

## Lecture 26 Air Pollution



Air Pollution – Elevated levels of aerosols and harmful gases



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## Volcanic Emissions

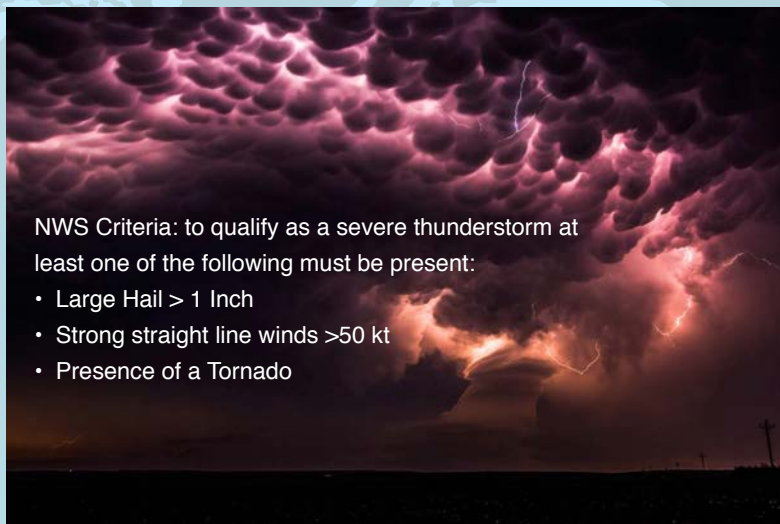
Mount Sinabung, North Sumatra, Indonesia

5 November 2013



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## Previous Lecture: Severe Thunderstorms



NWS Criteria: to qualify as a severe thunderstorm at least one of the following must be present:

- Large Hail > 1 Inch
- Strong straight line winds >50 kt
- Presence of a Tornado

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## Lecture 26

## 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

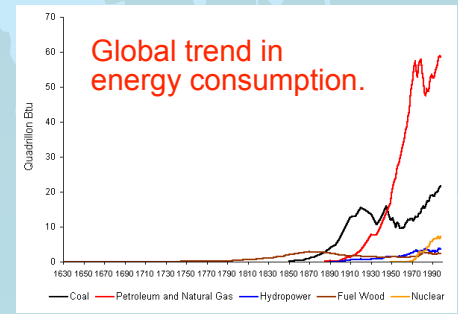
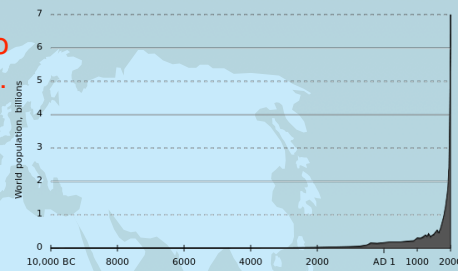
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## Air Pollution

Man-made pollution – related to population and industrialization.



Kuwait Oil Fires

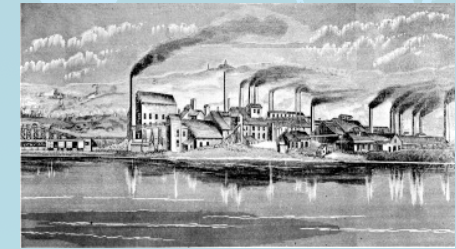


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## Historic Pollution Episodes

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



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## 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 daily 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.

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## 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.

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## Hazardous Pollutants

A particularly nasty bunch of pollutants

- Carbon Monoxide (CO) enters the bloodstream and causes cardiovascular damage
- Ozone and Nitrogen Oxides (NO<sub>2</sub> and NO) damage the lungs, leading to asthma and other respiratory illnesses (especially in children)
- Particulate matter (PM<sub>10</sub> and PM<sub>2.5</sub>), especially from diesel trucks, is carcinogenic
- Sulfur Dioxide (SO<sub>2</sub>) and NO<sub>2</sub> cause acid rain
- Lead (Pb) poisoning destroys the body's organs



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## 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



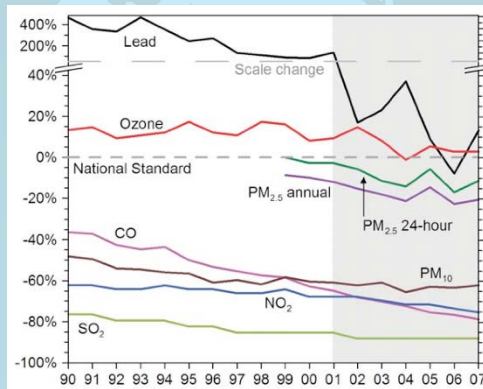
Mexico City

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## National Ambient Air Quality Standards

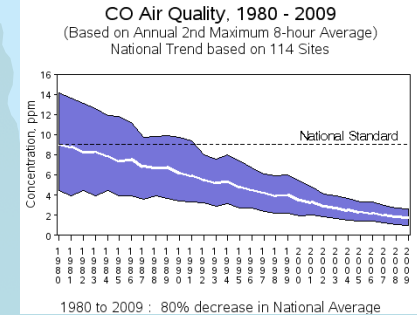
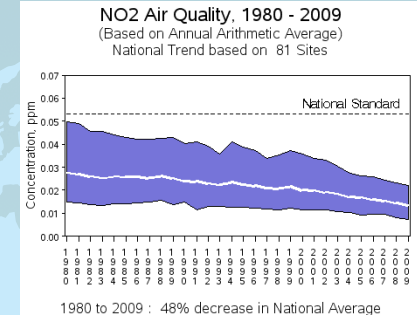
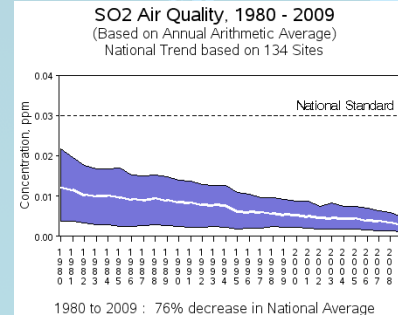
The Clean Air Act requires Environmental Protection Agency (EPA) to set National Ambient Air Quality Standards for six common air pollutants.

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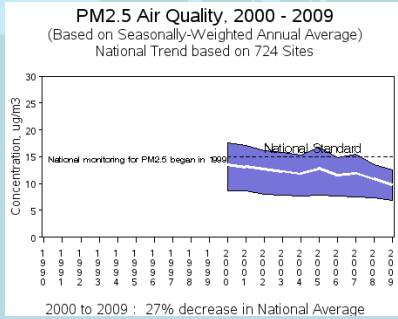
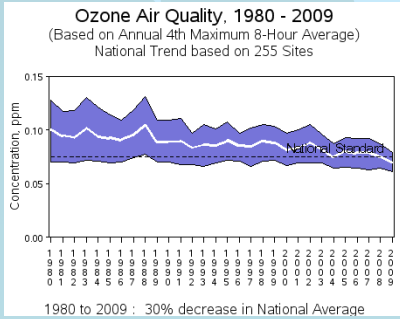
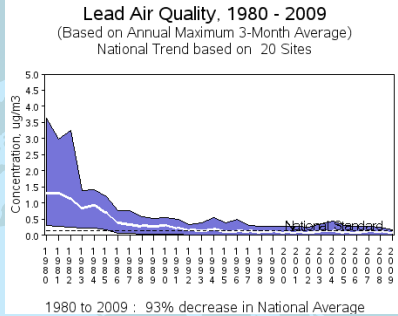
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## Pollution Trends 1980-2009



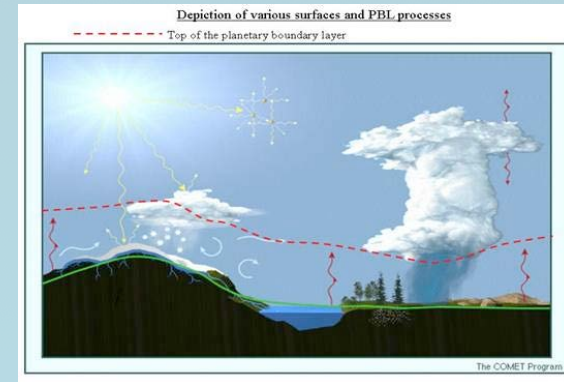
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## Pollution Trends 1980-2009



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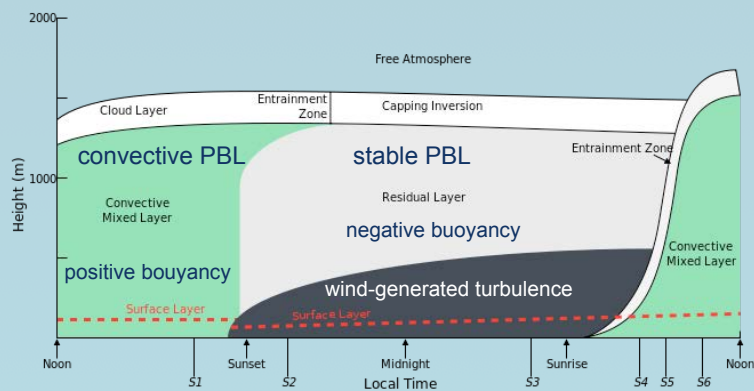
## Planetary Boundary Layer (PBL) aka Atmospheric Boundary Layer



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.

