NASA Goddard Space Flight Center

Fire Energetics and Emissions Research (FEER) Group

http://feer.gsfc.nasa.gov/

FEER Coefficient of Emission (C_e) Product User Manual

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Product Versions & Document Revisions

Version	Revision	Date	Editor(s)	Description of change
1.0	–	6 Nov 2013	Luke Ellison, Charles Ichoku	Original document.
	A	15 Jan 2015	Luke Ellison	Replaced references to Ichoku & Ellison (2013) with Ichoku & Ellison (2014); Replaced references to van Donkelaar et al. (2011) with Darmenov and da Silva (2013); Updated product file naming convention; Changed language concerning the FEER emissions product from tentative to accomplished.

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The Fire Energetics and Emissions Research (FEER) is a research initiative based out of NASA GSFC with the aim of developing an accurate and comprehensive understanding of the occurrence, distribution, behavior, energy release, smoke emissions, and various effects of wildfires and other types of biomass burning through in-depth and collaborative research using remote sensing, modeling, field and laboratory measurements, as well as other applicable approaches. The "FEER research group" maintains a website, which may be referred to simply as "FEER website" or "website", whose Uniform Resource Locator (URL) is http://feer.gsfc.nasa.gov/.

The "FEER Ce product", which may be simply referred to as "this product", is the coefficient of emission (Ce) product developed by the FEER research group.

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Introduction

The relatively new ability to measure radiant energy on a global scale with the use of powerful sensors aboard earth-observing satellites is revolutionizing the science of fire research. The advent of mid-infrared (MIR) narrowband channels on these orbital platforms has brought about the ability to quantitatively characterize fire on a global basis and for an extended period of time. By putting this unprecedented satellite capability to advantageous use, new emissions inventories based on remotely sensed fire data have continued to be created ever since it was established that there is a linear relationship between biomass consumed and emissions output (e.g. *Seiler and Crutzen* 1980). However, most of the initial satellite-derived inventories were based on the qualitative use of fire detects to estimate emissions. New inventories that are based on the quantitative use of fire radiative power (FRP) measurements are now being developed, although they use the common bottom-up methodologies that by their very nature are complex and prone to compounding uncertainties. The Fire Energetics and Emissions Research (FEER) coefficient of emission (C_e) version 1.0 dataset is the first global gridded product in the family of 'emission factors', that is based essentially on satellite measurements, and requires only direct satellite FRP measurements of an actively burning fire anywhere to evaluate its emission rate in near real time, which is essential for operational activities, such as the monitoring and forecasting of smoke emission impacts on air quality (*Ichoku and Kaufman 2005; Ichoku and Ellison 2014*). Therefore, the FEER C_e product is a revolutionary idea and product. This FEER C_e product user manual is provided to help the user in understanding the FEER C_e product and guide the user in extracting and using the data.

Background

The algorithm used to generate the FEER C_e product is an update from the original one published in (*Ichoku and Kaufman 2005*). This idea combines two established relationships: 1) that the mass of specific aerosols or trace gases released is directly proportional to the dry mass combusted *(e.g. Seiler and Crutzen 1980; Andreae and Merlet 2001*), and 2) that fire radiative energy (FRE), or the temporal integral of fire radiative power (FRP), is also directly proportional to the amount of dry biomass combusted *(e.g. Wooster 2002; Roberts et al. 2005; Wooster et al. 2005; Freeborn et al. 2008*). Therefore, the fundamental relationship defining this product is that the mass of smoke aerosol, for instance, can be linearly related to FRE, as has been verified experimentally using small laboratory fires *(Ichoku et al. 2008; Freeborn et al. 2008*). The rate of aerosol emission can similarly be related to that of FRP. Thus, the following equations are established:

$$R_{sa} = C_e \cdot FRP \qquad (1)$$

$$M_{sa} = C_e \cdot FRE \qquad (2)$$

where R_{sa} is the rate of smoke aerosol emission, M_{sa} is the mass of smoke aerosol emission, and C_e is the coefficient of emission.

