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Real-time monitoring of South American smoke particle emissions and transport using a coupled remote sensing/box-model approach

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[1] Since August 2000, the Wild fire Automated Biomass Burning Algorithm (WF_ABBA) has been generating half-hourly fire hot spot analyses for the Western Hemisphere using GOES satellites to provide the Naval Research Laboratory (NRL) Aerosol Analysis and Prediction System (NAAPS) with near-real-time fire products. These are used to generate smoke particle fluxes for aerosol transport forecasting to benefit the scientific, weather, and regulatory communities. In South America, fire hot-spot analysis is shown to be adequate for generating real-time smoke source functions for aerosol forecast models. We present smoke coverage and flux estimates based on the WF_ABBA and NAAPS products. Modeled fluxes of emissions for 2001–2002 are $\sim 25 + 10 \text{ Tg yr}^{-1}$, similar to previous estimates. Correlations of optical depth with MODIS and AERONET show good agreement with observations. Comparisons of NAAPS aerosol fields with MODIS also show potential clear sky and other biases as smoke is transported into the Atlantic Ocean and the ITCZ. **INDEX TERMS:** 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0330 Atmospheric Composition and Structure: Geochemical cycles; 0360 Atmospheric Composition and Structure: Transmission and scattering of radiation; 0368 Atmospheric Composition and Structure: Troposphere—constituent transport and chemistry. **Citation:** Reid, J. S., E. M. Prins, D. L. Westphal, C. C. Schmidt, K. A. Richardson, S. A. Christopher, T. F. Eck, E. A. Reid, C. A. Curtis, and J. P. Hoffman (2004), Real-time monitoring of South American smoke particle emissions and transport using a coupled remote sensing/box-model approach, *Geophys. Res. Lett.*, 31, L06107, doi:10.1029/2003GL018845.

1. Introduction

[2] The Fire Locating and Modeling of Burning Emissions (FLAMBE' <http://www.nrlmry.navy.mil/flambe/>)

project was initiated to monitor biomass-burning emissions globally. The goal is to provide reliable 5-day forecasts of significant biomass-burning smoke events and visibility to serve the scientific, weather, and regulatory communities. The project is centered on the NRL Aerosol Analysis and Prediction System (NAAPS-<http://www.nrlmry.navy.mil/aerosol/>), a prognostic global aerosol model, with smoke source functions provided by the NOAA generated Wildfire Automated Biomass Burning Algorithm (WF_ABBA: Prins *et al.* [2001]) from GOES East and West data.

[3] As NAAPS is an operational aerosol transport model, its needs are significantly different from more commonly used global climate or research aerosol models. Deriving correct monthly averages of smoke coverage is secondary to its ability to adequately forecast large changes in aerosol optical thickness (AOT) and visibility. Unlike the sources of other aerosol components that are wind driven (e.g., dust) or prescribed in a seasonal inventory (e.g., pollution), biomass-burning emissions have significant variability that defies easy parameterization. For timely forecasting, fluxes must be generated within 6 hours of emissions. Real-time fire hot spot monitoring by satellite is the only available method to construct a smoke flux for such a model. In this manuscript we demonstrate the capabilities of the system using South American biomass burning. We also use this opportunity to examine smoke emission variability and coverage over the region and show that our results are consistent with other studies.

2. Methods

[4] In September 2000 the NOAA National Environmental Satellite, Data, and Information Service (NESDIS) Office of Research and Applications (ORA) and the UW-Madison Cooperative Institute for Meteorological Satellite Studies (CIMSS) implemented the WF_ABBA, providing half-hourly fire products in real-time for most of the Western Hemisphere. The GOES-8/-10/-12 WF_ABBA is a modified version of the South American ABBA that has been used to monitor biomass burning in South America since 1995. The WF_ABBA is a dynamic multi-spectral thresholding contextual algorithm that uses the visible (when available), 3.9 μm , and 10.7 μm infrared bands to locate and characterize hot spot pixels. The algorithm is based on the sensitivity of the 3.9 μm band to high temperature sub-pixel anomalies and is derived from a technique originally developed by Matson and Dozier [1981]. The WF_ABBA incorporates ancillary data

