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Defining a Fire Year for Reporting and Analysis of Global Interannual Fire Variablility

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Defining a fire year for reporting and analysis of global interannual fire variability

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[1] The interannual variability of fire activity has been studied without an explicit investigation of a suitable starting month for yearly calculations. Sensitivity analysis of 37 months of global MODIS active fire detections indicates that a 1-month change in the start of the fire year definition can lead, in the worst case, to a difference of over 6% and over 45% in global and subcontinental scale annual fire totals, respectively. Optimal starting months for analyses of global and subcontinental fire interannual variability are described. The research indicates that a fire year starting in March provides an optimal definition for annual global fire activity.

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1. Introduction

[2] Recent research indicates that global interannual variability in terrestrial ecosystem fluxes, and thus atmospheric CO_2, are controlled primarily by drought and fire [*Patra et al.*, 2005a, 2005b]. Fire is both an important determinant of vegetation community structure [*Bond et al.*, 2005], and a globally significant source of greenhouse gas emissions [*Crutzen et al.*, 1979; *Crutzen and Andreae*, 1990]. There is an on-going debate on the relationship between climate change and interannual fire variability [*Stocks*, 1998; *Siegert et al.*, 2001; *Alencar et al.*, 2006; *Westerling et al.*, 2006]. Interannual vegetation dynamics have been studied using the multidecadal NOAA AVHRR satellite data record [*Myneni et al.*, 1997; *Nemani et al.*, 2003] but this global satellite data series does not provide temporally consistent fire data products due to factors including variable satellite overpass times and diurnal variability in fire activity [*Giglio*, 2007]. The recent NASA MODIS satellite includes features specifically for monitoring fires globally and has a constant Equatorial overpass time [*Kaufman et al.*, 1998; *Justice et al.*, 2002]. MODIS data have been used to develop a new generation of multiannual remotely sensed fire products, whose reduced margins of uncertainty allow the study of regional to global-scale fire interannual variability [*Schultz*, 2002; *Giglio et al.*, 2006a, 2006b; *Van Der Werf et al.*, 2006]. To date, little attention has been given to defining an optimal starting point for calculating yearly fire activity. Previous studies use the calendar year, i.e., starting in January [e.g., *Schultz*, 2002; *Hoelzemann et al.*, 2004; *Ito and Penner*, 2004; *Carmona Moreno et al.*, 2005; *Giglio et al.*, 2006a, 2006b; *Van Der Werf et al.*, 2006], while those

that use a different starting month [e.g., *Dwyer et al.*, 2000; *Tansey et al.*, 2008] do so without explicit justification. In this paper we use MODIS active fire detections to examine the sensitivity of yearly fire calculations to changing the starting month of the calendar year definition and the impact of using inappropriate starting months, and we suggest optimal starting months for analyses of global and select subcontinental-scale fire interannual variability.

[3] In various scientific fields, annual periods are often not defined to start in January. For example, the climate modeling community typically uses seasonal definitions (March−May, June−August, September−November and December−February) which are not subperiods of the January−December calendar year [*Rossow and Dueñas*, 2004]. In hydrological studies, the year is often considered to last from October to September in the Northern hemisphere, and from July to June in the Southern hemisphere, starting with the beginning of the major precipitation season and ending in the subsequent dry season [*Glickman*, 2000]. Aggregating annual precipitation data using this definition, rather than the January to December definition, allows for the generation of more consistent yearly statistics as the major rainy season precipitation is aggregated together, and so there is less "carry over" among consecutive years. The same properties are desirable for interannual fire analysis. A "fire year" defined with similar criteria would mean that the analysis of fire interannual variability is also the analysis of the variability between fire seasons, which in turn may be more unambiguously linked to other climatological events.

[4] Reliable definition of fire interannual variability from satellite data remains a challenge. Not least, because the appropriate spatial and temporal scale of analysis is poorly understood. The relative importance of contrasting physical influences acting under different circumstances determines the characteristic fire regime of a particular region [*Archibald et al.*, 2008]. Fire activity is dependent upon the availability of dry vegetation biomass for burning, which is largely dependent upon prevailing weather conditions, and preceding growing seasons precipitation required to grow vegeta-

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Figure 1. The 14 geographic regions used in the study, defined by *Giglio et al.* [2006a]. All these regions are considered together to derive the global results. Antarctica and the Arctic are assumed not to burn and are not considered.

tion fuel. The role of humans in igniting fires and the extent that their activities constrain or promote fire by modifying fuel loads and environmental conditions is not quantified at regional or global scale. In regions where there is sufficient rainfall to support closed-canopy woodlands and forests, the incidence of fire is mediated by moisture conditions, with drought increasing the incidence of fire, tree mortality and flammability [*Nepstad et al.*, 2004; *Spessa et al.*, 2005; *Kasischke et al.*, 1995]. Forests that burn may take hundreds of years to regrow before they can burn again, whereas grassland systems may burn every year dependent on factors including preceding years rainfall and herbivory [*Van Wilgen et al.*, 2004; *Bond et al.*, 2005]. Studies of fire interannual variability are evidently sensitive to the scale of the analysis. Further, geographical analyses of this kind are sensitive to the size and location of the sampling units in space and time and to the nature of the summary units used to aggregate the data [*Openshaw*, 1984].

