# What's in the Smoke?

M. O. Andreae
Max Planck Institute for Chemistry, Mainz, Germany

# What and how much do biomass fires emit?

- $CO_2$
  - climatically relevant only when there is no regrowth - e.g., deforestation
- $NO_x$, CO, $CH_4$, other hydrocarbons
  - Ingredients of smog chemistry, greenhouse gases
- Halogenated hydrocarbons (e.g. $CH_3Br$)
  - stratospheric ozone chemistry
- Aerosols & aerosol precursors ($NH_3$, $SO_2$)
  - light scattering and absorbing, cloud condensation nuclei

# Open issues related to "What"

- Measurements of some pyrogenic species are difficult (especially OVOC, HONO, $NH_3$, etc.) and therefore sparse
- Some measurements (esp. FTIR) suggest there are no major unmeasured species, but true closure experiments have not been made
- Modeling of key secondary species in plumes ($O_3$, acetic acid,…) is still unsatisfactory: Are we missing important emission species or reaction paths?
- Gas/aerosol partitioning is poorly understood. What is the role of semivolatile species? How does the primary mixture affect smoke aerosol evolution?

# “How much?” (and “When and Where”)

- The “classical” approach is still dominant today (Seiler & Crutzen, 1980):

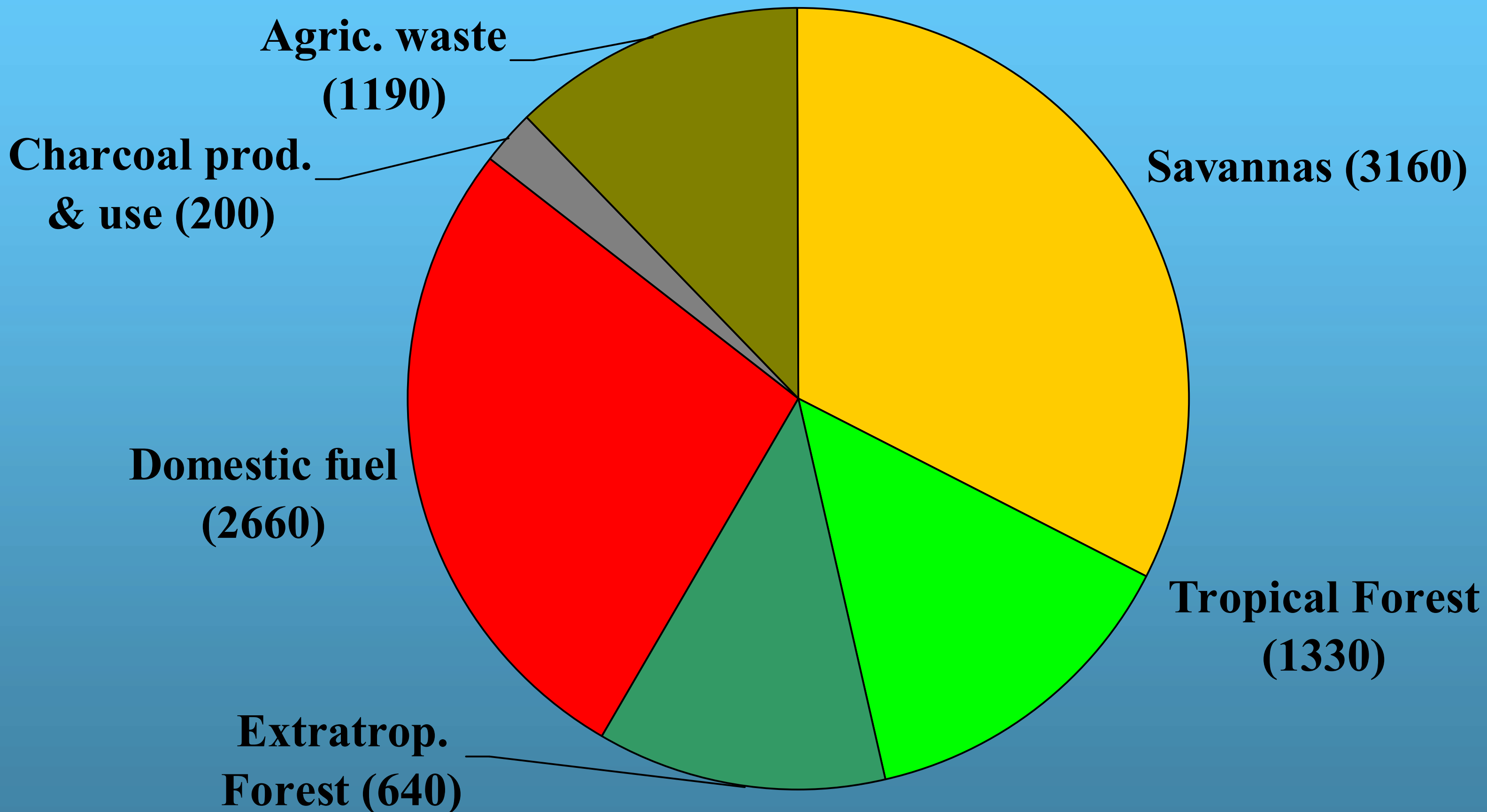
*“The total amount of biomass M burned annually in a biome is approximately given by the equation:*

$$M = A \times B \times \alpha \times \beta \text{ [g dry matter per year]}$$

*where A = total land area burned annually [$m^2$/yr], B = the average organic matter per unit area in the individual biomes [g(dm)/$m^2$], $\alpha$ = fraction of the average above-ground biomass relative to the total average biomass B, and where $\beta$ = the burning efficiency of the above-ground biomass.”*

- To get species emissions, we then multiply with an emission factor.