C_e is the coefficient that directly relates radiative power from a fire to its smoke aerosol emission rate. The FEER C_e product currently provides C_e for only total particulate matter (TPM) emissions, and subsequent work has extended this product to other common emitted species such as black carbon (BC), organic carbon (OC), particulate matter less than 2.5μm in aerodynamic diameter ($PM_{2.5}$), carbon monoxide (CO), and carbon dioxide (CO_2) using emission ratios. For a given species such as TPM, C_e values will vary for different biome types and locations. Thus, the FEER C_e product is generated on a 1°×1° global grid, such that FRE measurements within any of the grid cells multiplied by the corresponding C_e values according to Equation (2) will consistently give the TPM emissions generated from those fires.

In order to generate this C_e product, Equation (1) can be rearranged such that C_e can be taken as the slope of the linear least squares fit to a scatterplot between R_{sa} and FRP for each grid cell. FRP is easily obtained for instance from the MODIS fire product (MOD14/MYD14) (*Giglio et al. 2003; Justice et al. 2006*), whose version at the time of the current C_e product development was Collection 005, whereas R_{sa} is estimated from the difference between background aerosol optical depth (AOD) measurements and those affected by the smoke plume using the MODIS (Collection 051) aerosol product (MOD04_L2/MYD04_L2) *(Remer et al. 2005; Levy et al. 2009*), and wind vectors from the Modern Era Retrospective-Analysis for Research and Applications (MERRA) reanalysis dataset (*Rienecker et al. 2008; Rienecker et al. 2011*) produced by the Global Modeling and Assimilation Office (GMAO) and disseminated by the Goddard Earth Sciences, Data and Information Services Center (GES DISC).

The C_e algorithm calculates FRP and R_{sa} initially on a per-fire-pixel basis from both Terra and Aqua for the years 2003-2010 before aggregating the calculations into 1°×1° grid cells for the entire globe, thereby theoretically reducing the uncertainty in estimating these parameters on a larger scale (*Ichoku and Ellison 2014*). However, as part of this process of aggregation, certain key parameters and corresponding thresholds were identified and used to remove contaminated data from the dataset. Thus, the resulting filtered dataset produced much cleaner results, showing clear relationships that were previously undetectable. There were still a few examples, however, where clear outliers were adversely affecting the linear regression fit to the scatterplots between R_{sa} and FRP measurements. Therefore, an outlier correction algorithm was also created specifically for use with the type of non-normal distribution of points observed between R_{sa} and FRP. This outlier algorithm was able to correct several misleading results, after which the final aggregation of the data within each grid cell was performed. Individual C_e products were generated for both Terra and Aqua data, but having observed that the differences between the two are not biased in any one direction, the two datasets were combined to gain greater spatial coverage (which is referred to by the designation “MCD” in the metadata of the data files.) Finally, in order to create a gap-filled product, C_e values derived with progressively less stringent requirements during the filtering process were first used to fill existing gaps in the final C_e product. The remaining gaps were then filled using a gap-filling algorithm based on surrounding pixels and their fire-induced land cover types. In this way, a spatially complete (except for non-vegetated surfaces) gridded C_e product has been generated and released to the public through the FEER web site.

File Content

The FEER C_e product is provided in a Comma-Separated Values (.csv) file format with a filename convention of the form "FEERv#.#_Ce.csv" where the "v#.#" identifies the version of the product. The first few lines of metadata are followed by an empty line, which can be used to locate the subsequent header line and data set. Several parameters are reported for each grid cell, and so the data is organized as a list by latitude and longitude coordinates instead of using a full grid in order to save storage space. This admittedly may add an extra step in the user's extraction and use of the data.

The contents of the header include:

- Latitude/Longitude – the center latitude and longitude coordinates of the grid cells,
- N – the number of data points that were used in generating the values of C_e,
- Nol – the number of data points that the outlier algorithm removed before the calculation of C_e,
- Ce – the coefficients of emission in kg/MJ,
- R2 – the coefficients of determination in calculating C_e using a linear least squares fit passing through the origin (*Eisenhauer 2003*), and
- QA – the quality assurance flags.

Each of the parameters listed above, with the exceptions of Latitude and Longitude, have a suffix of "_850", which signifies that the wind vectors at the pressure level of 850mb (roughly corresponding to an altitude of 1.5km ASL) were used in the calculations. Plume injection heights that are more characteristic of the fire regimes in different regions may be utilized in future versions of the FEER C_e product.