[5] In this paper, we consider subcontinental- to continental-scale geographic regions, and 3 years of monthly MODIS active fire counts within these regions. We assume that these sampling units are sufficiently large to capture interannual fire variability that would be missed at smaller sampling scales. For example, forest stand replacing fires may occur only every several hundred years in a specific locality but at several locations in the same year at continental scale. We first analyze a multiyear data set of MODIS active fire detections to assess whether it is feasible to adopt a fixed 12-month fire year interval, then we assess the impact of changing the fire year starting month, and then define an optimal starting month definition to summarize annual fire activity globally and for select subcontinental regions.

2. Description of the Data Set

[6] Fire data were provided by the daily MODIS active fire product that describes the 1-km location of actively burning fires at the time of MODIS overpass [*Giglio et al.*, 2003]. The most recently reprocessed and available (at the time of writing) Collection 5 MODIS-Terra products from April 2000 to April 2003 were used. The first 2 months of MODIS active fire products (February and March 2000) were discarded as the data quality in this immediate post-satellite launch period was suboptimal [*Roy et al.*, 2002]. This provides 37 months, i.e., slightly more than 3 years, of global fire data.

[7] The MODIS active fire product is defined in $10° \times 10°$ degree tiles in an equal area sinusoidal projection [*Wolfe et al.*, 1998]. Each 1-km pixel records the occurrence of active fires detected over a 24 hour period and the detection confidence (high, medium or low) [*Giglio et al.*, 2003]. If no detections occurred then the surface state (water, snow, cloud, or unknown) is recorded. In this study, only active fire detections labeled with medium and high confidence were considered to reduce potential commission errors. These daily data were aggregated into monthly composites that define the location of 1-km pixels with one or more medium or high confidence active fire detections in that month, the land/water surface state, and the number of missing data days occurring due to cloud obscuration and/ or the MODIS sensing geometry.

[8] The analysis was conducted with respect to 14 subcontinental geographic regions (Figure 1) defined by *Giglio et al.* [2006a] on the basis of fire behavior and on their suitability for emission studies [*Van Der Werf et al.*, 2006]. The smallest region is Central America (CEAM, 2.7 10^6 km^2) and the largest is Central Asia (CEAS, 18.1 10^6 km^2), corresponding to 2.0% and 13.4% of the global land surface, excluding Antarctica, respectively. We assume that at this scale, 37 months of summary monthly fire count data are sufficient to characterize interannual fire variability. We note that the period recommended by the Intergovernmental Panel on Climate Change to capture grassland savanna fire interannual variability for smaller, national, scale emissions is 3 years [*Houghton et al.*, 1997].

[9] Monthly counts of the number of medium and high confidence active fire detections within the 14 subcontinental geographic regions and globally were derived. The MODIS-Terra acquisitions suffered some interruptions during the 3-year study period, the longest was for 15 days in June 2001. In order to minimize the impact of data inter-

ruptions, the monthly count data were normalized, following the method of *Giglio et al.* [2006b], by assuming that fire activity during missing days was equal to the average fire activity observed during the rest of the month. Normalized fire counts were computed for each region and globally by multiplying the monthly counts by the ratio between the number of days in the month and the number of non-missing days.

3. Preliminary Data Analyses

[10] Figure 2 shows monthly active fire counts for each of the 14 geographic regions and globally (Figure 1) for April 2000 to April 2003. Each region has a distinct fire season, characterized by several months of high fire activity occurring over approximately the same months each year. Yellow vertical lines are superimposed to show the month of maximum fire activity and blue vertical lines are superimposed to show the same months in preceding and/or subsequent years. Interannual variation in the timing of peak fire activity is evident as the blue lines do not always coincide with the timing of maximum fire activity; only Europe (EURO) which has consistently high fire activity in August shows no interannual variability in this respect. Europe (EURO) and Boreal North America (BONA) show particularly marked variations in the total amount of burning among the 3 years illustrated. Certain regions, such as Central America (CEAM), Northern Africa (NHAFR) and North Equatorial South America (NHSA), exhibit a distinct shift in the timing of the peak fire season, whereas other regions, like Equatorial Asia (EQAS) and Australia (AUST), have interannual differences in both the amplitude and the timing of the peak fire month. Northern Africa (NHAFR) is the single region with the highest number of active fire detections, 26% of the global fire counts in the period covered by this study, followed by Southern Africa (SHAFR) with 22%, Australia (AUST) with 13%, and Sub-Equatorial South America (SHSA) with 12%.

[11] At global scale, fire maxima occur in August–September and to a lesser extent in December–January (Figure 2, GLOBAL). This global distribution has been observed in other studies using different and similar satellite data sets [*Dwyer et al.*, 2000; *Shultz*, 2002; *Boschetti et al.*, 2004; *Van Der Werf et al.*, 2006]. The global maxima correspond to peak fire season months in the Southern hemisphere (August–September) primarily driven by the extensive burning in Southern Africa (SHAFR) and Australia (AUSTR) and in the Northern hemisphere (December–January) due primarily to burning North of the Equator across Northern Africa (NHAFR).

