MINISTÉRIO DA CIÊNCIA E TECNOLOGIA
INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS

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

Saulo R. Freitas, Karla M. Longo
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Grupo de Modelagem da Atmosfera e Interfaces
Modeling of the Atmosphere and its Interfaces Group

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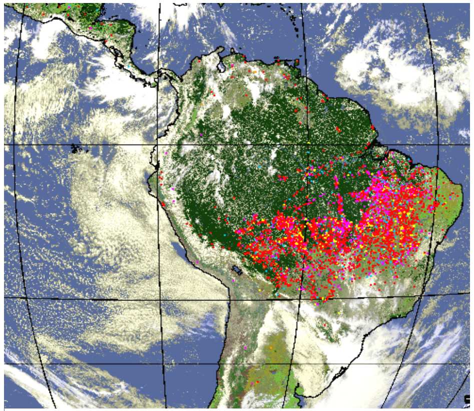
outline

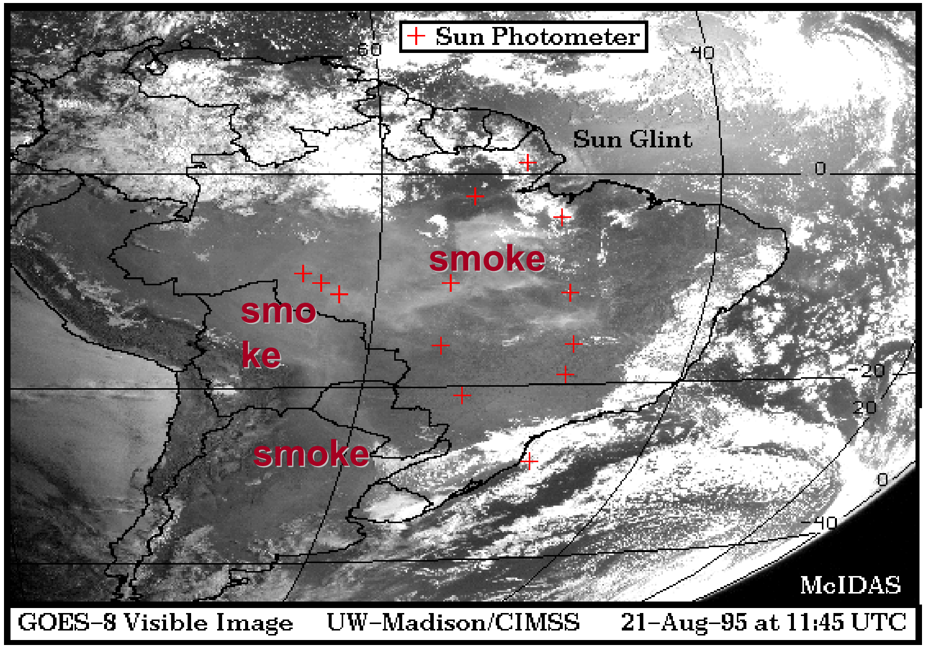
- Biomass burning on South America
- CCATT-BRAMS: mesoscale atmosferic-chemistry-aerosol model
- Near real time biomass burning emissions estimate
- Plumerise model for biomass burning smoke
- Real time forecast

Biomass Burning and Smoke on South America



GOES-8 WF_ABBA
(> 5000 fires)

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

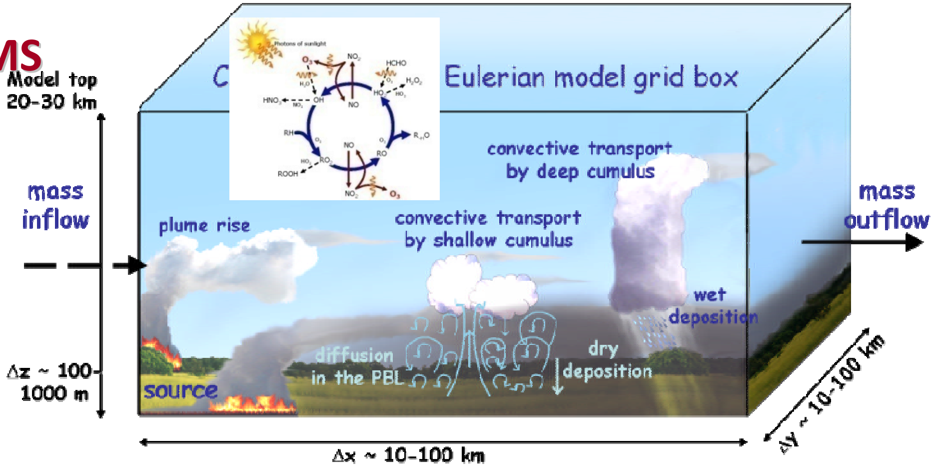


Regional smoke plume
~5 millions km^2
(Prins et al. 1998)

INPE developments on the atmospheric chemistry modeling

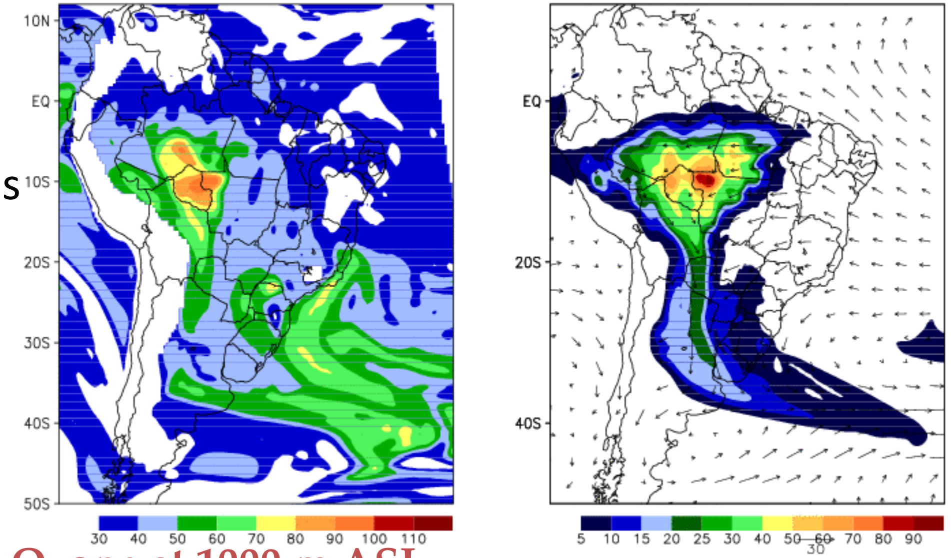
Coupled Chemistry-Aerosol-Tracer Transport model to the Brazilian developments on the RAMS

CCATT-BRAMS



- 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



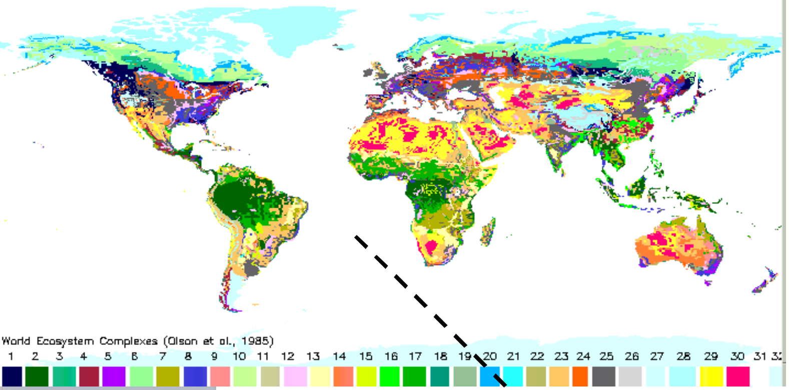
Ozone at 1000 m ASL

PM2.5 (bio. burn.) column

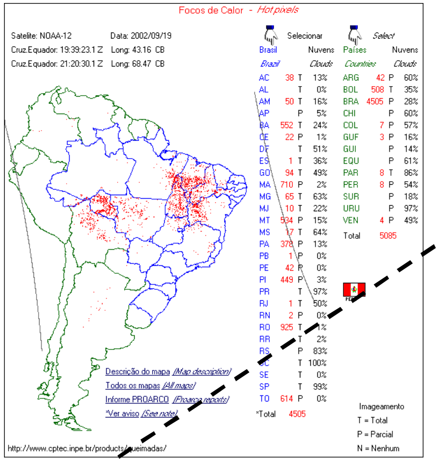
Biomass burning emissions inventory

Regional scale – daily basis

density of carbon data



near real time fire product



Focos de Calor - *Hot pixels*

Satelite: NOAA-12 Data: 2002/09/19

Cruz.Equador: 19:39:23.1 Z Long: 43.16 CB

Cruz.Equador: 21:20:30.1 Z Long: 68.47 CB

Brasil *Brazil*			Nuvens *Clouds*
AC	38	T	13%
AL		T	0%
AM	50	T	16%
AP		P	5%
BA	552	T	24%
CE	22	P	1%
DF		T	51%
ES	1	T	36%
GO	94	T	49%
MA	710	P	2%
MG	65	T	63%
MJ	10	T	22%
MT	534	P	15%
MS	17	T	64%
PA	378	P	13%
PB	1	P	0%
PE	42	P	0%
PI	449	P	3%
PR		T	97%
RJ	1	T	50%
RN	2	P	0%
RO	925	T	1%
RR		T	2%
RS		P	83%
SC		T	100%
SE		T	0%
SP		T	99%
TO	614	P	0%
*Total	4505		

Países *Countries*			Nuvens *Clouds*
ARG	42	P	60%
BOL	508	T	35%
BRA	4505	P	28%
CHI		P	60%
COL	7	P	57%
GUF	3	P	16%
GUI		P	14%
EQU		P	61%
PAR	8	T	86%
PER	8	P	54%
SUR		P	18%
URU		P	97%
VEN	4	P	49%
Total	5085		

Descrição do mapa *(Map description)*

Todos os mapas *(All maps)*

Informe PROARCO *(Proarco reports)*

*Ver aviso *(See note)*

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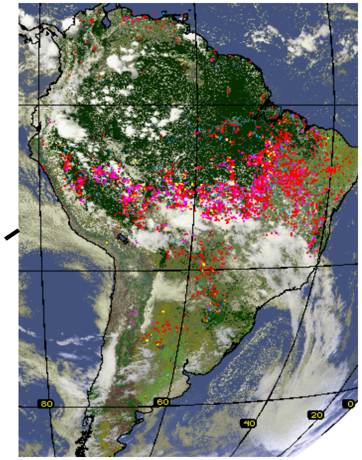
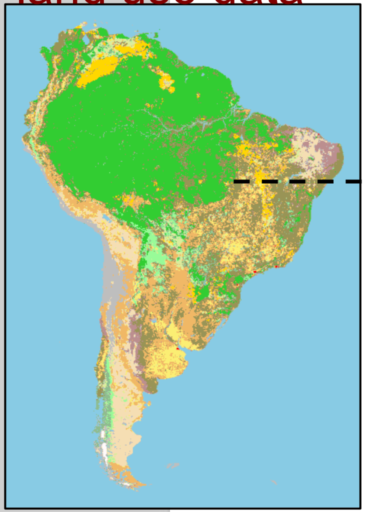
P = Parcial

