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Air Pollution Meteorology

Meteorology's Effect on Air Quality
Meteorological Products and Examples

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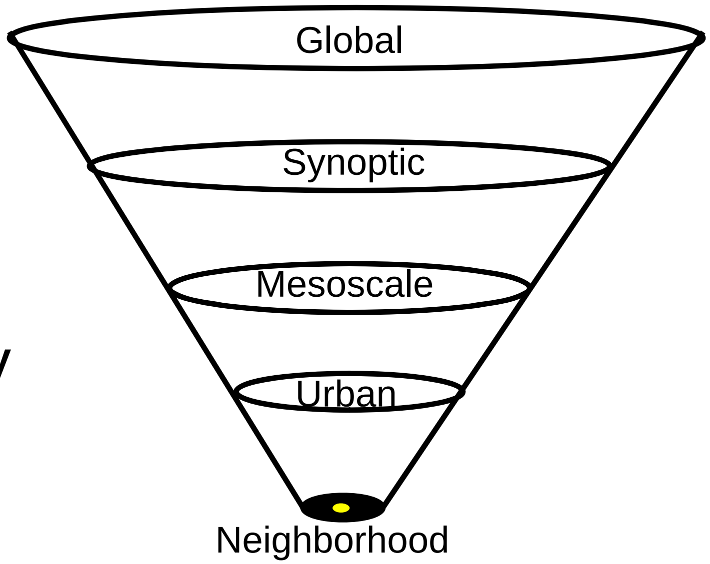
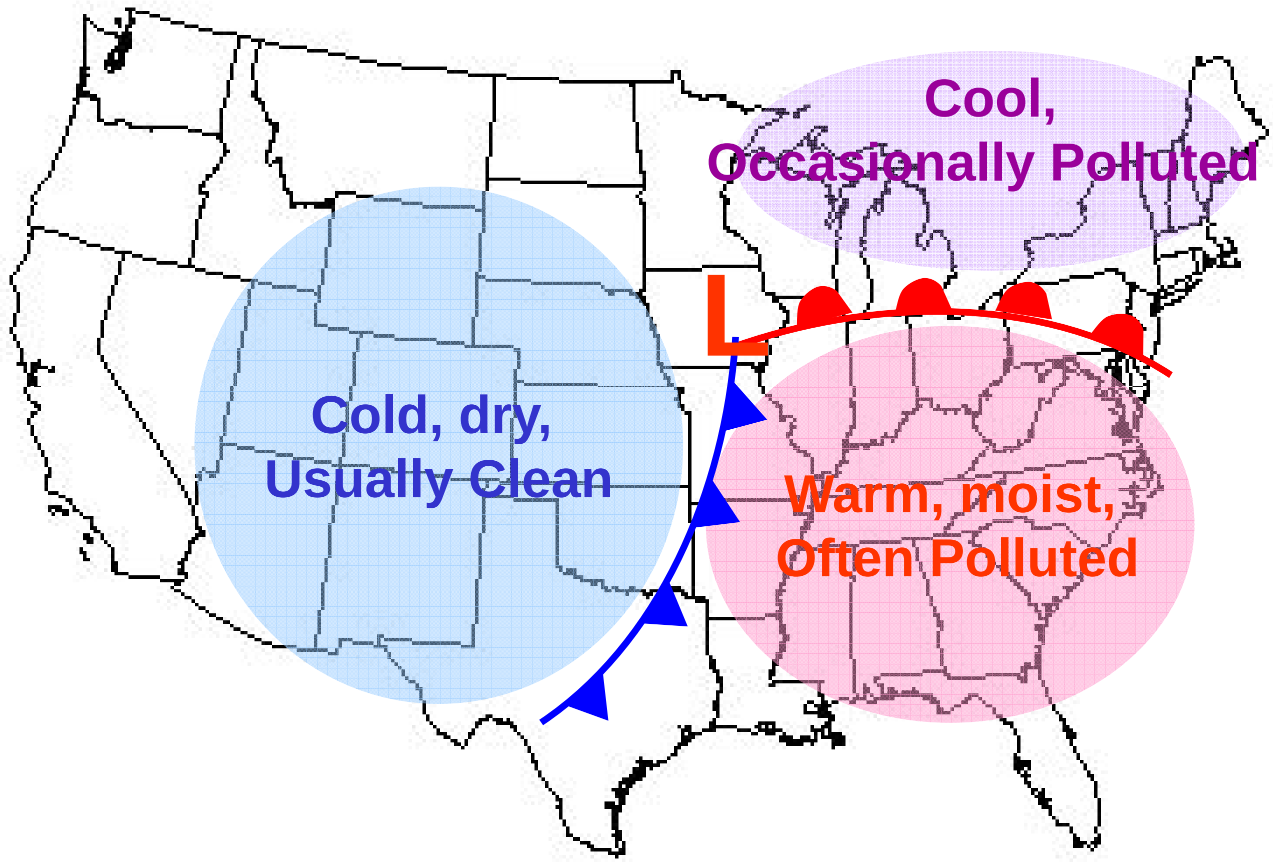
Overview (1 of 2)

- Meteorological processes that influence air quality
  - Sunlight
  - Horizontal dispersion
  - Vertical mixing
  - Transport
  - Clouds and precipitation
  - Temperature and humidity
- Large scale to local scale



Air Masses and Fronts (1 of 3)

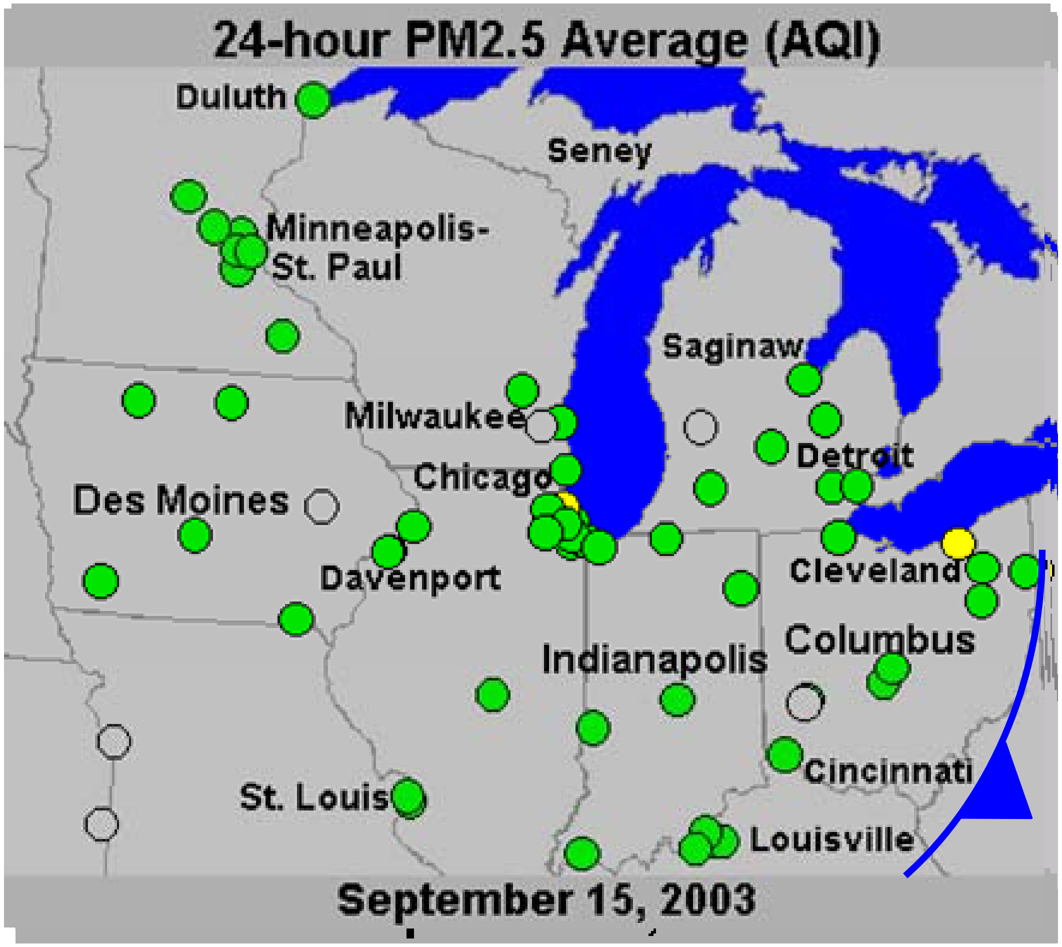
Fronts are regions where an atmospheric variable (temperature, dew point, etc.) changes rapidly across a small horizontal distance and divides air masses.



Air Masses and Fronts (2 of 3)

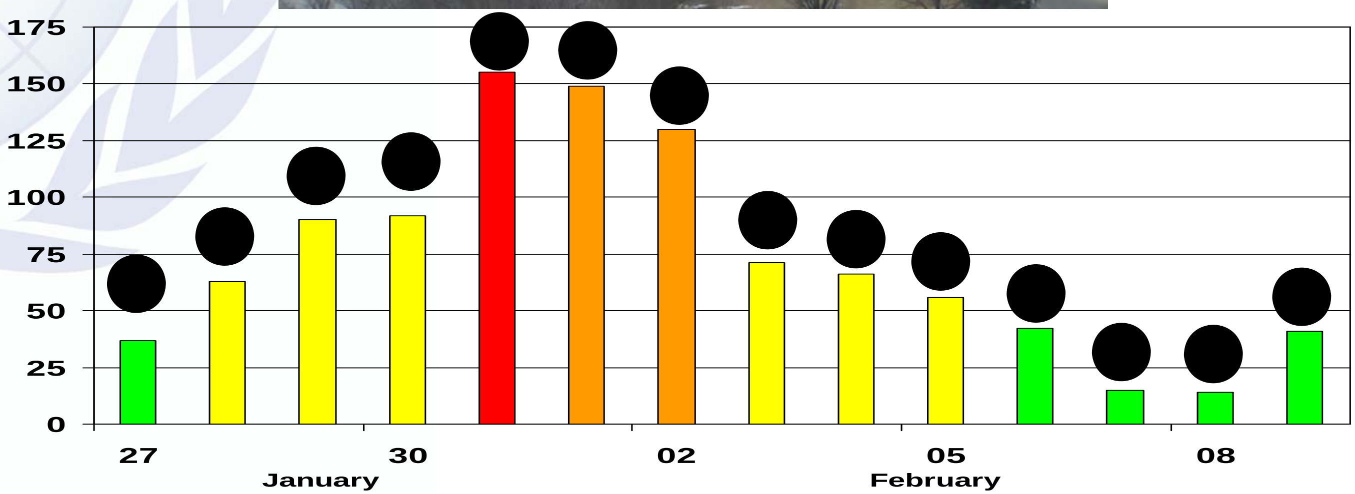
Example

- Fronts and air masses can cause rapid changes in air quality levels within a few hours of passage, particularly cold fronts
- Weak fronts can have little to no impact of their own; however, enhanced convection that occurs near them can improve air pollution
- A stationary front positioned near an area is often associated with high $PM_{2.5}$ levels because of light winds and no mass transfer



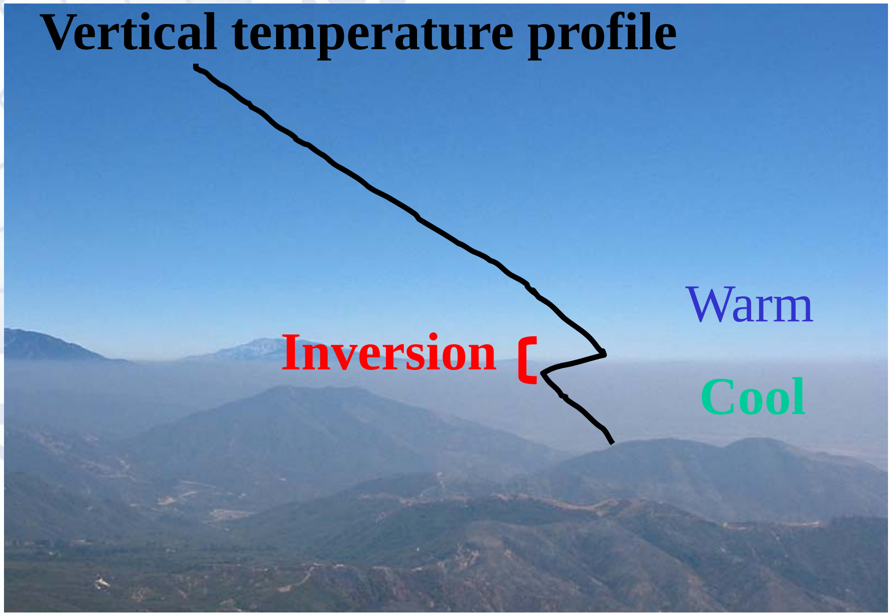
Air Masses and Fronts (3 of 3)

Minneapolis-
St. Paul,
Minnesota, USA



Temperature Inversions (2 of 3)

Inversions are important because they suppress vertical dispersion of pollution and often trap pollution near the surface where we live.



Dense fog over the Los Angeles Civic Center, 1955. Note that the buildings project above the base of the inversion layer, while the smog remains below.

Temperature Inversions (3 of 3)

- Subsidence
  - Created by sinking air associated with ridges
  - Can limit daytime mixing depth and plays important role in daytime pollutant concentrations
- Nocturnal or radiation
  - Created by cooling ground at night
  - Strongest with clear skies, light winds, and long nights
  - Can trap emissions, released during the overnight hours, close to the ground (e.g., wood smoke)
- Advection
  - Created when warm air aloft moves over cooler air below
  - Can occur ahead of an approaching cold front
  - Can cause poor air quality, despite the lack of an aloft ridge

Stability

- Stability is associated with how air parcels behave once they are displaced vertically from their initial positions.
- Three types
  - Positive stability implies that a displaced air parcel will return to its initial position; associated with high pollution
  - Neutral stability implies that a displaced air parcel will remain at its new position; associated with moderate pollution
  - Negative stability, or instability, means that a displaced air parcel will continue to accelerate away from its rest position; associated with low pollution

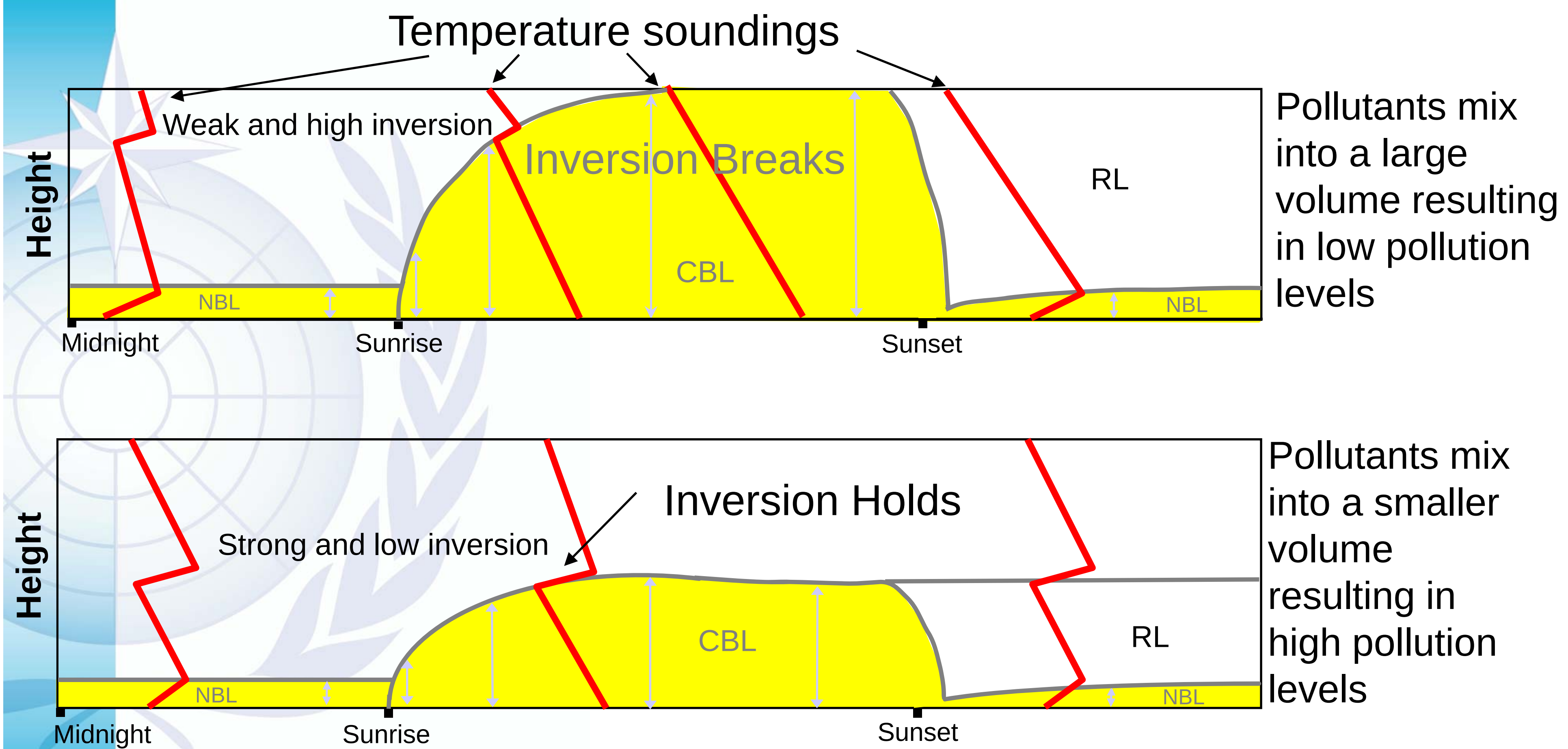
Stability

Paper Mill plume at dawn

Example of positive stability and negative stability – influence on a chimney plume (APM, Latrobe Valley, Victoria, Australia)

Paper Mill plume after Sunrise

Inversions, Stability, and Mixing (1 of 4)



RL = Residual Layer
CBL = Convective Boundary Layer
NBL = Nocturnal Boundary Layer

= **Surface-based mixing depth**

↕ = **Surface-based vertical mixing**

Inversions, Stability, and Mixing (3 of 4)

Sacramento, July 16-17, 1998

- Upper-level ridge over region
- Warm aloft temperatures
- Shallower mixing depths on July 17 compared to July 16