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## 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.

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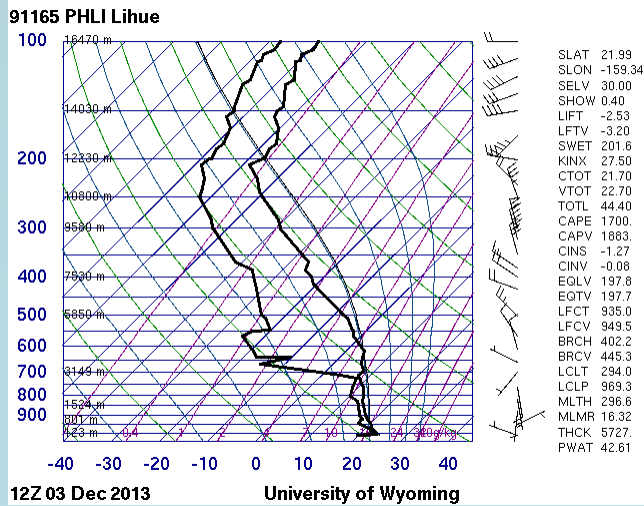
## The Free Atmosphere



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.

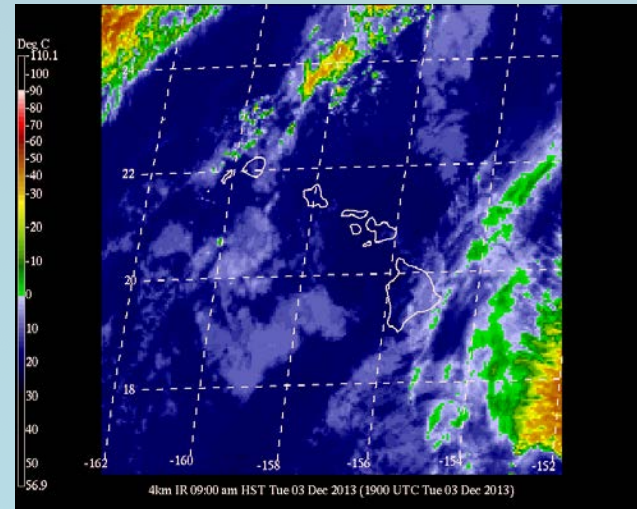
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## PBL Today



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## PBL Today



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## 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.



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## 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.



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## Pollution in the Boundary Layer



Most pollution enters the atmosphere near the surface.

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## 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.



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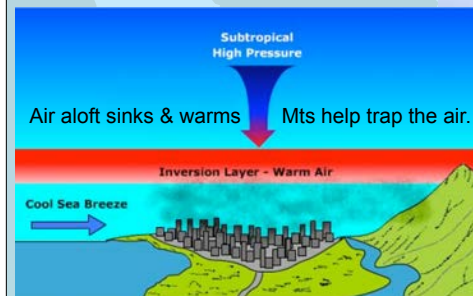
## Recent US Pollution Episode

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



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## 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.

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## Polluted Boundary Layer

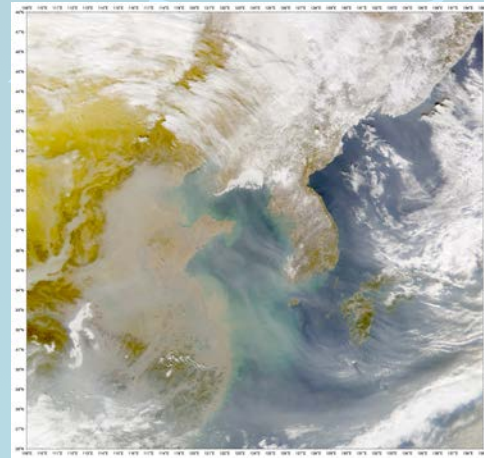


LA and Denver “brown clouds” primarily caused by automobile exhaust plus sunlight.



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## Polluted Boundary Layer



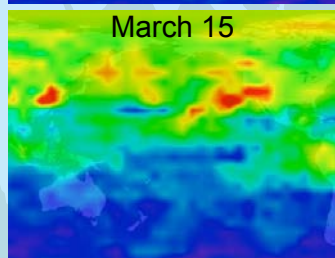
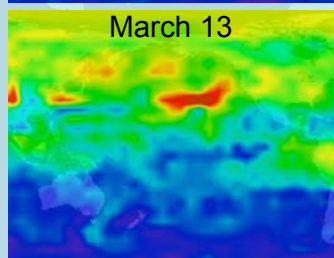
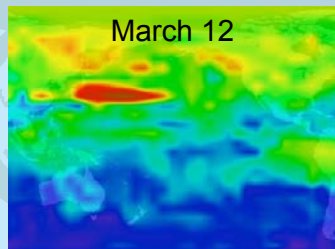
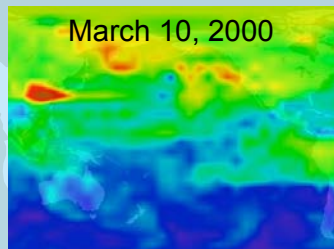
Mt. Rainier, WA

China from space.

Pollution in the atmosphere can travel great distances.

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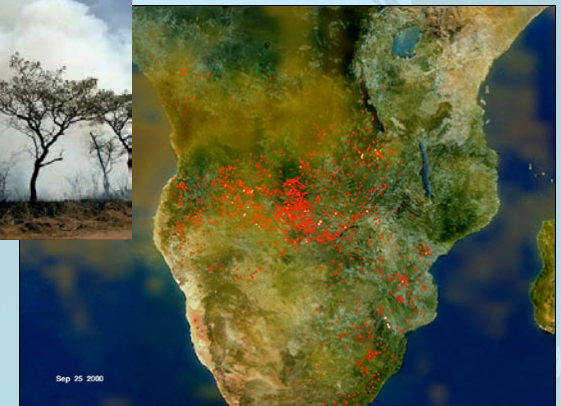
## CO concentration from Satellite



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

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## Anthropogenic Sources of Air Pollution



Sep 25 2000

Intentionally set fires are a large source of pollution and CO<sub>2</sub>

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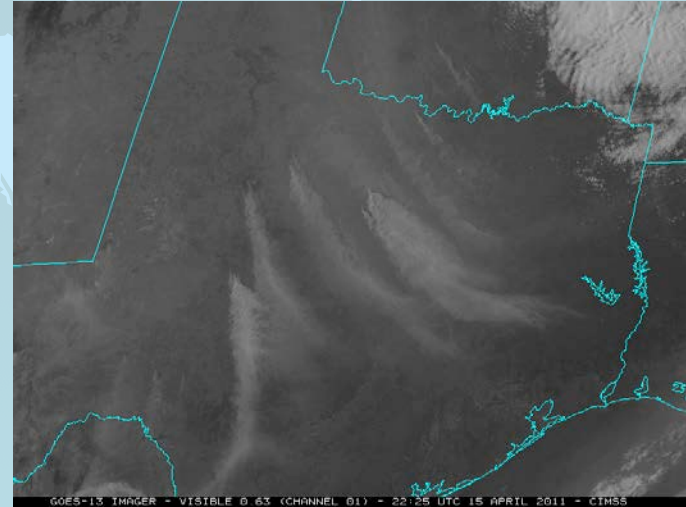
## Fires are Promoted by Droughts



Texas wildfires fanned by high winds in April 2011.

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## Texas Wildfires Fanned by High Winds



Most pollution enters the atmosphere near the surface.

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## Wildfires



Big Meadow controlled burn  
--> Wild fire

Yosemite NP,  
August 2009



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## Acid Rain

Acid rain is caused by sulfur dioxide ( $\text{SO}_2$ ) and nitrogen oxides ( $\text{NO}_x$ ) being released into the atmosphere and producing sulfuric acid and nitric acid.

Sources of  $\text{SO}_2$  and  $\text{NO}_x$  include factories, power plants, automobiles, trucks.