# For example…




**Biomass burned worldwide (9200 Teragram d.w. annually)**

# Combined with…

GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 15, NO. 4, PAGES 955–966, DECEMBER 2001

## Emission of trace gases and aerosols from biomass burning

M. O. Andreae and P. Merlet

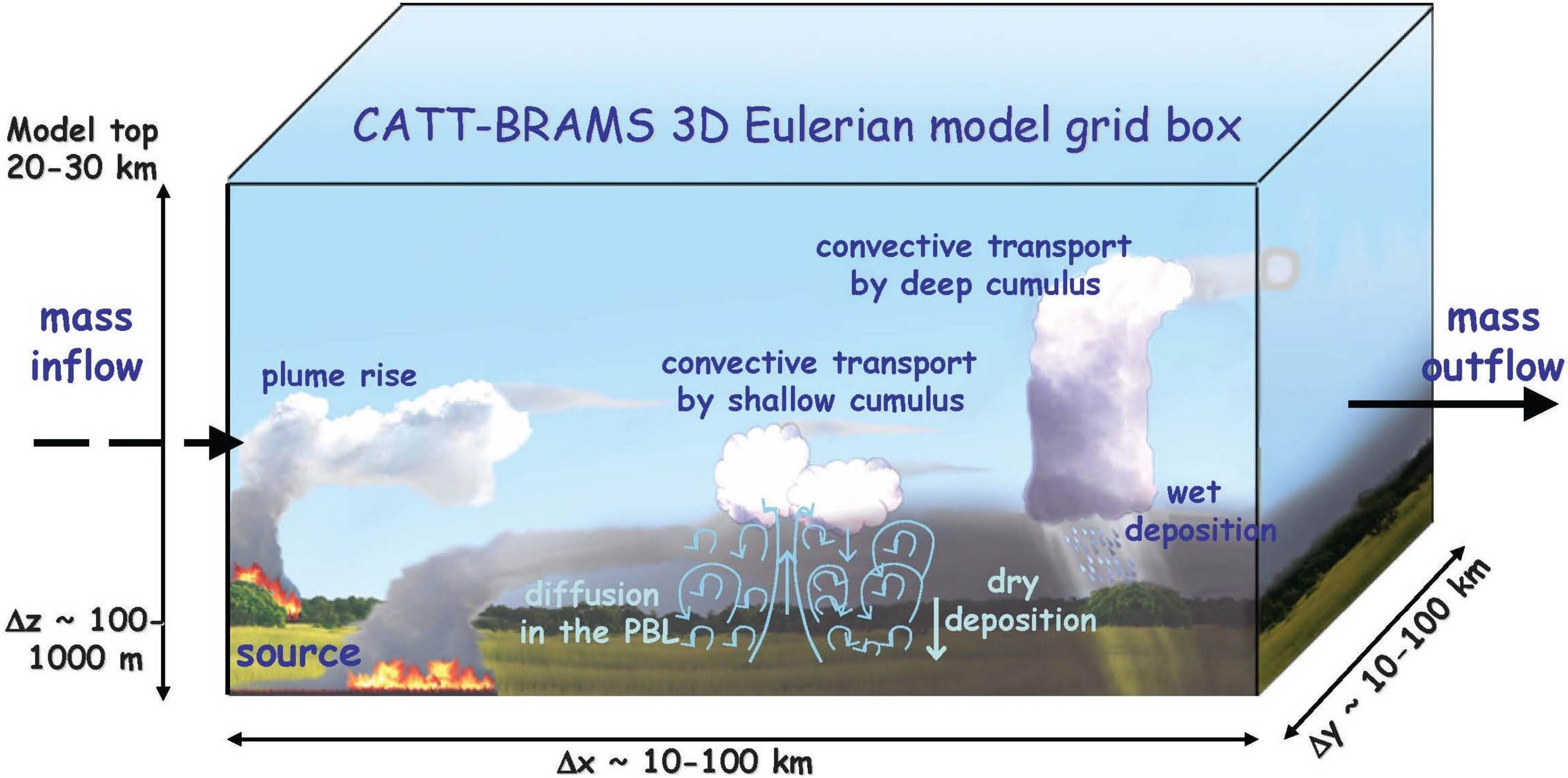
Biogeochemistry Department, Max Planck Institute for Chemistry, Mainz, Germany

**Abstract.** A large body of information on emissions from the various types of biomass burning has been accumulated over the past decade, to a large extent as a result of International Geosphere-Biosphere Programme/International Global Atmospheric Chemistry research

