Meteorology and Climatology 101

MARAMA Webinar
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- Forces of Motion
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- Transport and Ozone Episodes
- Climatology

Effects of Natural Events on Air Pollution

Why do we have weather?

Energy - Radiation from the Sun

- Temperature
- Pressure

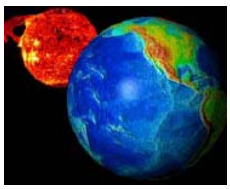


Figure from NASA

Meteorology – The Basics

The Energy Balance

Energy and Earth's Motion

- Orbit & Tilt create seasonal cycle
- Rotation create diurnal cycle – dark sides

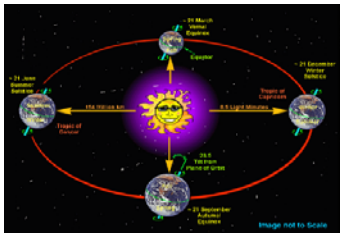


Figure from the Georgia Tech GLOBE Project

Energy and Earth's Tilt

- Radiation is distributed unevenly across the surface
- Higher latitudes have seasons of prolonged night and day
- Angle of incidence at higher latitudes creates a longer path-length through the atmosphere

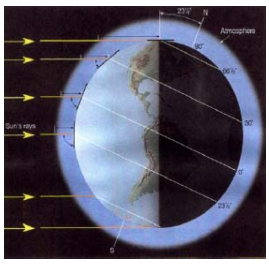


Figure from Ahrens

Solar and Thermal Energy

- Earth's energy budget represented by short and long wave radiation
- Atmospheric radiation interactions include scattering, reflection, absorption, and transmission

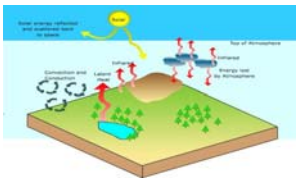
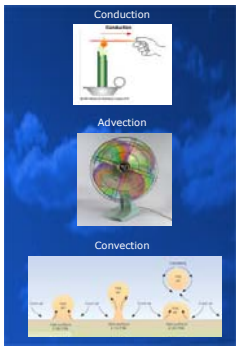


Figure from University of Wisconsin – Stevens Point

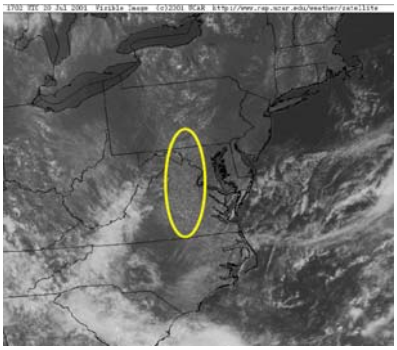
- Greenhouse gases and cloud droplets are efficient absorbers of infrared energy
- Is this a static system? Is weather static? No –the distributions of the parameters are dynamic. (i.e. different ground surfaces, gas & cloud distributions and magnitudes)

A Dynamic Fluid

- In addition to radiation transfer, energy is also exchanged in the atmosphere via conduction (molecules in contact), advection (horizontal air movement), and convection (vertical air movement)
- Additional energy exchange take place during evaporation, transpiration, and condensation



Early Afternoon Convection

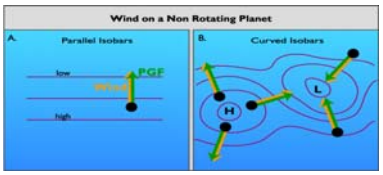


GOES Satellite Imagery

Meteorology – The Basics

Forces of Motion

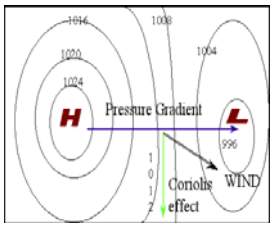
Winds on a Non-Rotating Planet



On a non-rotating planet the pressure gradient forces would create winds flowing from areas of high pressure into adjacent areas of low pressure

Winds on a Rotating Planet

- On a rotating planet (sphere), air parcels swerve away from straight-line motion (similar to walking across wheel-go-round): Coriolis Force
- Here the CF is drawn opposite the PGF creating winds that swerve 90 degrees from the PGF
- In the northern hemisphere winds curve to the right out of a High (southern hemisphere to the left)



Temperature Gradients and Atmospheric Motion

- Distribution of temperature wrt altitude (left) and wrt latitude (right)
- Temperatures decrease with altitude in the troposphere and generally decrease with latitude from equator to poles
- Instability wrt altitude leads to convection

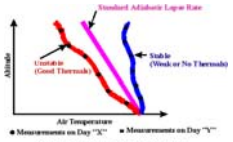


Figure 1: Atmospheric Stability

Figure from FlyMorningSide.com

- Instability wrt latitude by excess net radiational heating at equator leads to wind flow

Circulation Between Highs and Lows

- Now we discuss the third dimension – altitude
- If the center of this diagram is heated, an unstable temperature gradient will produce low pressure in the center and high pressure at the edges
- Vertical circulation begins

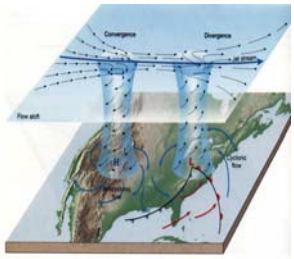


Figure from The Atmosphere, 8th Edition

Circulation Around High Pressure

- High Pressure = Divergence
- Sinking Air
- Air flows out toward areas of Low Pressure
- Interaction of PGF and Coriolis Force creates Clockwise Flow

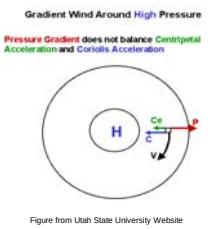


Figure from Utah State University Website

Circulation Around Low Pressure

- Low Pressure = Convergence
- Rising Air
- Air flows in toward areas of Low Pressure
- Interaction of PGF and Coriolis Force creates Counter-Clockwise Flow

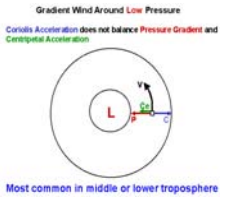


Figure from Utah State University Website

Tropical Hadley Circulation

- In the same way, excess heating of the equatorial region produces an unstable temperature gradient from the poles to the equator
- The three dimensional circulation starting with surface low pressure at the equator and surface high pressure at the poles is the Hadley Cell

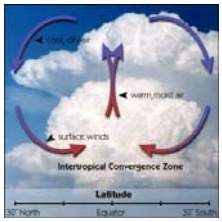
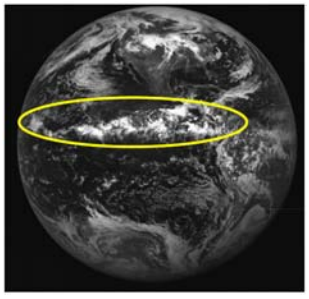


Figure from Whyflies.org

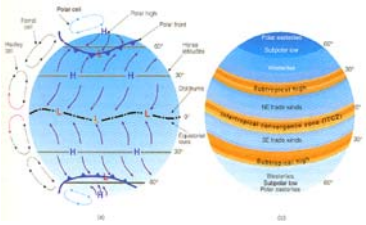
Inter Tropical Convergence Zone (ITCZ)

- Tropical Hadley circulation creates convective cloud formation at all longitudes around the equator



Tropical and Mid-Latitude Circulations

- In the tropics, Hadley circulation and convection occur
- In the mid-latitudes, the predominant winds are called "Westerlies" and they flow between the polar and subtropical Highs