[12] To verify that there is a yearly fire cycle is a *conditio sine qua non* for the definition of a fire year. Figure 3 illustrates temporal autocorrelations of the 3-year monthly 1-km active fire count data illustrated in Figure 2. Correlations with monthly lags from 1 to 24 months are shown. The dashed horizontal lines show the 95% confidence intervals. For most of the regions, and globally, the maximum autocorrelation occurs for a 12-month lag, and for most (including globally) the maxima are significant at the 95% confidence level. The boreal North America (BONA) region is the only region without any 12-month autocorrelation. This can be explained by examination of the corresponding

fire time series (Figure 2), which indicates high fire activity in 2000 followed by a year of relatively little activity and then by a year of high activity. As a consequence, the BONA 12-month correlation is negligible, while the 24-month correlation is significant at the 95% level. The regions Central Asia (CEAS), Central America (CEAM) and Boreal Asia (BOAS) have high autocorrelations at 12-month periods but maxima at 13 months. This is due to interannual variability in peak fire activity timing (evident in Figure 1). Despite this, it is apparent that a 12-month fire year is applicable for all regions; that is, at this scale of analysis, fire is a phenomenon with a significant annual cycle. As discussed in the introduction, at finer spatial scales of analysis and for regions with long fire return intervals, this 12-month fire cycle may not be observed.

[13] Examination of Figure 2 indicates that extracting yearly statistics using the January–December calendar year is inappropriate for analyzing fire interannual variability in certain regions and also globally. For example, in Northern Africa (NHAFR) and Northern South America (NHSA) the peak of the fire season occurs in December and January. Consequently, in these regions, the fire activity during the main fire season is split between two calendar years; any shift in the timing of the fire season would reflect in the yearly statistics of the 2 years involved. This is in contrast with regions, such as Southern Africa (SHAFR) and Central America (CEAM), where the main fire season occurs within the January–December calendar year, indicating that for these regions a calendar year is appropriate for interannual fire variability analysis.

[14] To illustrate the impact of changing the starting month of the 12-month fire year, Figure 4 shows the annual number of active fire detections for every possible starting month from April 2000 to May 2002, for each region and globally (black dots). These data are normalized as percentages of the 3-year annual average (estimated as the total 37-month count divided by 12) to enable comparison among the regions. The red dots in Figure 4 show the 1-month differences of the annual data, i.e., they reflect the rate of change of these data which is a measure of the sensitivity of the yearly fire totals to changing the starting month. If there were no interannual variability and the fire activity had exactly a 12-month periodicity then annual counts for any starting month would be constant. This is evidently not always the case; for example, Europe (EURO) shows the effect of strong interannual variability in the magnitude of the fire activity: the annual counts (black dots) starting after July 2001 progressively decrease as more months of the relatively low fire activity 2002 months are included. This sensitivity is reflected in the 1-month differences of these data (red dots).

[15] These preliminary analyses have demonstrated that fire is a periodic phenomenon, with a 12-month cycle at subcontinental and global scales, and that 12-month totals of fire activity are sensitive to the choice of the initial month. In order to quantify the magnitude of this sensitivity and to identify an optimal starting month, a rigorous sensitivity formulation that may be used as a monthly ranking criterion is required.

