Issues of modeling fire plumes

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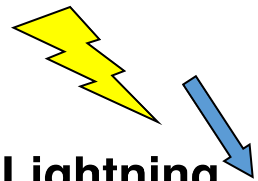
Modeling Atmospheric Chemistry

Solve continuity equation for chemical mixing ratios $C_i(x, t)$

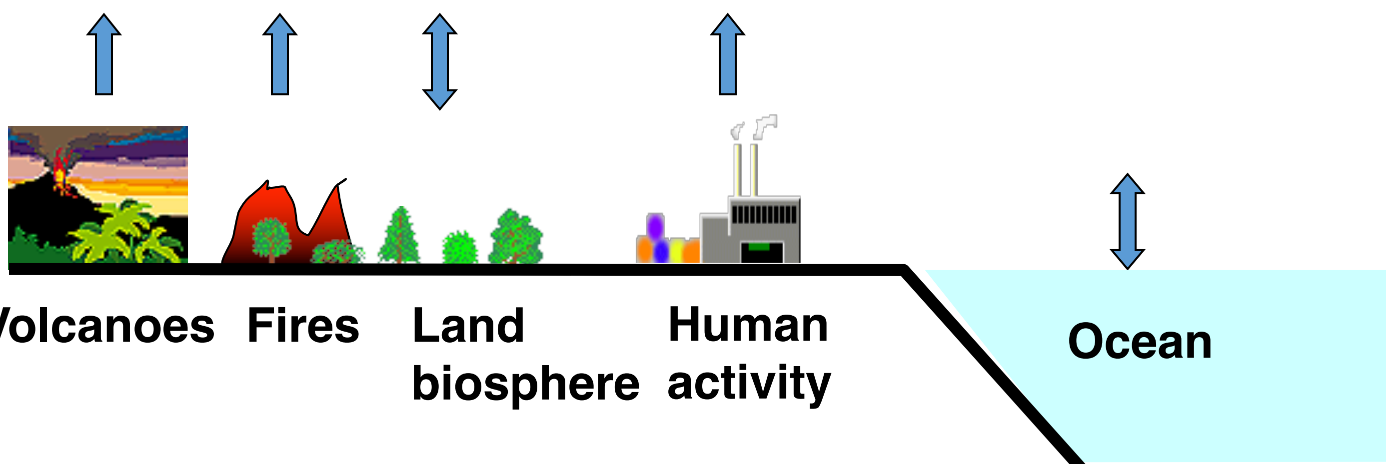


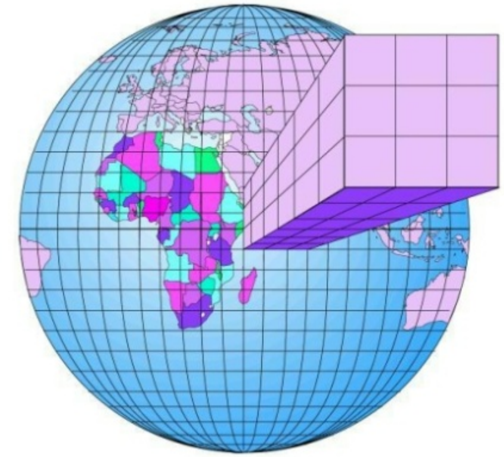
Eulerian form:

$$\frac{\partial C_i}{\partial t} = -\mathbf{U} \bullet \nabla C_i + P_i - L_i$$

Chemistry

Aerosol microphysics





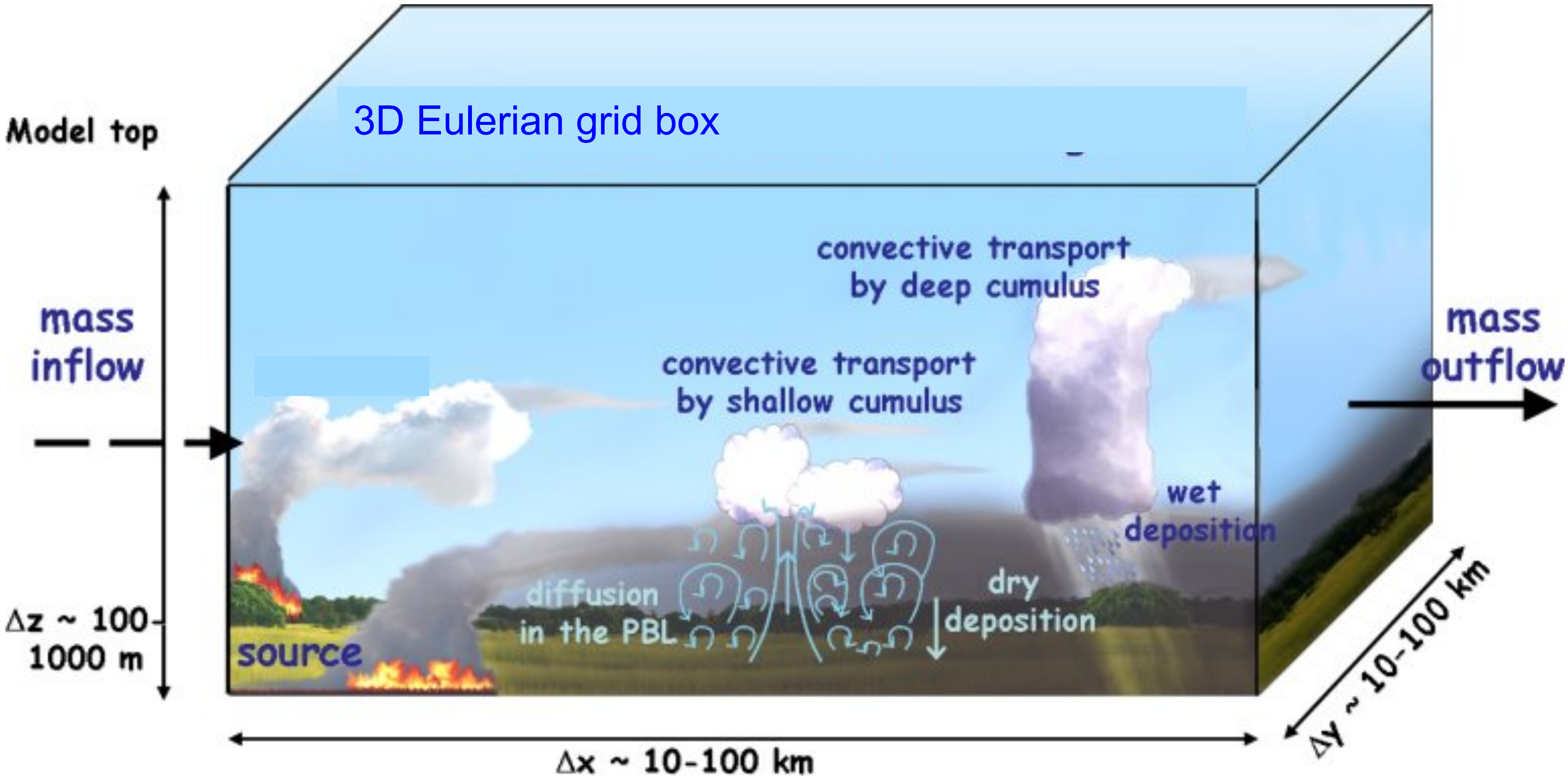
U = wind vector

P_i **= local source of chemical** i

L_i **= local sink**

C_i = "mixing ratio" (mole i / mole air)

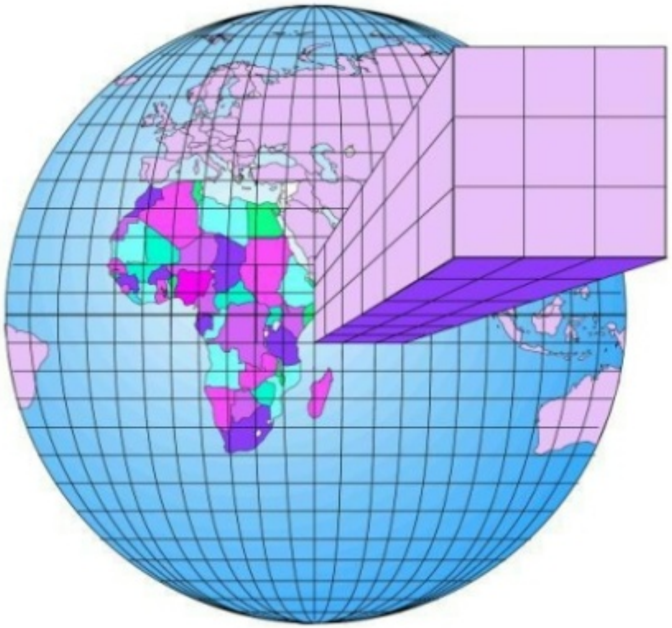
Sub-grid Processes in Gas/Aerosol Transport