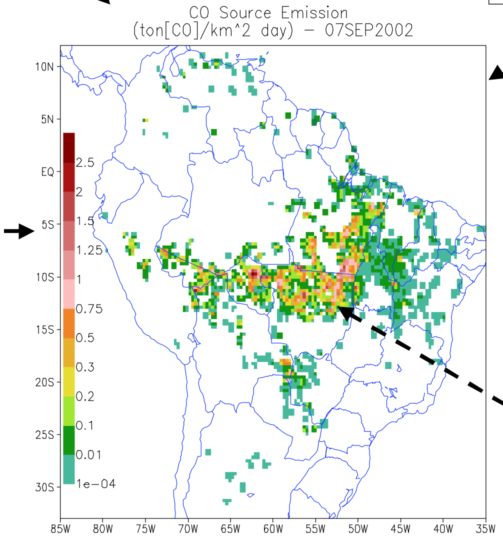
N = Nenhum

http://www.cptec.inpe.br/products/queimadas/



land use data





emission & combustion factors

Biome category	Emission Factor for CO (g/kg)	Emission Factor for PM2.5 (g/kg)	Aboveground biomass density (α, kg/m^2)	Combustion factor (β, fraction)
Tropical forest[1]	110.	8.3	20.7	0.48
South America savanna[2]	63.	4.4	0.9	0.78
Pasture[3]	49.	2.1	0.7	1.00

[1] Average values for primary and second-growth tropical forests, [2] Average values for campo cerrado (C3) and cerrado sensu stricto (C4), [3] value for campo limpo (C1). All numbers are from Ward et al.,

mass estimation

$$M_{[\eta]} = \alpha_{veg} . \beta_{veg} . \mathrm{E}f_{veg}^{[\eta]} . a_{fire} ,$$

CO source emission (kg m^{-2}day^{-1})

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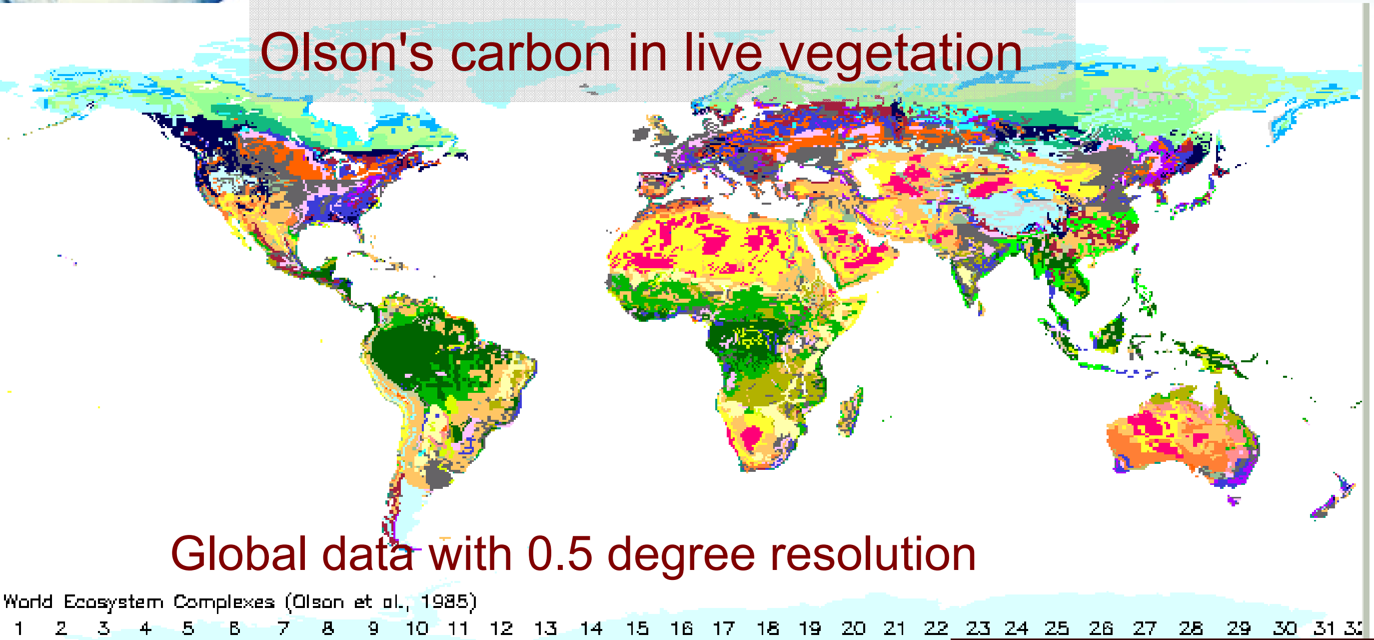
Aboveground Biomass Density

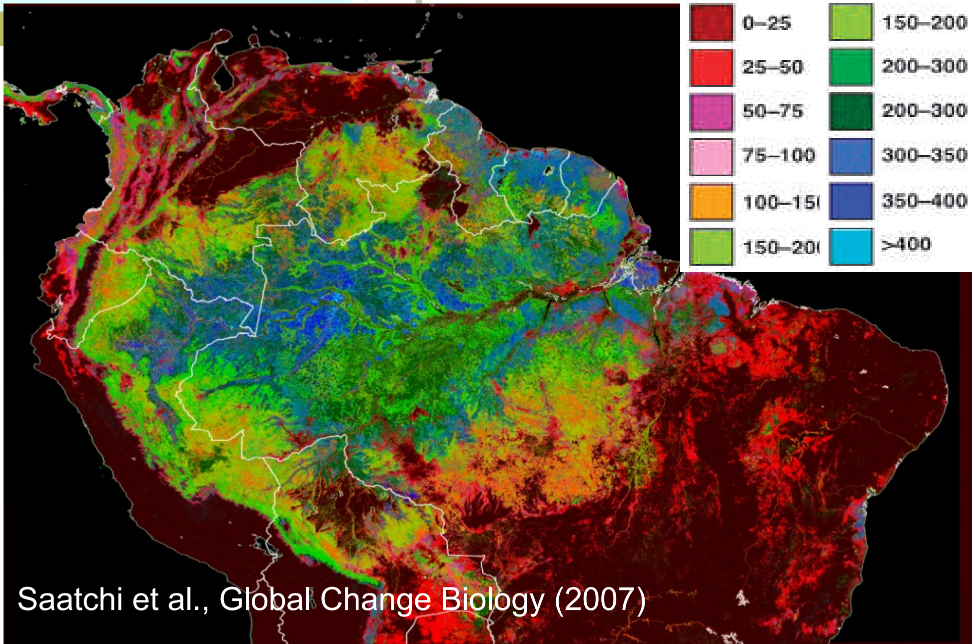


Olson's carbon in live vegetation

Global data with 0.5 degree resolution

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

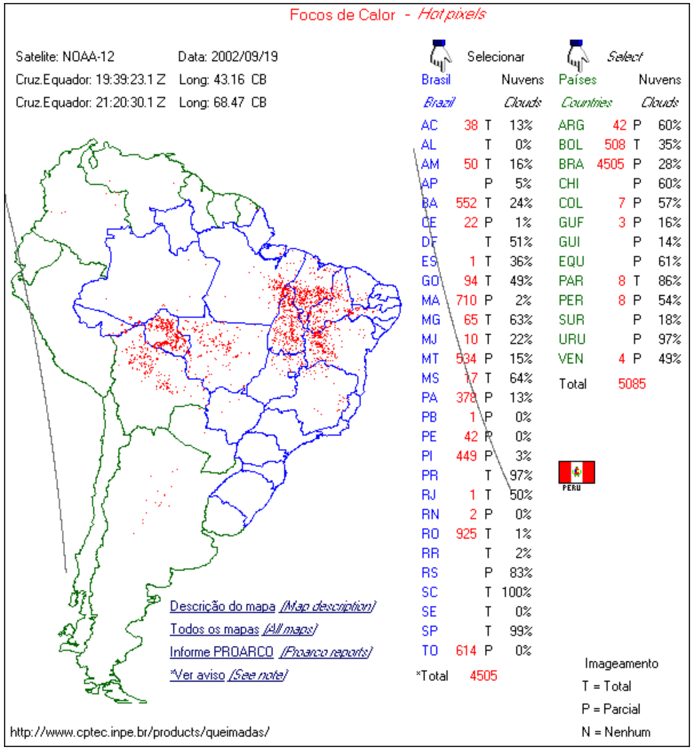
Amazon basin
1 km resolution



Saatchi et al., Global Change Biology (2007)

Fires position, timing and size using remote sensing products

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



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Selecionar *Select*

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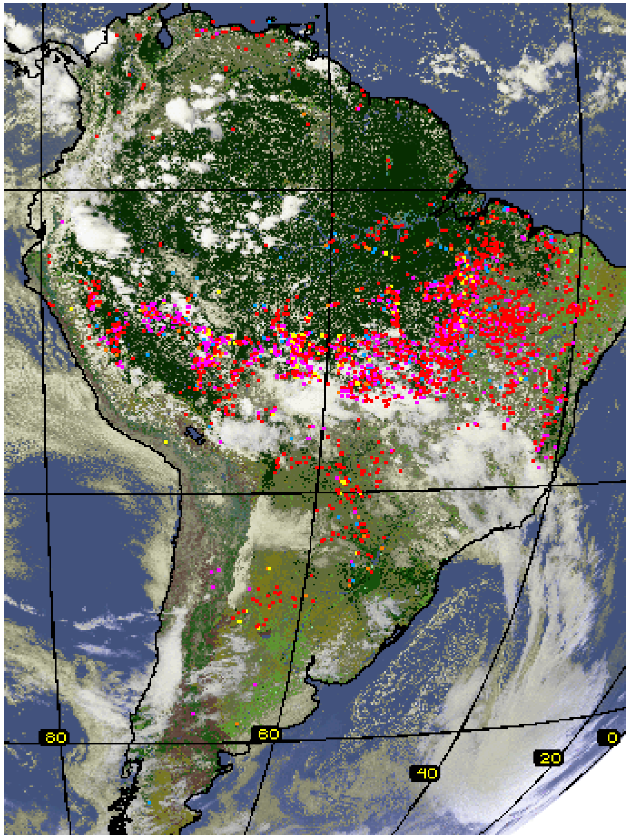
However, the burned area and the AGB are the main source of uncertainties for biomass burning emissions estimates

Fires WF_ABBA (GOES) CIMSS (E. Prins)



provides the diurnal cycle of the burning, each 1/2 hour.

provides an estimate of the instantaneous fire size.

Prep-Chem-Sources pre-processor

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): 8days/monthly – 1x1 degree.