Ozone	July 16	July 17
1-hour max (ppb)	120	152
8-hour avg (ppb)	95	137

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Winds

Horizontal dispersion and transport

- Synoptic-scale
  - Winds are driven by large high- and low-pressure systems
- Meso- and local scale
  - Create stagnation and recirculation
  - Local flows are often difficult for weather models to predict but can be predicted by forecasters with knowledge of the area
  - Types
    - Land/sea or lake breeze
    - Mountain/valley
    - Terrain forced
    - Diurnal cycles
- Surface vs. boundary layer
  - Transport at different vertical levels
  - Mixing during the day affects winds

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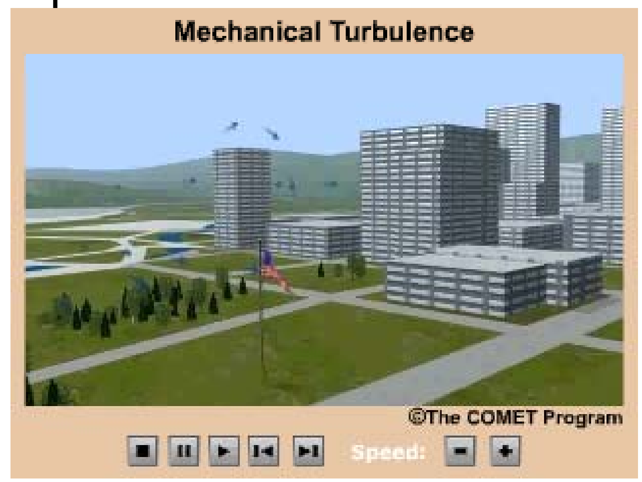
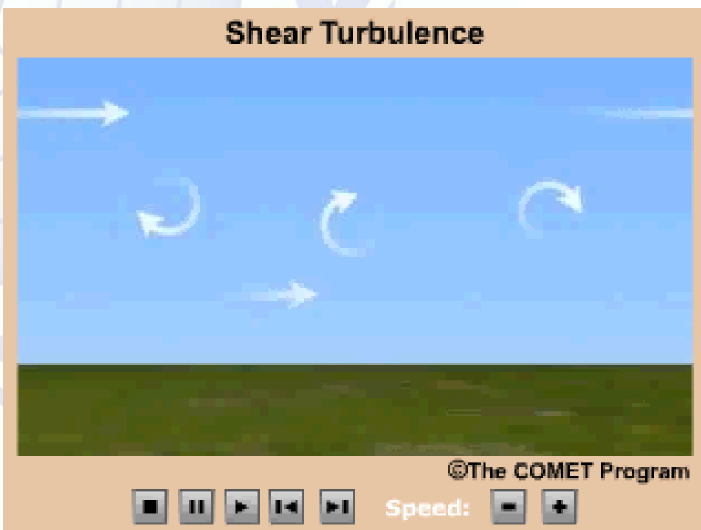
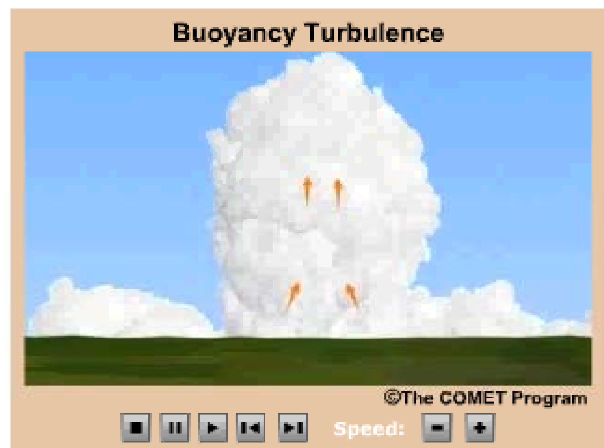
Winds – Dispersion

How do winds affect pollution?

- Disperse pollutants – the spreading of atmospheric constituents
- Dispersion is a dilution process
  - Molecular diffusion (not efficient)
  - Atmospheric turbulence
    - Mechanical
    - Shear
    - Buoyancy (convective)







Source: meted.ucar.edu/dispersion/basics/navmenu0.htm

Winds – Transport

How do winds affect pollution?

- Pollutant transport – movement of pollutants from one area to another by the wind
- Types
  - Neighborhood scale: monitor to monitor
  - Regional scale: city to city and state to state
  - National scale: country to country.
  - Global scale: continent to continent

Transport of pollution from the Los Angeles Basin to the Mojave Desert (Courtesy of Don Blumenthal)

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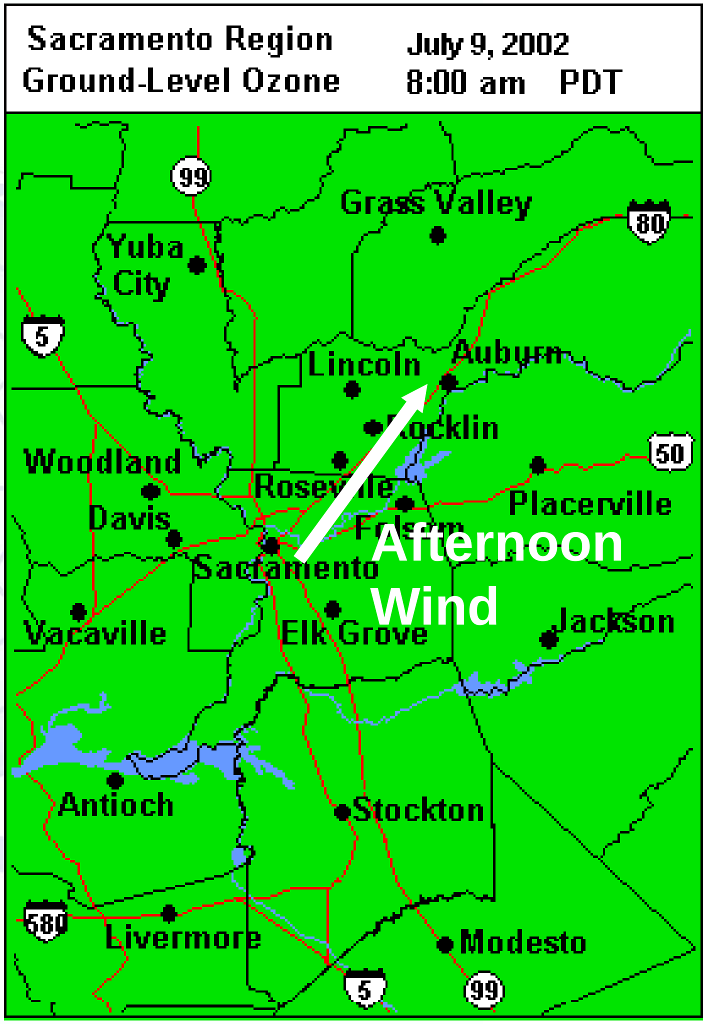
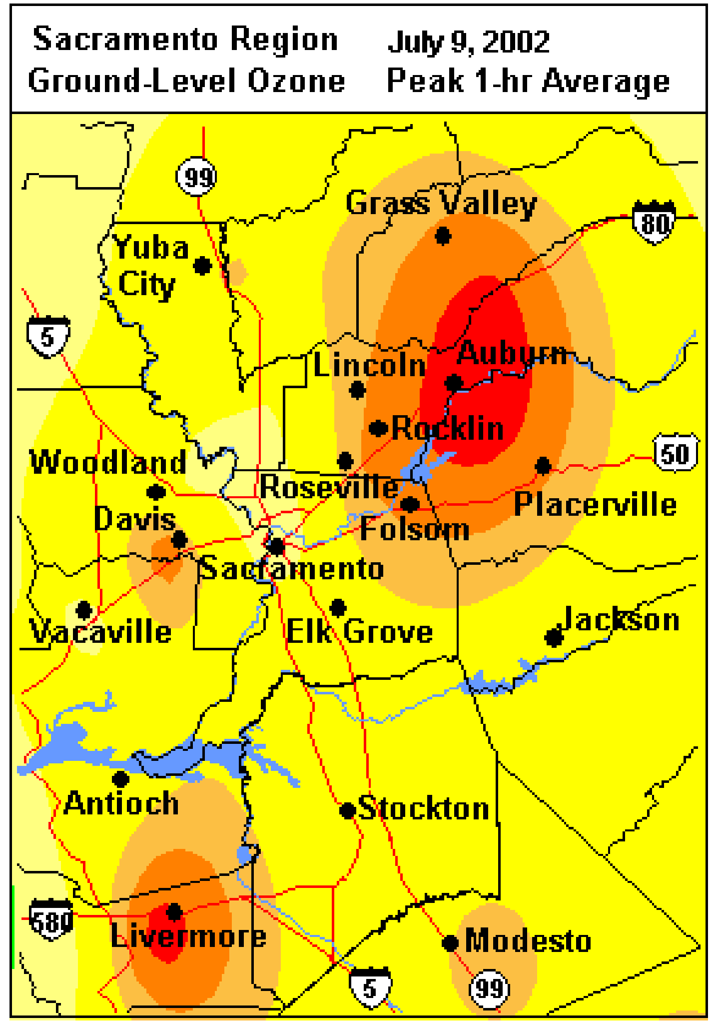
Transport – Local Scale (1 of 2)

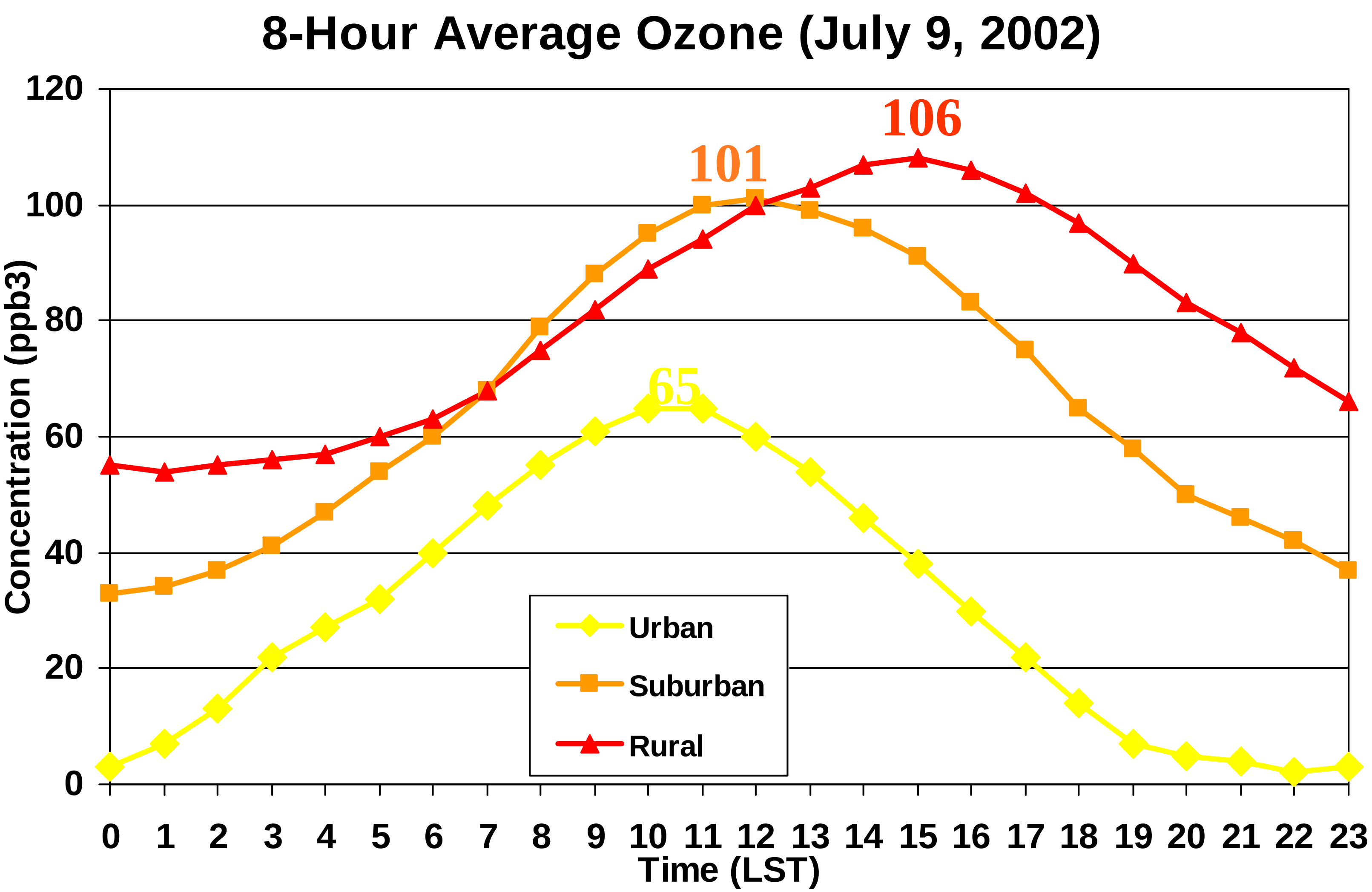


8-hr running averages



Peak 1-hr average

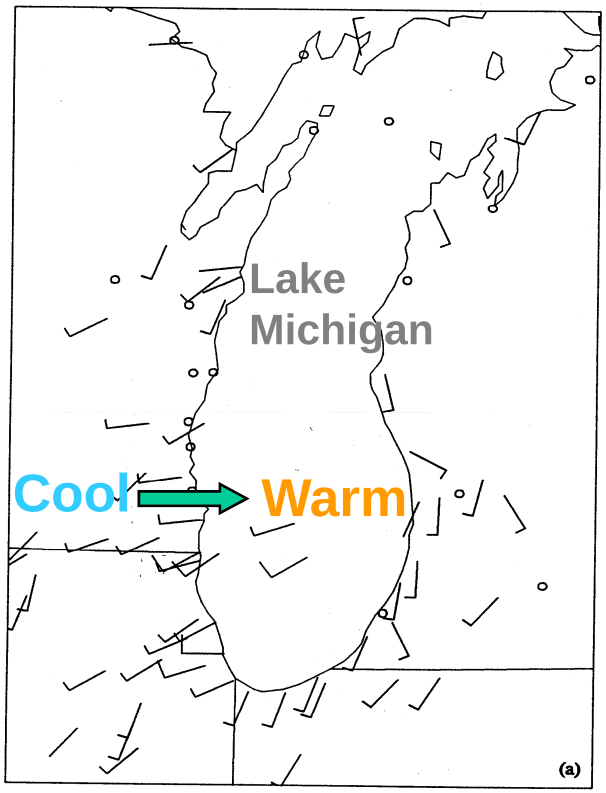
Transport – Local Scale (2 of 2)



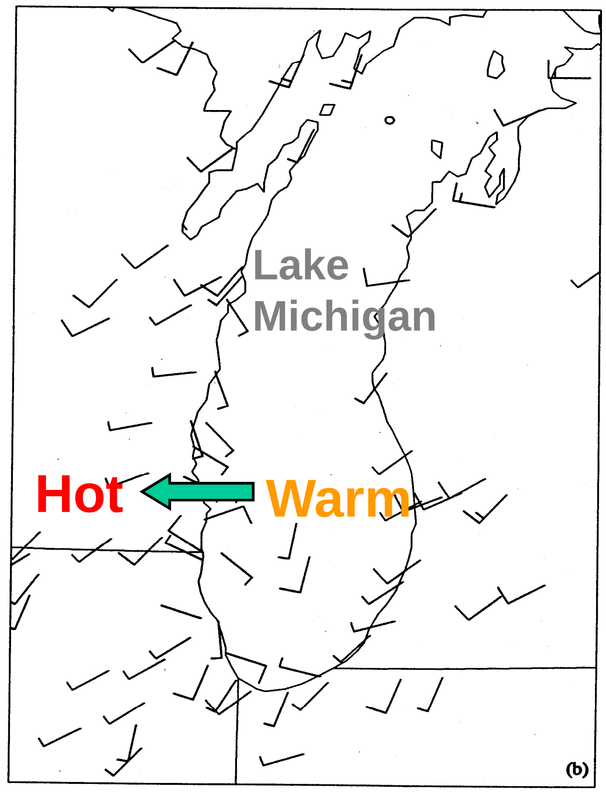
Transport – Regional Scale (1 of 5)

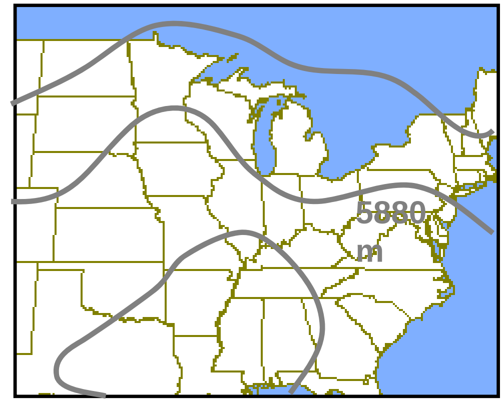
Recirculation can result in poor air quality

