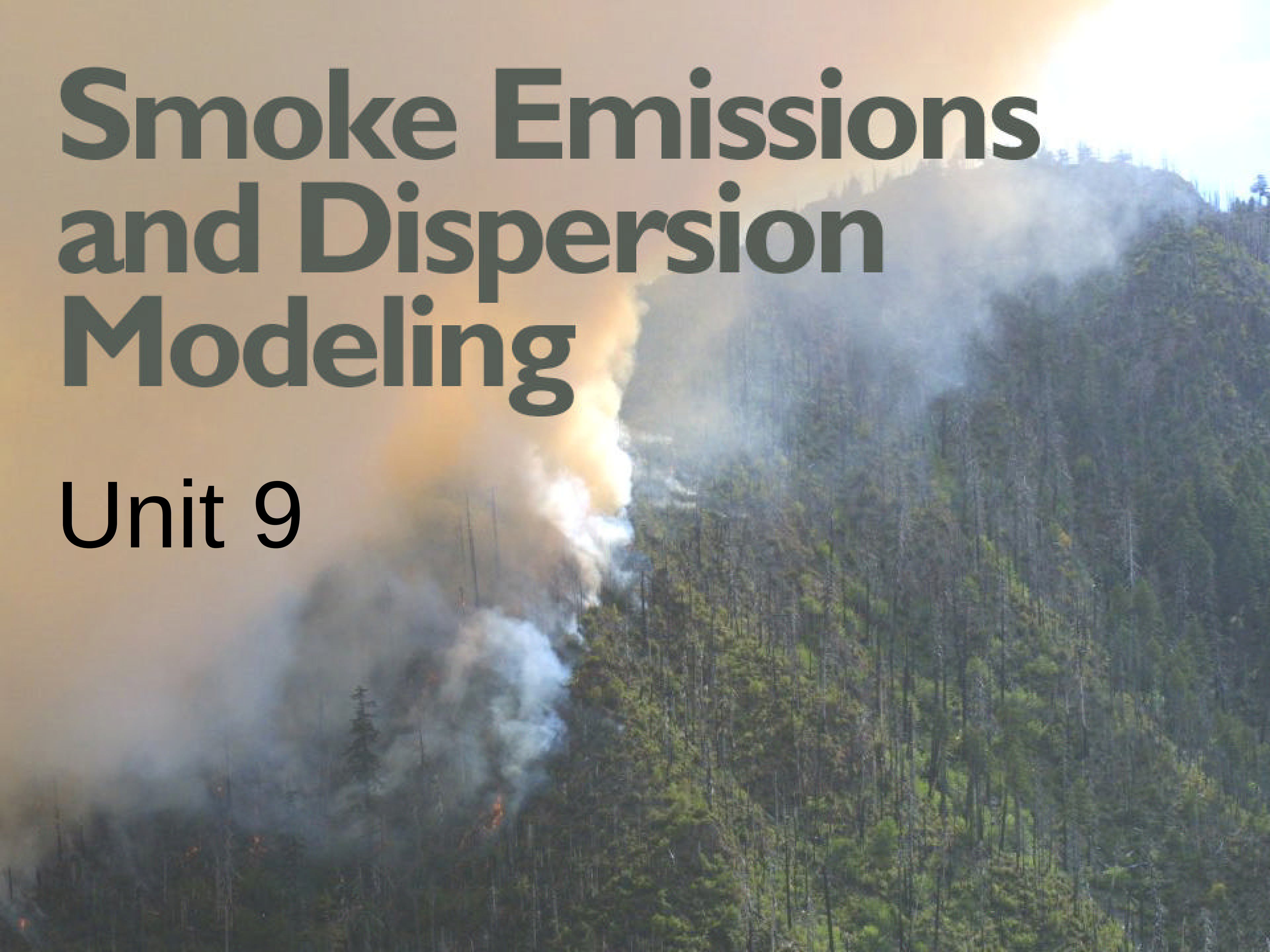
Smoke Emissions and Dispersion Modeling

Unit 9



Unit 9 Objectives

- An understanding of what smoke emissions and dispersion modeling is and why it is needed
- An understanding of important definitions and concepts in smoke emissions and dispersion modeling
- Identify common smoke emissions and dispersion modeling systems available to help the fire practitioner plan for and communicate the impacts of smoke.

Unit 9 Objectives

- Describe the data and expertise needed to run emissions and dispersion models.

- Hands-on training with an easy-to-use smoke emissions and dispersion model (SIS)

What is a Model?

- A "model" may be a series of manual calculations, a series of look-up tables, a computer program, or a physical mock-up (as in a wind tunnel) that describes a physical process.
- Modeling requires an understanding of inputs and processes that they are describing.
- Models change as the state of the science change.

What is smoke emissions and dispersion modeling?

- Smoke emissions and dispersion modeling is a well defined set of approaches and methods used to quantify and describe smoke generation and its fate in the atmosphere.
- These tools are used to communicate the impact of smoke on ambient air quality and visibility.

Why Perform Smoke Emissions or Dispersion Modeling?

1. **Demonstrate compliance with federal, state, and local regulations (NEPA, air quality)**
   - Wyoming, Arizona, and Colorado require dispersion modeling for prescribed burn plans.
   - Oregon and Washington have emission limits for prescribed burning.
   - Determination of conformity with State Implementation Plans in non-attainment areas
   - Determination of impacts for NEPA analyses
2. **Address health and safety concerns**
   - To prevent dangerous reductions in visibility over highways and airports.
   - To address health and safety concerns of residents and communities located downwind of fires.
   - To determine potential firefighter exposure to carbon monoxide and toxic air pollutants.

Why Perform Smoke Emissions or Dispersion Modeling?

3. **Promote positive public image**
   - To allow burn managers to test an action without having to experience adverse consequences from that action. This may help in preventing smoke intrusions into nearby sensitive areas.
   - To allow burn managers to determine the pollutant concentrations within a smoke plume at any downwind location. This will enable burn managers to respond proactively to public inquiry about the possible impacts from prescribed burning activities.
4. **Assist in establishing appropriate burn prescriptions**

Emissions Modeling

- The process of estimating pollutant emissions from wild or prescribed fires.

- Basic inputs include the type of fuel, the amount of fuel, and how it is distributed.

- The primary output from these models is the emission rate; e.g., pollutant grams/second.

  Other outputs include heat production, total emissions and emission factors.

Emissions Modeling

- In its simplest form, the emissions are an empirical functions of fuel burned.

Pollutant released (g) = EF(g/kg) * Total_Fuel_Burned (kg)

