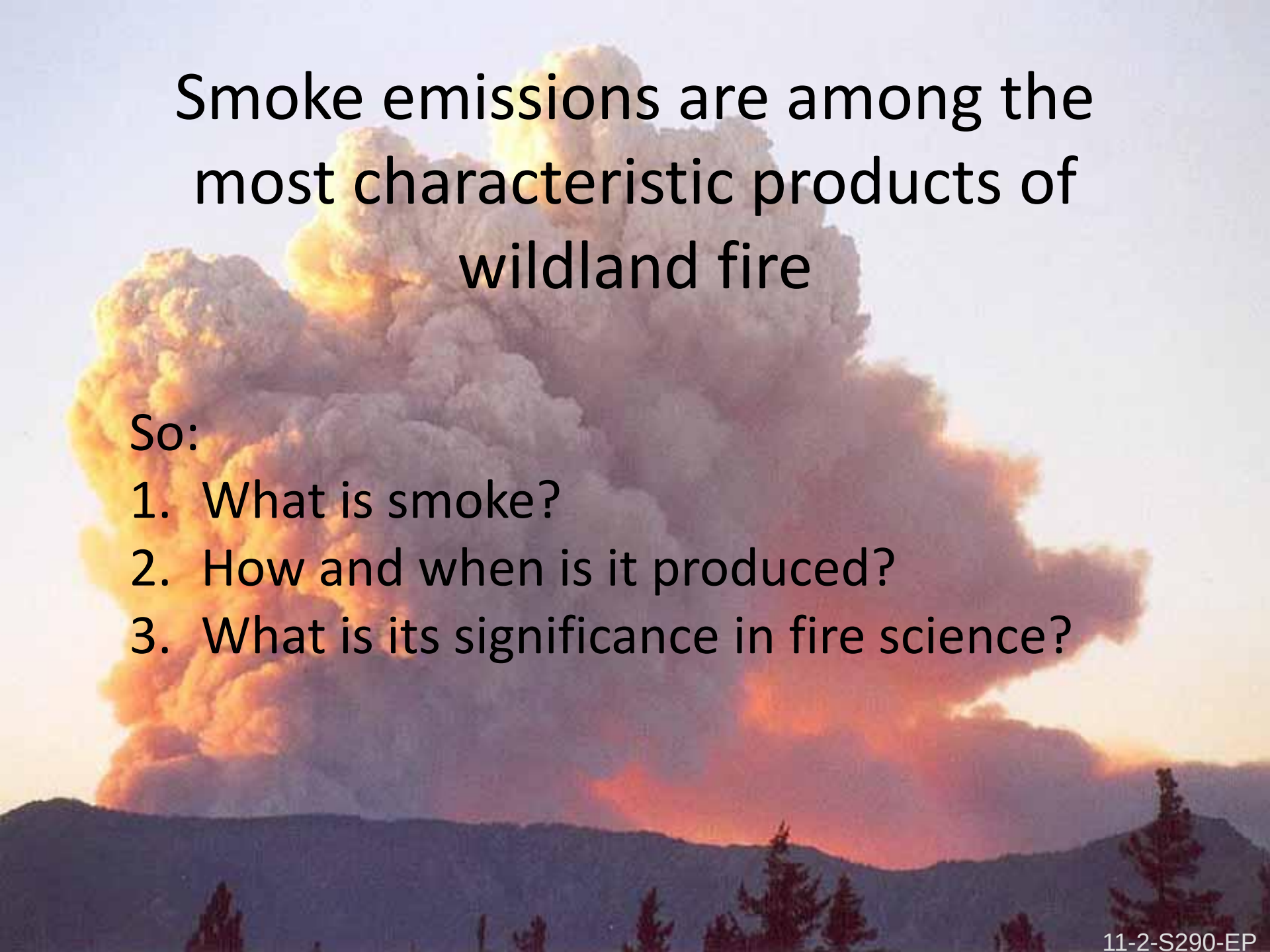
Lec. 1.5: Where there's fire, there's smoke



