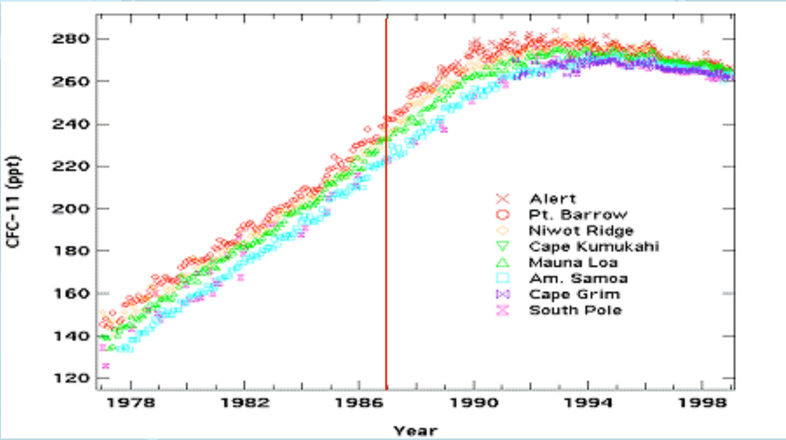


Formation of the Ozone Hole

- The polar winter leads to the formation of the polar vortex which isolates the air within it.
- Cold temperatures form inside the vortex; cold enough for the formation of Polar Stratospheric Clouds. As the vortex air is isolated, the cold temperatures and the clouds persist.
- Once the Polar Stratospheric Clouds form, chemical reactions take place and convert the inactive chlorine and bromine to more active forms of chlorine and bromine.
- No ozone loss occurs until sunlight returns to the air inside the polar vortex and allows the production of active chlorine and initiates the catalytic ozone destruction cycles. Ozone loss is rapid.

Ozone Policy

The Montreal Protocol of 1987 banned CFC's and Halons.
Latest projection shows ozone hole recovery by 2068.



The Inconvenient Truth about Vog

Kamoamoa Fissure

Formation of Vog

Vent emissions are composed primarily of water vapor, SO_2, CO_2 and various trace gases and metals.

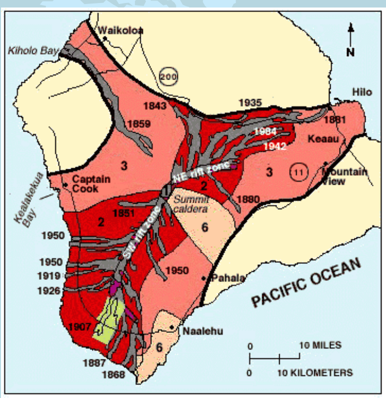
SO_2 rapidly mixes with water vapor to form gaseous sulfuric acid.

A majority of the liquid sulfate also quickly converts to various sulfate compounds forming aerosols via nucleation or condensation onto existing aerosol.

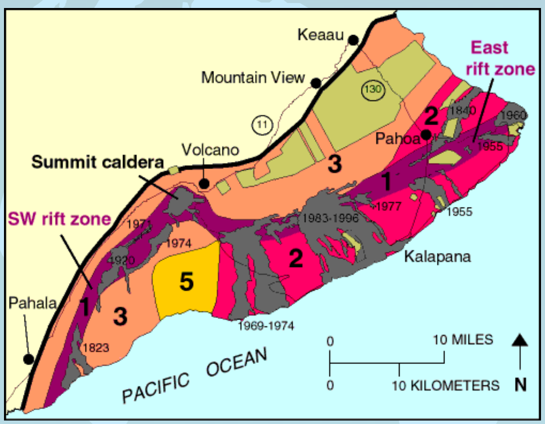
These sulfates form a layer of volcanic smog known as vog.

Halemaumau

Geography of the Lava Flow Hazard



Mauna Loa



Kilauea

Volcanic emissions are greatest where the lava first reaches the surface.

Volcanic Air Pollution (Vog) in Hawaii

Halema`uma`u Crater vent is part of the Kilauea summit crater.

Pu'u'O'o vent is part of the east rift zone

Volcanic emissions are greatest where the lava first reaches the surface.

