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Empirical normalization for the effect of volcanic stratospheric aerosols on AVHRR NDVI

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[1] The 1982 El Chichon and 1991 Mount Pinatubo volcanic eruptions produced large volumes of stratospheric aerosols that affected the environmental indices estimated from the Advanced Very High Resolution Radiometer (AVHRR) sensor. As a result the Normalized Difference Vegetation Index (NDVI) used to derive several vegetation health products exhibits a negative bias between approximately 20°N and 20°S during the post eruption years. In this work a statistical method based on Empirical Distribution Functions (EDF) and simple assumptions regarding the state of global vegetation is used to reduce these biases. Results show that the statistical technique effectively reduces the biases allowing the construction of consistent time series from this historical dataset for climate studies. **Citation:** Vargas, M., F. Kogan, and W. Guo (2009), Empirical normalization for the effect of volcanic stratospheric aerosols on AVHRR NDVI, *Geophys. Res. Lett.*, *36*, L07701, doi:10.1029/2009GL037717.

1. Introduction

[2] Volcanic eruptions are one of the natural sources of extreme aerosols in the troposphere and stratosphere. During the last quarter of the 1900s two major volcanoes erupted: El Chichon in Mexico in April 1982 (17.36°N, 93.22°W) and Mount Pinatubo in the Philippines in June 1991 (15.13°N, 120.35°E). Both volcanoes injected massive clouds of ash and tonnes of sulfur dioxide (SO_2) into the atmosphere. The SO_2 reacted with water vapor in the atmosphere to form sulfuric acid particles, a known form of aerosol. The aerosols were rapidly distributed around the globe by stratospheric winds, but at different times depending on the seasonal circulation patterns. The maximum concentration of aerosol particles was confined to tropical latitudes [*Stowe et al.*, 1992; *Reynolds*, 1993; *King et al.*, 1984; *Ardanuy and Kyle*, 1986] causing an increase in the aerosol optical thickness by more than one order of magnitude [*Pitari and Mancini*, 2002]. The aerosol cloud from these two volcanic eruptions remained in the atmosphere for several years [*Andersen et al.*, 2001; *Robock and Mao*, 1992].

[3] Sulfate aerosols from these volcanic eruptions reduced the transmittance of the atmosphere affecting incoming and outgoing radiation. These effects distorted measurements of the Earth made by satellites, including operational satellites managed by the National Environmental Satellite Data and Information Service (NESDIS) of the National Oceanic and Atmospheric Administration (NOAA). Of those NOAA/NESDIS satellites, observations in the visible (VIS) and near-infrared (NIR) parts of solar spectrum were severely affected including the NDVI [NDVI = (VIS − NIR)/(VIS + NIR)], which is one of the most widely used derived indices for characterization of land surface.

[4] NOAA/NESDIS has been producing NDVI since the late 1970s when the first NOAA polar-orbiting environmental satellite (POES) became operational. The NDVI based products included the 16 by 16 km Global Vegetation Index (GVI) data set [*Kidwell*, 1997] and currently the 4 by 4 km Global Vegetation Health (VH) produced from considerably improved GVI-x dataset (http://www.orbit2.nesdis.noaa.gov/corp/scsb/wguo/VH/vh_ftp.php). Unfortunately, these products experienced NDVI distortions during the periods of El Chichon and Mount Pinatubo aerosols presence [*Kogan et al.*, 1994].

[5] Several attempts were made in the past to correct the effect of volcanic aerosols on AVHRR derived NDVI. *Vermote et al.* [1997] using the previously computed optical thickness profile and radiative transfer code (assuming lambertian boundary condition), corrected each pixel of channels 1 and 2 before the computation of the NDVI. This correction is currently implemented in the Global Inventory Mapping and Monitoring Studies (GIMMS) dataset [*Julien et al.*, 2006]. *Ye et al.* [1995] proposed an algorithm to correct for stratospheric aerosols in the NOAA/NASA Pathfinder AVHRR land dataset. They derived the atmosphere optical thickness over the central Pacific Ocean, assuming a latitudinal homogeneous distribution of the volcanic aerosols in the stratosphere and developed corrections for the effects of these aerosols in visible channels, which indirectly changed the retrieved NDVI. Due to some difficulties with adequate aerosol observations other researchers just removed the pixels that were most likely contaminated by volcanic aerosol [*Jin*, 2004].