**Table 1.** Emission Factors for Pyrogenic Species Emitted From Various Types of Biomass Burning[a]

| Species | Savanna and Grassland[b] | Tropical Forest[c] | Extratropical Forest[d] | Biofuel Burning[e] | Charcoal Making[f] | Charcoal Burning[f] | Agricultural Residues[i] |
|---|---|---|---|---|---|---|---|
| $CO_2$ | 1613 ± 95 | 1580 ± 90 | 1569 ± 131 | 1550 ± 95 | 440 | 2611 ± 241 | 1515 ± 177 |
| CO | 65 ± 20 | 104 ± 20 | 107 ± 37 | 78 ± 31 | 70 | 200 ± 38 | 92 ± 84 |
| $CH_4$ | 2.3 ± 0.9 | 6.8 ± 2.0 | 4.7 ± 1.9 | 6.1 ± 2.2 | 10.7 | 6.2 ± 3.3 | 2.7 |
| Total nonmethane hydrocarbons | 3.4 ± 1.0 | 8.1 ± 3.0 | 5.7 ± 4.6 | 7.3 ± 4.7 | 2.0 | 2.7 ± 1.9 | (7.0)[h] |
| $C_2H_2$ | 0.29 ± 0.27 | 0.21–0.59 | 0.27 ± 0.09 | 0.51–0.90 | 0.04 | 0.05–0.13 | (0.36)[h] |
| $C_2H_4$ | 0.79 ± 0.56 | 1.0–2.9 | 1.12 ± 0.55 | 1.8 ± 0.6 | 0.10 | 0.46 ± 0.33 | (1.4)[h] |
| $C_2H_6$ | 0.32 ± 0.16 | 0.5–1.9 | 0.60 ± 0.15 | 1.2 ± 0.6 | 0.10 | 0.53 ± 0.48 | (0.97)[h] |
| $C_3H_4$ | 0.022 ± 0.014 | 0.013 | 0.04–0.06 | (0.024)[h] | – | (0.06)[h] | (0.032)[h] |
| $C_3H_6$ | 0.26 ± 0.14 | 0.55 | 0.59 ± 0.16 | 0.5–1.9 | 0.06 | 0.13–0.56 | (1.0)[h] |
| $C_3H_8$ | 0.09 ± 0.03 | 0.15 | 0.25 ± 0.11 | 0.2–0.8 | 0.04 | 0.07–0.30 | (0.52)[h] |
| 1-butene | 0.09 ± 0.06 | 0.13 | 0.09–0.16 | 0.1–0.5 | – | 0.02–0.20 | (0.13)[h] |
| i-butene | 0.030 ± 0.012 | 0.11 | 0.05–0.11 | 0.1–0.5 | – | 0.01–0.16 | (0.08)[h] |
| *trans*-2-butene | 0.024 ± 0.014 | 0.05 | 0.01–0.05 | 0.05–0.3 | – | 0.01–0.06 | (0.04)[h] |

# Even sophisticated models basically use this approach in the source parameterization




Freitas et al., ACPD, 2007


Can’t we do better?


Aerosol emissions make the high variability visible – it also applies to the trace gases!

# Key emitted species by combustion type:

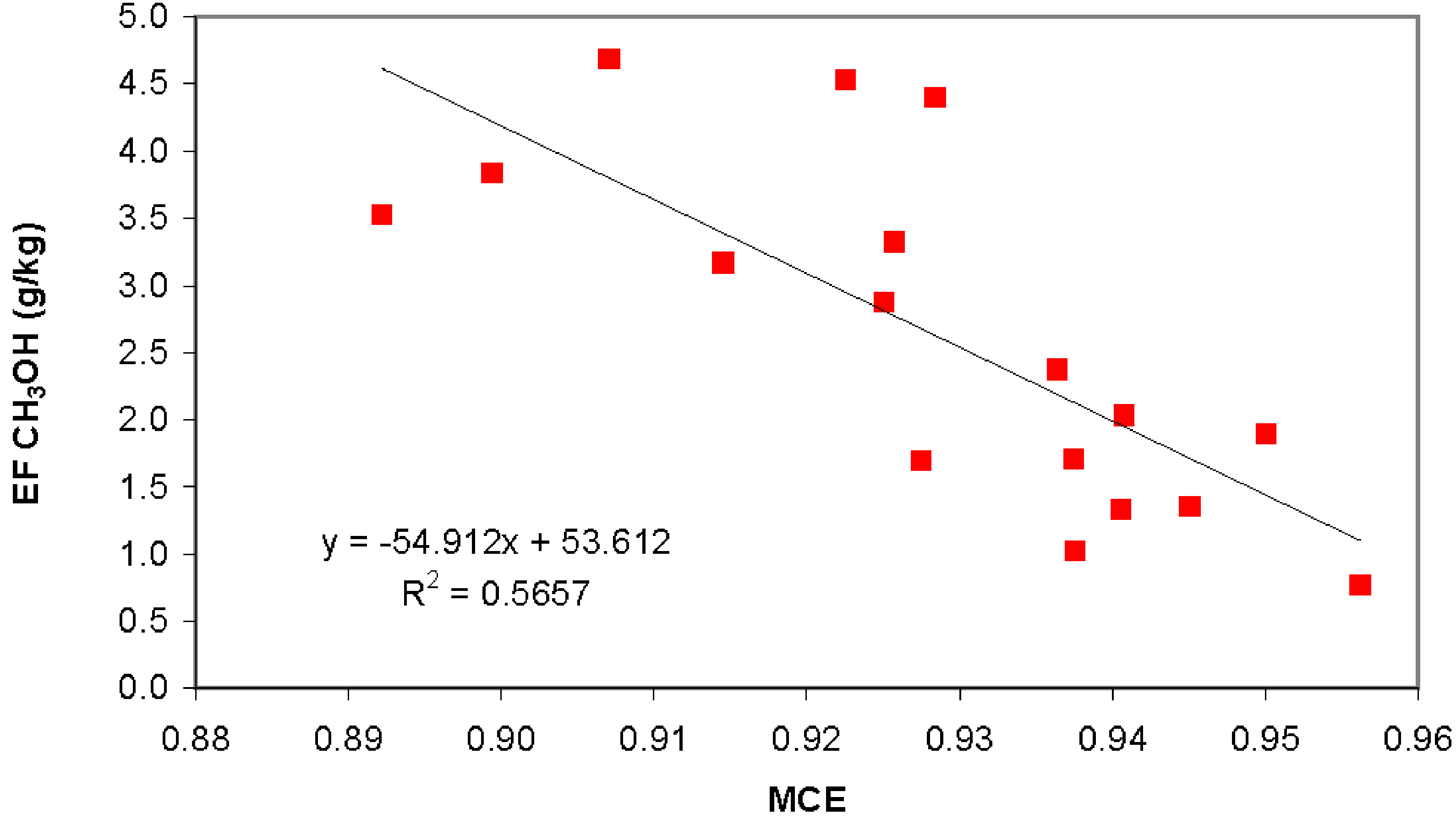
- **Non-flaming (pyrolysis, smoldering)**
  - **CO**
  - **$CH_4$, most VOCs**
  - **$CH_3Cl$, $CH_3CN$, HCN, $NH_3$, …**
  - **Organic aerosol**
- **Flaming**
  - **$CO_2$**
  - **$NO_X$, $N_2$**
  - **“Black carbon”, “soot carbon”**

