Numerical modeling and real time forecast of air pollution related to biomass burning on South America.

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- Biomass burning on South America
- **CCATT-BRAMS**: mesoscale atmospheric-chemistry-aerosol model
- Near real time biomass burning emissions estimate
- Plumerise model for biomass burning smoke
- Real time forecast
Biomass Burning and Smoke on South America

Local smoke plume
(deforestation fires)
(picture from A. Andreae)

Regional smoke plume
~5 millions km²
(Prins et al. 1998)

GOES-8 WF_ABBA
(> 5000 fires)
INPE developments on the atmospheric chemistry modeling

**Coupled Chemistry-Aerosol-Tracer Transport model to the Brazilian developments on the RAMS**

- SPACK: Pre-processor of chemical mechanism
- Pre-processor of emissions (anthropogenic, biogenic, biomass burning).
- Pre-processor of IC and BC for meteo-chemistry fields.
- 4DDA for meteo-chem fields.
- Grid and sub-grid scale transport fully coupled.
- Plume rise model for fires and volcanoes emissions.
- Rad. CARMA and FAST-TUV (on-line photolysis calculation).
- Chemistry (RACM, CB07, RADM, etc).
- Emission and deposition (dry and wet).
- On-line with BRAMS regional model.
- Being implemented in the CPTEC-GCM.

Ozone and PM2.5 biomass burning aerosol

**Ozone at 1000 m ASL**

**PM2.5 (bio. burn.) column**
Biomass burning emissions inventory
Regional scale – daily basis

- Density of carbon data
- Near real time fire product
- Land use data
- Emission & combustion factors
- Mass estimation

CO source emission (kg m\(^{-2}\) day\(^{-1}\))
Aboveground Biomass Density

Olson's carbon in live vegetation

Provides an estimate of the carbon content for each Olson's vegetation class.

Amazon basin
1 km resolution

Saatchi et al., Global Change Biology (2007)
Fires position, timing and size using remote sensing products

Fires from AVHRR-MODIS-GOES: INPE (A. Setzer)

Fires WF_ABBA (GOES) CIMSS (E. Prins)

However, the burned area and the AGB are the main source of uncertainties for biomass burning emissions estimates.

provides the diurnal cycle of the burning, each 1/2 hour.
provides an estimate of the instantaneous fire size.
Biomass burning sources

- Brazilian Biomass Burning Emission Model (Freitas et al., 2005; Longo et al., 2007): plume rise mechanism, daily and model resolution.
- GFEDv2 (van der Werf et al., 2006): 8 days/monthly - 1x1 degree.

110 species

<table>
<thead>
<tr>
<th>Biomes: TropFor, ExtratropF, Savanna, Pasture, charcoal, waste, lab</th>
</tr>
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<tbody>
<tr>
<td>CO2</td>
</tr>
<tr>
<td>CO</td>
</tr>
<tr>
<td>CH4</td>
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<td>NHMC</td>
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<tr>
<td>C3H6</td>
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<tr>
<td>C3H8</td>
</tr>
<tr>
<td>1_butyene</td>
</tr>
<tr>
<td>i-butyene</td>
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<tr>
<td>tr_2_butyene</td>
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<tr>
<td>cis_2_butyene</td>
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<tr>
<td>butadiene</td>
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</tbody>
</table>

| ethylamine | trimethylamine | n_pentylamine | 2_me_1_butylamine | HFo |
| HAc | Propanoic | H2 | NOx | NOy |
| EF_N2O | EF_NH3 | EF_HCN | cyanogen | SO2 |
| DMS | COS | CH3Cl | CH3Br | CH3I |
| Hg | PM25 | TPM | TC,OC,BC |
inter-comparison of bioburn inventories

Longo et al., 2009 – under review (EGU-ACP)
Including emission in the model

Biomass burning and wildfires

- Smoldering: mostly surface emission.
- Flaming: mostly direct injection in the PBL, free troposphere or stratosphere.