-Emission Factors from Andreae and Merlet (2001), Ward et al 1992, Yokelson et al (200X)

110 species

Biomes: TropFor, ExtratropF, Savanna, Pasture, charcoal, waste, lab

CO2
CO
CH4
NHMC
C2H2
C2H4
C2H6
C3H4
C3H6
C3H8
1_butene
i-butene
tr_2_butene
cis_2_butene
butadiene

n_butane
i-butane
1_pentene
2_pentene
n_pentane
2_Me_Butene
2_Me_butane
pentadienes
Isoprene
cyclopentene
cyclopentadiene
4_me_1_pentene
2_me_1_pentene
1_hexene
hexadienes

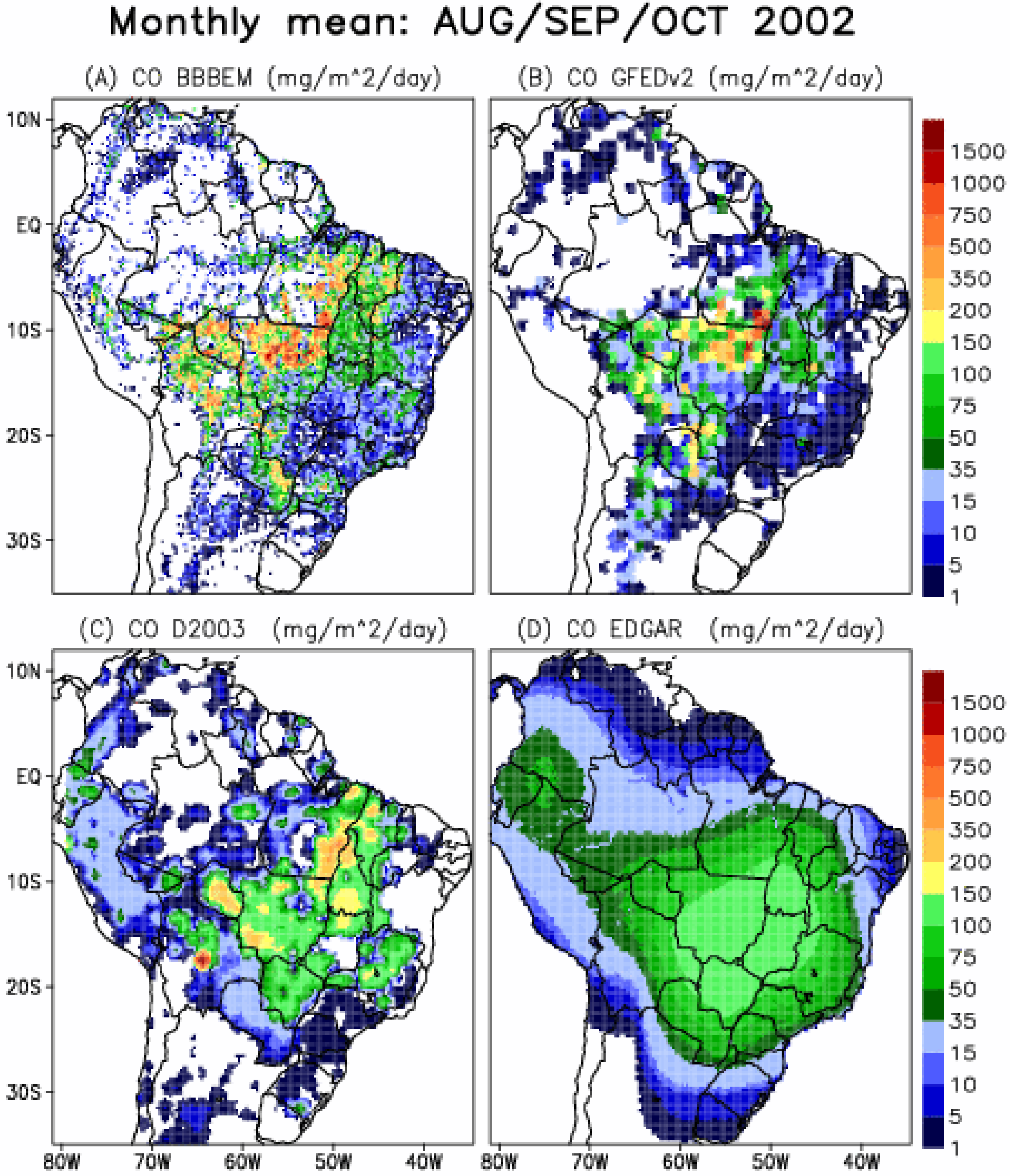
n_hexane
isohexanes
heptane
octenes
terpenes
benzene
toluene
xylenes
ethylbenzene
styrene
PAH
Methanol
Ethanol
1_Propanol
2_propanol

Butanols
cyclopentanol
phenol
Formaldehyde
Acetald
Hydroxyacetaldehyde
Acrolein
Propanal
Butanals
Hexanals
Heptanals
Acetone
2_Butanone
2_3_Butanedione
Pentanones
Hexanones

Heptanones
Octanones
Benzaldehyde
Furan
2_Me_Furan
3_Me_Furan
2_ethylfuran
2_4_dime_furan
2_5_Dime_furan
Tetrahydrofuran
2_3_dihydrofuran
benzofuran
Furfural
Me_format
Me_Acetate
Acetonitrile
Acrylonitrile
Propionitrile
pyrrole
trimethylpyrazole
methylamine
dimethylamine

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

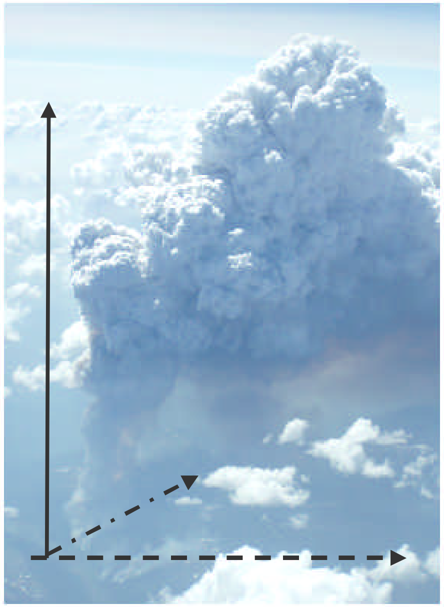


Longo et al., 2009 –
under review (EGU-ACP)

Including emission in the model

Biomass burning and wildfires

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

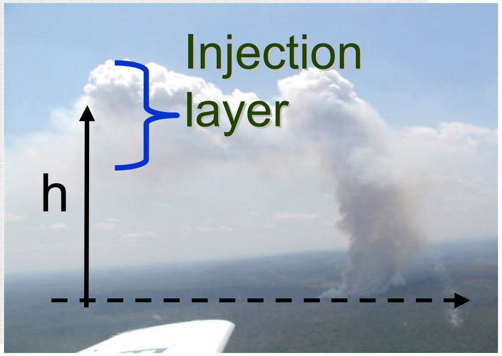


Plume rise model

total emission flux: F_η being λ the smoldering fraction

smoldering term : $E_\eta = \dfrac{\lambda F_\eta}{\rho_{air}\Delta z_{\text{first phys. model layer}}}$

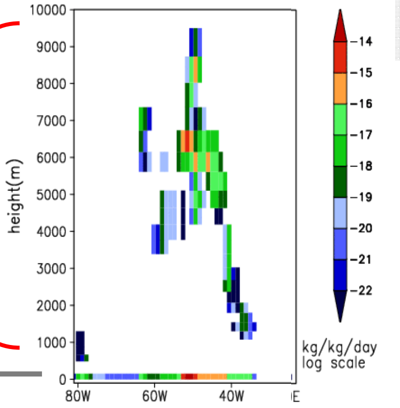
flaming term : $E_\eta = \dfrac{(1-\lambda) F_\eta}{\rho_{air}\Delta z_{\text{injection layer}}}$

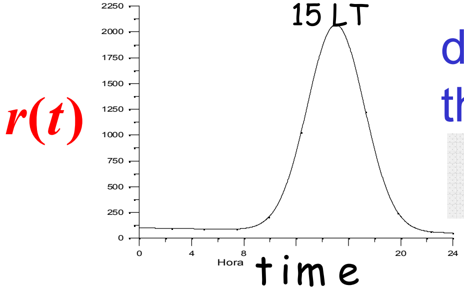


Example in the model:

flaming emission

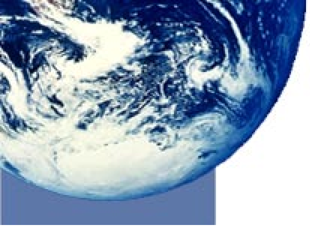
smoldering emission





diurnal cycle of the burning:

$E_\eta(t) = r(t) E_\eta$



The 1D cloud model: governing equations (original formulation from the PLUMP model)

dynamics for W

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

thermo-dynamics

$$\frac{\partial T}{\partial t} + w\frac{\partial T}{\partial z} = -w\frac{g}{c_p} - \frac{2\alpha}{R}|w|(T - T_e) + \left(\frac{\partial T}{\partial t}\right)_{\substack{micro-\\physics}}$$

water vapor conservation

$$\frac{\partial r_v}{\partial t} + w\frac{\partial r_v}{\partial z} = -\frac{2\alpha}{R}|w|(r_v - r_{ve}) + \left(\frac{\partial r_v}{\partial t}\right)_{\substack{micro-\\physics}}$$

cloud water conservation

$$\frac{\partial r_c}{\partial t} + w\frac{\partial r_c}{\partial z} = -\frac{2\alpha}{R}|w| r_c + \left(\frac{\partial r_c}{\partial t}\right)_{\substack{micro-\\physics}}$$

rain/ice Conservation

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

only lateral (non-organized) entrainment

$$L_{entr} = \frac{2\alpha}{R}|w|$$

bulk microphysics

$$\left(\frac{\partial \xi}{\partial t}\right)_{\substack{micro-\\physics}} \quad (\xi = T, r_v, r_c, r_{rain}, r_{ice}),\ \ \text{sedim}\left\{\begin{array}{l}\textit{bulk microphysics:}\\ \textit{Kessler, 1969; Berry, 1967}\\ \textit{Ogura \& Takahashi, 1971}\end{array}\right.$$

Latham, 1994; Freitas et al., 2006, 2007

Including plume rise mechanism trough *"super-parameterization"* concept

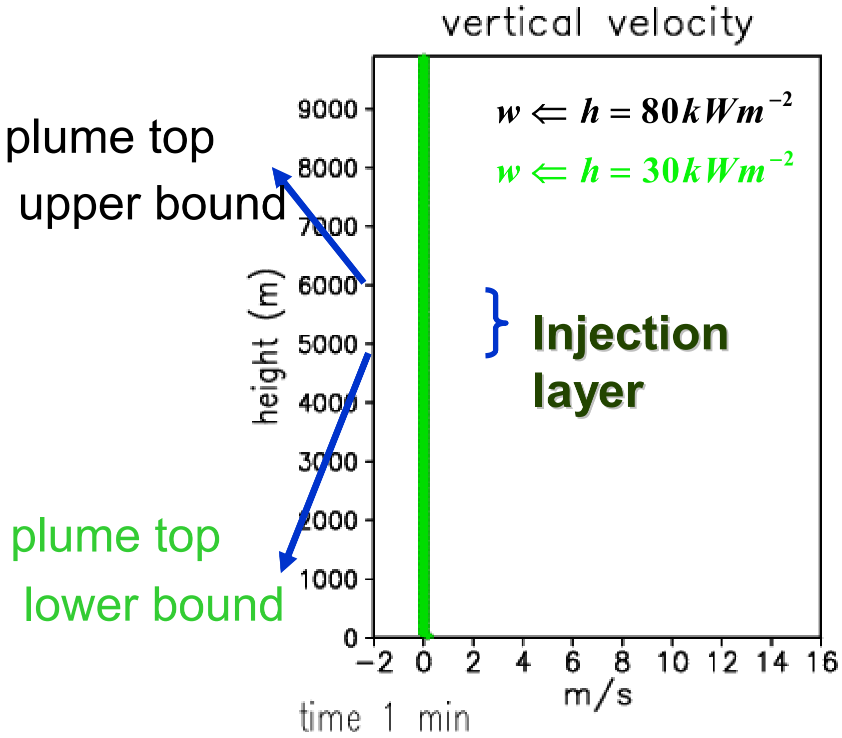
1D plume-rise model for vegetation fires