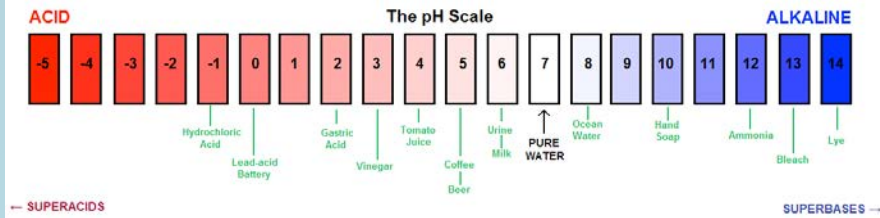


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## Acid Rain

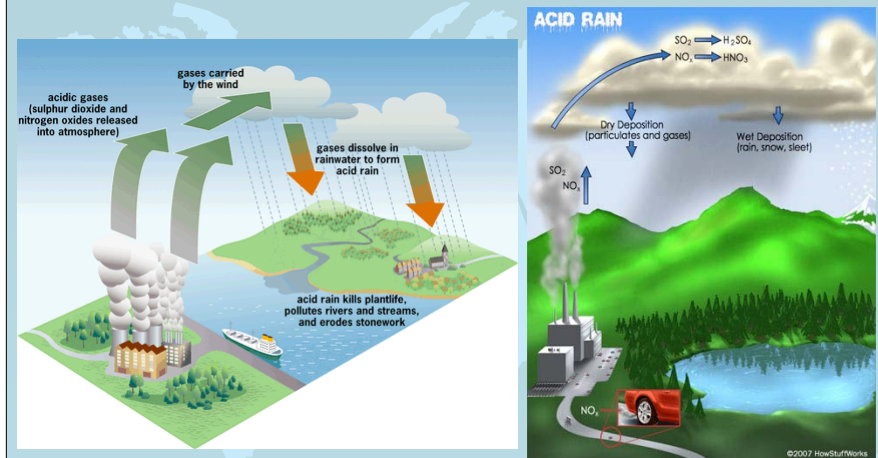
The pH scale measures how acidic or basic a substance is.



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).

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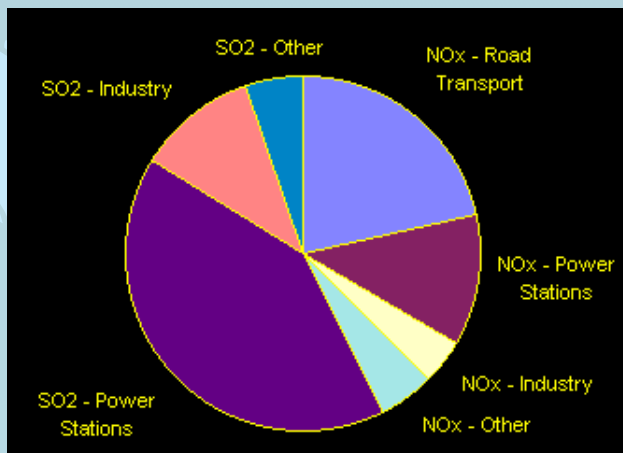
## Acid Rain



Sources of  $\text{SO}_2$  and  $\text{NO}_x$  include factories, power plants, automobiles, trucks and even pine forests.

34

## Acid Rain



Sources of  $\text{SO}_2$  and  $\text{NO}_x$  include factories, power plants, automobiles and trucks.

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## Acid Rain

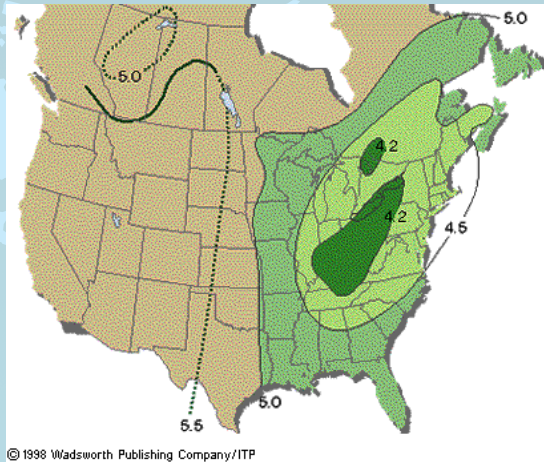
Impacts of Acid Rain

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



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## pH of US Rain



Acid rain leeches heavy metals into lakes and streams.

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## Acid Rain

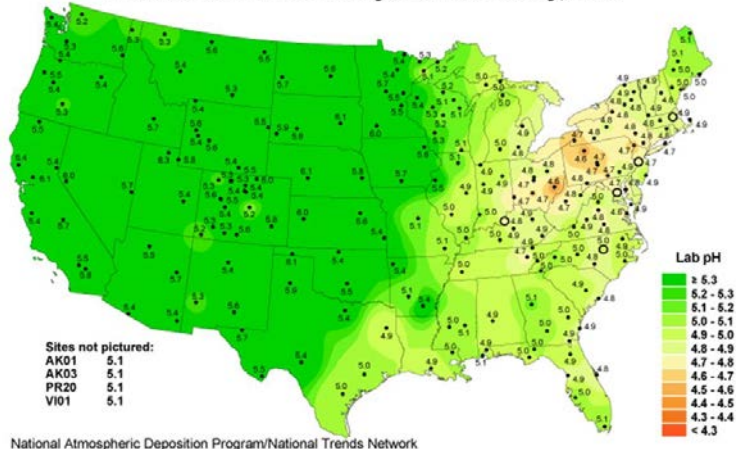
	pH 6.5	pH 6.0	pH 5.5	pH 5.0	pH 4.5	pH 4.0
TROUT	Light Blue	Light Blue	Light Blue	Light Blue	Dark Blue	Dark Blue
BASS	Red	Red	Red	Dark Blue	Dark Blue	Dark Blue
PERCH	Blue	Blue	Blue	Blue	Blue	Dark Blue
FROGS	Green	Green	Green	Green	Green	Green
SALAMANDERS	Bright Green	Bright Green	Bright Green	Bright Green	Dark Blue	Dark Blue
CLAMS	Yellow	Yellow	Dark Blue	Dark Blue	Dark Blue	Dark Blue
CRAYFISH	Magenta	Magenta	Magenta	Dark Blue	Dark Blue	Dark Blue
SNAILS	Olive	Olive	Dark Blue	Dark Blue	Dark Blue	Dark Blue
MAYFLY	Red	Red	Red	Dark Blue	Dark Blue	Dark Blue

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

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## Acid Rain Clean-Up

Hydrogen ion concentration as pH from measurements made at the Central Analytical Laboratory, 2009

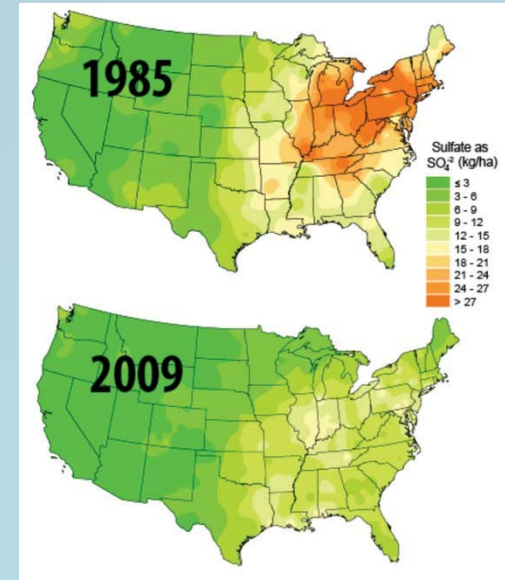


Acid rain leeches heavy metals into lakes and streams.

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## Acid Rain Clean-Up

U.S. sulfur deposition, shown in orange in the 1985 map, has been drastically reduced due in part to acid rain cleanup.



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## Acid Rain



Needles collect cloud water, which is extra acid.