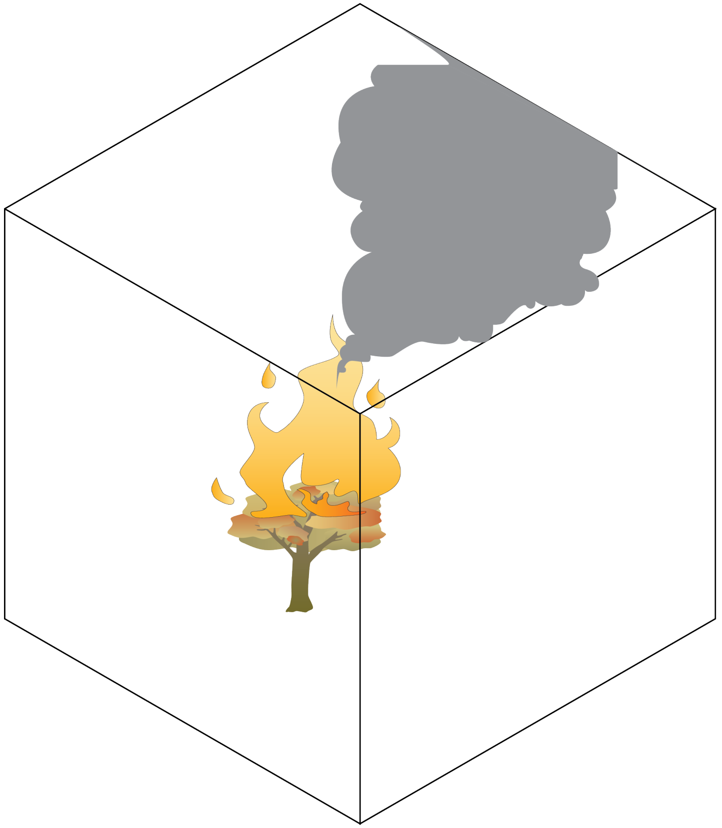


Issues in global models

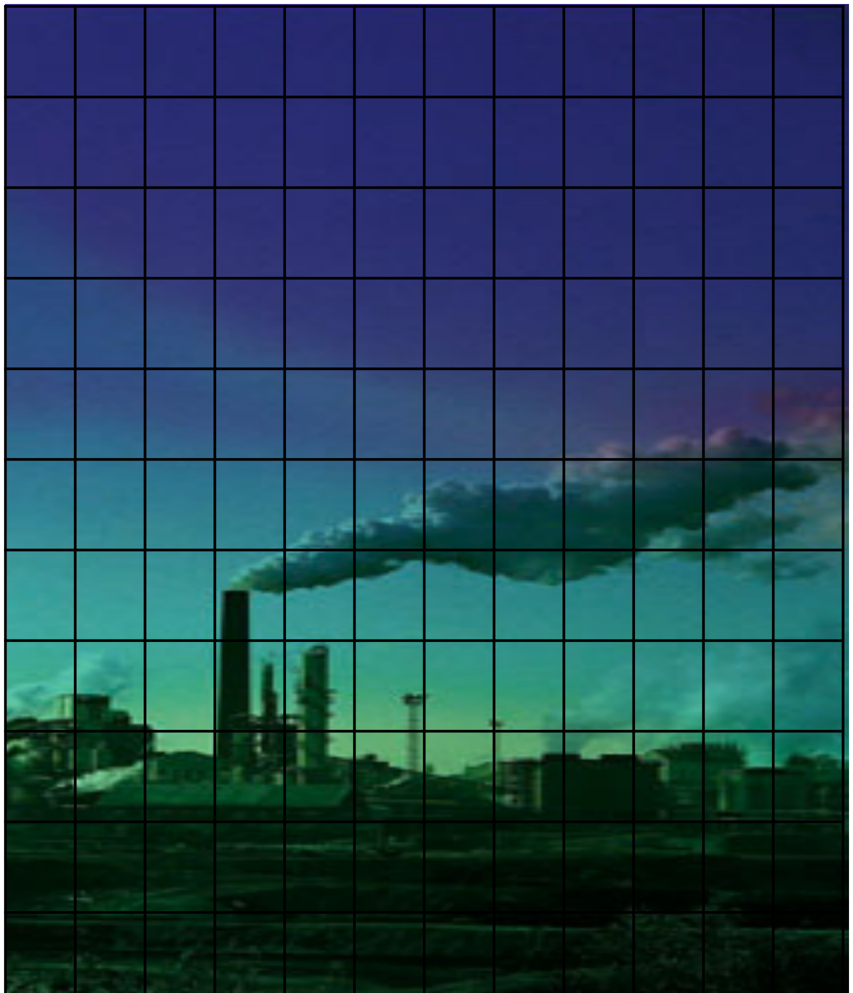
- Numerical diffusion
- Injection height
- Nonlinear chemistry
- Missing chemical compounds
- Other issues

