Reversal of trend of biomass burning in the Amazon

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[1] We use MODIS aerosol optical depth and AVHRR fire counts over the Amazon Basin to determine whether biomass burning is increasing or decreasing over continental scales in South America. We find a significant sustained increasing trend in both the seasonal mean optical depth and fire data that begins in the year 2000 and 1998, respectively, and continues through 2005. However, there is a sharp reversal of this trend in 2006 that causes the overall trend to become less significant. The sharp decrease of biomass burning in 2006 is linked to a tri-national policy shift first implemented in 2006. The results show how significantly human activity can affect the large scale environment. **Citation:** Koren, I., L. A. Remer, and K. Longo (2007), Reversal of trend of biomass burning in the Amazon, *Geophys. Res. Lett.*, *34*, L20404, doi:10.1029/2007GL031530.

1. Introduction

[2] Tropical biomass burning, either from deforestation or from annual agricultural practices, inputs significant aerosol particles into the atmosphere. The contribution of these smoke particles to the global aerosol burden is especially important because they are the primary source of anthropogenic aerosol in the southern hemisphere. Biomass burning aerosol plays a significant role in aerosol global climate forcing [*Hobbs et al.*, 1997], in modifying cloud properties and precipitation [*Koren et al.*, 2004; *Andreae et al.*, 2004] and causes serious health problems for those who live in the region [*Ministério da Saúde*, 2006].

[3] The scientific community began to recognize the importance of tropical biomass burning in the late 1980s [*Kaufman et al.*, 1989; *Setzer and Pereira*, 1991a]. Steps were soon taken by the government agencies in Brazil and neighboring countries to monitor the situation. Specifically INPE developed an operational fire count product from the AVHRR satellite sensor to monitor fires [*Setzer and Pereira*, 1991b]. The fire count product provides daily, monthly and annual counts of the number of fires observed by the satellite, broken down by state. Although begun in 1987, the long-term record is inconsistent because the fire counts are affected by changes in satellite and overpass time [*Setzer et al.*, 1994]. Only since the initiation of AVHRR aboard NOAA-12 in 1995 do we have a record sufficiently consistent to analyze long-term fire count trends.

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[4] While satellite monitoring of active fires was possible with AVHRR, similar operational monitoring of the smoke produced by those fires was not possible. The launch of NASA's Terra satellite in late 1999 with the MODIS and MISR sensors aboard was the first opportunity to make routine, operational measurements of aerosols over land and specifically for biomass burning [*Diner et al.*, 2001; *Remer et al.*, 2005]. We now have seven years of MODIS aerosol data. It is possible to look for trends in the smoke aerosol, as well as with the fires. In this paper we will analyze these data to answer the question: Have fires and smoke increased or decreased in the Amazon during the last decade?

2. Data

[5] We will use the long-term record of fire counts available from the AVHRR sensor, beginning with AVHRR aboard NOAA-12 that begins in 1998. The data product uses a 3.7 μm channel to identify a fire. The product and similar fire count products from other satellite sensors has enjoyed widespread use in monitoring fires and estimating smoke emissions [*Menzel et al.*, 1991; *Setzer and Pereira*, 1991b; *Li et al.*, 2000; *Giglio et al.*, 2006]. The AVHRR fire count product has been compared with similar products from GOES and MODIS and found to be highly correlated and able to represent the same characteristics of fire dynamics, although there is an offset. [*Schroeder et al.*, 2005].

[6] To address trends in smoke aerosol loading we will use the MODIS Collection 5 aerosol optical depth (AOD) at 550 nm [*Remer et al.*, 2005; *Levy et al.*, 2007]. The particular product we are using is the aerosol optical depth over land and ocean product, although only retrievals made over the land are included in this work. We use Level 3 monthly mean (MOD08_M3) from the Terra satellite, which enjoys a longer data record than from its twin sensor on Aqua. Our region of interest is the part of South America north of 30°S latitude.

3. Trend Analysis

[7] In order to demonstrate the drastic changes to South American biomass burning in the last year of the data record, we first characterize the trends prior to 2006. We calculate for each 1×1 degree monthly mean AOD the six year mean (2000–2005) for the entire biomass burning season (August through November). Figure 1 shows the region of interest and the distribution of the seasonal mean AOD at 550 nm, as calculated from the Terra-MODIS record.