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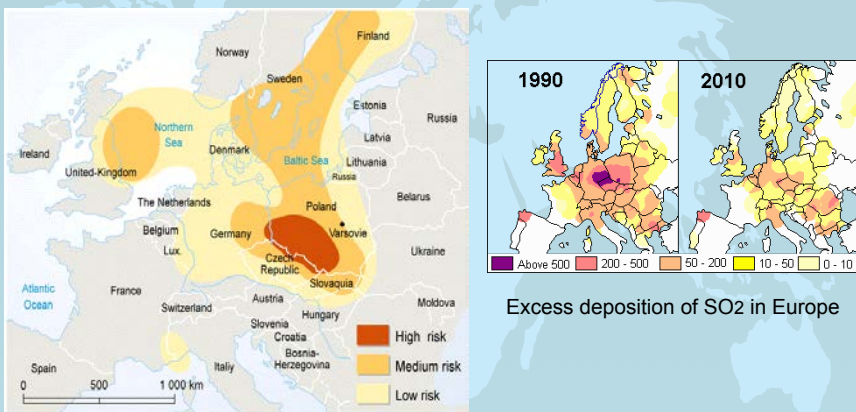
## Acid Rain



Spruce Forest in North Carolina impacted by Acid Rain

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## Acid Rain



Spruce Forest in Europe impacted by Acid Rain

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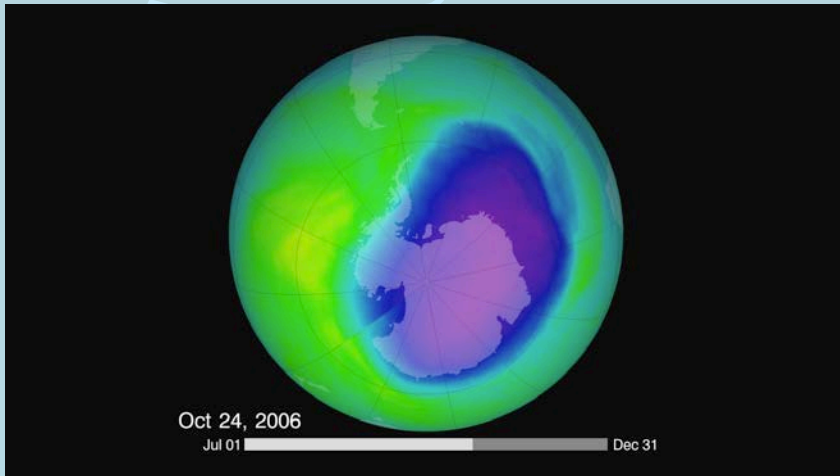
## Acid Rain



Buildings: Marble and Limestone are dissolved by acid rain.

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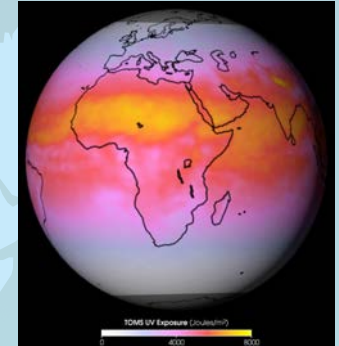
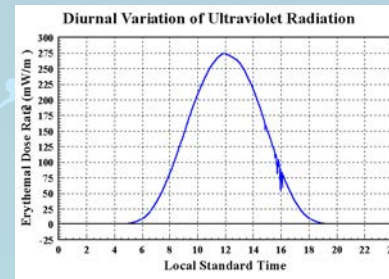
## Global Ozone Depletion



The ozone hole reached its maximum extent in 2006.

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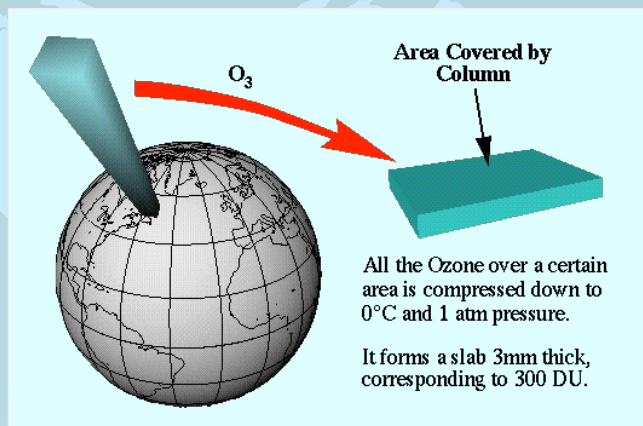
## Hazards of Ozone Loss



- 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.

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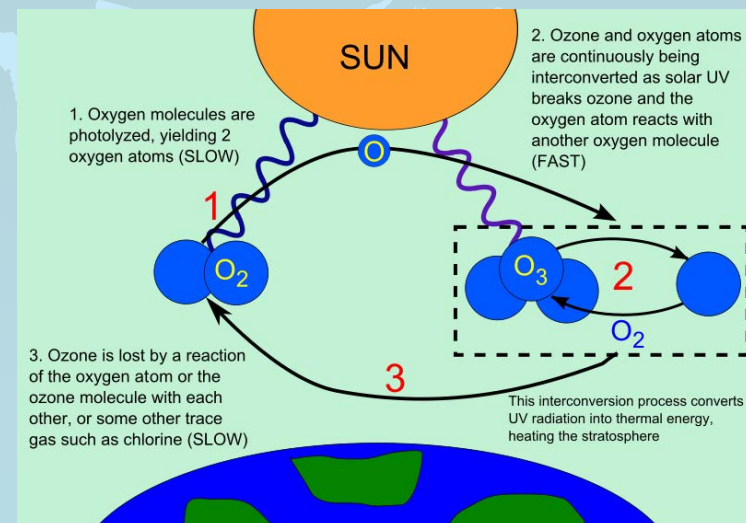
## Ozone Measurement



Atmospheric ozone is measured by Total Ozone Mapping Spectrometer (TOMS) instrument in Dobson Units.

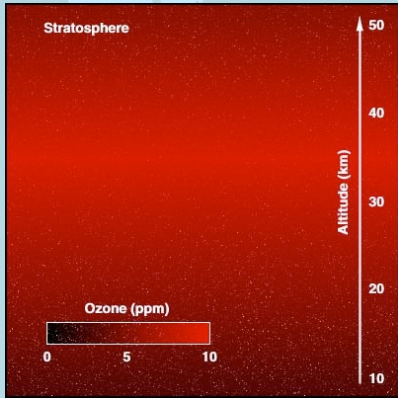
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## Natural Ozone Cycle

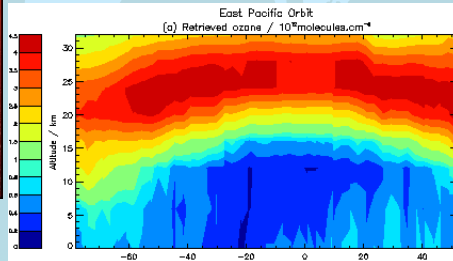
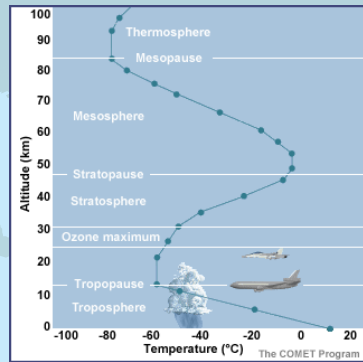


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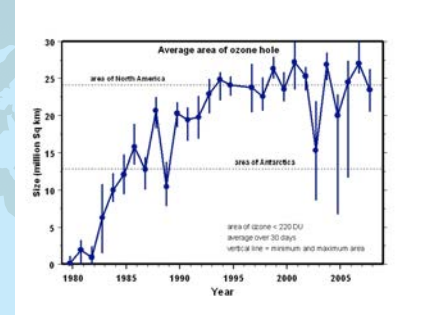
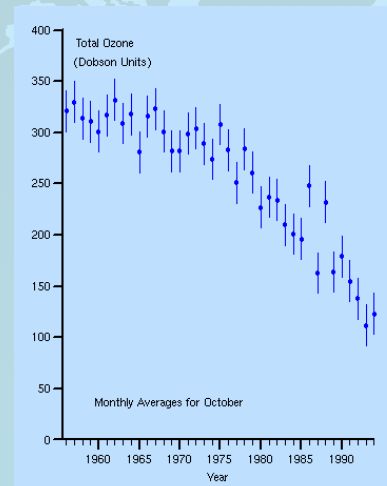
# Ozone Distribution



Ozone concentration is a maximum in the lower stratosphere

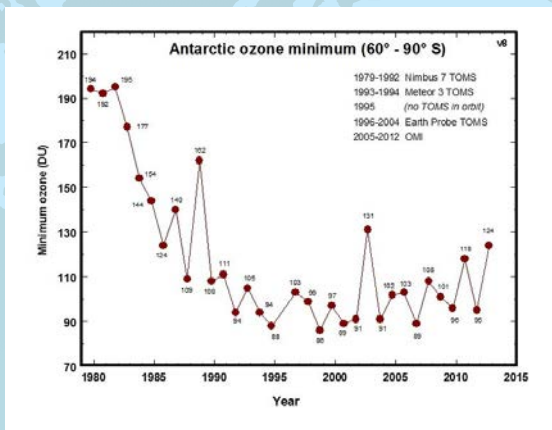


# Ozone Hole



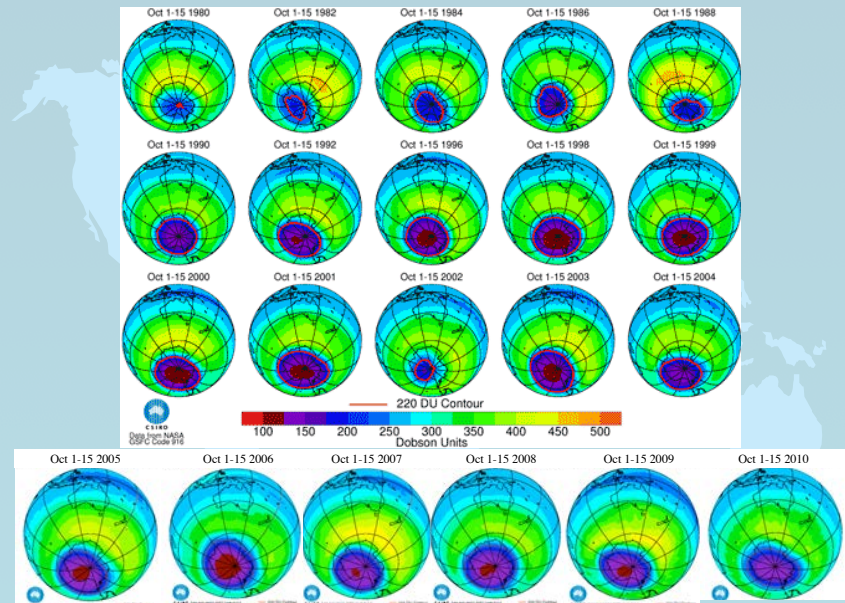
The decrease in ozone over the South Pole was first observed in the 1970's. It is linked to an increase in man made chemicals entering the atmosphere.