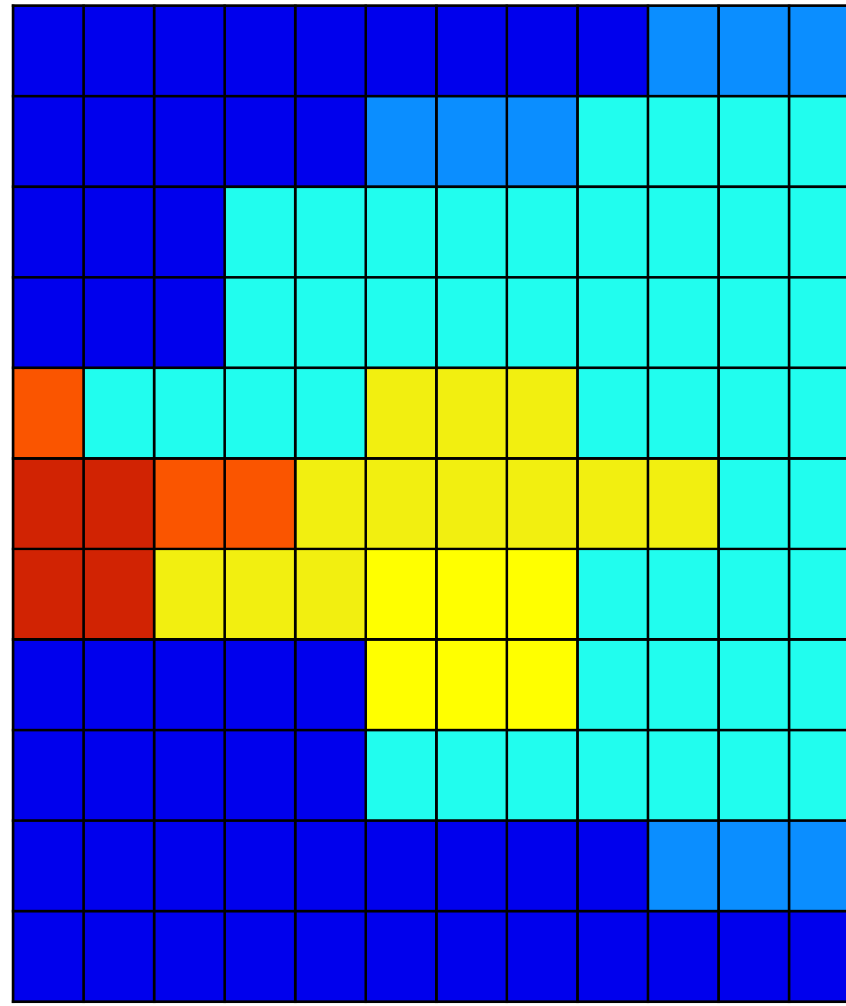
Fire plume is a sub-grid process



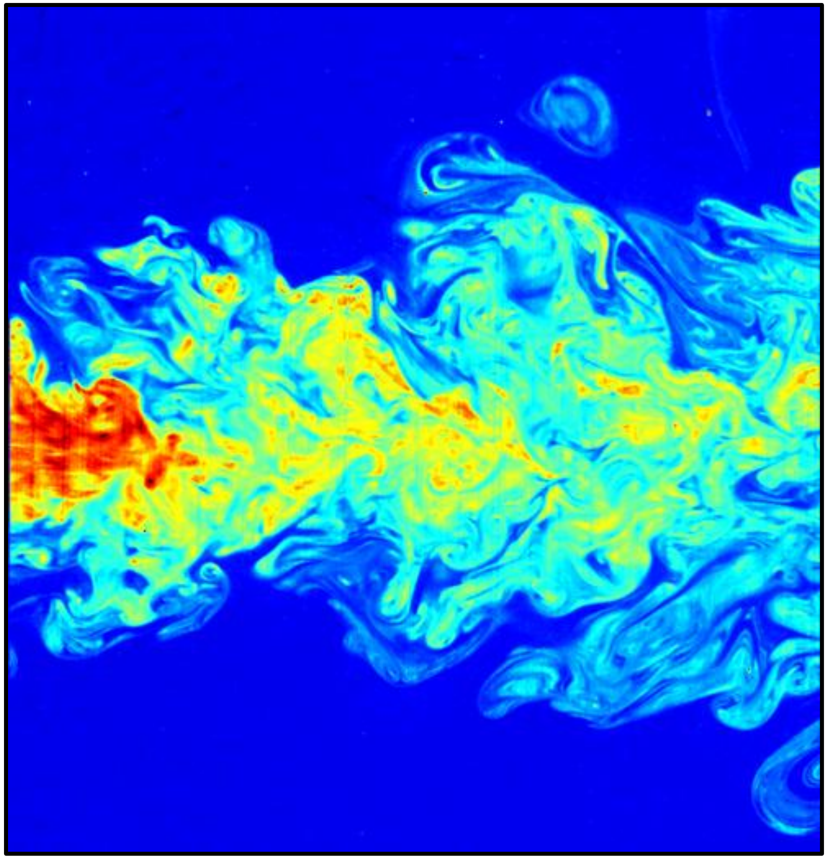


1. Numerical diffusion and stretching

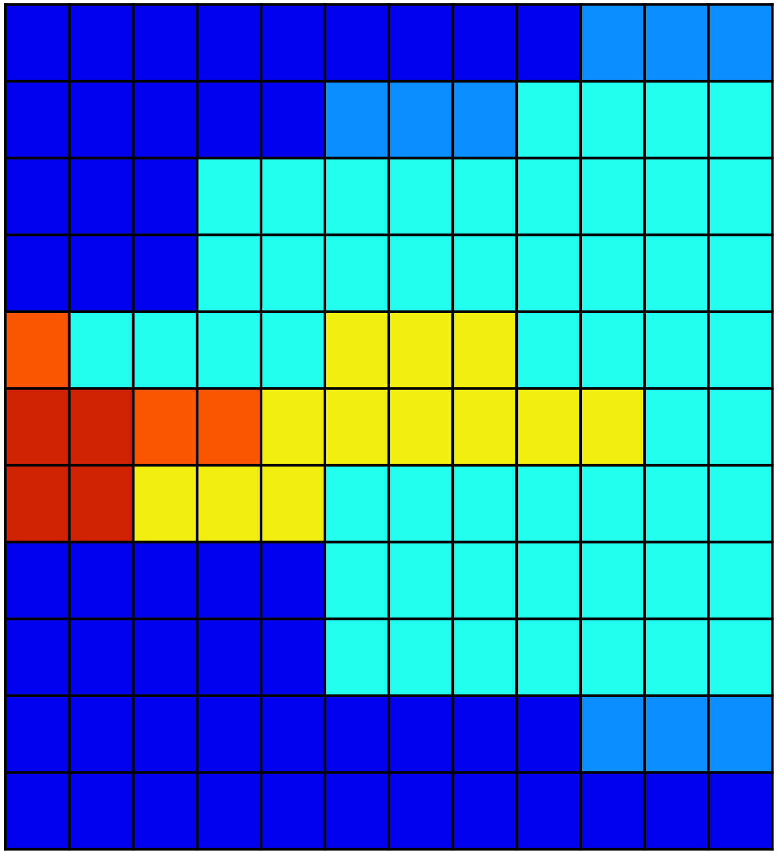




Numerical diffusion ≠ molecular diffusion

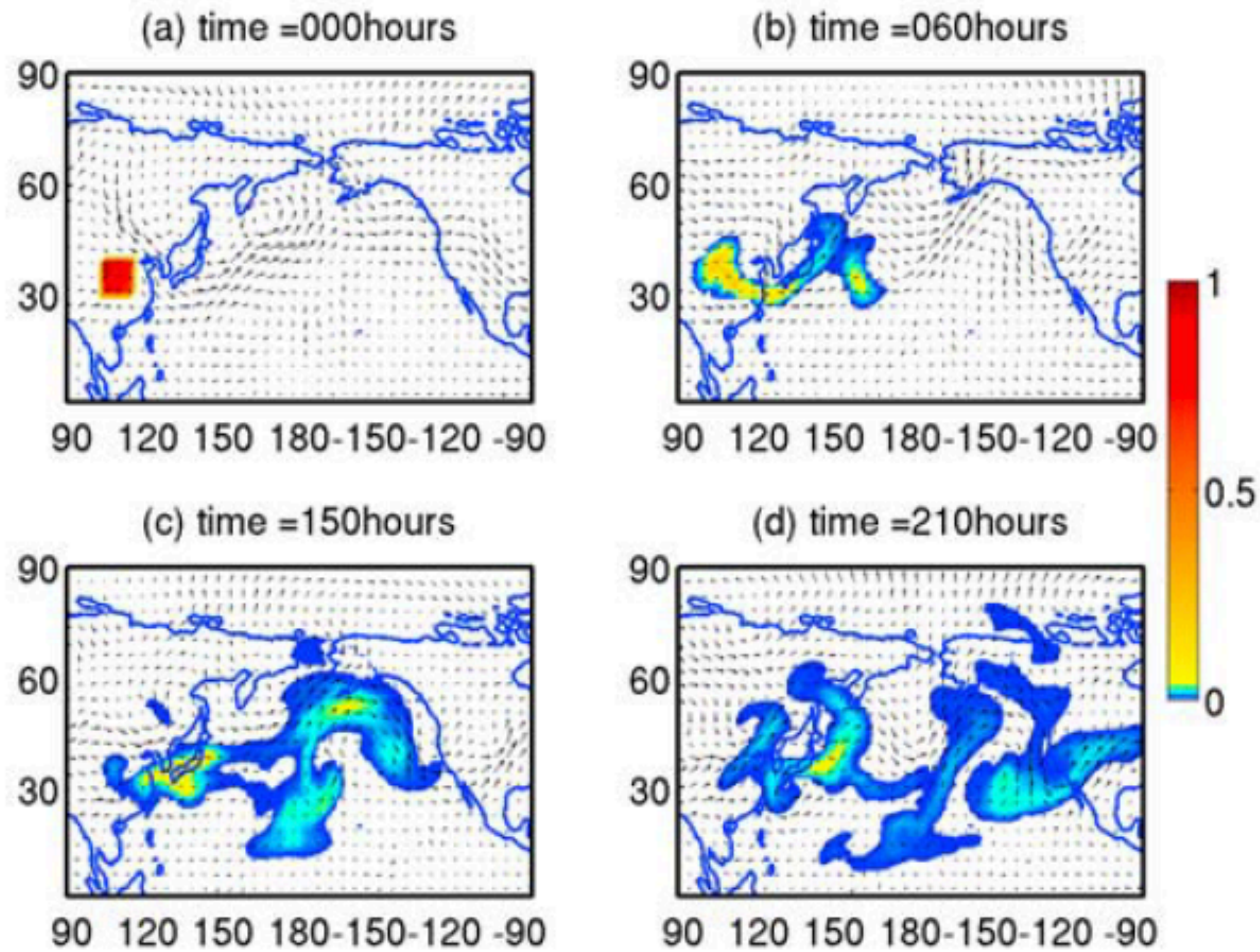


Real diffusion is **molecular** through **turbulent cascade**



Model diffusion occurs through **discretization error**

Flow stretching enhances numeric diffusion



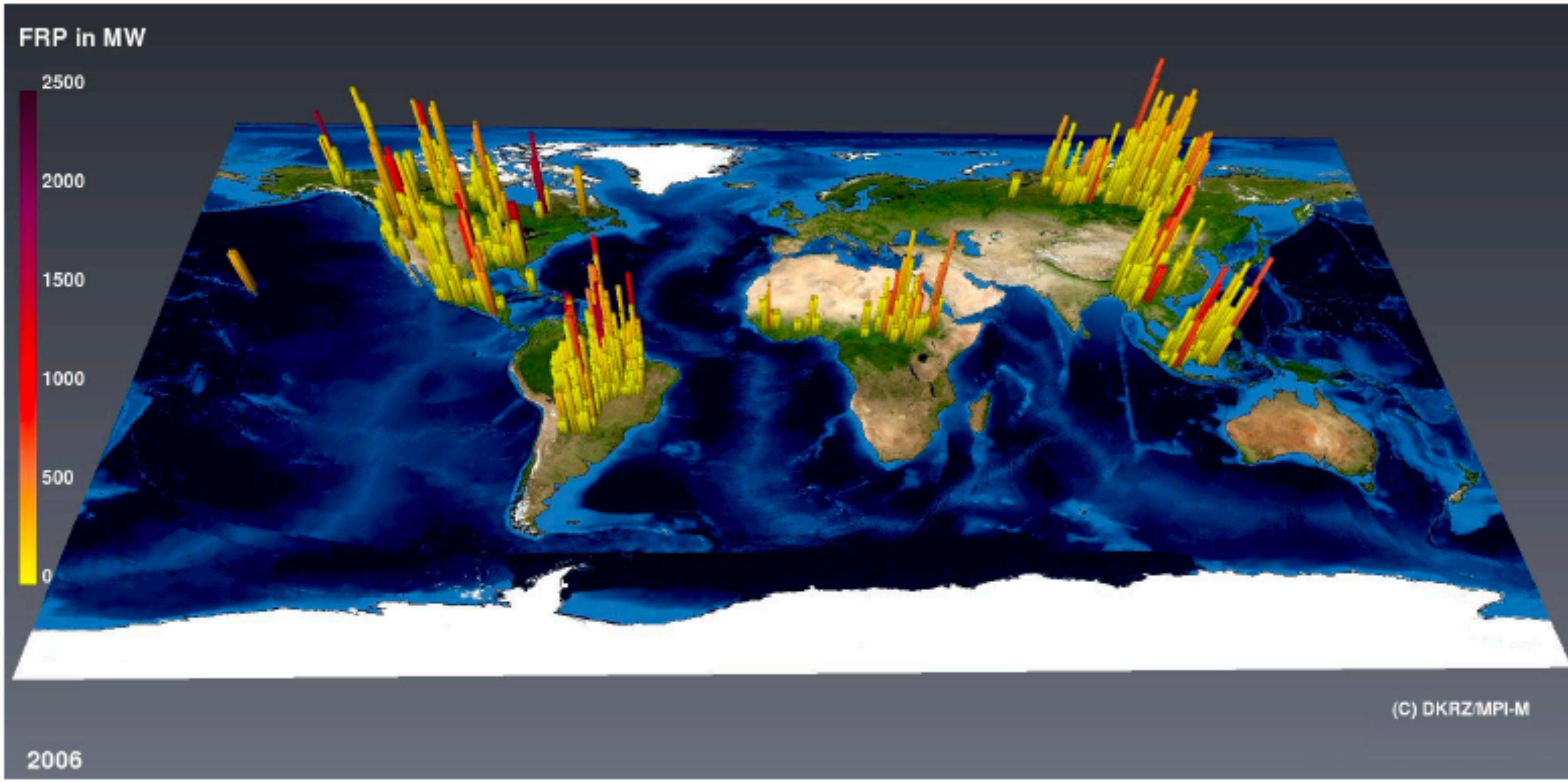
Solution: Increase horizontal resolution does NOT help much.
(Eastham et al., 2017, ACP; Rastigejev et al., 2010, JGR)

2. Injection heights of fire plumes

pyrocumulonimbus cloud
in southern Colorado

Most global models use fixed injection heights for biomass burning emissions, either in surface layer, boundary layer or a certain fraction into free troposphere.

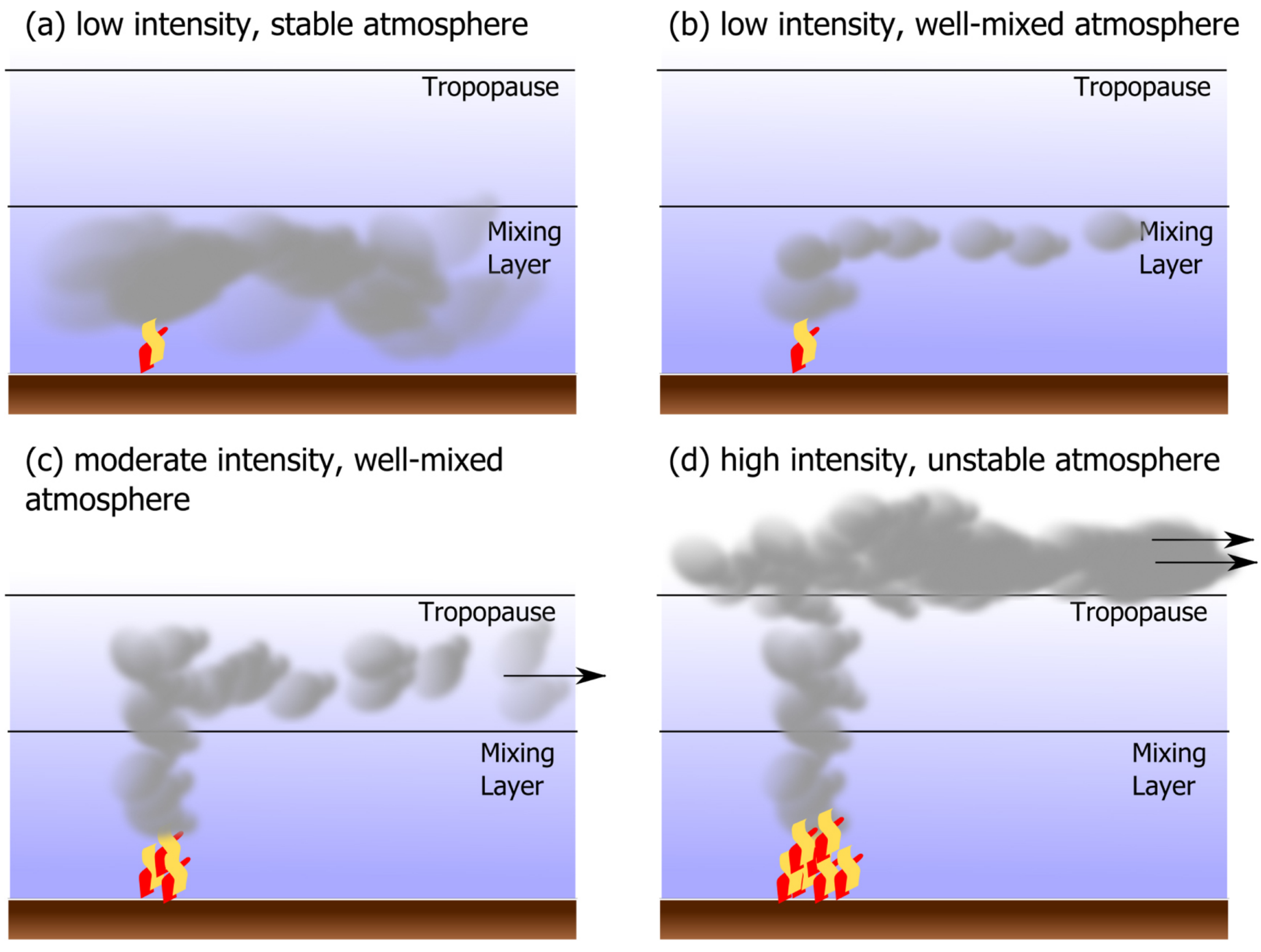
Fire injection heights derived from satellite observations



(Veira et al., ACP 2015)