Plume rise model

Total emission flux: \( F_\eta \) being \( \lambda \) the smoldering fraction

- Smoldering term: \( E_\eta = \frac{\lambda F_\eta}{\rho_{\text{air}} \Delta z}\) first phys. model layer
- Flaming term: \( E_\eta = \frac{(1 - \lambda) F_\eta}{\rho_{\text{air}} \Delta z}\) injection layer

Example in the model:

- Flaming emission
- Smoldering emission

Example in the model:

- Diurnal cycle of the burning:
  \[ E_\eta(t) = r(t) E_\eta \]
The 1D cloud model: governing equations
(original formulation from the PLUMP model)

\[
\frac{\partial w}{\partial t} + \frac{w}{\partial z} = \gamma g B - \frac{2\alpha}{R} w^2
\]

\[
\frac{\partial T}{\partial t} + \frac{w}{\partial z} = -w \frac{g}{c_p} - \frac{2\alpha}{R} w(T - T_e) + \left(\frac{\partial T}{\partial t}\right)_{\text{microphysics}}
\]

\[
\frac{\partial r_v}{\partial t} + \frac{w}{\partial z} = -\frac{2\alpha}{R} w(r_v - r_{ve}) + \left(\frac{\partial r_v}{\partial t}\right)_{\text{microphysics}}
\]

\[
\frac{\partial r_c}{\partial t} + \frac{w}{\partial z} = -\frac{2\alpha}{R} w r_c + \left(\frac{\partial r_c}{\partial t}\right)_{\text{microphysics}}
\]

\[
\frac{\partial r_{\text{ice, rain}}}{\partial t} + \frac{w}{\partial z} = -\frac{2\alpha}{R} w r_{\text{ice, rain}} + \left(\frac{\partial r_{\text{ice, rain}}}{\partial t}\right)_{\text{microphysics}} + \text{sedim}
\]

\[
(\frac{\partial \xi}{\partial t})_{\text{microphysics}} (\xi = T, r_v, r_c, r_{\text{rain}}, r_{\text{ice}}), \text{ sedim}
\]

\[
L_{\text{entr}} = \frac{2\alpha}{R} |w|
\]

\[
\text{only lateral (non-organized) entrainment}
\]

bulk microphysics:

Kessler, 1969; Berry, 1967

Ogura & Takahashi, 1971

Latham, 1994; Freitas et al., 2006, 2007
Including plume rise mechanism through *"super-parameterization"* concept

1D plume-rise model for vegetation fires

**Biome:** *Forest*

- Time duration: 50 min
- Fire size: 20 ha
- Heat flux: 80 kWm\(^{-2}\) / 30 kWm\(^{-2}\)

\[
T_{\text{ parcel}} - T_{\text{ env}} \begin{cases} h = 80 \text{kWm}^{-2} \\ h = 30 \text{kWm}^{-2} \end{cases}
\]

\[
\begin{align*}
T_{\text{ parcel}} - T_{\text{ env}} & = h = 80 \text{kWm}^{-2} \\
T_{\text{ parcel}} - T_{\text{ env}} & = h = 30 \text{kWm}^{-2}
\end{align*}
\]

![Diagram of plume rise model](image)
Example of CO source emission field with the plume-rise for vegetation fires at the CATT-BRAMS host model.

Plume-rise model for biomass burning
CO source emission for 18Z02SEP2002 at Lat 6.3S

Flaming emission

Smoldering emission

South America mostly forest fires

Africa mostly savanna fires

kg/kg/day log scale
Example of CO with and without plume-rise at level 5.8 km:
CATT-BRAMS comparison with AIRS 500 hPa CO

Model CO (ppb) at ~5.8 km
without plume rise
with plume rise

McMillan et al., GRL 2005.

1. Atmospheric InfraRed Sounder (AIRS) onboard NASA’s Aqua satellite.

2. CO abundances are retrieved from AIRS 4.55 μm spectral region.
Smoke plume rise under calm environment

Pictures taken by M.O. Andreae and M. Welling
Smoke plume rise under windy environment

Pictures taken by M. Welling.
The dynamic entrainment rate formulation

Consider a cylindrical volume of radius $R$ and depth $\Delta z$, the in-cloud horizontal mass flux is:

$$f_h = \rho_{\text{env}} (u_e - u)$$

The mass gained by cloud in $\Delta t$ is:

$$\Delta m = f_h (2R \Delta z) \Delta t = \rho_{\text{env}} (u_e - u) (2R \Delta z) \Delta t$$

The definition of the mass entrainment rate is

$$\delta_{\text{entr}} = \frac{1}{m} \frac{\Delta m}{\Delta t} = \frac{1}{\pi R^2 \Delta z \rho_{\text{cloud}}} \frac{\rho_{\text{env}} (u_e - u) (2R \Delta z) \Delta t}{\Delta t}.$$ 