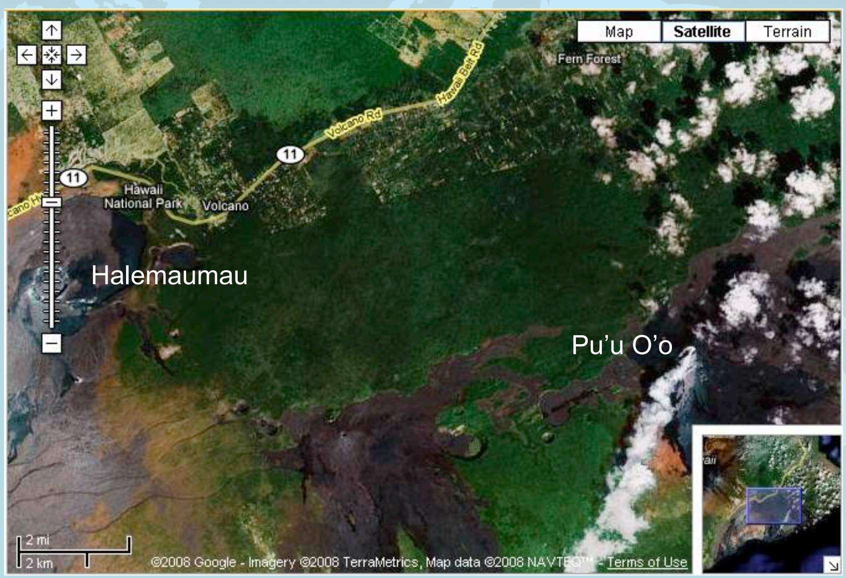
The Hazards from VOG

- Volcanic sulfate aerosol is of a size (0.1-0.5 μm) that can effectively reach down into the human lung, causing respiratory distress. Sulfur dioxide also promotes respiratory distress.
- Reduction of visibility in layers of high aerosol concentration near inversions represents a hazard to aviation.
- Acid rain negatively impacts ecosystems and reduces crop yields.

Vog Emissions Increased in 2008

Summit sulfur dioxide (SO_2) emissions reaching record high levels in March 2008; a new vent opening in Halema`uma`u Crater; a small explosive eruption at Kīlauea's summit, the first since 1924; and lava flowing into the sea for the first time in over eight months. A more recent event in March 2011 elevated SO2 emissions to over 11,000 metric tonnes per day.

Proximity of Hazard to Volcano Village



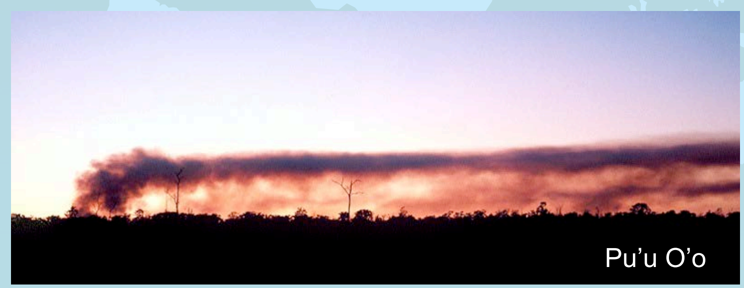
Proximity of Hazard to Volcano Village

2,231 Residents (2000 census).

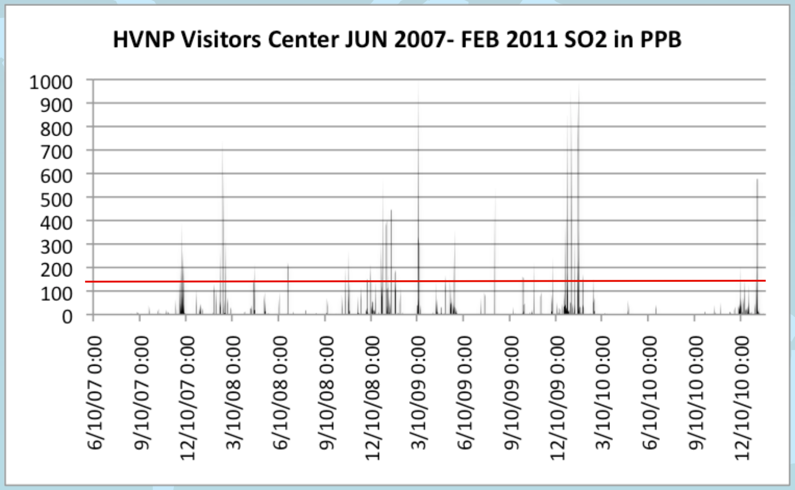
4 miles north of Kilauea. 8 miles northeast of Pu'u O'o vent.

Can be exposed to SO_2 levels as high as 2000 ppb

EPA's regulation: 24 hour average from man-made sources should not exceed 140 ppb SO_2



Increased Health Threat



EPA's regulation: 24 hour average from man-made sources should not exceed 140 ppb (red line).

Health Impacts from SO_2

In animal studies, high concentrations of SO_2 shows airway inflammation and hyper-responsiveness.

Studies on mild asthmatics that were introduced to SO_2 levels of 500 ppb showed increased airway resistance while exercising.


Kona

Health Impacts from Sulfate Aerosols

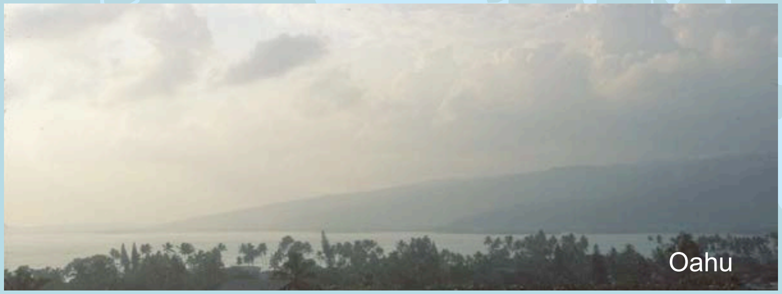
Volcanic aerosol is of a size (0.1-0.5 μm) that can effectively reach down into the human lung, causing respiratory distress.

Epidemiological studies show that sulfates increase bronchitis, chronic cough, and chest illness.

