Accounting for Fire Injection Height in Climate Studies

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Contributions from:
New Student (UCI)

Presented to: Somewhere over the Rainbow
(Web: `http://dust.ess.uci.edu/smn/smn_fr.pdf`)

1. Fire Energetics

1. Combusting a mass of fuel M liberates a total energy E in the form of radiation R, sensible heat (enthalpy) H, latent heat L, ground storage G, and chemical transformation C:

$$\begin{aligned} E &= \text{Total energy liberated by combustion} \\ E &= R + H + L + G + C \qquad (1) \end{aligned}$$

Controlled experiments show that Fire Radiative Energy R is proportional to total combustion $R \propto E$.

Field estimates of H range from 1474 $\mathrm{W\,m^{-2}}$ (vegetation fires in Brazil), 3255 $\mathrm{W\,m^{-2}}$ (cerrado and gallery forest burning in Brazil), 7205 $\mathrm{W\,m^{-2}}$ (burning slashed tropical forest in Brazil), and 28000 $\mathrm{W\,m^{-2}}$ (rainforest clearing in Brazil) (Freitas et al., 2006b).

2. Fire Radiative Power

Satellites retrievals use a Fire Thermal Anomaly (FTA) method to determine the (broadband) Fire Radiative Power (FRP):

$$\mathrm{FRP}\,[\mathrm{W\,m^{-2}}] = \frac{\mathrm{d}R}{\mathrm{d}t} \tag{2}$$

The MODIS FTA Giglio et al. (2003), e.g., inverts the difference between observed mid-infrared fire-radiance $I_{\mathrm{f}}^{+}(3.96\,\mu\mathrm{m})$ and fire-free, cloud-free radiance $I_{\mathrm{nf}}^{+}(3.96\,\mu\mathrm{m})$:

$$\mathrm{FRP} \propto I_{\mathrm{f}}^{+}(3.96\,\mu\mathrm{m}) - I_{\mathrm{nf}}^{+}(3.96\,\mu\mathrm{m}) \tag{3}$$

$I_{\mathrm{nf}}^{+}(3.96\,\mu\mathrm{m})$ can be estimated from nearby fire-free, cloud-free pixels. MODIS determines the absolute FRP using Kaufman et al. (1998)

$$\mathrm{FRP}\,[\mathrm{MW}] = C \times [T_{\mathrm{B,f}}^{8}(3.96\,\mu\mathrm{m}) - T_{\mathrm{B,nf}}^{8}(3.96\,\mu\mathrm{m})] \times A\,[\mathrm{km}^2] \tag{4}$$

$$\text{where} \quad C \equiv 4.34 \times 10^{-19}\,\mathrm{MW\,K^{-8}\,km^{-2}} \tag{5}$$

The European geostationary satellite SEVERI FTA/FRP algorithm is similar.

3. Fire Injection Modules

A Fire Injection Module (FIM) introduces physical perturbations of fires into a model for assessing the the fire-forcing of the environment. Perturbations which could be injected include

1. Radiant energy
2. Sensible heat
3. Ground heat
4. Water vapor
5. non-$\mathrm{H_2O}$ Gases (CO, $\mathrm{NO_x}$, etc.)
6. Black Carbon (BC)
7. Organics (OC)

The current CCSM FIM in SNICAR injects aerosols (only) using GFED2 interpolated monthly $1^\circ \times 1^\circ$ emissions from 1997–2006.

4. Current FIM Limitations

Limitations of current CCSM FIM include:

1. Surface emissions neglect convection (dry+moist)
2. Neglects diurnal cycle of emissions
3. Neglects precipitation/soil moisture/humidity controls
4. Neglects fuel hysteresis
5. BB optical properties independent of underlying PFT
6. BB optical properties independent of burn temperature

These significant limitations are largely mutually independent. They can all be reduced using existing data. Try to tackle pyro-convection because vertical transport important for:

1. Aerosol lifetime
2. Ratio of super:sub-cloud aerosol
3. Direct radiative forcing
4. Semi-direct radiative forcing
5. Cloud indirect effects