Assuming that $\rho_{\text{cloud}} \approx \rho_{\text{env}}$

$$\therefore \delta_{\text{entr}} \approx \frac{2}{\pi R} (u_e - u)$$

List of symbols:

- $\rho_{\text{env}}, \rho_{\text{cloud}}$: environment air, cloud mass densities
- $u_e, u$: environment air and cloud horizontal wind velocities
- $R$: cloud radius at height $z$
### The 1D cloud model: governing equations (original formulation from the PLUMP model)

<table>
<thead>
<tr>
<th>Term</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{\partial w}{\partial t} + w \frac{\partial w}{\partial z} = \gamma g B - \frac{2\alpha}{R} w^2 )</td>
<td></td>
</tr>
<tr>
<td>( \frac{\partial T}{\partial t} + w \frac{\partial T}{\partial z} = -w \frac{g}{c_p} - \frac{2\alpha}{R} w (T - T_e) + \left( \frac{\partial T}{\partial t} \right)_{\text{microphysics}} )</td>
<td>only lateral (non-organized) entrainment ( L_{\text{entr}} = \frac{2\alpha}{R}</td>
</tr>
<tr>
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<td></td>
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<td></td>
</tr>
<tr>
<td>( \frac{\partial r_{\text{ice, rain}}}{\partial t} + w \frac{\partial r_{\text{ice, rain}}}{\partial z} = -\frac{2\alpha}{R} w r_{\text{ice, rain}} + \left( \frac{\partial r_{\text{ice, rain}}}{\partial t} \right)_{\text{microphysics}} + \text{sedim} )</td>
<td></td>
</tr>
<tr>
<td>( \left( \frac{\partial \xi}{\partial t} \right)_{\text{microphysics}} )</td>
<td>bulk microphysics: ( \xi = T, r_v, r_c, r_{\text{rain}}, r_{\text{ice}} )</td>
</tr>
</tbody>
</table>

Latham, 1994; Freitas et al., 2006, 2007
The 1D cloud model: including the environmental wind effect on cloud scale dilution-governing equations

\[
\frac{\partial w}{\partial t} + w \frac{\partial w}{\partial z} = \gamma g B - \frac{2 \alpha}{R} w^2 - \delta_{entr} w
\]

\[
\frac{\partial u}{\partial t} + w \frac{\partial u}{\partial z} = -\frac{2 \alpha}{R} |w|(u - u_e) - \delta_{entr}(u - u_e)
\]

\[
\frac{\partial T}{\partial t} + w \frac{\partial T}{\partial z} = -w \frac{g}{c_p} - \frac{2 \alpha}{R} |w|(T - T_e) + \left( \frac{\partial T}{\partial t} \right)_{micro-\text{physics}} - \delta_{entr}(T - T_e)
\]

\[
\frac{\partial r_v}{\partial t} + w \frac{\partial r_v}{\partial z} = -\frac{2 \alpha}{R} |w|(r_v - r_{ve}) + \left( \frac{\partial r_v}{\partial t} \right)_{micro-\text{physics}} - \delta_{entr}(r_v - r_{ve})
\]

\[
\frac{\partial r_c}{\partial t} + w \frac{\partial r_c}{\partial z} = -\frac{2 \alpha}{R} |w| r_c + \left( \frac{\partial r_c}{\partial t} \right)_{micro-\text{physics}} - \delta_{entr} r_c
\]

\[
\frac{\partial r_{\text{ice,rain}}}{\partial t} + w \frac{\partial r_{\text{ice,rain}}}{\partial z} = -\frac{2 \alpha}{R} |w| r_{\text{ice,rain}} + \left( \frac{\partial r_{\text{ice,rain}}}{\partial t} \right)_{micro-\text{physics}} + \text{sedim} - \delta_{entr} r_{\text{ice,rain}}
\]

\[
\frac{\partial R}{\partial t} + w \frac{\partial R}{\partial z} = \frac{6 \alpha}{5R} |w| R + \frac{1}{2} \delta_{entr} R
\]

\[
\left( \frac{\partial \xi}{\partial t} \right)_{micro-\text{physics}} \quad (\xi = T, r_v, r_c, r_{\text{rain}}, r_{\text{ice}}), \quad \text{sedim} \quad \text{Kessler, 1969; Berry, 1967}
\]

\[
\delta_{entr} = \frac{2}{\pi R} |u_e - u|
\]

