ESTIMATING CARBONACEOUS AEROSOL EMISSIONS FROM FOREST FIRES IN NORTH AMERICAN BOREAL FORESTS IN JULY 2004

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by

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1. Introduction

Aerosol particles are known to play an important role in Earth radiation budget through absorbing and scattering solar light and serving as cloud condensation nuclei. Optical properties of aerosol depend on their chemical composition, as well as other properties (e.g. size, type of mixing, relative humidity, wave of incident light) (Bohren and Huffman, 1983). While the composition of aerosol is highly variable in space and time, it is known that carbonaceous material (composed mostly of black carbon (BC) and organic matter) is one of the primary components of the terrestrial aerosol (NARSTO, 2003; Seinfeld and Pandis, 1998). It is, therefore, necessary to take into account the strength and the location of the sources of these compounds when trying to predict their concentrations.

Biomass burning is known to be one of the major sources of carbon-containing aerosol. Open burning (both natural fires and controlled forest or crop residue burning) is reported to contribute around 42 % to total BC and 74% to total organic carbon (OC) emissions from all combustion sources (Bond et al., 2004). These emission sources, especially natural, such as forest fires, are variable in location and strength and are impossible to predict and are very difficult to quantify on a global scale. This leads to the fact that the uncertainties associated with the concentrations of carbonaceous aerosol are quite high. The main uncertainties come from the (1) quantitative estimates of the area burned - fire locations, extend and severity vary on various time scales, and the algorithm to retrieve these variations from the satellite observations has not yet been developed, (2) the amount of biomass available to burn at some specific location - ecozone and vegetation types are very variable across the globe, and are a dynamic system, where the vegetation types are changed by the natural and anthropogenic activity, and (3) the conversion factors that show how much carbon stored in the biomass goes into the substance of interest (here – BC or OC) (Andreae and Merlet, 2001; Bond et al., 2004; Giglio et al., 2005; Soja et al., 2004). Quantification

of the uncertainties associated with the sources of carbonaceous aerosol is an on-going work as well as the effort to construct more detailed global inventory of such sources and estimate the emission factors associated with various fuel types and combustion processes (Bond et al., 2004; Duncan et al., 2003; Liousee et al., 2003).

Global inventories of carbonaceous aerosol sources used in the climate models are often coarse and static. Obtaining a finely-resolved dynamic dataset of the natural and anthropogenic emissions from combustion sources is a non-trivial task requiring a global international effort and a balance of desired detail with available computational abilities. This work shows an attempt to estimate carbon emission from the fires North American boreal forest by combining the 1x1 degree (longitude x latitude) dataset, which defines the particular type of ecozone within the boreal forest, with the daily measurements of the number of fires in this area from the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on Terra satellite. This combination allows the estimate of daily carbon emissions from the forest fires in this area as opposed to the previously used monthly emission estimates provided in Global Fire Emissions Database version 2 (GFEDv2), which also considers boreal forest as a single ecosystem with the fixed emission factor. Estimates of the carbon emitted from the North American boreal forest fires were put into the Goddard Chemistry Aerosol Radiation and Transport (GOCART) model to calculate aerosol optical depth and observe how the better temporal and spatial resolution of the input emission affects the model result. The calculations were performed for every day of the month of July, 2004 with the intention to compare the estimated carbon emissions and model results with the satellite and in-situ measurements of aerosol properties obtained during the extensive field campaign INTEX-NA (Intercontinental Chemical Transport Experiment – North America).

2. Methods

2.1 North American boreal forest

The boreal forest of North America is concentrated in Canada and Alaska and is represented by 10 different ecozones, the geographical distribution of which is shown in Fig.1. Both the spatial distribution and the estimate of the carbon emission from each of these ecozones (termed 'carbon consumption') for three classes of fire severity (low, medium, and high) were provided by A. Soja (personal communication).

