Derivation of fires from Space and their climatic effect

Robert Frouin

Scripps Institution of Oceanography
8605 La Jolla Shores Drive, La Jolla, California 92037

1. Introduction

Biomass burning, by releasing carbon dioxide to the atmosphere, is a potentially critical initiator of climate change. As much as 40% of the annual gross release of carbon dioxide through combustion may be due to biomass burning (Levine, 1991). In addition to carbon dioxide, biomass burning releases other greenhouse gases, particularly methane, carbon monoxide, and nitrous oxide. These gases also contribute to increase tropospheric ozone, another greehouse gas. Particulate matter emitted during fires (smoke), on the other hand, may cause a climate forcing comparable in magnitude yet opposite in sign to the greenhouse-gas forcing. Biomass-burning particles consist mostly of condensed organic species, but also contain black, elemental (soot) carbon. The black carbon may absorb sunlight and, like greenhouse gases, may exert a warming influence on the atmopshere.

On a global scale, about 9000 Tg of biomass (dry material) is consumed by annual burning, with the largest contribution from savanna grasslands (45%). The other components of biomass burning, i.e., agricultural waste, forests, and fuel wood, contribute approximately 25, 15, and 15% of the total biomass consumed. Biomass burning occurs not only in the tropics, but also in temperate and higher latitudes (e.g., boreal forests). Human activity is responsible for most biomass burning, and the scope and magnitude of this activity is thought to be increasing with time.

Until the 70's carbon emissions from the burning of fossil fuel were highly correlated with the increase in atmospheric carbon dioxide, but in the 80's the correlation became low as the fossil fuel source stopped to increase (e.g., IPCC, 1996). One wonders, therefore, whether the continued increase in atmospheric carbon dioxide may be due to an increase in biomass burning. This stresses the need for accurate inventories of biomass burning sources.

2. Fire Detection

Biomass-burning studies generally lack quantitative information on the spatio-temporal variability of fires at regional and global scales. Extending local results to large areas may give some idea of the global fire patterns (i.e., distribution of fires, amount of area burned, carbon emission rates), but errors may be large. Ground-based observations are inadequate to describe regional variability, making it necessary to exploit the capabilities of Earth-observing satellites. Ground-based measurements are needed, however, to evaluate the performance of satellite techniques.

Fire-related studies using satellite data include acquiring pre-fire information (e.g., vegetation fuel content), detecting active fires and smoke plumes, and quantifying fire effects (burned areas, vegetation re-generation). Justice et al. (1993) have discussed the potential and limitations of various remote sensing systems and have outlined the current trends in fire studies. The choice of remote sensing system depends on the geographical extent and spectral characteristics of the fire signal. High spatial resolution sensors such as Thematic mapper (TM) and High Resolution Visible (HRV) radiometer, owing to the high cost and low time frequency of the data, are limited to local monitoring. Coarser resolution sensors such as the Advanced Very High Resolution radiometer (AVHRR) provide daily data that are adapted to regional studies. Local Area Coverage (LAC) data at 1-km resolution and sampled Global Area Coverage (GAC) data at 4-km resolution are available for this purpose. GAC data are more convenient to use on a global scale, but they are not recommended for quantitative studies related to fires (Kennedy et al., 1994; Belward et al., 1994).

2.1 Active fires

The detection of active fires is usually accomplished with infrared sensors. The technique is based on the sensitivity of the measured radiance in the short-wave infrared (3-5 μm) to fire radiative energy, and also on the sensitivity of the measured radiance in the thermal infrared (8-12 μm) to temperature. A review of fire detection using infrared remote sensing can be found in Robinson (1991). Various methods have been developed to enhance the detection capability in the infrared (Matson and Holben, 1987; Lee and Tag, 1990; Kaufman et al., 1990; Langaas, 1993a; etc.). Images at night can be used to detect active fires, but the results may not represent the actual burnings since the number of fires is often reduced at night due to nocturnal weather conditions (Langaas, 1993b). Nevertheless, studies such as those of Cahoon et al. (1992), who processed Defense mapping Satellite Program (DMSP) night time images of Africa, suggest that useful information on the distribution of fires can be obtained using available techniques.

2.2 Burn scars

While the detection of active fires has been studied expensively, less research has focused on the spectral characteristics of burn scars and the areas actually burned. Matson and Dozier 91981) described a method to deduce sub-pixel fire size and temperature using AVHRR data. The method is not applicable to saturated infrared pixels. Pereira et al. (1991) used AVHRR fire counts to estimate burned areas from active fires assuming that the fire occupies the entire pixel. their results, when compared with those from higher resolution TM images, show an overestimate of the fire size by 43% on average and an underestimate of the fire size of long, continuously burning fires.