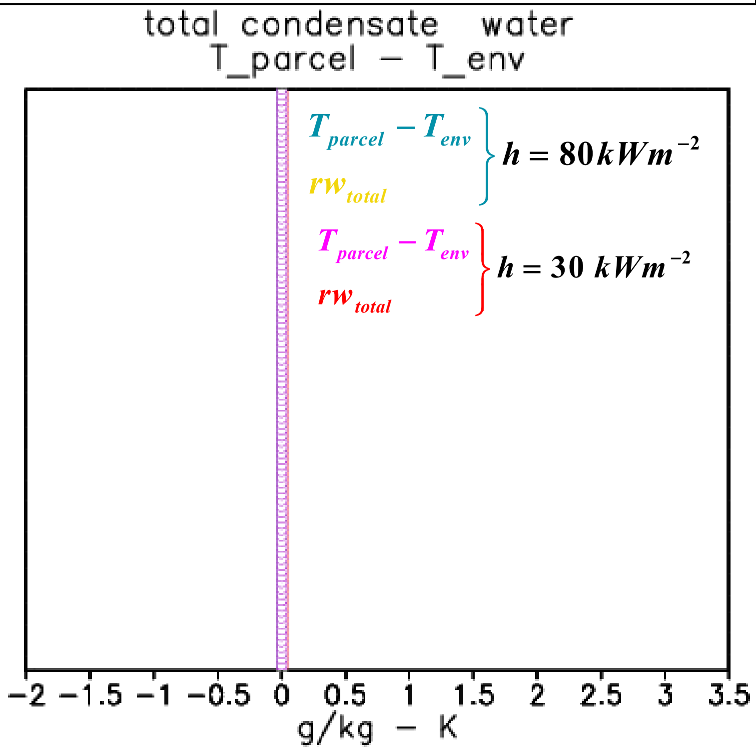
Biome: Forest

Time duration: 50 mn

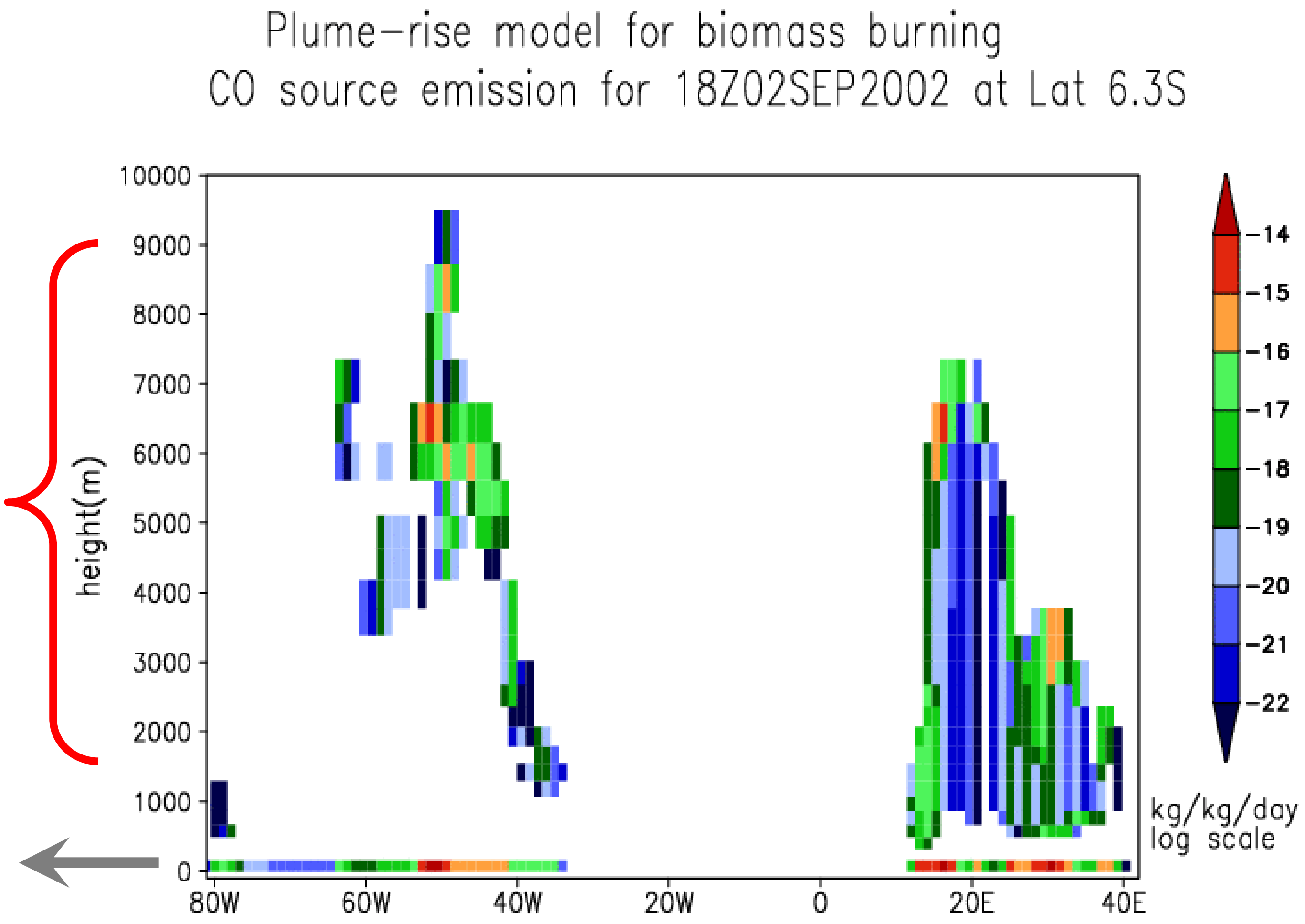
Fire size: 20 ha

Heat flux: 80 kWm^{-2} / 30 kWm^{-2}





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

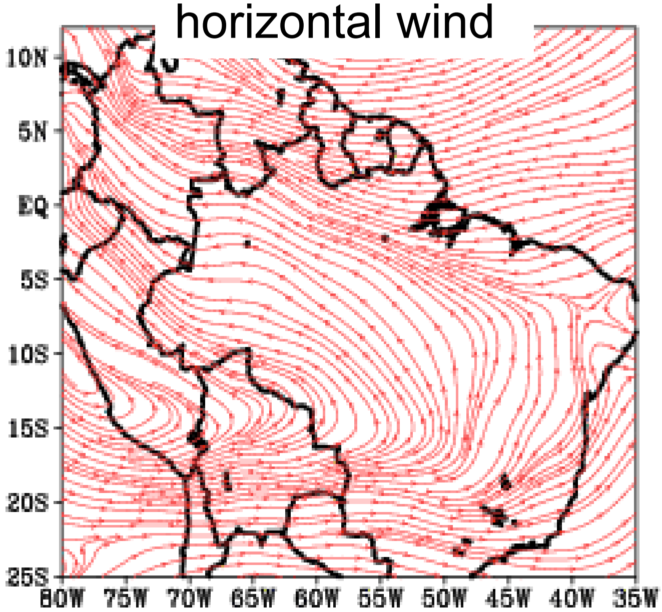
smoldering emission

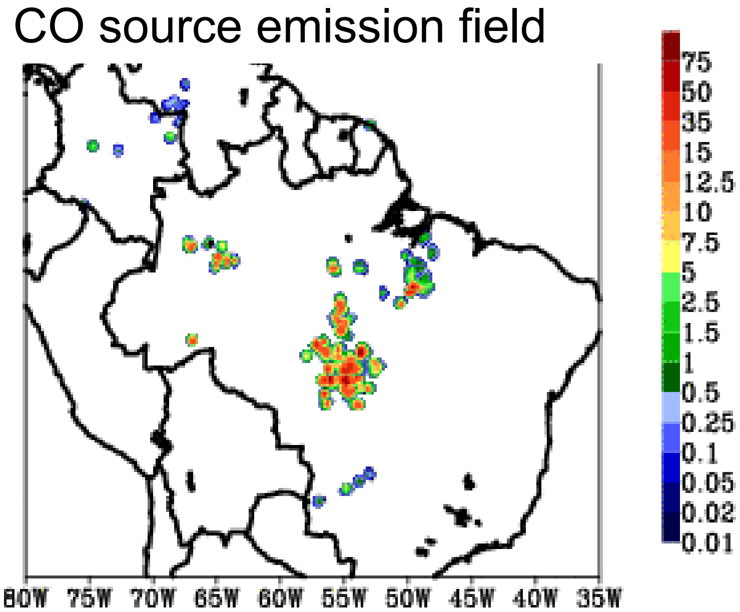
South America mostly forest fires

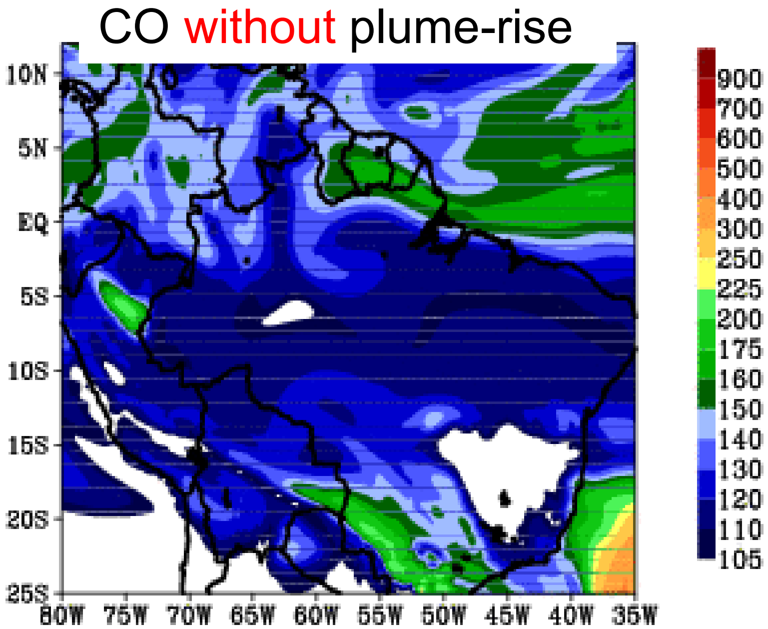
Africa mostly savanna fires

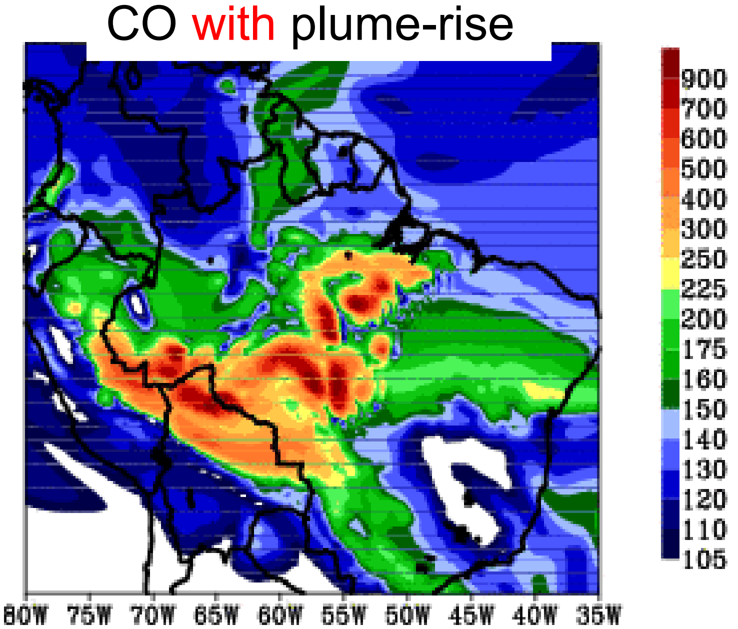
Example of CO with and without plume-rise at level 5.8 km:

03Z20SEP


horizontal wind


CO source emission field


CO without plume-rise

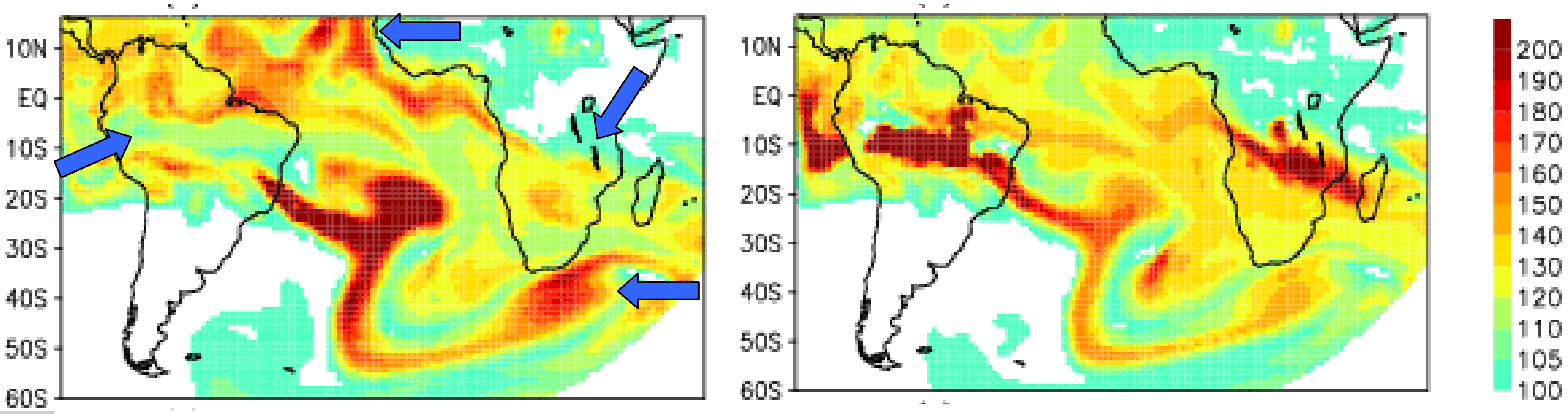

CO with plume-rise

CATT-BRAMS comparison with AIRS 500 hPa CO

Model CO (ppb) at ~5.8 km

without plume rise

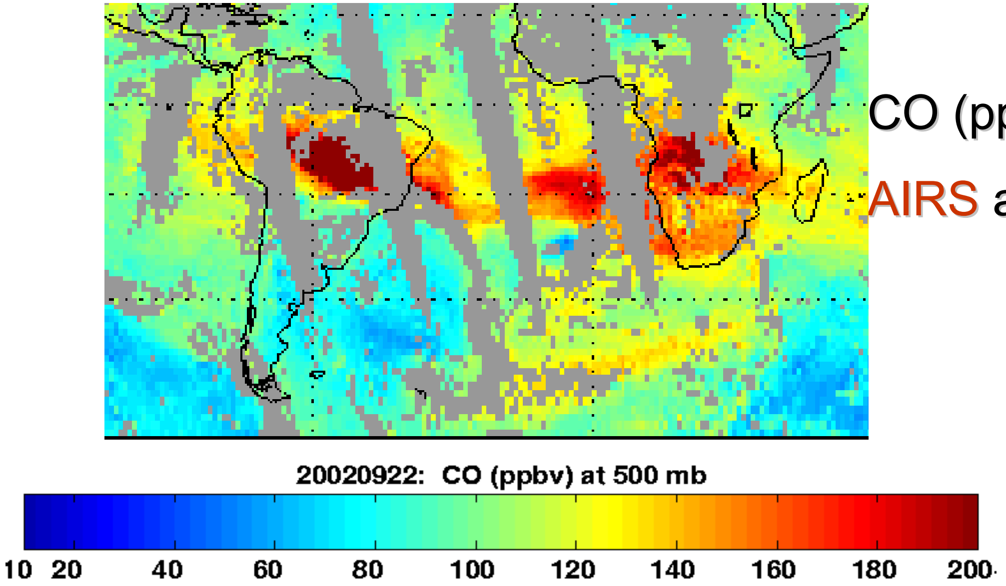
with plume rise



22 SEP 2002

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.**



CO (ppb) from AIRS at 500 hPa

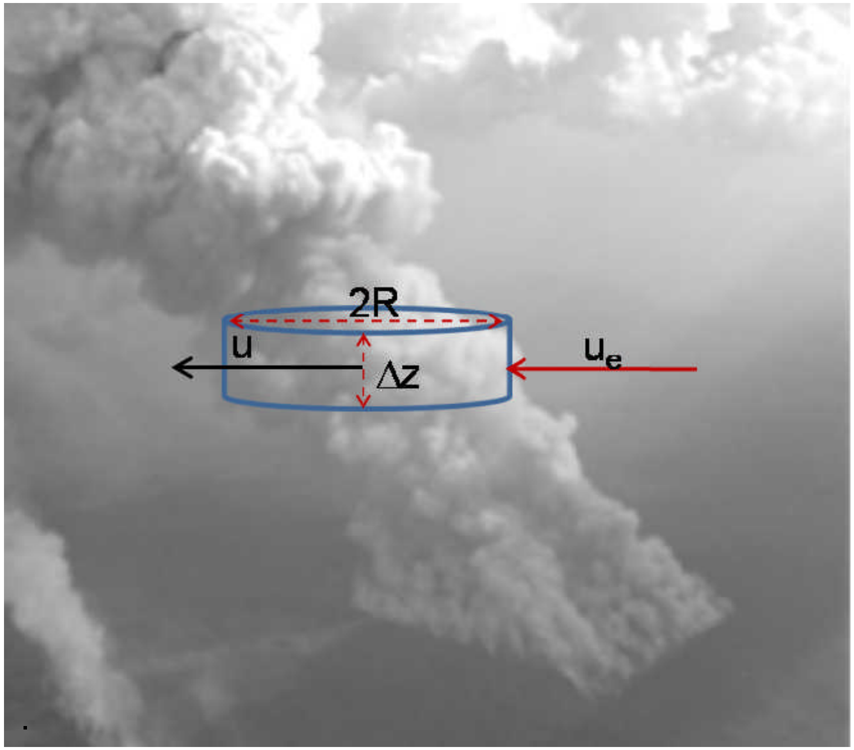
Smoke plume rise under calm environment

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 Δz, the in-cloud horizontal mass flux is:

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

The mass gained by cloud in Δt is:

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

The definition of the mass entrainment rate is

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

Assuming that $\rho_{cloud} \cong \rho_{env}$

$$\therefore$$

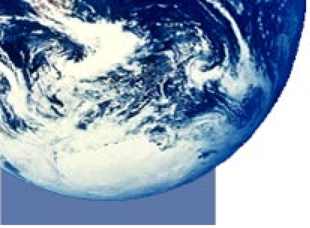
$$\delta_{entr} \cong \frac{2}{\pi R}(u_e - u)$$

List of symbols:

ρ_{env}, ρ_{cloud} : enviroment air, cloud mass densities

u_e, u : enviroment air and cloud horizontal wind velocities

R : cloud radius at height z



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water vapor conservation

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only lateral (non-organized) entrainment

$$L_{entr} = \frac{2\alpha}{R}|w|$$

bulk microphysics

$$\left(\frac{\partial \xi}{\partial t}\right)_{micro-physics} \quad (\xi = T, r_v, r_c, r_{rain}, r_{ice}), \quad \text{sedim}$$

bulk microphysics:
Kessler, 1969; Berry,1967
Ogura & Takahashi,1971

Latham, 1994; Freitas et al., 2006, 2007

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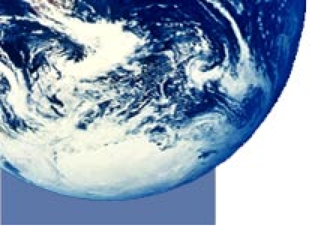

The 1D cloud model: including the environmental wind effect on cloud scale dilution- governing equations

dynamics for W

$$\frac{\partial w}{\partial t}+w\frac{\partial w}{\partial z}=\gamma gB-\frac{2\alpha}{R}w^{2}-\delta_{entr}w$$

dynamics for U

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

thermo-dynamics

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

water vapor conservation

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

cloud water conservation

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

rain/ice conservation

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

dynamic entrainment

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

equation for radius size

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

bulk microphysics

$$\left(\frac{\partial \xi}{\partial t}\right)_{\substack{micro-\\ physics}}\quad(\xi=T,r_v,r_c,r_{rain},r_{ice}),\quad \mathbf{sedim}\left\{\begin{array}{l}\textit{bulk microphysics:}\\ \textit{Kessler, 1969; Berry,1967}\\ \textit{Ogura \& Takahashi,1971}\end{array}\right.$$

See Freitas et al. (2009 ACPD) for 1d cloud model comparisons with fully 3D ATHAM simulations