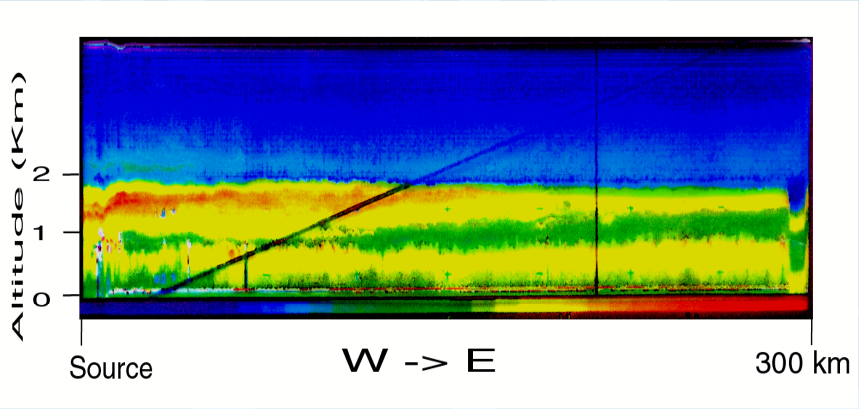

Kamoamoa Fissure

Health Impacts from Sulfate Aerosols

"I'm seeing a 30 to 40 percent increase in vog-related symptoms," said allergist and immunologist Dr. Jeffrey Kam on Oahu, "The main complaints associated with the vog are the increasing breathing difficulties. The worst one is obviously the asthma flare-up. They can have nasal congestion, wheezing, itchy and watery eyes and irritated throat."


Oahu

Plume Cross Section



Lidar cross section shows vog concentrated at 1500 m, just below the boundary layer inversion.

Visibility Obscured by Vog

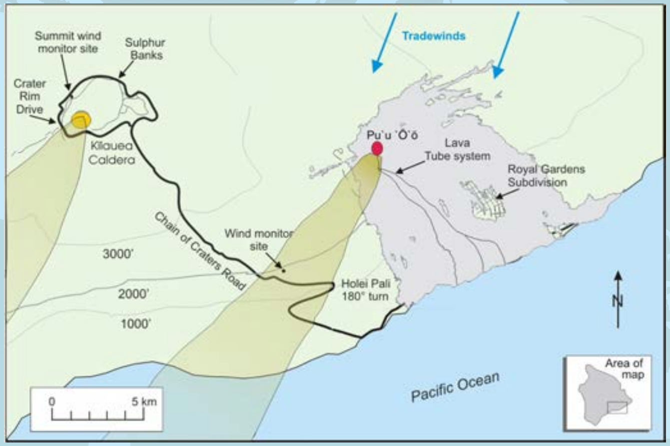
Aerial photograph of Maui as aerosol obscures the lower slopes of Haleakala January 25, 2000. Reduction of visibility represents a hazard for general aviation.

Monitoring VOG

The Flyspec, pictured here strapped to an HVO vehicle, has replaced the larger, heavier, and more expensive optical correlation spectrometer (COSPEC), which was used to measure SO2 emissions at Kīlauea for over two decades. A scientific comparison of Flyspec and COSPEC showed no loss in accuracy or precision of data collected with the mini-spectrometer.

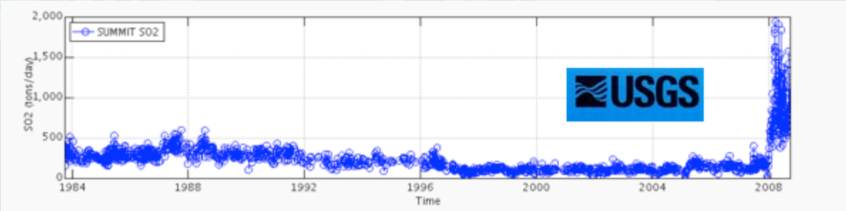
- Correlation Spectrometer (COSPEC) - COSPEC measures the amount of ultraviolet light absorbed by sulfur dioxide molecules within a volcanic plume. The instrument is calibrated by comparing all measurements to a known SO_2 standard mounted in the instrument. COSPEC can be mounted on a car or aircraft

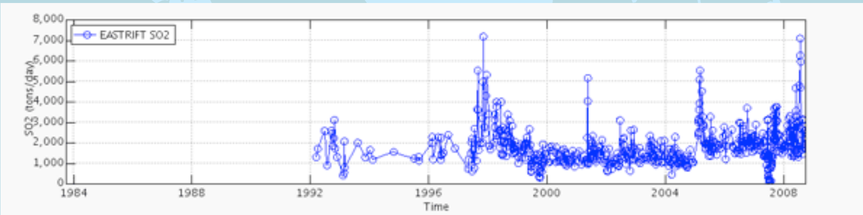
Monitoring VOG



Vehicle-based SO2 measurements are made downwind of the summit and east rift zone plumes on Crater Rim Drive and Chain of Craters Road during trade-wind conditions.