Land Breeze

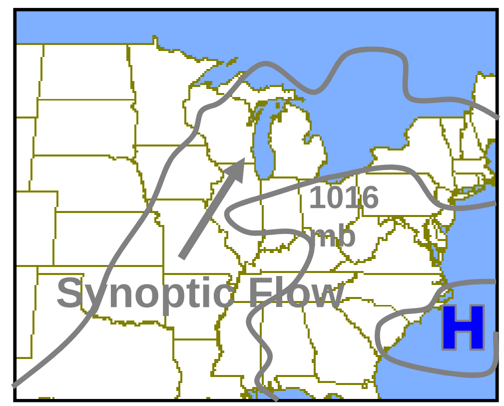


Lake Breeze





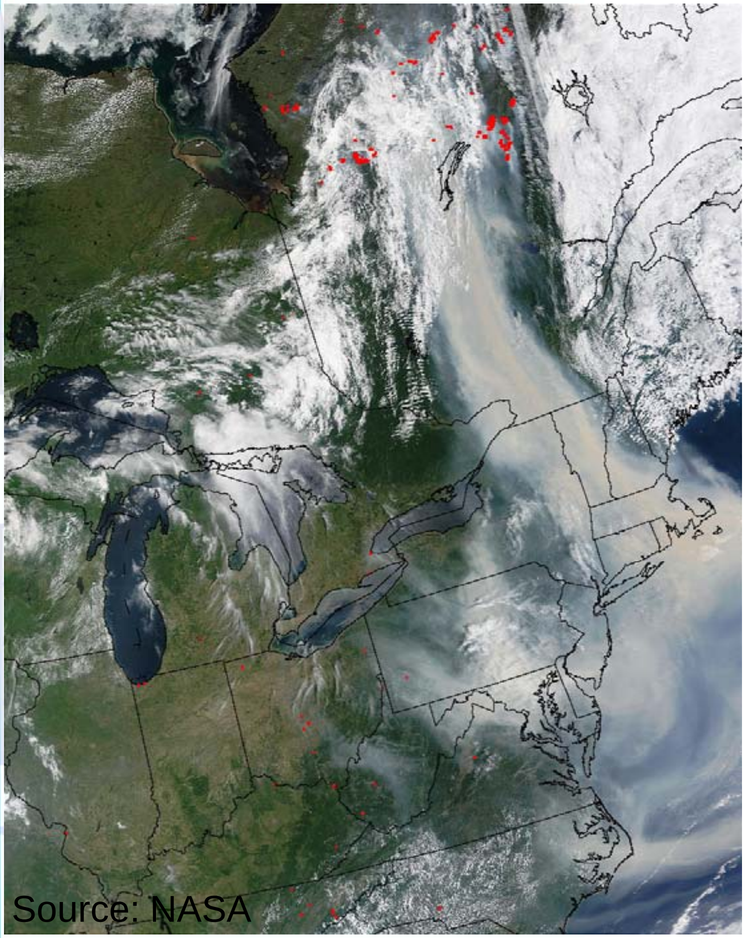
500-mb heights on July 18, 1991



Surface pattern on July 18, 1991

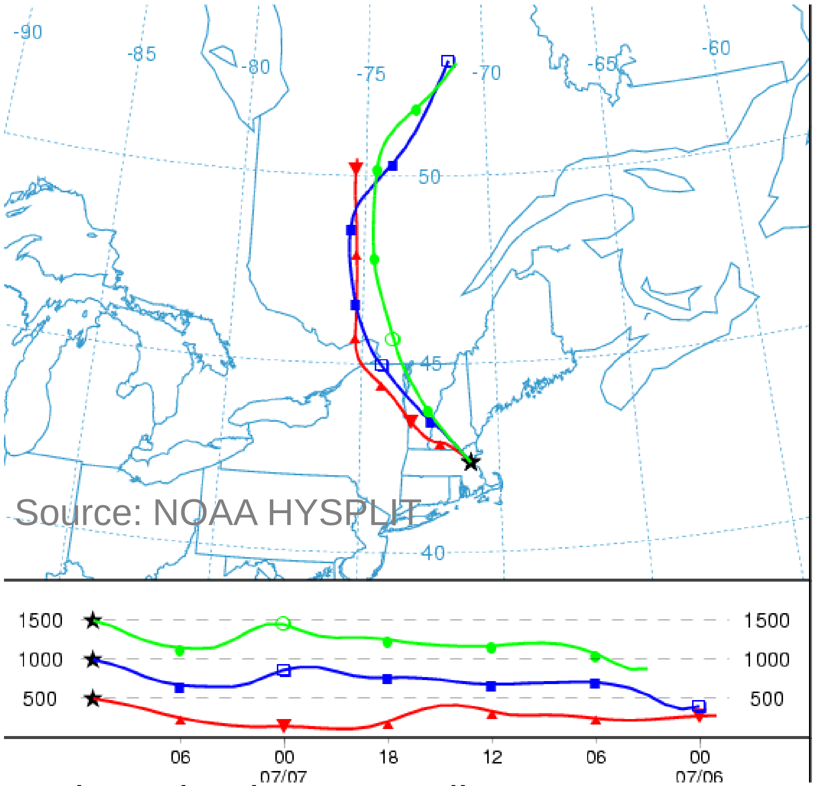
Surface winds on July 18, 1991, at (a) 0600 CDT and (b) 1500 CDT. Peak ozone concentrations on this day were about 170 ppb. (Dye et al., 1995)

Transport – Regional Scale (2 of 5)



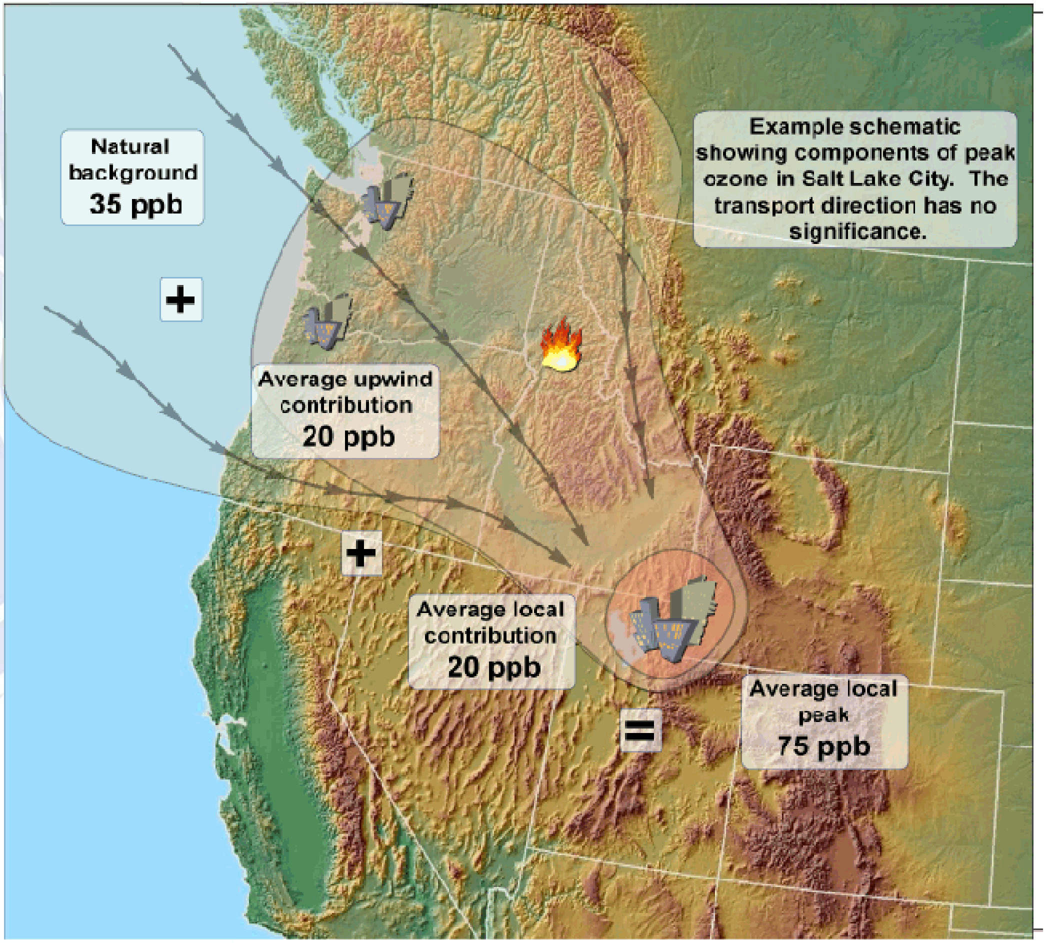
2-km satellite image from 1235 EST on 7 July 2002

The 24-hr average $PM_{2.5}$ concentration in Boston on 7 July 2002 was 62.7 µg/m^3



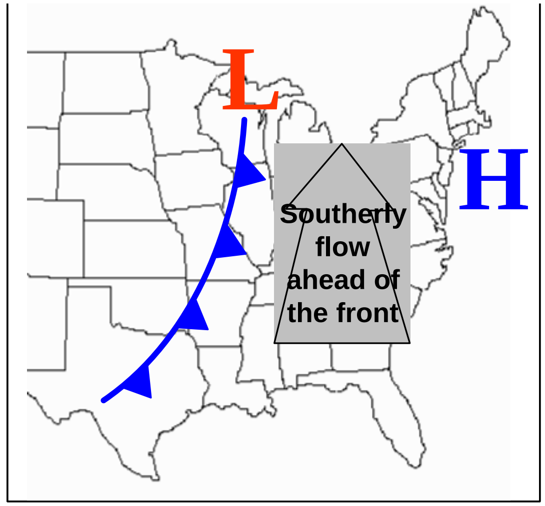
Backward trajectory ending at 0600 EST on 7 July 2002

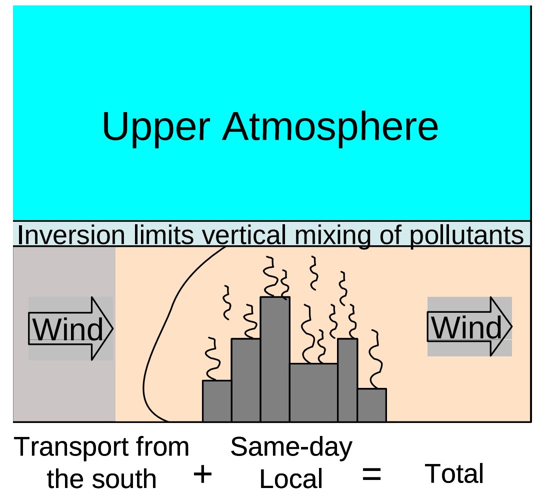
Transport – Regional Scale (3 of 5)

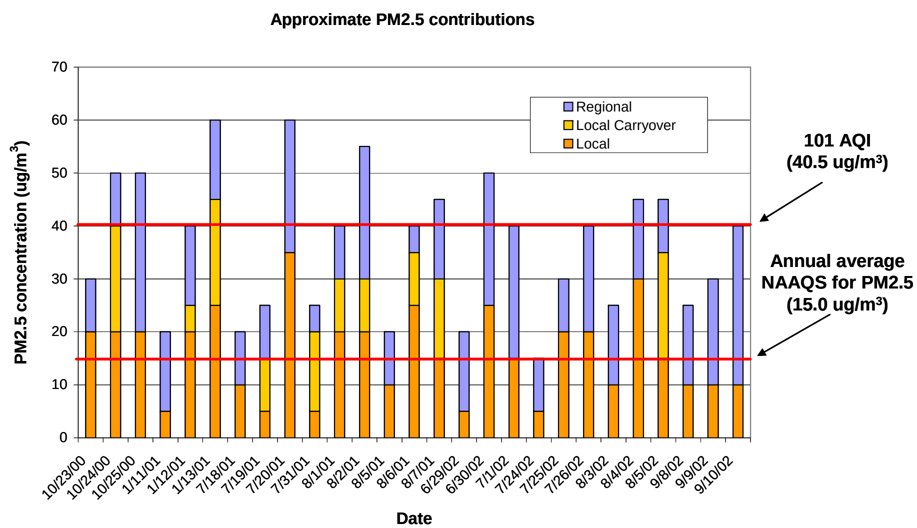


Transport – Regional Scale (5 of 5)

High pollutant concentrations upstream can be transported into a different area and can cause substantial increases in air quality concentrations than would otherwise occur







Chinkin et. al., 2003

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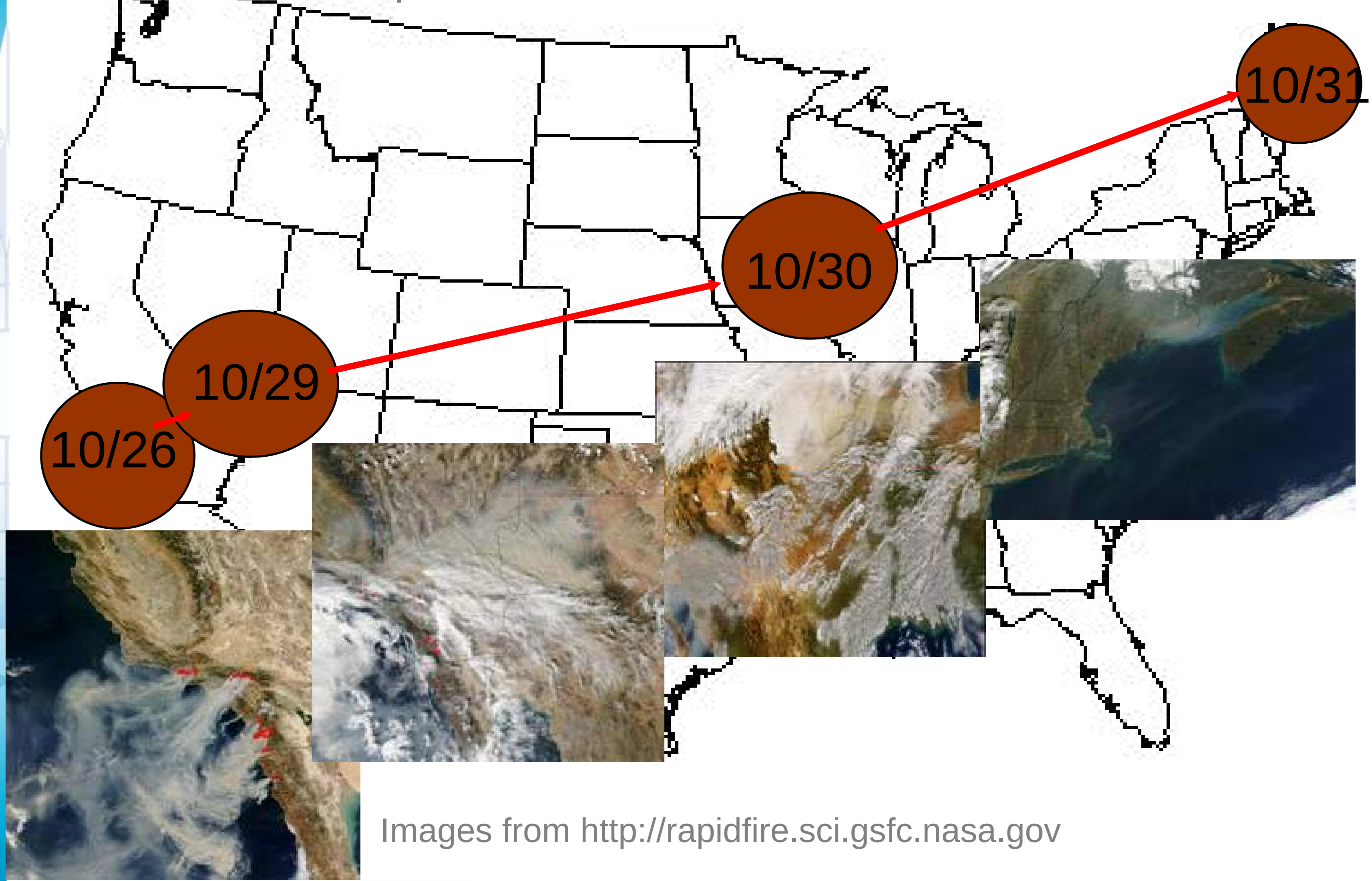
Transport – National Scale

Transport of smoke from California wildfires in 2003



Images from http://rapidfire.sci.gsfc.nasa.gov

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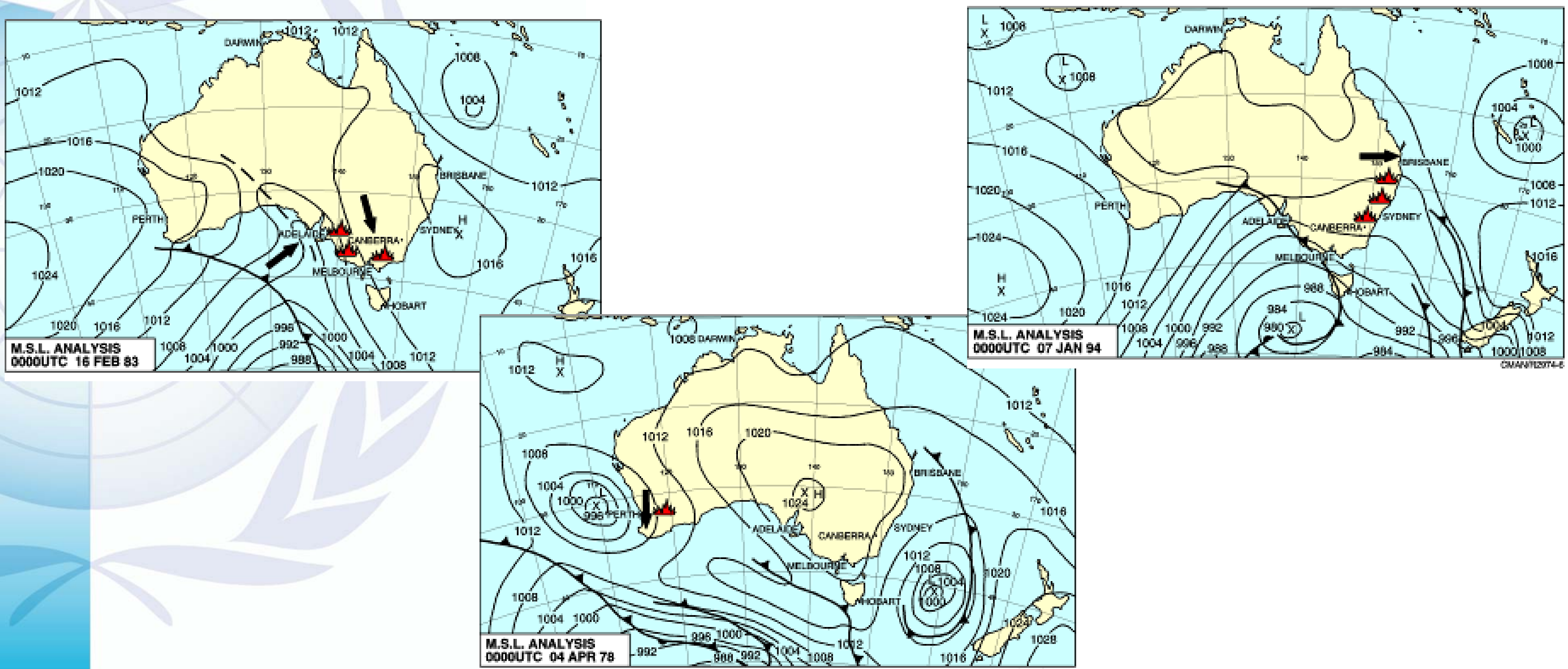
Synoptic-Scale Winds and Fire

Meteorological conditions for (left) Ash Wednesday, 16 February 1983, (right) the Sydney Fires, January 1994, and (below) fires in Perth region, 1978.



The most devastating fires in Australia in recent years occurred during periods of strong hot winds originating at the centre of the continent after a prolonged period of low rainfall.