Model plumes biased low due to average elevation

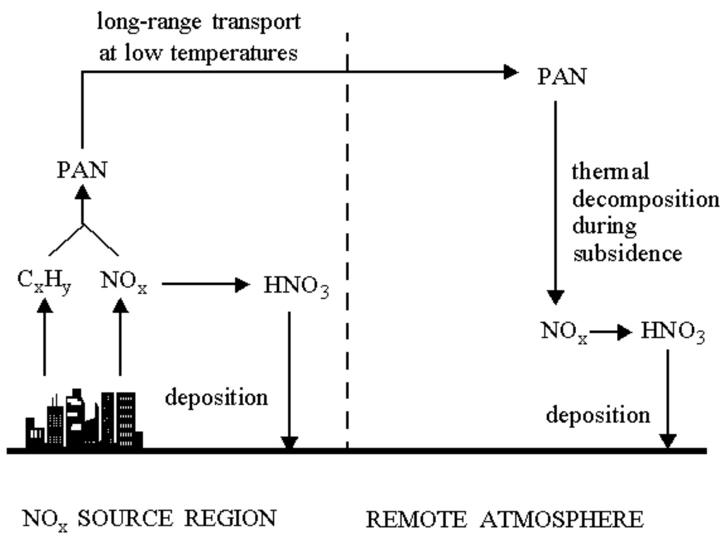
Different heights lead to different chemistry

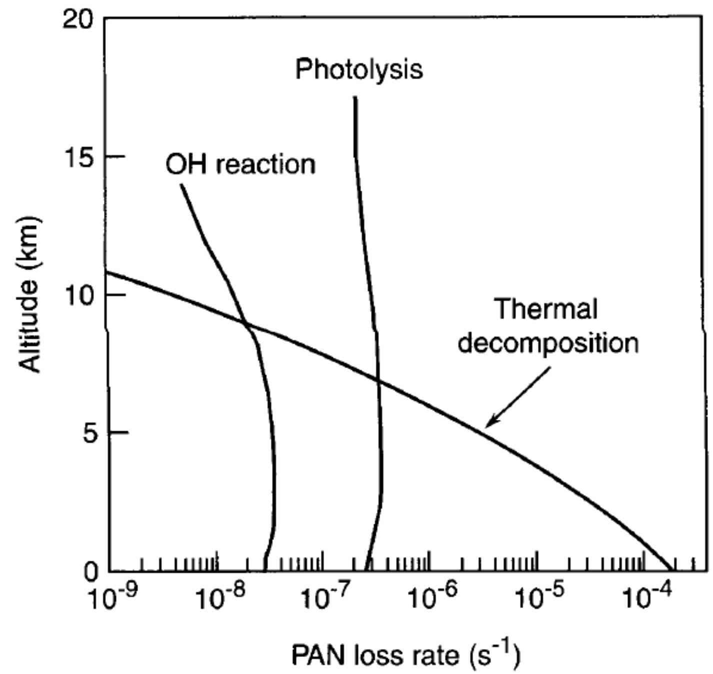


(Williamson et al., 2016, ERL)

Different heights lead to different chemistry

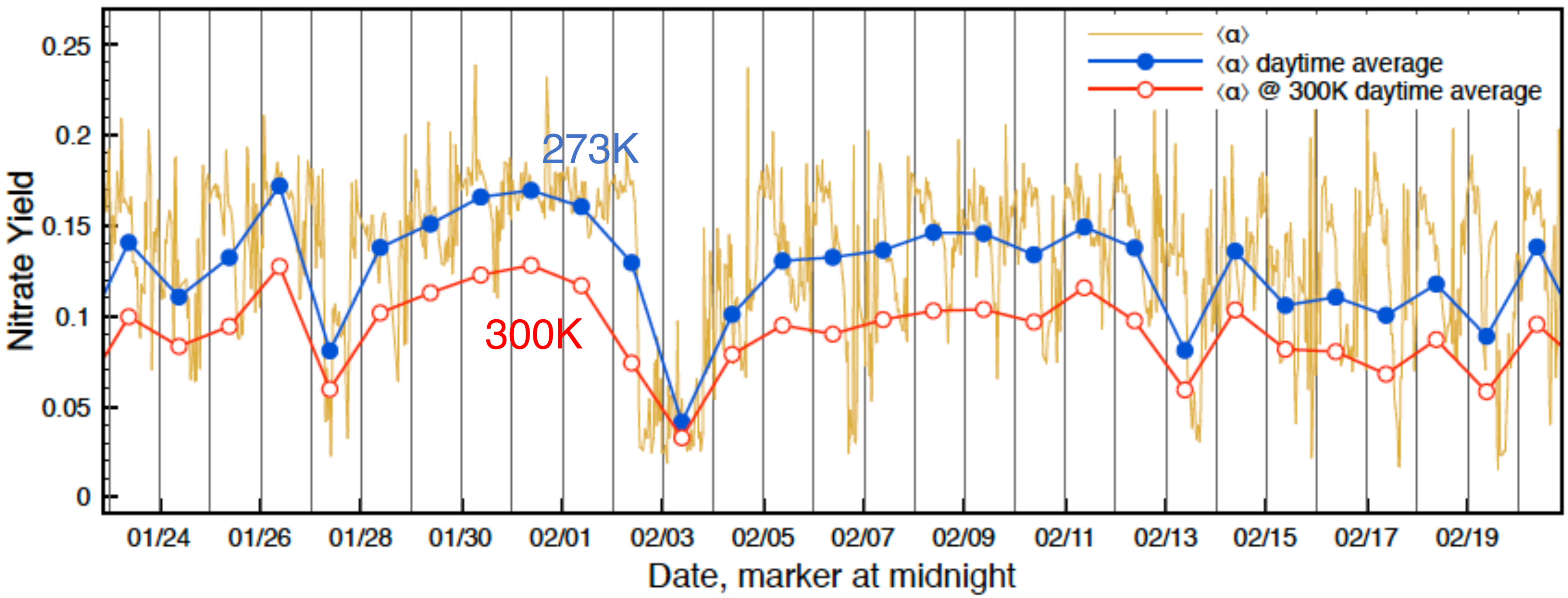
1. PAN is far more stable in free troposphere





Different heights lead to different chemistry

2. Yield of Alkyl nitrate is significantly higher at lower temperature.



None of the global models accounts for the temperature-dependence of alkyl nitrate yields.

(Lee et al., 2014, ACP)

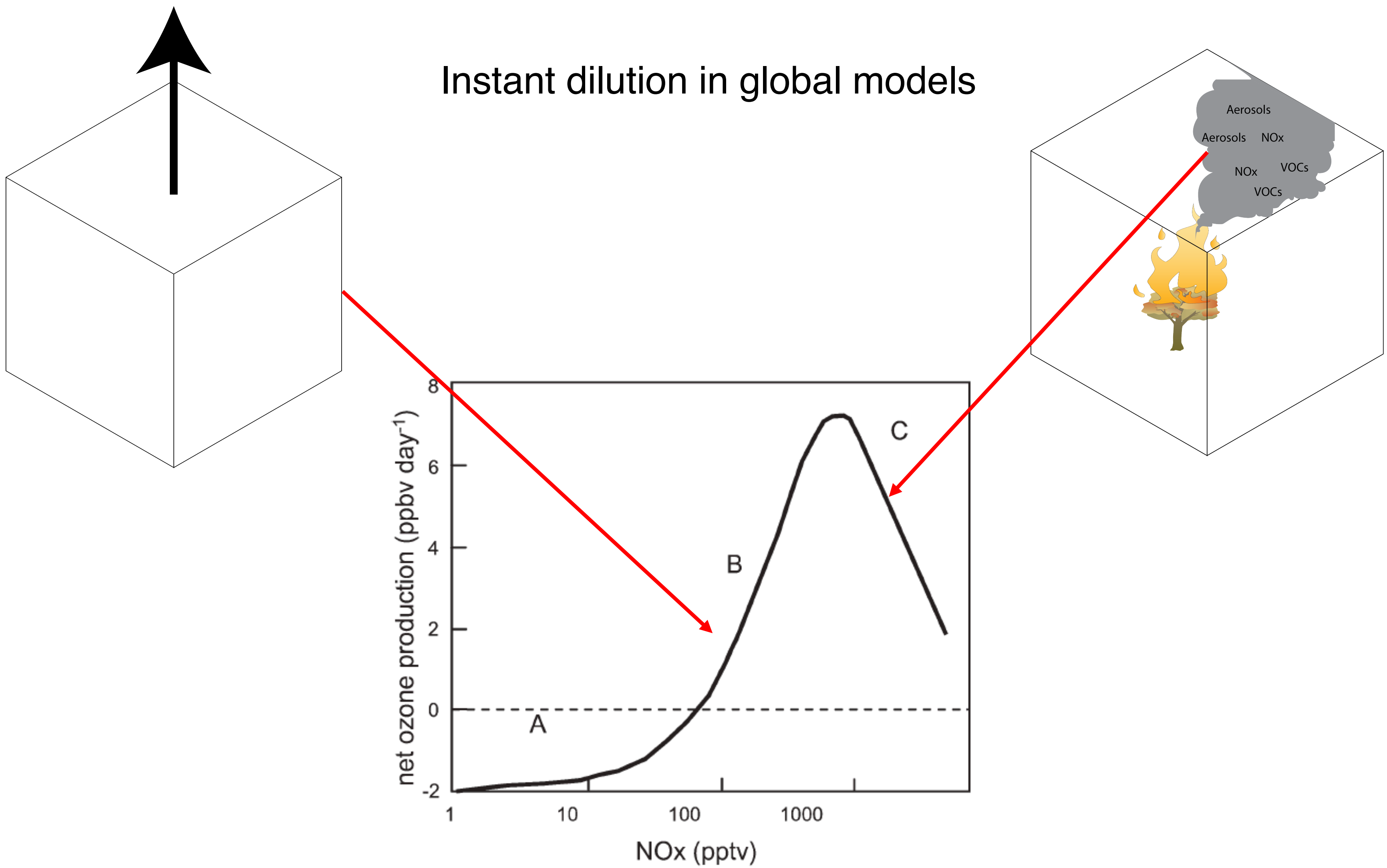
Solution

Computing injection height on-line with fire radiative power (val Martin et al., 2012, JGR; Veira et al., 2015, ACP)????

- Several studies suggest that fire radiative power may not be a good indicator (peak during smoldering Wooster et al., 2011, ACP)
- Fire radiative power may be decoupled from plume rise (Peterson, et al., 2015, BAMS).

Need better chemical kinetics at low temperature.