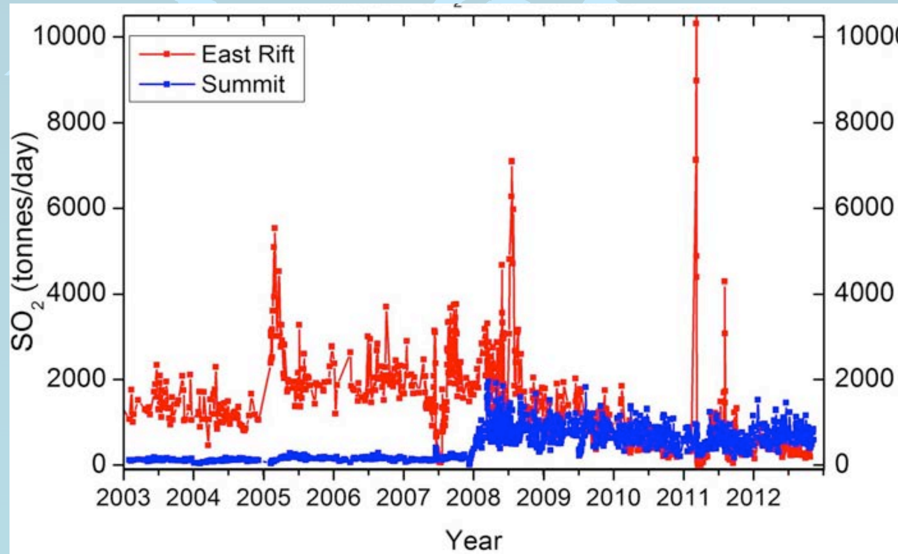
Kilauea SO_2 Emissions (1984-2008)



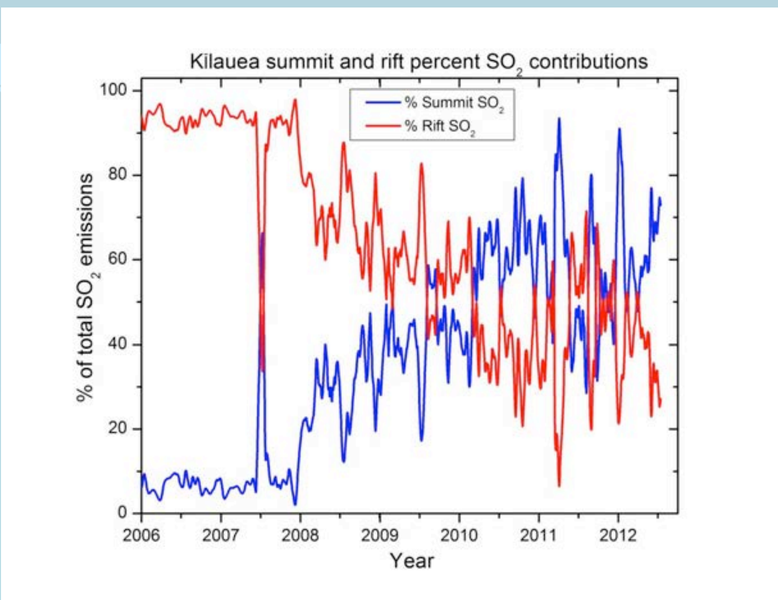


Averaged SO_2 emissions from Kilauea's east rift zone 1992 to 2008.