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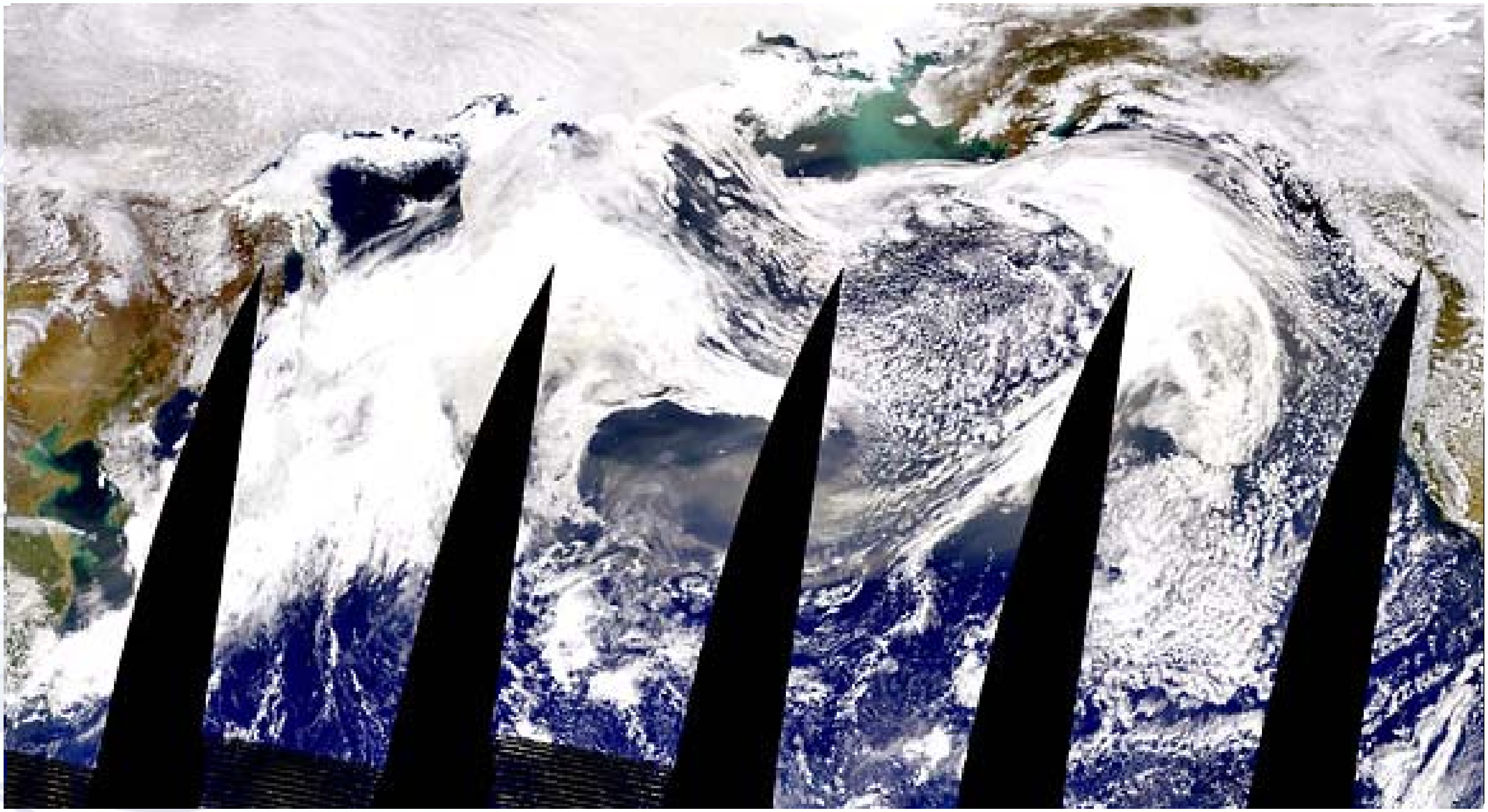
Transport – Global Scale



April 2[illegible],1998

Asian dust transport across the Pacific

Image from http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/OCDST/asian_dust_sequence.html#apr_20 and "The Asian Dust Events of April 1998" by Husar and 28 co-authors (Journal of Geophysical Research - Atmospheres, 106 (D16), 18317-18330, August 27, 2001) discusses these events.

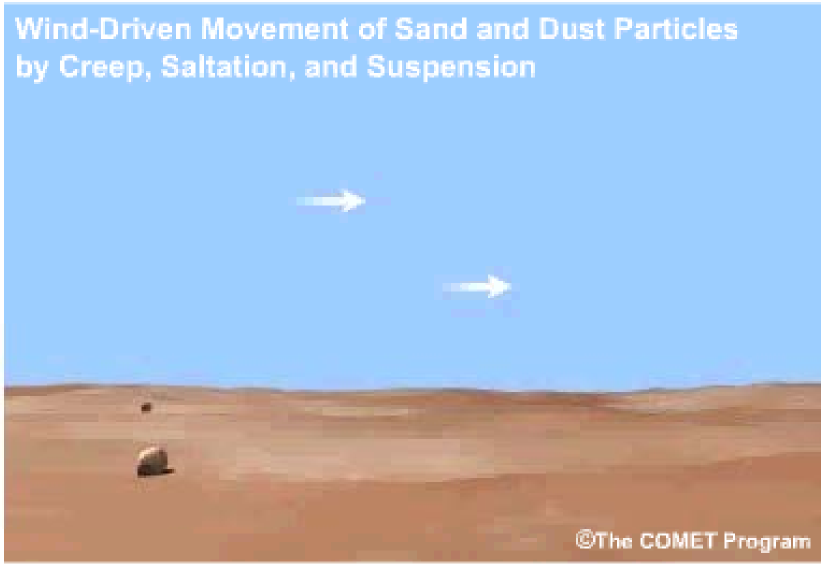
Wind – Dust (1 of 3)

How do winds affect pollution?

- Create pollution – wind-blown dust
- Two requirements
  - Dusty land/soil
  - Winds 7 m/s can loft dust

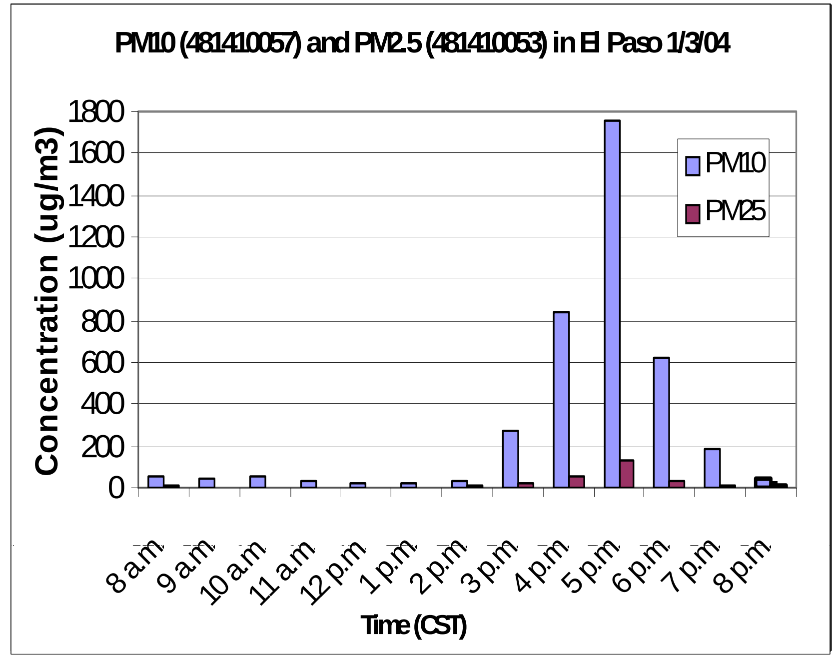
Threshold dust-lofting wind speed for different desert environments

Land Environment	Threshold Wind Speed
Fine to medium sand in dune-covered areas	4.5-7 m/s
Sandy areas with poorly developed desert pavement	8 m/s
Fine material, desert flats	9-11 m/s
Alluvial fans and crusted salt flats (dry lake beds)	12-16 m/s
Well-developed desert pavement	17+ m/s



Source: http://meted.ucar.edu/mesoprim/dust/frameset.htm

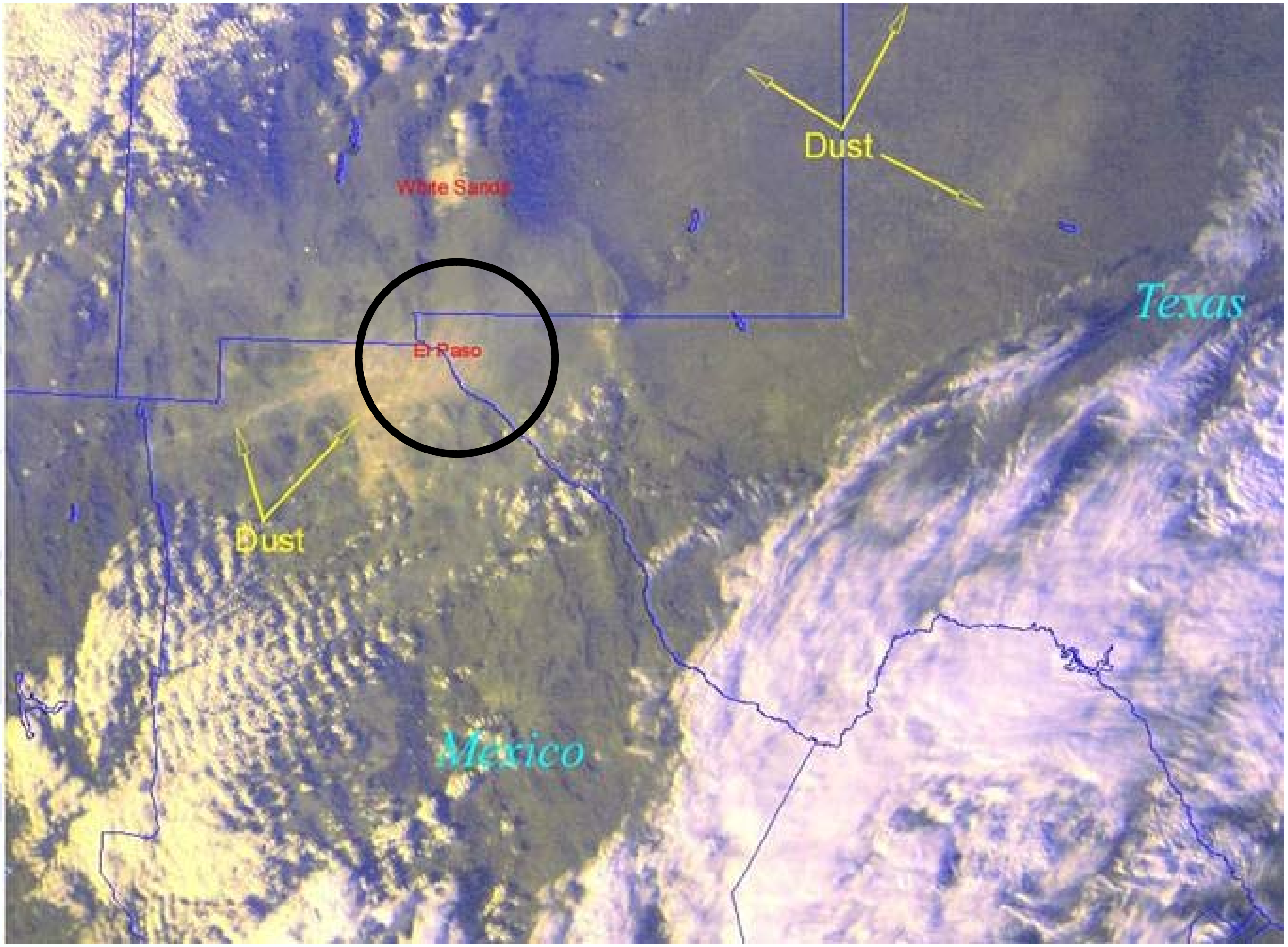
Wind – Dust (2 of 3)



Dust event January 3, 2004, 11:00 a.m. to 5:30 p.m.,
El Paso, Texas

Source: TCEQ

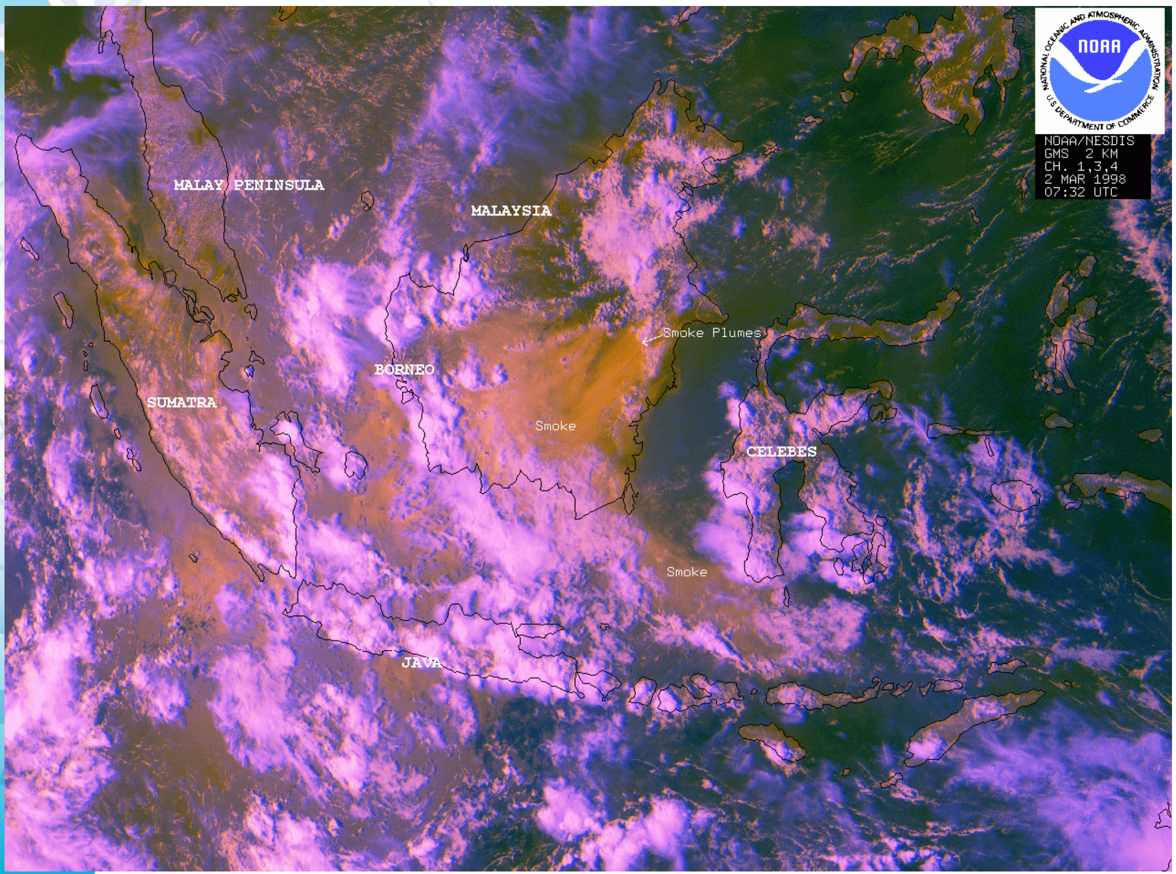
Wind – Dust (3 of 3)



Dust event January 3, 2004, 11:00 a.m. to 5:30 p.m., El Paso, Texas

Source: TCEQ

Smoke



- Smoke plumes (orange) from biomass fires over Borneo in 1998 were transported southwest-ward by the prevailing NE Trade winds prevalent over the region at that time of the year
- Drought, caused by El Niño, resulted in increased biomass burning

Clouds and Precipitation (1 of 3)

- Clouds form when the air becomes saturated
  - Adding water vapor
  - Cooling air
- Many processes add water vapor or cool air
  - Rising motion
    - Trough
    - Daytime heating
    - Cold front undercutting warm air (or vice versa)
    - Orographic
  - Air in contact with cooler surface
  - Air moving over water
  - Others

Clouds and Precipitation (2 of 3)

- Clouds and fog can increase the conversion of sulfur dioxide to sulfate from 1% per hour to 50% per hour
- Clouds reduce ozone photochemistry
- Precipitation removes PM_{10} but has little direct impact on $PM_{2.5}$
- Convective clouds can vent pollution from the boundary layer under stable conditions
- Clouds reduce surface heating and ability to break inversion
- Clouds delay NO_2 photolysis

Clouds and Precipitation (3 of 3)

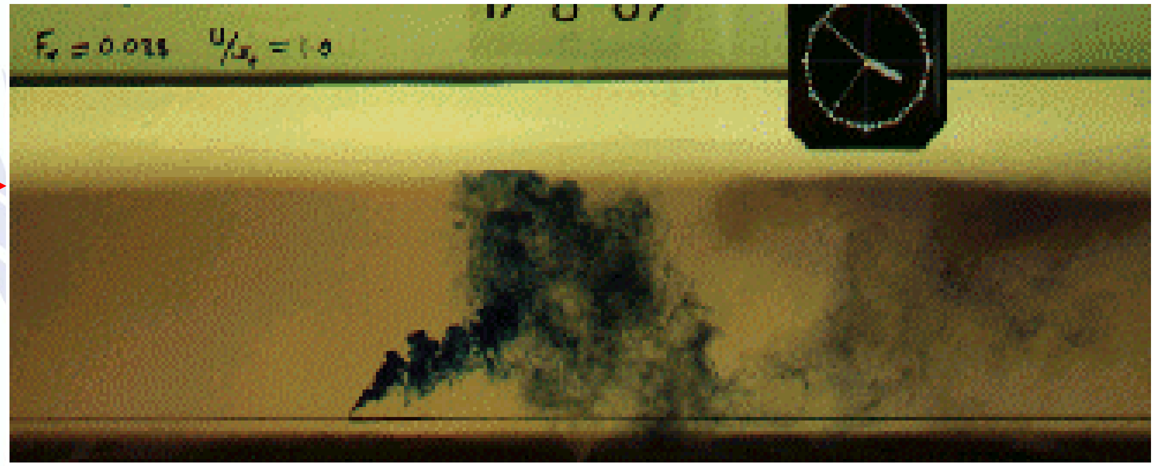
Effect on $PM_{2.5}$ and ozone and why

	$PM_{2.5}$	Ozone
Sunlight	↑ Photochemistry	↑ Photochemistry
Clouds	↑ Aqueous Chemistry ↓ Reduce Photochemistry	↓ Reduce Photochemistry
Precipitation	↔ Minor direct impact	↔ Minor direct impact