Smoke emissions are among the most characteristic products of wildland fire

So:

1. What is smoke?
2. How and when is it produced?
3. What is its significance in fire science?

Recall your basic combustion chemistry:

Oxidation of the cellulose component (which is mainly what burns in biomass) in a pure oxygen environment looks like this:

$4C_6H_9O_4 + 25O_2 \rightarrow 24CO_2 + 18H_2O$ + ~5.2 MkJ energy released

This is complete combustion: all of the reactants have been converted to CO_2, H_20, and energy

Recall: Composition of vegetative biomass (e.g. wood and grasses)

- Live, sound wood composed of 40-55% cellulose
- Smaller fractions of
  - hemicellulose (15-25%)
  - lignin (16-30%)
  - extractives (10-45%)
  - water
  - other components

Recall the stages of combustion
Phase I: Pre-heating (pre-ignition)

- Fuels ahead of the fire are pre-heated by convection and radiation
- Dehydration: Water is driven out of the fuel (so fuels become drier) ~ 100° C
- Volatiles (extractives) evaporate into gas phase
- *Pyrolysis* of solid fuels ~ 325° C
- These reactions are mostly *endothermic*

Phase II: Gas (ignition) phase

- Volatiles generated in Phase I (by evaporation and pyrolysis) ignite and oxidize
- This is when we start to see *flames*
- Phase II is *exothermic* – chemical bond energy is being released
- Wildland fire temperatures typically 350-1000^{o}C
- H_2O and CO_2 released as by-products
- Time ~ minutes

Phase III: Smoldering phase

- After the volatiles have ignited, what's left?
  - Un-pyrolized wood, esp. lignin component
  - Char
  - Tar
- Lower temperatures (300 – 400° C)
- Surface oxidation, heat travels by conduction (think of a glowing log)
- Time ~ hours to months!

So: Do we get complete combustion in a wildland setting?

- Temperatures may not be high enough to pyrolyze all fuel components
  - Some, like lignin, need higher temperatures

- Fuels may not be completely dry
  - This means that some energy is used to evaporate water, which may not occur completely

- Oxygen may circulate poorly in some fuel beds
  - E.g. dense litter or duff

In practice, complete combustion rarely occurs in wildland fire settings

- Combustion reactions come to equilibrium before complete combustion occurs
- Wide variety of compounds are present, including carbon dioxide, carbon monoxide, and pure carbon (soot or ash).
- Combustion in atmospheric air (recall 78 % N), will also create nitrogen oxides, especially > 1500 ^{o}C.

Some of the main combustion reactions:

$CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O$

$2\ CH_4 + 3\ O_2 \rightarrow 2\ CO + 4\ H_2O$

$N_2 + O_2 \rightarrow 2\ NO$

$N_2 + 2\ O_2 \rightarrow 2\ NO_2$

Combustion efficiency

Simply put, the carbon released in combustion compared to the total carbon contained in the fuel:

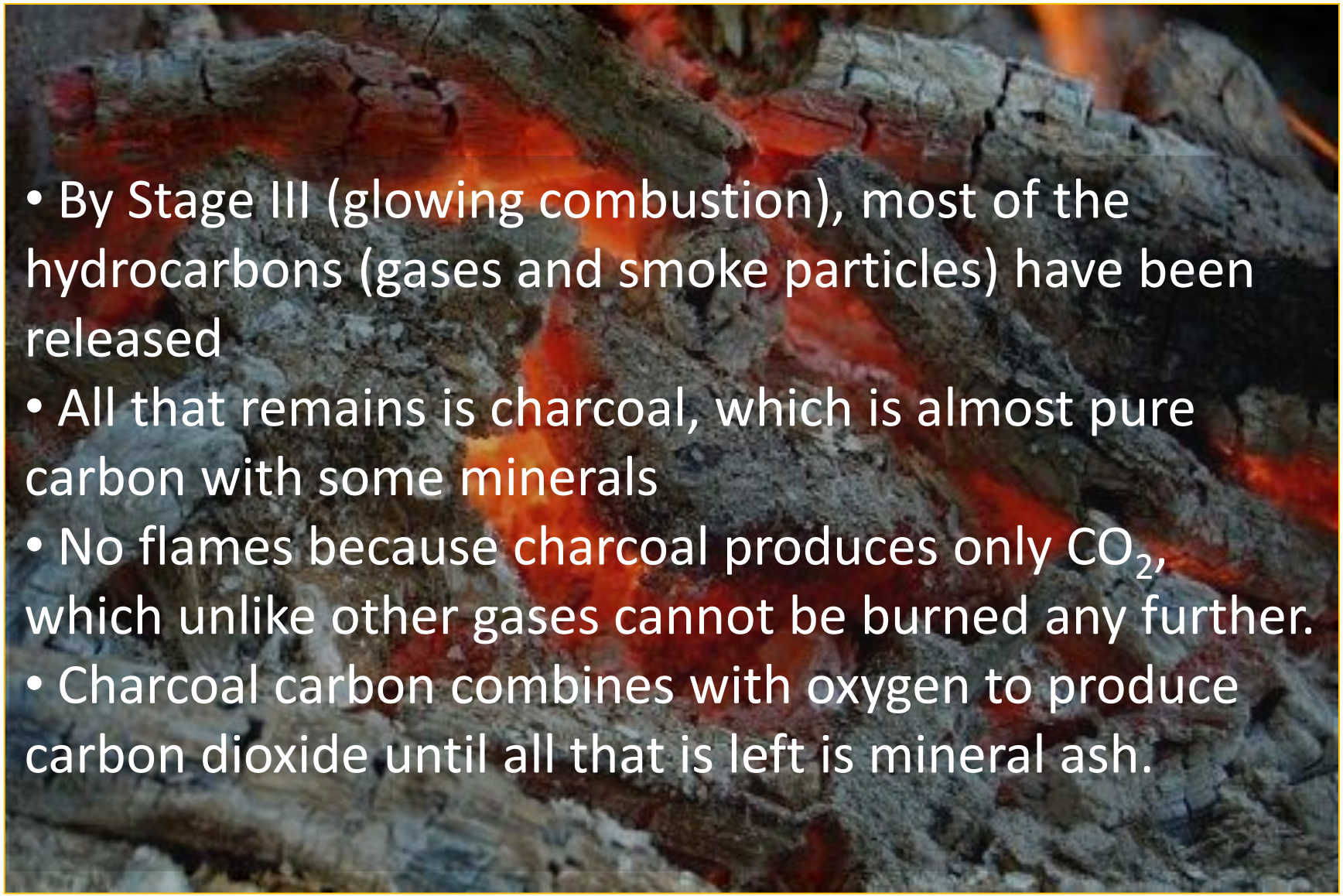
$$\frac{\text{C emitted}}{\text{C total in fuel}}$$

Wildland fire CE: typically <50%

- Highest in flaming combustion with high temperatures and good ventilation

  Lowest at lower temperatures or where oxygen is limiting

Surprisingly, pure surface glowing combustion produces less smoke than flaming combustion