The parameters *N* and *Nol* collectively represent the total number of data available within each grid cell, and this number is roughly correlated to the parameter *QA* due to the fact that higher QA values have thrown out more data than lesser values of QA. The bare minimum number of points that are deemed acceptable in reporting a C_e value is six, as can be inferred from the data table. However, there are many cases where $N=0$, which signify instances where C_e is determined from the final gap-filling procedure.

The C_e values generally fall within 0.01 and 0.1 kg/MJ, although there is a small fraction of the global dataset that fall well outside of this range. Figure 1 shows the full set of C_e as provided in the FEER C_e product. The differences in C_e from region-to-region justify the necessity for such a gridded C_e product; yet the homogeneity of C_e within each region gives reassurance that this product does indeed represent a physical process.

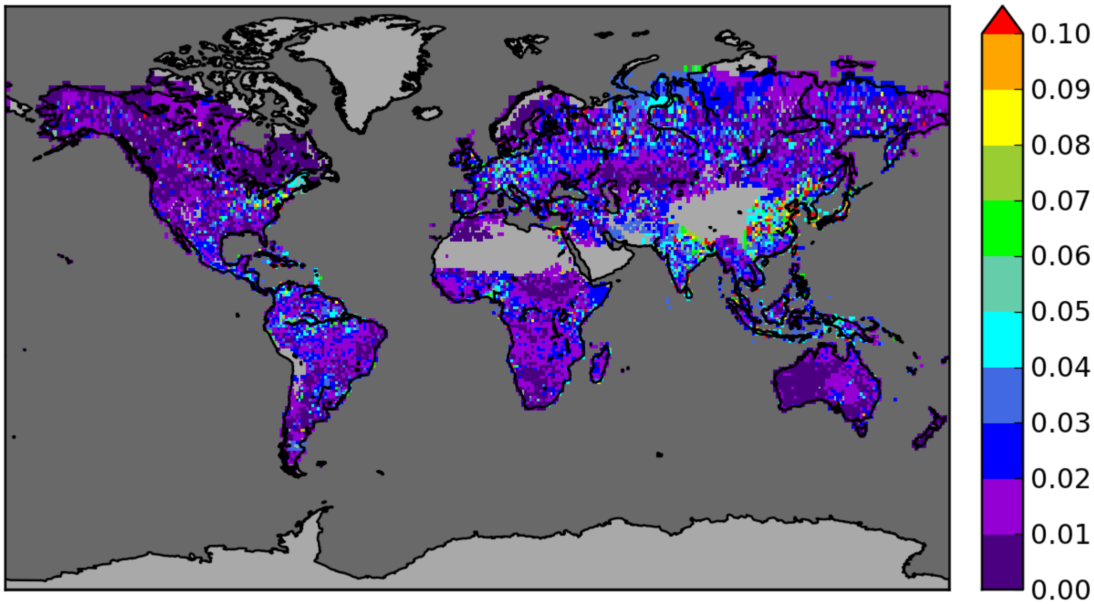

Figure 1: FEER coefficients of emission (C_e) at 1°×1° resolution are shown here, derived from MODIS data from both Terra and Aqua during 2003-2010.