- Westerlies exist in both hemispheres

Global Circulation

- Unlike the Mid-Latitude Westerlies, the tropics have "Trade Winds" flowing from the east
- Horse latitudes have calm surface flow
- 3 cells of circulation

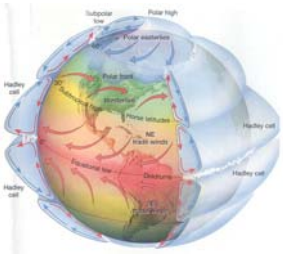
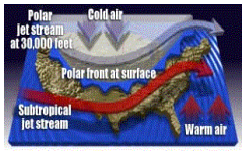


Figure from The Atmosphere, 8th Edition

- 2 areas of convection correspond to areas of precipitation – tropics and polar front

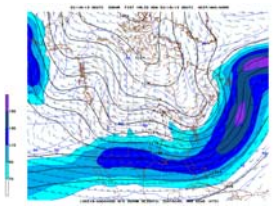
Polar Front

- Boundary between colder, drier air to the north and warmer, moister air to the south
- Polar front is strongest in the winter and weakest in the summer
- Above the Polar Front is the Jet Stream – can extend to the subtropics during the winter



Jet Stream

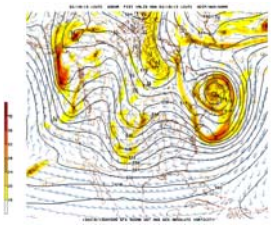
- Northern Hemisphere at 300 mb – winds are colored in knots, heights are white isolines in meters
- Trace areas of High and Low pressure, approximate Polar Front, Jet Stream aloft – fast winds
- Extension across middle North America



Upper Air and Surface Charts

- 500 MB Chart

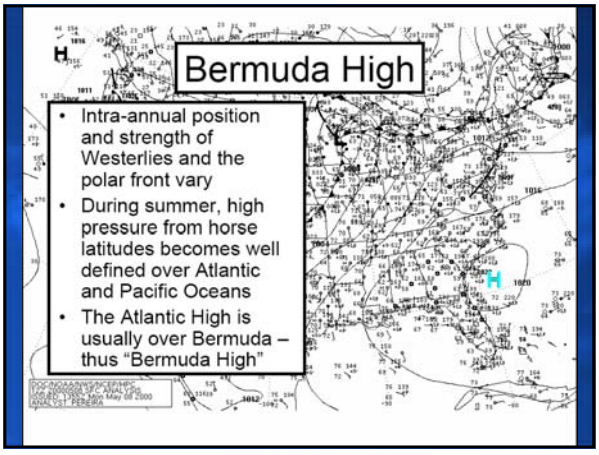
February 18, 2013

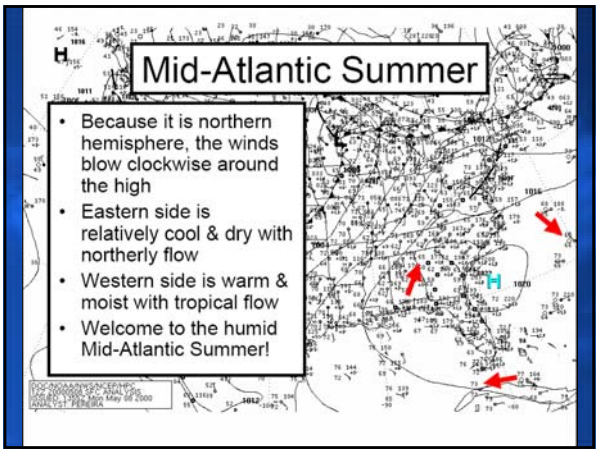


- Surface Analysis

Cold vs. Warm Fronts

Bermuda High





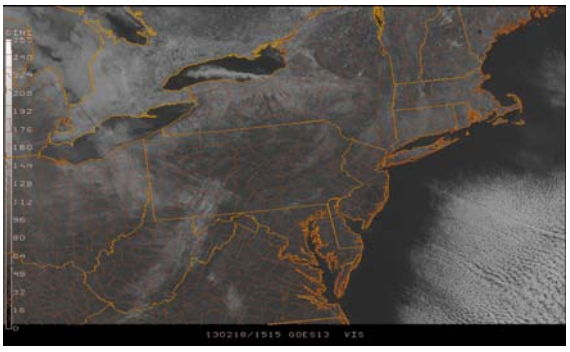
Tools We Can Use

Thanks to the internet, we are able to retrieve data very quickly.

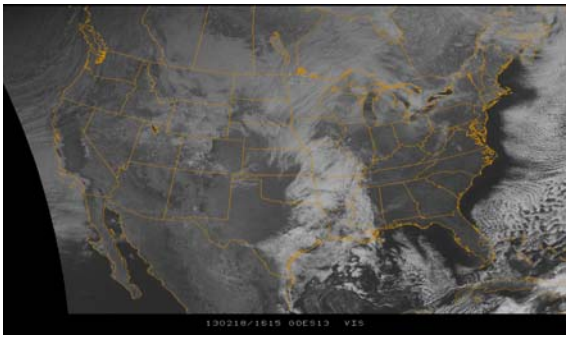
Several tools that we can use to enhance our understanding of the weather

- Satellite Imagery
  There are three types:
  Visible, Infrared, Water Vapor
- Radar Data
- Sounding Data (vertical view of the atmosphere)

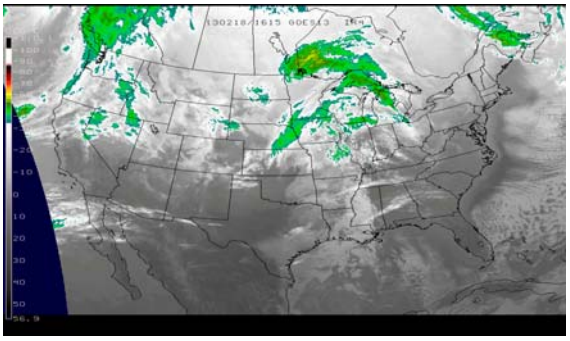
Satellite Imagery - Visible



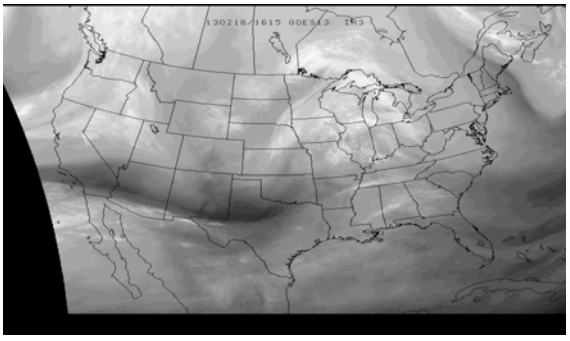
Satellite Imagery - Visible



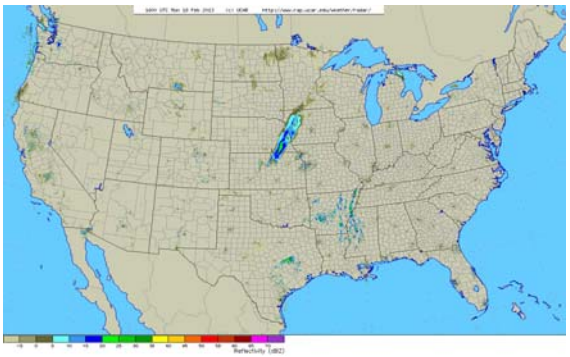
Satellite Imagery - Infrared



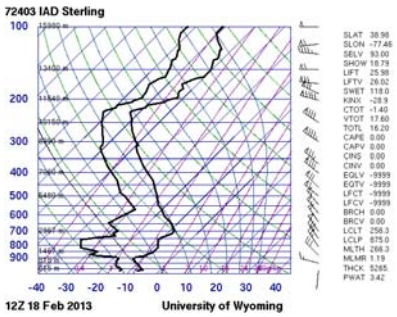
Satellite Imagery - Vapor



Radar Composite



Sounding Data – KIAD (Dulles Int'l)