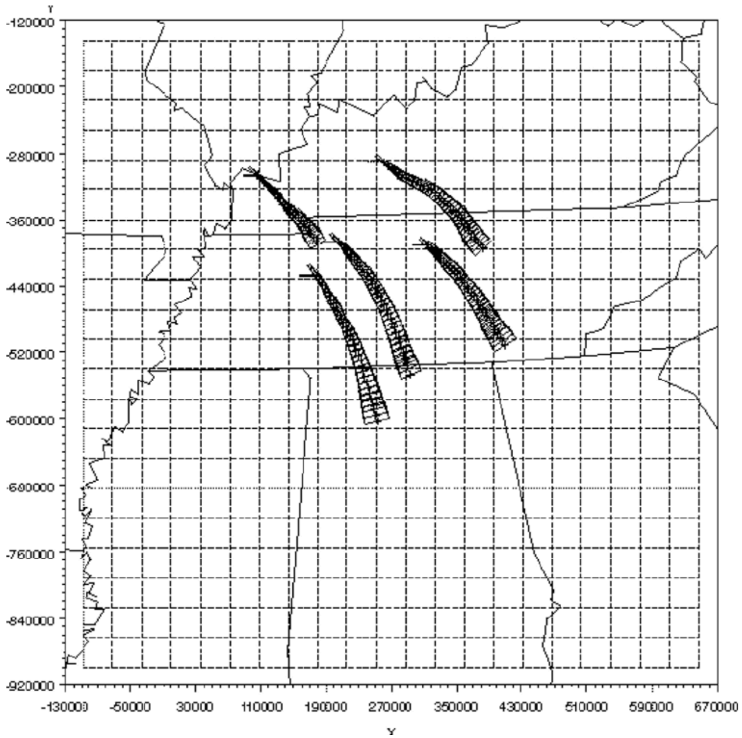
3. Nonlinear chemistry

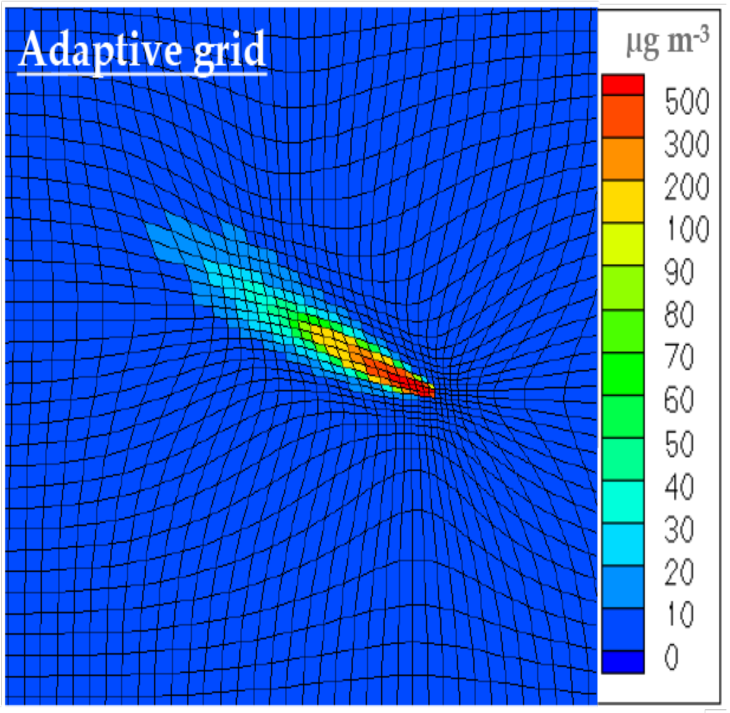


Emission fluxes in models will be evenly distributed in a gridbox, leading to different ozone production rate.

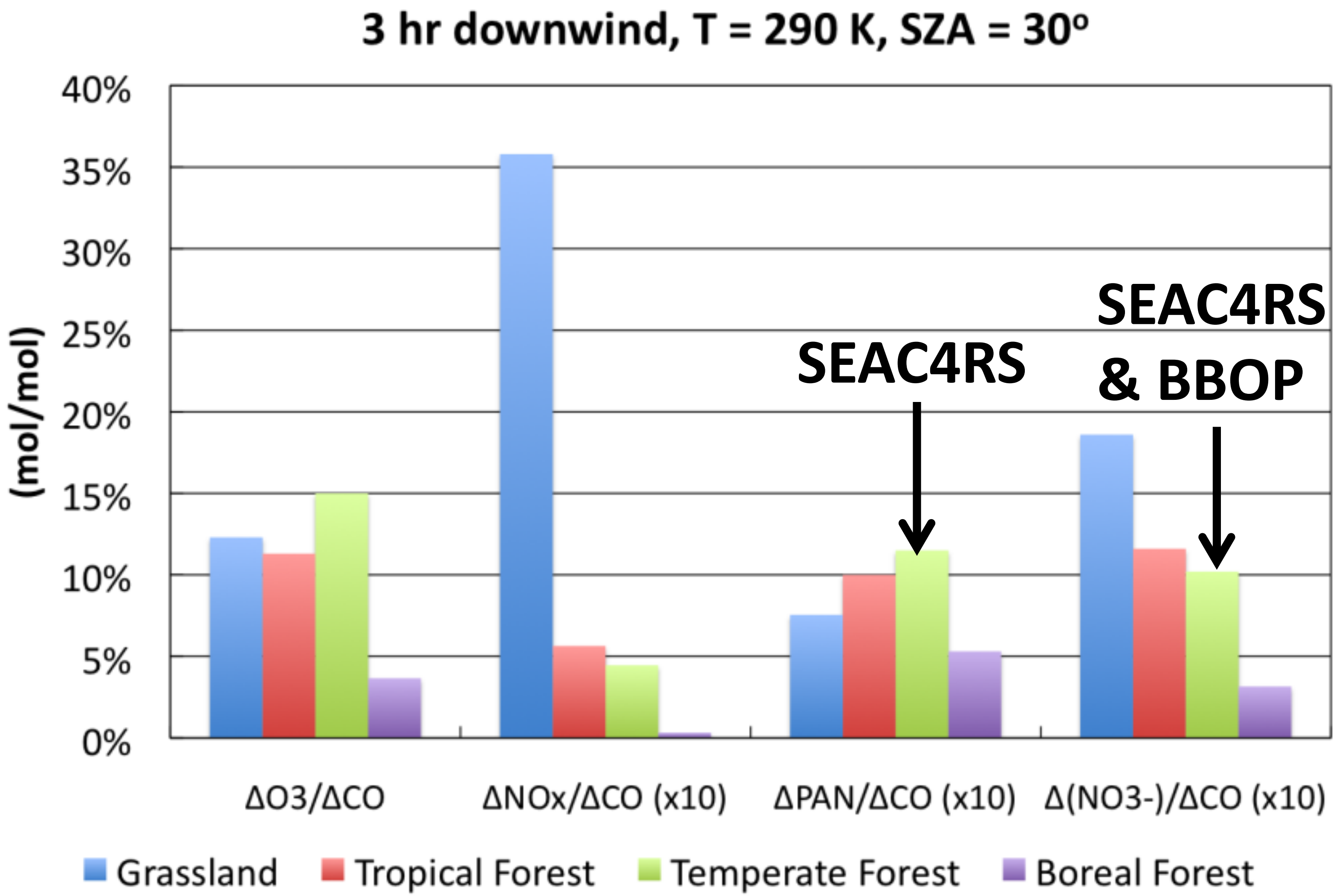
Solution

- Look up table to map from plume chemistry to gridbox chemistry .
- Adaptive grids
- Plume in grid (CMAQ, CAMx)



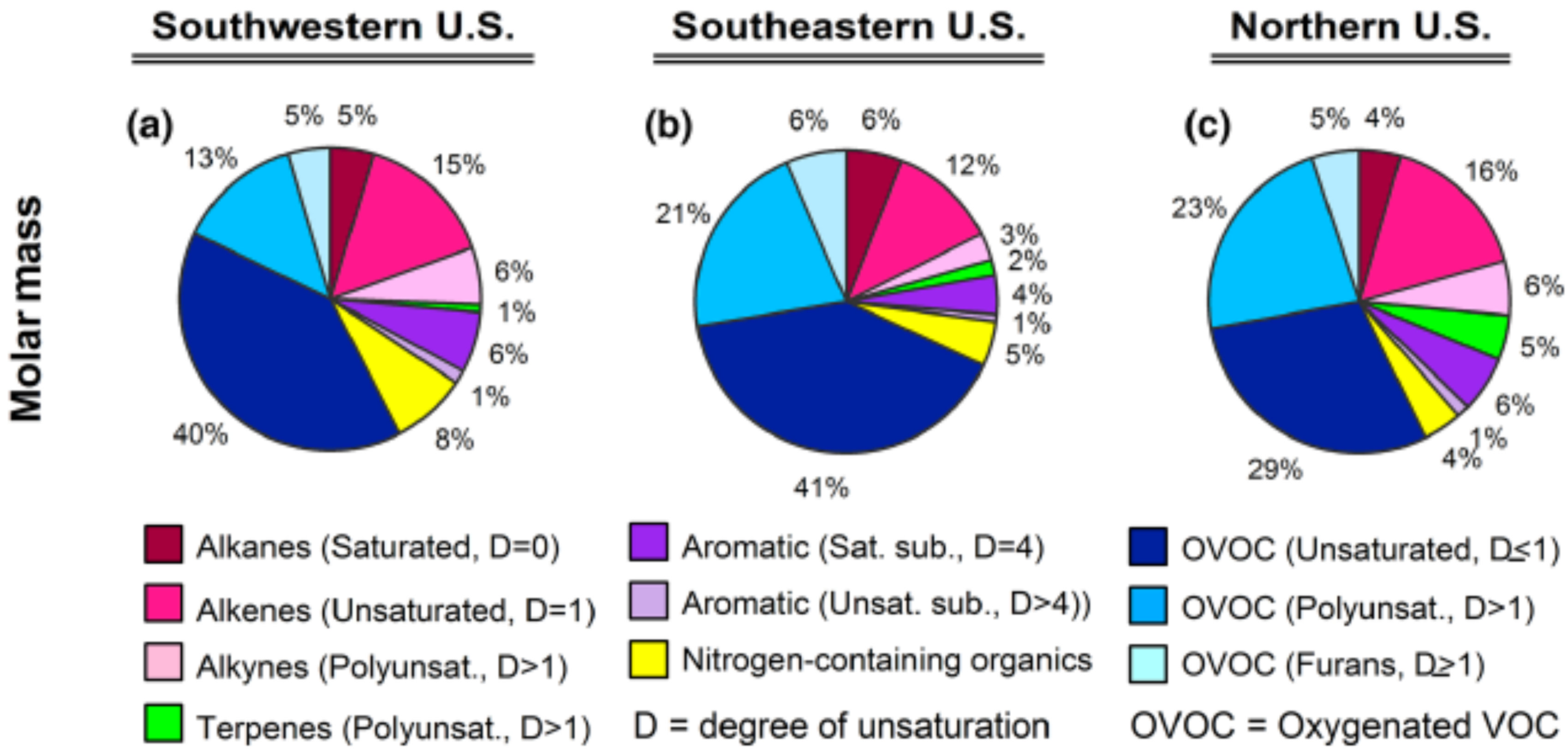


Evolution: look-up tables for GEOS-Chem



Courtesy: Matthew Alvarado and Chantelle Lonsdale, Atmospheric Environmental Research

4. Missing compounds in current models

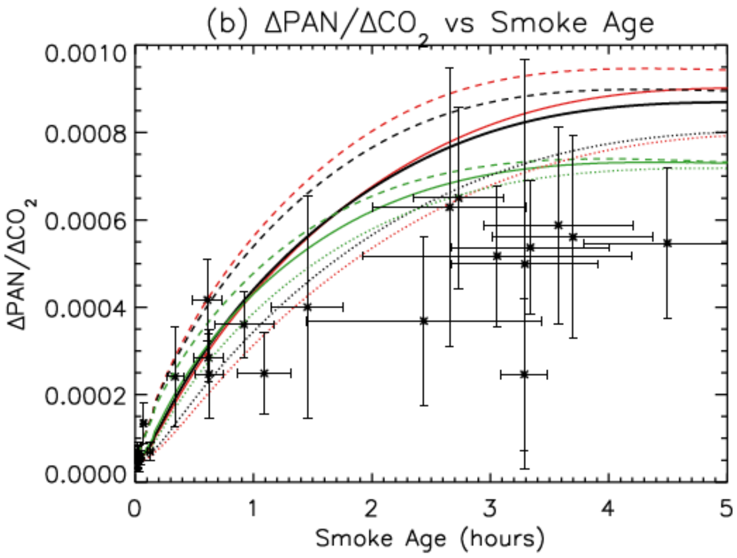


- Recent papers suggest model underestimates organic compounds by a factor of 2-3.
- Most of these compounds are not accounted for in global models.