Heating and Winds – Local Scale

Convective Mixing of Plumes

Mixed-layer height controls ground-level concentrations



Chimney as source of pollution

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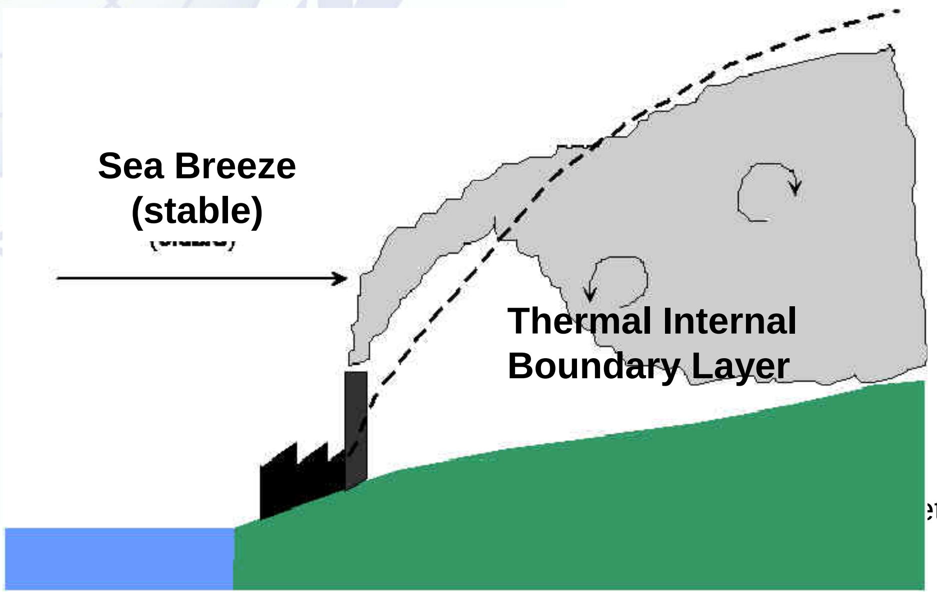
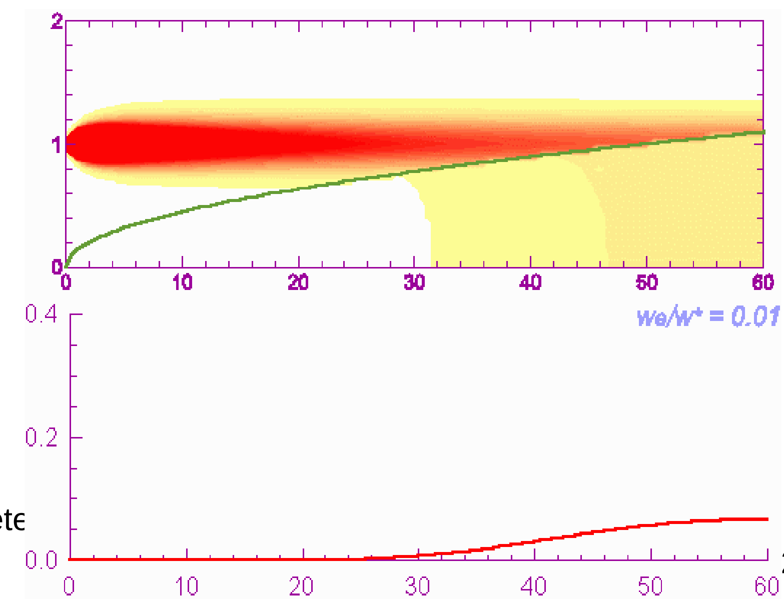
Heating and Winds – Local Scale

Seabreeze Fumigation

- Advection of cool marine air inland by the sea breeze. The air is heated from below by the warm land surface.
- Formation of the Thermal Internal Boundary Layer (TIBL).
- Fumigation occurs when pollutants released into the stable marine air mass encounter the TIBL boundary, and are mixed downward to the Earth's surface by convective motion.
- The stable air mass above the TIBL acts as a "lid," trapping pollutants released into the marine air, in the unstable TIBL.





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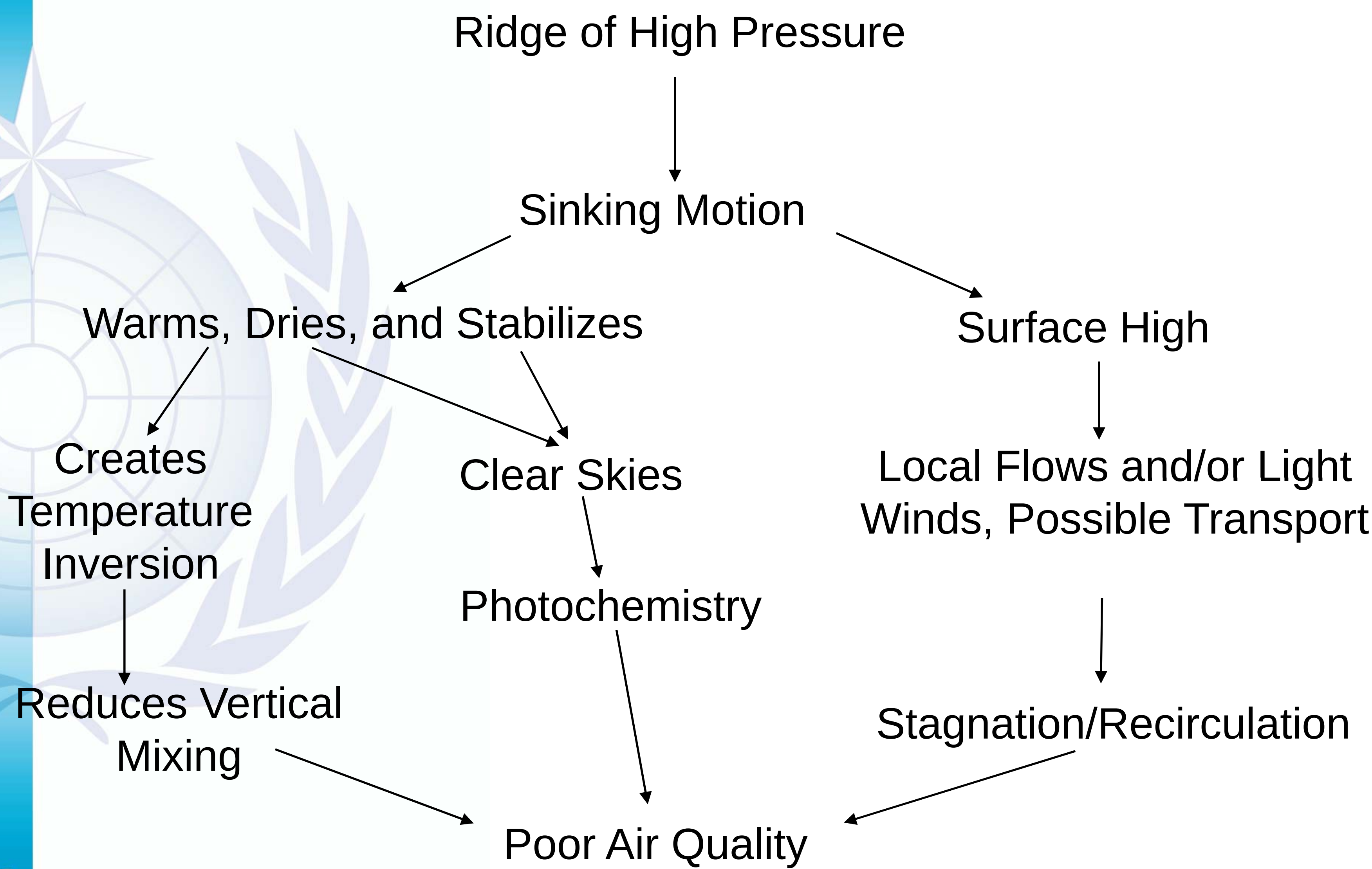
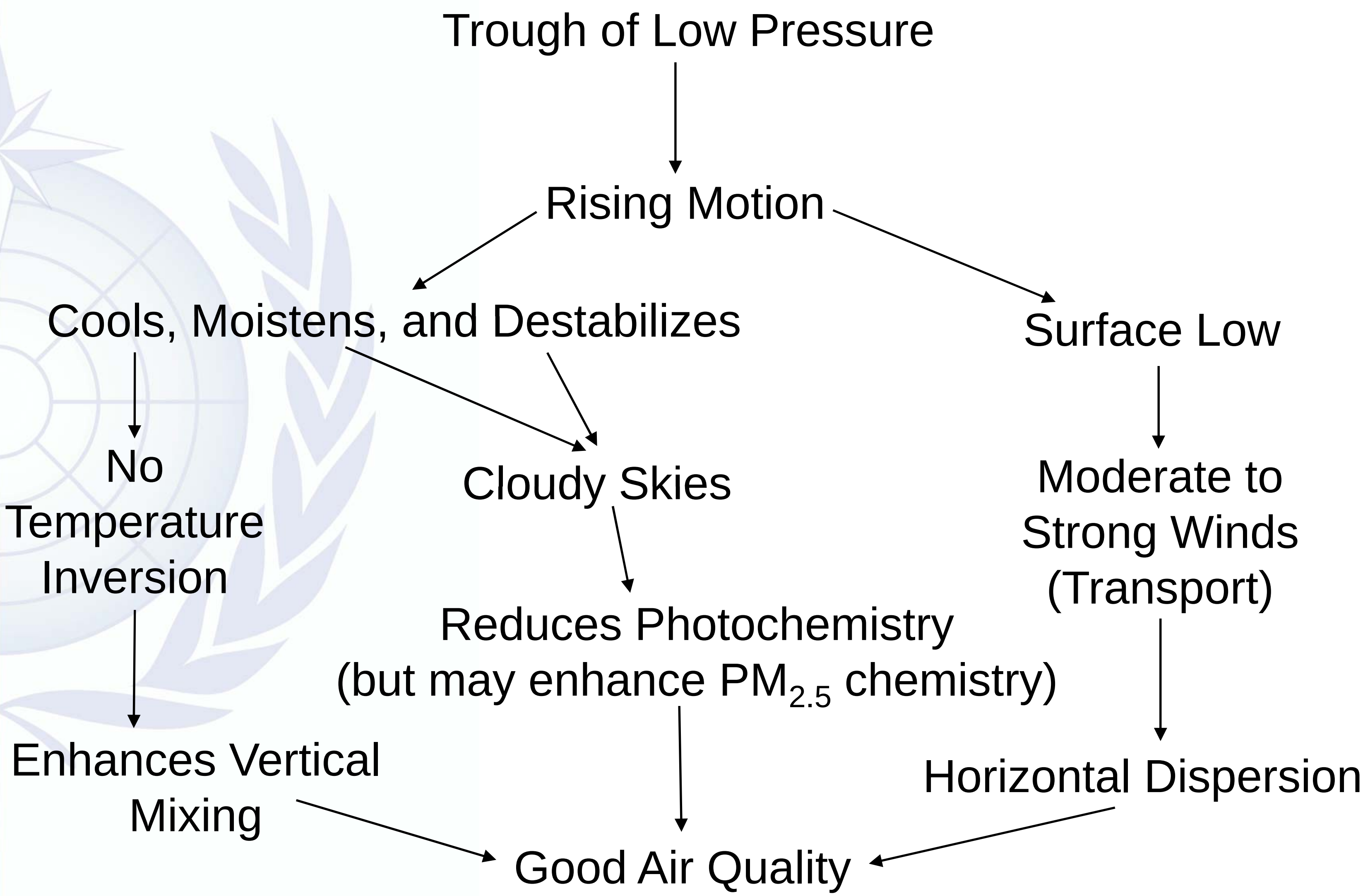
Summary
Meteorology Associated with Poor AQ



Summary

Meteorology Associated with Good AQ



Key Weather Features – Summary

- Upper-air and surface patterns
- Fronts and air masses
- Inversions, stability, and mixing
- Winds
- Clouds
- Precipitation
- Recirculation, especially on coasts, in complex terrain can lead to the worst air pollution events.

Other Useful Products

- 850-mb temperature and 700-mb vertical velocity charts
- HYSPLIT trajectories
- Satellite data
- Ground-based remote sensors (sodar, radar profiler, lidar)

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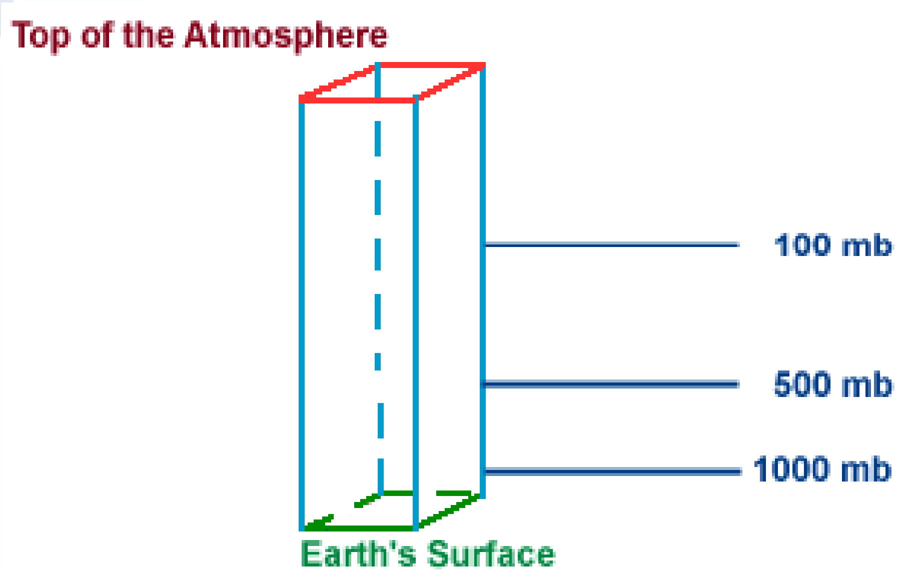
Using Weather Charts to Help Forecast Air Quality

- Depict upper-air meteorological patterns as a horizontal slice of the atmosphere
- Show forecasted meteorological variables at a particular time on a particular pressure level



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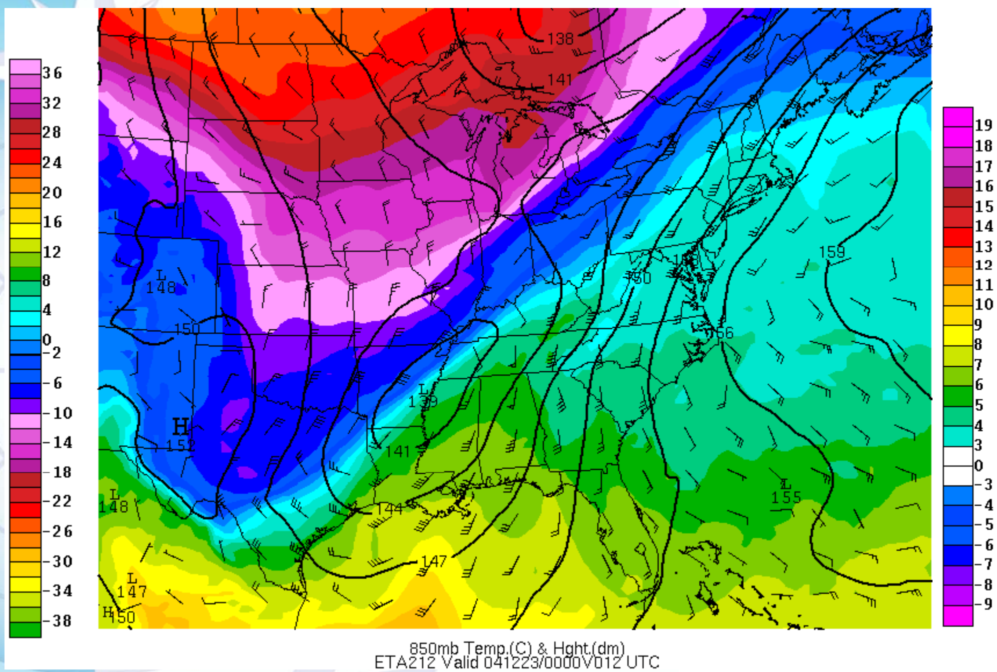
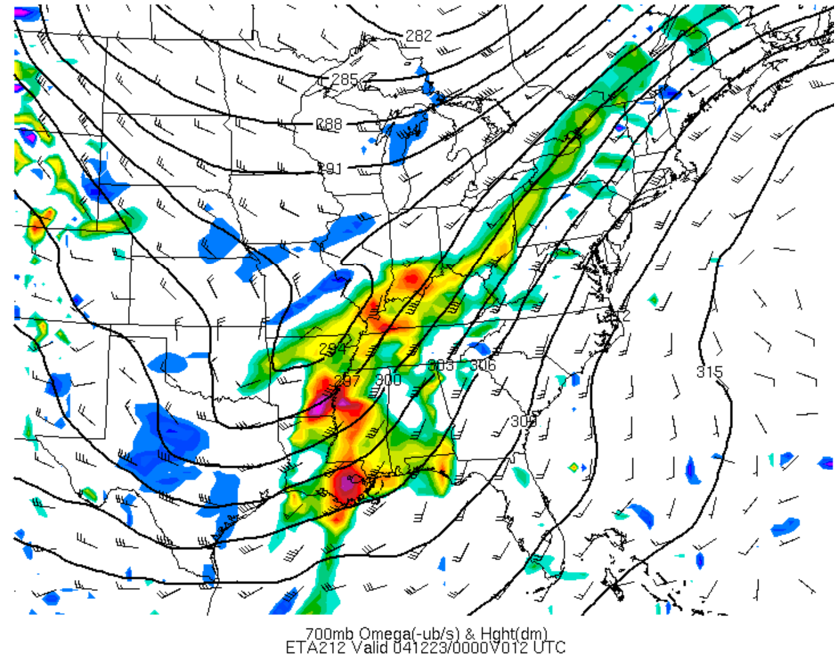
Weather Charts – Aloft

- 850-mb temperature
  - Good indicator of stability
  - Boundary layer transport winds
- 700-mb vertical velocity
  - Downward vertical motion (negative on charts shown here) indicates stable conditions and is associated with poor air quality
  - Upward vertical motion (positive on charts shown here) indicates unstable conditions and is associated with good air quality