Meteorology Basics

Scales of Weather

Scales of Motion

- Embedded within the large-scale features we have discussed are smaller-scale features
- Global: ITCZ, ENSO (5000 km, days – weeks)
- Synoptic: Mid-latitude storm, hurricane, cold and warm fronts, high and low pressure centers (2000 km, hours – days)
- Meso-scale: Sea-breeze, mountain-valley breeze, thunderstorm, tornado (20 km, mins – days)
- Micro-scale: Small turbulent eddy (2 m, secs – mins)
- Interaction of all these scales together accounts for the daily procession of weather patterns

Scales of Motion

- Nocturnal inversion – surface cools more quickly than air above on clear nights
- Pollution trapped below the inversion may remain through the night and / or receive more pollutants
- Can occur at various levels in the atmosphere

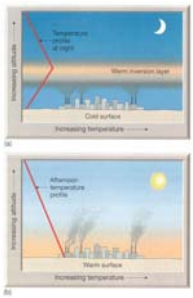
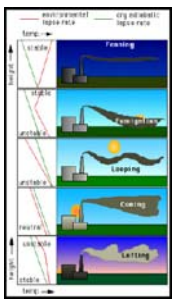


Figure from The Atmosphere, 8th Edition

Stability and Plumes

- Dry adiabatic rate decreases temperature with increasing height
- Environmental rate is actual stability
- Fanning allows little mixing, totally stable, surface inversion, clear nights
- Fumigation has capping inversion and mixes pollution down
- Looping - thermals and subsidence impact
- Coning - neutral
- Lofting - increasing instability with height



Conclusion – Complex System

- Atmosphere is a dynamic complex system
- Chaos theory and the Butterfly Effect show how minor perturbations in the atmosphere can be amplified upon each iteration of the perturbation

- Forecasting and modeling of the atmosphere is a difficult task but very interesting

Air Pollution in the Mid-Atlantic Region

Pollutants of Concern

Various Pictures of Pittsburgh 1940-1950

Corner of Liberty and Fifth Avenue (Archives Services Center, U. of Pittsburgh)

Various Pictures of Pittsburgh 1940-1950

Corner of Liberty and Fifth Avenue (Archives Services Center, U. of Pittsburgh)

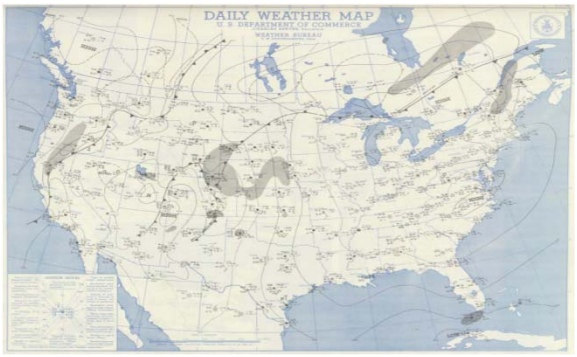
Various Pictures of Pittsburgh 1940-1950

Midday Darkness (Archives Services Center, U. of Pittsburgh)

One Historical Case of Air Pollution in PA

- Donora, PA – Oct. 26-31, 1948
- Air pollution episode left 20 dead out of 14,000 people
- Figure to the right:
  Donora at Noon on Oct. 29

One Historical Case of Air Pollution in PA

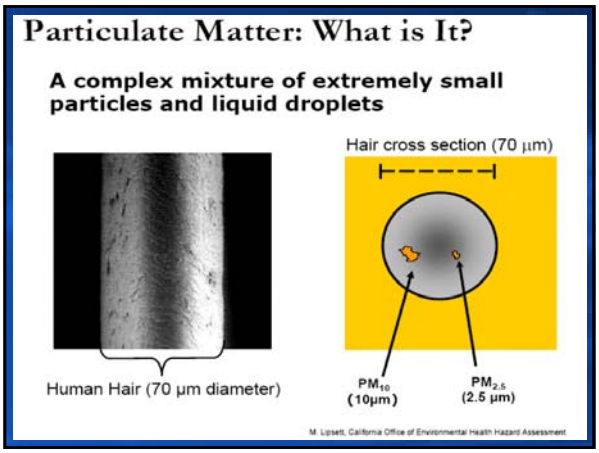


Pollutants of Concern During Poor Air Quality Events

- Photochemistry, Precursors, Health, NAAQS (prior class)
- Particulate Matter > 10 microns and > 2.5 microns (primary & secondary)
  Ex. Diesel soot, dust, sulfates, nitrates, organics
- Haze (primary & secondary)
- Ozone (secondary)

What is PM 2.5?

- Particulate matter (PM) is a complex mixture of solid and liquid particles that vary in size and composition
- Particulate matter 2.5 (PM 2.5) is particulate matter with the size of 2.5 micrometers or less



Sources of PM 2.5

PM is composed of a mix of primary and secondary compounds.

Primary PM (directly emitted):

- Suspended dust
- Sea salt
- Organic carbon (OC)
- Elemental carbon (EC)
- Metals from combustion
- Small amounts of sulfate and nitrate

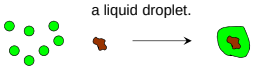
Secondary PM (gases that form PM in the atmosphere):

- Sulfur dioxide (SO_2) – forms sulfates
- Nitrogen oxides (NO_x) – forms nitrates
- Ammonia (NH_3) – forms ammonium compounds
- Volatile organic compounds (VOC) – forms organic carbon compounds

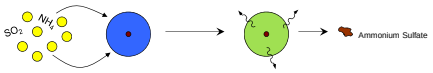
Formation of PM 2.5

Coagulation: Particles collide with each other and grow.

Condensation: Gases condense onto a small solid particle to form a liquid droplet.



Cloud/Fog Processes: Gases dissolve in a water droplet and chemically react. A particle exists when the water evaporates.



Chemical Reaction: Gases react to form particles.