# Ozone Hole

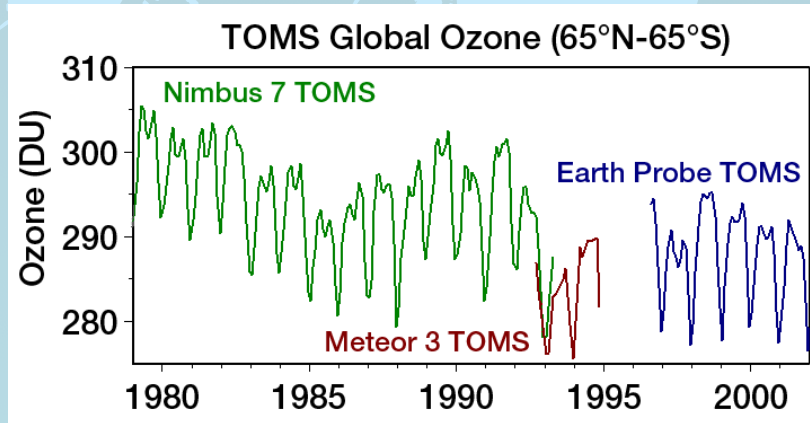


Lowest value of ozone measured by TOMS each year in the ozone hole.

# Ozone Hole



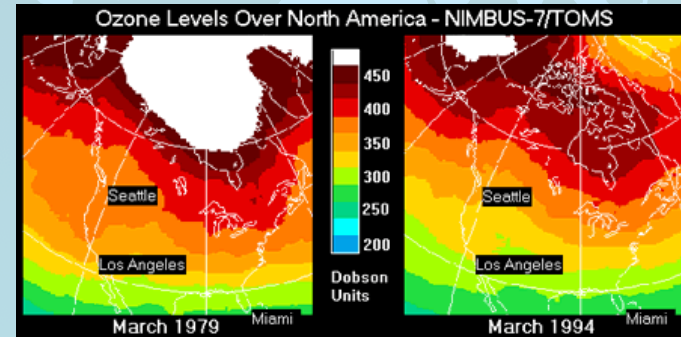
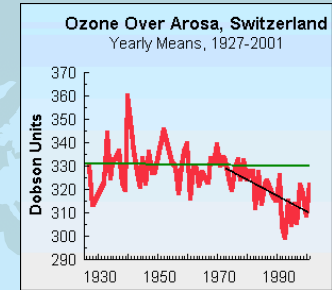
## Global Monthly Average Total Ozone



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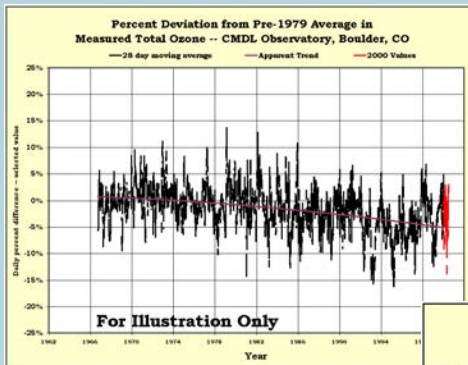
## Ozone Hole

The decrease in ozone also observed at lower latitudes.

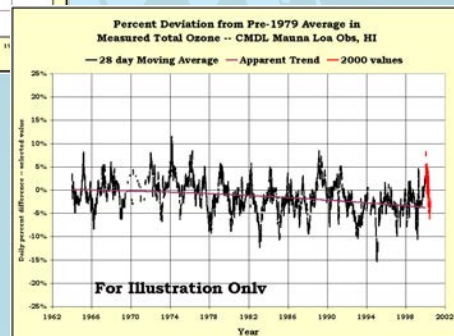


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## Ozone Depletion

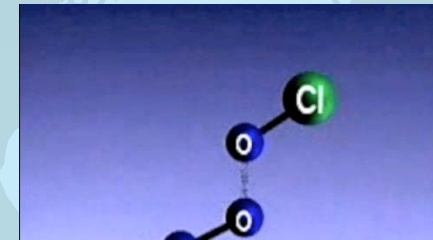
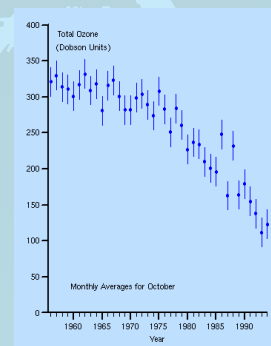


Decrease in ozone observed in Colorado and Hawaii.



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## 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.

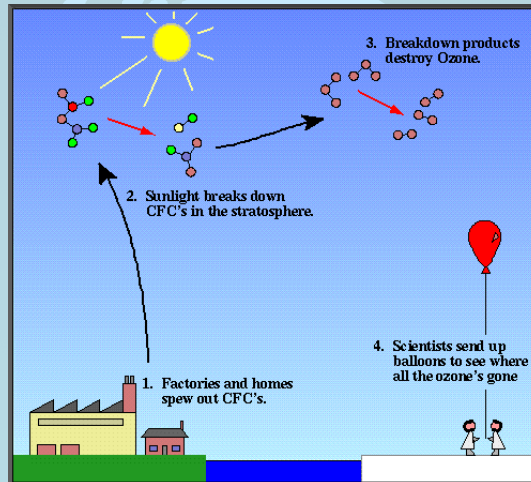
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## Causes for Stratospheric Ozone Depletion

CFCs release chlorine atoms, and halons release bromine atoms

Chlorine and Bromine atoms result in ozone depletion.

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



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## 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.

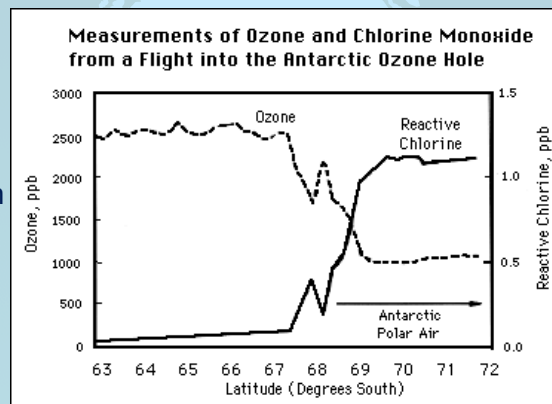


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## Causes for Stratospheric Ozone Depletion

Chlorine and Bromine compounds result in ozone depletion.

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



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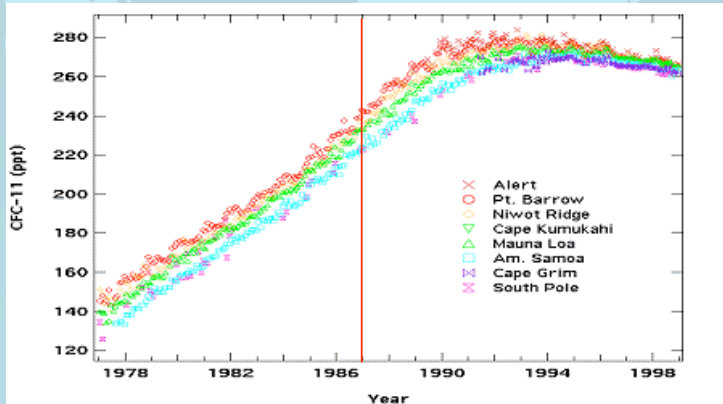
## Formation of the Ozone Hole

- 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.