Weather Charts
Predicting Surface and Aloft Patterns



850-mb heights and temperature

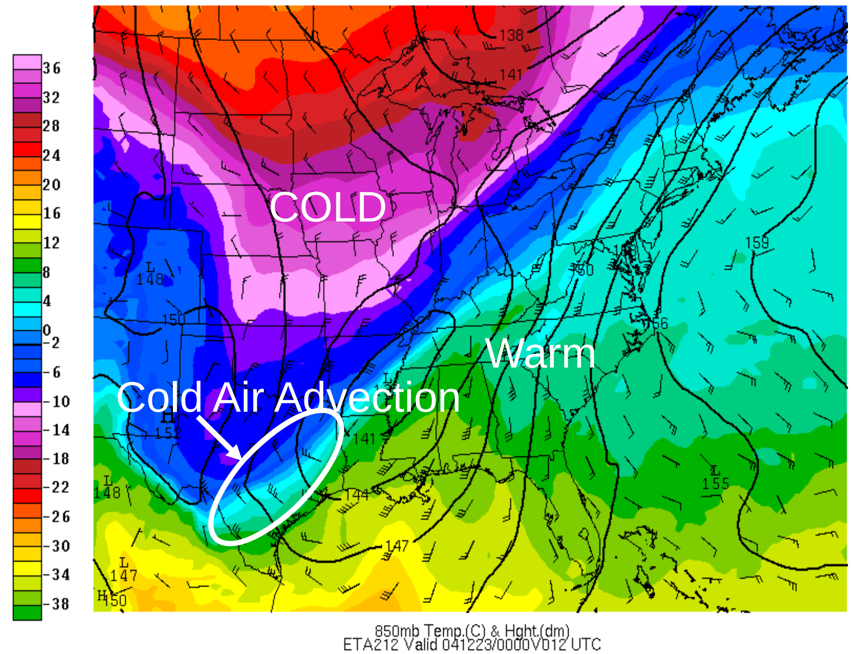


700-mb heights and vertical velocity

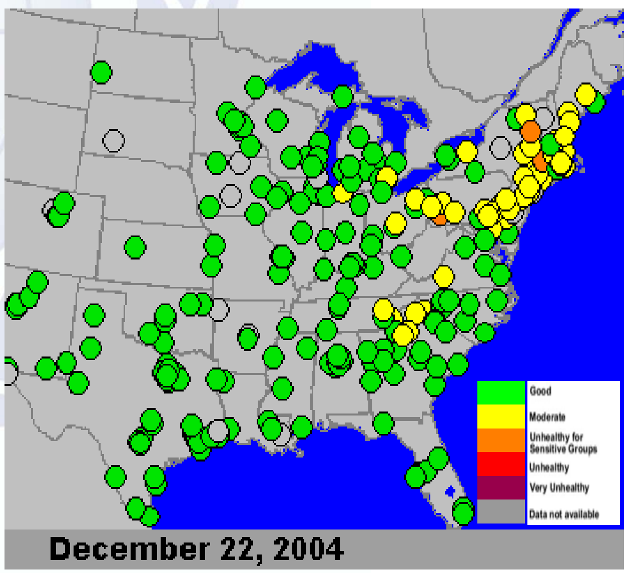
Weather Charts
850-mb Temperature Example

- Warm 850-mb temperatures can stabilize the atmosphere, which can lead to poor air quality by reducing vertical mixing
- Cool 850-mb temperatures can destabilize the atmosphere, which can lead to good air quality by enhancing vertical mixing

January 22, 2004



Courtesy of San Jose State University Meteorology Department

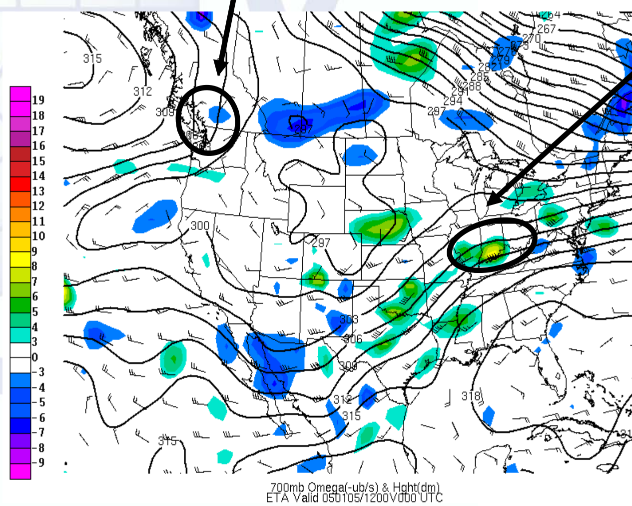


$PM_{2.5}$ 24-hr averages (AQI) from www.airnow.gov

Weather Charts
700-mb Vertical Velocity Example

Downward vertical motion stabilizes the atmosphere which can lead to poor air quality

Upward vertical motion destabilizes the atmosphere which can lead to good air quality even under a ridge



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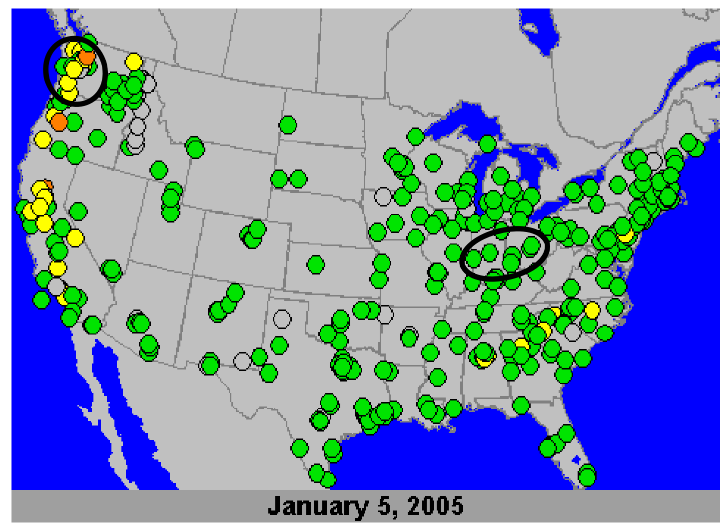
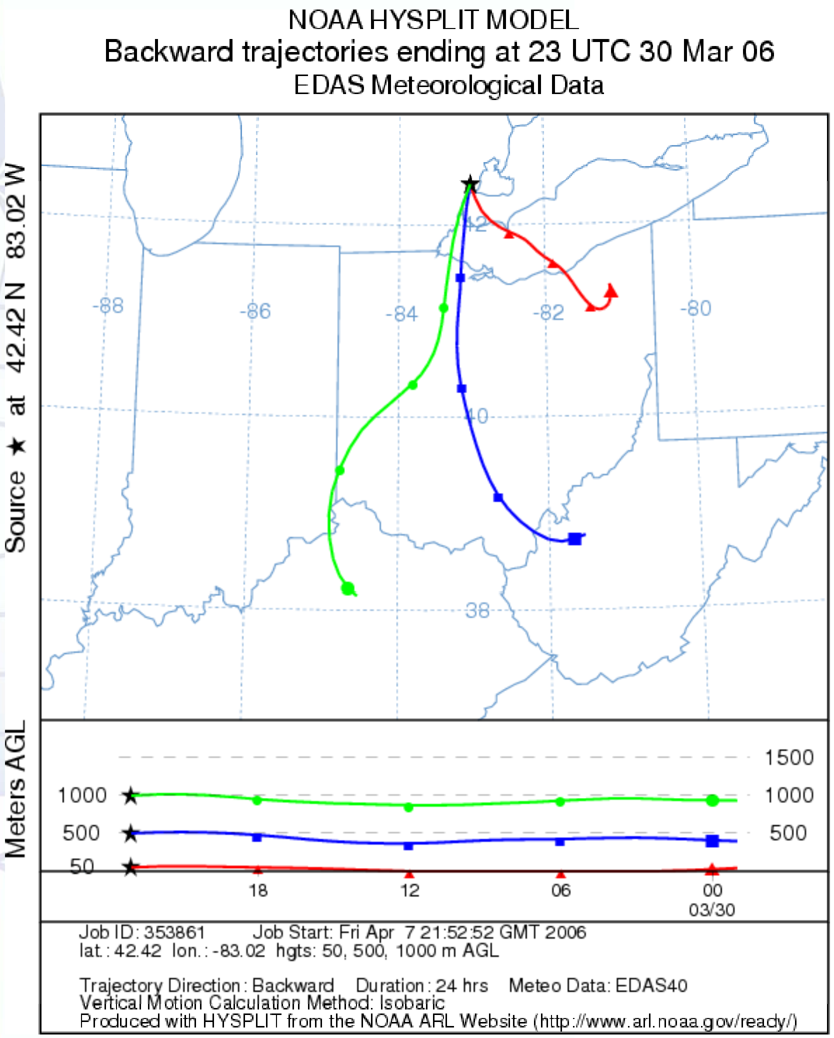


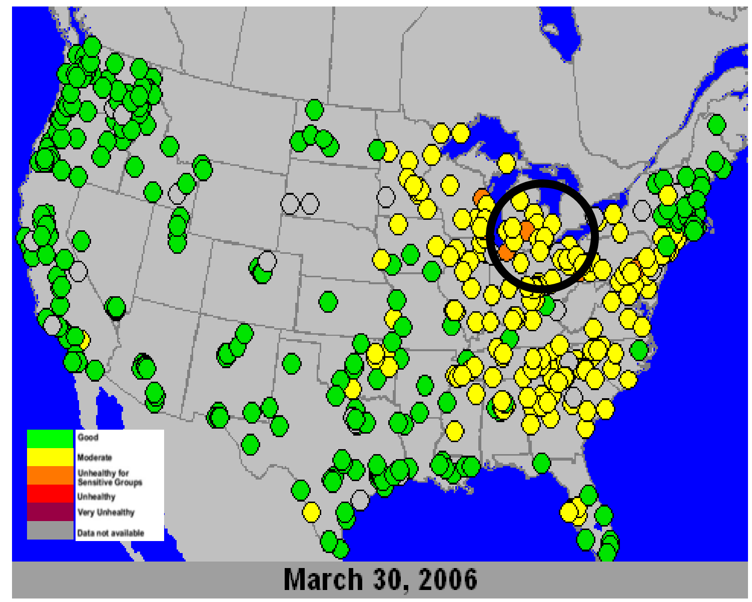
Transport Tool – HYSPLIT (1 of 3)

Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT)

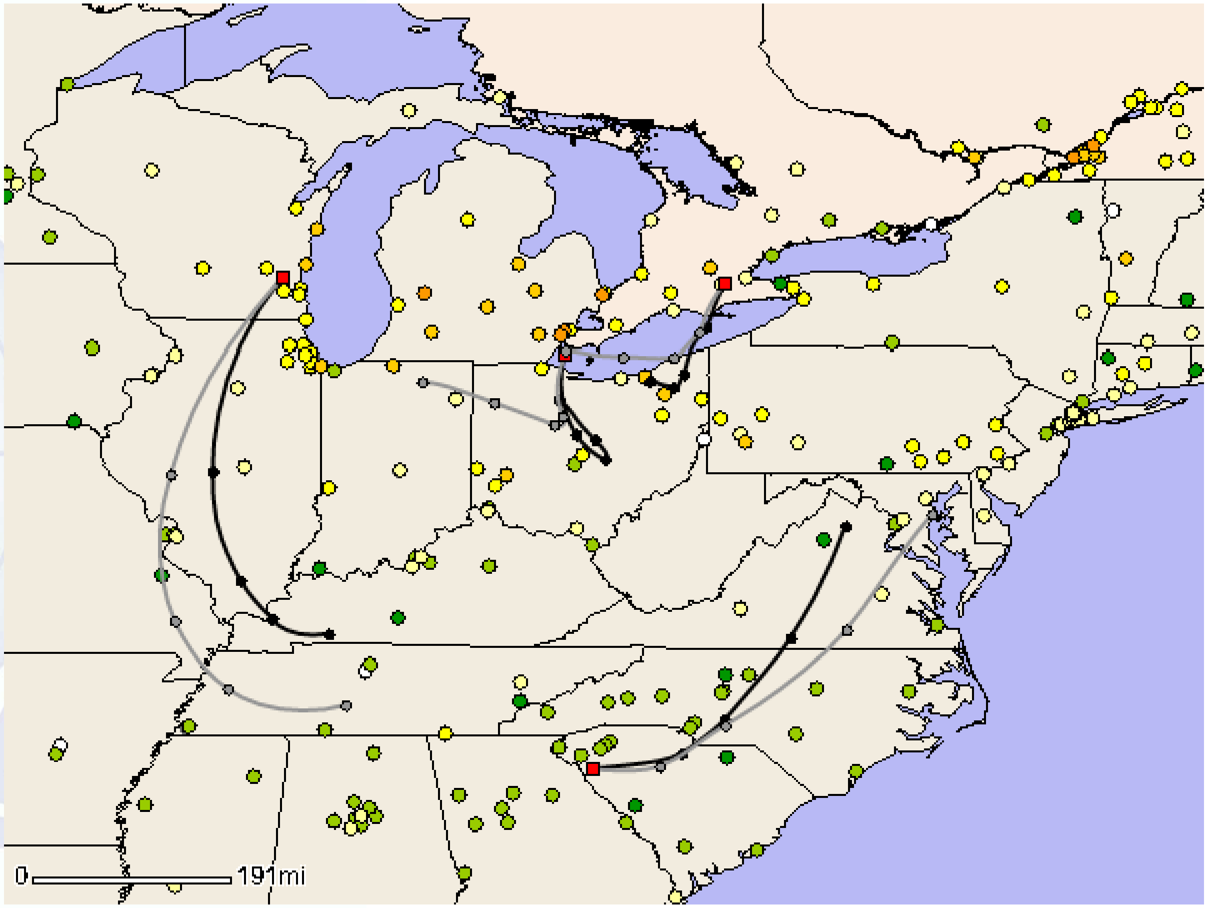
- Uses meteorological model data to estimate trajectories and dispersion in the past or future
- Run on NOAA's Realtime Environmental and Display System (READY) web site
- Can run locally with gridded model data
- Intended for meso- and syntopic scale transport

Transport Tool – HYSPLIT (2 of 3)





Transport Tool – HYSPLIT (3 of 3)



AIRNow $PM_{2.5}$ (mg/m^3) for 02/05/2005 23:00 PST

Satellite (1 of 4)

- Satellite data can help forecasters
  - Estimate aerosol concentrations in areas without continuous $PM_{2.5}$ monitors
  - Track aerosols from
    - Regional haze episodes
    - Wildfires
  - Estimate upwind $PM_{2.5}$ concentrations or aerosol loading
- Aerosol optical depth provides this information

Satellite (2 of 4)

- Aerosol optical depth (AOD)
  - A satellite-derived measure of light extinction through the atmosphere
  - Proportional to the number of particles in the atmospheric column

Satellite (3 of 4)

- Factors for forecasters to consider when using AOD products
  - Clouds: AOD can only be computed when skies are clear.
  - Vertical resolution: AOD does not differentiate between particles aloft and particles near the ground.
  - Surface/land use: The AOD algorithm works best over flat, dark terrain.
  - Aerosol type: The AOD algorithm works best when aerosols are spherical. Irregular particles do not scatter light well.
  - Availability: AOD data can only be computed during daylight hours.

Satellite (4 of 4)

- The AOD algorithm does well detecting
  - Spherical particles that scatter light well such as sulfates and nitrates
  - Volatile organic compounds, a component of smoke
- The AOD algorithm does not do well detecting
  - Dust particles are irregularly shaped and do not scatter light well; because of this, they are not captured well by the AOD algorithm.
  - Black carbon, a large component of smoke

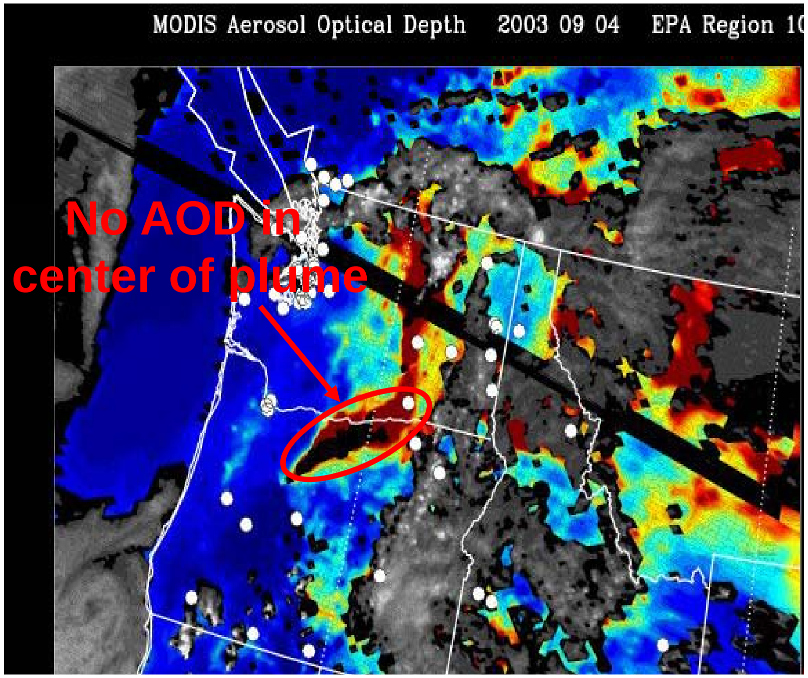
Satellite – Forecasting Applications (1 of 5)

- Goal is to show
  - How AOD data can be used to identify smoke from large fires
  - How to predict where the smoke will be transported
  - How to evaluate whether the smoke is mixing to the surface
- Considerations
  - The AOD can be used to detect smoke from large fires well
  - AOD tracks aerosols after they cannot be seen on visible satellite imagery
  - Very dense smoke can be mistaken for clouds and, consequently, not be included in the AOD algorithm

Satellite – Forecasting Applications (2 of 5)

- The B and B Complex Fire, Oregon (August 19 to September 26, 2003)
  - Burned 91,000 acres
  - The MODIS (Terra) visible image (left) shows the smoke plume spreading northeast from the fire on September 4, 2003
  - The AOD plot (right) shows the smoke plume well; the area of black inside the red plume is where the algorithm failed due to dense smoke
- Key forecast questions:
  - Where is it going?
  - Is it mixing down?

