RELATION BETWEEN FOSSIL FUEL TRACE GAS EMISSIONS AND SATELLITE OBSERVATIONS OF NOCTURNAL LIGHTING

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ABSTRACT

The vast majority of the world's fossil fuel trace gas emission sources can be detected and mapped using nighttime low light imaging data from the U.S. Air Force Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS). This includes human settlements, industrial and commercial facilities, and gas flares. Nocturnal lighting could be regarded as one of the defining features of concentrated human activity. Outdoor lighting is used extensively worldwide in residential, commercial, industrial, public facilities and roadways. The spatial linkage between nocturnal lighting and the locations of concentrated fossil fuel consumption suggests the possibility that observations of the extent or brightness of nocturnal lighting may be used to make national estimates of fossil fuel trace gas emissions and to model the spatial distribution of these emissions at high spatial resolution (~1 km). The relevance of such products to the objectives of the Kyoto Protocol is discussed.

1 INTRODUCTION

A number of scientific and policy objectives related to the build up of atmospheric CO_2 and other trace gases are on hold due to the lack of an global capability to observe and monitor fossil trace gas emission sources. Traditional satellite remote sensing systems with global data acquisition capabilities have all focused on the observation of natural systems as their design criteria. If global observation of human activity was set as a design criteria, what wavelength(s) would be investigated? Radio frequencies emitted by power lines, electrical devices and cellular telephones might be a good starting point!

For the past six years we have been investigating the satellite observation of nocturnal lighting collected by the U.S. Air Force Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) as a proxy measure of human activity. This instrument has a low-light imaging capability, which was designed for the observation of clouds illuminated by moonlight. In addition to moonlit clouds, the data can be used to detect light sources present at the earth's surface such as cities, towns, industrial sites, gas flares and fires present at the earth's surface (see Figure 1). These are the principal sources of anthropogenic trace gas emissions. We have found that the cumulative brightness of lights to be highly correlated to the annual carbon emissions at the state level in the USA (Figure 2).

While national level fossil fuel consumption levels are believed to be reported with reasonable accuracy, national level maps depicting the spatial and temporal distribution of emissions are not available. In this paper we describe how radiance calibrated nighttime lights could be used to make independent estimates of national trace gas emissions from fossil fuel consumption. We also describe how the lights could be used to model the global spatial distribution of fossil fuel trace gas emissions. We conclude with a discussion of the relevance such products would have in service to the Kyoto Protocol.

Figure 1. Radiance calibrated nighttime lights of Europe from the 1996-97 global nighttime lights product generated by NGDC. This product does not have an atmospheric correction applied. Note the detection of lights from human settlements and gas flares (North Sea).

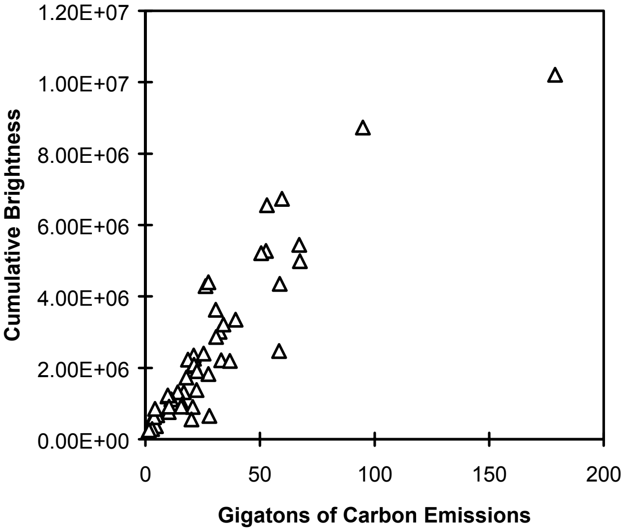

Figure 2. Cumulative brightness of 1996-97 DMSP-OLS nighttime lights (radiances) versus 1996 energy related carbon emissions for the conterminous 48 states of the USA.

2 RADIANCE CALIBRATED NIGHTTIME LIGHTS: 1999-2000

The basic methods for generating global maps of nighttime lights using cloud-free sections of OLS time series has been described by Elvidge et al., 1997 and 1999. Under normal operations the OLS low-light gain is set high and the resulting data of urban centers is saturated. It is possible for the gain to be turned down to avoid saturation, but a set of three gain settings are required to cover the full dynamic range of settlement brightnesses from bright urban cores to the diffused lighting present in rural environments. This style of data acquisition is referred to as "low-gain". NGDC produced a global product calibrated to at-sensor radiances using 28 nights of data acquired in 1996-97 (Elvidge et al., 1999). Figure 1 shows a sample of the radiance calibrated global nighttime products from 1996-97. Although the product has not had an atmospheric correction applied, we did find that the cumulative brightness of individual states of the USA to be highly correlated to carbon emissions from fossil fuel consumption (Figure 2). It is anticipated that the relation to energy related carbon emissions will improve once the nighttime data are corrected to surface radiances (atmospheric correction), the statewide use of non-fossil fuel energy sources (hydroelectric, geothermal, and nuclear power), and diffuse versus point source emissions are factored in to the analysis.