NO_x → HNO_3 + NH_3 ⟷ (Fn (Temp, RH)) → NH_4NO_3 (particle)

Nitric Acid Ammonia Ammonium Nitrate

Haze in the Mid-Atlantic and Northeast

- Haze is a subset of PM and is primarily composed of sulfur and nitrogen compounds
- Particles of a certain size can reflect or refract light, causing a reduction in visibility
- This reduction in visibility is known as haze
- Hazy conditions occur frequently in conjunction with severe ozone events

Example of Haze

Burlington, VT (Overlooking Lake Champlain)

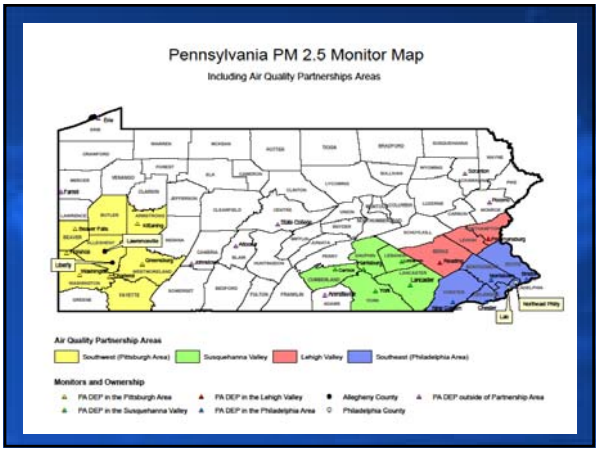
Clear Day

Hazy Day

PM 2.5 in the Mid-Atlantic and Northeast

- At the end of 2011, Pennsylvania currently had 22 real-time fine particulate monitors and 30 Federal Reference Method (filtered) monitors deployed throughout the Commonwealth

- Data analysis within the Mid-Atlantic region show that there are more exceedances of the 24-hour standard (35 ug/m3) than the annual standard (15.5 ug/m3)



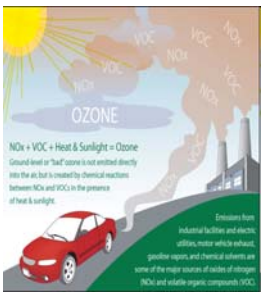
What is Ozone?

- Ozone is a gas composed of three (3) oxygen atoms.

- Ozone is a photochemical pollutant (needs sunlight, along with NOx and VOC to form)

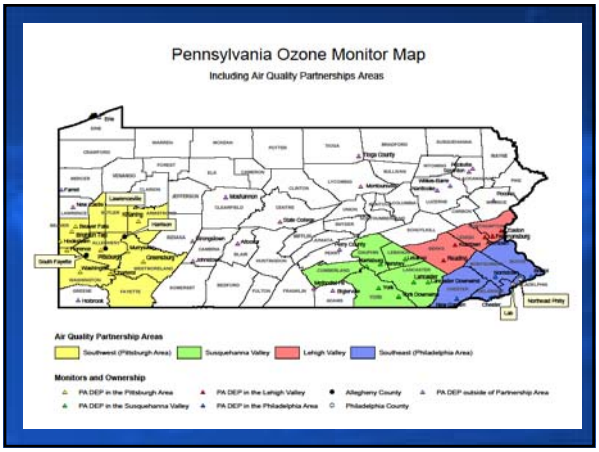
- Good ozone: Found in stratosphere

- Bad ozone: Found at the surface



Ozone in the Mid-Atlantic and Northeast

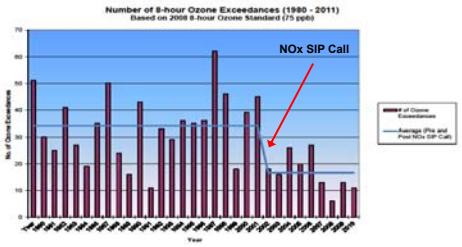
- At the end of 2012, Pennsylvania had 45+ monitors deployed throughout the Commonwealth
- Over the past several years, we have seen a decline in the number of exceedances over the area (as compared to the 1990s and early 2000s)
- Could be contributable to
  - Emission Reductions
  - Economic Downturn
  - Other Meteorological Factors



Ozone in the Mid-Atlantic and Northeast

- Have a long standing record of ozone throughout the region
- Most areas in Pennsylvania are meeting the 2008 8-hour ozone standard. 2012 ozone data forced a few more areas into nonattainment.
- A lot of states have non-attainment issues with the 8-hour standard
- A major emission reduction in NOx (the NOx SIP call) caused for a reduction in ozone exceedances the past several years
- With high ozone events, haze can be present

Ozone Exceedances in the Pittsburgh Area



Ozone Exceedances in the Washington, DC Area

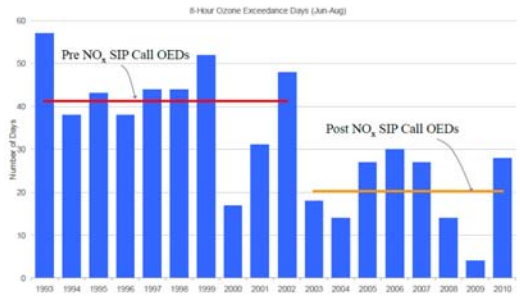


Image Originally Developed from MDE: http://www.marama.org/presentations/2011_DataAnalysis/Nguyen_AQCycle.pdf

Ozone Exceedances in the Baltimore Area

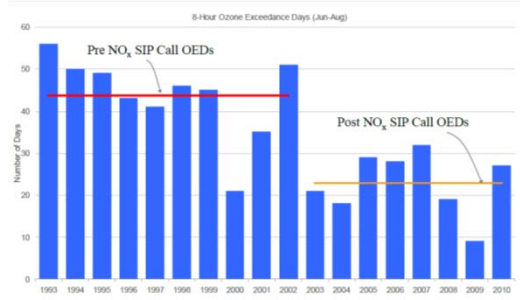


Image Originally Developed from MDE: http://www.marama.org/presentations/2011_DataAnalysis/Nguyen_AQCycle.pdf

Ozone Exceedances in the Philadelphia Area

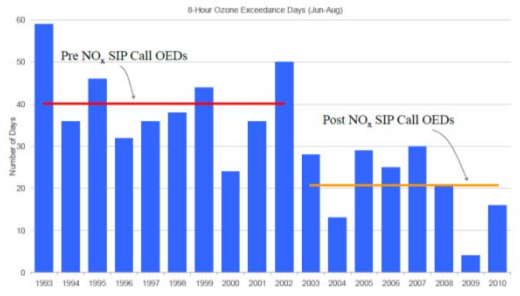


Image Originally Developed from MDE: http://www.marama.org/presentations/2011_DataAnalysis/Nguyen_AQCycle.pdf

What Modulates O_3 Concentrations?

The amount of O3 produced each day depends on a variety of factors including:

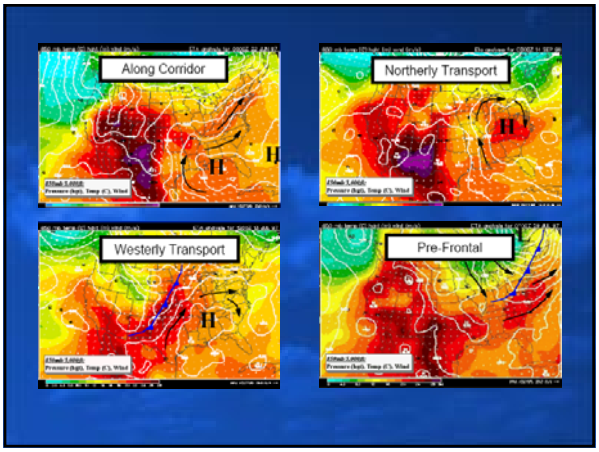
- Temperature
- Concentrations of O_3 and precursors transported and mixed downward during the late morning
- Wind speed and direction
- Local emissions of O_3 precursors
- Amount of available sunlight (clouds & day length)
- Depth of vertical mixing

The Four Hs

- Most unhealthy air quality days occur in the summer season. Summer weather in the Mid-Atlantic can be characterized by the "4 Hs"
- These weather conditions occur frequently during Mid-Atlantic summers and are often BUT NOT ALWAYS associated with unhealthy air quality

Weather Patterns During Ozone Episodes

- Largely depends on the location of the Bermuda High and fronts
- Four Patterns
  - Along Corridor (SW to NE)
  - Westerly Transport
  - Northerly Transport
  - Pre-Frontal
- When these patterns exist for multiple days, the chance for a violation increases
- However, the Mid-Atlantic is capable of producing weak violations without strong transport from non-local sources



Forecasting Air Quality and Air Quality Action Days

To warn the public of poor air quality and encourage voluntary reduction of emissions of O3 and PM 2.5 precursors, forecasts are issued daily year-round.