[6] In this research we bypass possible corrections made to VIS and NIR channels, correcting NDVI directly. We applied the Empirical Distribution Function (EDF) normalization approach to weekly NDVI collected from 4 km Global Vegetation Index-extended version (GVI-x). After that we tested the normalized data with in-situ observations.

2. Data and Methodology

[7] The 4-km AVHRR-derived GVI-x dataset was developed from the Global Area Coverage (GAC) data collected from several afternoon NOAA polar orbiting satellites: NOAA-7, 9, 11, 14, 16 and 18. GAC daily data were composited over 7-day periods saving those observations having maximum NDVI. The 7-day composites were

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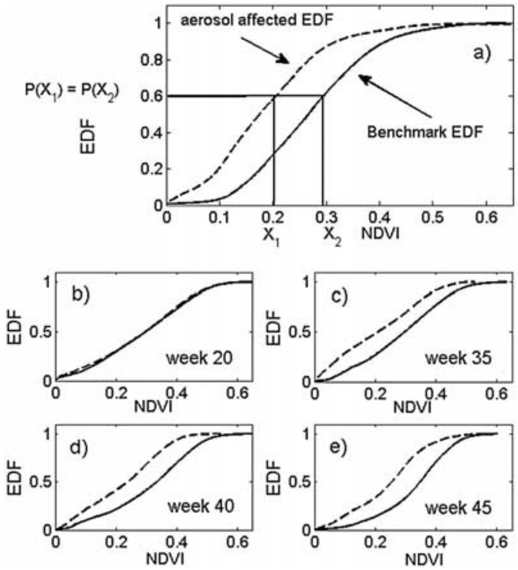

Figure 1. Aerosol-affected (dashed line) and benchmark (solid line) NDVI's EDF. (a) Principles of NDVI EDF normalization. 1991 NDVI EDFs for latitude band 7°N, (b) week 20 (May) pre-eruption and weeks (c) 35 (August), (d) 40 (October) and (e) 45 (November) post-eruption of Mount Pinatubo.

mapped on the 4 by 4 km GVI-x grid and stored into arrays having 3616 pixels (north to south) by 10000 pixels (west to east) covering the region 75°N–55°S. The EDF technique was used to statistically remove the negative bias on NDVI caused by aerosols from the volcanic eruptions of El Chichon and Mt. Pinatubo; this technique has been applied before for calibration of Geostationary Operational Environmental Satellites (GOES) imager channels [*Wu et al.*, 2005], to remove striping and banding from satellite imagery [*Weinreb et al.*, 1989], to perform inter-satellite calibration [*Crosby et al.*, 1996], and to adjust for long trends in satellite data [*Jiang et al.*, 2008].

[8] An EDF is a cumulative distribution function that gives the probability that a random variable X is less than a given value x [$F(x) = Pr\{X < x\}$]. The application of the EDF technique to reduce the negative effect of volcanic aerosols on NDVI is based on the assumption that for large areas, the NDVI reduction due to technical and external forces (orbital drift, volcanic eruptions, etc.) is larger than the weather-related NDVI changes from year to year. Following this assumption, large changes in NDVI can signal unexpected disturbances due to non-weather related volcanic aerosols. This negative effect can be reduced by adjusting the affected NDVI's EDF with a benchmark NDVI's EDF from other years which were not affected by external sources. The benchmark NDVI statistical sample was composited from five years of NDVI data (1989, 1990, 1995, 1996, and 1997). These years were selected because they were not affected by stratospheric aerosols and satellite orbital drift. An 188032 sample of benchmark NDVI EDFs were developed, one for each of the 3616 latitude lines and each of the 52 weeks of the year. The benchmark NDVI's EDFs were stored in LookUp Tables (LUTs) to be used in the normalization process. The normalization of all aerosol affected weekly NDVI images was performed for each pixel of each latitude line by adjusting these with the corresponding benchmark NDVI's EDF taken from the LUTs. The threshold of 0.01 for applying the correction was selected by analysis of dynamics of NDVI differences over the period 1981 to 2006.