After a fire, the area burned is covered by ash, and ash is generally darker than the original background. This changes the top-of-atmosphere radiance in the visible and near-infrared and, therefore, the Normalized Difference Vegetation Index (NDVI), providing the basis of methods to detect burned areas from space. Studies have shown that burned areas can be identified using Multi Spectral Scanner (MSS) data (Tanaka et al., 1983) or TM data (Pereira and Setzer, 1993). Discrimination between burned and unburned areas, however, is difficult to make the presense of water (similar spectral signature) and, in the case of savanna ecosystems, is limited by the rapid regrowth of the vegetation just a few days after the fire (Fredericksen et al., 1990). For such ecosystems, data should be used with a higher frequency (e.g., once a day). Radiances in AVHRR visible and near-infrared bands and the derived NDVI have been used in Senegal (Fredericksen et al., 1990), Congo (Malingreau, 1990), and boreal forests (Kasischke et al., 1993), and have been found sensitive to fire-affected areas. In boreal forests, burned scars remain for a longer period of time (several months), making remote sensing easier.

The existing techniques to estimate burned areas, when applied to coarse spatial resolution sensors, generally assume that a pixel is either totally burned or totally unburned. The burned area is estimated by counting the number of pixels classified as burned or unburned. The procedure is adequate for fire extents larger than the sensor resolution, but becomes unreliable when a large number of partially burned pixels are present within a scene. In the savannas of West Africa, fires occupy typically a pixel or two in AVHRR LAC imagery. For such ecosystems and others with small fire size, Razafimpanilo et al. (1995) have established theoretical relationships between fraction of pixel burned and near-infrared reflectance (linear) and fraction of pixel burned and NDVI (non-linear). Their sensitivity analysis suggest that fraction inaccuracies of 0.2 and 0.1 may be obtained, respectively, in the case of uniform pixels.

3. Climate change

The greenhouse gases produced by biomass burning contribute 10 to 15% of the expected surface temperature increase due to all greenhouse gases emitted to the atmosphere from A. D. 1980 to 2030, as computed by a 1-dimensional climate model (Ramanathan et al., 1985). This contribution is smaller than fossil fuel combustion, but may dominate the total climate forcing in some regions. Uncertainties in emissions and the relative impact of the different gases are large, however, and the actual contribution of biomass burning may lie in the range 5-30%.

The climatic impact of biomass burning aerosols is not well understood. Organic carbon aerosols can reflect sunlight back to space and thus reduce the amount of heat received by the planet. Black carbon aerosols, on the contrary, may absorb sunlight and warm the atmosphere. The direct radiative forcing by condensed organic species is a loss of reflected flux of about -0.8 W/m^2 (Penner et al., 1992; Iacobellis et al., 1999), but because of uncertainties in emission factor, average lifetime of smoke, amount of biomass burned, and mass scattering efficiency, the actual value is probably between -2.2 and -0.3 W/m^2 (Penner et al., 1994). Penner et al. (1992) indicated that black carbon aerosols could reduce the amplitude of forcing by organic species by a few tenths of W/m^2, but uncertainties in the size-dependent optical properties of black-soot particles make the confidence level of any calculation very low.

The influence of biomass burning particles on the behavior of clouds (indirect climate forcing) is beyond current understanding, due to complex interactions such as the influence of cloud entrainment an mixing processes. In principle, the more aerosols, the more cloud condensation nuclei, therefore the more cloud droplets, and the smaller droplets. Clouds with smaller droplets reflect more solar radiation back to space, with the potential of affecting climate substantially.

Climate model simulations with only greenhouse gases predict a strong winter warming in high northern latitudes (IPCC, 1996), and a greater warming over land than over the ocean. The presence of biomass burning aerosols, mostly confined over land because of their relatively short life time, may reduce the warming and the land-ocean contrast (Taylor and Penner, 1994). In regions such as Southeast Asia, significant changes in atmospheric circulation and hydrology might occur. Improving our projections of future climate certainly requires a better knowledge of the geographic distribution of biomass-burning sources, including their seasonality. This can hardly be accomplished without satellite observations of fires and satellite estimates of burned areas and carbon stock available for burning before fires.

References

Belward, A. S., Kennedy, P. J., and Grégoire, J.-M., 1994: The limitations and potential of AVHRR GAC data for continental scale fire studies. Int. J. Rem. Sen., 15, 2215-2234.