EnvirocastTM StormCenter Communications, Inc



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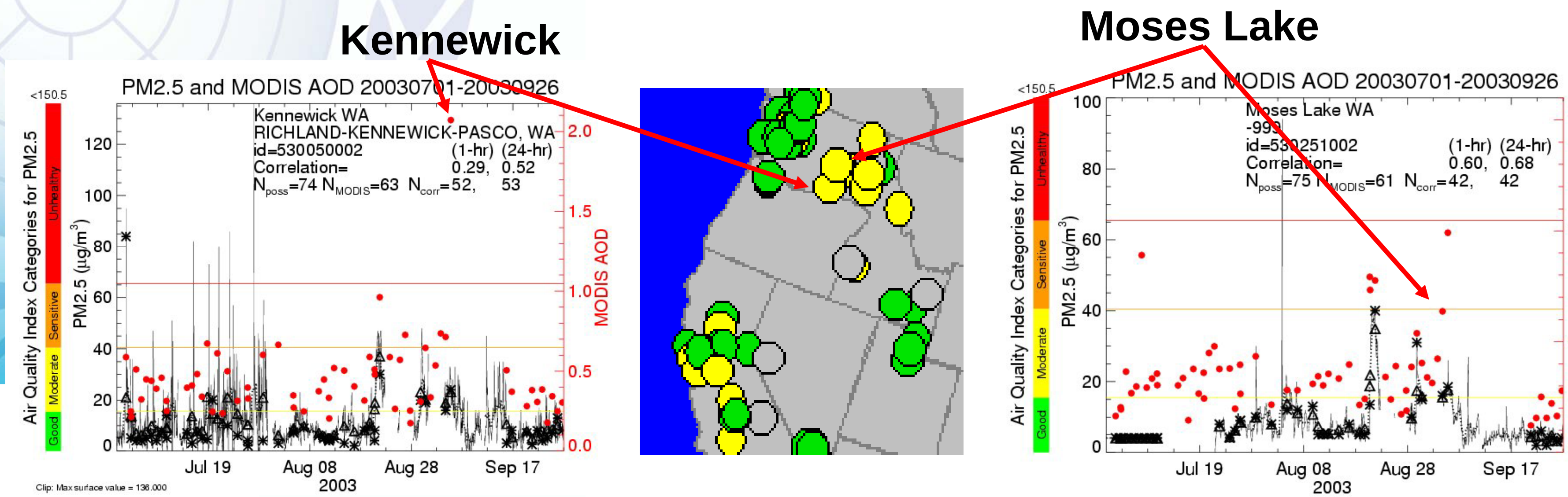
GAW

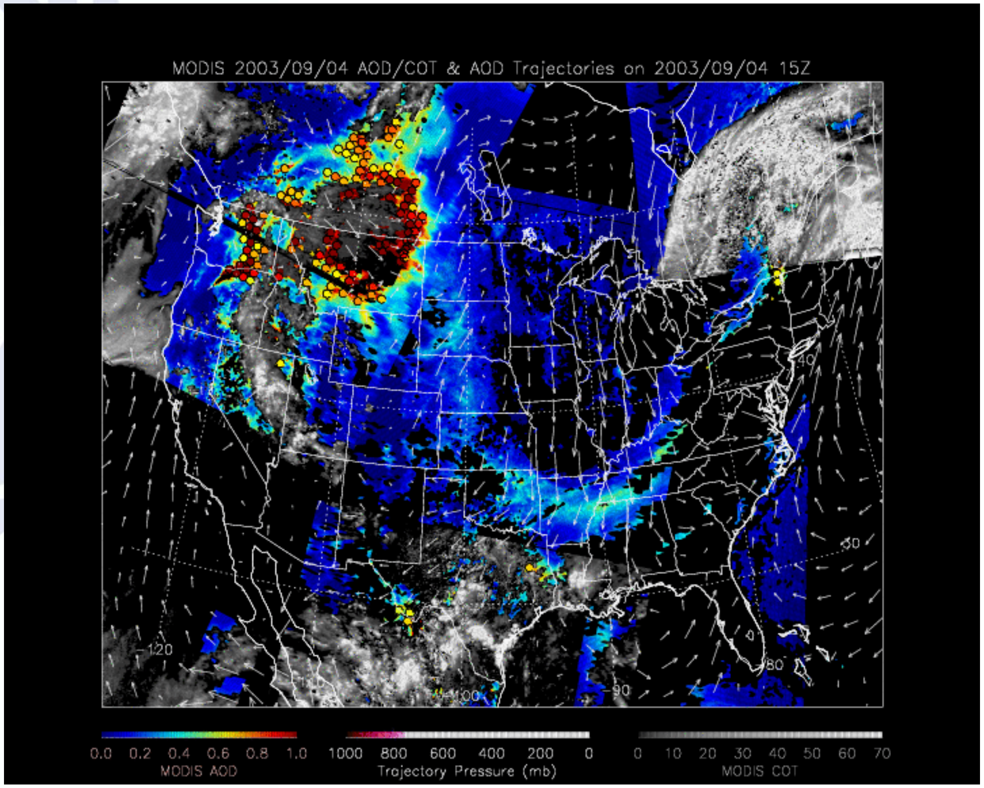
Satellite – Forecasting Applications (3 of 5)

- Need to determine mixing
- Compare correlations between AOD and observed $PM_{2.5}$
  - Moderate AQI levels on the AIRNow $PM_{2.5}$ map from September 4, 2003, in eastern Washington State (center)
  - $PM_{2.5}$ sites collocated with the high AOD values show poor correlation with the AOD on September 4 and on previous days.
  - This indicates that the aerosols may not all be mixing down to the surface.



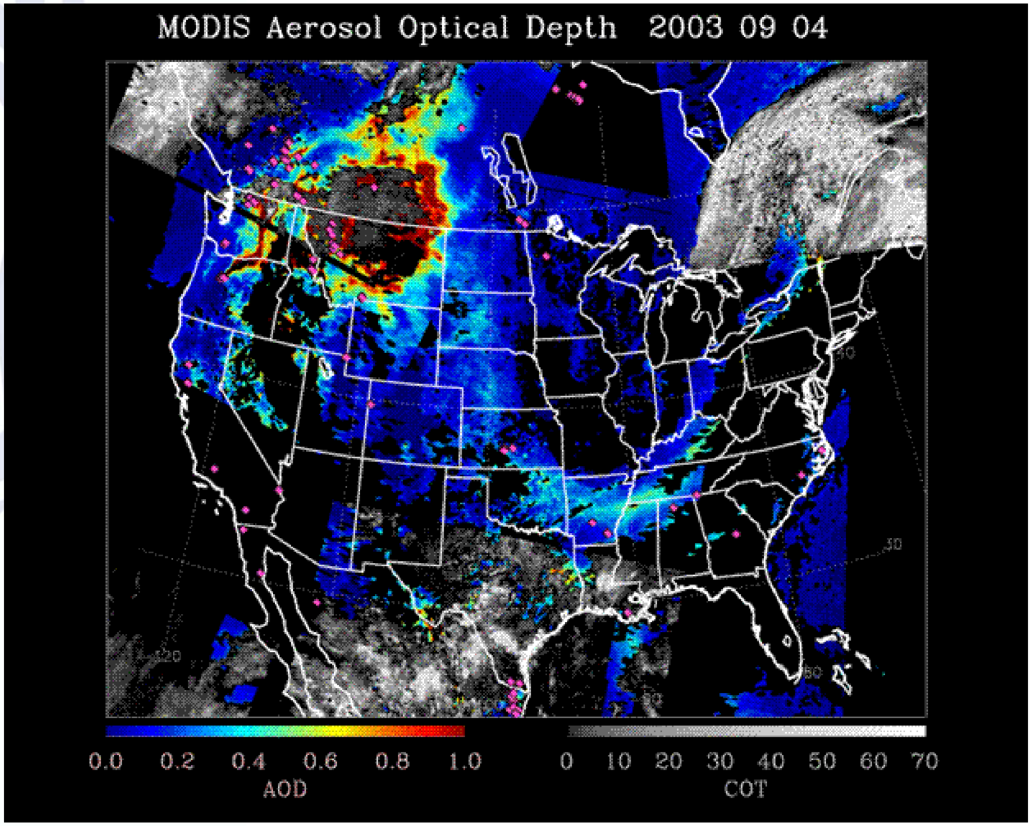
Satellite – Forecasting Applications (4 of 5)

- Trajectory plots indicate transport of smoke into the Northern Plains
- Forecasters should analyze mixing characteristics in the Northern Plains to determine potential smoke impact



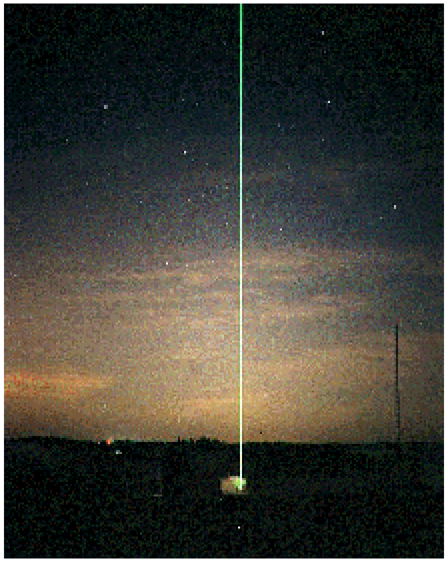
Satellite – Forecasting Applications (5 of 5)

- Static AOD plots can be used to assess transport
- The loop below shows the progression of the high AOD from the Pacific Northwest into the Ohio Valley from September 4 through September 10, 2003



Lidar (1 of 3)

- LIght Detection And Ranging (LIDAR) transmits light out to a target. Some of this light is reflected or scattered back to the lidar.
- Lidar can measure
  - Winds
  - Turbulence
  - Clouds
  - Aerosols
  - Water vapor
  - Other atmospheric constituents such as ozone and carbon dioxide



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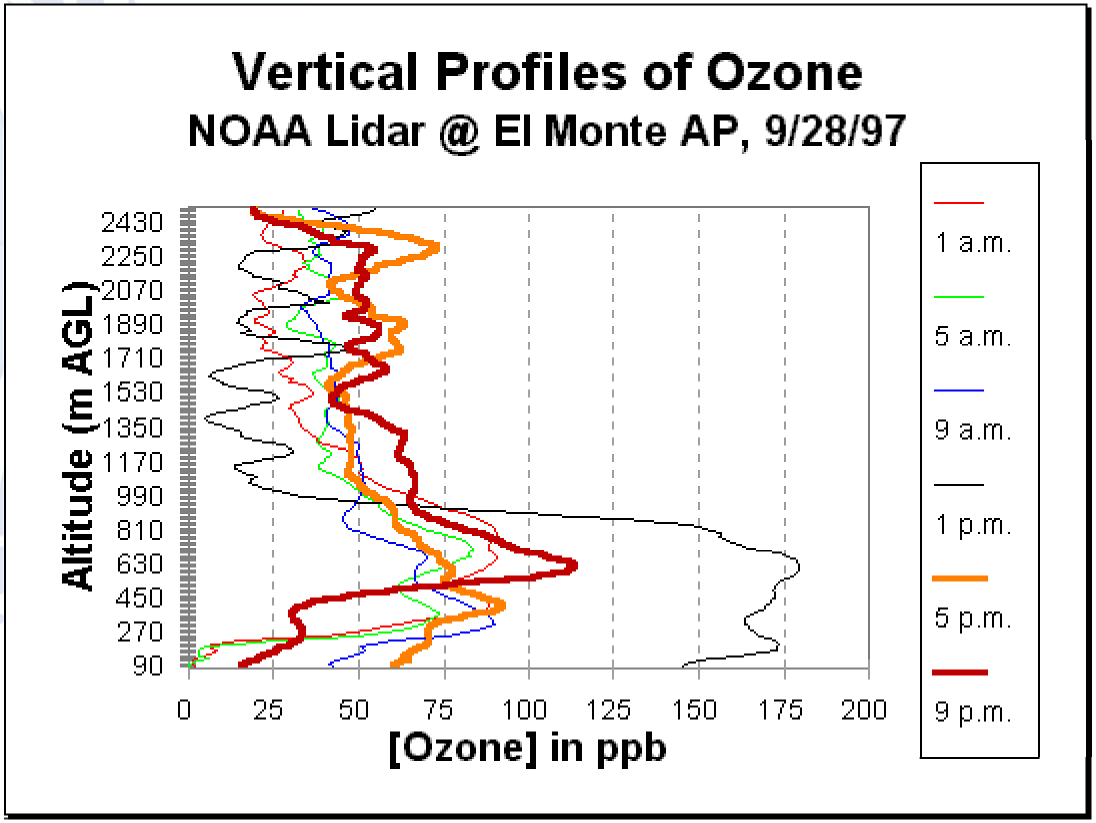
Lidar (2 of 3)

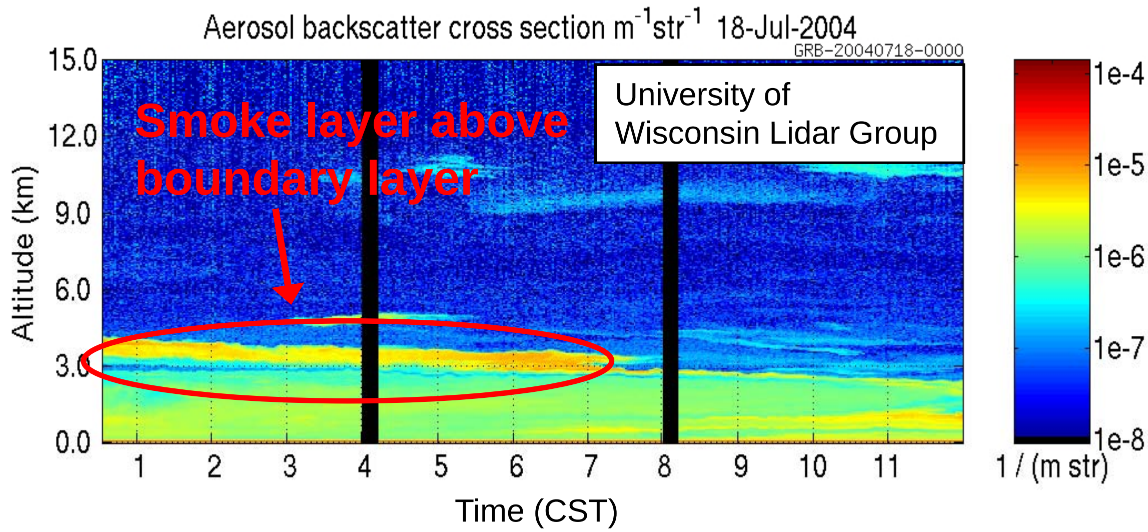
- Lidar is useful for forecasting because it can vertically resolve ozone and aerosol layers.

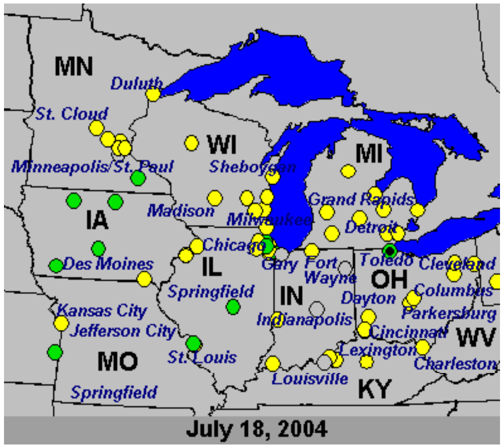


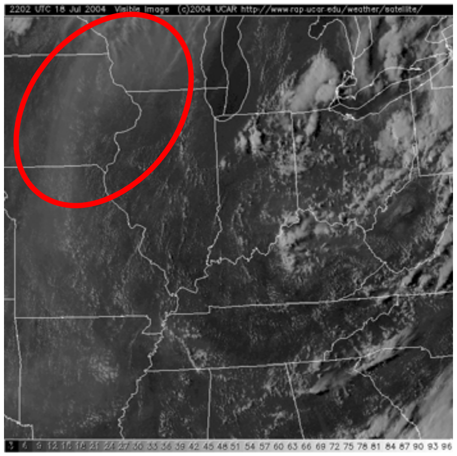
WMO
OMM

Lidar (3 of 3)

- Lidar shows a layer of smoke at about 3 km altitude.
- Smoke evident on visible satellite image.
- No unusually high $PM_{2.5}$ at the surface.
- For forecasting, run forward trajectories at 3 km to determine movement of smoke layer.
- Determine if vertical mixing will bring particles down to the surface.