[16] In any given month the variation of the annual total fire count can be expressed by comparing the 12-month sum obtained in the current month with the one obtained in the
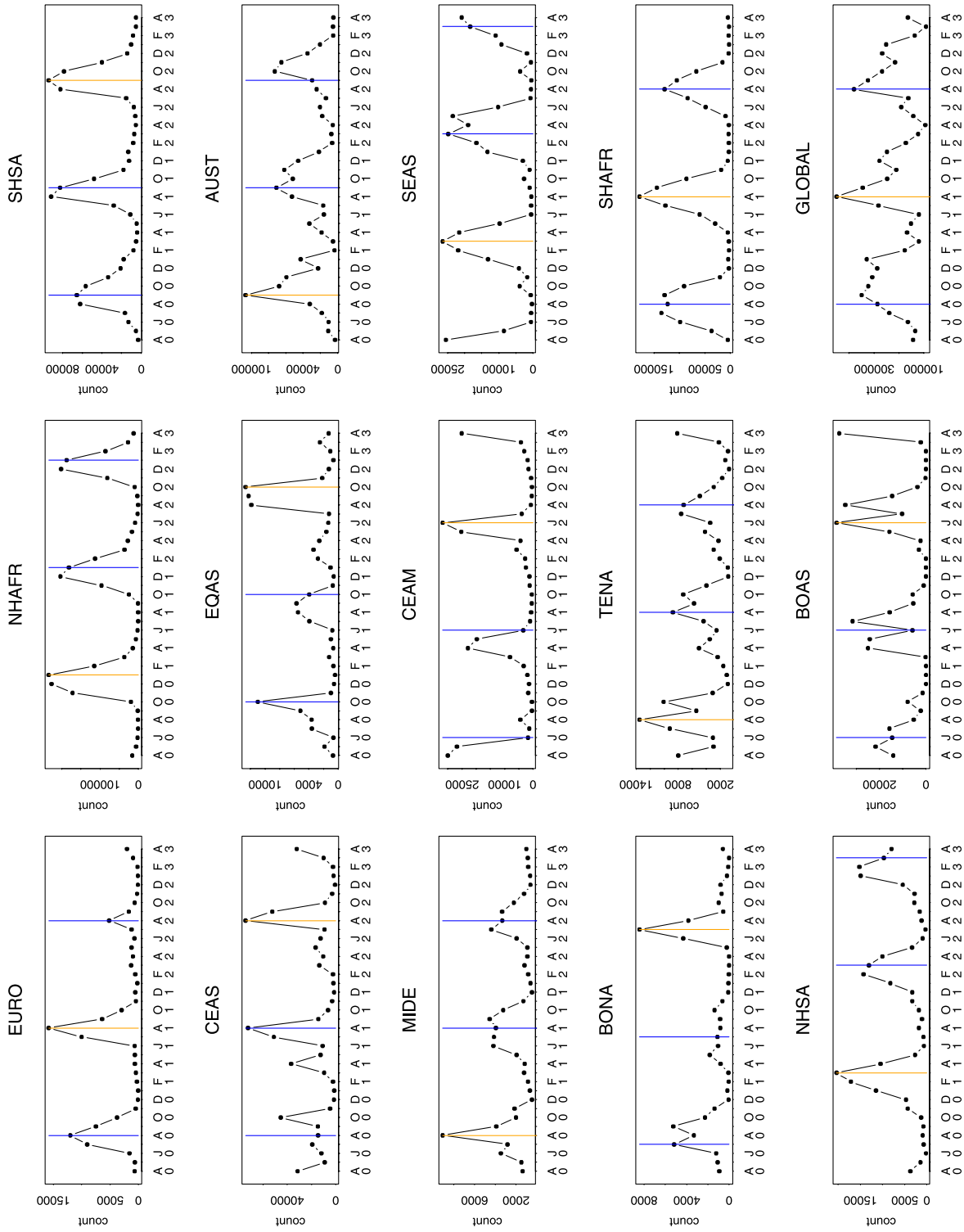
Figure 2. Total monthly MODIS Collection 5 Terra 1-km active fire counts for each of the 14 geographic regions (Figure 1) and all regions (Global) for the 3-year period of April 2000 (A 0) to April 2003 (A 3). The yellow vertical lines show for each region the month of maximum fire activity and the blue vertical lines show the same months falling in preceding and/or subsequent years.
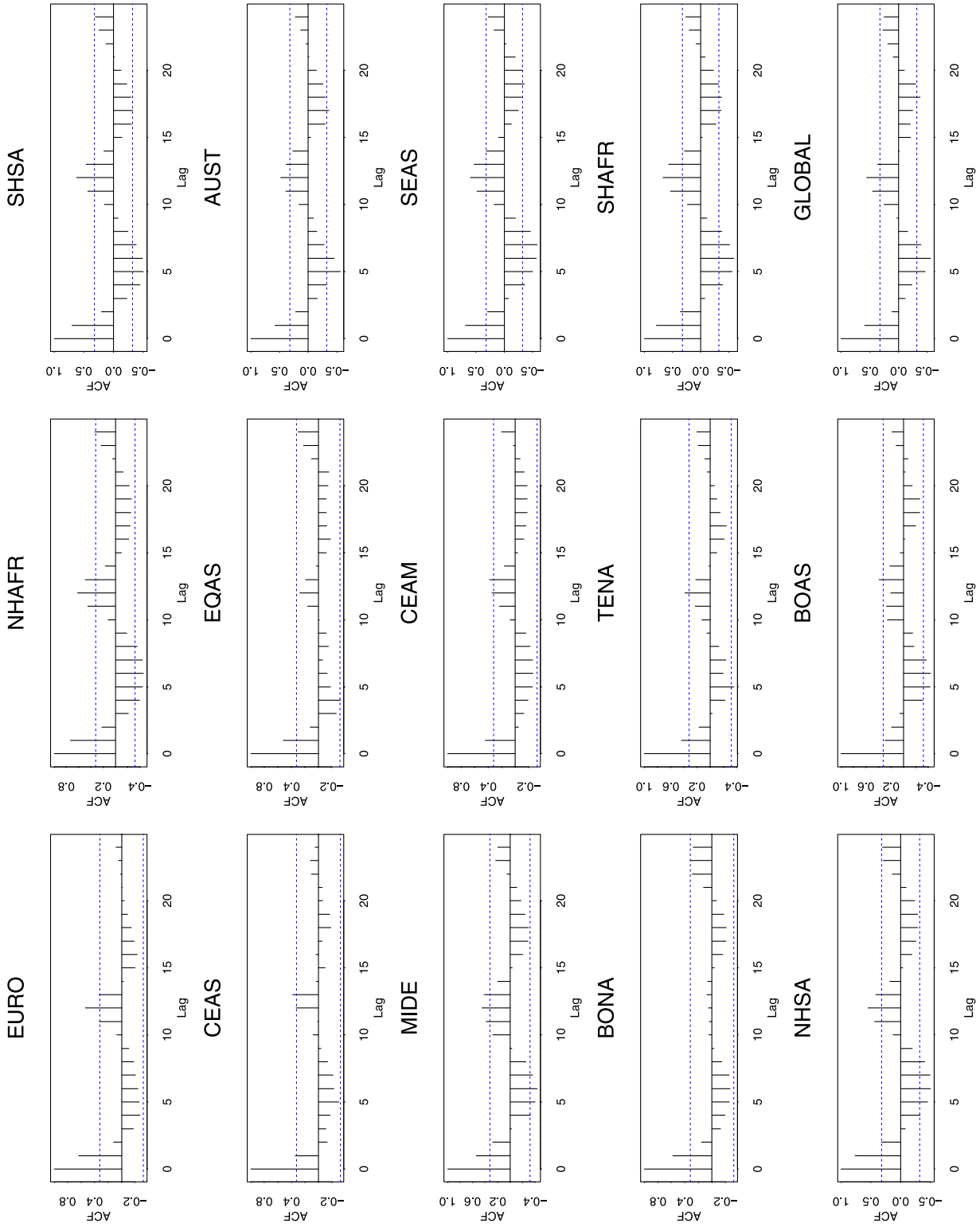