[8] The six year trend associated with each 1 degree box appears in the top plot of Figure 2. In the heart of the biomass burning region of Figure 1 and extending to the north and west we see a region of positive trends of aerosol

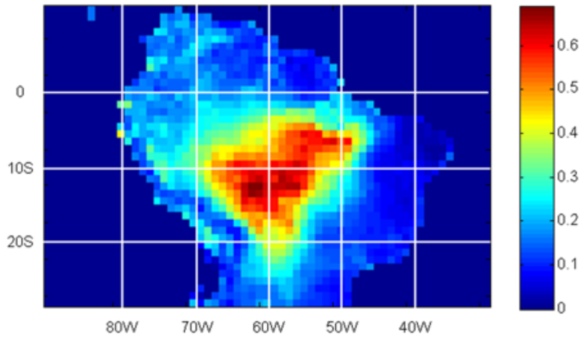

Figure 1. Six year seasonal mean (August–November) aerosol optical depth at 550 nm (AOD) from the Terra MODIS Level 3 aerosol product calculated for the period 2000 to 2005.

optical depth. These trends are as high as 0.05 to 0.1 AOD per year, which represents an increase in AOD of 0.30 to 0.60 over the six year period. The amount of increase in the areas of the highest slopes is approximately equivalent to the magnitude of the six-year mean of Figure 1. In effect, in these areas the amount of aerosol loading more than doubled. Furthermore, the increased amount only during this time period roughly corresponds to typical total AOD values measured in major cities of the United States when air quality exceeds the indexed category labeled "good" and approaches the category identified as "unhealthy for sensitive groups" [*Al-Saadi et al.*, 2005].

[9] Not only do the trends represent large increases of AOD, the slopes are significant at the 95% confidence interval despite the short duration of the time series. The t-statistic calculated for each 1-degree square from the calculated correlation coefficients is shown in the bottom plot of Figure 2. The color bar is stretched so that yellows and oranges represent the cases when $t > 2.7765$, corresponding to the 95% confidence interval for the two-tailed distribution with 6 years − 2 = 4 degrees of freedom. Furthermore, the spatial coherence of the trends in Figure 2 shows the wide scale increase of AOD in the Amazon. Such spatial coherence supports the significance of the trends. These trends are not random, but a strong statement demonstrating a significant increase of aerosol over a broad region of South America from 2000 to 2005.

[10] The strong positive trend established between 2000 to 2005 ends dramatically in 2006. Figure 3 shows the mean AOD and the difference between AOD in 2006 and 2005, for each 1 degree square. Over a large swath of our domain including the heart of the biomass burning region of Figure 1, the AOD of 2006 is 0.2 to 0.4 less than it was in 2005. The reason for this sharp reversal of trends will be discussed below.

[11] The significant positive trend for the period 2000 to 2005 and the sharp reversal of this trend in 2006 is not isolated only to measures of smoke AOD, but is also found in the fire count data. We accumulate AVHRR fire counts for each biomass burning season for the entire Legal Amazon zone using the consistent data set beginning with NOAA-12. We have chosen to work with the entire domain as a unit rather than individualized local areas, because we expect the best correlation between the aerosol optical depth (AOD) which represents the smoke loading during the dry (biomass burning) season and the fire counts to occur on continental scales. The assumption is that most of the smoke emitted from the fires is captured within this large domain. The relationship between these variables starts to break down on smaller scales due to sparse distribution of fires and transport of the smoke away from the local fire region. Therefore, we calculate a single mean AOD for the entire domain for the whole biomass burning season (August through November) of each year of the Terra-MODIS record. The two time series are plotted in Figure 4. Note that domain wide AOD values are less than those mentioned above that occur in the heart of the biomass burning region.

[12] Seasonal domain-wide mean aerosol optical depth from MODIS is highly correlated ($R = 0.94$) with the total fire counts observed from AVHRR. We include analysis of the fire count time series because it begins two years earlier than the MODIS time series, and thus, provides additional information towards understanding the trends of biomass burning in the Amazon. The tight correlation between the AOD and fire counts show convincingly that the aerosol occurring during this season is primarily biomass burning smoke, resulting from fires, and not from another source such as natural biogenic particles or transported dust. The vast majority of fires burning in the Amazon are started by human activity, either to promote deforestation or agriculture.