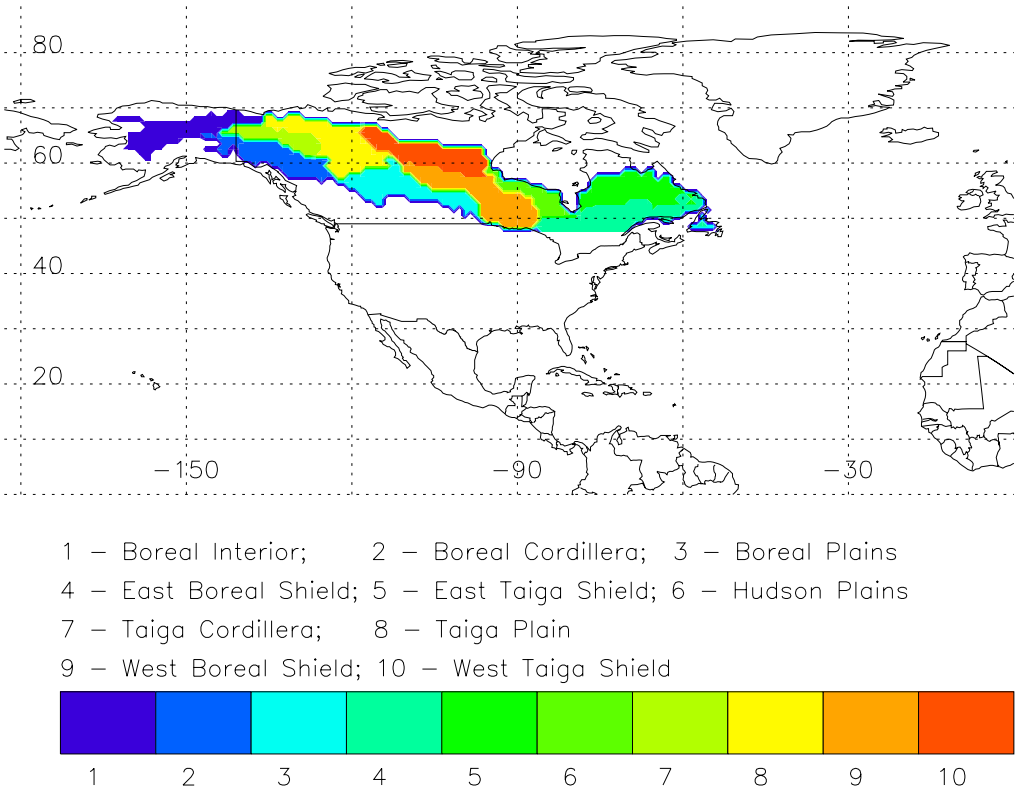

Figure 1. Ecozone types within North American boreal forest.

Carbon consumption values (Table 1.) were estimated taking into account the biomass availability that includes the above ground, peatland and surface organic carbon storage in each of the defined ecozones and assumes 50% flaming and 50% smoldering (A. Soja, personal communication, (Soja et al., 2004). For this study we assumed all fires were medium severity and

used the appropriate carbon consumption estimates from Table 1.

Table 1. Carbon consumption estimates for North American boreal forest ecozones for three levels of severity (A. Soja, personal communication). All values are in t C ha^{-1}, ecozones defined in Fig.1.

Carbon consumption	Ecozone type									
	1	2	3	4	5	6	7	8	9	10
Low	18.88	19.26	09.29	07.23	03.53	06.46	16.54	07.19	06.12	03.11
Medium	37.77	38.52	18.57	14.47	07.07	12.92	33.09	14.38	12.24	06.22
High	58.12	59.83	40.63	39.96	24.71	39.59	56.27	42.29	29.97	17.31

2.2 Estimating carbon emissions from forest fires

The fires are responsible for bringing carbon stored in the biomass into atmosphere. The amount of the carbon released during a forest fire depends on the amount of carbon available in the ecosystem (biomass density or fuel loading), the characteristics of the fire (area burned, fire intensity, burning vs. smoldering), and the factor describing the completeness of burning, which shows what fraction of the total biomass in the forest will be converted to airborne carbonaceous material (e.g. soot, primary aerosol particles and gaseous carbon-containing species). If the goal is to estimate the emission of a certain compound of interest (in this study BC or OC) the emission factor is taken into account. This factor represents the fraction of the total carbon emitted into the atmosphere that is in the compound of interest (or tracer).

The mass of the black carbon and organic carbon emitted during the fires was calculated in this study according to the formula M=AB(I)E, where M is the mass of the tracer, A is the area burned, B(I) is the intensity-dependent carbon consumption with intensity noted by I, and E is the tracer-specific emission factor. B(I) already includes the percentage of carbon in the given biomass and efficiency of burning. Burned area was estimated from the daily measurements of the fire counts obtained from the MODIS instrument on Terra satellite. Carbon consumption estimates were provided by A. Soja, and the species-specific emission factors used in the model are given below.