(Gilman et al., ACP, 2015; Akagi et al., 2011, ACP)

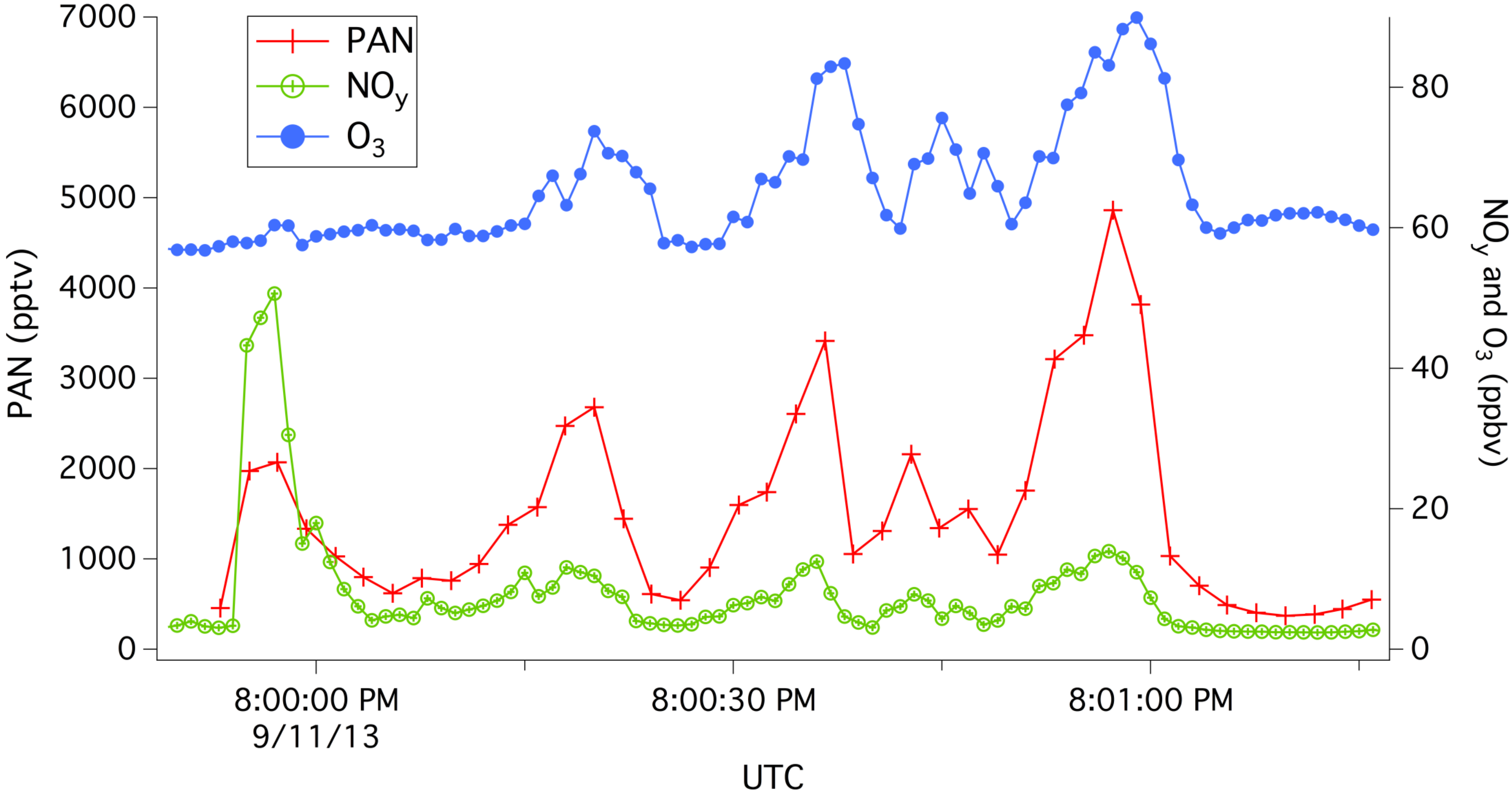
Consequence of missing organic compounds

- Underestimate of CO from biomass burning plumes.
- Underestimate of PAN and other organic nitrates produced from plumes.
  - Alvarado et al. (2010) treats fire NOx emissions 40% as PAN.
- Miscalculation of ozone production.



(Alvarado et al., 2015, ACP)

Ag-fire smoke plume evolution cloud-free



PAN: Xiaoxi Liu, Greg Huey, Dave Tanner GA Tech. NOy, O_3: Tom Ryerson NOAA.

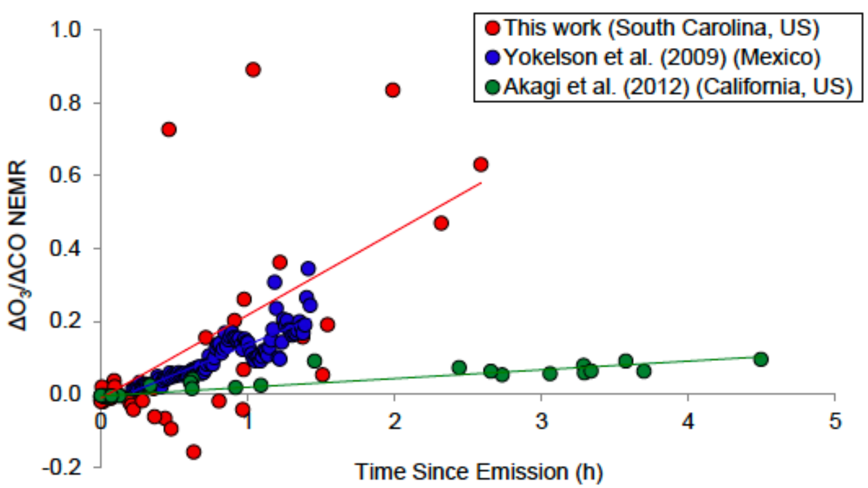
Courtesy of Bob Yokelson

Ozone production is still unclear

dO_3/dCO has been used to quantify ozone production from fire plumes.

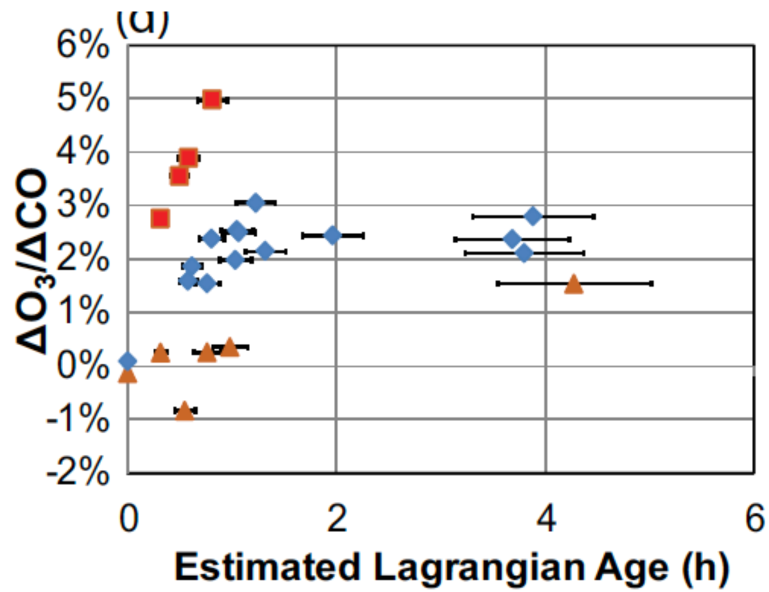
Measured dO3/dCO varies from -0.1 to 0.9 from different studies [Jaffe et al., 2012].

Mid latitude



(Akagi et al., 2013, ACP)

High latitude



(Alvarado et al., 2010, ACP)

Solution

Species currently emitted by biomass burning in standard GEOS-Chem:
CO2, CO, CH4, NO, SO2, OC, BC, NH3, ACET, ALD2, ALK4, BENZ, C2H2, C2H4, C2H6, C3H8, CH2BR2, CH2O, CH3BR, GLYC, GLYX, HAC, MEK, MGLY, PRPE, TOLU, XYLE

Box model would be a great tool to lump these species into global models (John Orlando’s talk).