# Measures of flaming/smoldering ratio:

- $CO/CO_2$ ratio
- Combustion efficiency (CE):
  $CO_2/(CO_2 + CO + VOC + OC + \ldots)$
- Modified combustion efficiency (MCE):
  $CO_2/(CO_2 + CO)$

# Key emitted species scale with MCE:

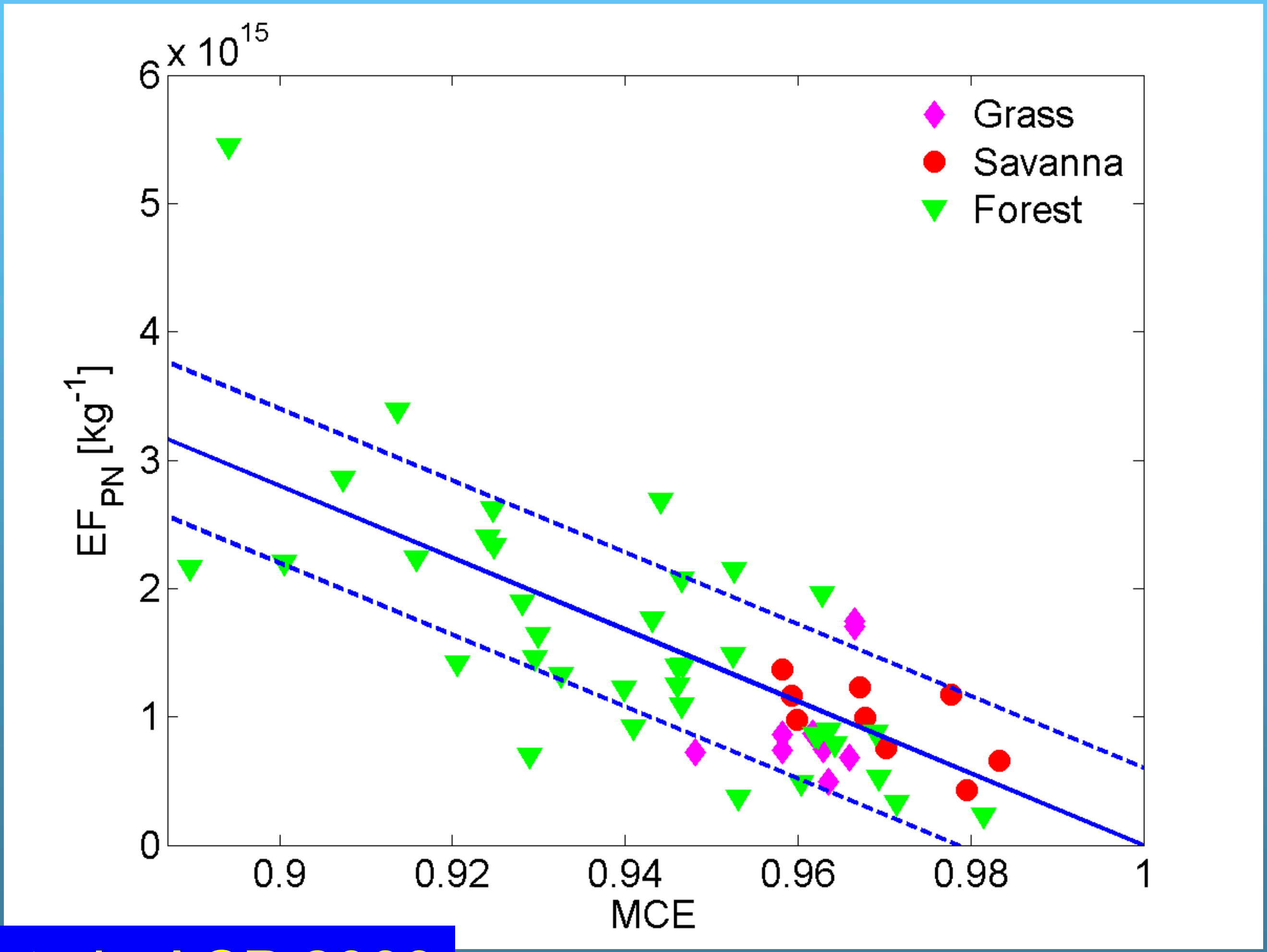
- e.g. VOC and OVOC emissions:



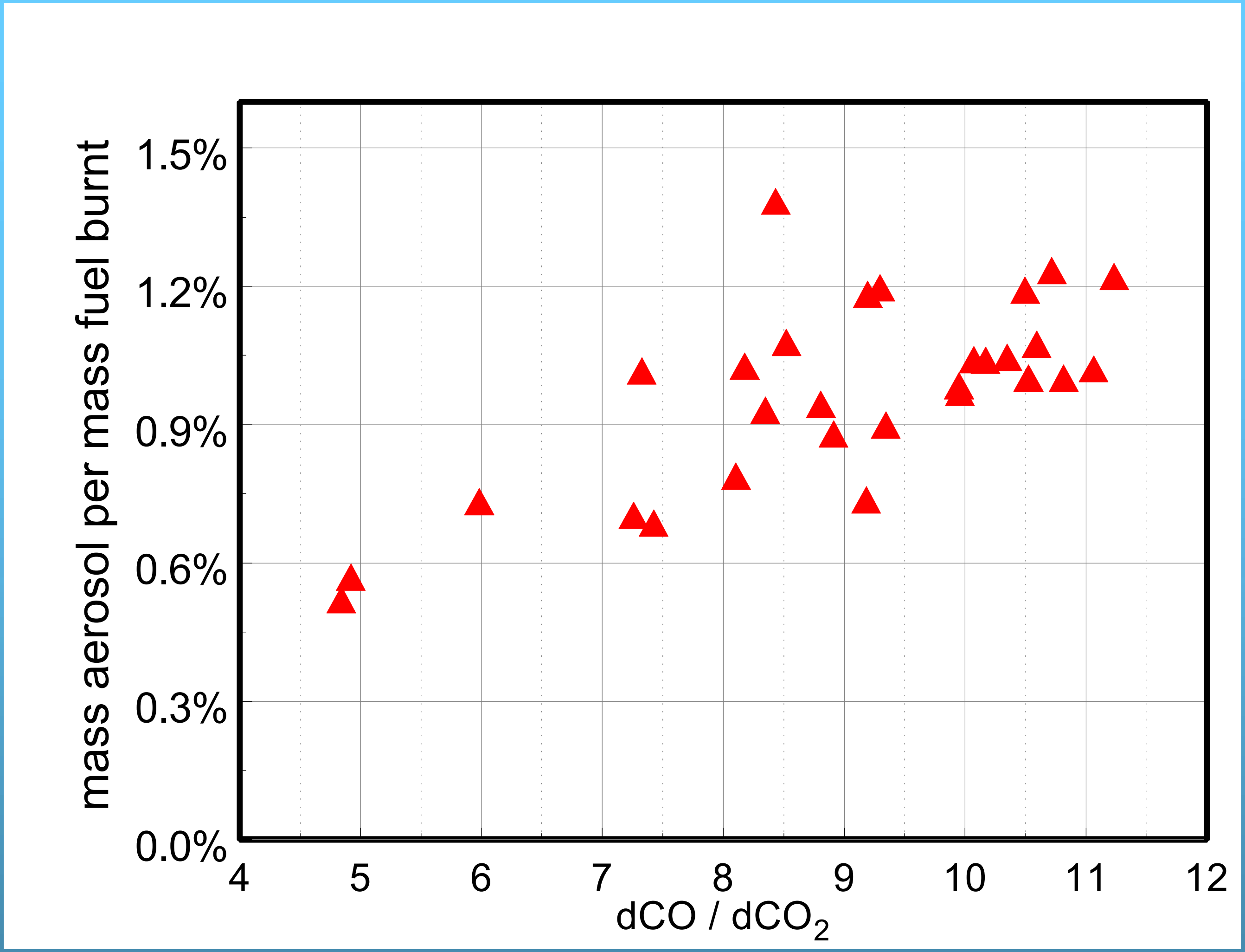

Yokelson et al., ACP 2009

# Key emitted species scale with MCE:

- e.g. particle number emission

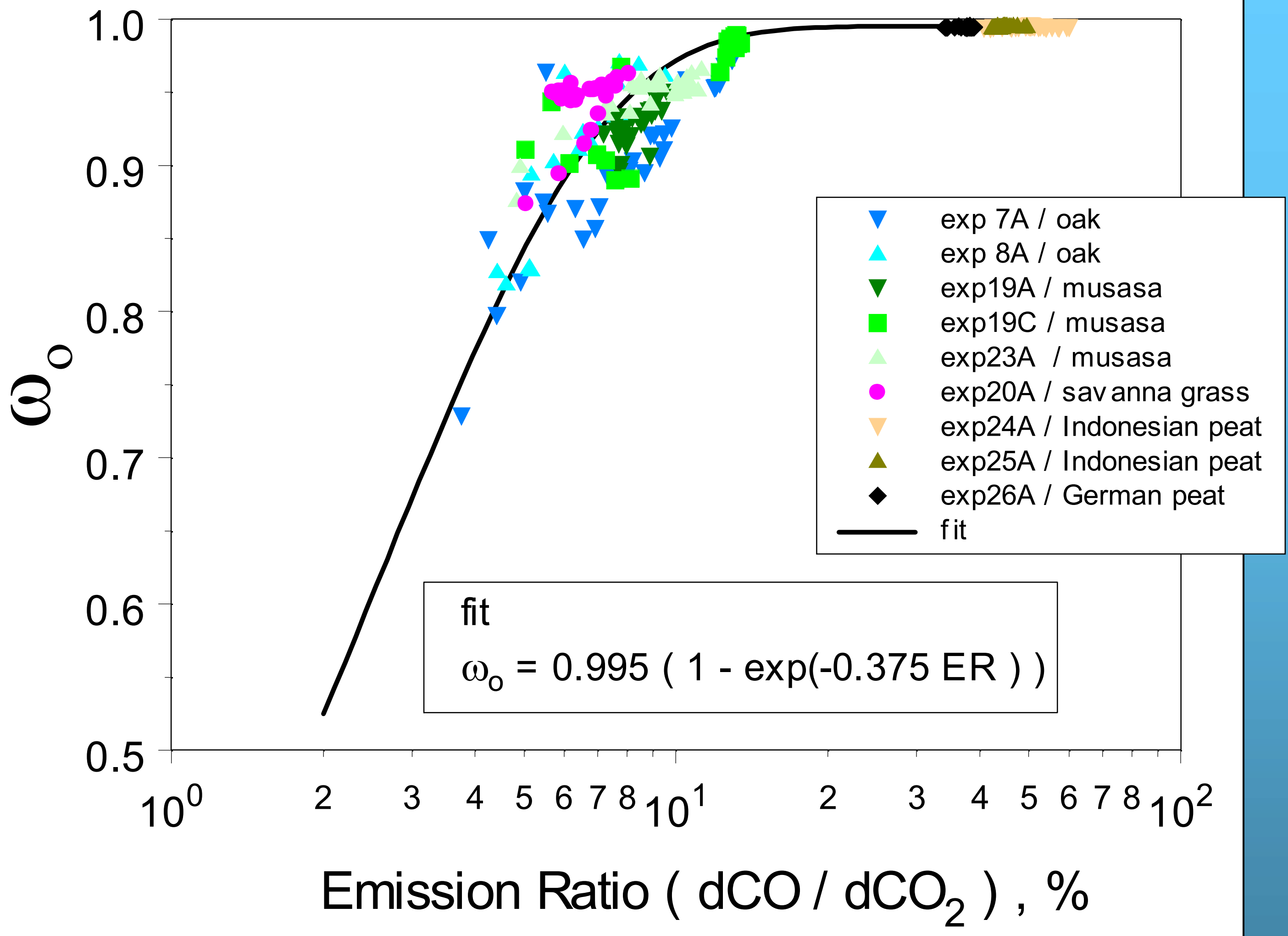