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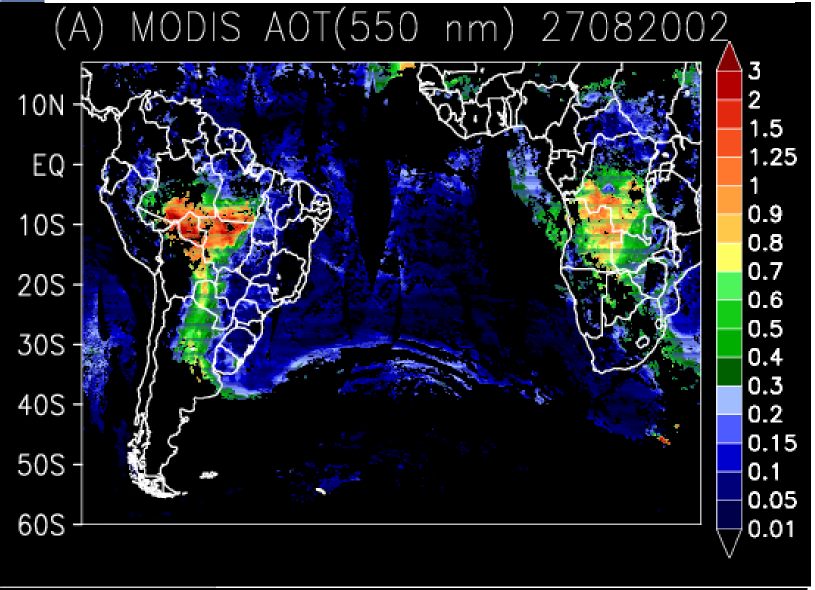
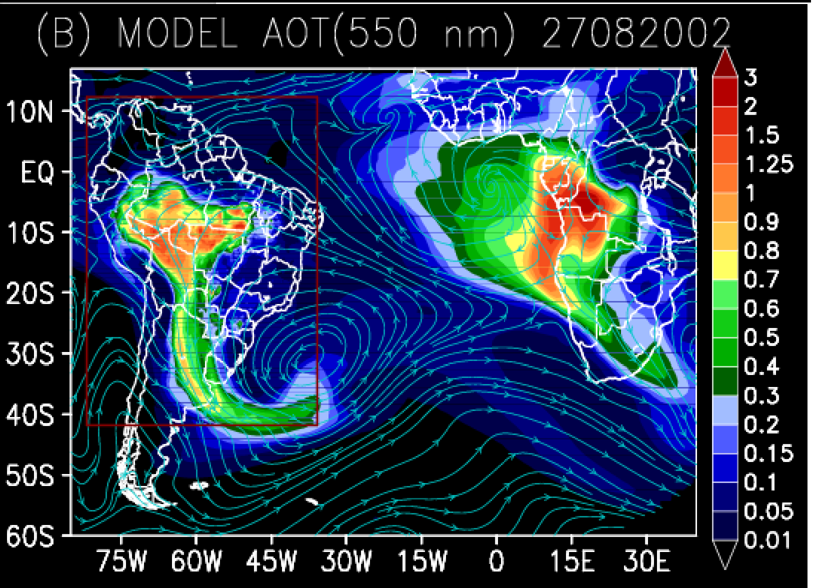
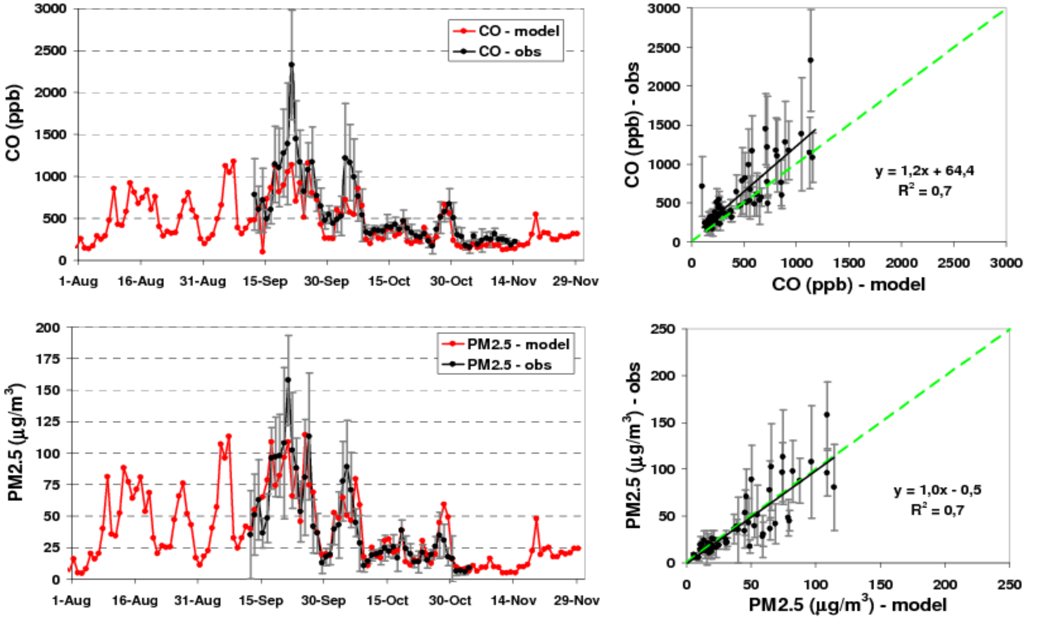
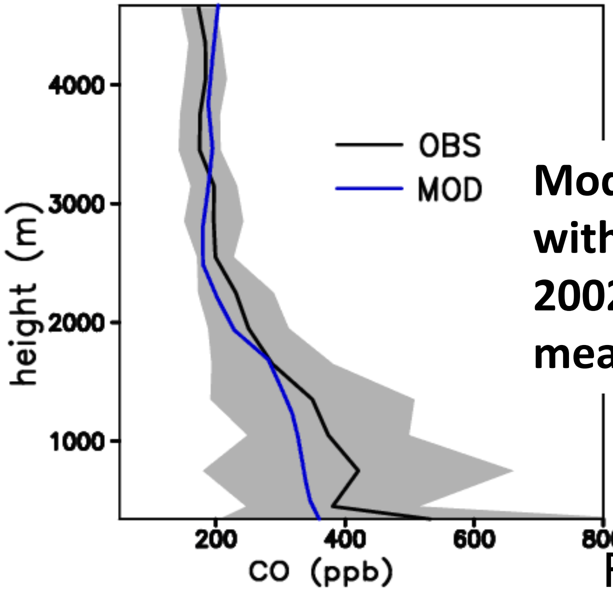
Aerosol Optical Depth (550 nm) : MODIS x MODEL





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

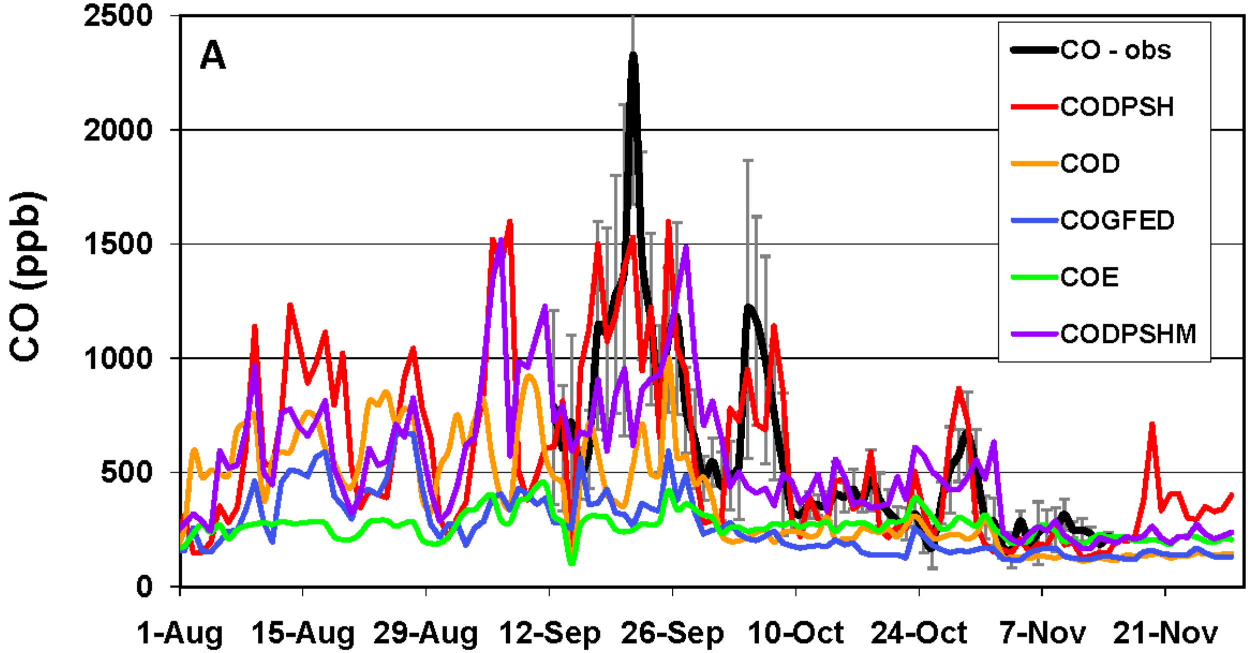


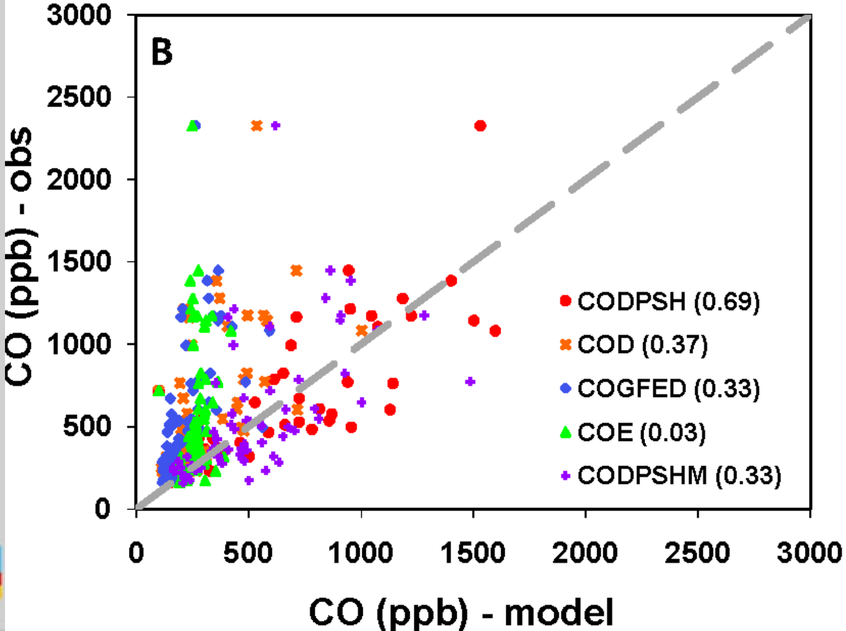


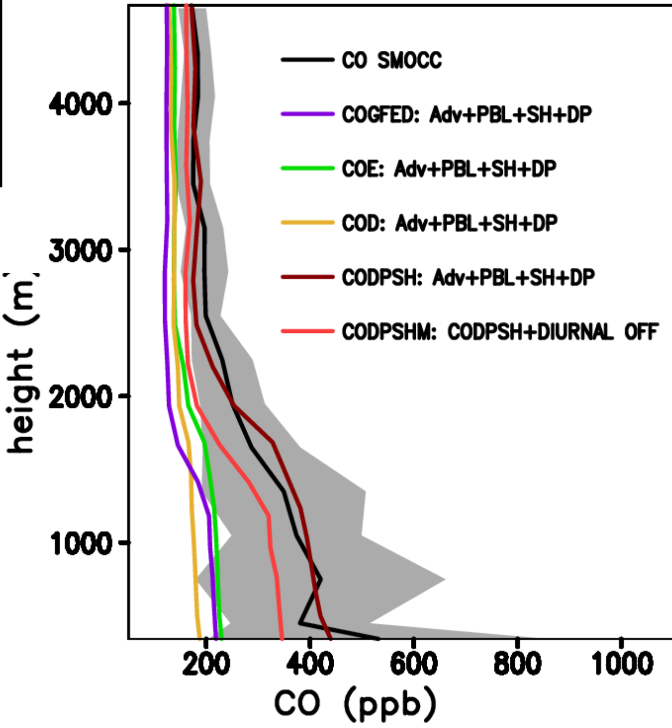
Model evaluation with SMOCC/RaCCI 2002 with airborne measurements (CO)

Freitas et al., 2009

Effect of time resolution of the inventory







Longo et al., 2009
(under review)