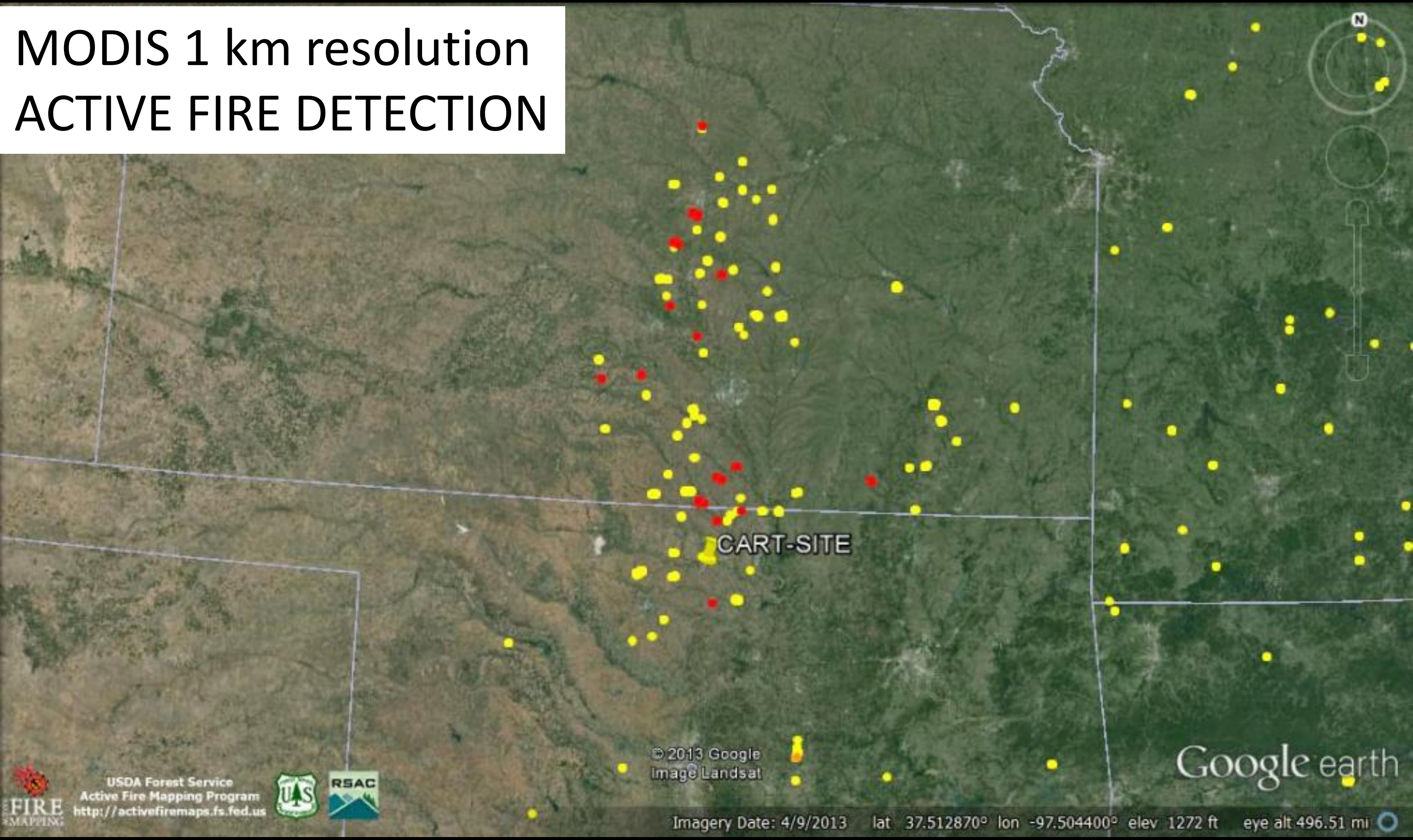
Other issues

Fire detection

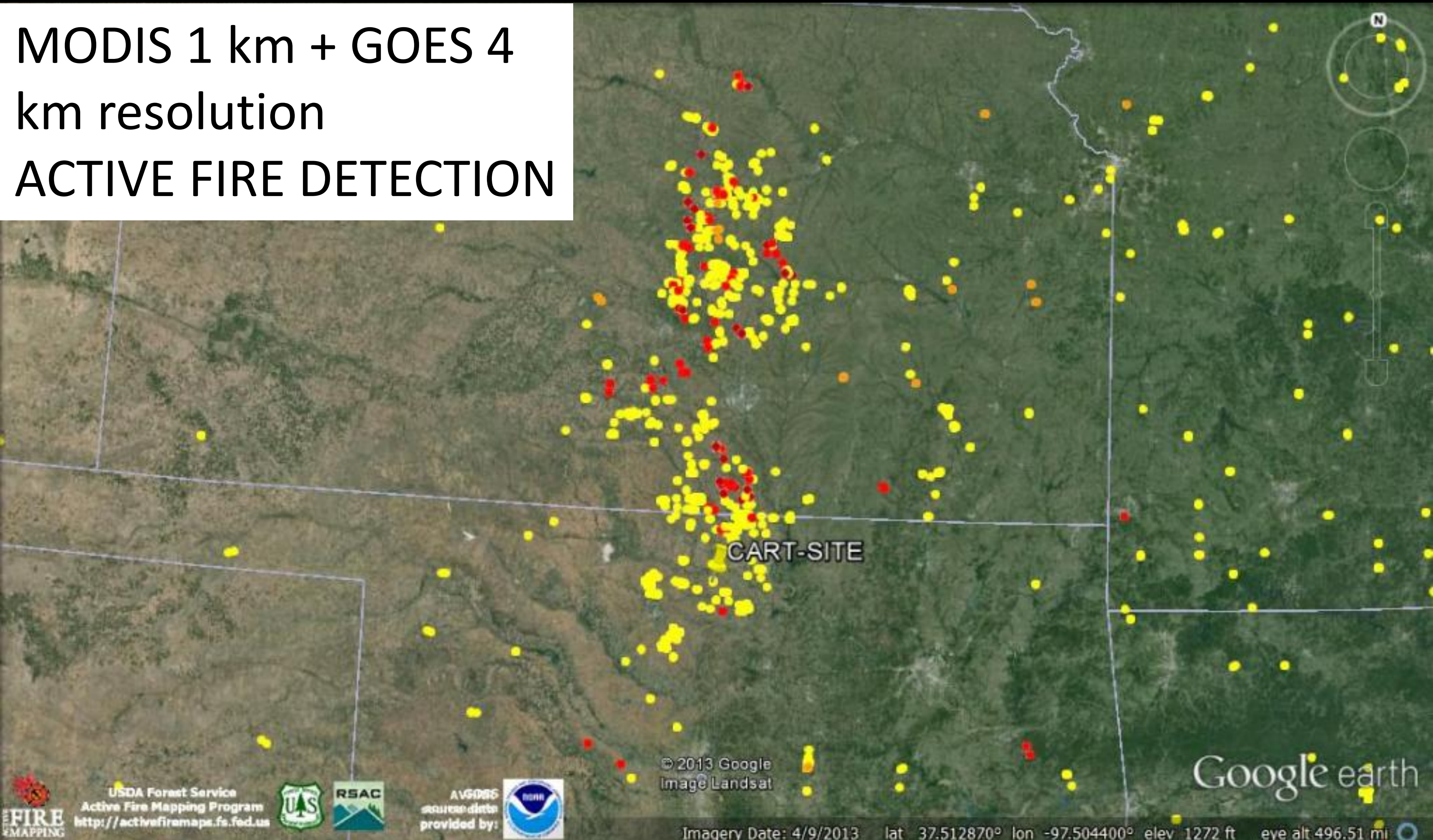
Diurnal cycle of fire emissions

Courtesy of Bob Yokelson

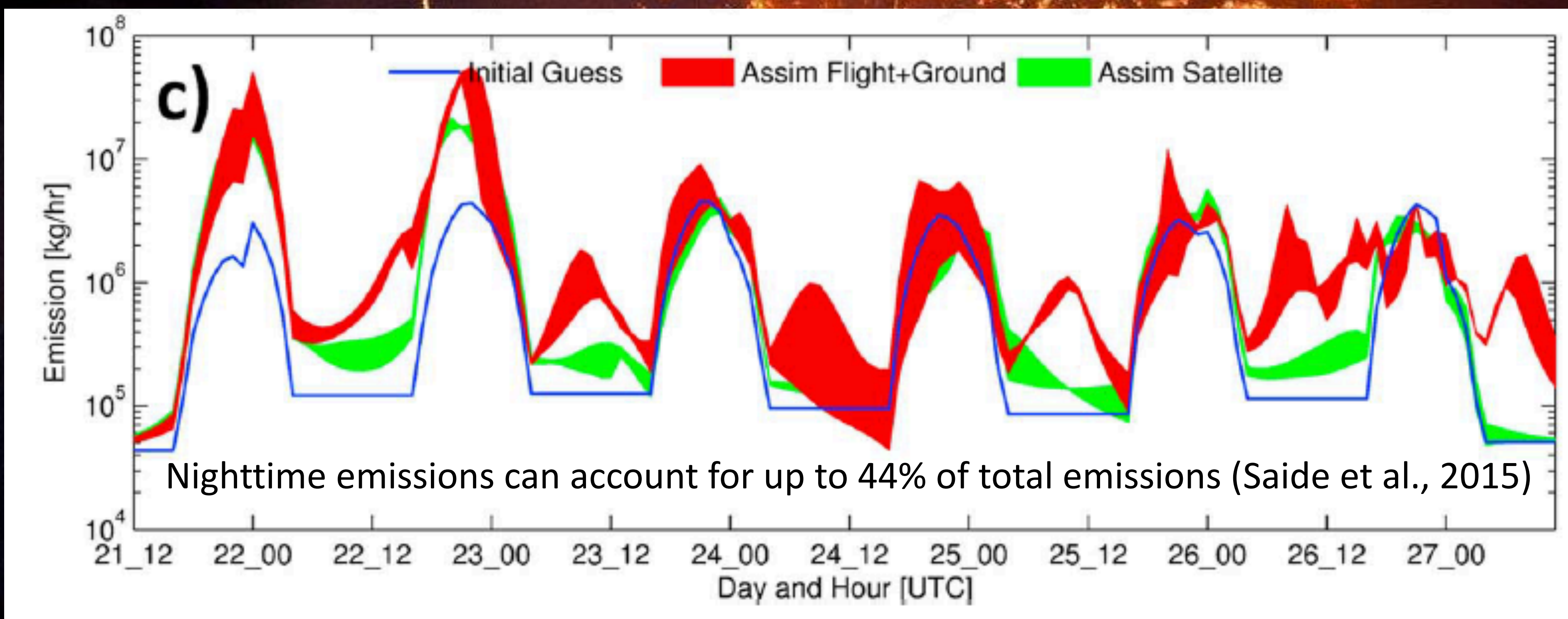
MODIS 1 km resolution ACTIVE FIRE DETECTION



MODIS 1 km + GOES 4 km resolution ACTIVE FIRE DETECTION



Emissions: "Diurnal cycle"



Nighttime emissions can account for up to 44% of total emissions (Saide et al., 2015)

Summary

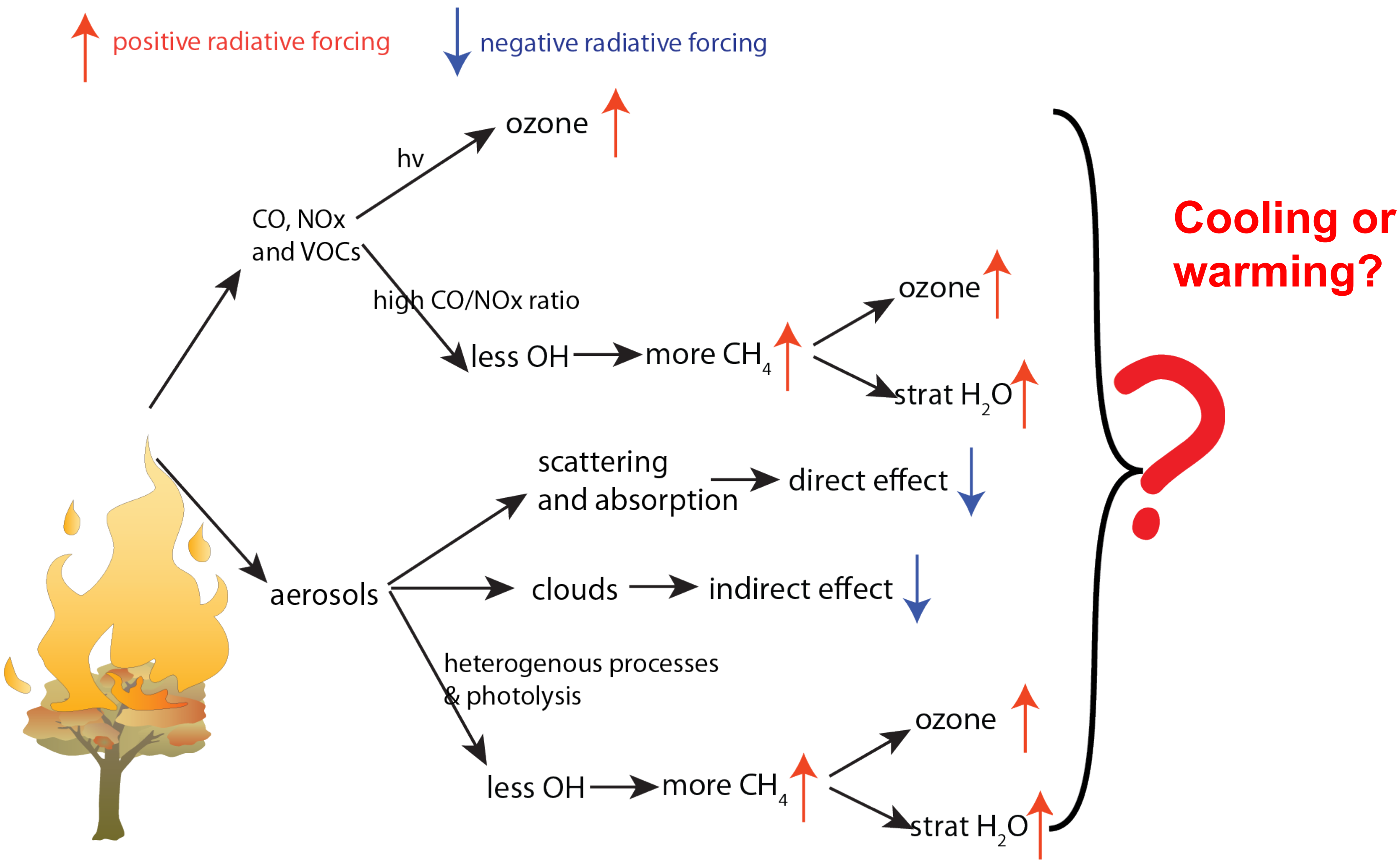
Many issues for modeling fire plumes….