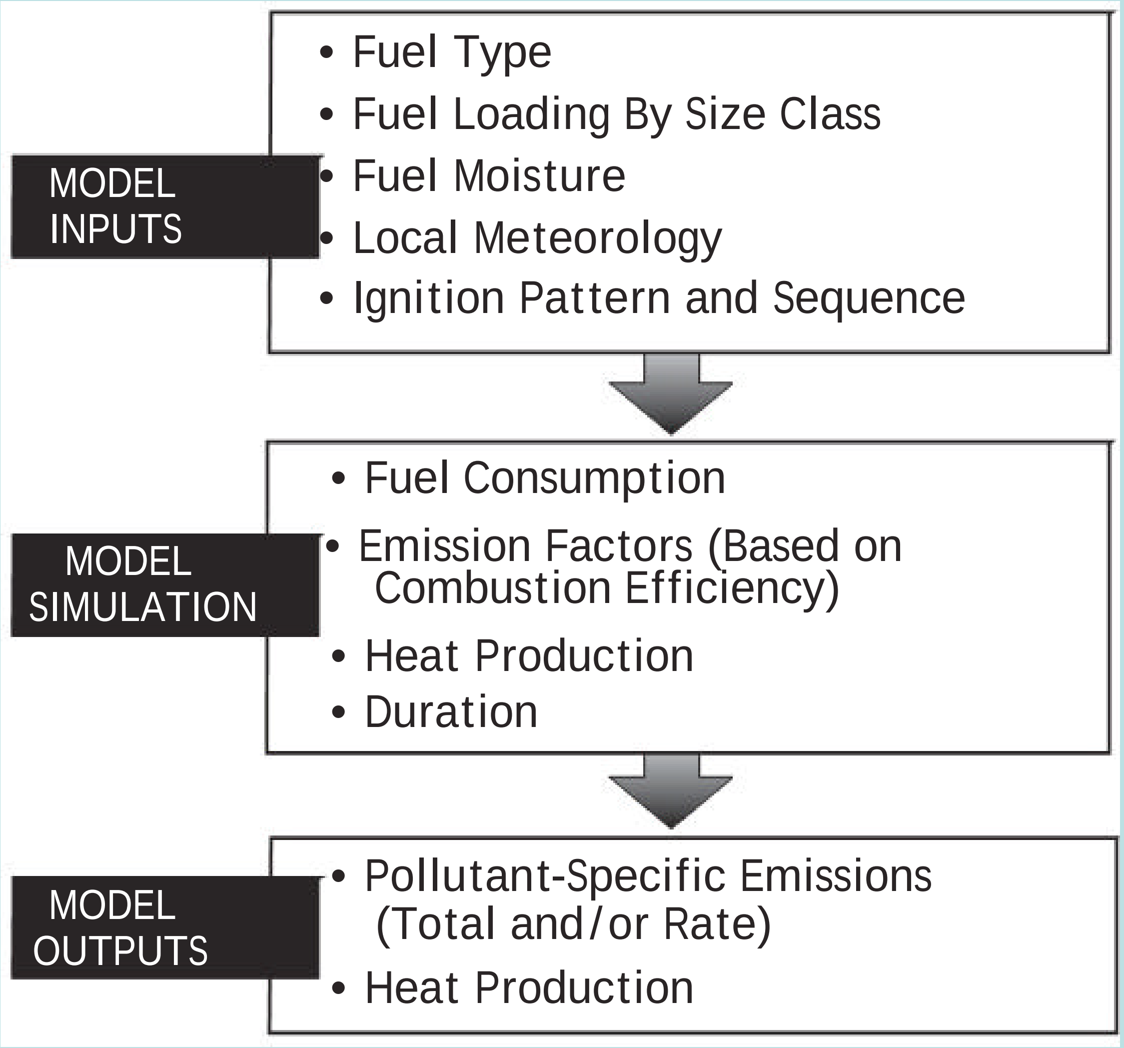
Table 13.1-3 (Metric Units). EMISSION FACTORS FOR PRESCRIBED BURNING[a]

Fire/Fuel Configuration	Phase	Pollutant (g/kg)						Fuel Mix (%)	EMISSION FACTOR RATING
		Particulate			Carbon Monoxide	Volatile Organics			
		PM-2.5	PM-10	Total		Methane	Nonmethane		
Broadcast logging slash									
Hardwood	F	6	7[b]	13	44	2.1	3.8	33	A
	S	13	14[b]	20	146	8.0	7.7	67	A
	Fire	11	12[b]	18	112	6.1	6.4		A
Conifer									
Short needle	F	7	8[c]	12	72	2.3	2.1	33	A
	S	14	15[c]	19	226	7.2	4.2	67	A
	Fire	12	13[c]	17	175	5.6	3.5		A
Long needle	F	6	6[d]	9	45	1.5	1.7	33	B
	S	16	17[d]	25	166	7.7	5.4	67	B
	Fire	13	13[d]	20	126	5.7	4.2		B
Logging slash debris									
Dozer piled conifer									
No mineral soil[d]	F	4	4	5	28	1.0	ND	90	B
	S	6	7	14	116	8.7	ND	10	B
	Fire	4	4	6	37	1.8	ND		B

From U.S. EPA AP-42 Chapter 13.1 Prescribed and Wildfire Burning

Emission Modeling

More complex approaches include models like FOFEM5 and CONSUME which require more detailed inputs and provide more detailed outputs.



Emissions Modeling

- Emissions modeling predicts what is release into the atmosphere during a burn but does not predict *where* emissions will disperse!
- Emission Models give a pollutant mass or emission rate but not a concentration.

Dispersion Modeling

Dispersion modeling describes the atmospheric process of transport and diffusion of pollutants when released to the atmosphere.

Transport – Winds move pollutants away from the source.

Diffusion – The plumes mixed with the ambient air, thus increasing its volume and decreasing their pollutant concentration.

Dispersion Modeling

- In some modeling and meteorological literature, the term “atmospheric diffusion” (or simply “diffusion”) is used interchangeably with “dispersion.”
- The faster the transport and mixing, the faster the plume disperses.
- The rate of mixing depends on the atmospheric conditions.

Dispersion Modeling

- Primarily, dispersion modeling is a technique for calculating the concentrations of pollutants in the air downwind of one or more emission sources.
- Alternative approaches involve estimating the capability of the atmosphere to disperse smoke (e.g. an index).

Dispersion Modeling

Many type of dispersion modeling systems

1. Indexes of dispersion (VI, ADI)
2. Plume models
3. Puff models
4. Trajectory/Particle Models
5. Grid/Box Models

Indexes

Methods used to estimate the dispersive potential of the atmosphere

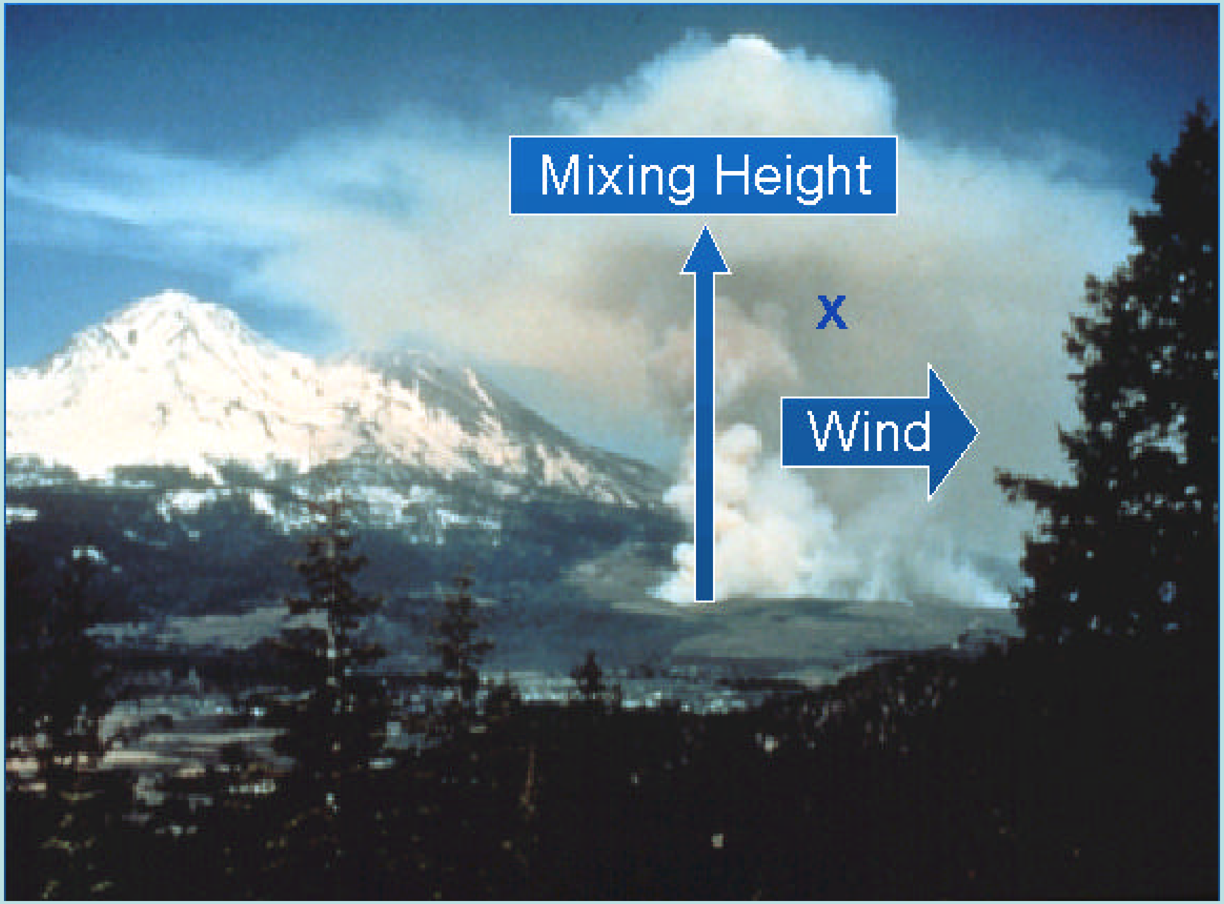
- No emissions involved

Many indexes are online as part of fire forecasts

- Ventilation Index (VI)
  - VI is a function of transport wind speed and mixing height
- Atmospheric Dispersion Index (ADI)
  - It utilizes stability, mixing height, and transport wind as the major factors. Based on a statistical model.