See Freitas et al. (2009 ACPD) for 1d cloud model comparisons with fully 3D ATHAM simulations
Aerosol Optical Depth (550 nm): MODIS x MODEL

Model evaluation with SMOCC/RaCCI 2002 using near surface measurements (CO and PM2.5)

(A) MODIS AOT (550 nm) 27082002

(B) MODEL AOT (550 nm) 27082002

Model evaluation with SMOCC/RaCCI 2002 with airborne measurements (CO)

Freitas et al., 2009
Effect of time resolution of the inventory

Longo et al., 2009 (under review)
Air Quality forecast for South America:
http://meioambiente.cptec.inpe.br

Surface level CO (ppb)
12Z12SEP2007

500 hPa CO (ppb)

Mega Cities pollution
Biomass burning pollution
new fresh plume injected by pyrocumulus
Forecast 21UTC14SEP2009
Field campaign to evaluate plume model: prescribed fire in Alta Floresta (aug – 2010)

Avião Bandeirante do INPE para coleta de dados (meteorológicos e de química da atmosfera) e altura da pluma.

Radiossonda para aquisição do perfil atmosférico do ambiente no horário da queima.

Torre instrumentada com sensores de temperatura e velocidade vertical dentro da pluma.

Área de fogo.

Altura final de injeção da fumaça na atmosfera.
The lower boundary condition

Morton, Taylor & Turner (1956):
"Turbulent grav. convection from maintained and instantaneous sources"

\[
F = \frac{gR}{\pi c_p} E \quad \text{buoyancy flux}
\]

\[
R = \frac{6\alpha}{5} z \quad \text{plume radius}
\]

\[
w(z_v) = \frac{5}{6\alpha} \left( \frac{0.9\alpha F}{z_v} \right)^{1/3} \quad \text{boundary condition for } w
\]

\[
\Delta \rho \rho_e = \frac{5}{6\alpha} \frac{F}{g} z_v^{-5/3} \quad \text{density correction}
\]

\[
T(z_v) = \frac{T_e(z_v)}{1 - \frac{\Delta \rho}{\rho_e}} \quad \text{boundary condition for } T
\]

where: \( \alpha = 0.2 \) \quad \text{entrainment coefficient,}

\( z_v = 0.9\alpha^{-1} R_{surf} \) \quad \text{virtual boundary height}

\( A \equiv \text{plume area} \approx \text{instantaneous fire size} \)

\( E \equiv \text{convective energy from fire (Wm}^{-2}\) \)

\( E \approx 0.4 - 0.8 \quad \mathcal{E}_{\text{flux}} \quad \text{(McCarter & Broido, 1965)} \)

\[
\mathcal{E}_{\text{flux}} \quad \text{(heat flux)} = \frac{h\beta c}{\Delta t} \quad \beta = \text{fuel load / combustion factor}
\]

\( \Delta t = \text{flaming phase duration} \)

\[
W_{\text{flux}} \quad \text{(water flux)} = 0.5\beta c
\]
Example of the diurnal cycle of CO source emission field

Equiv. Pot. Temperature

CO without plume-rise

Source emission

(C) CO without PR (ppb)

CO with plume-rise

(D) CO with PR (ppb)
Plume-rise of vegetation fires: typical energy fluxes (kWm⁻²)

<table>
<thead>
<tr>
<th>Biome type</th>
<th>Lower bound kWm⁻²</th>
<th>Upper bound kWm⁻²</th>
<th>Flaming consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical forest</td>
<td>30.</td>
<td>80.</td>
<td>45%</td>
</tr>
<tr>
<td>Woody savanna - cerrado</td>
<td>4.4</td>
<td>23.</td>
<td>75%</td>
</tr>
<tr>
<td>Pasture - grassland cropland</td>
<td>3.3</td>
<td></td>
<td>97%</td>
</tr>
</tbody>
</table>

Directions to improve

1) Plume model needs the initial plume size (or fire size) and convective energy
Size of fire: 10 ha (dry/calm and wet/windy cases)

Main injection layer simulated by the ATHAM model.