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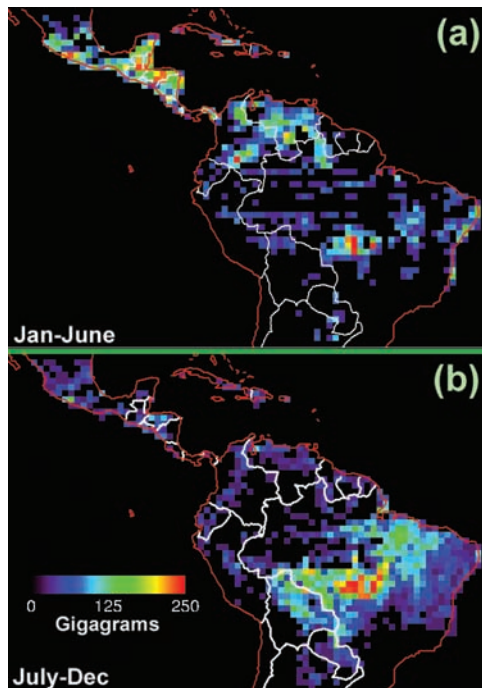


Figure 1. Annual averaged smoke particle emissions as derived from GOES-8 WF_ABBA products for the years 2001 and 2002.

in the process of screening for false alarms and correcting for water vapor attenuation, surface emissivity, solar reflectivity, and semi-transparent clouds. The USGS derived Global Land Cover Characteristics (GLCC) database is used to assign surface emissivity and to screen for false alarms (<http://edcdaac.usgs.gov/glcc/glcc.html>). Numerical techniques are used to determine instantaneous estimates of sub-pixel fire size and average fire temperature. For more information on the algorithm and the determination of sub-pixel fire characteristics, refer to *Prins et al.* [1998, 2001].

[5] Half-hourly WF_ABBA fire products are assigned smoke particle flux rates in 9 land cover sub-categories derived from the 1 km GLCC classification (e.g., tropical forest, woody savanna, etc.). These flux rates are a function of estimated fuel load, emission factors, and combustion fractions. Specifics and references are on the FLAMBE web site listed above and by J. S. Reid et al. (A review of biomass burning emissions, part II: Intensive physical properties of biomass burning particles, manuscript in preparation, 2004). For South America these values are drawn from the work of *Guild et al.* [1998]. Particle emission factors are taken from *Ferek et al.* [1998]. To ensure that the number of false alarms is minimized, only processed fire products assigned an instantaneous sub-pixel fire size estimate and saturated fire pixels (assumed size of 5 ha because that is the size hot/intense fires tend to saturate) are used to compute the flux (roughly 50% of ABBA pixels). It is assumed the entire retrieved area is consumed. From these fire products, six-hourly flux files are generated.

[6] NAAPS is a real-time operational system for forecasting the global distribution of tropospheric sulfate, dust, and smoke. NAAPS is a modified form of a model of sulfate

aerosols developed by *Christensen* [1997] and uses global meteorological fields from the Navy Operational Global Atmospheric Prediction System (NOGAPS) [*Hogan and Brody*, 1991] data on a 1×1 degree grid, at 6-hour intervals and 24 vertical levels reaching 100 mb. Global runs are made twice daily to generate 5-day forecasts. Light scattering and absorption are currently modeled through the use of bulk parameterizations assuming mass extinction efficiency and hygroscopicity values given by *Reid et al.* [1998] and *Kotchenruther and Hobbs* [1998]. Validation was performed using Aerosol Robotic Network (AERONET-*Holben et al.* [2001]) Sun/sky radiometers and MODIS Level-3 550 nm optical depth data [*Chu et al.*, 2002] validation for the year 2001 is used in this study.