Ventilation Index

The product of a mixing height times the average wind speed through the mixing layer



Common values of ventilation indices and associated smoke conditions

VI (knot-ft) = MH x traj WS	VI (knot-ft)/100 = MH x Layer Avg WS	VI (m^2/sec)= PBL x 40 m WS	Smoke Condition
0-28999	<200	< 2,350	Poor
29,000 – 37,999	200 – 400	2,350 – 4,700	Marginal
38,000 – 49,999	400 – 500	4,700 – 7,050	Fair
50,000 – 94,999	> 500	> 7,050	Good
> 95,000			Excellent

From Smoke Management Guide, Table 9.1

VI = Ventilation Index

MH = Mixing Height

PBL = Planetary Boundary Layer

Atmospheric Dispersion Index (ADI) (Generally Used in the Southeast)

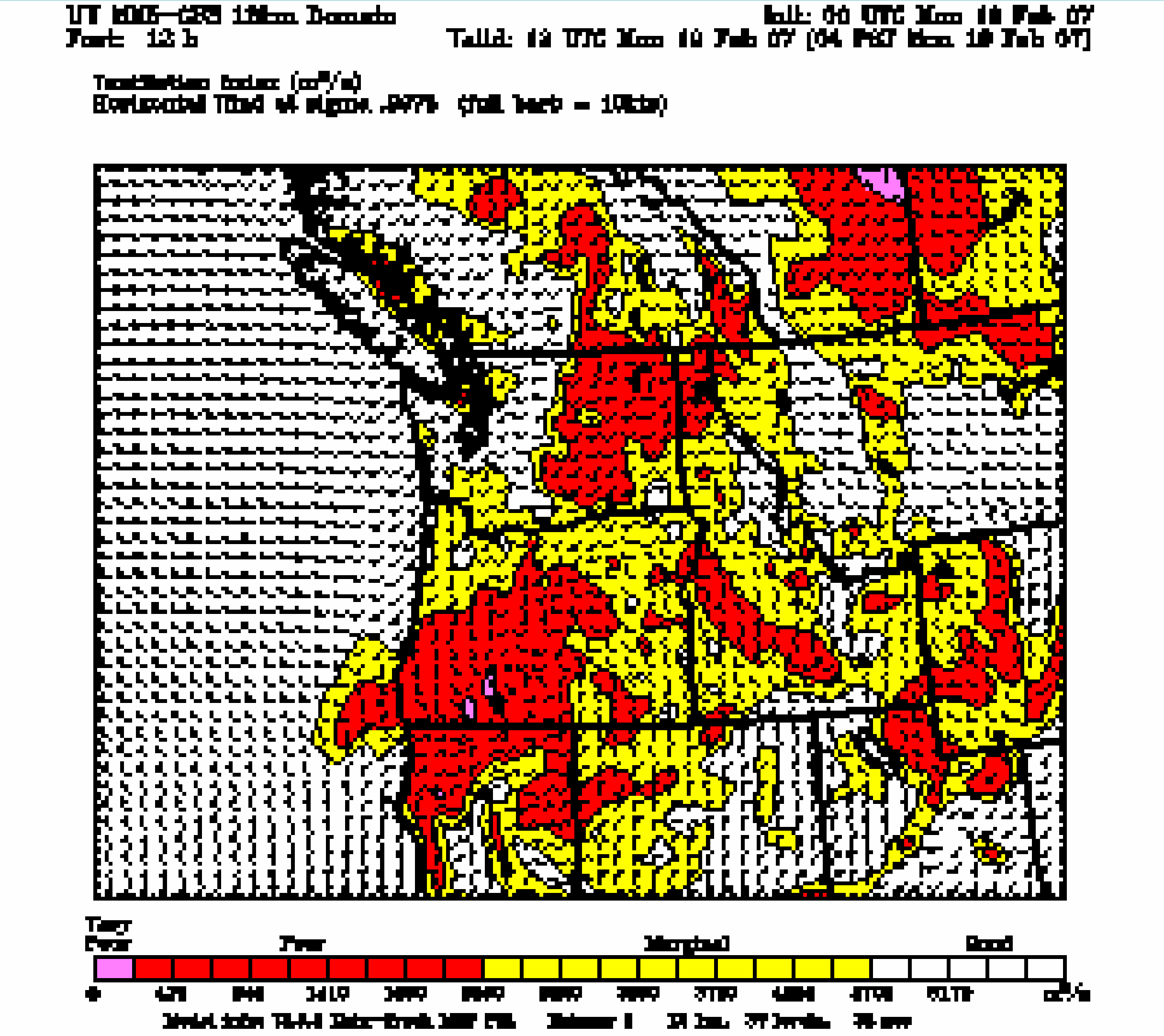
ADI	Interpretation
1-6	Very poor dispersion
7-12	Poor dispersion
13-20	Generally poor dispersion
21-40	Fair dispersion
41-60	Generally good dispersion
61-100	Good dispersion
>100	Very good dispersion (but high fire hazard)