In defining the burned area within every grid box the information about the number of fires detected by MODIS was combined with the area covered by forest in this grid box. In the grid box completely covered by one type of forest, the area burned was determined by the number of MODIS-detected fires, each of which covers 1 km^2. In case of multiple forest types in the same grid box, all forest types were assumed burning in the amount proportional to their relative grid box coverage, so that the total area of fires in sq. km was equal to MODIS fire counts. The smaller value of the fire counts and the forest area determined the area burned in the partially forested grid boxes.

2.3 Fire counts and Aerosol Optical Depth measurements by MODIS

There are two MODIS instruments mounted one on each Terra and Aqua satellites, and they are continuously measuring multiple properties of land, ocean, atmosphere and cryosphere. Both Terra and Aqua satellites are polar-orbiting, with Terra on a descending orbit (southward) passing over the same location around 10:30 local sun time, and Aqua on an ascending orbit (northward) overpassing around 13:30 local sun time. Each of the MODIS instruments has a view of about 2330 km and with the carrying satellites orbiting the Earth every 99 minutes; each MODIS instrument observes the entire globe on a daily basis. The orbit repeats every 16 days (Remer et al., 2002).

MODIS performs measurements in the solar thermal infrared spectrum in the wavelength region 0.41- 14.235 µm. Two standard MODIS data products were used in this study: aerosol product (aerosol optical thickness) and the thermal anomalies product (location and time of fires).

Fire counts

MODIS can detect fires because of their very high temperatures. Every time the instrument detects the ‘hot spot’ its location is recorded in the dataset. In the non-ideal conditions (e.g. differing satellite positions, all view angles and both hot and cold fires) the instrument can routinely detect fires of about 900 m2 giving the detection of fires of a size close to four MODIS pixels (one pixel covers the area of 250 m2) around 100% (www.modis.gsfc.nasa.gov). The 1x1 degree

(longitude x latitude) dataset describing the number of fires per grid box as counted by the MODIS instrument on Terra satellite was used to estimate the area burned. Each fire count was assumed to represent the burned area equal to 1 km2. Thus, the number of fires detected by MODIS was directly translated into the area in km2.

Aerosol Optical Depth (AOD)

Aerosol optical depth (or aerosol optical thickness) is a measure of atmospheric extinction through a vertical column of atmosphere as sensed by the satellite visible sensor. This study uses a combination of Terra and Aqua MODIS level-3 daily column AOD at 550 nm with a 1°x1° horizontal resolution. Aerosol is not retrieved in cloud-covered areas, over bright land surfaces (e.g. ice and snow covered surfaces or deserts) and ocean sun glint areas. (Remer et al., 2002)

2.4 Aerosol Optical Depth calculations in GOCART

Goddard Global Ozone Chemistry Aerosol Radiation and Transport (GOCART) model is a global chemistry transport model, which simulates the major tropospheric types of aerosol: sulphate and its precursors, organic carbon (OC), black carbon (BC), dust, and sea salt. It uses assimilated meteorological fields from the Goddard Earth Observing System Data Assimilation System (GEOS DAS), which includes winds, temperature, pressure, specific and relative humidity, cloud fraction, cloud mass flux, precipitation, boundary layer depth, surface winds, and surface wetness. The horizontal resolution of the model used in this work is 2.5° longitude by 2° latitude with 30 vertical layers. Chemical processes in the model include gas and liquid phase reactions that convert sulfate precursors (dimethylsulfide, or DMS, and SO2) to sulfate. Physical processes include emission, advection, convection, and wet and dry deposition (Chin et al., 2004; Chin et al., 2000).

Aerosol optical depth is determined from the dry mass concentrations and mass extinction coefficients if the major aerosol types. Extinction coefficients are functions of size distributions, refractive indices, and humidity-dependent hygroscopic growth of each of the aerosol types. Used in

this study is the total vertical column AOD averaged daily. The GOCART-output AOD referred to here is the sum of total-column optical depth from sulfate, organic carbon and black carbon.