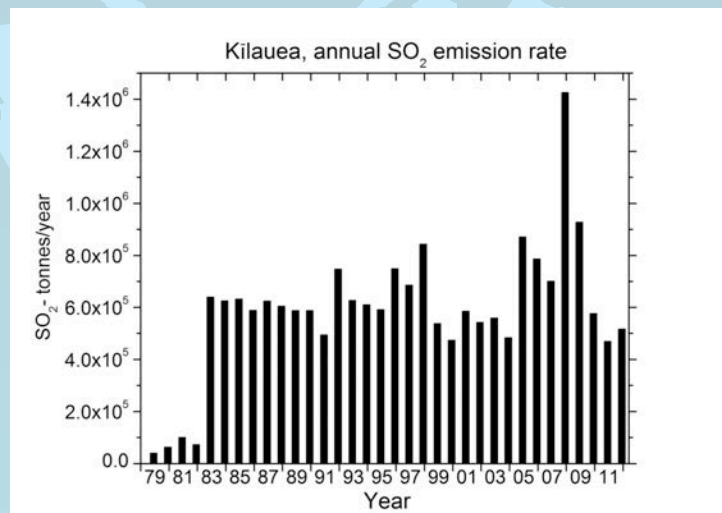
Kilauea SO_2 Emission Rates



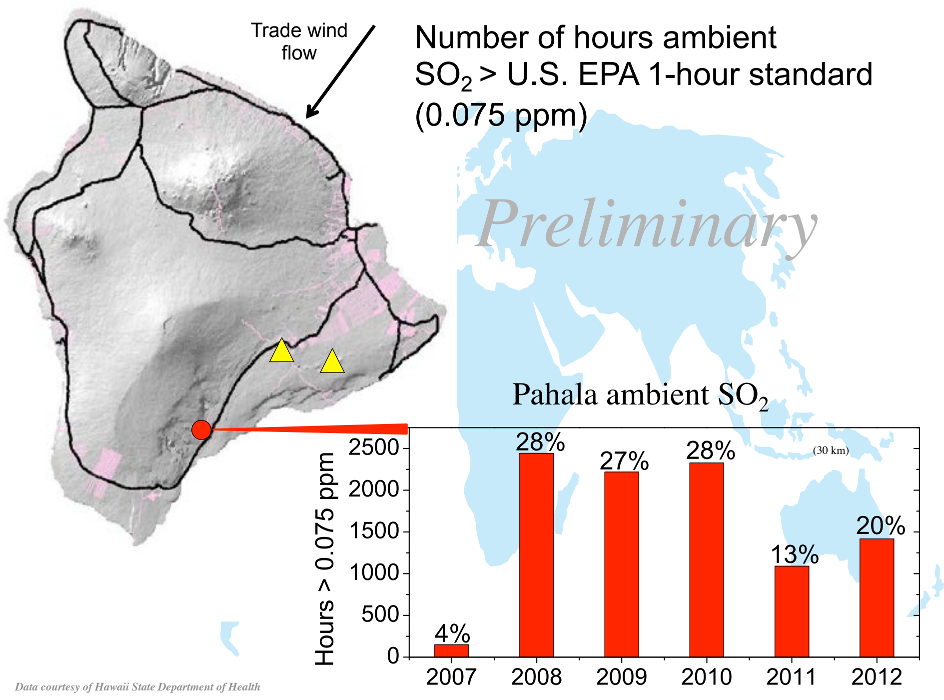
Kilauea SO_2 Emission Rates



Kilauea SO_2 Emission Rates



(2012 value projected to year's end)


Trade wind flow
Number of hours ambient SO2 > U.S. EPA 1-hour standard (0.075 ppm)
Preliminary
Pahala ambient SO2
Hours > 0.075 ppm
2500
2000
1500
1000
500
0
4%
28%
27%
28%
13%
20%
(30 km)
2007
2008
2009
2010
2011
2012
Data courtesy of Hawaii State Department of Health

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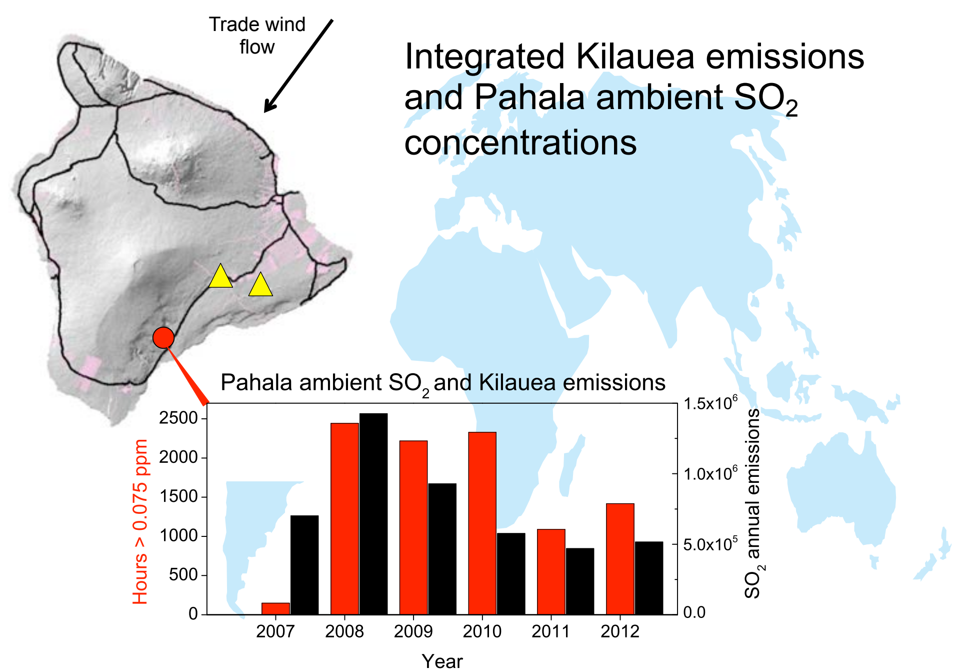
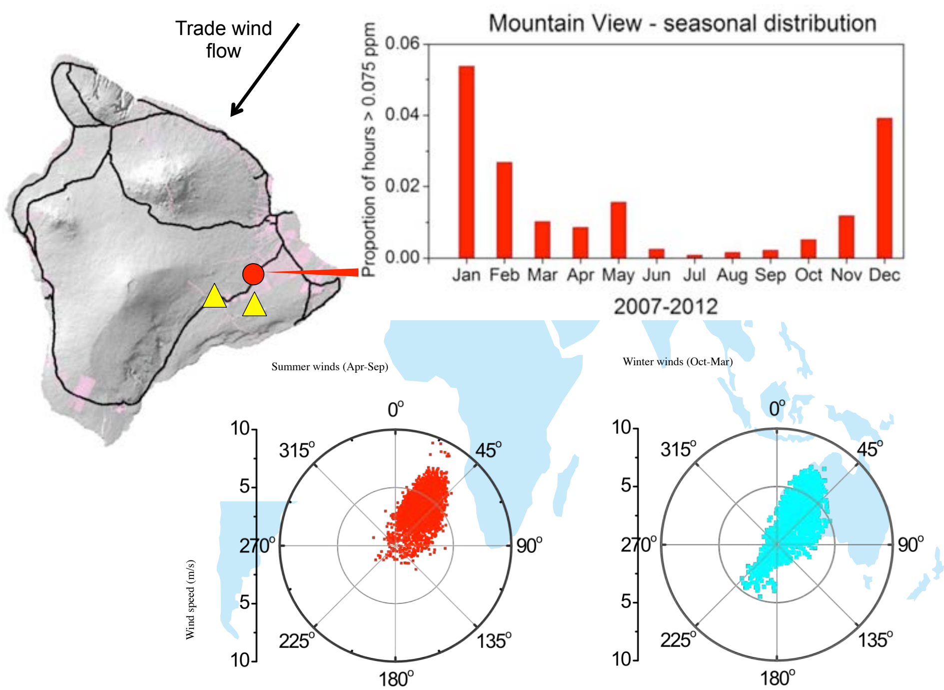
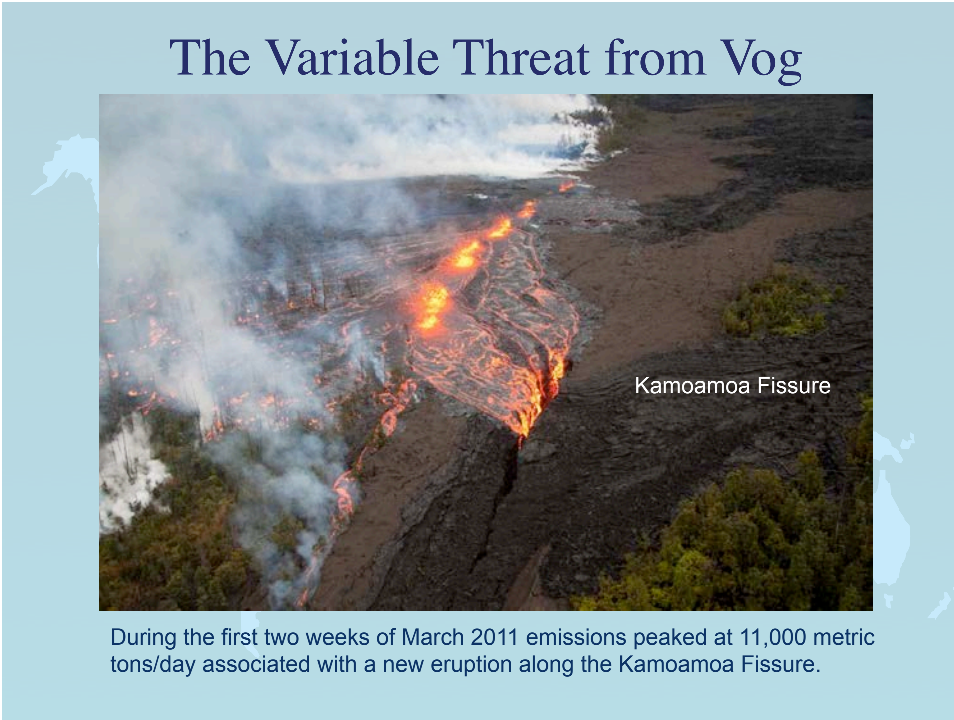