For more information on ozone and PM 2.5 forecasts, visit:

USEPA EnviroFlash Program (email):
http://www.enviroflash.info
(Includes forecasts for DE, MD, NC, NJ, and PA)

USEPA Airnow Website: http://www.airnow.gov

Color Coded Air Quality Forecast (Based on EPA's AQI Scale)

Color Code	Message	AQI Scale	8-Hour Ozone (ppb)	24-hour PM 2.5 (ug/m3)
Green	Good	0-50	0 - 59	0 - 12.0
Yellow	Moderate	51-100	60 - 75	12.1 - 35.4
Orange	Unhealthy for Sens. Groups	101-150	76 - 95	35.5 - 55.4
Red	Unhealthy	151-200	96 - 115	55.5 - 150.4
Purple	Very Unhealthy	201 and Up	116 - 374	150.5 and Up

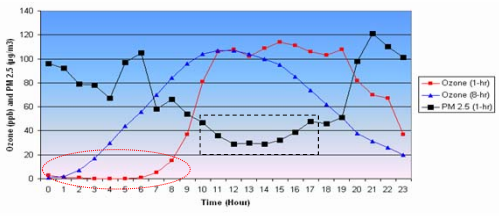
Air Pollution in the Mid-Atlantic Region

An Ozone Episode

An Air Quality Episode in 10 Slides

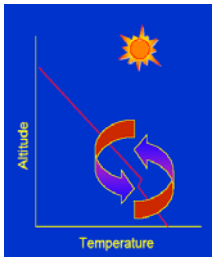
A typical summer day with ozone and PM 2.5 in Pittsburgh area

O_3 concentrations reach a minimum in the morning whereas PM 2.5 levels reach a minimum during the day



During the Late Morning

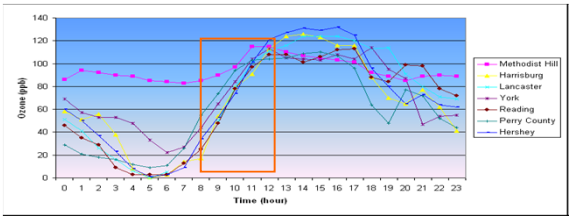
- Surface heats up air beneath the nocturnal inversion and the air becomes warmer than the air aloft – rises and mixes
- The inversion layer disappears
- Pollutants above the inversion mix with pollution under the layer
- Causes a dramatic increase in ground-level ozone, beginning around 10 AM



Regional Scale O_3

Air mixed down during the late morning and early afternoon hours is typically high in O_3 as well as other pollutants and concentrations are often uniform over large distances

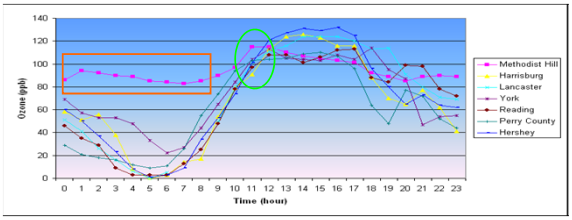
All sites increase after the inversion disappears



Regional Scale O_3

In this case from August 12, 2002, the high elevation monitor at Methodist Hill in southcentral PA is above the nocturnal inversion

By late morning, mixing has brought all monitors to the common regional level

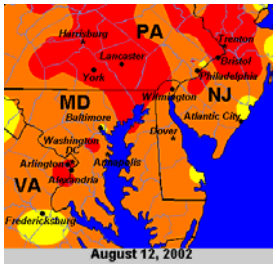


By the Afternoon

- By late morning, downward mixing of O_3 leads to relatively uniform concentrations across the region
- Local effects, related to emissions available, then dominate in the early afternoon hours
- O_3 is formed as UV radiation drives reactions of O_3 precursors
- Depending on a variety of factors, peak O_3 concentrations are reached during the mid to late afternoon hours
- The highest concentrations occur downwind of the urban center

Highest Daily O_3 Values

- Transported ozone added to locally produced ozone, results in the high concentrations just downwind of cities
- On this day, winds were generally west or southwest and high O3 levels are found north and east of the big cities with lower concentrations near the city centers



Vertical Mixing Depth

Just as surface-based inversions at night can trap pollutants near the surface, higher level inversions can form in the afternoon hours and prevent pollution from mixing vertically.

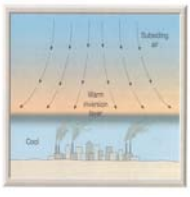
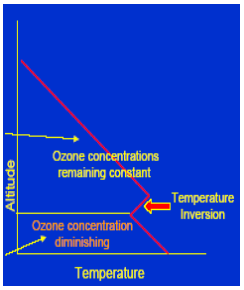


Figure from The Atmosphere, 8th Edition

After Sunset

- If meteorological conditions remain the same, the temperature inversion forms again after dark as the ground cools faster than the air above
- Ozone concentrations above the inversion come into equilibrium with other pollutants and then remain at a constant, relatively high level
- Ozone trapped under the inversion reacts with other pollutants, particles and the surface; the ozone concentration diminishes



The End of an Ozone Episode

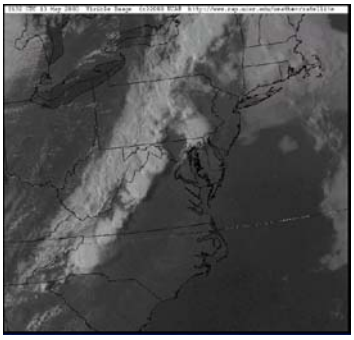
- An ozone episode usually ends with the arrival of a 'clean' air mass:

This can occur with a cold front or other low-pressure system like a tropical storm

- An episode may also end prior to the passage of a cold front if widespread thunderstorms develop ahead of the front

Thunderstorm Development

- This is an example of a strong squall line bringing a high ozone event to an end
- Timing precipitation is a key to forecasting ozone

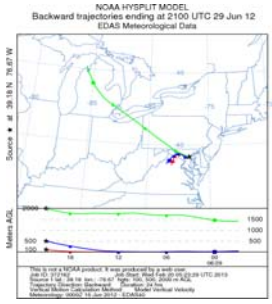


Air Pollution in the Mid-Atlantic Region

Transport and Ozone Episodes

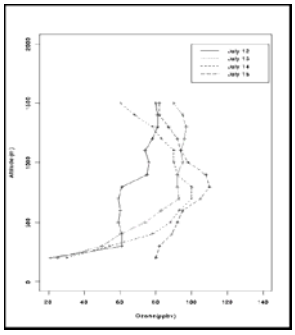
What Do We Know About Air Parcels Entering the Region

- Using back trajectories models, we're able to estimate the source region of air entering the region
- An example of output from the NOAA-ARL HYSPLIT back trajectory model for June 29, 2012
- Boundary layer wind direction from the west, southwest (and light)

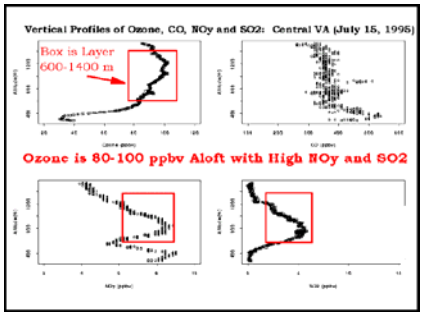


Transport of High O_3

- O3 vertical profiles in rural south-central PA – July 12-15, 1995
- Air entering the region is already close to the NAAQS without local O3
- Profiles near daybreak – Winds west and northwest
- Data: NARSTO-NE, Sonoma Technologies



Transport of Precursors

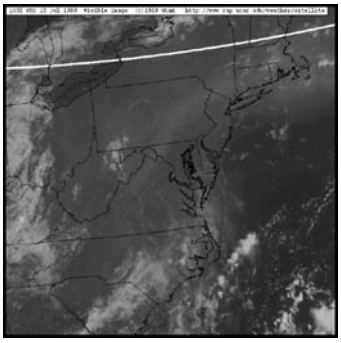


Recirculation

- On days when winds are in the opposite direction as they were the previous day, an area will experience the previous day's air mass, often polluted, a second time
- The longer residence time for pollutants means more potential for ozone production.