Figure 3. Temporal autocorrelations of the 3-year monthly 1-km active fire count data illustrated in Figure 2. Correlations with monthly lags from 1 to 24 months are shown. The dashed horizontal lines show the 95% confidence intervals.
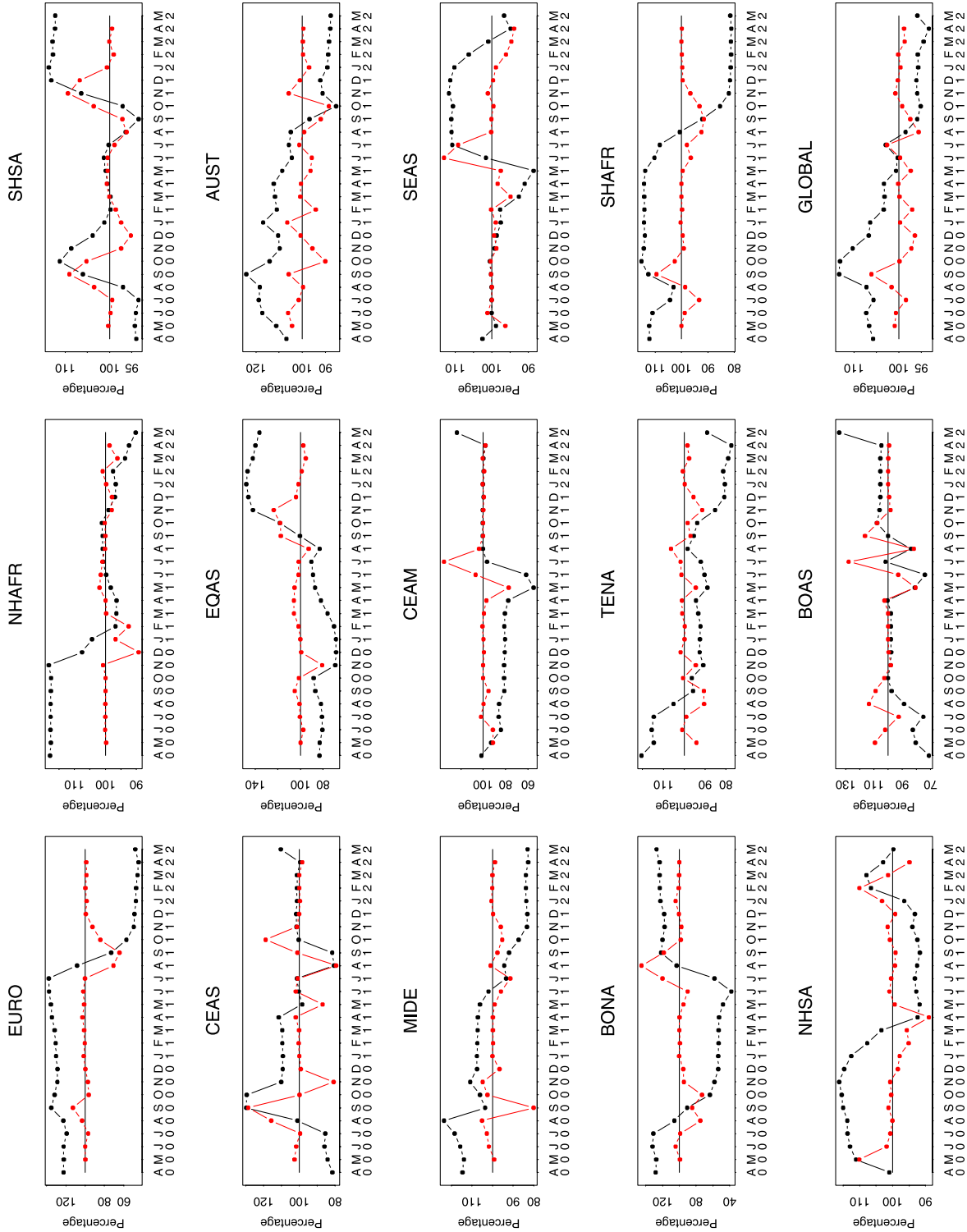
Figure 4. Annual (12 months) number of 1-km active fire counts (black) and 1-month differences of these data (red) computed for monthly periods starting April 2000 (A 0) to May 2002 (M 2). These data are shown as percentages of the annual 12-month average count (estimated as the total 37-month active fire count divided by 12). The horizontal lines show 100% values for reference.