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## Ozone Policy

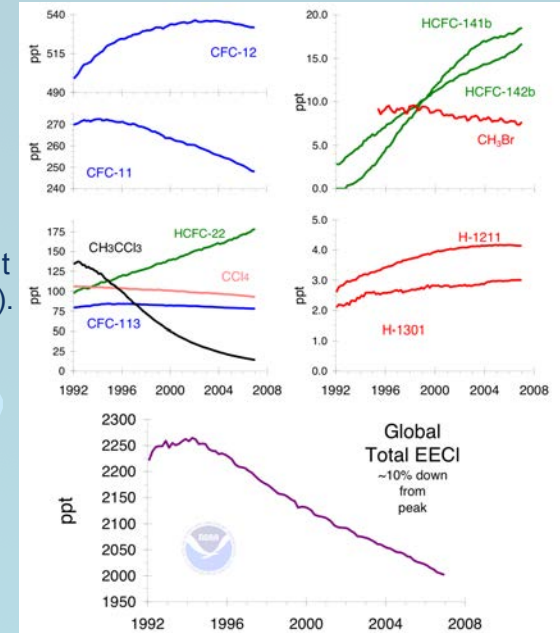
The Montreal Protocol of 1987 banned CFC's and Halons. Latest projections show ozone hole recovery by 2068.



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## Depleting Gas Trends

Ozone-depleting gas trends and equivalent chlorine effect (EECI).



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## The Inconvenient Truth about Vog



Kamoamo Fissure

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## Formation of Vog

- Vent emissions are composed primarily of water vapor,  $\text{SO}_2$ ,  $\text{CO}_2$  and various trace gases and metals.
- $\text{SO}_2$  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.

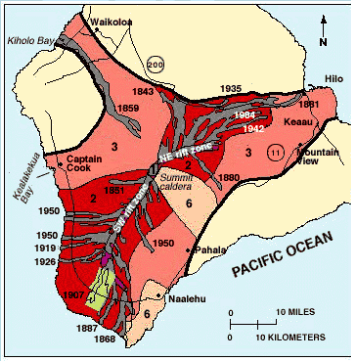


Halemaumau

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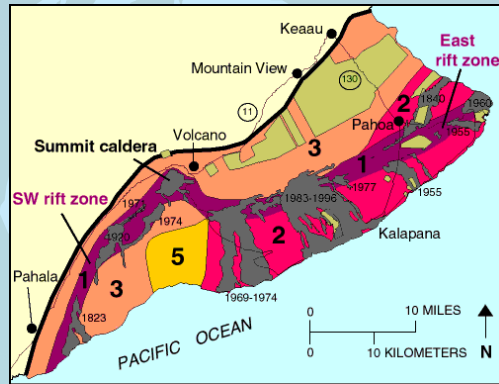


## Geography of the Lava Flow Hazard



Mauna Loa

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



Kilauea

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## 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.

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## The Hazards from VOG



Halema'uma'u

- Volcanic sulfate aerosol is of a size (0.1-0.5  $\mu\text{m}$ ) 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.

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## Vog Emissions Increased in 2008



Summit sulfur dioxide ( $\text{SO}_2$ ) emissions reaching record high levels in March 2008; a new vent opening in Halema'uma'u Crater; a small explosive eruption at Kilauea'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  $\text{SO}_2$  emissions to over 11,000 metric tonnes per day.

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## Proximity of Hazard to Volcano Village



69

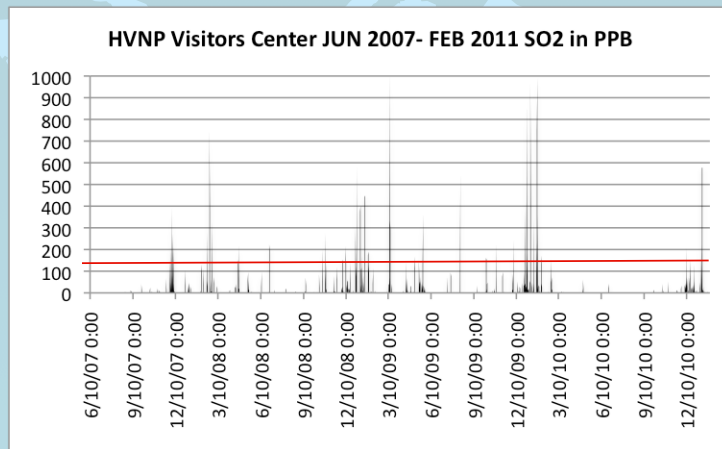
## Proximity of Hazard to Volcano Village

- 2,231 Residents (2000 census).
- 4 miles north of Kilauea. 8 miles northeast of Pu'u O'o vent.
- Can be exposed to SO<sub>2</sub> levels as high as 2000 ppb
- EPA's regulation: 24 hour average from man-made



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## Increased Health Threat



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

71

## Health Impacts from SO<sub>2</sub>

- In animal studies, high concentrations of SO<sub>2</sub> shows airway inflammation and hyper-responsiveness.
- Studies on mild asthmatics that were introduced to SO<sub>2</sub> levels of 500 ppb showed increased airway resistance while exercising.



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## Health Impacts from Sulfate Aerosols

- Volcanic aerosol is of a size (0.1-0.5  $\mu\text{m}$ ) that can effectively reach down into the human lung, causing respiratory distress.
- Epidemiological studies show that sulfates increase bronchitis, chronic cough, and chest illness.



73

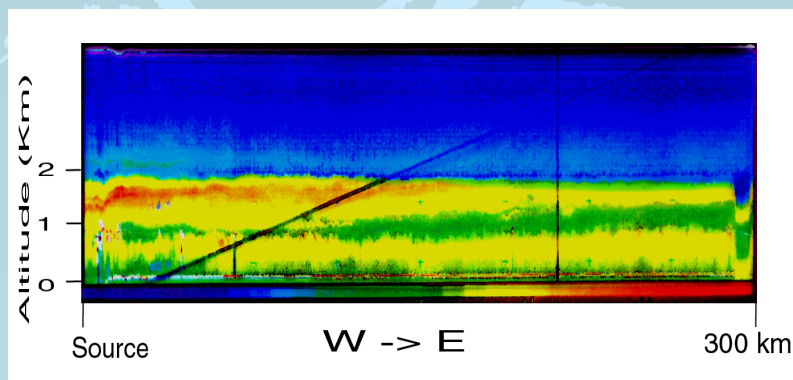
## Health Impacts from Sulfate Aerosols

- "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."



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## Plume Cross Section



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

75

## 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.

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## Monitoring VOG

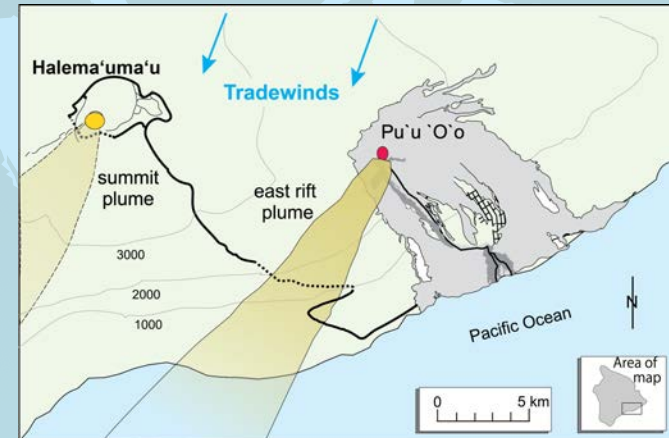


The Flyspec, pictured here strapped to an HVO vehicle, has replaced the larger, heavier, and more expensive optical correlation spectrometer (COSPEC), which was used to measure SO<sub>2</sub> emissions at Kilauea for over two decades. A scientific comparison of Flyspec and COSPEC showed no loss in accuracy 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<sub>2</sub> standard mounted in the instrument. COSPEC can be mounted on a car or aircraft

77

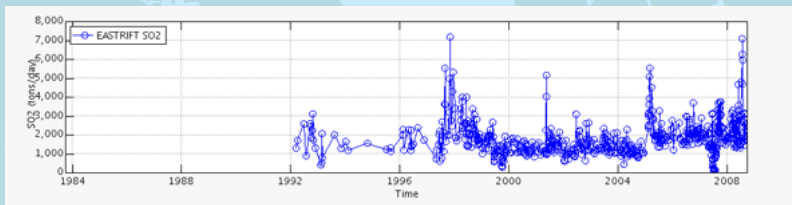
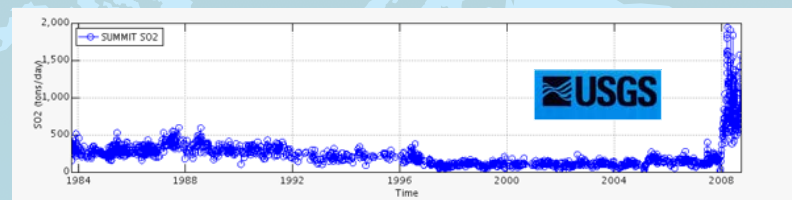
## Monitoring VOG



Vehicle-based SO<sub>2</sub> 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.