Natural and anthropogenic emissions of sulfate precursors and carbonaceous aerosols are accounted for and read-in from the available global inventories, along with the meteorology-dependent estimates of dust, sea salt and oceanic dimethylsulfide emissions. Information about carbonaceous aerosol emissions from open biomass burning used in the GOCART runs came from the Global Fire Emissions Database version 2 (GFEDv2). This dataset, intended to be used in the large-scale modeling exercises, contains 1°x1° monthly estimates of burned area, fuel loads, combustion completeness and fire emissions (carbon, CO2, CO, CH4, non-methane hydrocarbons (NMHC), H2, NOx, N2O, PM2.5, TPM, TC, OC, and BC).

GFEDv2 data were used to run GOCART for the month of July 2004 to obtain the reference AOD. The data from this run will be referred to as GOCART_GFED. Another model run was performed for the same time period but with the carbon emissions from the North American boreal forest fires estimated from the dataset described above. The data source for the emissions from the rest of the biomass burning events during this period was GFEDv2. For daily carbon emissions, the GFEDv2 monthly emission estimate was divided into 31 (number of days in July). Emission factors used in the model were constant for all biomass burning events and were equal to 0.001 kg BC/kg DM, 0.008 kg OC/kg DM, and 0.0012 kg SO2/kg DM, where DM is the amount of dry mass in the ecosystem, of which 45% is assumed to be converted to the airborne carbon species.

3. Results and Discussion

North American boreal forest has experienced abundant forest fire events in July 2004. Total number of fires detected by MODIS on Terra satellite in the area of interest (color-coded region in Fig. 1) is shown in Fig. 2. As will be seen later (Fig. 3 and 5) most of these fires were located in north-east Canada and Alaska.

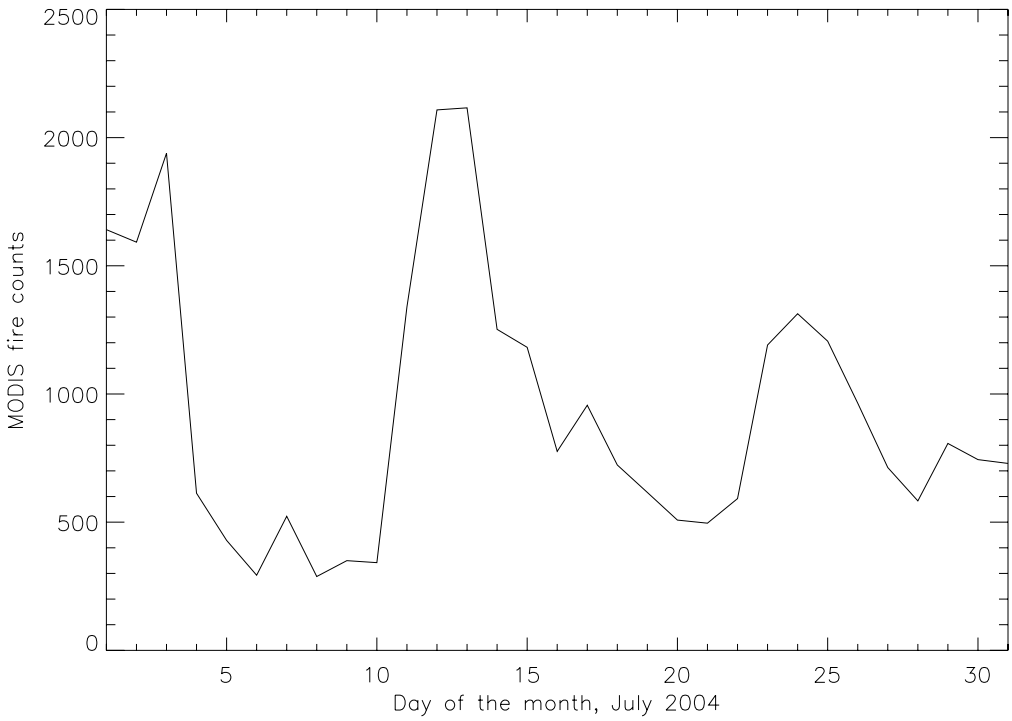

Figure 2 Total number of fires in North American boreal forest detected by MODIS Terra

Total amount of carbon emitted into the atmosphere during each day of July 2004 was calculated by combining the carbon consumption estimates for medium severity fires for all ecozone types with the spatially and temporally resolved fire counts detected by MODIS instrument on Terra satellite. The carbon emission rates (kg C / m^2 / month) summed over the entire month were compared with those reported by GFEDv2 and spatial distribution of the carbon emissions associated with the fires is shown in Fig. 3. Total actual amount of emitted carbon summed over the area of North American boreal forest equals to 5.82 x 10^{11} kg, which is about 1.8 times greater than 3.11 x 10^{11} kg obtained from GFEDv2 dataset for the same area and time period. This is consistent with the previous works that claimed that GFED version 2 reports carbon emissions that are lower than expected (Liousee et al., 2003).