[13] In Figure 4 we see interannual variability but also an obvious increasing trend in both MODIS AOD and AVHRR

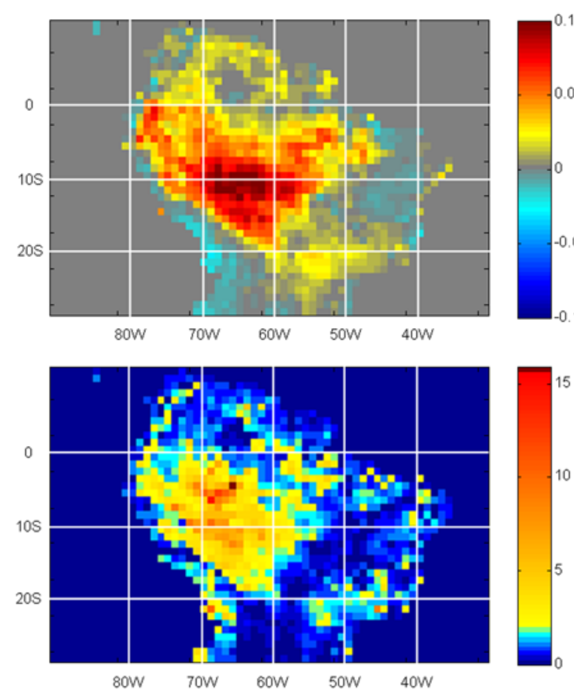

Figure 2. (top) Slopes of the trend regression line for each 1 degree square for the six year period (2000–2005). Units are in AOD per season. (bottom) The t-statistic for the student's t-test of the calculated trends in each 1 degree square. The color bar has been stretched in such a way that yellows and oranges denote significance at the 95% confidence level ($t > 2.7765$) and light blue denotes significance at the 90% confidence level ($t > 2.1318$).

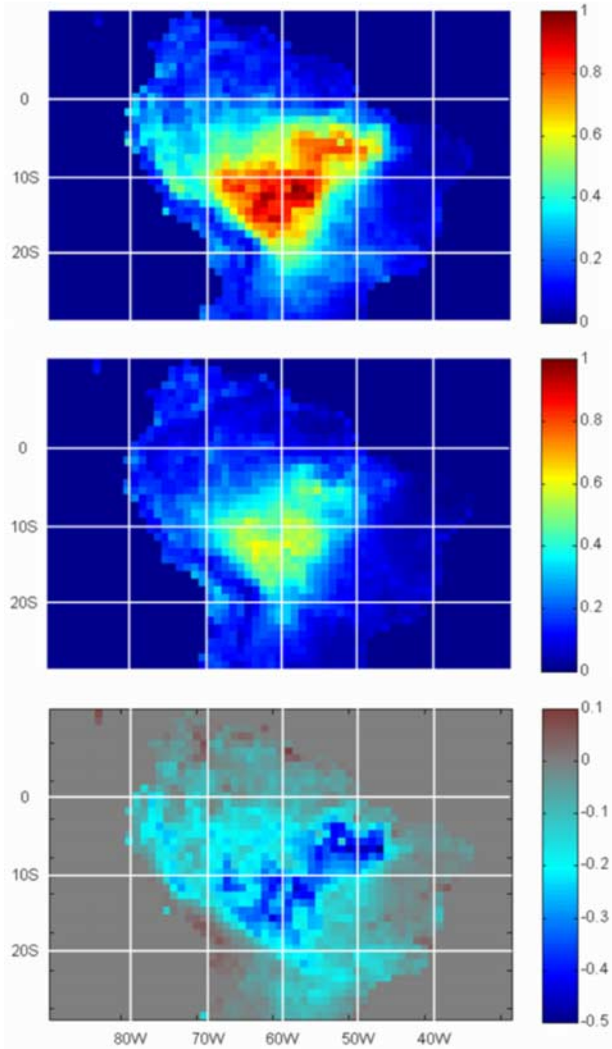

Figure 3. (top) Mean aerosol optical depth for the dry season of 2005. (middle) Mean aerosol optical depth for the dry season of 2006. (bottom) Difference in AOD between the biomass burning season of 2006 and that of 2005 for each 1 degree square. The brightening blue color indicates increasing negative differences showing that AOD in 2006 was dramatically lower than it was in 2005.

fire counts that begin at the start of each time series and continues through 2005. Linear regressions through this subsetted time range of six years yield slopes of increasing AOD of 0.02 per year and increasing fire counts of more than 14700 additional fires per year with R = 0.90 for both variables. This trend is significant at the 95% confidence level for both AOD and fires. The rate of increase of 0.02 of AOD per year from 2000 to 2005 is much less than the numbers quoted above for the regions of highest trends. The large domain average includes areas with much lower AOD and lower trends. However the domain average shows that the area of increasing smoke dominates the entire portion of the continent in our domain. The rate of increase of 0.02 (AOD/yr) represents an overall increase of more than 50% in AOD over the six year period.