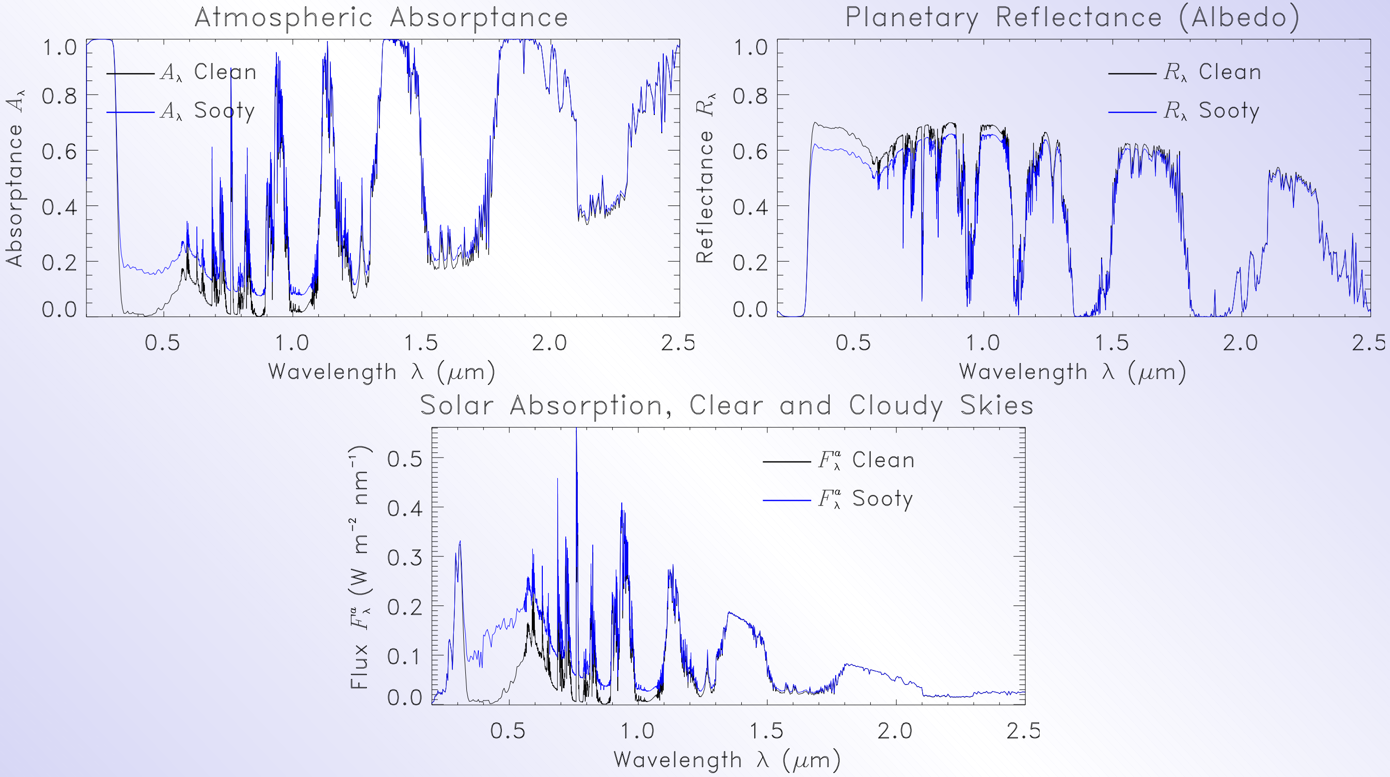


Figure 1: BC semi-direct effect: (a) Atmospheric absorptance, (b) planetary reflectance, and (c) spectral absorption of sunlight in clean and polluted cloud conditions (BC, MLS, $\tau = 0.1$, LWP $= 100\,\mathrm{g\,m^{-2}}$).

5. Existing FIMs

5.1. ATHAM

Trentmann et al. (2006) and Luderer et al. (2006) use ATHAM, an embeddable non-hydrostatic model with turbulence, radiation, prescribed aerosol activation (5% BB are CCN). Their simulations of the (huge) Chisholm fire in Alberta, Canada, May 2001 demonstrate:

1. Outflow significantly higher than LNB of background atmosphere
2. Fire sensible heat H more important than fire $q_{\mathrm{H_2O}}$ in determining convective profile
3. Fire sensible heat H is only $\sim 30\%$ of pyroCb condensation!
   $\longrightarrow$ Cloud effects dominate deep pyroCb
4. PyroCb unlikely to scavenge most BB
5. BB aerosol delay freezing onset and thereby inhibit pyroCb. Other (less realistic?) studies conclude the opposite.