78

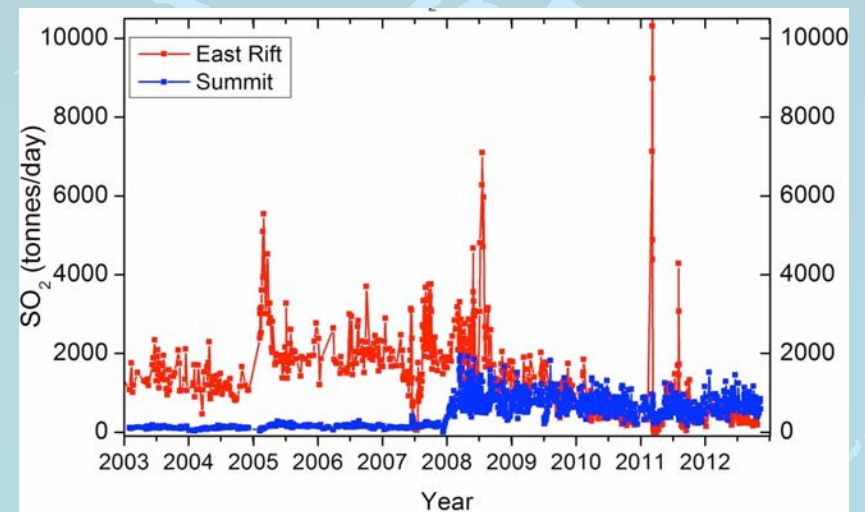
## Kilauea SO<sub>2</sub> Emissions (1984-2008)



Averaged SO<sub>2</sub> emissions from Kilauea's east rift zone 1992 to 2008.

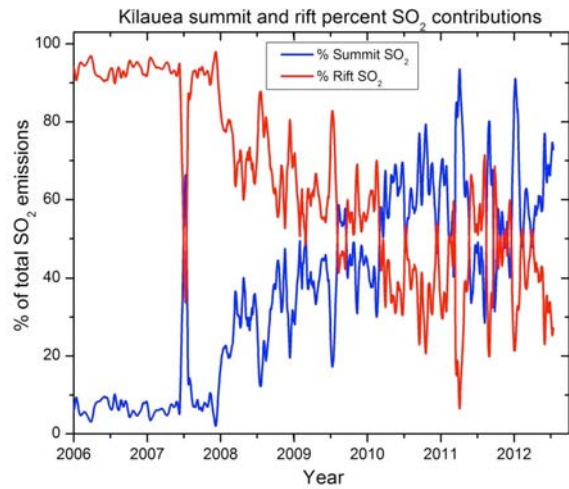
79

## Kilauea SO<sub>2</sub> Emission Rates

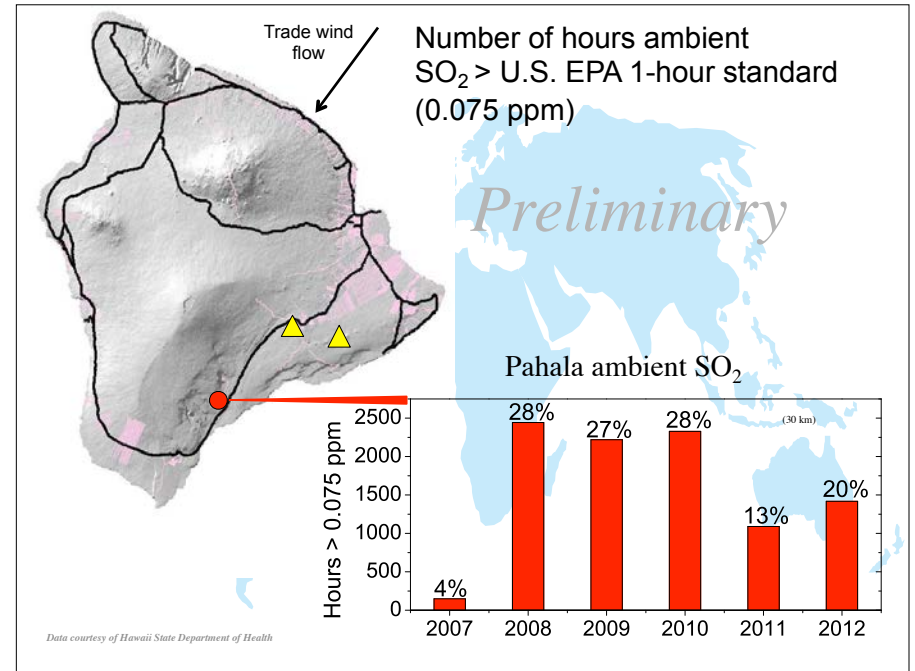


80

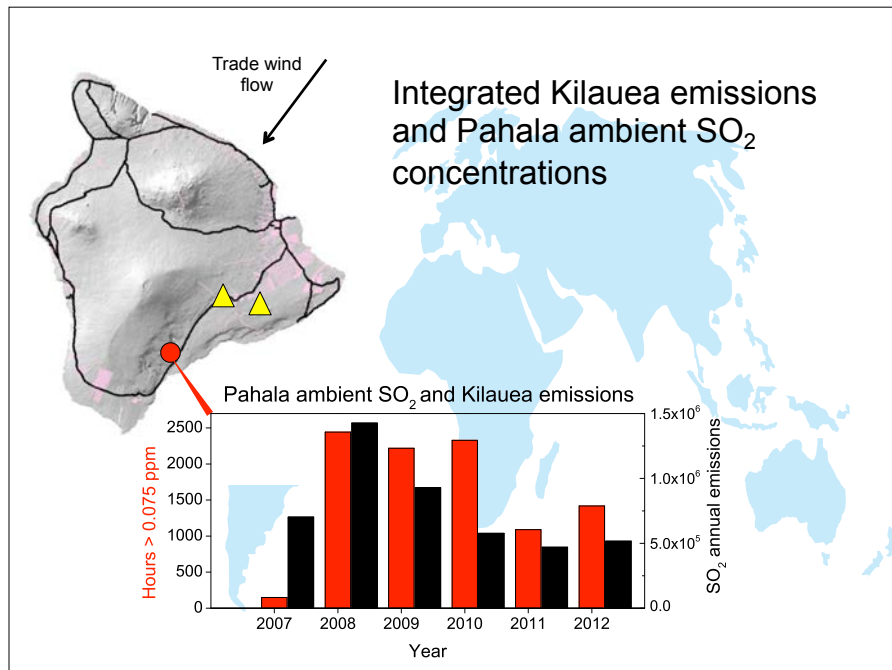
# Kilauea SO<sub>2</sub> Emission Rates



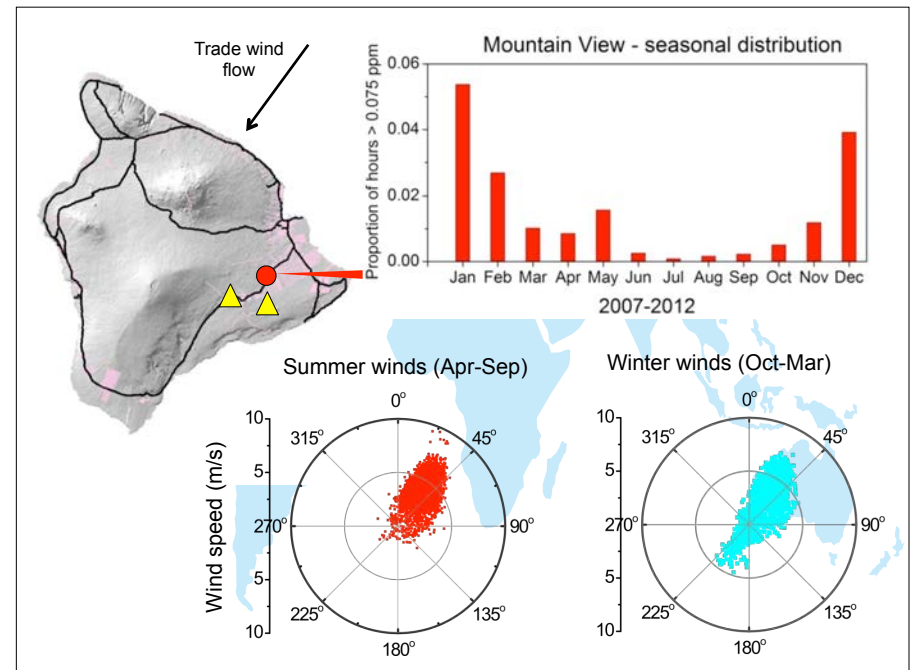
81



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## The Variable Threat from Vog



Kamoamooa Fissure

During the first two weeks of March 2011 emissions peaked at 11,000 metric tons/day associated with a new eruption along the Kamoamooa Fissure.