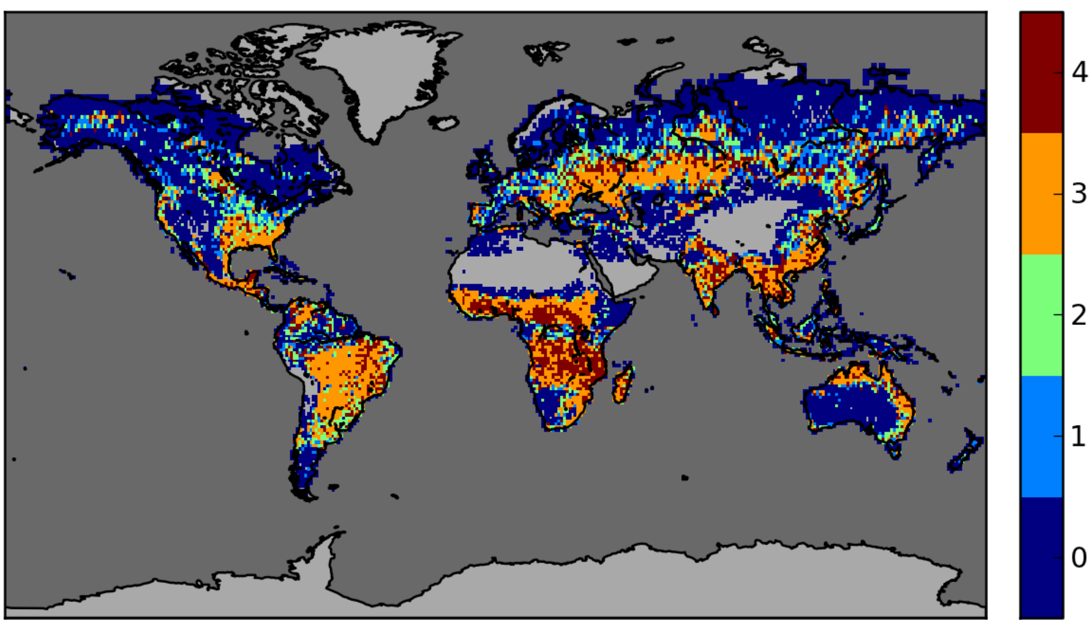

Figure 2: Quality assurance flags from the FEER C_e product at 1°×1° resolution are shown here, derived from MODIS data from both Terra and Aqua during 2003-2010.

Likewise, Figure 2 shows the full set of QA as provided in the FEER C_e product. The QA was developed during the process of applying different degrees of data filtering, as well as during the final gap-filling procedure. A QA of three or four implies the highest level of filtering, whereas a QA of zero implies either the lowest level of filtering or the final gap-filling procedure. The measure that separates QA's of three and four is that the latter must also have an R^2 value of at least 0.7.

Application

The coefficient of emission is appropriately described as a conversion factor between fire-attributed radiation and smoke emissions. Therefore, users of this FEER C_e product are able to generate emissions estimates of smoke aerosols in a straightforward way by simply multiplying it with FRP or FRE products. Although this requires more work to be done on the user's part at present, it demonstrates the great flexibility of the FEER C_e product in that it allows the user to use any FRP or FRE dataset of their choice. The following discussion will guide the user on the best practices for using the FEER C_e product.

Quality Assurance (QA)

In order to properly use the FEER C_e product with any given application, both the user's goals and the characteristics of the C_e product must be considered. The included QA parameter is a simplified guide that qualitatively describes the levels of confidence in the C_e data and outlines the underlying classification criteria between different values. The QA values are therefore beneficial to the user in handling the C_e product.

The final C_e product is a compilation of several different levels of filtering as previously described, leading to different values of QA where a value of zero represents the largest uncertainly and a value of four represents the highest confidence. The user may therefore control the quality of the emissions output by limiting the calculations to fires within grid cells with QA values at or above a designated value. If, however, the user's spatial domain is large and covers all levels of QA and if the user's intent is to calculate a total set of emissions estimates for the entire region, for instance, then it would suit the user best to disregard QA values altogether so as not to introduce a low bias.

The use of the QA product is even more necessary for applications that have a small sample size. The user must keep in mind that the FEER C_e product: 1) is derived on the basis of linear least squares fits on scatter plots, and 2) has a resolution of 1°×1°. For applications with a large sample size, any bias (in measurements of FRP and/or R_{sa}) introduced by one data point is likely offset by another; but if there are only a few detected fires, then such biases could easily go undetected by the user. This is especially apparent when the spatial resolution of the C_e product itself is considered. For instance, in some cases when FRP vs. R_{sa} scatterplots for grid cells at 1°×1° resolution are compared against corresponding plots at 0.5°×0.5° resolution, the values of C_e that are derived can be significantly different. Thus, applications with a small sample size are extremely susceptible to any existing internal variability. This caution might be disregarded in some cases for higher QA, but certainly may not be ignored for lower QA (i.e. higher uncertainly).