3. Results

[7] Annual average emissions from WF_ABBA data for South America in 2001–2002 are presented in Figure 1 (as is discussed below, these are corrected values and are our best estimates). Time series of regional optical depths from NAAPS and MODIS for northern South America (56° – 84° W, 5° – 12° N) and the southern Amazon Basin (50° – 70° W, 5° – 17° S) are presented in Figure 2 where each data point corresponds to a 5-day average.

[8] The WF_ABBA fire products and derived emissions match with what is known about the region [*Franca and Setzer*, 1998; *Stroppiana et al.*, 2000; *Feltz et al.*, 2001; *Holben et al.*, 2001]. Because NAAPS does not include natural or background aerosol in the region, it does not reproduce the background optical depth of ~ 0.1 (higher values in MODIS by ~ 0.1 are likely in part due to cloud contamination). Fire frequency follows a strong annual cycle opposite in phase to the Inter-Tropical Convergence Zone (ITCZ). Burning in central and northern South America (principally Venezuela) occurs in the Northern Hemisphere spring with a maximum in late April and early May. Seasonal optical depths from MODIS give values averaged over the entire northern South America region that are on the order of 0.3–0.4 (The Yucatan Peninsula of Central America, not shown, yields similar optical depths). Conversely, the bulk of the burning in the Amazon Basin occurs in the region's dry season (August–October) with a maximum in September and early October. Fires are prevalent over a large area of central Brazil, but the bulk of the emissions are concentrated along the arc of deforestation. Smoke often moves south-southeast due to the presence of the Andes mountain range where it can be

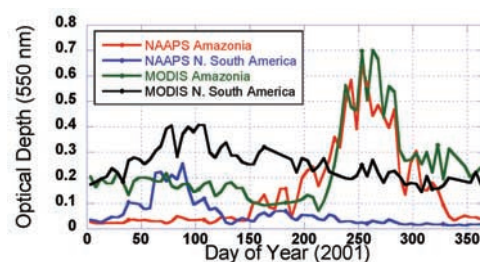


Figure 2. Time series of South American regional optical depths (each data point is a 5 day average).

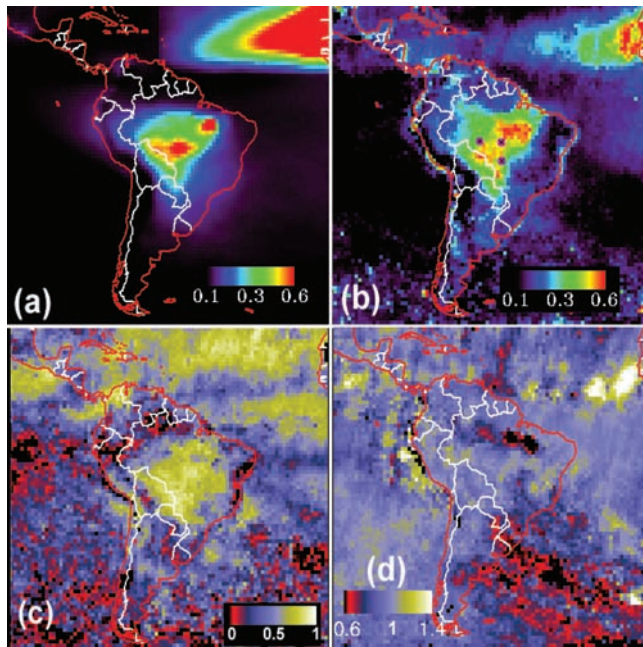


Figure 3. (a) Plot of South American Spring (Aug, Sept, Oct) 550 nm optical depth from NAAPS for only those data points where MODIS is available (e.g., pairwise with MODIS), (b) average MODIS optical depth for the same time period as (a), (c) the 5 day average correlation coefficient for the year 2001 (d) Clear sky bias for data in (a) and (b) (ratio of NAAPS data pair-wise with MODIS to all NAAPS data). Also in (b) are the locations for the Abracos Hill (Upper Left), Alta Floresta (Upper right), and Cuiaba (lower) AERONET sites. High AOTs in the upper right corner is from African dust.