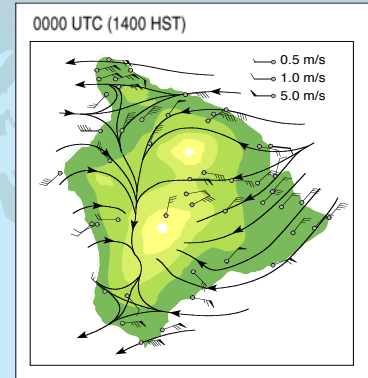
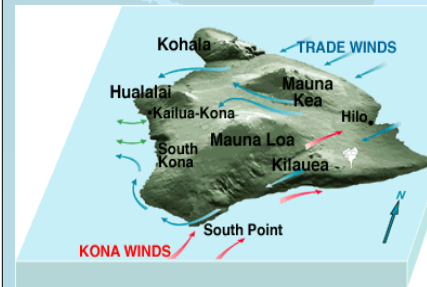
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## Dispersion of Vog

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

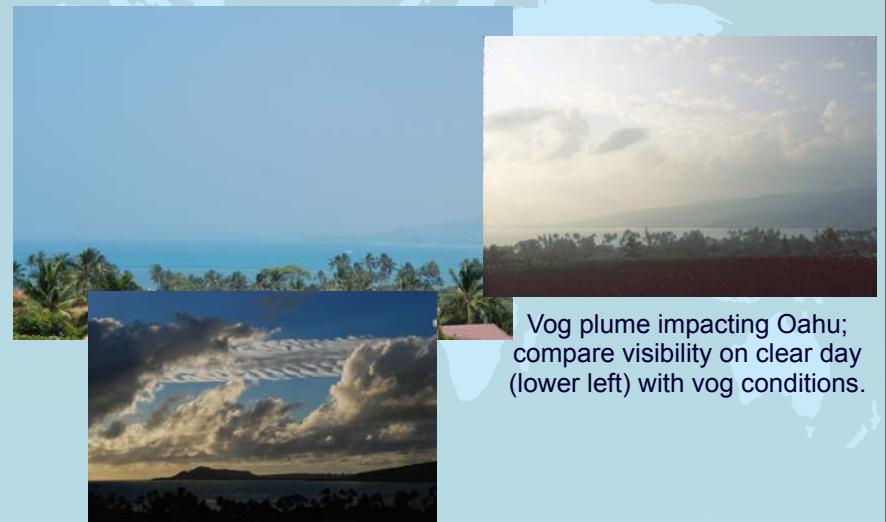
86

## Effects Felt far Downstream



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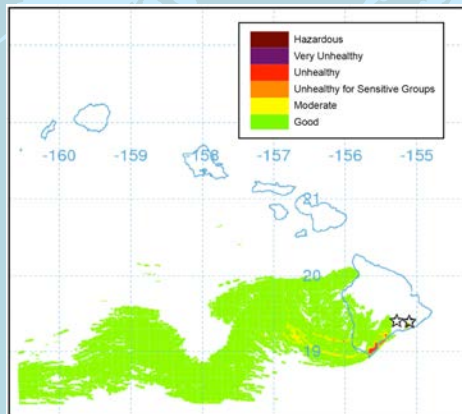
## Effects Felt far Downstream



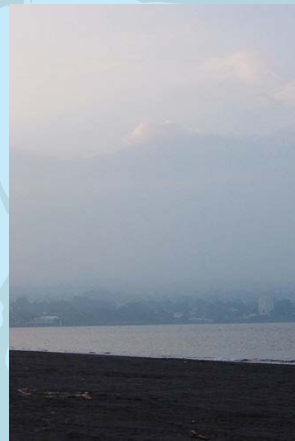
Vog plume impacting Oahu; compare visibility on clear day (lower left) with vog conditions.

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## Model Simulation of VOG



Sea breeze brings vog onto Kona coast.



Thick vog plume over Hilo during light southerly flow.

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## Gaussian Dispersion Model

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

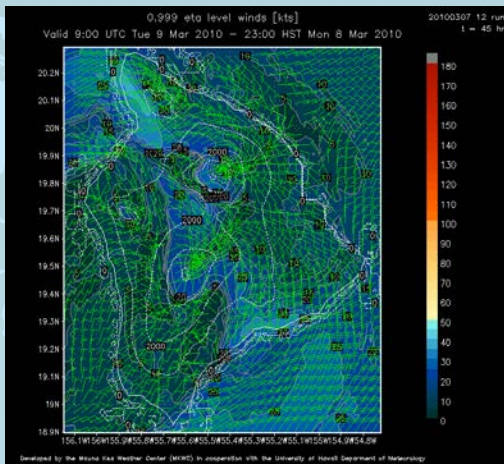
$$C = \frac{Ee^{-\left(\frac{(y-y_0)^2}{2\sigma_y^2}\right)} e^{-\left(\frac{(x-x_0)^2}{2\sigma_x^2}\right)} e^{-\left(\frac{(z-fz)^2}{2\sigma_z^2}\right)}}{2\Pi\sigma_y\sigma_x u}$$

where  $E$  is the source emission,  $u$  is the average wind speed,  $f$  is the particle fall speed,  $\sigma_x$ ,  $\sigma_y$ , and  $\sigma_z$  are the horizontal and vertical dispersion coefficients as a function of downwind distance.

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## Input for Vog Model

WRF Domain 3  
sample winds for  
3/7/10



1. Weekly Averaged  $\text{SO}_2$  emissions from HVO for the summit and East Rift Zone.
2. Meteorological Fields from the Weather Research and Forecast (WRF) model.

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## 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

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## 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

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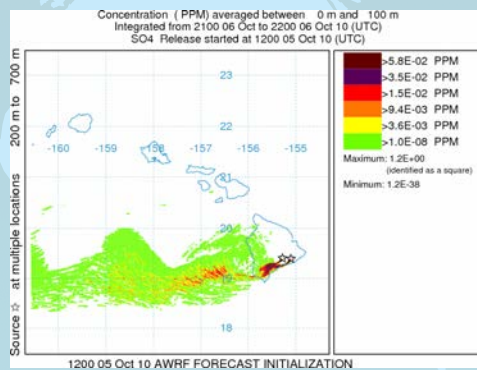
## Conversion Rate: SO<sub>2</sub> to SO<sub>4</sub>

- Conversion rate of SO<sub>2</sub> to SO<sub>4</sub> (sulfate aerosol) in the model is set at a constant rate of 1% per hour.
- Dry deposition velocity for SO<sub>2</sub> = 0.48 cm/s
- Dry deposition velocity for SO<sub>4</sub> = 0.25 cm/s
- Trajectories follow isobaric surface with full reflection assumed at the surface.



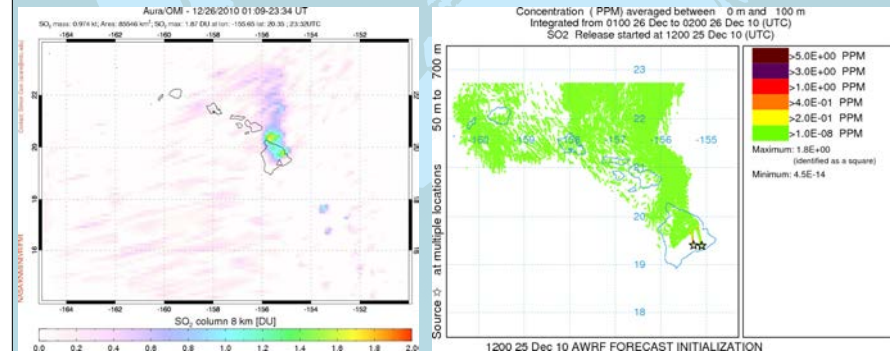
94

## Satellite Validation



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## Satellite Validation

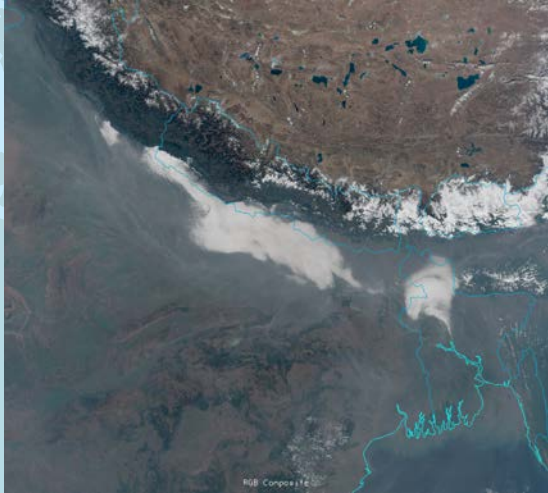


December 26, 2010

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Questions?



India vs Tibet