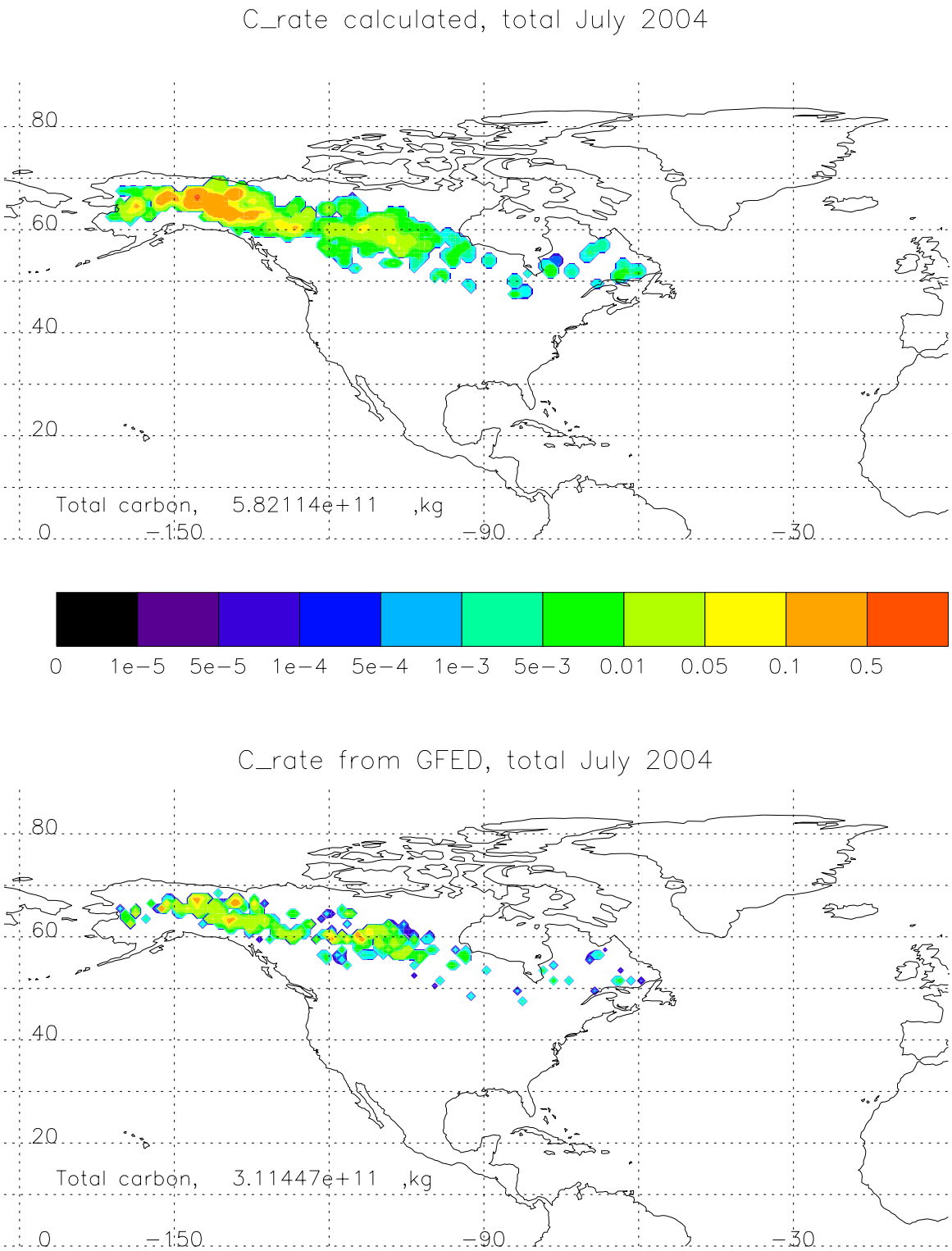

Figure 3 Carbon emission rates from fires in North American boreal forest.

Colors represent the emission rates in kg/m^2/month.