previous month, i.e., the backward derivative (illustrated by red dots in Figure 4), or by comparing it with the sum calculated in the following month, i.e., the forward derivative. An optimal fire year starting month would minimize sensitivity to changes in the timing of the fire season both forward and backward in time. To assess this, the two values are aggregated using two different criteria: (1) the average of the absolute values of the forward and backward derivatives, (2) the higher of these two absolute values. These correspond to the Laplace (1) and the Wald criteria (2) used for decision making under conditions of uncertainty [*Walker*, 2001]. With the Laplace criterion we assume that there is equal probability of shifts in the fire activity in either temporal direction, which is a reasonable assumption as climatic factors can delay or bring forward the onset of fire. With the complementary, more conservative, Wald criterion we instead quantify the worst-case, rather than the average sensitivity to changing the fire year definition by 1 month.

4. The Impact of Inappropriate Fire Year Definitions

[17] Figure 5 shows the Laplace and Wald values for every possible starting month from April 2000 to May 2002, for each region and globally. These values are summarized as percentages of the 3-year annual average fire count (estimated as the total 37-month count divided by 12). They quantify for each month the average (Laplace, solid circles) and maximum (Wald, open circles) difference in annual fire totals if the start of the fire year is changed by a single month. There is an evident positive correlation between these sensitivity values (circles) and monthly fire activity (orange lines): the months of low sensitivity are also those of low fire activity, while in general the sensitivities peak during the main fire seasons. The variation in sensitivity is due both to variations in the amplitude and the timing of the fire seasons. For example, in Sub-Equatorial South America (SHSA), the timing of the 2001 peak fire season (August) is earlier by a month compared to the preceding and the following years (Figure 2), this causes an August–September 2000 sensitivity peak (as the 2001 fire season starts to be included in the yearly totals) and an October–November 2001 sensitivity peak (as the 2001 fire season stops to be included in the yearly totals).

[18] For all regions the Laplace and Wald values have maxima greater than 7% and 9% respectively; that is, for certain months in each region, changing the start of the fire year by a month, may lead to a difference of over 7% of the 3-year annual average fire count. In the worst case, Boreal North America (BONA), changing the start of the fire year by a single month around July 2001 leads to a difference of one third or more of the 3-year annual average fire count (32.6% Laplace, 45.1% Wald). The most fire prone regions, Northern Africa (NHAFR), Southern Africa (SHAFR), Australia (AUST), Sub-Equatorial Southern America (SHSA) have maximum differences ranging from 7.0 to 9.8% (Laplace) and from 9.4 to 11.5% (Wald).

[19] At global scale, sensitivity to changing the fire year definition is lower than regionally because of the different regional fire season timings and is driven mainly by the regions with the most burning. Global sensitivity to the starting month is greatest in August and September of 2000

and 2001 because of the high sensitivities in Southern Africa (SHAFR) and Australia (AUST) in these periods. Global sensitivities are also high from October 2000 to February 2001, but not in the same period a year later, primarily because of the temporal distribution of fire activity in Northern Africa (NHAFR). The most sensitive month in both years is August, when changes of 1-month result in a global annual fire total difference of 3.8% or 3.5% (Laplace 2001 and 2002) and 6.1% or 4.4% (Wald 2001 and 2002). If a calendar fire year definition is used, i.e., starting in January, then the difference with Laplace values is 1.7% or 0.3% and with Wald values is 3.0% or 0.4% in 2001 and 2002 respectively.

5. Defining a Global Fire Year

[20] Figure 6 illustrates for each month of the year the mean Laplace (solid circles) and the maximum Wald (open circles) values derived from the 2 years of data shown in Figure 5. For each region and globally, the month with the lowest mean Laplace value and the month with the lowest maximum Wald value is indicated in color. Globally, and for all regions, except Sub-Equatorial South America (SHSA), there is a single month that not only has the lowest sensitivity on average (lowest mean Laplace value, yellow), but also has the highest robustness against extreme values (lowest maximum Wald value, green). Globally March satisfies both these criteria. Quantitatively, a change in the start of the year by 1 month around March causes a change in the yearly total fire counts of 0.7% on average (mean Laplace value) and 1.3% in the worst case (maximum Wald value). For a calendar year starting in January, the change is slightly higher than in March on average (1.1%) but significantly higher in the worst case (3.0%). The greatest changes occur for a global fire year starting in August: 3.7% on average, and 6.1% in the worst case.

[21] Figures 2 and 6 illustrate that in all cases, the months with minimum fire activity are also those with lowest mean Laplace and lowest maximum Wald values. The month of March has the minimum fire activity globally and for twelve out of the fourteen regions. Evidently, a global fire year starting in March will maximize the separation between consecutive fire seasons. Conversely, August is the worst possible starting month for the global fire year, as it is the month of maximum fire activity and greatest sensitivity.

[22] A possible alternative approach for interannual global fire analysis, would be to use the regionally specific fire year definitions and then aggregate the regional results to global scale. This would have several drawbacks, not least because it may introduce inconsistencies at region boundaries, and because it would make it harder to compare fire data with other environmental variables, as they would also need to be similarly aggregated in space and time.