Generally burning not allowed

Table 9.2 from Smoke Guide

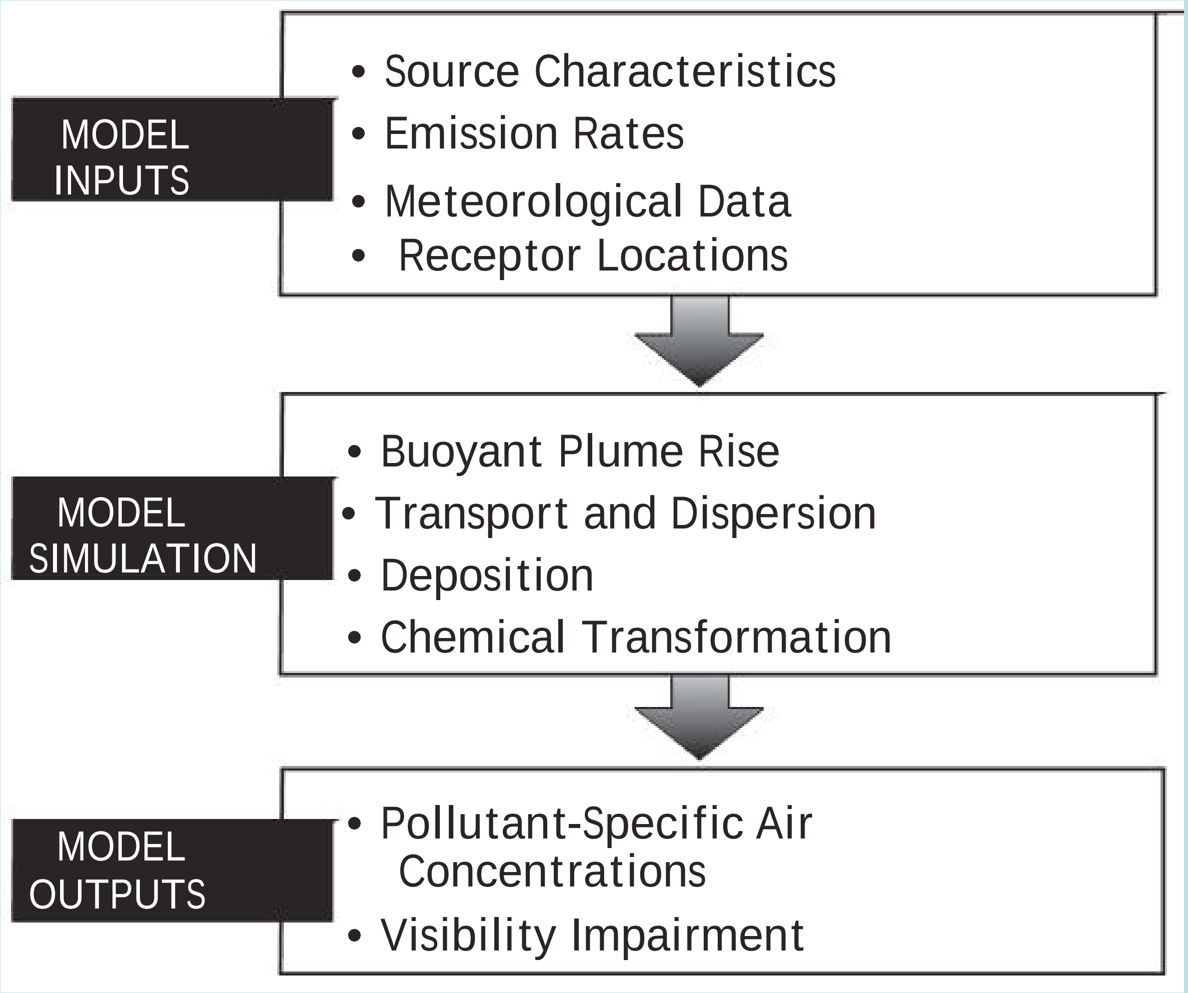
Indexes

- Many indexes are on-line as part of regular fire forecasts



Numerical Dispersion Models

- More complex modeling requires more inputs



Screening versus Refined Modeling

- Screening modeling:
  - Relatively simple analysis techniques to determine if a given source is a threat to air quality or visibility.
  - Minimal data input requirements
  - Typically uses a set of representative worst-case meteorological data.
  - Conservative (high) estimates of concentration or visibility impairment.
  - Eliminates the need for more detailed modeling analyses (as long as threshold is not exceeded).

Screening versus Refined Modeling

- Refined modeling:
  - Analytical techniques that provide more detailed treatment of sources, terrain, and atmospheric processes.
  - Requires more detailed and precise input data.
  - Provides more specialized, and less conservative, concentration estimates.
  - Uses actual sequential hourly meteorological data (for example, from an onsite meteorological monitoring station or outputs from mesoscale weather forecast model like MM5).
- Current smoke models are either exclusively screening models or refined models.

Modeling Elements

- Source
- Meteorological Data
- Receptors
  - Simple Terrain
  - Complex Terrain

Source

- Point of origin of emissions. Can be a single emission unit (e.g., a slash pile) or a combination of emission units (e.g., a burn unit)

Source types

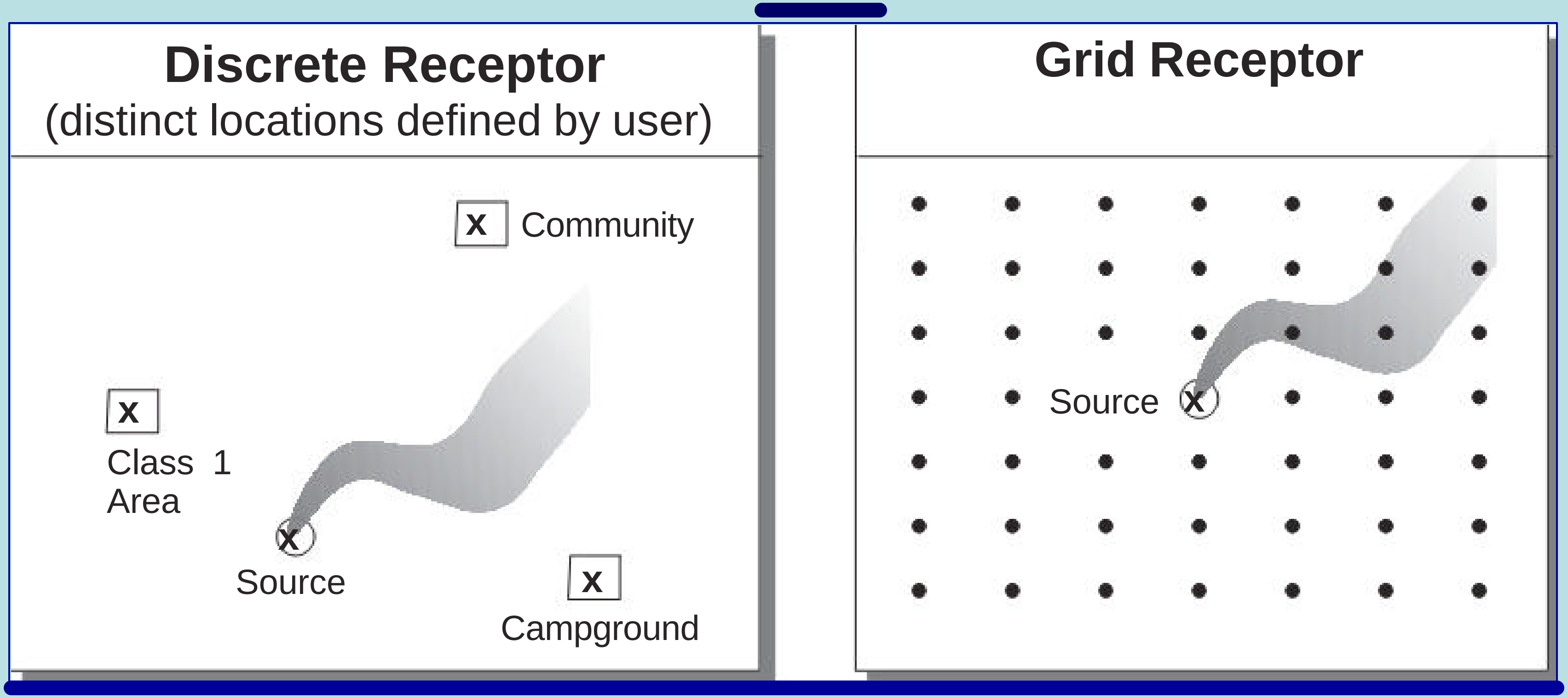
- If model is not linked to an emissions model, then the modeler must characterize the time evolution of the emissions, heat release for plume rise, and burn size and shape.
- The modeler must decide the appropriate level of detail for the source(s).
- Types of sources:
  - Buoyant Point (e.g., slash pile)
  - Buoyant Area (e.g., burn unit)
  - Volume (e.g., burn unit with known plume height)
  - Line (e.g., fire line)

Meteorological Data

- Meteorological data includes wind speed, wind direction, air temperature, a measure of atmospheric stability (e.g., Pasquill-Gifford stability class), and mixing height.
- Averaged over specified period of time, typically, one-hour averages.
- Depending on the model used, either measured (actual) or assumed (representative) meteorological data may be required.
- Meteorological data can be either uniform over domain or spatially and/or temporally varying.

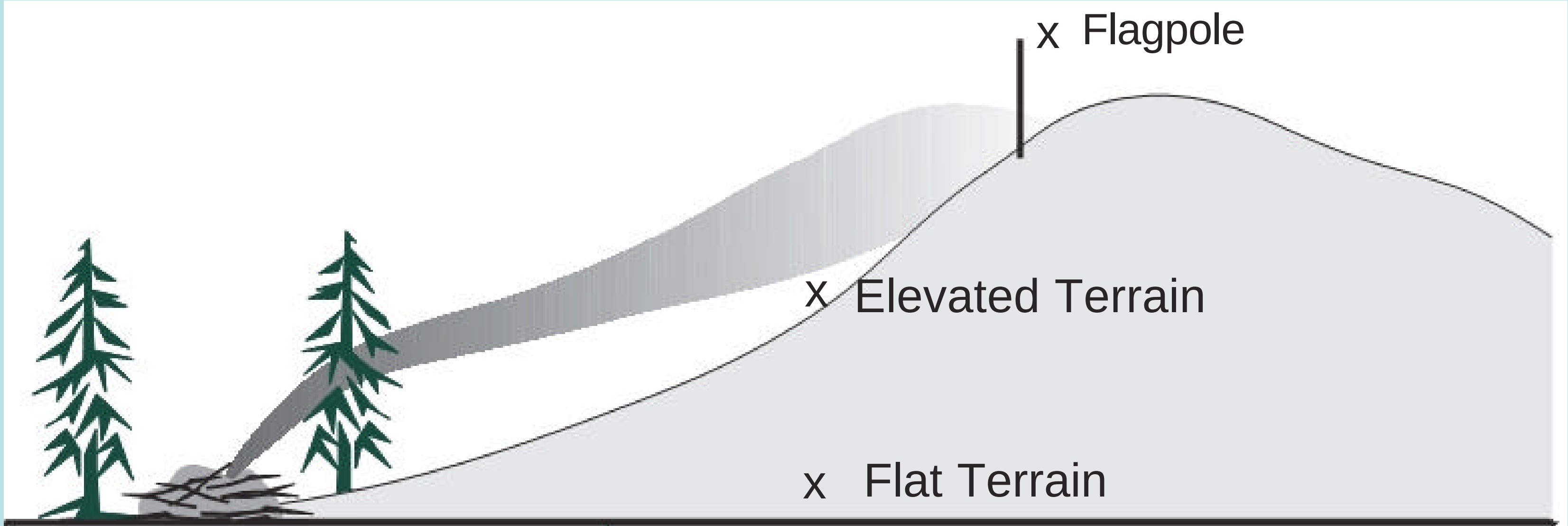
Receptors

- The theoretical point on a map at which pollutant concentrations are predicted using a model.
- May be characterized by discrete locations or an grid of points.