Fire Radiative Energy (FRP, FRE)

Despite the fact that development of the FEER FRE product is yet to commence, the flexibility of the FEER C_e product gives the user the freedom to select any other appropriate FRE data source to generate emissions. Generating emission rates from FRP using Equation (1) is fairly simple and straightforward because FRP is determined from instantaneous measurements of radiance from various spaceborne and airborne platforms. The World Meteorological Association (WMO) through their Observing Systems Capability Analysis and Review Tool (OSCAR) has provided an extensive list of FRP-capable spaceborne instruments (*World Meteorological Organization 2012*). The two MODIS polar-orbiting instruments provide a high quality FRP product (*Giglio et al. 2003; Justice et al. 2006*), which was used in the making of the FEER C_e product (*Ichoku and Ellison 2014*). MODIS FRP data record continuity will be assured by the NPP-based VIIRS instrument, which offers better spatial resolution and spatial coverage than MODIS (*Baker 2011*).

FRE is needed in order to generate total emissions. Finding or generating an FRE product can be quite difficult, especially when a global product is desired. FRE is related to FRP by,

$$FRE = \int FRP(t)\, dt \tag{3}$$

where t is time. Thus, the diurnal FRP cycle within each grid cell must be known or at least fairly well estimated. This immediately makes FRP databases from low earth orbit (LEO) satellites much more difficult to incorporate into the calculation of emission because even the most effective LEO satellites view a certain ground location at a maximum of twice per day. Figure 3 shows the disparity between LEO and GEO satellites of the ability to calculate FRE from FRP measurements. Studies have been done to find ways to estimate the diurnal cycle of FRP using only the few measurements from LEO satellites both globally (*Kaiser et al. 2012; Vermote et al. 2009*) and over certain regions (*Roberts et al. 2005; Roberts and Wooster 2008; Freeborn et al. 2009; Freeborn, Wooster, and Roberts 2011*).

If the user wishes to avoid techniques of estimating diurnal cycles and does not need a global emissions dataset, there are a few GEO satellite options available. For instance, the LSA SAF group has provided FRP data from SEVIRI on the MSG satellite series, coupled with MODIS LEO FRP data to account for the missing fires of low intensity, to generate a temporally regular FRP dataset over Africa (*Wooster et al. 2005; Lattanzio 2008*). Other groups have made an effort to combine the currently available FRP datasets from GEO satellites to create a global FRP product at regular temporal intervals (*Prins et al. 1998; Weaver et al. 2004*), and these have been used to generate a global emissions product as well (*Zhang et al. 2012*).