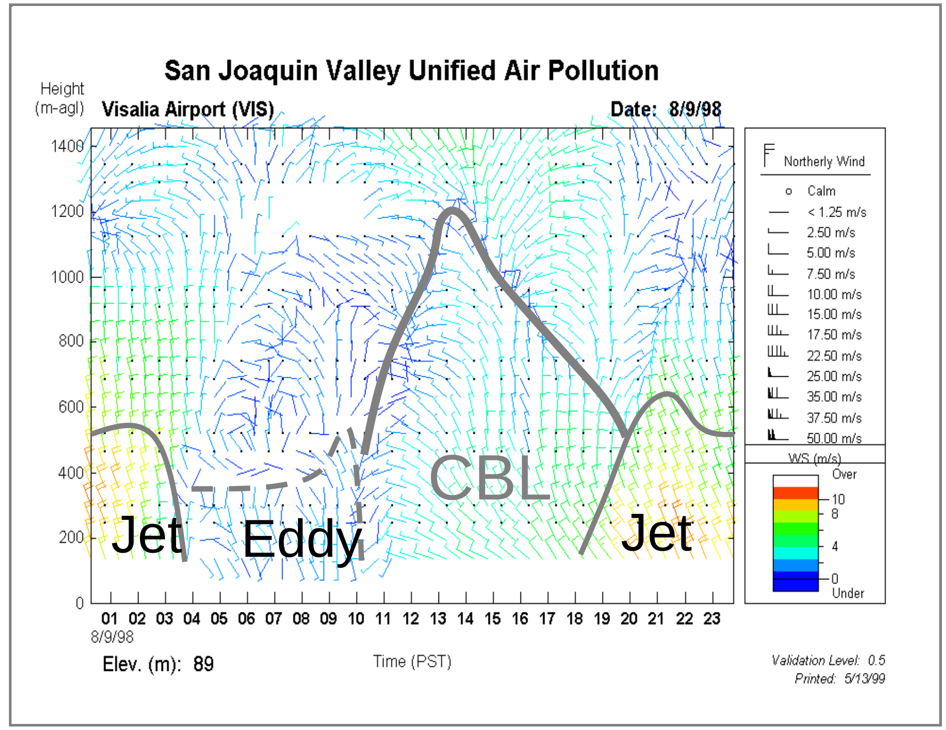






Radar Wind Profiler – Winds

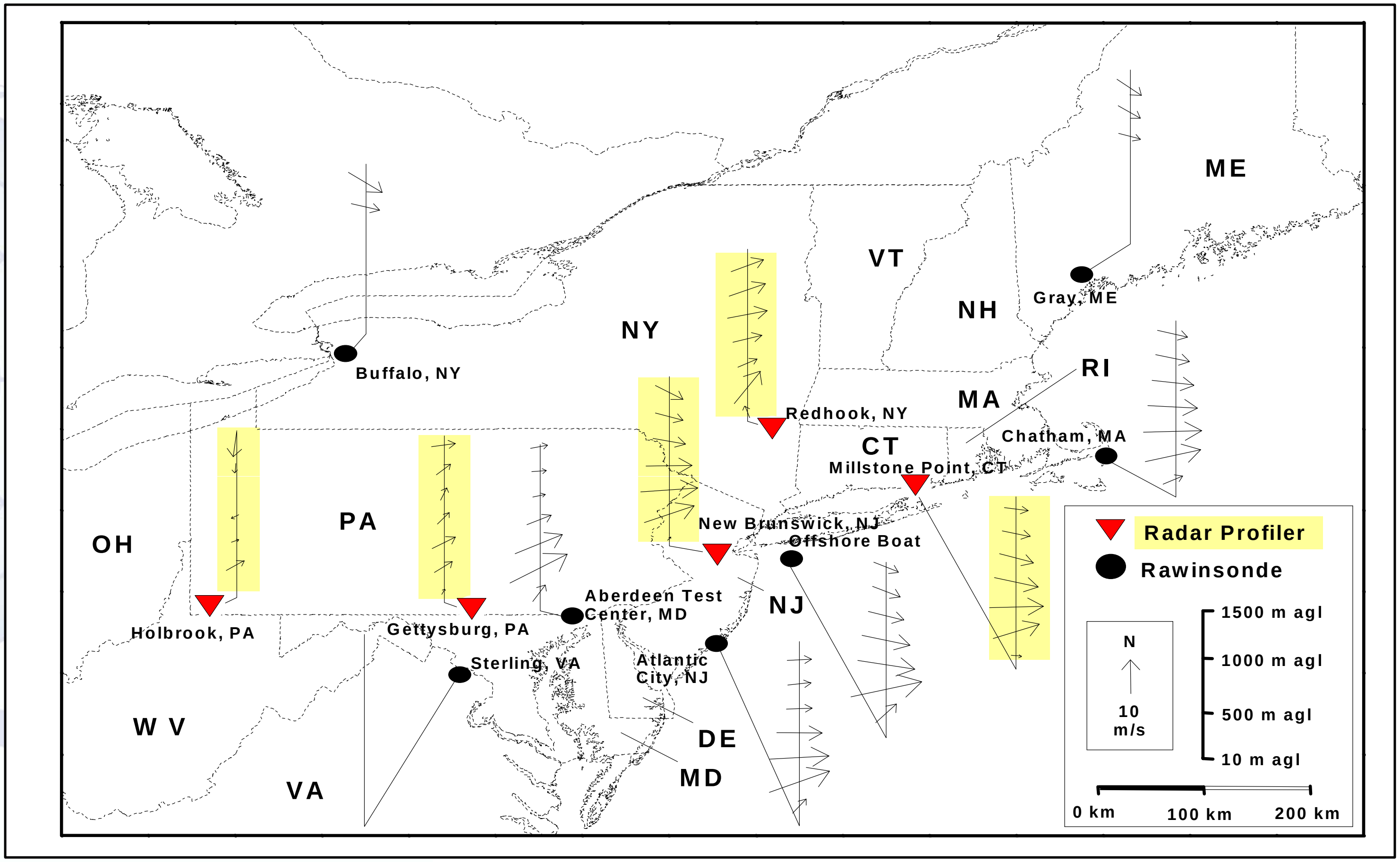
- Used to understand processes and help forecast
- Provides
  - Continuous winds
  - Continuous temperature profiles
  - Continuous mixing



Radar profiler wind data at Visalia on August 9, 1998, showing the nocturnal jet, convective boundary layer (CBL), and eddy flow. This wind pattern was observed on the majority of the episode days (MacDonald et al., 1999).

Radar Wind Profiler –Transport (1 of 2)

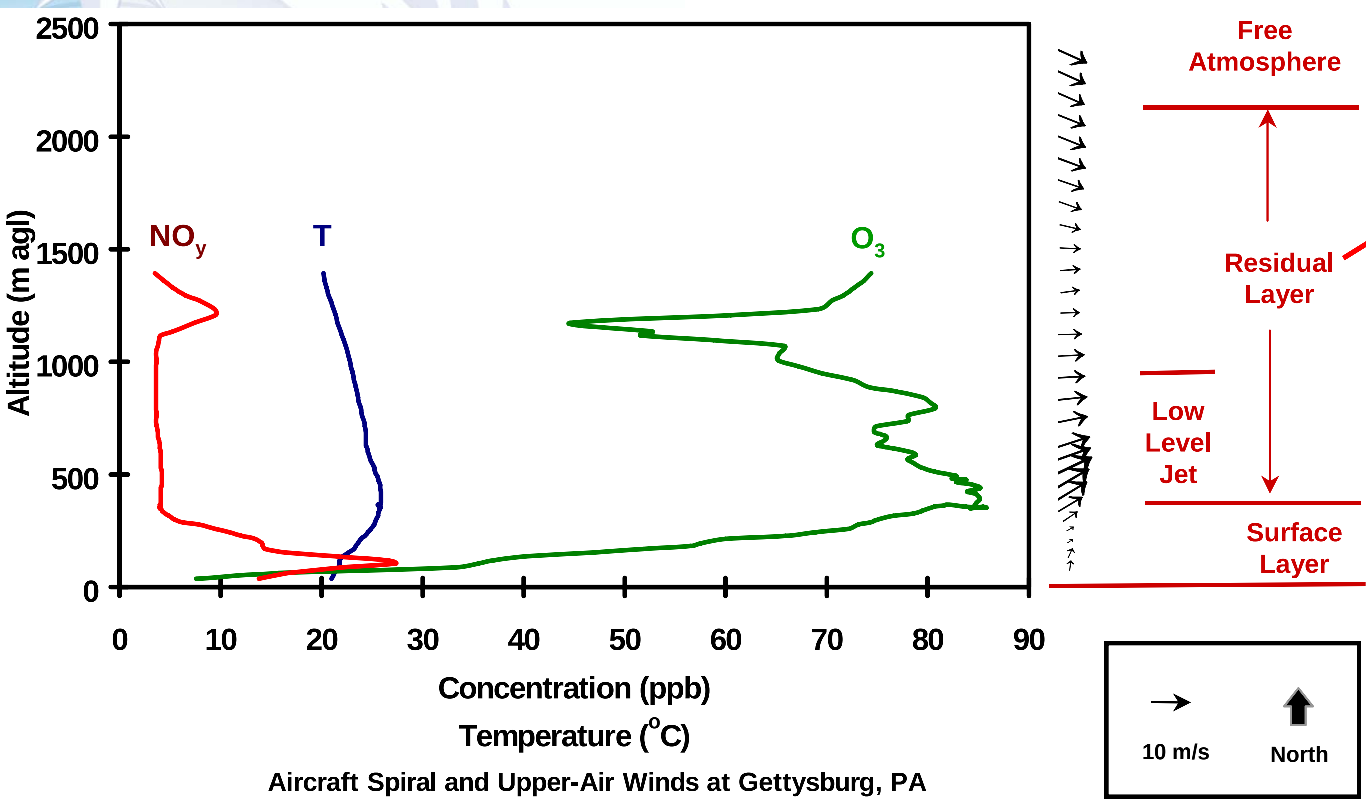
Regional extent of low-level jet

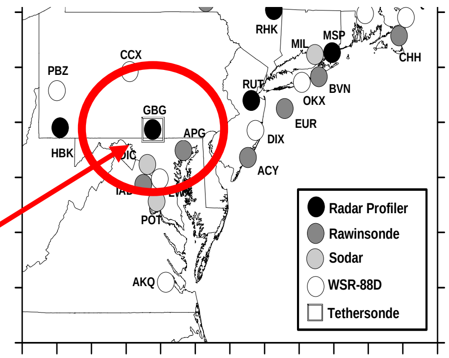


Upper-air winds on July 14, 1995, at 0300 EST, used to locate the low-level jet during an air pollution episode

Radar Wind Profiler –Transport (2 of 2)

The nocturnal jet can transport air pollution over several hundred kilometers during the overnight hours. This aloft pollution mixes to the surface the following day. The RWP data can be used to diagnose the existence and strength of the nocturnal jet.





Aircraft Spiral and Upper-Air Winds at Gettysburg, PA
(0600 EST on August 1, 1995)

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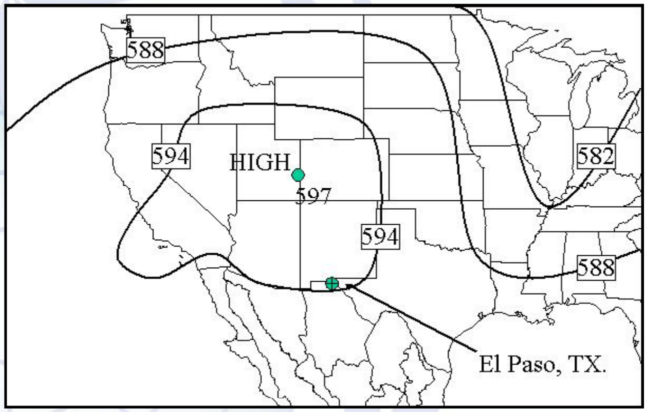
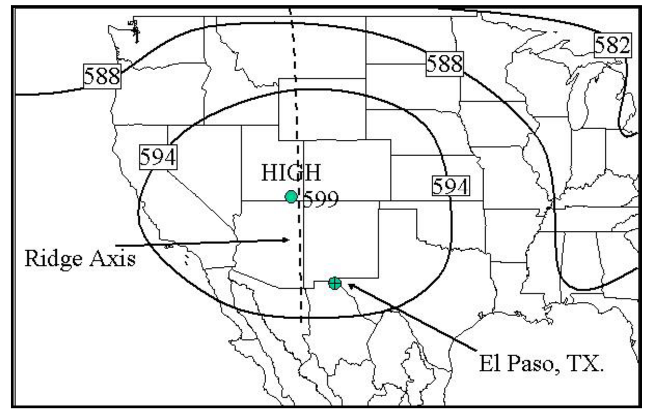
Radar Wind Profiler Mixing Depth Example (1 of 4)

1996 Paso del Norte Summer Ozone Study

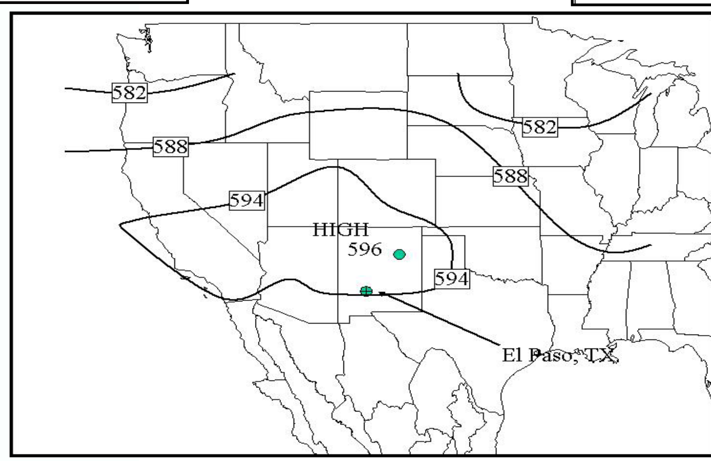
August 12, 1996



August 13, 1996



August 14, 1996



500-mb heights at 1700 MST for August 12 through August 14, 1996 (MacDonald et al., 2001b)

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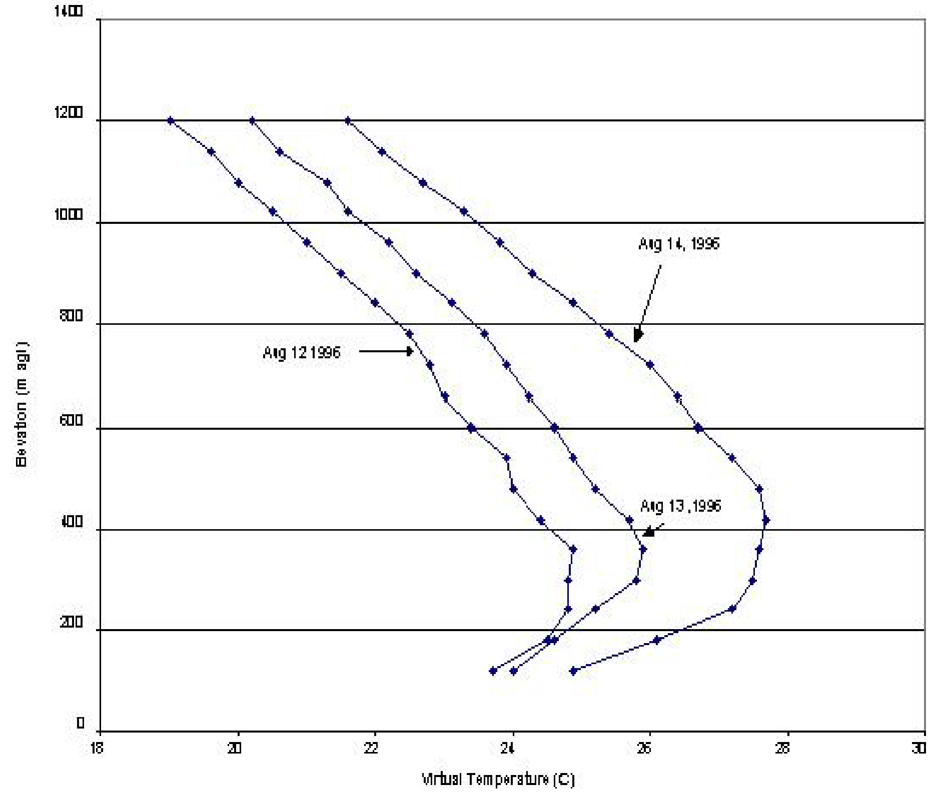
Radar Wind Profiler Mixing Depth Example (2 of 4)

1996 Paso del Norte Summer Ozone Study

Morning inversion increased from 6.5^{o}C on August 12 to 8.7^{o}C on August 13, to 9.7^{o}C on August 14

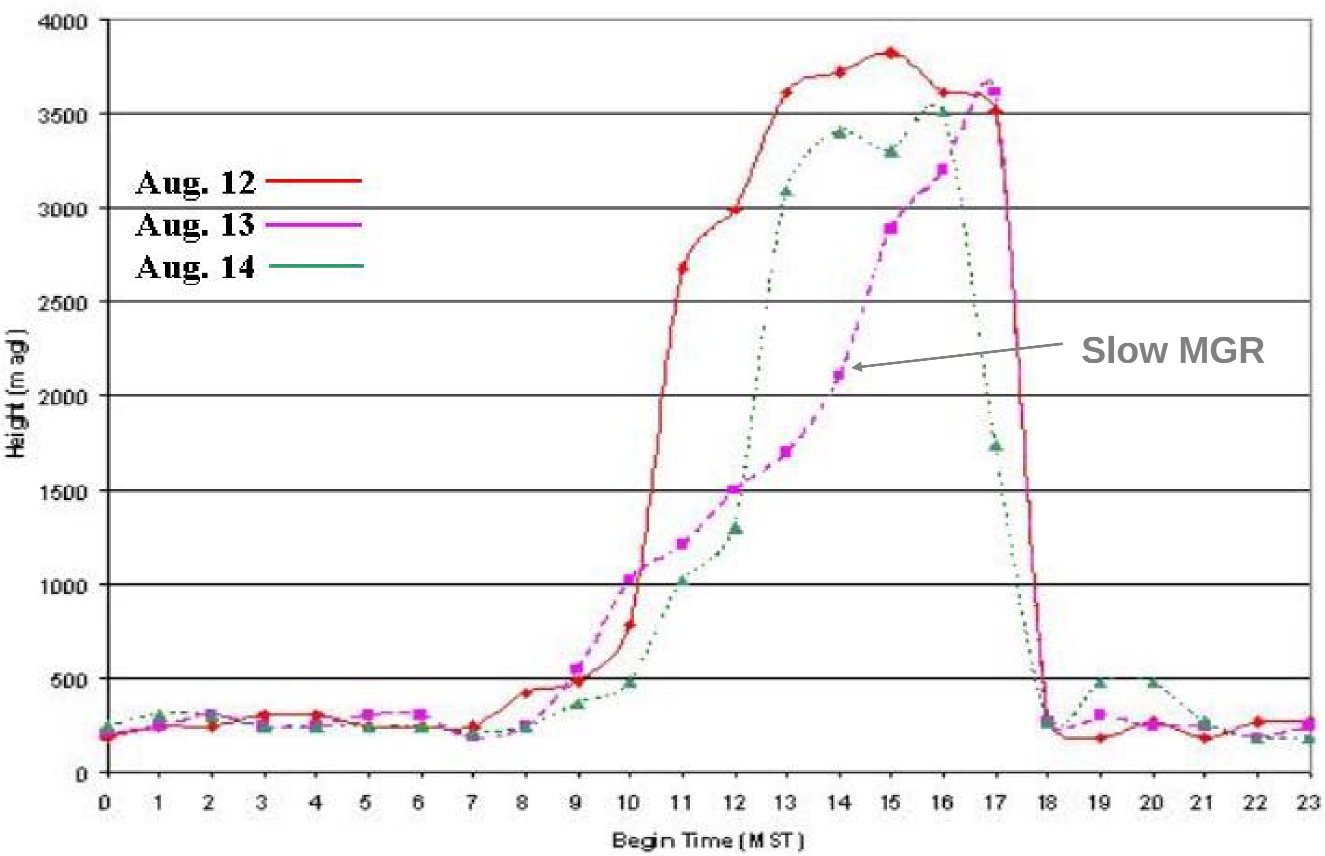


RASS virtual temperature on August 12 through 14, 1996, at 0600 MST (MacDonald et al., 2001b)

WMO
OMM

Radar Wind Profiler Mixing Depth Example (3 of 4)

1996 Paso del Norte Summer Ozone Study



Mixing depths on August 12 through 14, 1996 (MacDonald et al., 2001b)

Radar Wind Profiler Mixing Depth Example (4 of 4)

1996 Paso del Norte Summer Ozone Study

Summary of Results

Parameter	August 12	August 13	August 14
MGR (m/hr)	380	150	120
Peak Mixing Depth. (m)	3800	3700	3600
Avg. Surface Wind Speed (m/s) (0600-1000, local time)	1.3	0.9	2.0
Peak Ozone (ppb)	77	137	79

A slower Mixing Depth Growth Rate (MGR) and light winds lead to a higher peak ozone value on August 13, 1996 (MacDonald et al., 2001b)