Receptors

Characterized by terrain height:



Elevated terrain receptor	At actual terrain elevation
Flat terrain receptor	At base elevation of source
Flagpole receptor	At an elevation that is above the actual terrain elevation; not found in current smoke dispersion models

Terrain

- Simple Terrain: Flat or rolling.
  Local terrain does not strongly influence winds.
- Complex Terrain: Hilly or mountainous.
  Local terrain has effect on winds by channeling winds (e.g., nighttime downwind drainage flows and daytime heating upslope flows)

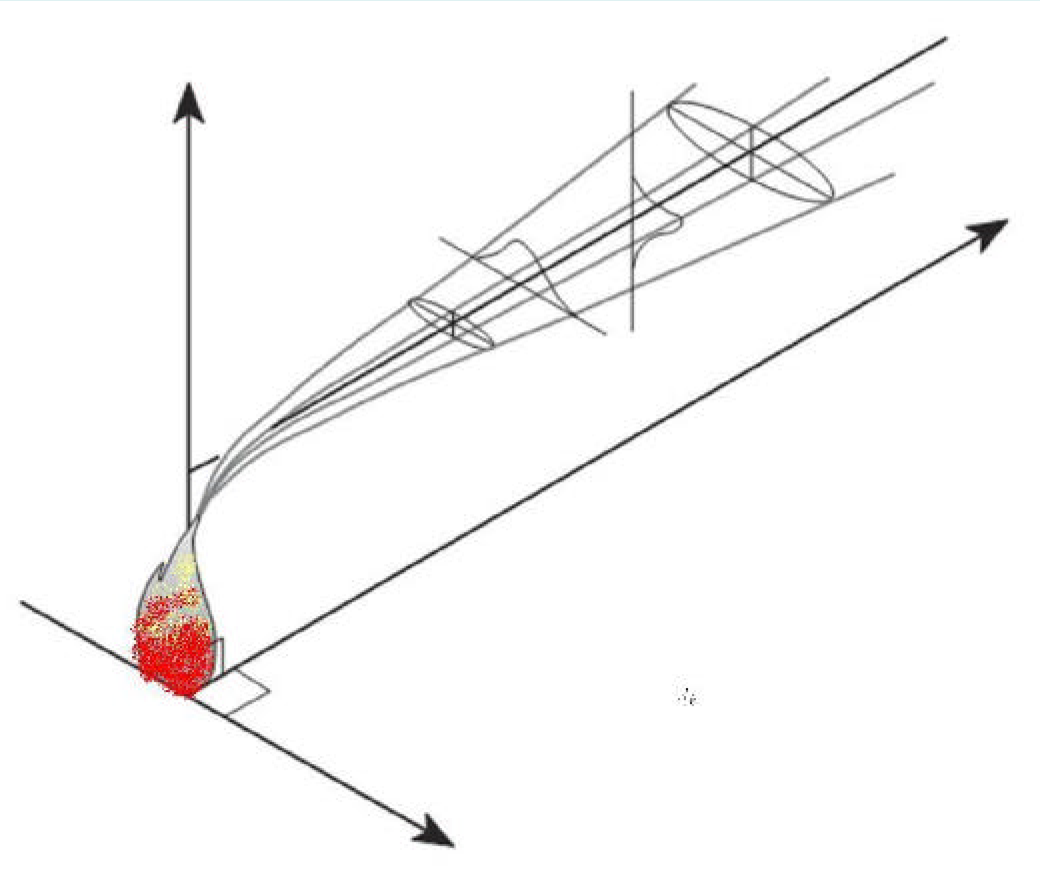
Dispersion Models

- Plume Models
  SASEM, VSMOKE, ISCST/AERMOD
- Puff Models
  SIS, CALPUFF, NSFpuff, BlueSky
- Particle Models
  HY-Split; PB-Piedmont
- Grid Models/ Box Models
  CMAQ/Model3; CAMx/ VALBOX

Plume Models

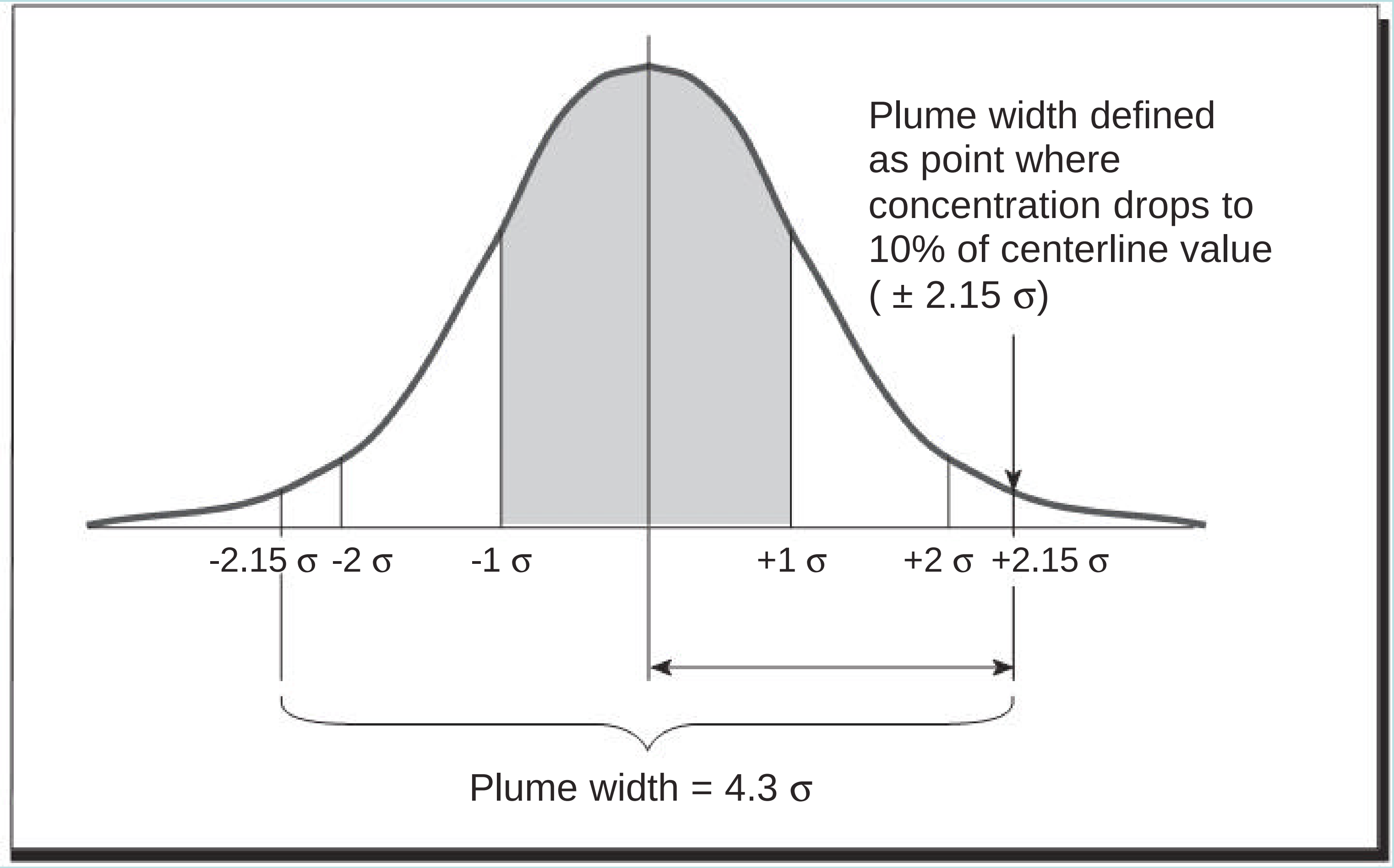
- Assumes smoke travels in a straight line under steady state conditions (speed and direction of particles do not change during the meteorological averaging time)
- Each hour is independent, the plume “instantly” changes as conditions change.
- Commonly used with flat or rolling terrain
- Examples: SASEM, VSMOKE, and ISCST

Plume Model



- Plumes are characterized by a bell-shaped concentration profile in both the horizontal and vertical directions (i.e., by a normal or "Gaussian" distribution).
- This is a mathematically simplified way to simulate dispersion.