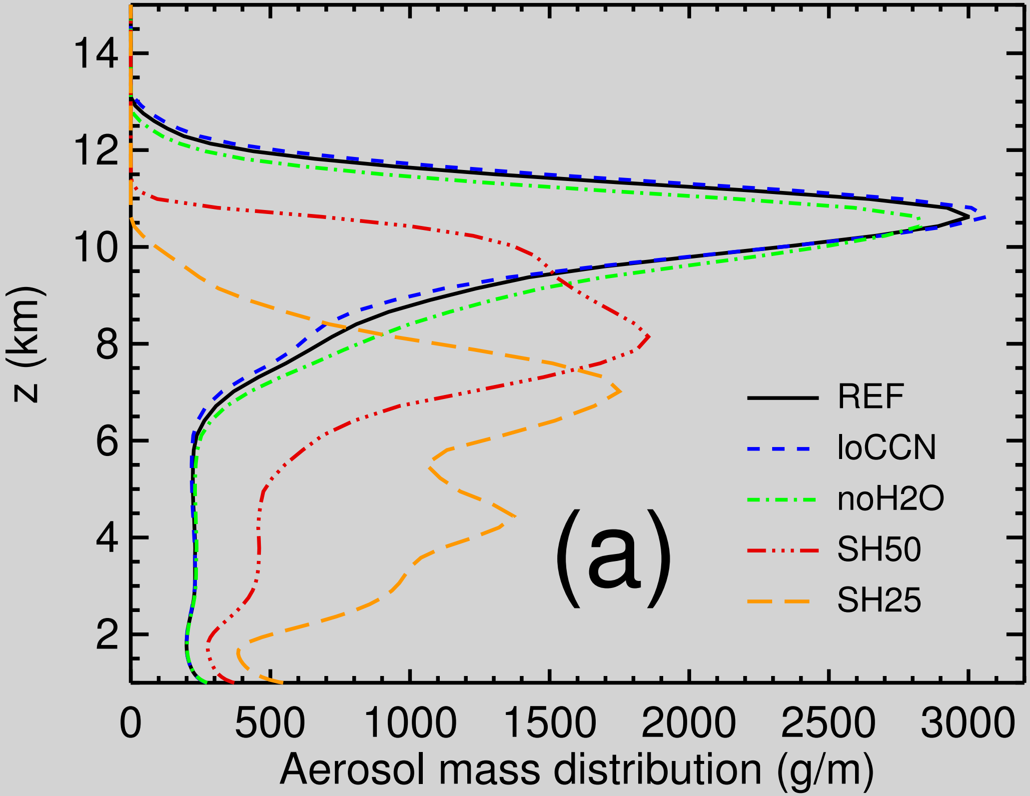


Figure 2: Simulated horizontal mean aerosol mass distribution after 40 minutes of Chisholm fire, Alberta, Canada, May 2001 (Luderer et al., 2006, Figure 7).

5.2. Freitas et al.

Freitas et al. (2006a) and Freitas et al. (2006b) embed a 1-D (vertical) sub-grid cloud model in each CTM gridcell.

1. Improves vertical distribution of CO relative to aircraft measurements and MOPPITT retrievals during Amazon campaigns
2. Seems to account for additional buoyancy of
3. Separately converty fuel mass to combustion energy for savannah and for Amazon forest
4. Convert combustion energy to sensible heat (their “convective energy”) using factor of fxm

5.3. GEOS-CHEM

F.-Y. Leung (Harvard, Jacob group) prescribed 40% of boreal BB emissions in PBL, 60% in free troposphere. Simulations of 1998 fires demonstrate:

1. Improved agreement between modeled/measured surface/column CO
2. Now using stability to estimate plume height, evaluating with MISR

6. Desired Characteristics

Utilize and/or be as consistent as possible with

1. Satellite-estimated FRP(x, y, t) (for empirical studies now)
2. Future model-predicted FRP$(x, y, t, \mathrm{PFT}, T, P, q_{\mathrm{H_2O}}, \theta)$ in future
3. Atmospheric thermodynamic structure: $T(z)$, $A(z)$, LFC, LCL, LNB, CAPE, CIN
4. Atmospheric processes: $P(z)$, entrainment/mixing
5. Fire processes: Consistent ratios of $H : R : E$