Haze is Associated with Recirculated Air

Haze is seen from western MD through southeastern PA and northeastward into New England



Recirculation

Recirculation wind patterns can occur in a number of different situations:

– A change in frontal position: Cold fronts often stall over the region in summer and return north as a warm front
– Land/sea interactions: Sea breezes often push concentrate O_3 and precursors back into the Philadelphia area
– Changes in position of pressure system centers

Recirculation at low levels can occur in conjunction with continued westerly transport aloft

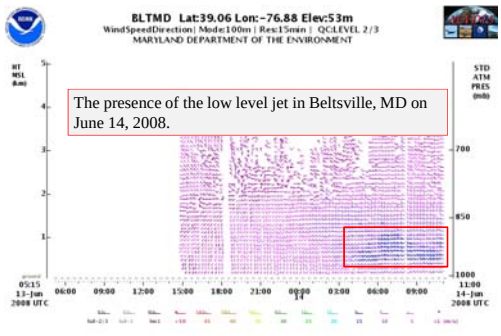
Intra-Regional Transport: The Low Level Jet

In weather patterns conducive to high O3, a strong nocturnal inversion typically develops

During the overnight hours, a region of strong west to southwest winds will develop just above the nocturnal boundary layer

Recent advances in remote sensing instruments (radar profilers) have allowed these phenomena to be observed

Intra-Regional Transport: The Low Level Jet

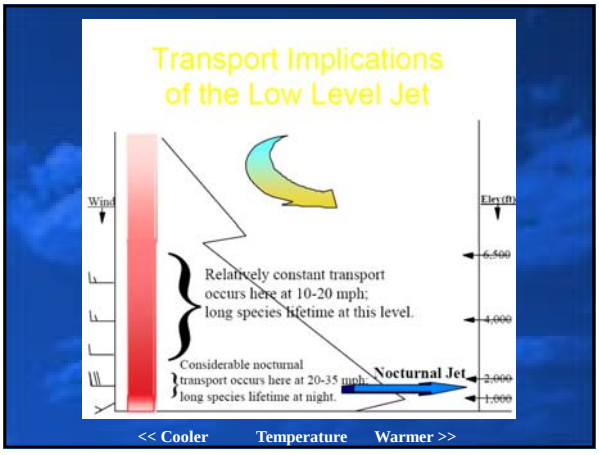


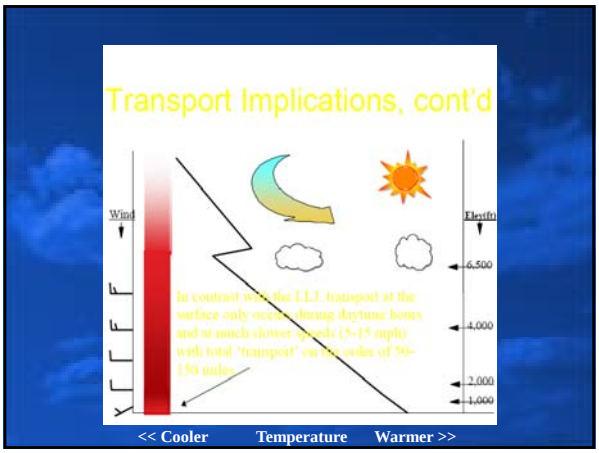
The Low Level Jet (LLJ)

- The low level jet is “low” because its altitude is only 300-600 m (~1000-2000 ft.) above ground level on average
- High wind speeds (30-40 mph) are seen at this level
- The jet occurs at night and in the early morning and is found on the eastern side of mountain ranges

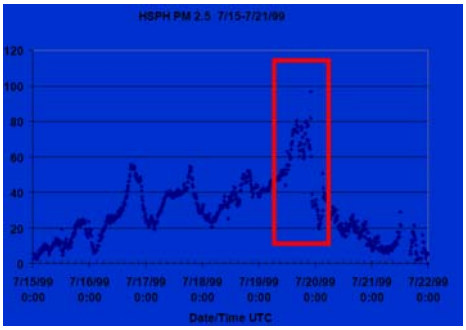
The Low Level Jet (LLJ)

- Low level jets typically are found in the lee (downwind) of mountain ranges
- The most famous LLJ is found in the Great Plains east of the Rockies but another, weaker jet can be observed east of the Appalachians





PM Concentrations Also Peak as Transport Pattern Reverses



Conclusions

- Mid-Atlantic air pollution episodes occur in the summer, when high temperatures, moderate westerly winds and temperature inversions are present
- Several regions within the Commonwealth regularly exceed the NAAQS for 8-hour O_3
- While meteorological conditions are the main influence on the chemical reactions which take place to form pollution episodes, the relationship between weather and pollution is complex
- Hot, sunny weather is necessary but not sufficient for pollution events

Conclusions (cont.)

• In addition to local weather, the regional and intra-regional transport of O_3 and its precursors often determines if Code Orange conditions are reached

• Air pollutant transport can occur on different scales, large scale westerly transport from pollution sources to our west, intra-regional transport overnight by the low level jet, and local recirculation along the I-95 corridor

• The most severe events occur when one or more of these transport effects are present, especially the larger scale transport

Air Pollution in the Mid-Atlantic Region

Review of 2012 Episode

Review of 2012 Episode

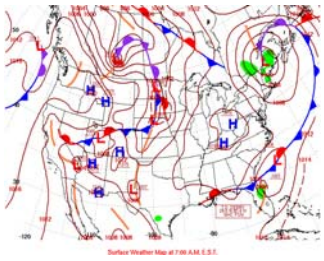
Period of Episode: June 28-29, 2012

Discussion Includes the Following:

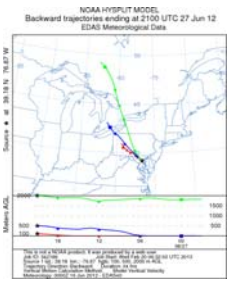
- The Setup
- The Event
  - Meteorological Conditions
  - Air Quality Levels
- The Finale

Meteorological Conditions (The Setup)
Wed, Jun 27, 2012

Surface Map – 7 AM



Forecasted Trajectory – 5 PM

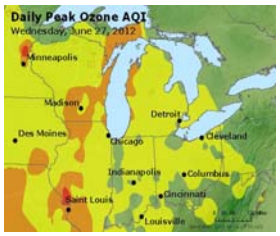


High Temps: Richmond (87), Washington DC (87), Baltimore (90), Philly (86), Pittsburgh (86)