Gaussian Shape

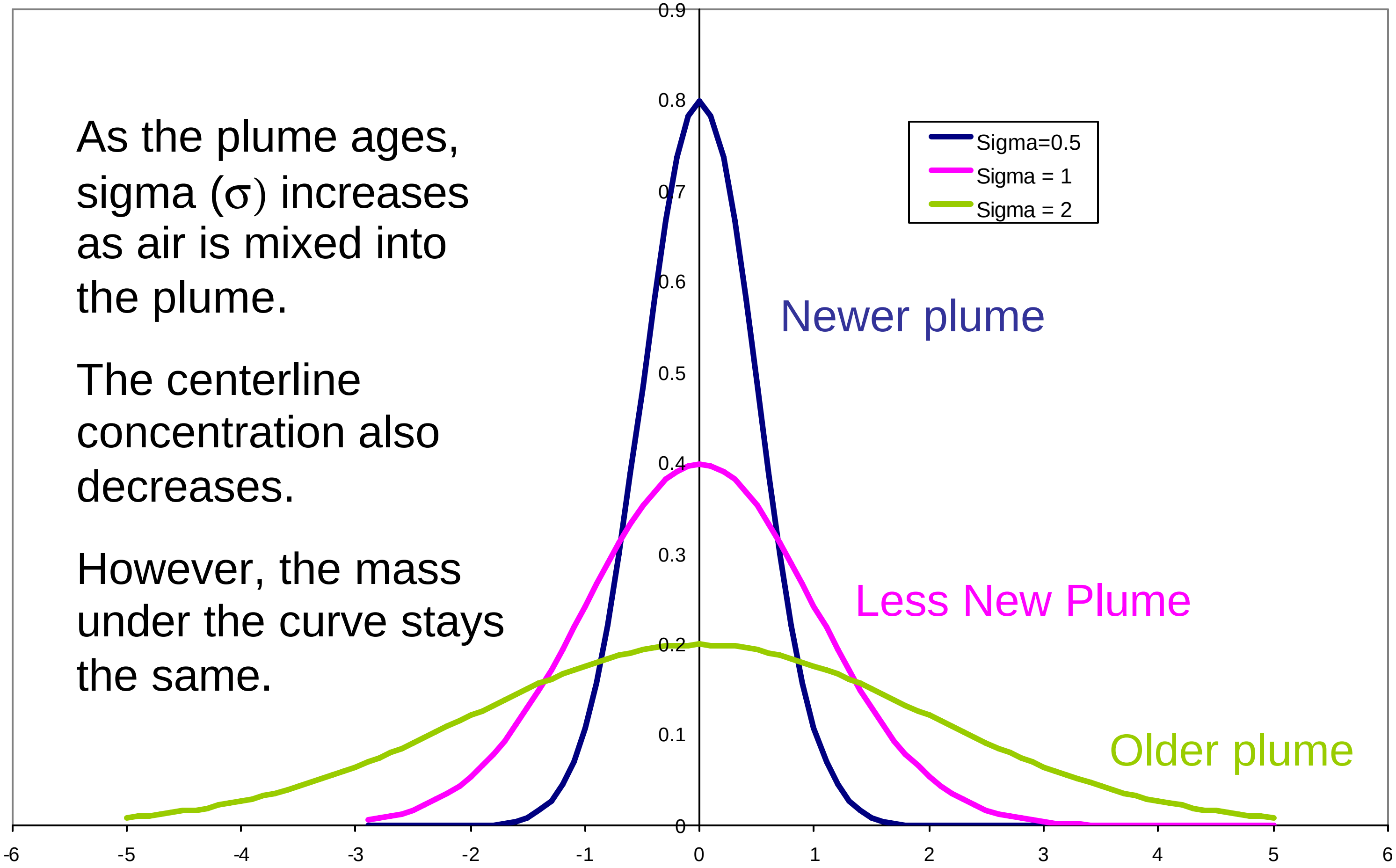


Gaussian Shape

As the plume ages, sigma (σ) increases as air is mixed into the plume.

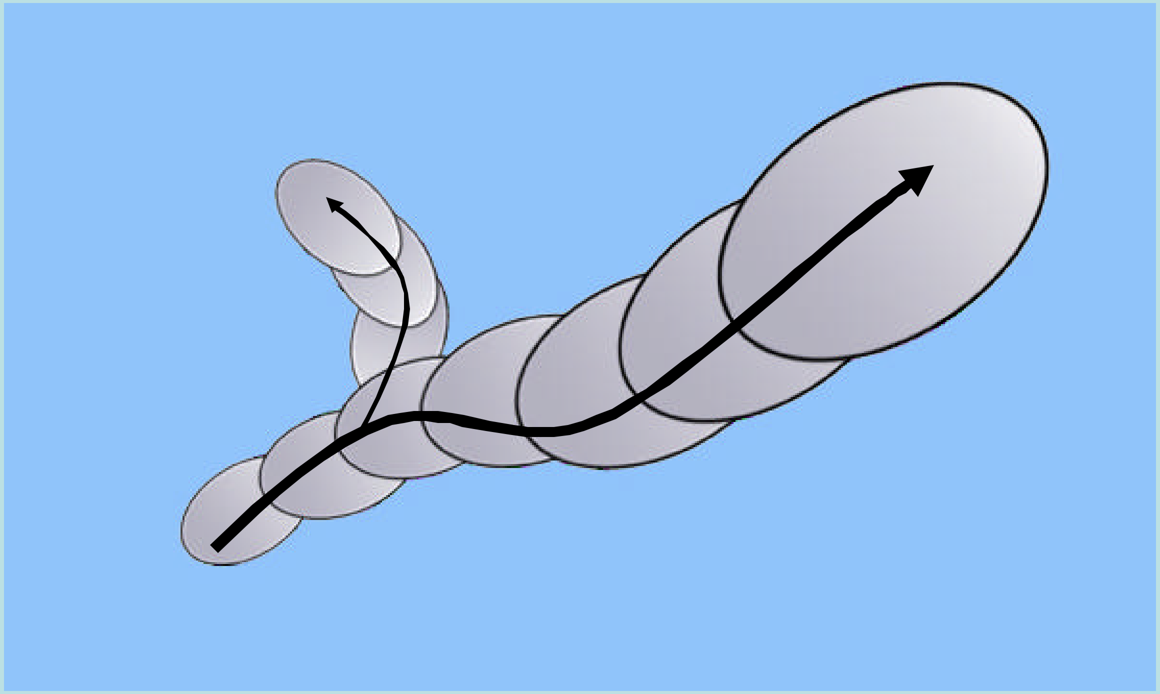
The centerline concentration also decreases.

However, the mass under the curve stays the same.



Puff Models

- A discrete volume (parcel) of air representing a nearly instantaneous emission from a source.
- Puff models track the individual puffs as the move through the model domain.