Carbon emission estimates from the GFEDv2 are used routinely in the GOCART model as an open burning carbon source. A model run for the month of July 2004 was performed with both the original GFEDv2 dataset and also the dataset in which the carbon emissions from the boreal forest fires were estimated using the technique described above. The comparison of the daily total aerosol optical depth (summed over the entire global model domain) calculated with the two carbon emission datasets all other parameters kept constant (Fig. 4) show that estimating carbon emissions on daily basis are improving the model's ability to capture the change in aerosol due to the variation in the number of fires. Increasing the temporal and spatial resolution is also improving the model performance in resolving the spatial deviations of carbon emissions from the mean. It can be seen from Fig. 5 that fires were underestimated in GFEDv2 in Alaska and overestimated in northern and central Canada.

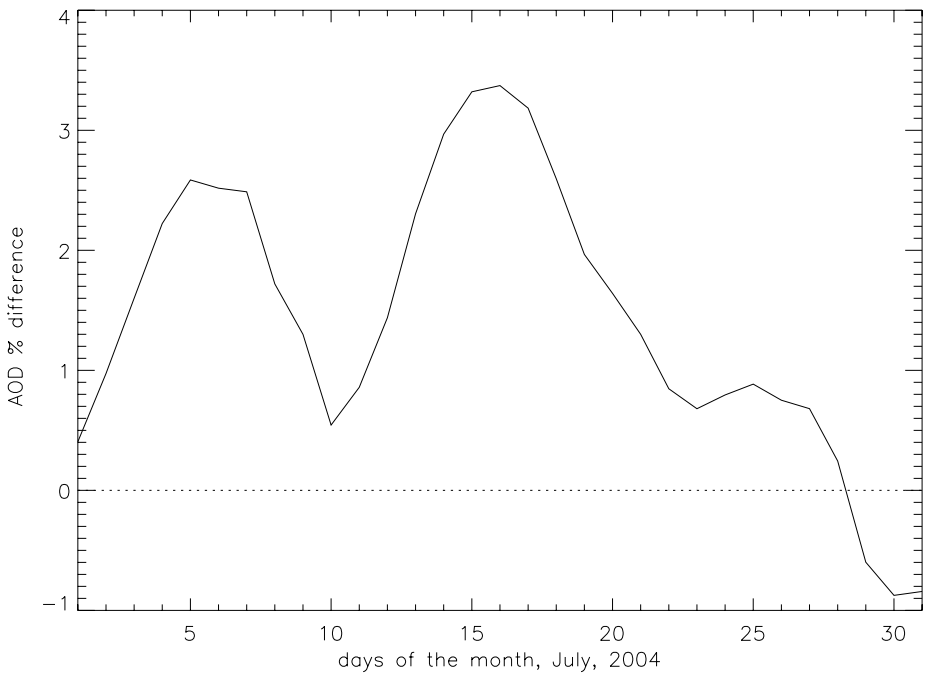

Figure 4 Difference in total global aerosol optical depth (in %) calculated by GOCART using GFEDv2 modified by North American fire emissions estimates and 'pure' GFEDv2.