Need field observations to validate models (Louisa's talk).

Need engineering approach to get something right (emit NO_x as PAN???)

How do wildfires impact global OH/ozone?

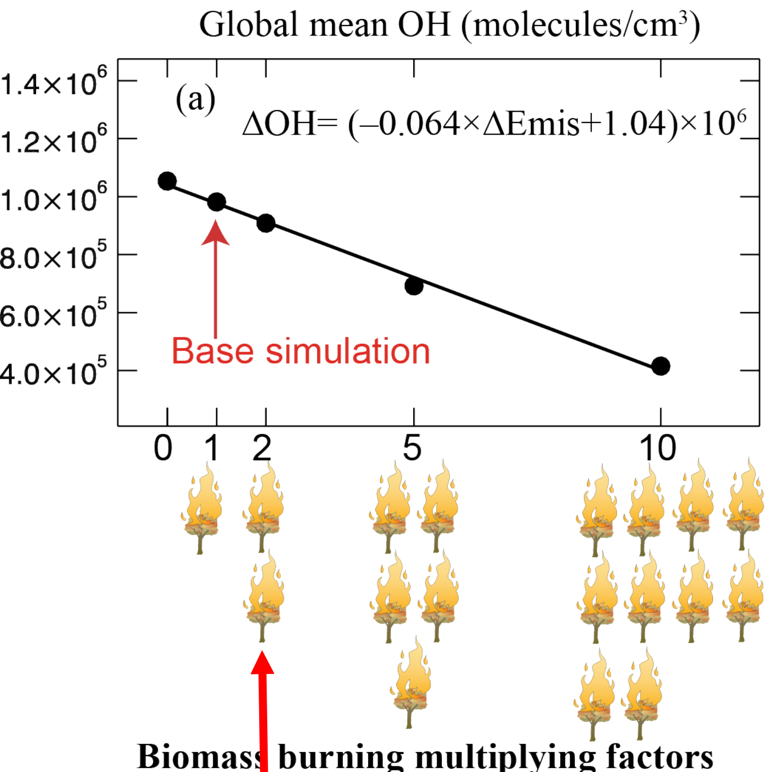
The impact of biomass burning emissions on oxidants and radiative forcing

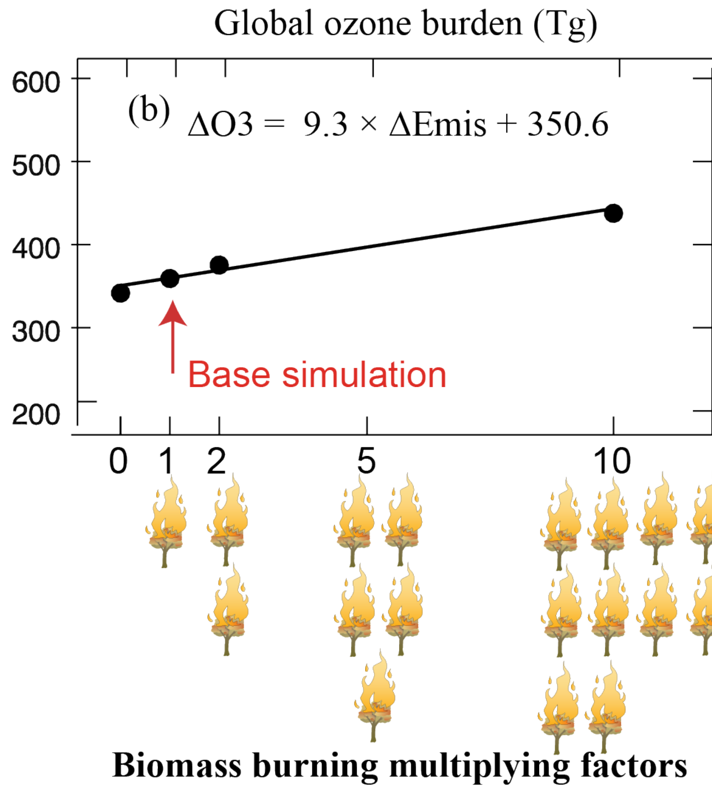


IPCC AR4 only estimates the direct forcing from biomass burning aerosols (+0.03 ±0.12 W m^{-2}).

Perturbation tests of biomass burning emissions on global OH and ozone

AM3 model with different magnitude of biomass burning emissions (for year 2000).



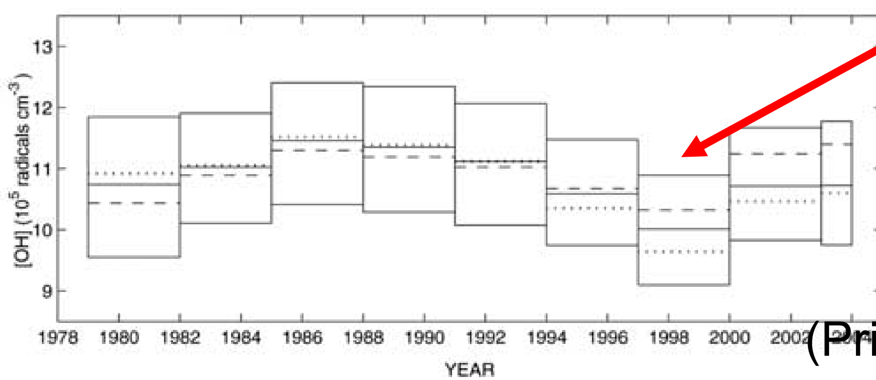


(Mao et al., 2013, GRL)

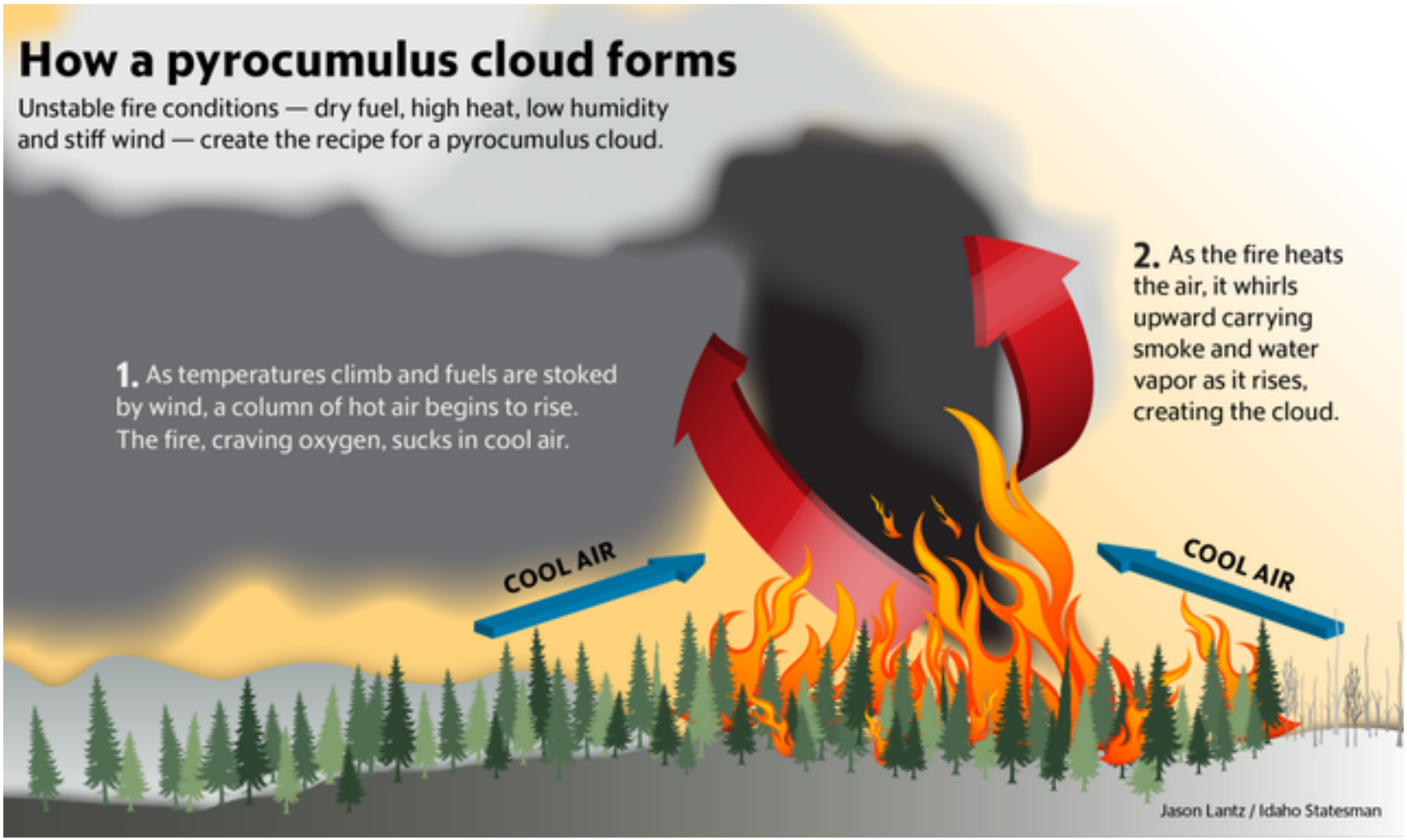
Computed change of global mean OH is 6.3% for doubling 2000 bb emissions.

Estimated global OH from CH3CCl3

1997 Indonesian fires, 6%



(Prinn et al., 2005)


How a pyrocumulus cloud forms
Unstable fire conditions — dry fuel, high heat, low humidity and stiff wind — create the recipe for a pyrocumulus cloud.
1. As temperatures climb and fuels are stoked by wind, a column of hot air begins to rise. The fire, craving oxygen, sucks in cool air.
2. As the fire heats the air, it whirls upward carrying smoke and water vapor as it rises, creating the cloud.
COOL AIR
COOL AIR
Jason Lantz / Idaho Statesman