Puff Models

- Puff trajectories changes as hourly wind conditions change.
- Puffs are also typically Gaussian.
- Used where trajectory winds may change or in areas of complex terrain
- Under steady state conditions, a series of puffs simulate a continuous plume.
  - Examples: NSFpuff, CALPUFF, Bluesky

Particle Models

- Simulates motion of many particles released over the burn duration
- Track many individual particles over possible trajectories
- Some models include atmospheric diffusion for particle meandering
- Used for smoke movement and trajectory analyses.
- Examples: PB-Piedmont, HY-Split

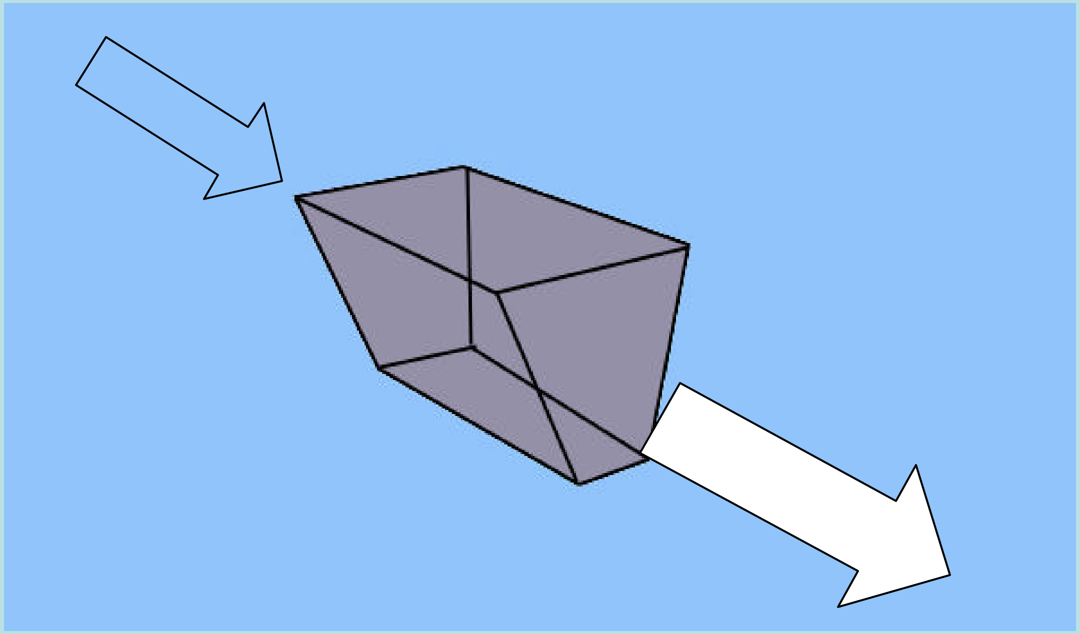
Grid/Box Models

- The atmosphere is modeled as a set of interconnected boxes through which air flows.
- For each time step, the mass of air entering the a grid or box is balanced by the mass of air leaving.
- Mixing is assumed to be complete and instantaneous within each box

Simple Box Model

Simple Box Models (e.g., VALBOX) are used to model valley flows.

- Valley drainage is modeled as a set of interconnected boxes through which air flows only up or down the valley
- Air flow is based on wind speed
- Air buoyancy and its relationship to temperature and relative humidity is ignored



Grid Models

- Grid Models (e.g., CMAQ, CAMx) simulate the troposphere in the context of "one" atmosphere perspective where the complex interactions between atmospheric pollutants and atmospheric processes are modeled on regional and urban scales.
- These models solve the pollutant and air mass continuity equations in a system of three-dimensional grids.
- These systems are used address tropospheric ozone, secondary fine particulate formation, acid deposition, visibility, and other air pollutant issues.

Grid Models

- Very data intensive – Gridded wind fields and source characterization
- Very resource intensive – typically run for episodes.
- Very complex – research style model

Overview of Dispersion Models

Indexes

•Ventilation Index (VI)

• Atmospheric Dispersion Index (ADI)

Plume Models

•SASEM

•VSMOKE

•VSMOKE-GIS

•ISCST/AERMOD

Puff Models

•CALPUFF

•SIS

•BlueSky

•NSFpuff

Particle Models

•HY-Split

•PB-Piedmont

Box Model

•VALBOX

Grid Models

•CMAQ/Models3

•CAMx

Model Applications

- Plume models appropriate for:
  - Relatively flat terrain
  - When input data are scarce
  - Easy to setup and run for single unit
  - Evaluating concentrations “near” a source (0 to 50 km)
- Puff models appropriate for:
  - Flat and complex terrain
  - Modeling discrete sources in a larger domain
  - Variable weather
  - Short and long-range transport (0 to ~400 km)

Model Application (cont'd.)

- Particle Models appropriate for:
  - Tracking pollution "signatures"
  - Trajectory analyses
- Grid Models appropriate for:
  - Relatively large domain
  - Modeling many sources
  - Applicable to fully integrated "one" atmosphere impacts like regional haze or ozone
  - Data and resource intensive to run.

Summary of Smoke and Dispersion Modeling Tools

Summary of Modeling Approaches				
Approach	**Type**	**Model**	**Terrain**	**Emissions Model**
VI	Index	Index	None	None
ADI	Index	Index	None	None
ValBox	Screening	Box Model	Valley	EPM,SASEM
SASEM	Screening	Plume	Flat	SASEM,EPM
SIS	Screening	Puff	Flat, Semi-Complex	FOFEM, CONSUME
NSFpuff	Screening	Puff	Flat, Complex	EPM
VSMOKE	Screening	Plume	Flat	Internal
CALPUFF/CALMET	Refined	Puff	All	User Specified
Bluesky (CALPUFF)	Refined	Puff	All	EPM, CONSUME
	(Centralized)			
PB-Piedmont	Refined	Particle	Flat	No
HY-SPLIT	Refined	Particle	All	No
	(Centralized)			
CMAQ/CAMx	Refined	Eulerian Grid	All	User Specified

Summary of Smoke and Dispersion Modeling Tools

Approach	Met data type	Concentrations?	Ease of Use
VI	WS, MH	No	1
ADI	WS, MH	No	1
ValBox	WS, MH	Yes	2
SASEM	24-hr values	Yes	2
SIS	daytime/nightime user defined	Yes (1-hr; 24-hr)	2
NSFpuff	User defined, forecast	Yes	2
VSMOKE	User defined	Yes	3
CALPUFF/CALMET	MM5, NWS, or user defined	Yes	4
Bluesky (CALPUFF)	MM5 (centralized)	Yes	3
PB-Piedmont	Single site	No	4
HYSPLIT	Mesoscale Winds	Yes	4
CMAQ/CAMx	MM5	Yes	5

Web-Based Modeling Systems

- Web-based modeling systems are becoming more common.
  - HY-Split
    - Forward and back trajectories
    - Concentration estimates

    http://www.arl.noaa.gov/ready/hysplit4.html
  - On-Line Smoke Simulations (e.g., BlueSky)

    The BlueSky smoke prediction system (Ferguson et al. 2001; O'Neill et al. 2003) is an automated centralized framework for predicting cumulative concentrations of smoke from wildland and agricultural fire.

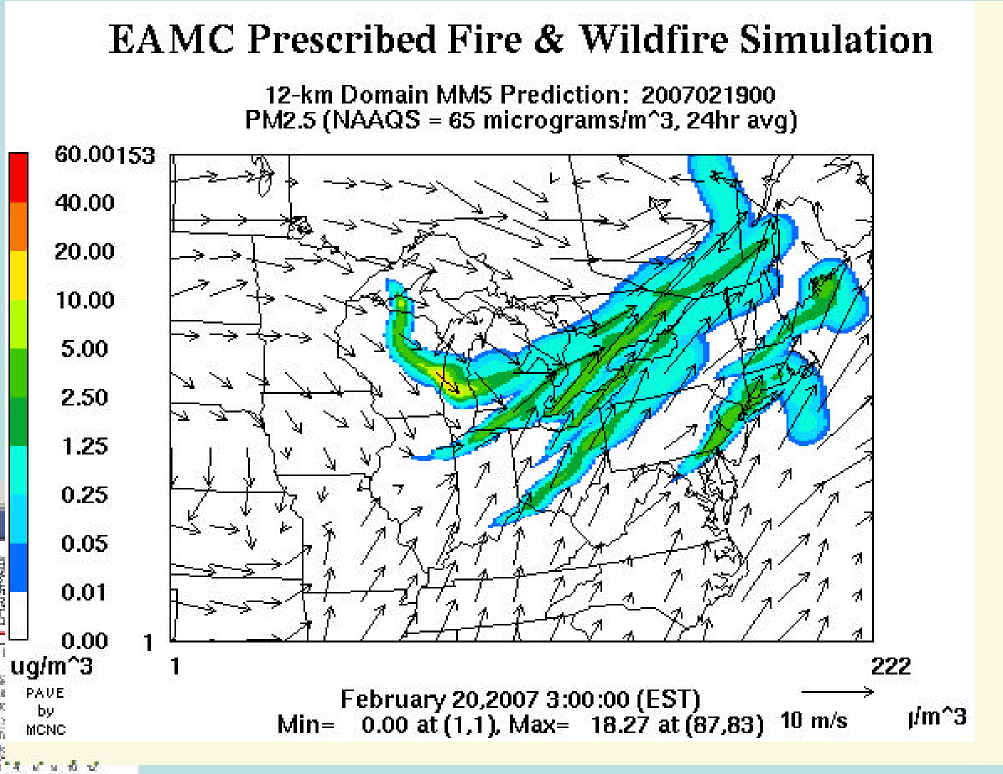
    http://www.airfire.org/bluesky/index.html