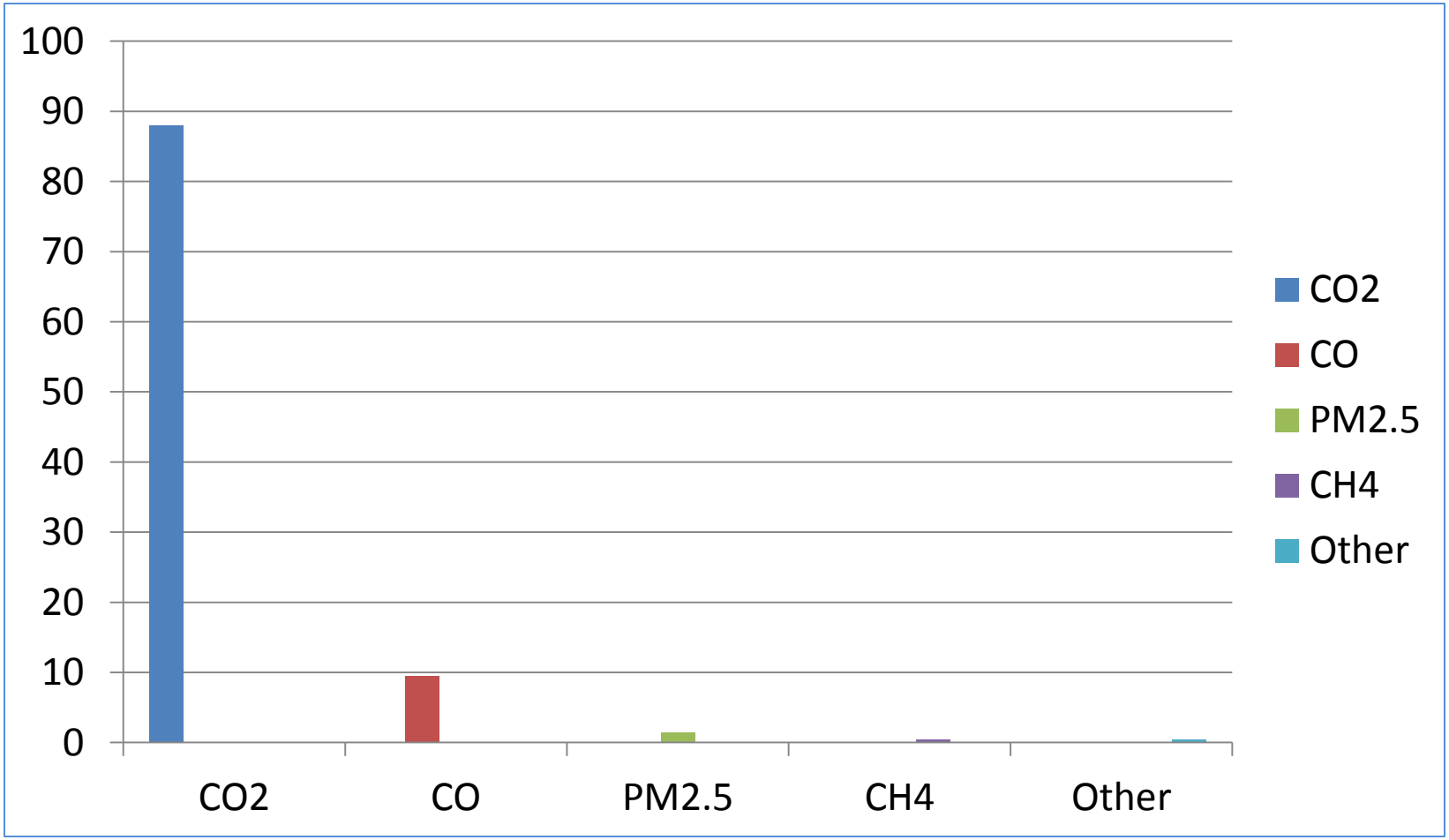


- By Stage III (glowing combustion), most of the hydrocarbons (gases and smoke particles) have been released
- All that remains is charcoal, which is almost pure carbon with some minerals
- No flames because charcoal produces only CO_2, which unlike other gases cannot be burned any further.
- Charcoal carbon combines with oxygen to produce carbon dioxide until all that is left is mineral ash.

What happens to the burned and unburned material?

- Products of both complete and incomplete combustion released to the air as smoke
- Smoke is a complex suspension of gases and particulates
- Gases include CO_2, CO, CH_4, oxides of nitrogen and sulfur
- Particulates include soot (unburned carbon) and other organic (C-containing) particles, tar
- Minerals in plant cells (Ca, K, Mg) which are non-burnable and become ash.