Trade wind flow
Integrated Kilauea emissions and Pahala ambient SO2 concentrations
Pahala ambient SO2 and Kilauea emissions
Hours > 0.075 ppm
2500
2000
1500
1000
500
0
1.5x10^6
1.0x10^6
5.0x10^5
0.0
SO2 annual emissions
2007
2008
2009
2010
2011
2012
Year

78


Trade wind flow
Mountain View - seasonal distribution
Proportion of hours > 0.075 ppm
0.06
0.04
0.02
0.00
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
2007-2012
Summer winds (Apr-Sep)
Winter winds (Oct-Mar)
Wind speed (m/s)
0°
45°
90°
135°
180°
225°
270°
315°
10
5
5
10

79


The Variable Threat from Vog
Kamoamoa Fissure
During the first two weeks of March 2011 emissions peaked at 11,000 metric tons/day associated with a new eruption along the Kamoamoa Fissure.

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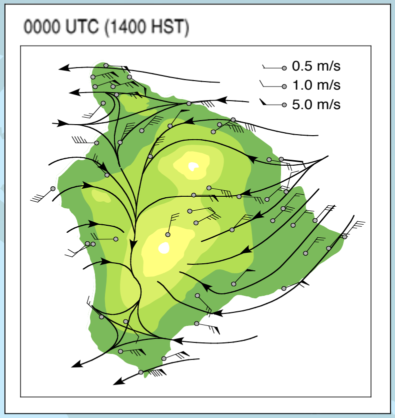
Dispersion of Vog

Heavily dependent on wind patterns and stability.