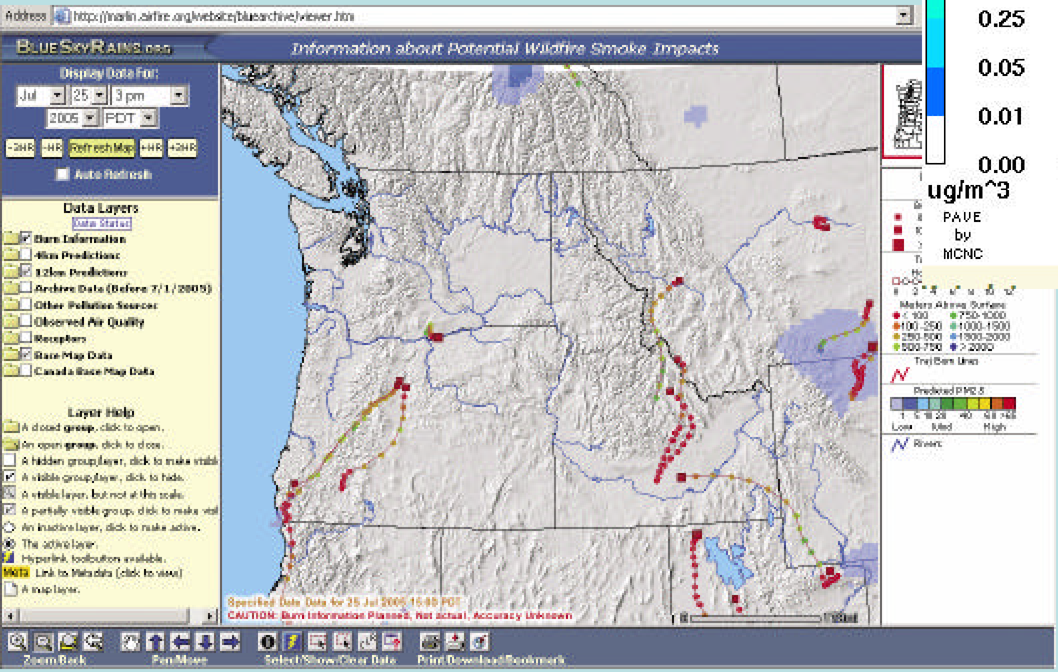
    http://www.blueskyrains.org/

On-Line Smoke Simulations (BlueSky)

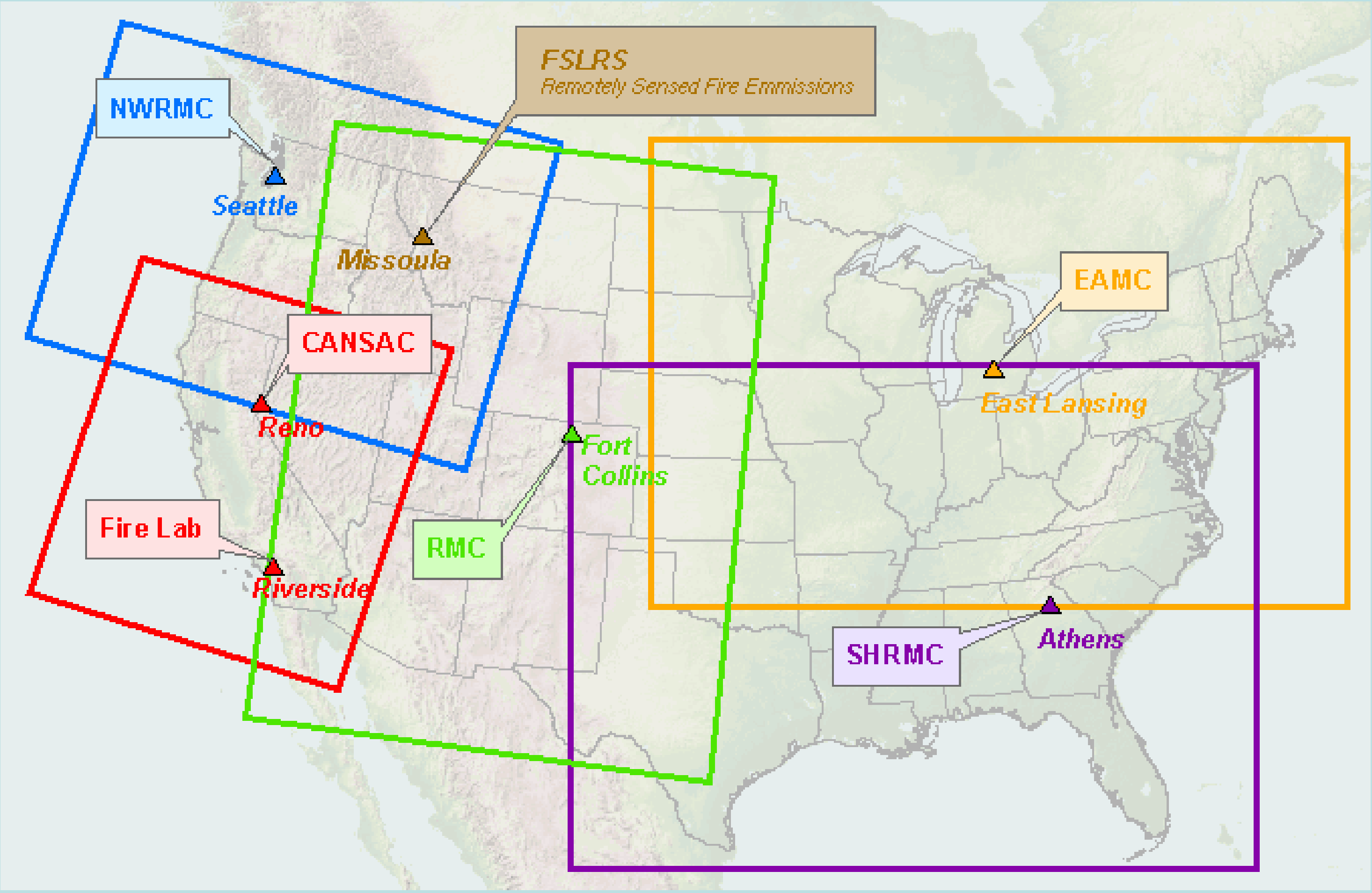
- In BlueSky, fire emission estimates are obtained through the coupling of CONSUME and EPM with real-time fire activity reports.
- Real-time estimates and forecasts of smoke impacts for active smoke management programs are generated through the integration of the high-resolution mesoscale meteorological model MM5 with EPM and the dispersion model CALPUFF.

Smoke Simulations Examples





Smoke Simulation Regions



Regions Status

Domain	Resolution	Forecast period	FCAMMS	Station	Wildfire	Prescribed burning	Agricultural fire	RAINS	In operation since
Northwest	12 km 4 km	72 hrs 48 hrs	NWRMC	PNW	X X	X X	X X	X X	2002
California/Nevada	4 km	48 hrs	CANSAC	PSW	X	M	—	*	2004
Northeast	12 km	48 hrs	EAMC	NCRS	X	M	—	*	2004
Rocky Mountain	12 km 8 km	48 hrs	RMC	RMRS	X X	M	— —	*	2004
Southeast	12 km	48 hrs	SHRMC	SRS	X	M	—	*	2006
West (demo)	36 km 12 km	48 hrs	NWRMC/RMC	RMRS/PNW	X X	M	— —	X X	Operated in 2005

FCAMMS = Fire Consortia for the Advanced Modeling of Meteorology and Smoke.
X = in operation.
— = not yet available.
M = manual only.
* = implementation of RAINS is in progress as of June 2006.
FCAMMS information: http://www.fs.fed.us/fcamms/
BlueSky information: http:///www.fs.fed.us/bluesky/
Contact: Dr. Allen Riebau, USDA Forest Service National Program Leader for Atmospheric Science Research, 703-605-5280, ariebau@fs.fed.us.

Fall, 2006

On to the Hands-ON