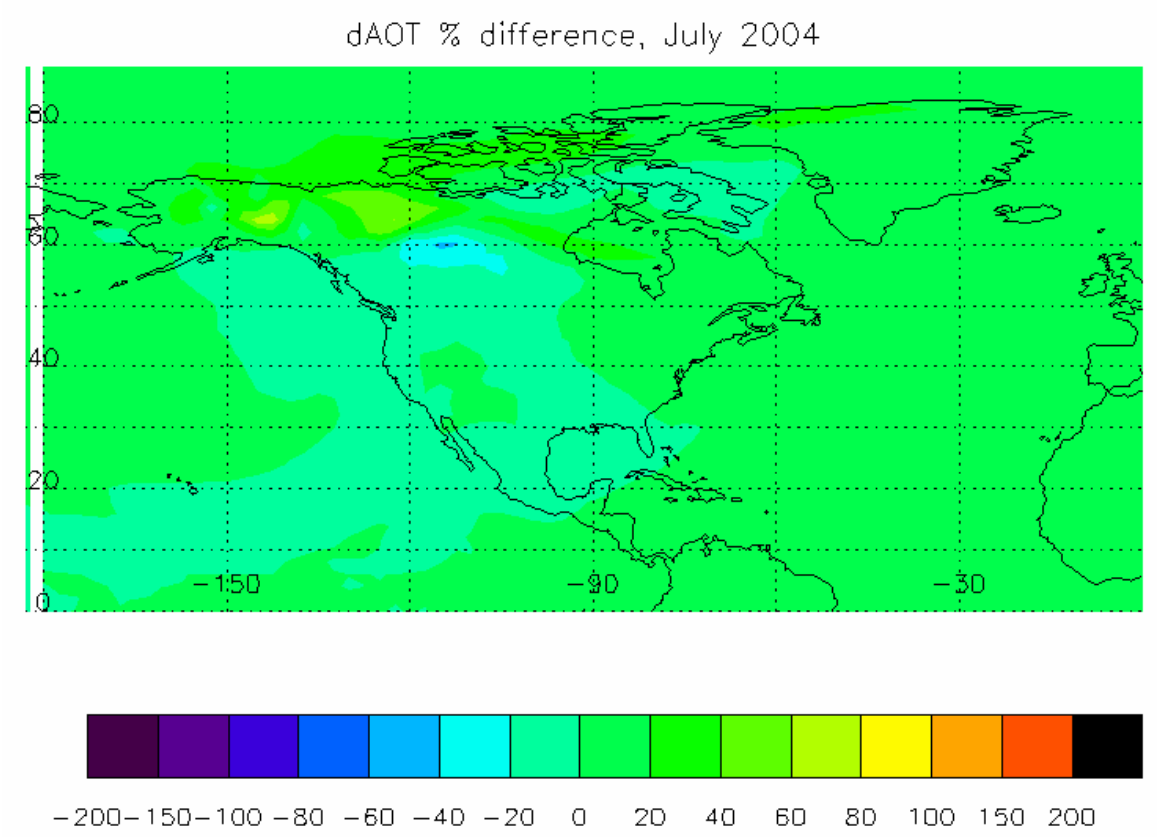

Figure 5 Difference in aerosol optical depth (in %) calculated by GOCART using GFEDv2 modified by North American fire emissions estimates and 'pure' GFEDv2.

GOCART-calculated aerosol optical depth from both runs was compared to the observed AOD measured by the MODIS instrument from both Terra and Aqua satellites. The comparison of monthly averaged AOD is shown in Fig. 6. This comparison, nevertheless, bears a certain bias associated with the MODIS data availability. As has been mentioned above that aerosol optical properties are not retrieved over cloudy and bright areas, therefore a substantial amount of data pixels are reported as missing data. When obtaining the monthly product, the averaging was done in each pixel over as many days as that data were available in this pixel, therefore some grid boxes may not be representative of the whole month.