NGDC has recently developed an atmospheric correction to extract surface radiance values from nighttime visible band OLS data. Using a radiative transfer model, this algorithm corrects for path length differences encountered across individual OLS scan lines, surface terrain variations, and differences in the atmospheric transmission properties for different seasons and latitudinal bands.

Previous global nighttime lights products generated by NGDC were not entirely satisfactory due to low numbers of cloud-free observations in humid-tropical regions. At NGDC's request, the U.S. Air Force has acquired seven nights of gain controlled OLS data each lunar cycle for a fifteen month time period (January, 1999 through March, 2000). This data will be processed using the recently developed atmospheric to generate the world's first global map of nighttime lights calibrated to surface brightness levels. The lights sources will be divided into four primary source groups: human settlements, gas flares, biomass burning , and fishing boats. Fires (biomass burning) will be identified based on their short temporal duration. Gas flares will be identified based on their extreme high brightness levels, location, and limited spatial extent. Fishing boats will be identified using a land-sea mask.

3 INDEPENDENT ESTIMATION OF NATIONAL FOSSIL FUEL TRACE GAS EMISSIONS

Figure 2 shows the relationship between cumulative brightness and annual carbon gas emissions from fossil fuel consumption for individual states of the USA for 1996. With the radiance calibrated global map of nighttime lights being produced for 1999-2000 by NGDC (described above), it would be possible to generate a similar plot for each nation of the world. The precise relationship between cumulative brightness and fossil fuel trace gas emissions undoubtably varies among countries due to differences in electric power source apportionment, per capita income, lighting technology in use and cultural preferences for lighting. However, countries can likely be grouped into clusters that have similar income levels, power sources, and lighting styles. Of these, we anticipate income level would be the predominant factor affecting the clustering. For countries where emissions levels are in question, it then becomes possible to use the data within clusters to make independent estimates of fossil fuel trace gas emissions based on the cumulative brightness of individual nations. By analyzing the outliers it may be possible to identify countries that are either under-reporting or over-estimating their emissions. By tracking the cumulative brightness of countries over time it may be possible to confirm or call into question reported increases or decreases in energy related trace gas emissions.

4 GENERATING A HIGH SPATIAL RESOLUTION GLOBAL DEPICTION OF FOSSIL FUEL TRACE GAS EMISSIONS

4.1 Assembly of National Level Data on Annual Fossil Fuel Consumption

One of the premier sources of data on national fossil fuel consumption levels is the International Energy Agency (IEA). This organization, based in Paris, is an autonomous agency linked with the Organisation for Economic Co-operation and Development (OECD). The IEA collects and publishes data on the consumption of fossil fuels broken down by final use sector. This style of breakdown, indicating the estimated quantity of each fossil fuel type used in electric power generation, industrial, commercial, transportation, and residential use provides the easiest starting point for assembling an emissions database suitable for use with the nighttime lights. The IEA data could be augmented with data from other sources, such as the U.S. Department of Energy's Carbon Dioxide Information and Analysis Center (CDIAC - http://cdiac.esd.ornl.gov/cdiac/home.html) and Energy Information Administration (http://www.eia.doe.gov/).

4.2 Assembly of Georeferenced Data on the Location and Probable Magnitudes of Fossil Fuel Emission Sources

Data from multiple sources could be used to assemble a Geographic Information System (GIS) compatible database on locations and probable magnitude of point sources of fossil fuel trace gas emissions from gas flares and electric power plants. Data sources and assembly procedures will include:

4.2.1Gas Flares

The location, size and frequency of operation for major gas flares could be extracted from DMSP data (see Figure 1). This individual gas flare radiances could be used to allocate the quantity of gas flaring reported by the IEA. The associated CO_2 emissions could then be estimated using software from the International Panel on Climate Change (IPCC). The software is described at (http://www.iea.org/ipcc.htm).

4.2.2 Electric Power Plants

Locations, fuel type and capacities of electric power plants can be extracted from the McGraw-Hill World Electric Power Plants Database (WEPPD), which includes over 91,000 generating units in 220+ countries and territories. The WEPPD (http://infostore.mhenergy.com) lists units are operated by utilities, non-utility generators and industrial autoproducers. The information is based on direct survey, trade and business press references, manufacturers' experience lists, company statistical reports and other sources. This data source is cumbersome to use due to the fact that locations of the units are reported as the nearest city or town rather than a geographic coordinate. Other sources for geographical locations, such as the World Bank could be investigated.