Ozone Conditions
Wed, Jun 27, 2012

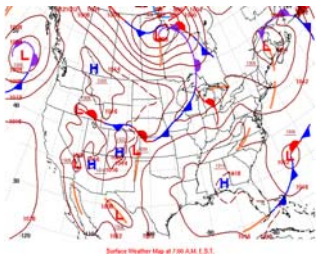
Locally: Only GOOD and MODERATE Levels

Out West: Levels Rising into ORANGE/RED

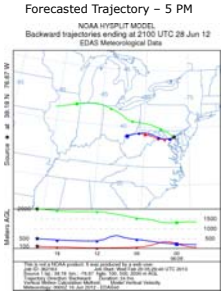


Meteorological Conditions (The Episode)
Thu, Jun 28, 2012

Surface Map – 7 AM

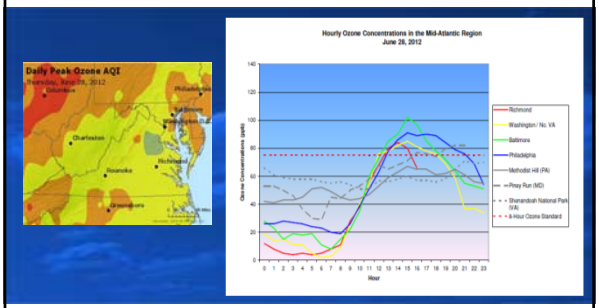


Forecasted Trajectory – 5 PM



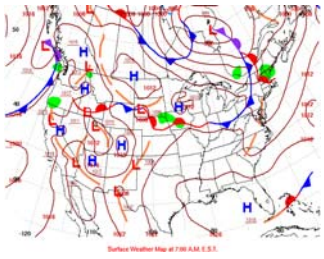
High Temps: Richmond (96), Washington DC (93), Baltimore (96), Philly (92), Pittsburgh (95)

Ozone Conditions
Thu, Jun 28, 2012

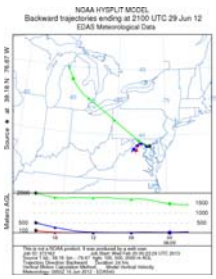


Meteorological Conditions (The Episode)
Fri, Jun 29, 2012

Surface Map – 7 AM

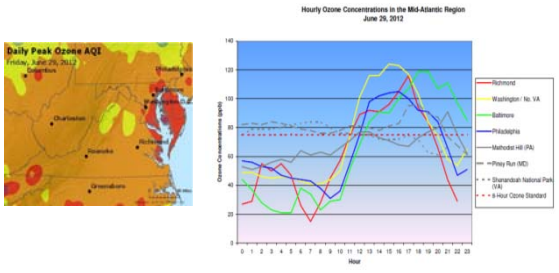


Forecasted Trajectory – 5 PM



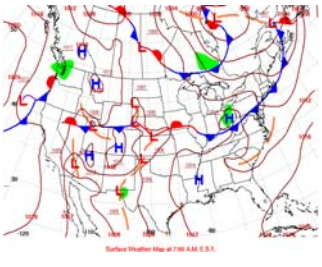
High Temps: Richmond (103), Washington DC (102), Baltimore (100), Philly (98), Pittsburgh (97)

Ozone Conditions
Fri, Jun 29, 2012

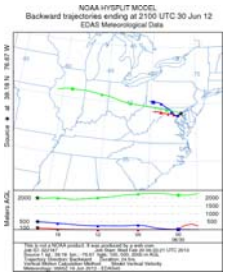


Meteorological Conditions (The Finale)
Sat, Jun 30, 2012

Surface Map – 7 AM

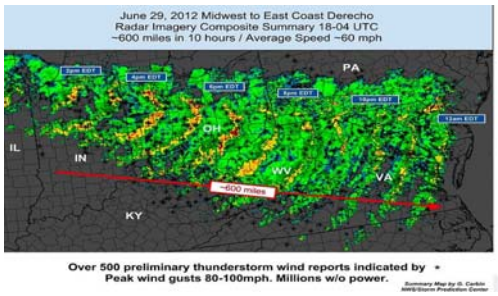


Forecasted Trajectory – 5 PM



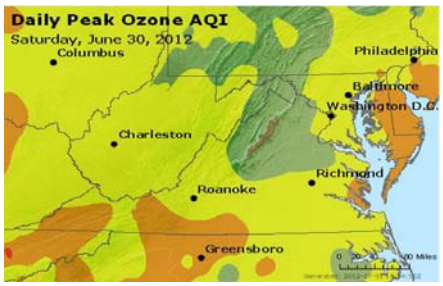
High Temps: Richmond (96), Washington DC (94), Baltimore (95), Philly (94), Pittsburgh (89)

Meteorological Conditions (The Finale)
Derecho (Late on Fri, Jun 29)



Precipitation: Richmond (0.61”), Washington DC (0.38”), Baltimore (0.52”), Philly (0.18”), Pittsburgh (0.07”)

Ozone Conditions
Sat, Jun 30, 2012



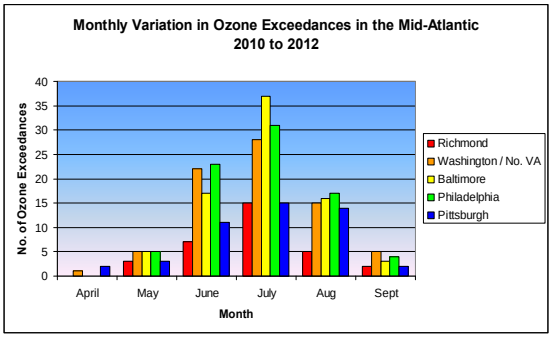
Air Pollution in the Mid-Atlantic Region

Climatology

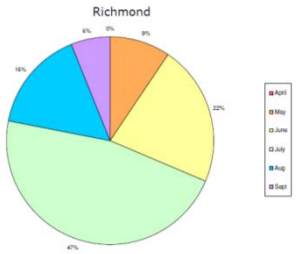
Climatology of Air Pollutants

- Focused on ozone
- Took a look at several factors:
  - Monthly variation
  - Days of the week
- Trends indicate that most ozone and PM 2.5 exceedances occur in the summer. PM 2.5 exceedances also occur during the winter, just not as frequent as summer.
- Climatological look focused on the Mid-Atlantic