Typical contents of smoke from forest fires



Ward 1990

So the main gaseous products of combustion in wildland settings are:

- CO_2 (carbon dioxide)
- H_20 (water vapor)
- CO (carbon monoxide)
- PM (Particulate matter)
- HC_x (unburned hydrocarbons)
- NO_x (oxides of nitrogen)
- O_3 (ozone)

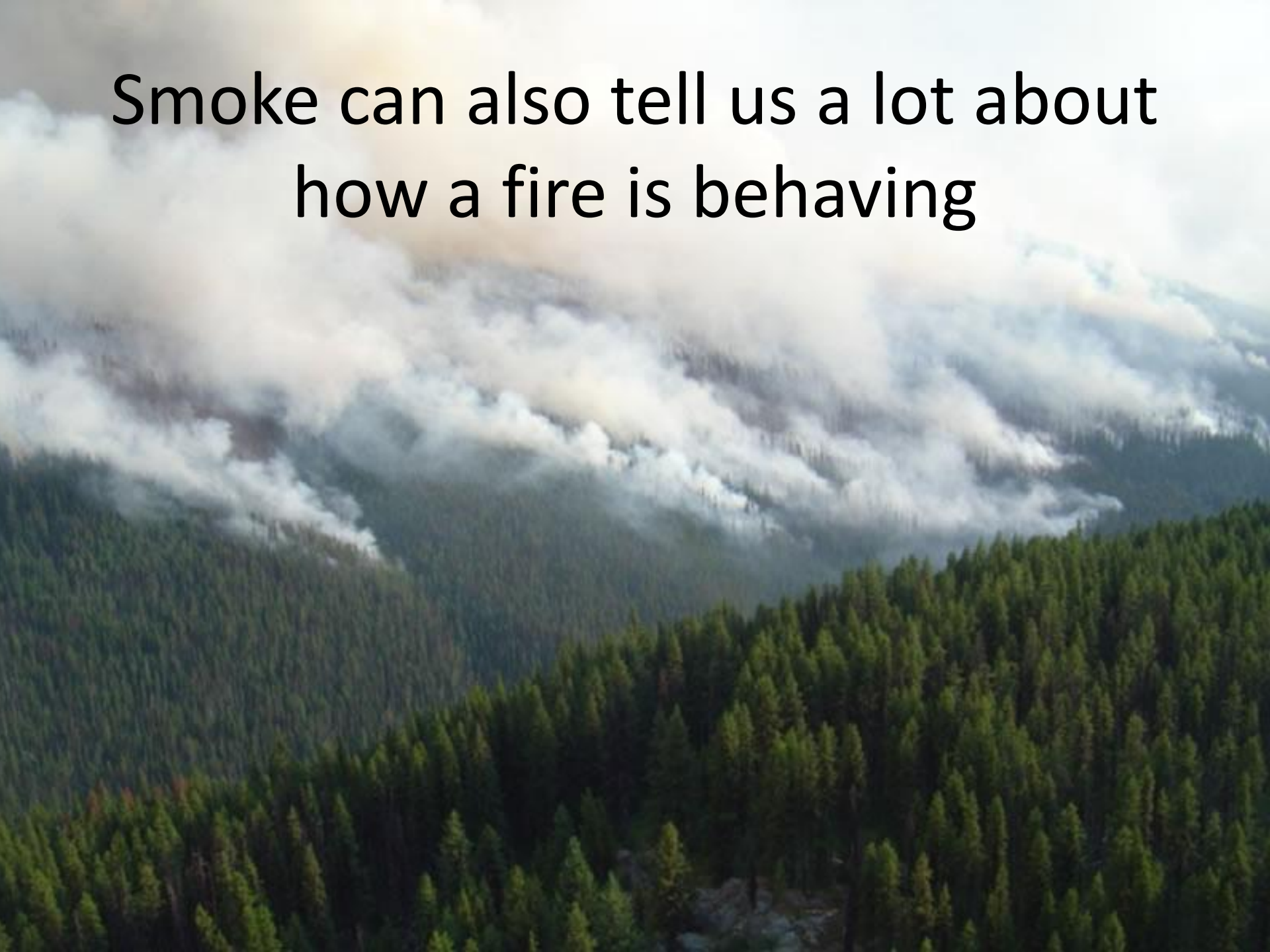
Particulate matter (PM)