Cahoon, D. R., Jr., Stocks, B. J., Levine, J. S., Cofer, W. R. , III, and O'Neill, K. P., 1992: Seasonal distribution of African Savanna fires. Nature, 359, 812-815.

Frederiksen, P., Langaas, S., and Mbaye, M., 1990: NOAA AVHRR and GIS-based monitoring of fire activity in Senegal - a provisional methodology and potential applications. In Fire in the Tropical Biota, J. G. Goldammer, Ed., Ecological Studies 84, 400-417.

Justice, C. O., Malingreau, J. P., and Setzer, A. W., 1993: Remote sensing of fires: potential and limitations. In Fire in the Environment, P. J. Crutzen and J. G. Goldammer, Eds., 77-88.

Iacobellis, S. F., Frouin, R., and Somerville, R. C. J., 1999: Direct climate forcing by biomass-burning aerosols: Impact of correlations between controlling variables. J. Geophys. Res., 104, 12,031-12,045.

Intergovernmental Panel on Climate Change (IPCC), Climate Change 1995, the Science of Climate Change, J. T. Houghton, L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell, Eds., Cambridge Univ. Press, New York, 572 pp.

Kaufman, Y. J., Setzer, A., Justice, C., Tucker, C. J., Pereira, M. C., and Fung, I., 1990. Remote sensing of biomass burning in the tropics. In Fires in the Tropical Biota, , J. G. Goldammer, Ed., Ecological Studies 84, 371-399.

Kasischke, E. S., French, N. H. F., Harrell, P., Christensen, N. L., Ustin, S. L., and Barry, D., 1993: Monitoring of wild fires in boreal forests using large area AVHRR NDVI composite image data. Rem. Sen. Environ., 45, 61-71.

Langaas, S., 1993a: A parameterised bispectral model for savanna fire detection using AVHRR night images. Int. J. Rem. Sen., 14, 2245-2262.

Langaas, S., 1993b: Diurnal cycles in savanna fires. Nature, 363, 120.

Lee, T. F., and Tag, P. M., 1990: Improved detection of hotspots using the AVHRR 3.7 μm channel. Bull. Am. Meteor. Soc., 71, 1722-1730.

Levine, J. S., 1991: Global biomass burning: atmospheric, climatic, and biospheric implications. In Global Biomass Burning, J. S. Levine, Ed., MIT Press, Cambridge, MA, xxv-xxx.

Malingreau, J. P., 1990: The contribution of remote sensing to the global monitoring of fires in tropical and subtropical ecosystems. In Fires in the Tropical Biota, J. G. Goldammer, Ed., Ecological Studies 84, 337-370.

Matson, M., and Dozier, J., 1981: Identification of subresolution high temperature sources using a thermal infrared sensor. Photogr. Eng. Rem. Sen., 47, 1311-1318.

Penner, J. E., Dickinson, R. F., and O'Neill, C. A., 1992: Effects of aerosols from biomass burning on the global radiation budget, Science, 256, 1432-1433.

Penner, J. E., et al., 1994: Quantifying and minimizing uncertainty in climate forcing by anthropogenic aerosols. Bull. Am. Meteor. Soc., 75, 375-400.

Pereira, M. C., Alfredo, C., Setzer, A. W., and Dos Santos, J. R., 1991: Fire estimates in savannas of central Brazil with thermal AVHRR/NOAA calibrated by TM/Landsat. In Proc. 24th Int. Sym. on Remote Sensing of the Environment, Rio de Janeiro, Brazil, 27-31 May.

Pereira, M. C., and Setzer, A. W., 1993: Spectral characteristics of fire scars in Landsat 5 TM images of Amazonia. Int. J. Rem. Sen., 14, 2061-2078.

Ramanathan, V., Cicerone, R. J., Singh, H. B., and Kiehl, J. T., 1985: Trace gas trends and their potential role in climate change. J. Geophys. Res., 90, 5547-5566.

Razafimpanilo, H., Frouin, R., Iacobellis, S. F., and Somerville, R. C. J., 1995: Methodology for estimating burned area from AVHRR data. Rem. Sen. Environ., 54, 273-289.

Robinson, J. M., 1991: Fire from Space: global fire evaluation using infrared remote sensing. Int. J. Rem. Sen., 12, 3-24.

Tanaka, S., Kimura, H., and Suga, Y., 1983: preparation of a 1:25,000 landsat map for assessment of burnt area on Etajima Island. Int. J. Rem. Sen., 4, 17-31.

Taylor, K. E., and Penner, J. E., 1994: Response of the climate system to atmospheric aerosols and greenhouse gases, Nature, 369, 734.