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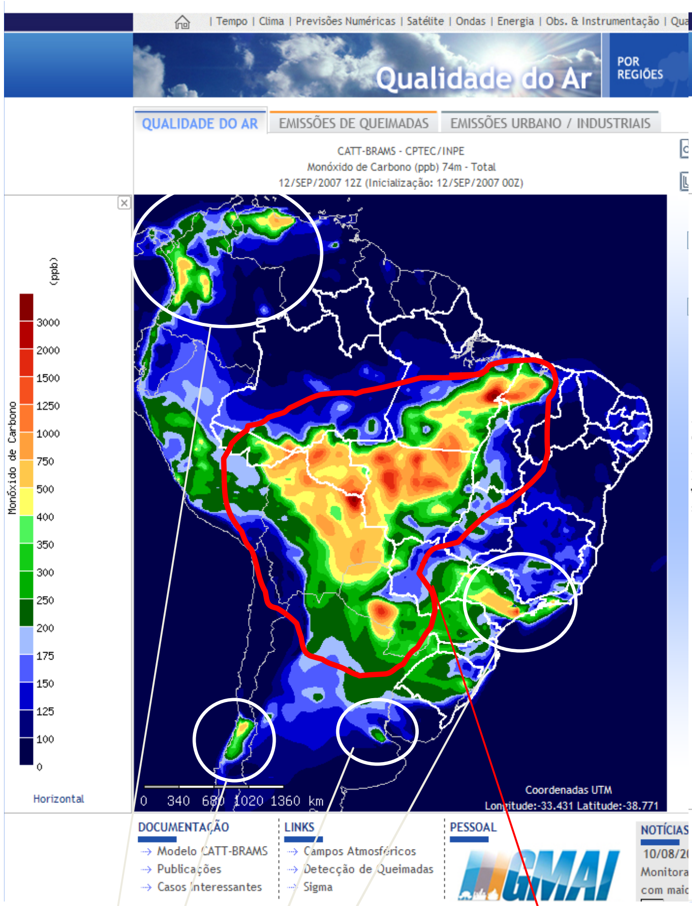
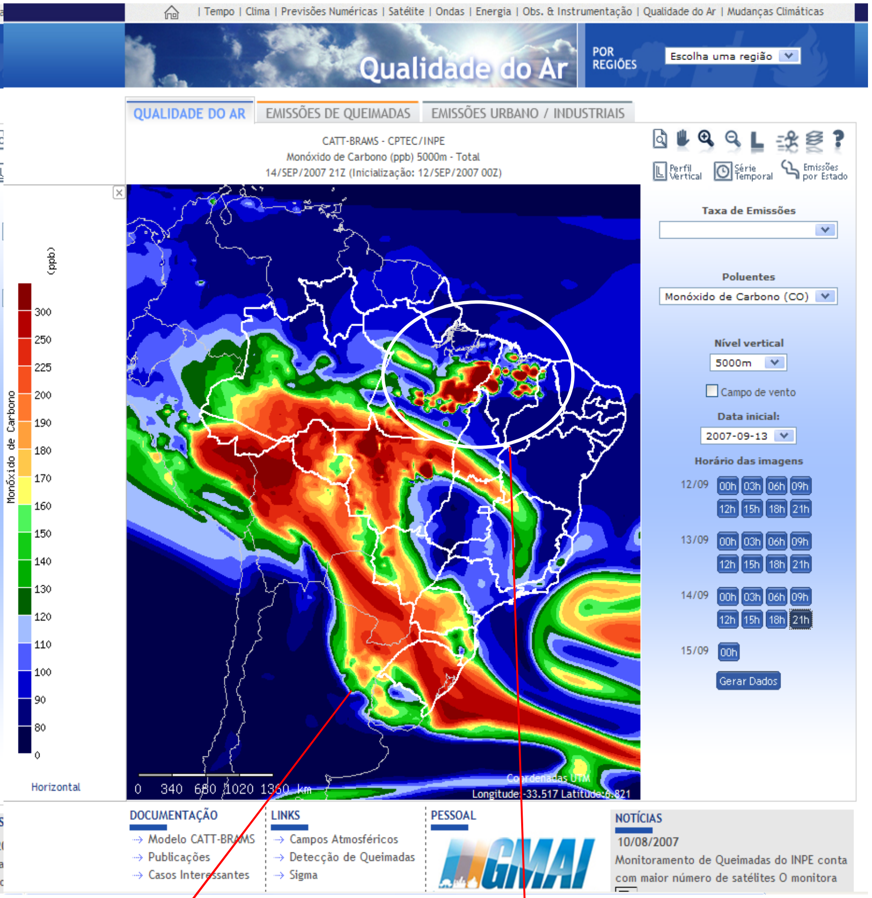
Air Quality forecast for South America: http://meioambiente.cptec.inpe.br

Surface level CO (ppb)
12Z12SEP2007

500 hPa CO (ppb)


CATT-BRAMS - CPTEC/INPE
Monóxido de Carbono (ppb) 74m - Total
12/SEP/2007 12Z (Inicialização: 12/SEP/2007 00Z)

Coordenadas UTM
Longitude:-33.431 Latitude:-38.771


CATT-BRAMS - CPTEC/INPE
Monóxido de Carbono (ppb) 5000m - Total
14/SEP/2007 21Z (Inicialização: 12/SEP/2007 00Z)

Poluentes: Monóxido de Carbono (CO)
Nível vertical: 5000m
Data inicial: 2007-09-13

Coordenadas UTM
Longitude:-33.517 Latitude:6.821

NOTÍCIAS
10/08/2007
Monitoramento de Queimadas do INPE conta com maior número de satélites O monitora

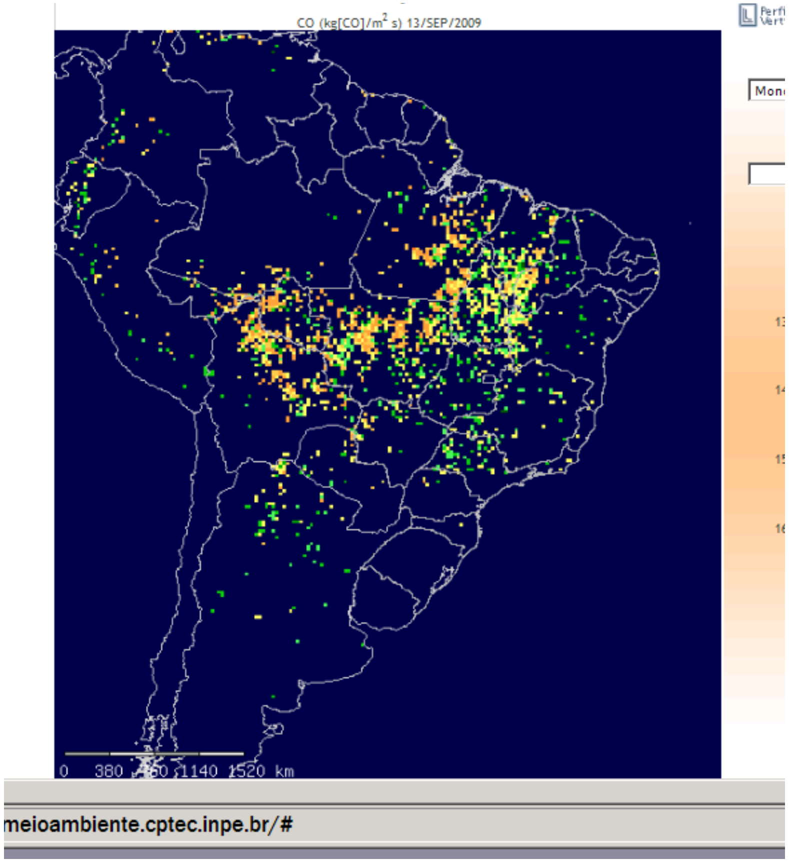
Mega Cities pollution

Biomass burning pollution

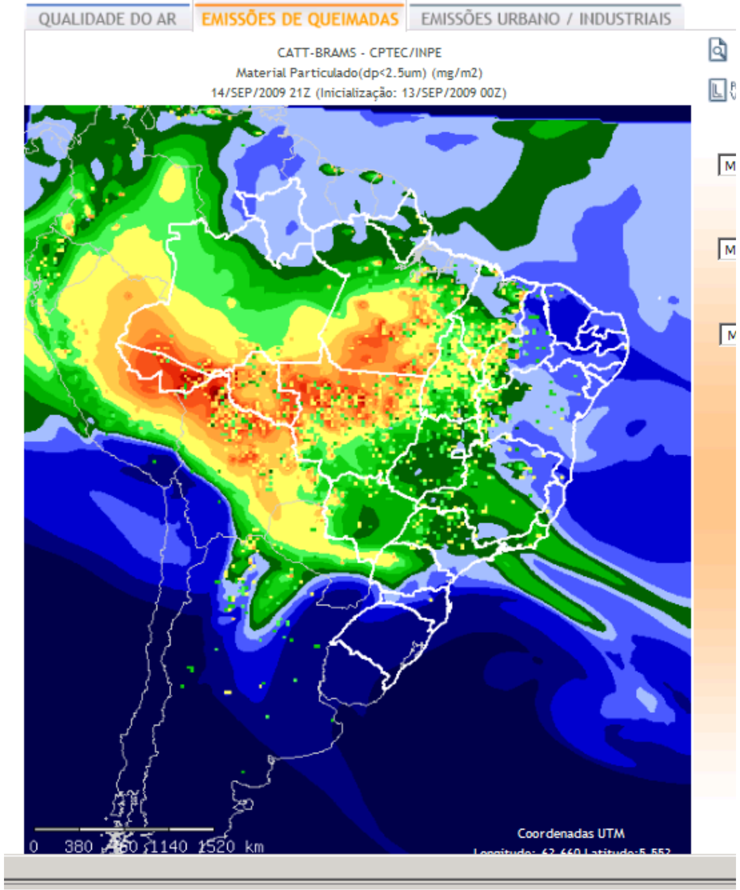
new fresh plume injected by pyrocumulus

BRAMS

Forecast 21UTC14SEP2009

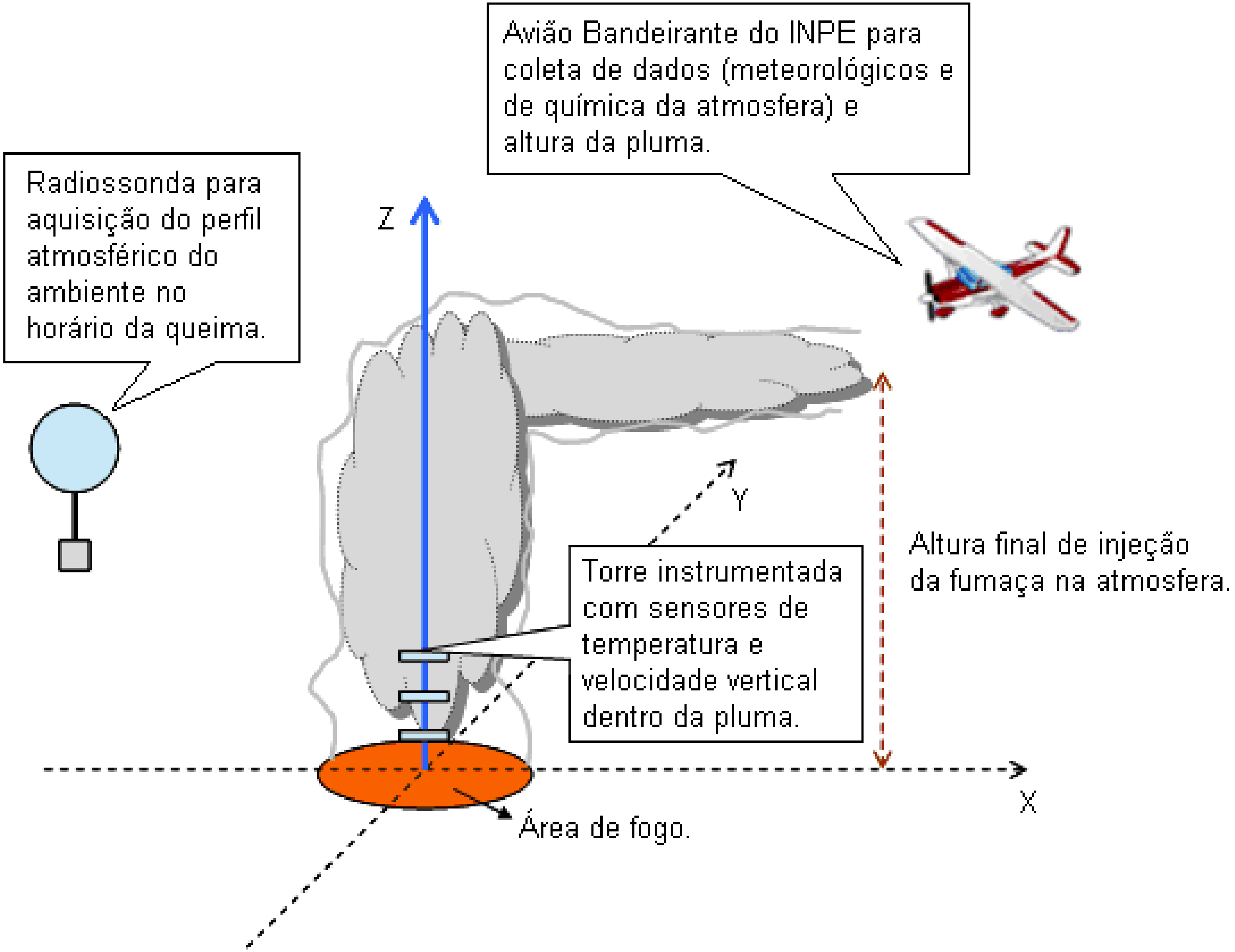

CO (kg[CO]/m^2 s) 13/SEP/2009

meioambiente.cptec.inpe.br/#



CATT-BRAMS - CPTEC/INPE
Material Particulado(dp<2.5um) (mg/m2)
14/SEP/2009 21Z (Inicialização: 13/SEP/2009 00Z)

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.