[14] If the year 2006 is added to the time series, the correlation coefficients fall to R = 0.27 for AOD and R = 0.50 for the fires, neither of which is a significant trend. Note that the additional two years of data in the fire count time series increases the correlation coefficient for the trend regression line, but not sufficiently to create a significant trend.

4. Discussion

[15] The year 2006 stands out as an anomaly. For eight years, from 1998 through 2005, the number of fires and subsequently the smoke in the Amazon shows interannual variability, but generally steady increase. The number of annual fires doubles during this period and the mean smoke AOD increases by 60%. Then in 2006, abruptly both fires and smoke return to values that are among the lowest in the data record. What happened?

[16] In the 2005 dry season the tri-national region of Peru, Brazil and Bolivia in the southwestern Amazon experienced a drought that reached the dimension of a significant disaster with severe environmental, human and economic consequences [*Brown et al.*, 2006]. The interchange of information between scientists active in the Amazon, government and civil society led to the establishment of a permanent alert service for drought and fire activities [*Brown et al.*, 2006]. This initiative has been highly effective. In May 2006, the river water levels were below those of the same period in 2005 and there was indication that similar disastrous drought conditions would happen again. However, with the concerted effort of the information exchange and alert system, the devastation did not repeat. In August 2006 the fire activity was 50% below values from 2005 in the same period over all Brazil, with the reduction in Acre reaching 94%.

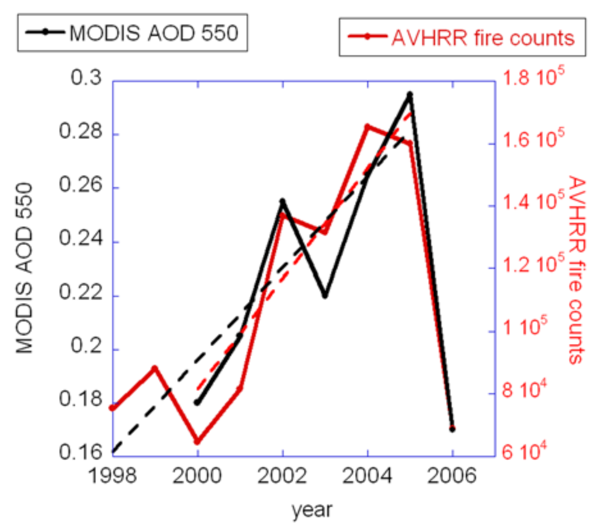

Figure 4. Mean MODIS aerosol optical depth at 550 nm (left axis, black) and total AVHRR fire counts (right axis, red) for the entire domain and biomass burning season of August through November plotted as a function of year. Also plotted are the linear trend lines through the time series with 2006 omitted (dashed lines). The subsetted time series with 2006 omitted results in significant trend correlations of R = 0.90 for both variables, while the full time series including 2006 results in insignificant trend correlations of R = 0.27 for the AOD and R = 0.50 for the fire counts.

[17] The reduction in biomass burning in 2006 also had a meteorological component. The precipitation in the Brazilian states of the deforestation arc (Acre, Rondonia, Mato Grosso, Southern Amazonas and Southwestern Para) was indeed above the climatologic mean for 2006 but these rains came late in the season. Before September, Acre was most likely the only state of the deforestation arc where weather could have affected the burning activity. Even so, the strong reduction over all Brazil and specifically in Acre before the onset of the rains points to the critical role human activity plays in creating, controlling and mitigating biomass burning and deforestation.

[18] Biomass burning in the Amazon basin experiences significant interannual variability, some of which can be attributed to natural factors such as weather. However, the sharp reversal of a 6 year trend seen in the MODIS smoke observations and the 8 year trend seen in the AVHRR fire counts demonstrates that cultural practices do make a difference. Smoke from biomass burning is a serious environmental hazard, but unlike earthquakes and severe weather, effective policy can mitigate the severity of the danger to human health, the well-being of the rain forest and the whole climate system.

[19] **Acknowledgments.** This paper is dedicated to the memory of Yoram J Kaufman, a dear friend and a brilliant scientist. This research was supported in part by the Israel Science Foundation (grant 1355/06) and NASA's Radiation Sciences Program and Interdisciplinary Studies. We thank the reviewer for helpful comments. I. K. is incumbent of the Benjamin H. Swig and Jack D. Weiler career development chair.

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