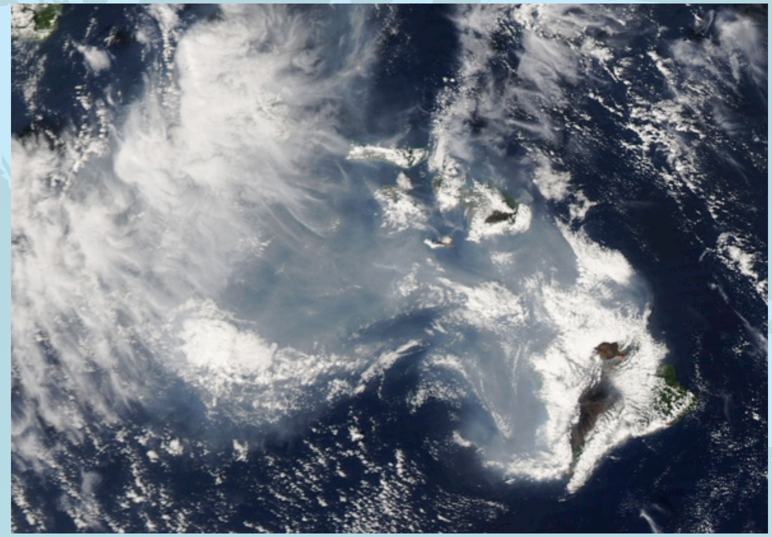
Predominantly tradewinds (from the northeast) from May to October.

More frequent periods of “Kona winds” from the south from November to April.

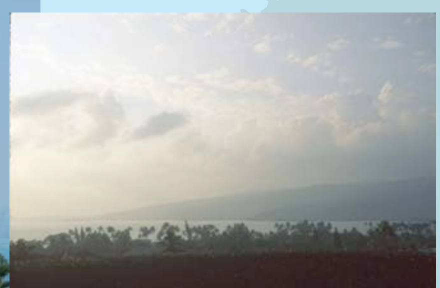


Mean Island Flow 2:00pm HST in summer

Effects Felt far Downstream

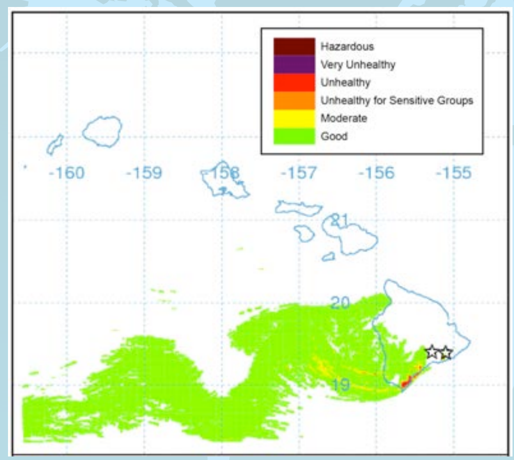


Effects Felt far Downstream

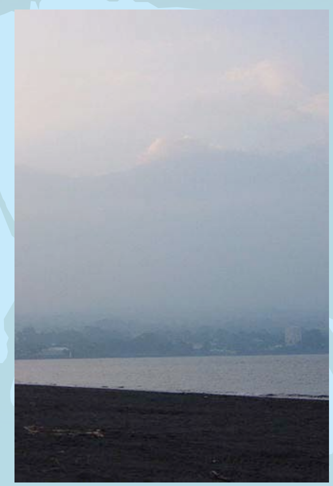


Vog plume impacting Oahu; compare visibility on clear day (lower left) with vog conditions.

Model Simulation of VOG



Sea breeze brings vog onto Kona coast.



Thick vog plume over Hilo during light southerly flow.

Gaussian Dispersion Model

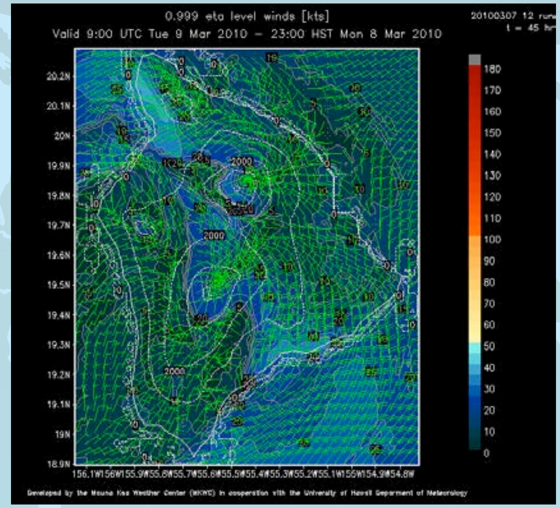
The concentration C ($\mu g/m^3$) is given by

$$C = \frac{E e^{-\left(\frac{(y-y_0)^2}{2\sigma_y^2}\right)} e^{-\left(\frac{(x-x_0)^2}{2\sigma_x^2}\right)} e^{-\left(\frac{(z-fz)^2}{2\sigma_z^2}\right)}}{2\Pi \sigma_y \sigma_x u}$$

where E is the source emission, u is the average wind speed, f is the particle fall speed, σ_x, σ_y, and σ_z are the horizontal and vertical dispersion coefficients as a function of downwind distance.

Input for Vog Model

WRF Domain 3 sample winds for 3/7/10



1. Weekly Averaged SO_2 emissions from HVO for the summit and East Rift Zone.
2. Meteorological Fields from the Weather Research and Forecast (WRF) model.