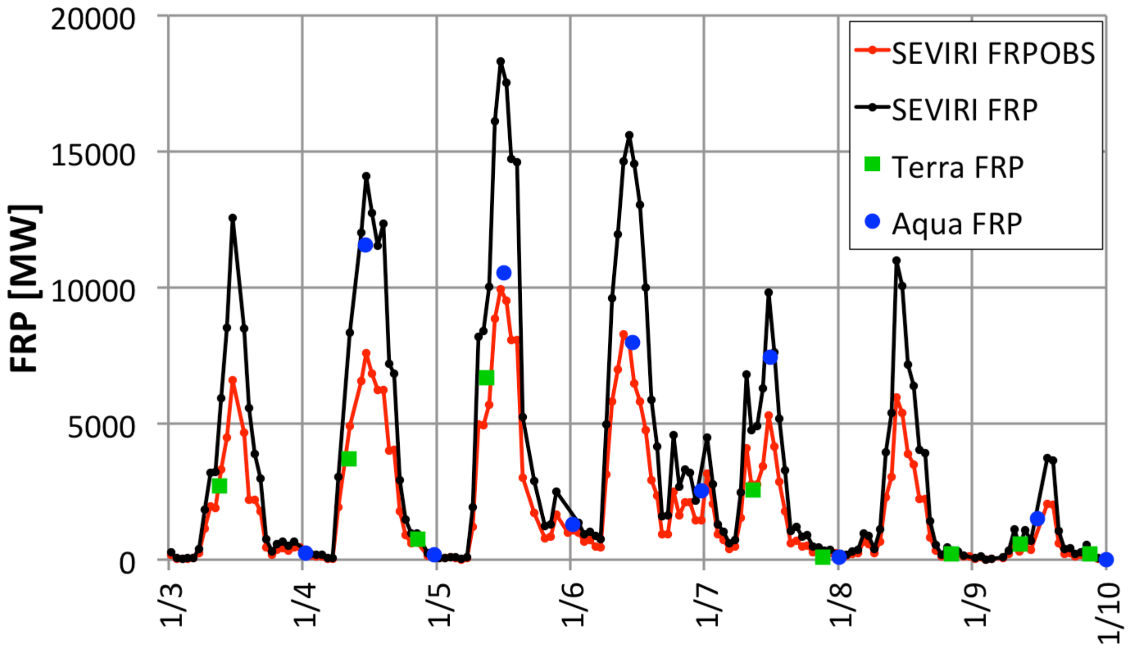

Figure 3: The FRP measurements from MODIS on Terra and Aqua as well as for SEIVIRI on the MSG series are shown here during the first full week of 2010 for the 1°×1° grid cell centered at 6.5°N and 26.5°E. SEVIRI "FRP" measurements are the raw "FRPOBS" measurements that have been corrected for missing, low-intensity fires.

Emissions (R_{sa}, M_{sa})

The major source of work required by the user in deriving emissions from C_e is in compiling the FRP or FRE dataset. Once the FRP or FRE data have been obtained for a given region and time period, calculating emission rates (R_{sa}) or emissions (M_{sa}) according to Equation (1) and Equation (2), respectively, is very straightforward. Figure 4 shows emissions that have been generated over Africa using the temporally integrated LSA SAF FRP product for the years 2009 and 2010.

Of particular interest to any users who wish to gain a global emissions dataset with FEER C_e but without the task of obtaining or developing the intermediate FRE dataset, an official FEER emissions product (Ichoku and Ellison 2014) has been produced using the FRE data provided with the Global Fire Assimilation System version 1.0 emissions product (*Kaiser et al. 2012*). Figure 5 shows a comparison between this FEER emissions product and three other global emissions inventories: the Global Fire Emissions Database version 3.1 (*van der Werf et al. 2006; van der Werf et al. 2010*), the Global Fire Assimilation System version 1.0 (*Kaiser et al. 2012*), and the Quick Fire Emission Dataset version 2.4 (*Darmenov and da Silva 2013*). Emissions based on the FEER C_e product and FRE from (in this case) the GFAS v1.0 product are on average almost twice as large than those of GFED v3.1 and GFAS v1.0, both of which are based on bottom-up approaches from satellite fire observations and have been found to be underestimated relative to satellite aerosol distributions in recent studies (*Kaiser et al. 2012*). On the other hand, the FEER C_e-based emissions are overall slightly underestimated relative to QFED v2.4

emissions. However, all four emissions exhibit the same general temporal patterns of variation. These results suggest that there is great opportunity for improvement in fire emission estimations using the FEER C_e product. Further testing and implementation of this FEER C_e product will reveal its level of authenticity in estimating emissions.