7. Approaches

FIM strawmen from less- to more- complex:

1. Surface mass flux injection (current method)
2. Prescribed injection profiles
3. Integrated GCM Injection
4. Sub-grid parameterized injection
5. Prognostic pyro-cumulus

7.1. Parameterized Profiles

1. Partition BB($z, \ldots$) using empirical data
2. Fit non-dimensionalized profiles within current atmospheric state, e.g., beneath LCL
3. Source for BB($z, \ldots$) could include MISR (CALIPSO?) plume height database

Advantages/Disadvantages:

1. Fast, no computational expense
2. Can capture all conditions sampled by observations
3. Database and profiles (i.e., look-up tables) improve with time
4. Neglects details of current atmospheric state
5. Generalization to other climates questionable

7.2. Integrated GCM Injection

1. Add fire H (and possibly $q_{\mathrm{H_2O}}$) into GCM grid-cell mean surface fluxes
2. GCM dry+moist convection, mixing, and diffusion respond

Advantages/Disadvantages:

1. Piggybacks on existing physics, little computational expense
2. BB advection internally consistent with GCM
3. Fire H diffuses through entire gridcell $\longrightarrow$ underestimate outflow height?
4. Deep convection routine does not “understand” pyroCb physics and may cause excessive wet scavenging
5. Extreme events may push convection routines beyond valid range
6. Alters GCM energy budget/climate (i.e., no “forcing only” runs)
7. Not easy to run and evaluate off-line

7.3. Sub-Grid Parameterized Injection

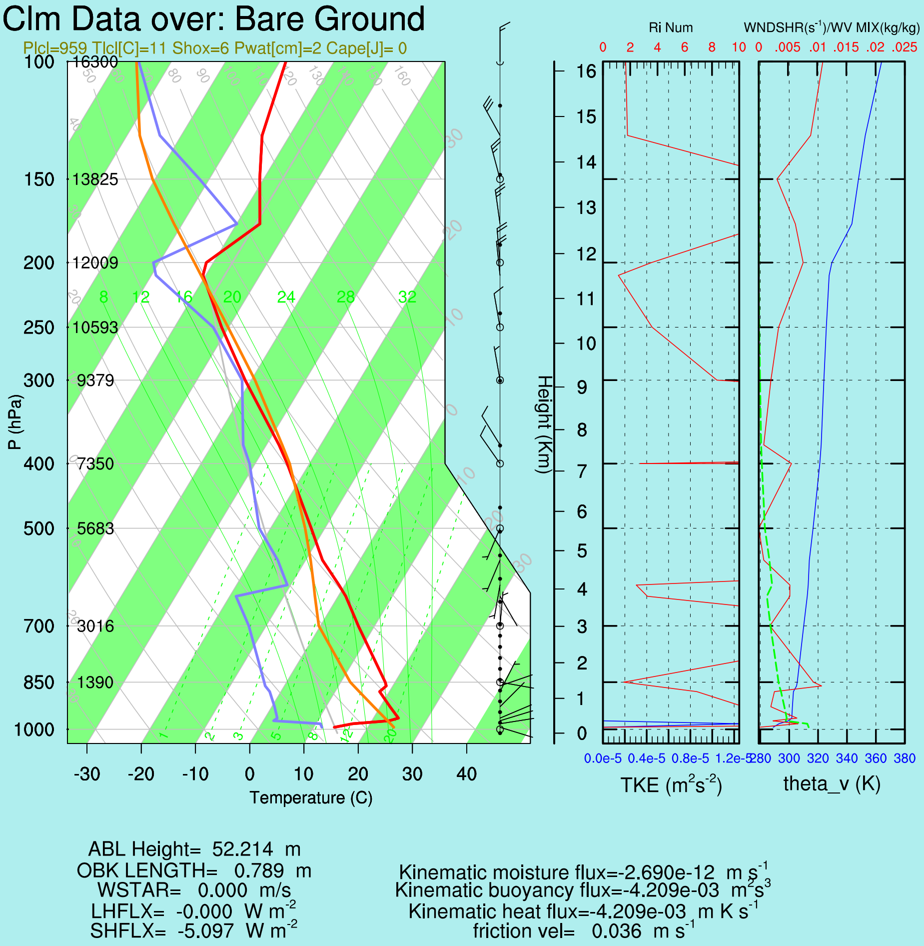
1. Determine sub-grid (fractional burn area) fire thermodynamic perturbation ΔT using sensible heat H (and possibly $\Delta q_{\mathrm{H_2O}}$)
   (a) Diagnose multiple categories, e.g., ΔT_{active}, $\Delta T_{\text{smolder}}$
   (b) Base categories on, e.g., active and smolder burn fractions:

$$H(t)\,[\mathrm{J\,m^{-2}\,mon^{-1}}] \;=\; A_{\text{active}} \times H_{\text{active}} + A_{\text{smolder}} \times H_{\text{smolder}} \tag{6}$$

   (c) "Adjust" burn areas consistent with estimated T_{active}, Δz, H
2. Diagnose sub-grid lifting based on ΔT (and $\Delta q_{\mathrm{H_2O}}$) and static thermodynamics of current environmental profile ($T(z)$, $A(z)$, s, LFC, LCL, CAPE, CIN)
3. Lift, detrain, and mix homogeneously aloft
4. Optional: use grid-mean fire sensible heat H (and possibly $q_{\mathrm{H_2O}}$) as GCM surface fluxes (i.e., IGI)

Advantages/Disadvantages:

1. Lifting need not alter GCM energy budget
2. Non-diffusive: captures vertical ascent of instantaneous sub-grid FRP and H
3. Can run and be evaluated offline
4. Applies equally well to non-fire injection (e.g., smokestacks)
5. Sub-grid numerics problematic, e.g., arbitrary thresholds



ABL Height= 52.214 m
OBK LENGTH= 0.789 m
WSTAR= 0.000 m/s
LHFLX= -0.000 W m^{-2}
SHFLX= -5.097 W m^{-2}

Kinematic moisture flux=-2.690e-12 m s^{-1}
Kinematic buoyancy flux=-4.209e-03 m^2s^3
Kinematic heat flux=-4.209e-03 m K s^{-1}
friction vel= 0.036 m s^{-1}

Figure 3: Measured sounding (Miramar, CA) with CAM stability diagnostics (S. Capps, UCI)

7.4. Prognostic Pyro-Cumulus

1. Time-split convection (dry and moist) with fully prognostic T, $q_{\mathrm{H_2O}}$, interacting with cloud processes and full (bin) microphysics and radiation (Trentmann et al., 2006)
2. Time-split sub-grid convection (dry and moist) with prognostic sub-grid (non-interacting) T, $q_{\mathrm{H_2O}}$, cloud, vertical velocity. Bulk (mode) microphysics (Freitas et al., 2006b)

Advantages/Disadvantages:

1. Captures aerosol direct, semi-direct, and indirect effects
2. Current grid-cell cloud schemes are much less complex so full pyroCb cloud model on sub-gridscale may be unrealistic

8. Questions

Two approaches for determining fire sensible heat flux H:
First, use GFED with an x_1 factor:

$$H(t)\,[\mathrm{J\,m^{-2}\,mon^{-1}}] \;=\; \mathrm{BF} \times \mathrm{CC} \times \mathrm{FL} \times x_1 \tag{7}$$

where GFED supplies BF = burned fraction, CC = combustion completeness, FL $[\mathrm{g\,C\,m^{-2}}]$ = fuel load, and x_1 $[\mathrm{J\,(g\,C)^{-1}}]$ = $x_1(\mathrm{PFT}, \theta, \ldots)$ is sensible heat released per unit fuel.

A second approach assumes a relationship between FRP and H:

$$H(t) \;=\; \mathrm{FRP} \times x_2 \tag{8}$$

and x_2 may also depend on $\mathrm{FRP}, \mathrm{PFT}, \theta, \ldots$.

9. Tasks

1. Choose appropriate FIM
2. Identify case studies and species for evaluation (MISR, CALIPSO?)
3. Implement FIM (volunteers welcome!)
    - (a) Diagnostic (i.e., prescribed or parameterized sub-gridscale) lifting
    - (b) GCM gridscale prognostic lifting

10. References

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