Dispersion Calculation

- In the HYSPLIT (Lagrangian particle) model, the source is simulated by releasing many particles over the duration of the release.
- In addition to the advective motion of each particle, a random component to the motion is added at each step according to the atmospheric turbulence at that time.
- A cluster of particles released at the same point will expand in space and time simulating the dispersive nature of the atmosphere.
- In a homogeneous environment the size of the puff (in terms of its standard deviation) at any particular time will correspond to the second moment of the particle positions.

Dispersion Calculation

- A fixed number of particles are released and followed for the duration of the model run.
- Operational model uses 20,000 particles per time step in the initial release. Particles are lost due to deposition and passing the model boundary
- Particles within the domain at the end of the previous run provide an initial condition for the subsequent run.
- Maximum number of particles allowed in model during the run is 500,000. This number is a compromise between the CPU needed to track particles and the accuracy of the model output at the edges of the domain at the end of the model run.
- The turbulent velocity variance is obtained from WRF's TKE (turbulent kinetic energy field).
- Model uses Kanthar/Clayson vertical turbulence computational method.

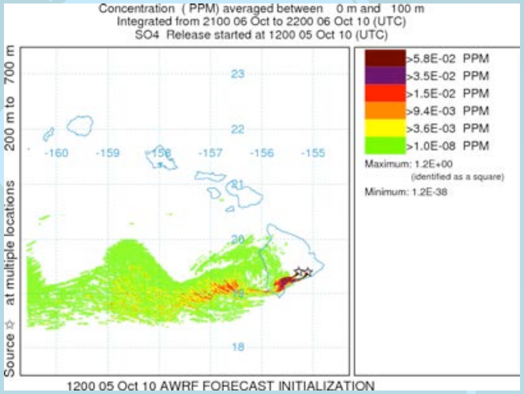
Turbulent Diffusion

- The turbulent velocity variance is obtained from WRF's TKE (turbulent kinetic energy field).
- Model uses Kanthar/Clayson vertical turbulence computational method. These equations have the following form:
- $w'^2 = 3.0\, u_*^2 (1 - z/Zi)^{3/2}$
- $u'^2 = 4.0\, u_*^2 (1 - z/Zi)^{3/2}$
- $v'^2 = 4.5\, u_*^2 (1 - z/Zi)^{3/2}$
- where the turbulence is a function of the friction velocity, height, and boundary layer depth. The horizontal and vertical components are explicitly predicted.

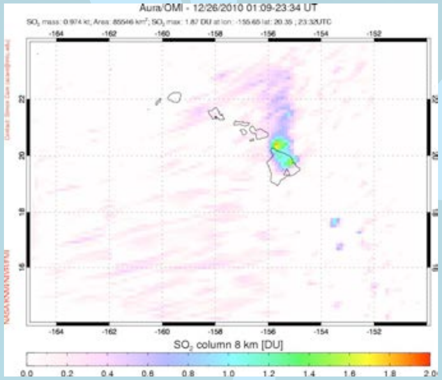
Conversion Rate: SO_2 to SO_4

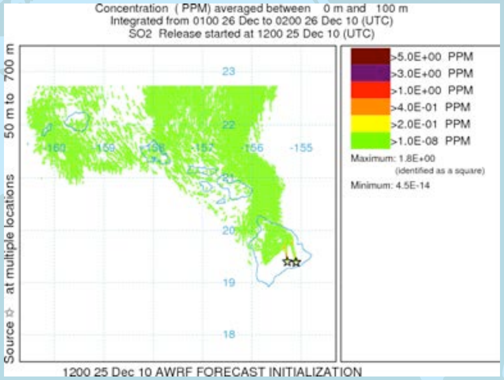
- Conversion rate of SO_2 to SO_4 (sulfate aerosol) in the model is set at a constant rate of 1% per hour.
- Dry deposition velocity for SO_2 = 0.48 cm/s
- Dry deposition velocity for SO_4 = 0.25 cm/s
- Trajectories follow isobaric surface with full reflection assumed at the surface.

Satellite Validation



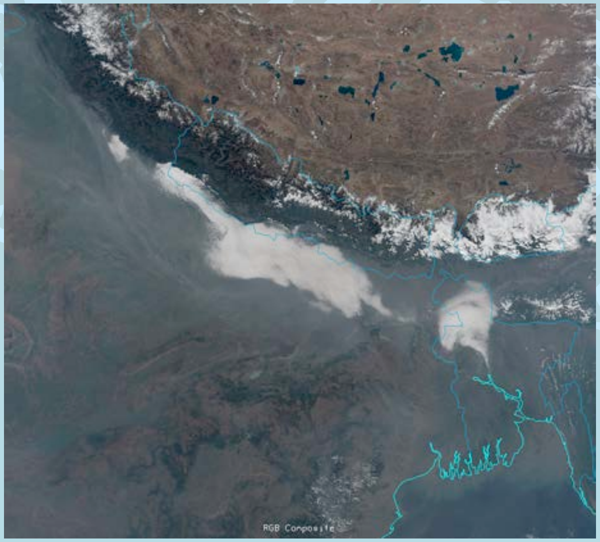
Satellite Validation





December 26, 2010

Questions?



India vs Tibet