Janhaell et al., ACP 2009



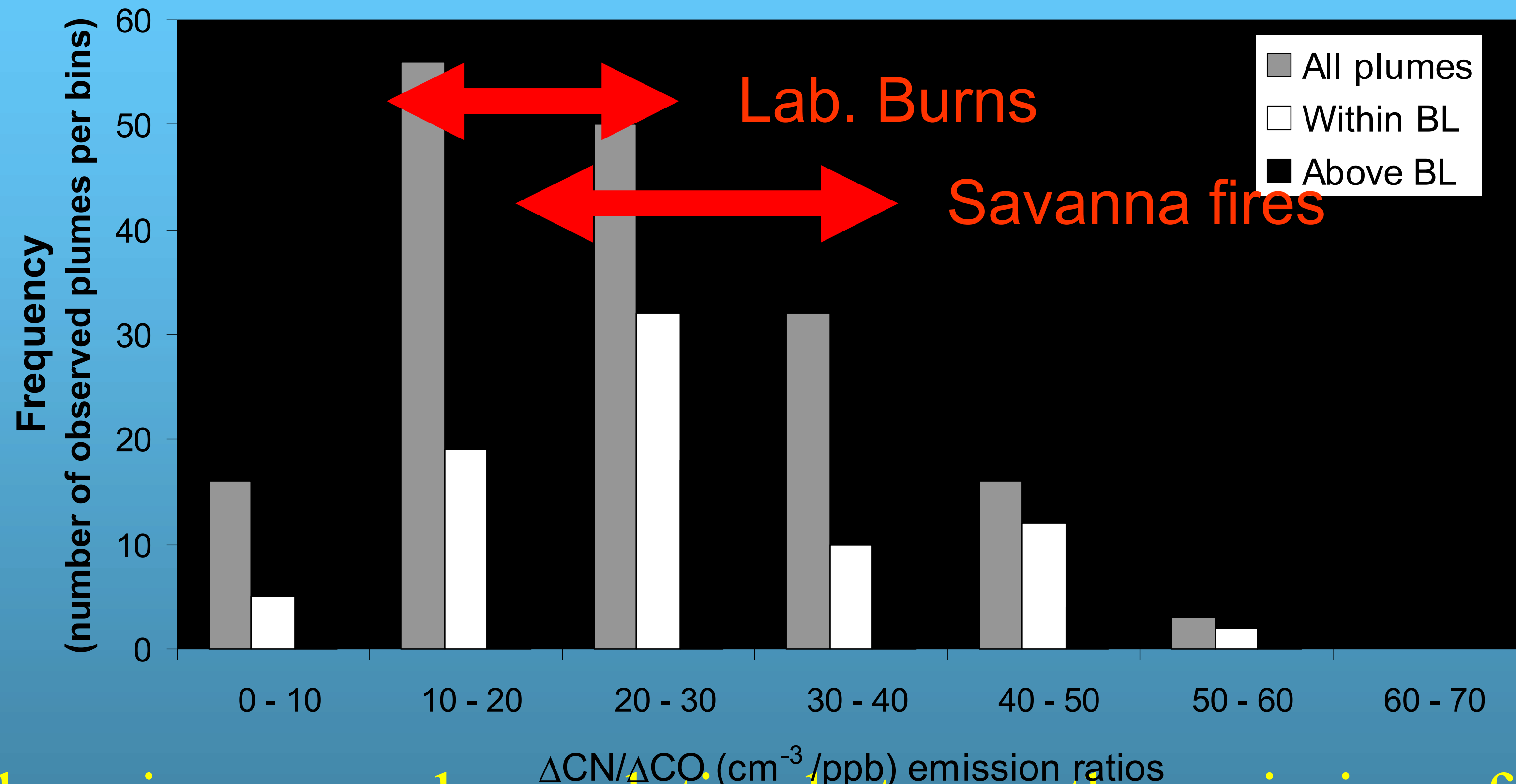

Aerosol emission factor is proportional to emission ratio ($dCO/dCO_2$ )