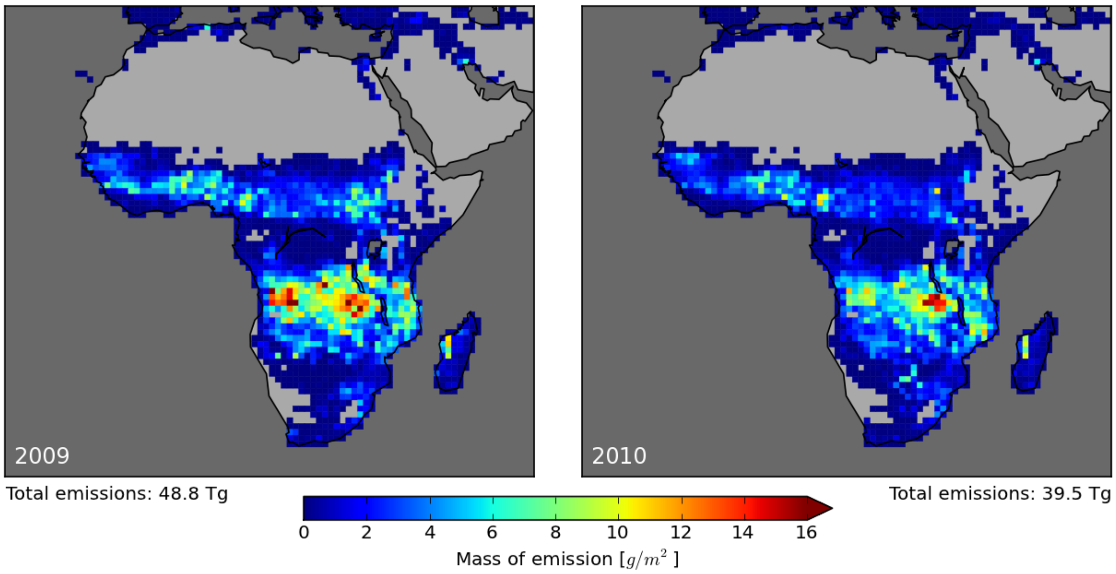

Figure 4: Emissions shown here are calculated at 1°×1° resolution over Africa for the years 2009 and 2010 by using the FEER C_e product in conjunction with integrated LSA SAF SEVIRI hourly FRP data.

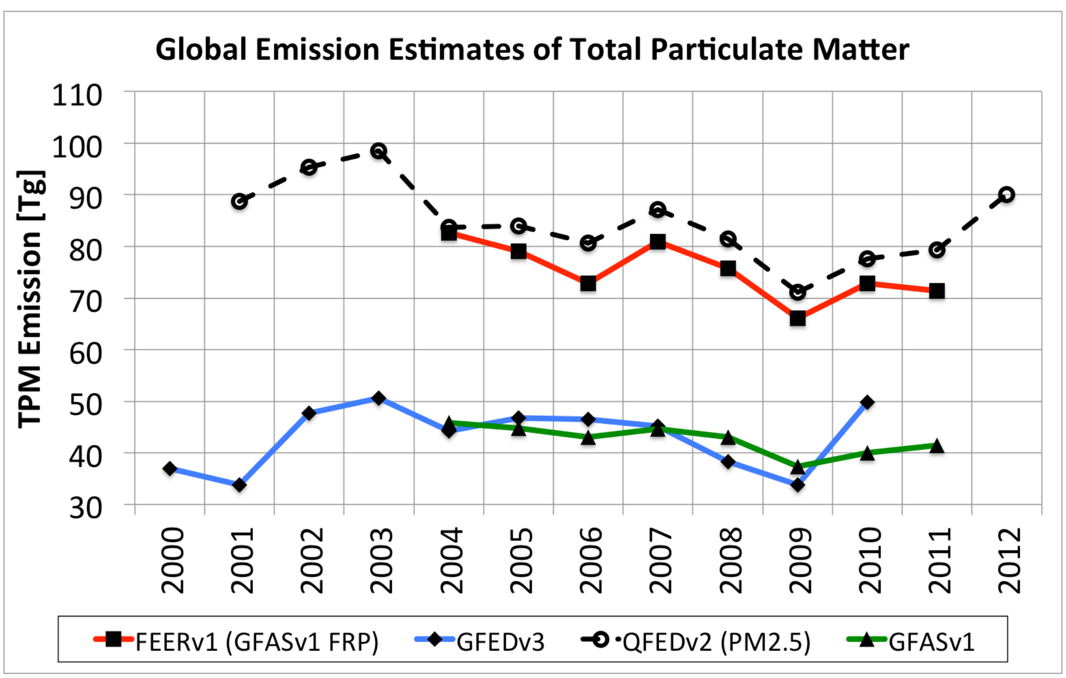

Figure 5: Annual global emission inventories between 2000 and 2012 are shown here for comparison. The FEER inventory incorporates the FEER C_e product and the monthly FRP dataset

from the GFAS emissions product into Equation (2) to derive emissions. These are compared against the burned-area-based GFED v3.1 product (van der Werf et al. 2006; van der Werf et al. 2010), the FRP-based GFAS v1.0 product (Kaiser et al. 2012), and the top-down, FRP-based QFED v2.4 $PM_{2.5}$ product (Darmenov and da Silva 2013).

Related Documents

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