transported over the South Atlantic Ocean ahead of frontal boundaries. Optical depths averaged over the whole Amazon Basin exceed 0.5, with instantaneous values as high as 3. Based on AERONET data going back to 1994, the average AOTs during the August, Sept., Oct. time frames of the years 2001 and 2002 can be considered typical for the region (based primarily from the analysis of the Abracos Hill [10 S; 62 W], Alta Floresta [9 S; 56 W] and Cuiaba [15 S; 56 W] sites by AERONET personnel-to be published and Holben *et al.* [2001]).

[9] The total number of processed or saturated fire pixels in South America was 915,000 and 1,010,000 for the years 2001 and 2002, respectively. Roughly 77% are south of the equator. Many of these fire pixels represent multiple detections of the same sub-pixel fire(s). As expected, 70% of fires in northern South America are grass, savanna, or agriculture related. This is compared to only 50% south of the equator. Although there are fewer fires from forest ecosystems (mostly seasonal tropical forest, 20% and 40% for north and south of the equator, respectively), emissions in the model are dominated by forest and woody fuels (~80%). Given that forested ecosystems have a fuel load over an order of magnitude greater than grass and shrub, and have significant smoldering combustion, forest burning emissions are disproportionately dominant.

[10] Model performance was evaluated by comparing NAAPS, AERONET Level 2 and MODIS Level-3 optical

depths. Presented in Figure 3 for the year 2001 burning season (Aug–Oct.) are the average optical depths from NAAPS and MODIS data for South America. To ensure no bias in the comparison, we show average NAAPS data for only those values that correspond to daily MODIS retrievals (i.e., for a pair-wise ratio with MODIS). Figure 3c shows the correlation coefficient (r) of 5-day average AOT for the year 2001 between daily MODIS/NAAPS pair-wise data (monthly average correlations, not shown are all >0.15 higher). The ratio of NAAPS data when MODIS data were present to all NAAPS data is shown in Figure 3d.

[11] Seasonally, the comparison between NAAPS and MODIS in Figures 2 and 3 is strong, with monthly correlation coefficients being in excess of 0.8 for grid points impacted by smoke (regions with low optical depths have little monthly variance and hence have low r values). Despite significant differences between the fuel loads, combustion fractions, and emission factors of forest and grass type fuels, the correlation between raw fire counts for the region and total estimates of emissions is extremely strong ($r > 0.8$ -not shown); thus indicating that all types of burning co-vary strongly over the region. Through a series of test runs, we found that the absence of real-time correction for clouds in this current form of the algorithm does not significantly alter this correlation but does change the slope. This is because the meteorology of the whole Amazon region tends to behave similarly on a day-to-day basis particularly with respect to trade cumulus and minor convection.

[12] Regionally, there are noticeable differences between NAAPS and MODIS coverage patterns. While the 5-day correlation coefficient is good ($r > 0.7$ over the burning region), NAAPS overestimates smoke coverage and smoke optical depth relative to MODIS in Rondonia (near the northern Bolivian border with Brazil). Since this region is rapidly developing we suspect this is in part due to ecosystem assignment bias. Given that GOES has a 4 km footprint and much of the burning is in the arc of deforestation where forest and fields are very mixed, the pixel resolution may not be high enough to identify the ecosystem. Errors also likely exist in the application of the land use database that includes components up to

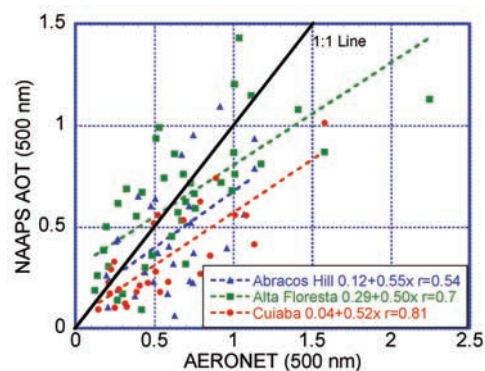


Figure 4. Scatter plot of 2-day average (Aug, Sept, Oct) 500 nm optical depth from NAAPS and AERONET at the Abrago Hill, Alta Floresta and Cuiaba sites.