- Defined as solid matter < 100 μ in diameter
- Wildland fires typically emit 5 – 50 g / kg
- Important pollutant with significant health effects
- Size classes:
  - PM_{10} = Particles < 10 μ in diameter (20% of biomass emissions)
  - $PM_{2.5}$ < 2.5 μ in diameter (70% of biomass emissions)

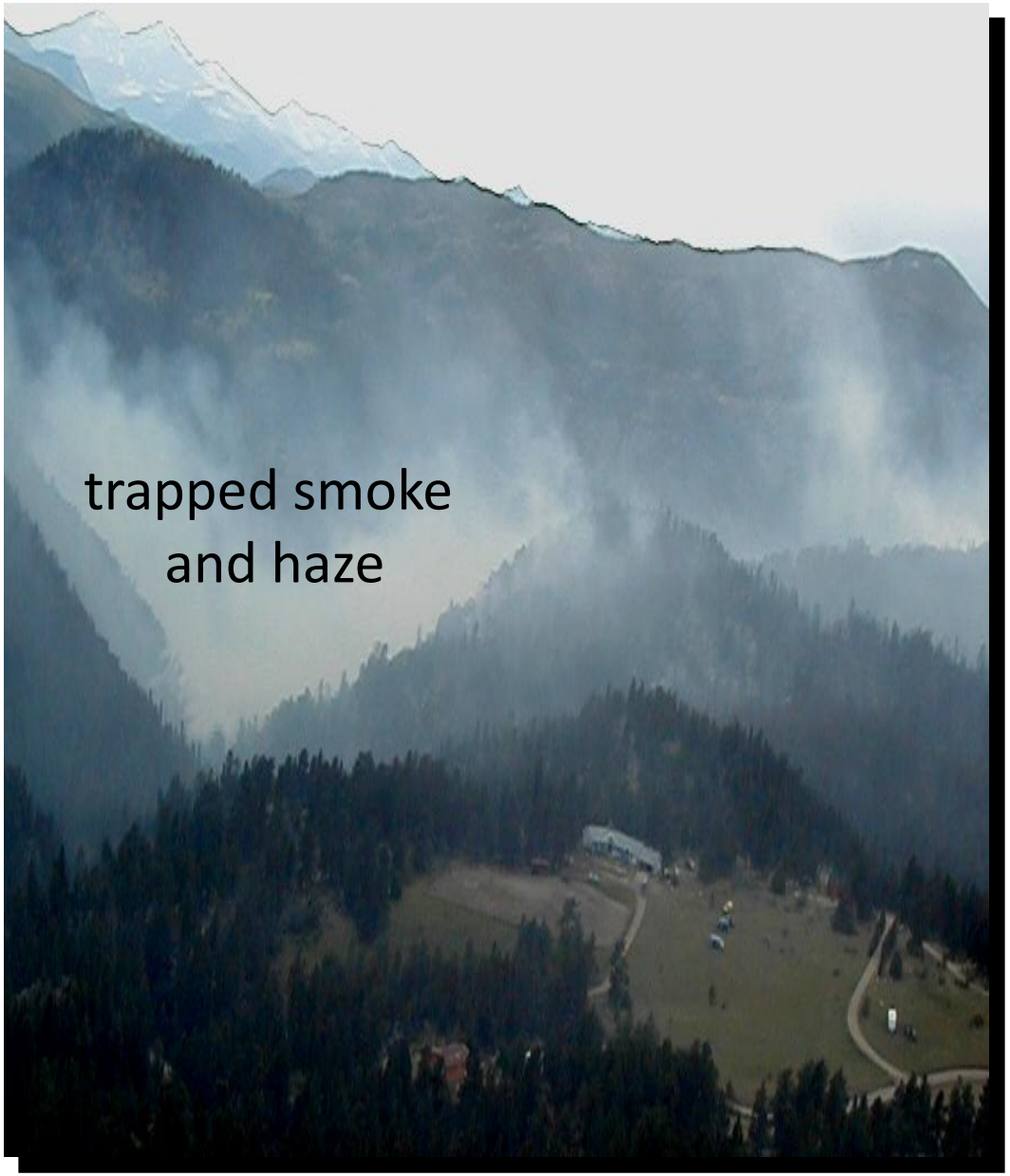
See graphic from Ottmar Rx-410 Slide 24

How do fires generate ozone?