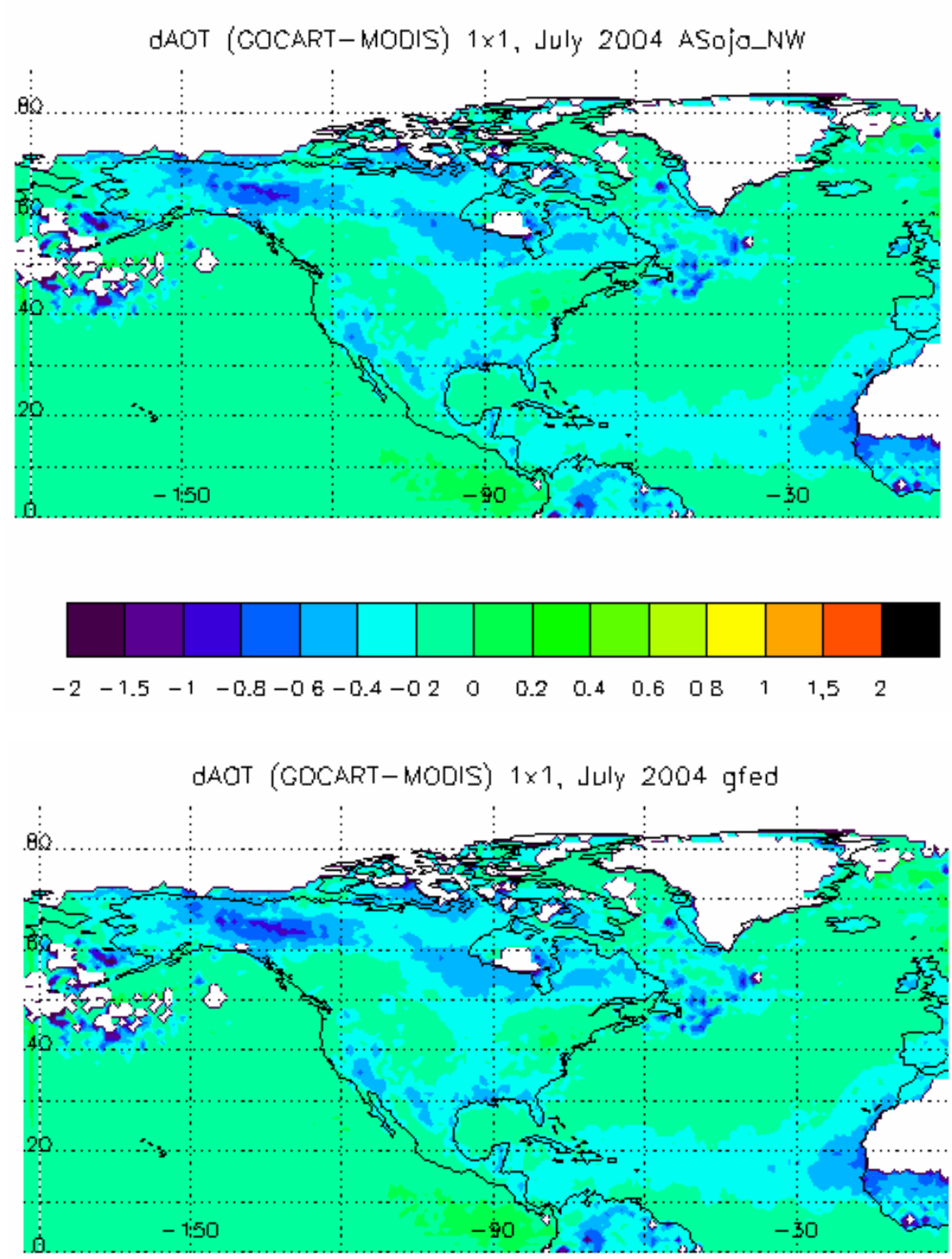

Figure 6 Difference in aerosol optical depth (absolute value) calculated by GOCART using GFEDv2 modified by North American fire emissions estimates and MODIS measurement (upper), and GOCART simulation using 'pure' GFEDv2 and MODIS measurement (lower).

As can be seen from Fig. 6, the negative values over central Canada are larger in the case when the GOCART used 'pure' GFEDv2 dataset in AOD simulation, as well as the area where the model values are lower than those measured by MODIS is larger. Thus, the use of the new daily estimates of carbon emission from the forest fires has improved the comparison of the model-predicted aerosol optical properties with those observed from the satellite.

4. Conclusions

The use of the boreal forest ecozone dataset and daily estimates of burned area from MODIS instrument is an alternative approach to estimating the monthly averaged total carbon emissions from forest fires. It has been demonstrated that this approach can be used to improve both the spatial and temporal resolution of the aerosol properties predicted by the GOCART model.

Total carbon emission based on the ecozone classification by A. Soja and MODIS fire counts is 1.8 larger than total carbon emissions reported by GFEDv2 dataset. These datasets when serving as input for the GOCART model affect the model-predicted aerosol properties. Thus, the daily total global AOD simulated by GOCART for July 2004 using the carbon fields from GFEDv2 only is lower than that when the carbon estimates from North American boreal forest fires were calculated based on the ecozone dataset from A. Soja and MODIS fire counts.

The same tendency holds true when comparing a monthly average AOD output by the model and the AOD measured by MODIS on Terra and Aqua satellites.

5. Future Work

The results of the case study are considered positive and call for the continuation of the project. Several are planned to improve the comparison of the model-output AOD with the satellite observations. The major goal is to estimate the fire severity based on the environmental conditions using the Lower Atmospheric Stability Index (Haines index) (www.wildfirenews.com/hainesindex/)

and apply the resultant information to estimating the appropriate carbon emissions.

The comparison of the modeled aerosol properties with the in-situ (both aircraft and ground-based) measurements carried out during the INTEX-NA campaign will be performed. This comparison will help to assess the performance of the model in both horizontal and vertical dimensions.

When performing comparisons with the MODIS AOD measurements an alternative averaging method will be looked for to have a better representation of the data in the pixel.

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