**ER(AerosolMass/CO) is ~ constant!**




# Single scattering albedo of biomass burning aerosol increases with decreasing combustion efficiency

# Variability within plume is similar to variability between biomes:




There is a very close relation between the emission of CO and CN particles from fires:

about 20 $cm^{-3}$ CN per ppb CO!

# To predict emissions we would need:

- Amount of fuel burned **and** F/S ratio (or MCE)

- Or -

- Amount of $CO_2$ **and** CO emitted

- And –

- Fuel nitrogen (and halogen) content

# Depending on the application, this information can come from:

- Observation only
  - Remote sensing of CO
  - Fire radiated energy
  - Burnt area, fire pixels, fuel loading and condition, fire weather, topography
- Modeling only, e.g. in climate models with biosphere
  - Fuel loading and condition, fire climate or weather, …
- Combination of observation and modeling, data assimilation, etc.

# What do we need?

**Targeted fire experiments to determine:**

- **Relationship between FRE and biomass burned (and F/S ratio?)**
- **Relationship between fuel conditions, fire weather, terrain slope, etc. and F/S ratio**
- **Remotely sensed proxies of F/S ratio**
  - **Smoke SSA?**
  - **Ratio CO/FRE?**

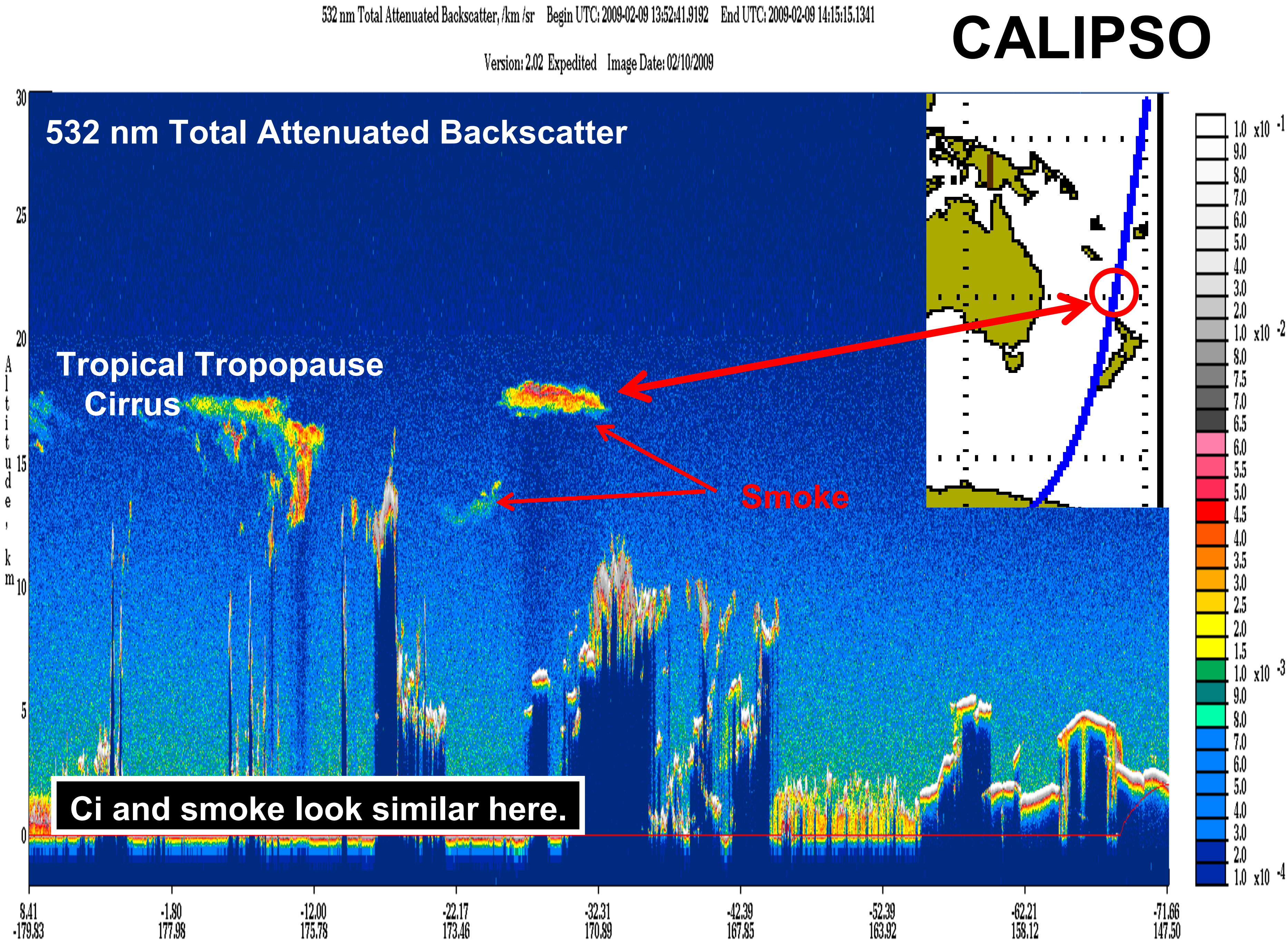
# Injection height

**Deforestation fire, Brazil: a "Smoking Cloud"**

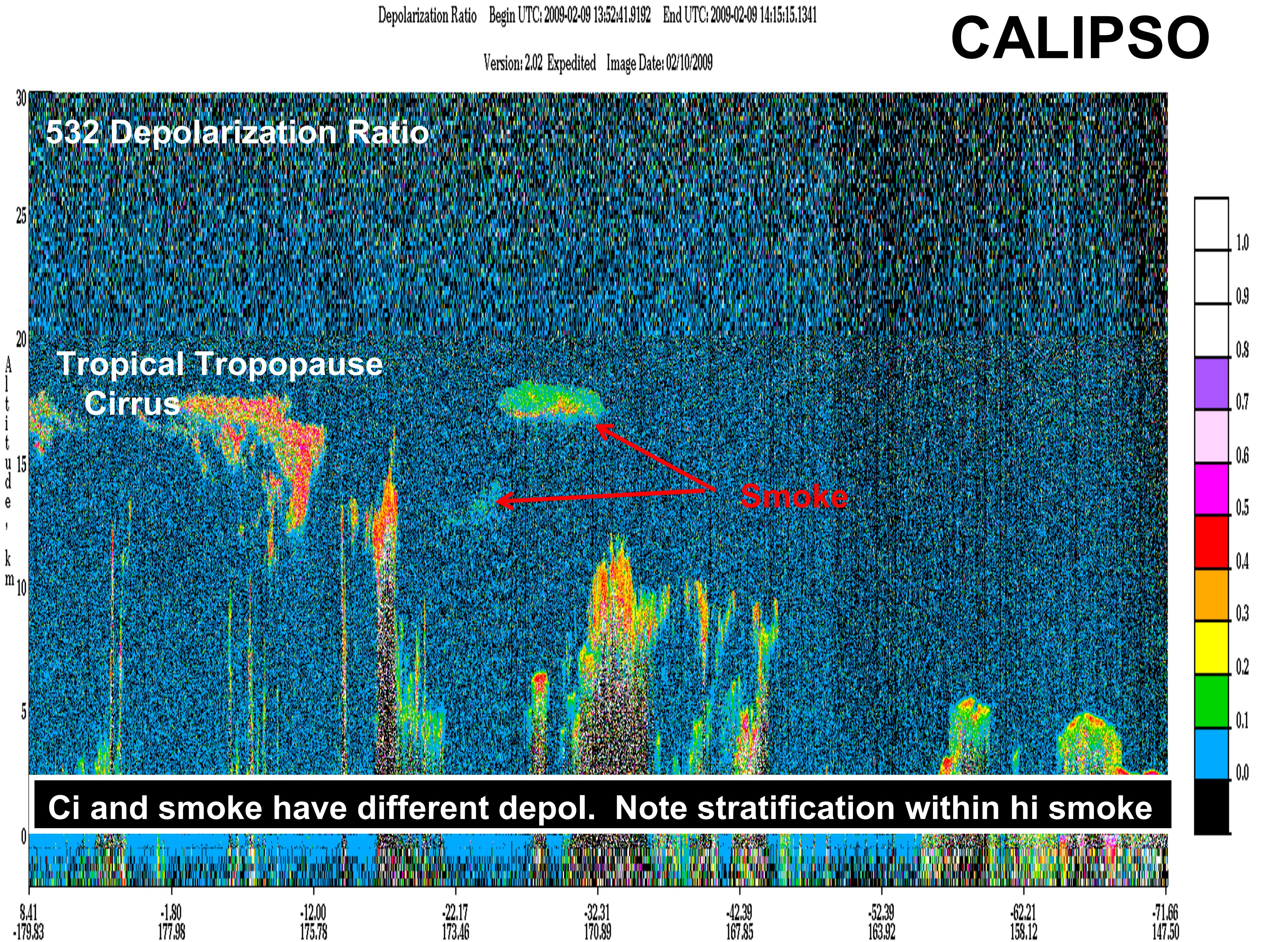

Smoke detraining from cloud top

# Smoldering in the evening remains at the surface

# CALIPSO



532 nm Total Attenuated Backscatter, /km /sr Begin UTC: 2009-02-09 13:52:41.9192 End UTC: 2009-02-09 14:15:15.1341
Version: 2.02 Expedited Image Date: 02/10/2009
532 nm Total Attenuated Backscatter
Tropical Tropopause Cirrus
Smoke
Ci and smoke look similar here.
Altitude, km


Depolarization Ratio Begin UTC: 2009-02-09 13:52:41.9192 End UTC: 2009-02-09 14:15:15.1341
Version: 2.02 Expedited Image Date: 02/10/2009
CALIPSO
532 Depolarization Ratio
Tropical Tropopause Cirrus
Smoke
Ci and smoke have different depol. Note stratification within hi smoke
Altitude, km
30
25
20
15
10
5
0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
8.41 -179.83
-1.80 177.98
-12.00 175.78
-22.17 173.46
-32.31 170.89
-42.39 167.85
-52.39 163.92
-62.21 158.12
-71.66 147.50

**Combination of**

- Emission model
- Injection model
- Transport model
- Chemical process model

**gives accurate large- and meso-scale prediction of biomass smoke distributions**