- Wildland fires emit both nitrogen oxides (NO_x) and volatile organic compounds (VOCs)
- In the presence of sunlight, VOCs and atmospheric O_2 react with NO_2 to produce O_3, ozone ("haze")

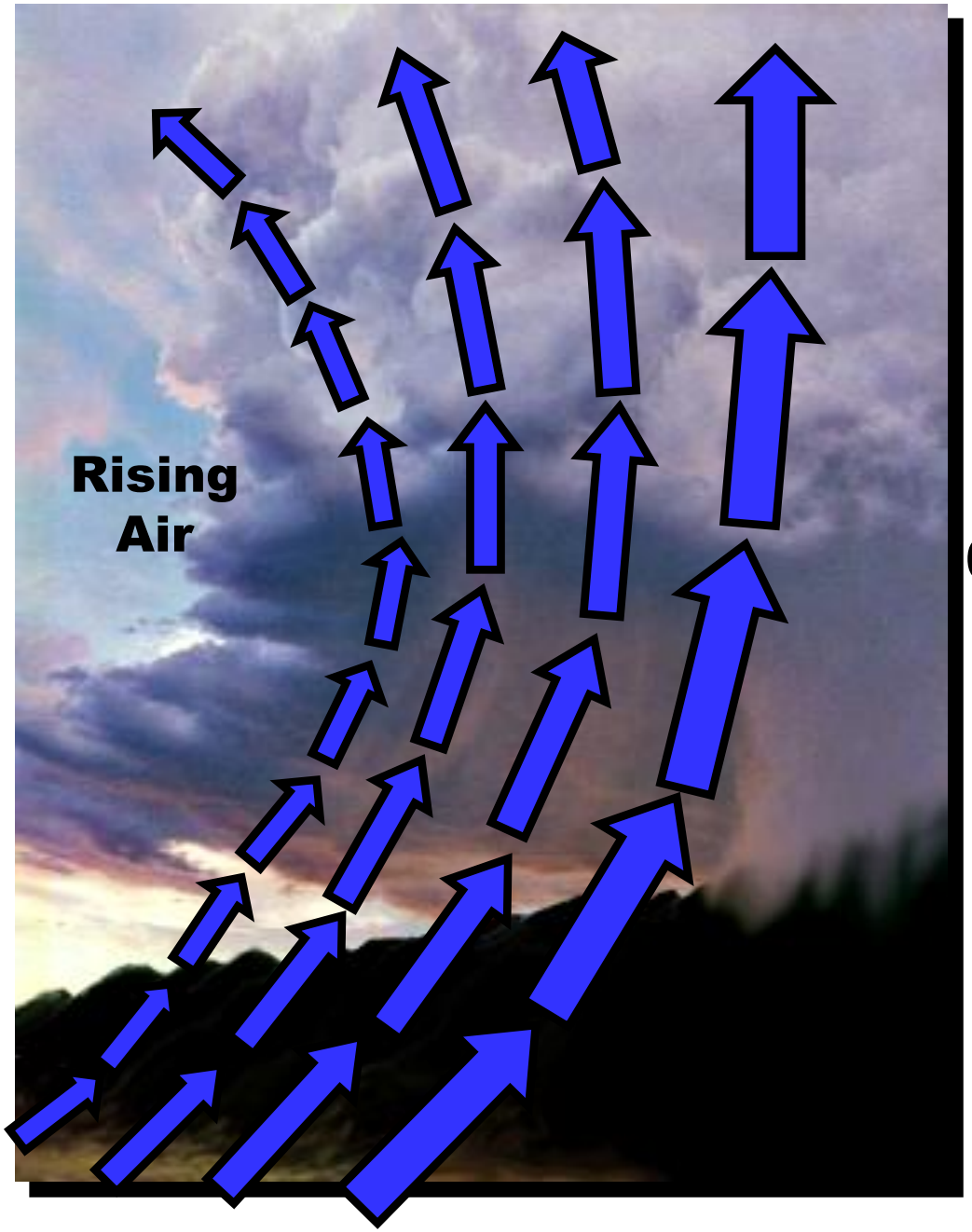


Smoke can also tell us a lot about how a fire is behaving



Stable Atmosphere

Light winds and poor smoke dispersal from poor vertical mixing



Unstable Atmosphere

Promotes the formation and growth of vertically developed clouds, thunderstorms and tall smoke columns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Plume-dominated fire

Results from convective activity of the plume

Spread rate and direction very unpredictable – plume fires “make their own weather”

When plumes collapse, strong winds can blow outward from the fire

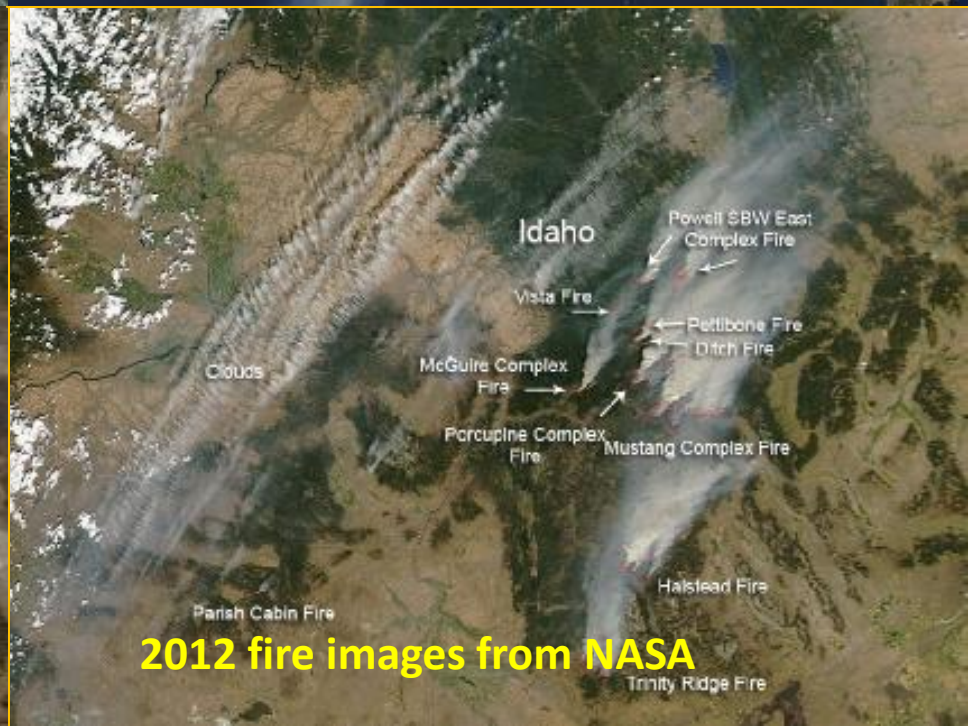
Spotting can be intense in all directions

Smoke is the mechanism for carbon emissions into the atmosphere from fires*

Globally, fire-derived releases may constitute 10-15% of all CO_2 emissions into the atmosphere

* This includes <u>all</u> biomass burning, including wildfires, wood burning for cooking and industry, clearing fields for agriculture, etc.

NASA says: “Forests and bog land in eastern Russia have been burning since the beginning of June 2012. Contributing to the record fires have been the record temperatures of this past summer. This summer in Siberia has been the hottest on record. The average temperature ranged around 93 degrees F and there doesn't seem to be any break in the weather coming anytime soon.”



2012 fire images from NASA

Next week:

- Monday: No class (Labor Day).
- Wednesday: Unit 1 Quiz. Review all lectures and readings!
- Friday: Begin Unit 2 (fire behavior). Exercise 1 due in class.