6. Conclusions

[23] Quantitative analyses of fire interannual variability are required for a number of scientific applications, including study of the interactions between fire, climate, land cover land use, vegetation dynamics, and pyrogenic emissions to the atmosphere [*Crutzen et al.*, 1979; *Stocks*, 1998; *Siegert et al.*, 2001; *Bond et al.*, 2005; *Patra et al.*, 2005a,
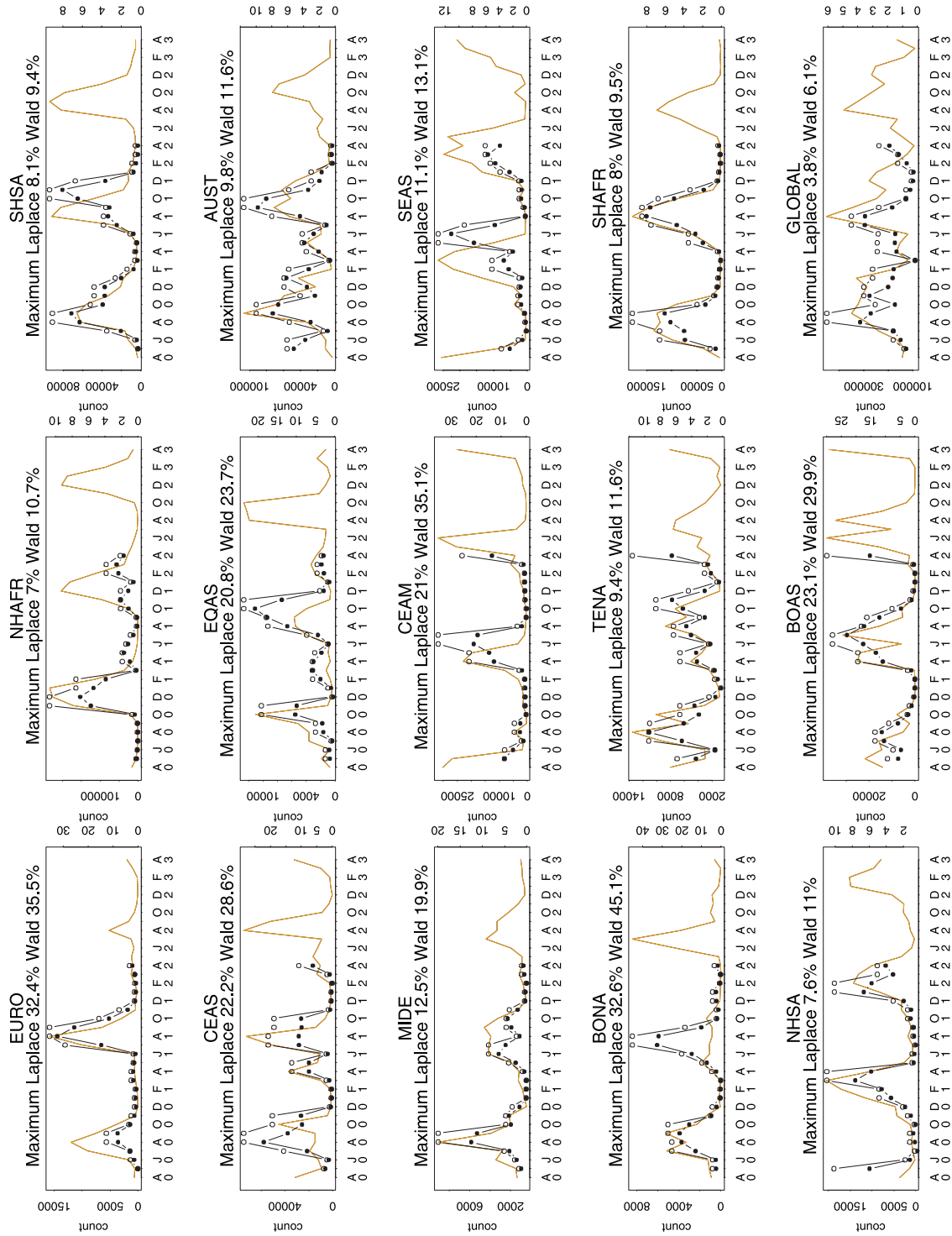
Figure 5. Sensitivity of the annual 1-km total active fire counts to one month differences for monthly periods starting May 2000 (M 0) to April 2002 (A 2). The Laplace (average) and Wald (maximum) absolute values of the one month differences moving forwards in time (the discrete right derivative) and backwards in time (the discrete left derivative) are plotted as solid circles (Laplace) and open circles (Laplace); the values, expressed as percentage, are reported on the y axis on the right side of each plot. For reference, the monthly fire counts (Figure 2) are superimposed in orange for the 37 month study period, with the values reported on the left side of each plot.
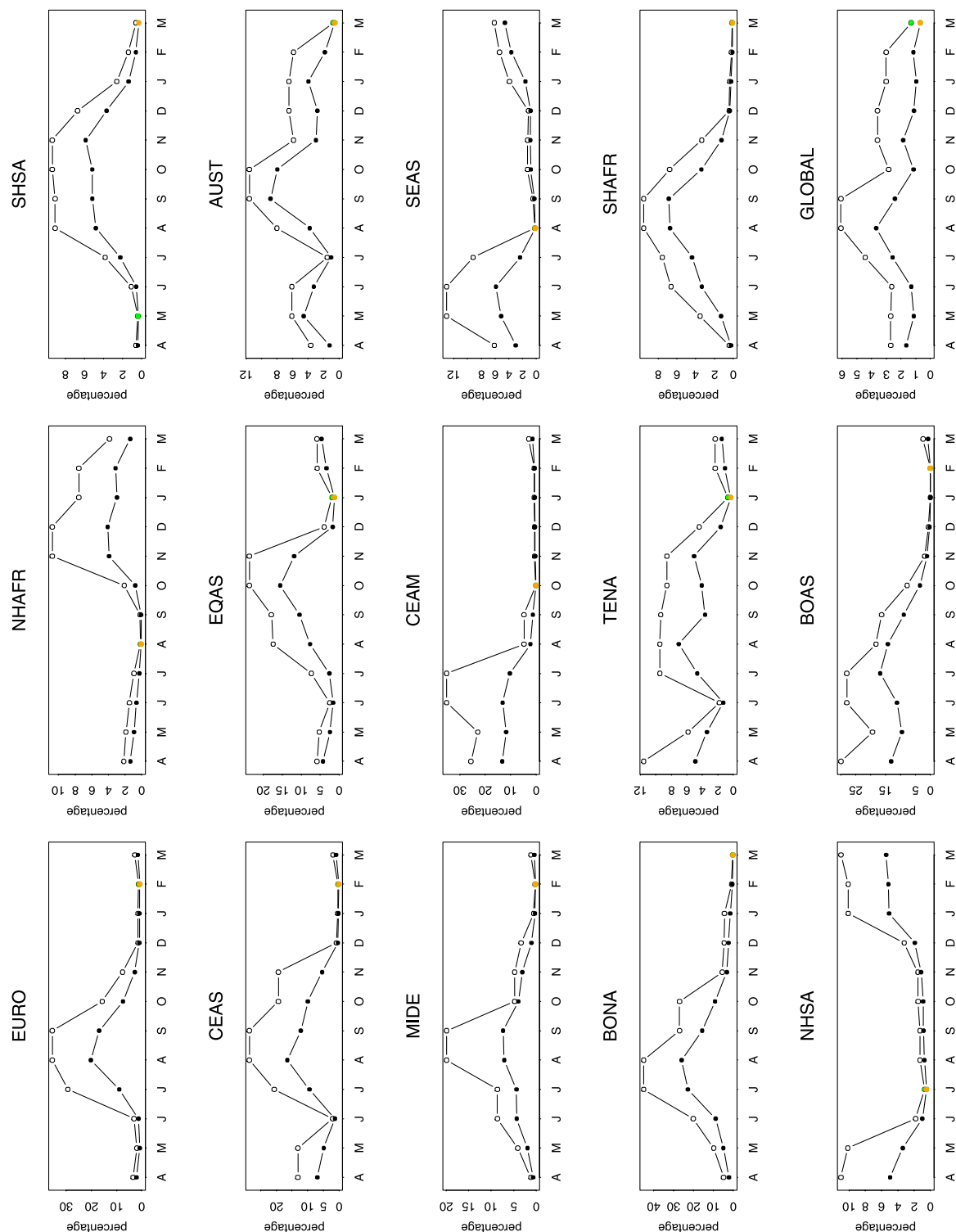
Figure 6. Sensitivity of the annual 1-km total fire counts to the starting month, April (A) to March (M). The mean Laplace (solid circles) and the maximum Wald (open circles) values derived from the 2 years of data illustrated in Figure 5 are plotted. For each region and globally, the month with the lowest mean Laplace value (i.e., minimum average sensitivity) is plotted in yellow, and the month with the lowest maximum Wald value (i.e., minimum worst-case sensitivity) is plotted in green. For most regions these two minima coincide.