10 years old. What was forest a few years ago might quite easily be agricultural terrain today.

[13] As MODIS also has its own set of biases, validation was also performed using available AERONET data in the region. Further, for a model such as NAAPS, validation must occur not only on a seasonal and 5 day basis, but also on very short time scales. Figure 4 shows 2-day regressions of NAAPS optical depth versus Abracos Hill, Alta Floresta, and Cuiaba AERONET sites for the year 2001 burning season (we use 2-day averages to diminish the impact of local burning on singular AERONET point data). Similar to the 5-day data, correlations are generally good although optical depths in this case have a low bias of 30%. Interestingly such a bias is contrary to comparisons with MODIS data. Further, the comparison to the Abracos Hill AERONET site, in Rondonia, does not show the high bias of the NAAPS AOTs relative to the MODIS retrievals.

[14] NAAPS emissions are in general agreement with previous estimates. To start, emissions did produce optical depths generally low by $\sim 30\%$ relative to AERONET, and raw particle emissions that totaled $\sim 14 \text{ Tg yr}^{-1}$ for the entire Amazon Basin. The significant digit in this calculation is $\sim 5 \text{ Tg yr}^{-1}$. Based on regional corrections to reproduce the optical depths from MODIS and AERONET for the Amazon and northern South America area, we derive a rounded value of $\sim 20 \text{ Tg yr}^{-1}$ for the year 2001 (Some burning also occurs in southern South America, but this is small compared to the Amazon and northern regions and we cannot compare to MODIS due to the higher background levels and the intermittent transport from the Amazon). In 2002, there were $\sim 25\%$ more fires and 35% higher flux. Based on our emissions for the years 2001 and 2002, a reasonable rounded average for all of South America is $\sim 25 \text{ Tg yr}^{-1}$, only slightly lower than the values derived by Hao and Liu [1994]. After an uncertainty analysis on particle emissions and optical properties, we find this value is likely good to $\sim 50\%$. While not specific, it does show that current estimates of particle emissions are of the correct order. We also realize that this agreement is only possible through cancellation of errors processes. For example, Giglio and Kendall [2001] found that the fire size estimate from the Dozier technique applied to GOES Imager data may be high. Limited validation studies with the GOES ABBA, utilizing a modified Dozier technique, show that for fires greater than 1 ha in size, GOES estimates of sub-pixel instantaneous fire size are typically from 33% to a factor of 2 to 3 too high [Menzel and Prins, 1996; Prins et al., 1998]. This is offset with our observations that in certain biomes ABBA can only detect 25% of fires.

[15] Figure 3d also shows the potential for clear sky bias in MODIS data. Here we ratio the seasonal average of NAAPS data when MODIS data were available to a seasonal average of all NAAPS data. (e.g., $\langle \text{AOD} \rangle_{\text{MODIS-NAAPS concurrences}} / \langle \text{AOD} \rangle_{\text{NAAPS}}$) Negative biases were detected in NAAPS data corresponding to MODIS in two regions. First, modeled clear sky biases on the order of -50% were detected along the northern Amazon basin; likely due to MODIS cloud masking in the ITCZ. Similarly, -50% clear sky biases were found in the south of Brazil, Argentina and the Atlantic Ocean. Reid et al. [2002] showed in a series of

case studies that this bias was due to smoke advection in association with cold fronts and their cloud systems. Because of the lower smoke concentrations in these regions, the relative amount of impact on indirect forcing per gram of smoke is likely to be relatively high (i.e., Twomey effect). The relative difference in convective clouds in the north versus stratiform in the south makes the transport of smoke in South America a good laboratory for studying smoke indirect effects.

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