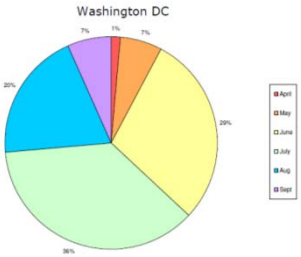
Ozone by Month



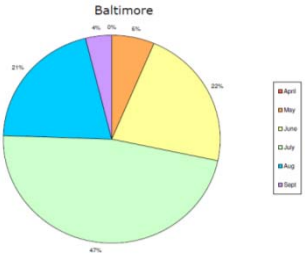
Ozone by Month
2010 to 2012



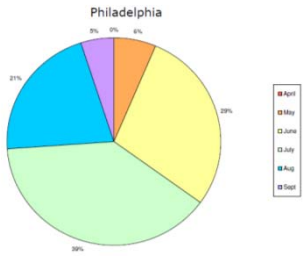
Ozone by Month
2010 to 2012



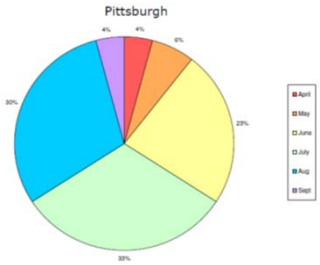
Ozone by Month
2010 to 2012



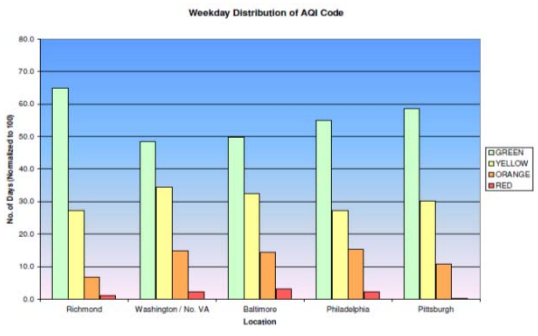
Ozone by Month 2010 to 2012



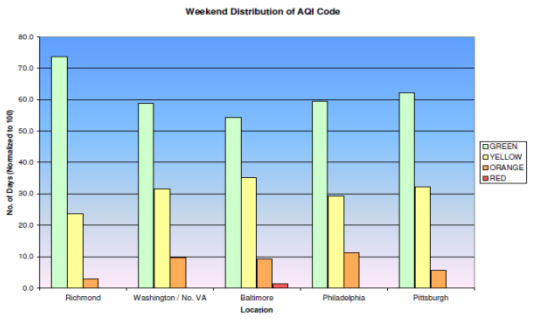
Ozone by Month 2010 to 2012



Ozone – Weekday vs Weekend 2010 to 2012



Ozone – Weekday vs Weekend 2010 to 2012



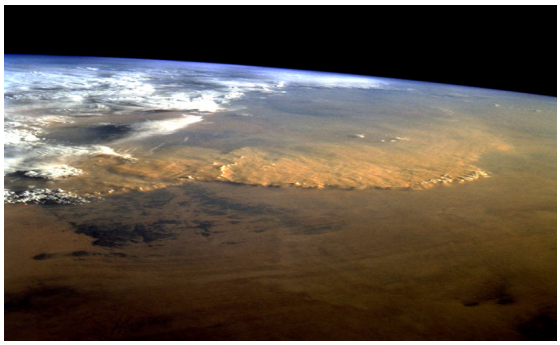
Effects of Natural Events On Air Pollution

Saharan Dust and Forest Fires

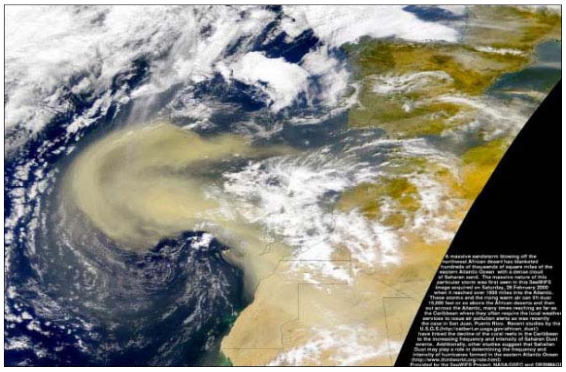
Natural Events

- Natural events such as Saharan dust and forest fires create air pollution concerns across the US
- Some of these effects are also seen across PA
- Most of the effect is seen in the PM 2.5 concentrations, but can also be seen in ozone concentrations as well
- These events lead to elevated pollutant levels, sometimes exceeding the NAAQS

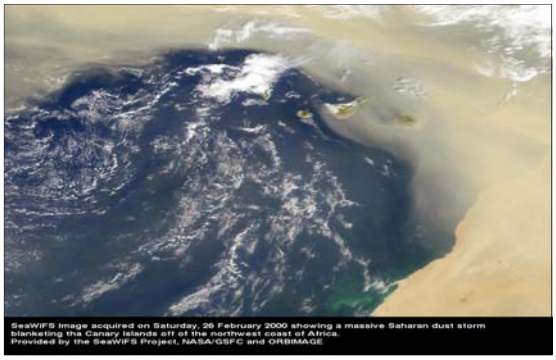
Saharan Dust



Saharan Dust

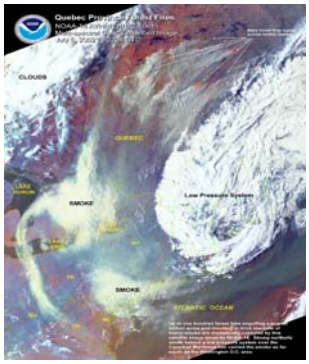


Saharan Dust

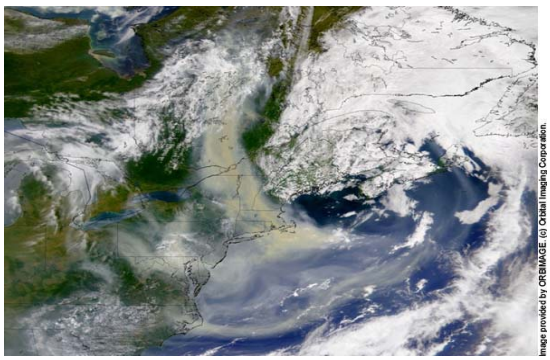


Typical Affect Dust has on Local Area

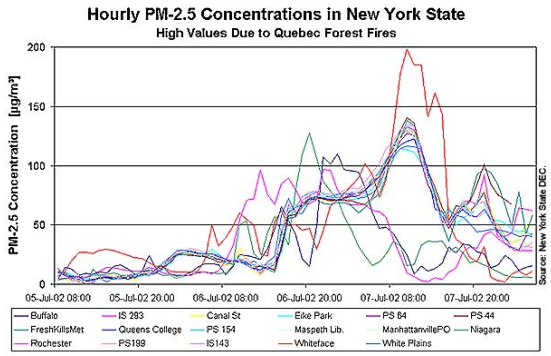
Quebec Fires – July 2002



Quebec Fires – July 2002



Quebec Fires – July 2002



Southwestern, CA – October 2003

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Southwestern, CA – October 2003

Southwestern, CA – October 2003

Southwestern, CA – October, 2003

	DTN PM2.5	DTN AQI	DTN Category	ESC PM2.5	ESC AQI	ESC Category	Comments
Thu, 10/23/2003	27.2	74	MODERATE	24.5	69	MODERATE	
Fri, 10/24/2003	31.9	83	MODERATE	18.8	57	MODERATE	
Sat, 10/25/2003	57.2	134	UNHEALTHY for SENSITIVE GROUPS	23.3	66	MODERATE	Cedar Fire Started late PM
Sun, 10/26/2003	111.7	178	UNHEALTHY	14.3	46	GOOD	
Mon, 10/27/2003	179.1	229	VERY UNHEALTHY	73.9	156	UNHEALTHY	
Tue, 10/28/2003	154.4	205	VERY UNHEALTHY	348.1	398	HAZARDOUS	Paradise Fire affecting ESC
Wed, 10/29/2003	47.4	115	UNHEALTHY for SENSITIVE GROUPS	154.2	205	VERY UNHEALTHY	
Thu, 10/30/2003	9.6	31	GOOD	5.0	16	GOOD	
Fri, 10/31/2003	5.6	18	GOOD	3.3	11	GOOD	
Sat, 11/1/2003	6.1	20	GOOD	1.8	6	GOOD	
Sun, 11/2/2003	6.9	22	GOOD	9.3	30	GOOD	

The End

Picture Details: Linfen, China (taken in the 2000s)