The power plant data will be paired with national level reporting on fossil fuel consumption for electric power generation from IEA to estimate the quantity of fuel being consumed by each of the identified power plants. The annual CO_2 emissions for each plant will then be estimated using software from the IPCC.

It is anticipated that we will be able to identify and account for all the major power plants in individual countries. The estimated emissions from smaller plants which we are unable to locate will be merged with the diffuse emissions.

4.2.3 Transportation

The IEA provides estimates of fossil fuel volumes and fuel types used in transportation. Emissions associated with ground transportation (gasoline and diesel fuel) could be spatially allocated based vector roads and railroads from the Digital Chart of the World (DCW - http://www.esri.com/data/catalog/esri/dcw_fact.html), with weighting provided by the nighttime lights. Spatial distribution of emissions from jet fuel are problematic, but may be satisfactorily resolved by working with airport locations from DCW and estimates of the proportion of jet fuel used on the ground. This does not address the distribution of in-flight emissions.

4.2.4 Distribution of Emissions From Diffuse Sources

The quantity of trace gas emissions associated with diffuse sources (e.g. residential, commercial, and governmental) can be defined as the difference between the total emissions minus those accounted for from gas flares, electric power plants, and transportation. Emissions from diffuse sources will be apportioned based on the brightness of DMSP observed nocturnal lighting. For each nation we will calculate the cumulative brightness and divide this number into the total quantity of diffuse emissions from fossil fuel consumption. This will yield a conversion factor for estimating the CO_2 emissions proportionally based on the satellite observed radiance. This procedure will account for national differences in lighting patterns and variations in levels of technical development. When this conversion factor is applied, we will have an image map in which depicts the estimated annual quantity of CO_2 emissions in each grid cell.

4.3 Global Map of Fossil Fuel Trace Gas Emissions

By adding the four emission map layers (gas flares, electric power plants, transportation and diffuse) a global map of fossil fuel trace gas emissions could be generated.

5 CONCLUSION - RELEVANCE TO THE KYOTO PROTOCOL

The high spatial resolution radiance calibrated map of the nighttime lights of the world and the depiction of trace gas emissions from fossil fuel consumption has two primary applications relevant to the Kyoto Protocol:

5.1 Inverse modeling to estimate the magnitude of regional land-atmosphere and ocean-atmosphere fluxes. Because nearly the entire Earth surface can exchange carbon with the atmosphere, it is quite difficult to make reliable measurements of the carbon fluxes between major reservoirs. For example, how is it possible to estimate the annual quantity of carbon absorbed by the land surface in the United States? The approach that has been developed to estimate these fluxes is to analyze continuous observations of trace gas concentrations from networks of sites which integrate regional carbon fluxes. These measurements come from tall towers, high altitude observatories, aircraft and sea surface sites. The measurements document the spatial and temporal distributions of carbon gases. The magnitude of sources and sinks are estimated using a process known as "inverse modeling". At present, only a small number of independent source/sink components can be reliably estimated by inverse analysis and only at the largest spatial scales (e.g. Northern Hemisphere). A major limitation of current inverse modeling is that source inputs do not include the fine spatial and temporal detail known to be present in the pattern of fossil fuel consumption. For instance, current modeling of annual trace gas emissions from fossil fuel combustion are simply based on national statistics on the consumption of various types of fossil fuel products. In actuality, trace gas emissions associated with fossil fuel combustion are concentrated at major point sources (such as electric power plants) and in the vicinity of human population centers. Incorporation of a high spatial resolution depiction of trace gas emissions from these sources is expected to lead to major improvements in the spatial resolution and accuracy of current inverse modeling efforts.

5.2 Evaluating the Validity of National Trace Gas Emission Estimates. Under the United Nations Framework Convention on Climate Change and the Kyoto Protocol nations of the world are beginning to report their annual trace gas emissions and setting targets for stabilization or reduction in their emissions. Independent methods for evaluating the magnitude of emissions and changes in emissions are crucial to the success of any international agreements. If it cannot be demonstrated that the nationally reported emissions can be confirmed and validated by independent means the agreements may never be ratified. Preliminary evidence suggests that it is possible to evaluate the veracity of national emission estimates by searching for outliers in comparisons of OLS derived cumulative radiances versus reported emissions within clusters of countries having comparable levels of economic development.

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REFERENCES

Elvidge, C.D., Baugh, K.E., Kihn, E.A., Kroehl, H.W., Davis, E.R., 1997. Mapping of city lights using DMSP Operational Linescan System data. Photogrammetric Engineering and Remote Sensing, v. 63, pp. 727-734.

Elvidge,C.D., Baugh, K.E., Dietz, J.B., Bland, T., Sutton, P.C., Kroehl, H.W. 1999. Radiance calibration of DMSP-OLS low-light imaging data of human settlements. Remote Sensing of Environment, v. 68, pp. 77-88.