2005b; *Alencar et al.*, 2006; *Westerling et al.*, 2006]. To date, annual summaries of fire have been computed using either the calendar year January–December, or, when a different annual definition has been adopted, without explicit characterization of the underlying temporal fire variability. Given that 26% of the active fire detections in this global study occur in Northern Africa, where the peak fire season is December–January, global interannual variability extrapolated from calendar year fire series are likely to be affected even by small anticipations or delays in fire activity.

[24] The research described in this paper demonstrates that the choice of the starting month can have a significant effect on regional annual fire totals, with changes of a single month in the start of the year definition causing a change in global annual fire totals of up to about 10% in the regions most affected by fire, i.e., Northern Africa (NHAFR), Southern Africa (SHAFR), Australia (AUST) and Sub-Equatorial Southern America (SHSA), and up to more than 30% in Europe (EURO), Central America (CEAM) and boreal regions (BOAS and BONA). Evidently, the choice of the starting month for yearly aggregations is not a neutral one, and inappropriate starting months may bias subsequent interannual analyses.

[25] At global scale, previous studies indicate that the interannual variability of fire–induced phenomena is in the range of several percent. For example, the coefficient of variation of annual emissions estimated on a calendar year basis by *Van Der Werf et al.* [2006], when limited to the years covered by MODIS (2001–2004), is 3% for carbon and CO_2, 6% for CO, and 7% for CH_4. The magnitude of these variations are comparable to variations that we report, changing the start of the global fire year definition by a single month around January (on average 1.0% and worst case 3.0%). Our analyses indicates that at global scale, a change of 1 month of the start of the year around August (the month with highest fire activity at global scale) changes the global yearly estimates the most, on average by 3.7% and by 6.1% in the worst case.

[26] The present paper identifies an optimal fire year both globally and for select subcontinental regions on the basis of the minimization of the sensitivity of the total yearly fire counts to the starting month of the fire year. March is the optimal global fire year starting month, and is also the month of minimum global fire activity. For the 3 years of data used in this study, changing the start of the global fire year definition by a single month around March affects the yearly totals by 0.7% on average and by 1.3% in the worst case. Although small, these amounts are nonnegligible, and they reflect the likely magnitude of variability imposed by using a monthly temporal aggregation scheme in interannual comparisons of fire activity.

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