Altura final de injeção da fumaça na atmosfera.

Área de fogo.

The lower boundary condition

Morton, Taylor & Turner (1956):

"Turbulent grav. convection from maintained and instantaneous sources"

$$F = \frac{g\Re E}{\pi c_p \rho_e} A$$ buoyancy flux

$$R = \frac{6\alpha}{5} z$$ plume radius

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

$$\frac{\Delta\rho}{\rho_e} = \frac{5}{6\alpha}\,\frac{F}{g}\,\frac{z_v^{-5/3}}{\left(0.9\alpha F\right)^{1/3}}$$ density correction

$$T(z_v) = \frac{T_e(z_v)}{1 - \frac{\Delta\rho}{\rho_e}}$$ boundary condition for T

where: $\alpha = 0.2$ entrainment coefficient,

$z_v = 0.9\alpha^{-1} R_{surf}$ virtual boundary height

the closure

$\mathbf{A} \equiv$ plume area $\approx$ instantaneous fire size

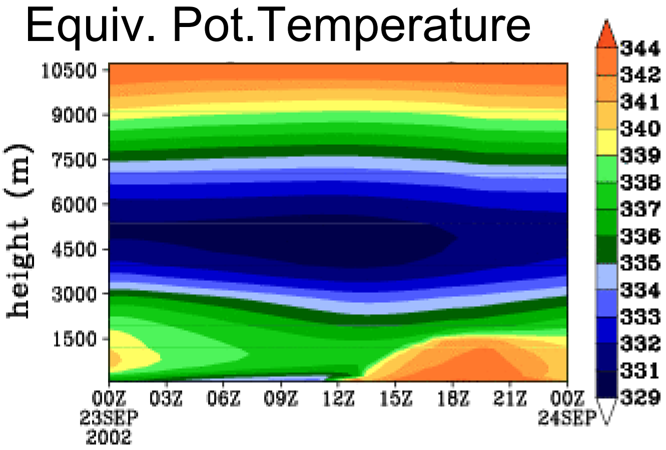
$\mathbf{E} \equiv$ convective energy from fire (Wm^{-2})

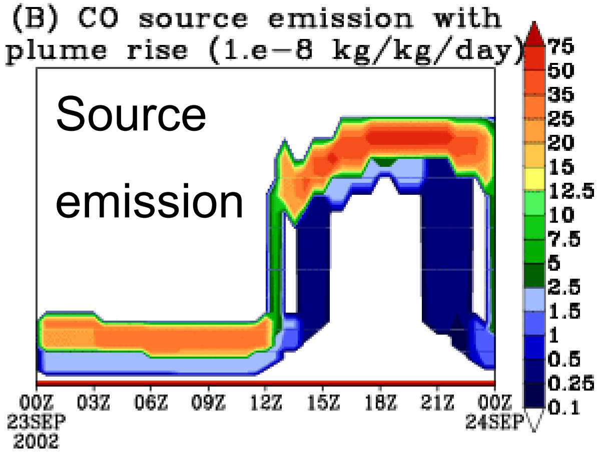
$\mathbf{E} \cong 0.4 - 0.8\ \Xi_{\mathbf{flux}}$ (McCarter & Broido, 1965)

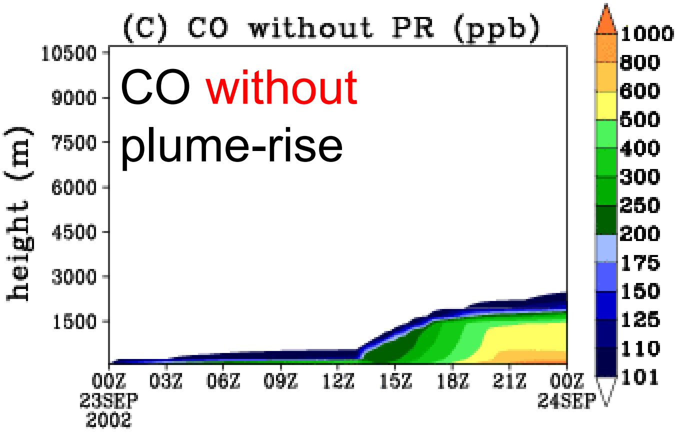
$$\Xi_{\mathbf{flux}}\text{(heat flux)} = \frac{\mathbf{h}\beta\mathbf{c}}{\Delta\mathbf{t}} \begin{cases} \mathbf{h} = 1.5 \text{ to } 2.1\ 10^7 \text{ joules kg}^{-1} \\ \beta\mathbf{c} = \text{ fuel load / combustion factor} \\ \Delta\mathbf{t} = \text{ flaming phase duration} \end{cases}$$

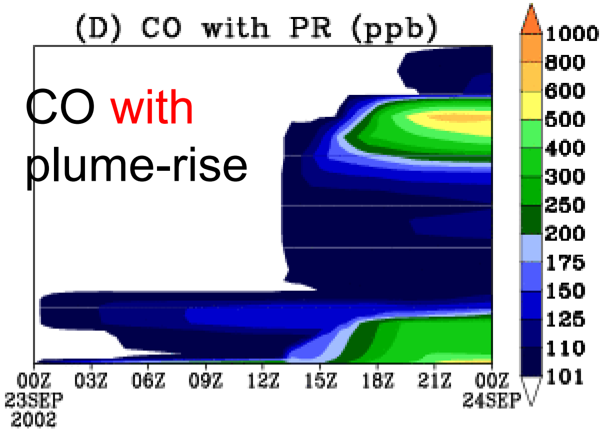
$$\mathbf{W}_{\mathbf{flux}}\text{(water flux)} = \mathbf{0.5}\beta\mathbf{c}$$

Example of the diurnal cycle of CO source emission field









00Z time 24Z

00Z time 24Z

Plume-rise of vegetation fires:
typical energy fluxes (kWm^{-2})

Biome type	Lower bound kWm^{-2}	Upper bound kWm^{-2}	Flaming consumption
Tropical forest	30.	80.	45%
Woody savanna - cerrado	4.4	23.	75%
Pasture - grassland cropland	3.3		97%

Refs: Carvalho et al, 1995-2001-2005 (com. pessoal);

Riggan et al, 2004;

Ward et al, 2002;

Ferguson et al, 1998;

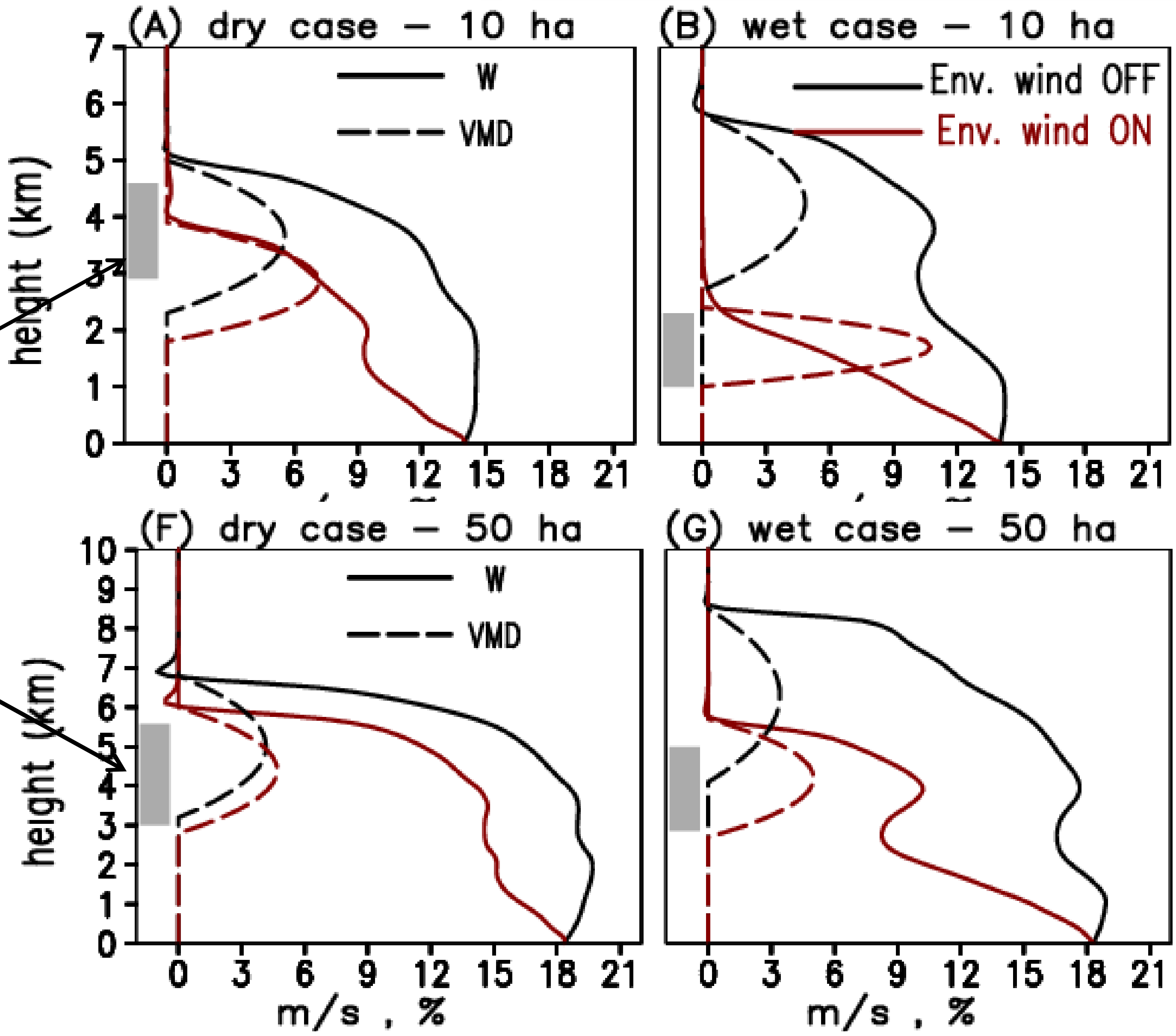
Cochrane et al; 200X-com. pessoal;

Miranda et al, 1993.

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