[9] Figure 1a displays the normalization procedure. In this hypothetical example, for the NDVI affected pixel value of 0.2 (X_1) the corresponding value $P(X_1) = 0.6$ from the aerosol affected EDF was found. The intersection of line $P(X_1) = P(X_2)$ with the benchmark NDVI's EDF provides a normalized NDVI pixel value of 0.29 (X_2) for the pixels of the affected NDVI. This normalization procedure was applied to each pixel in the latitude line being processed if the difference between the benchmark NDVI and the corresponding actual NDVI pixel value is greater than the pre-established NDVI threshold (0.01).

3. Results

[10] Figures 1b–1e provide real data during the pre and post-Pinatubo weeks of 1991. In pre-Pinatubo time (week 20, Figure 1b) no difference was observed between the two EDFs. This fact supports our assumption about statistical stability of the non-disturbed land surface vegetation. After the eruption, the affected NDVI's EDF shifted to the left of the benchmark NDVI's EDF (towards lower NDVI values). This difference gradually increased over time as the volcanic aerosols encircled the Earth. The NDVI reduction was approximately 0.1–0.15 for the NDVI benchmark range between 0.2 and 0.45.

[11] For El Chichon aerosols the normalization was done from week 13 (April), 1982 to week 52 (December), 1984 and for Mount Pinatubo from week 26 (June), 1991 to week 52, 1993. Figure 2 shows latitudinal profiles of aerosol-affected and normalized NDVI. As seen, for latitudes 20N°–20S° in pre-eruption time (week 20, May) the two lines coincide. In post-eruption time (weeks 35, 40 and 45) the affected NDVI shifted left to the lower NDVI values. In central latitudes the normalized NDVI during the build up of Mt. Pinatubo aerosols increased up to 0.15. Approaching the north and south borders of the affected area (±20°) these values decreased considerably. Similar results were obtained for El Chichon.

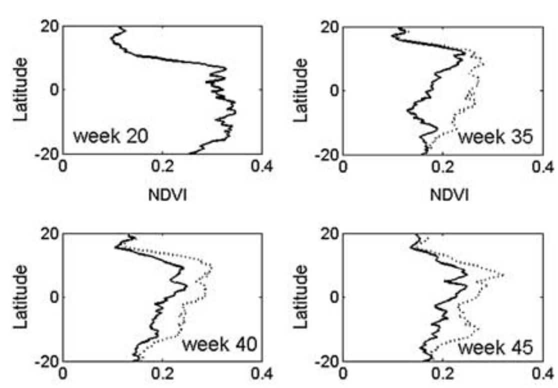

Figure 2. Latitudinal profiles of NDVI (actual – solid line, normalized – dotted line) for year 1991; week 20 pre-Pinatubo and weeks 35, 40 and 45 post-Pinatubo.

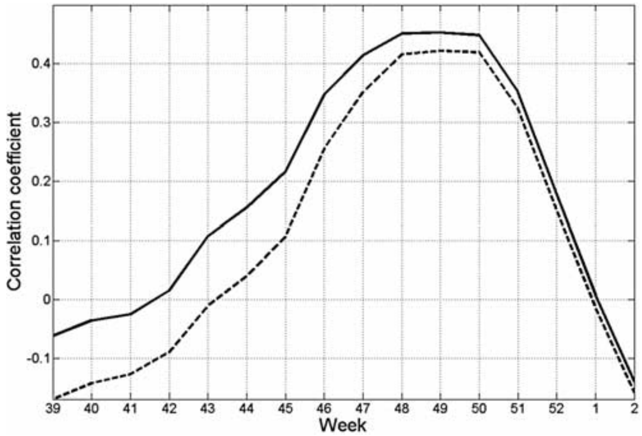

Figure 3. Dynamics of correlation coefficient between end-of-season MG corn yield departure from trend and spatial-average VCI during corn silking (critical period), solid line is normalized NDVI, dashed line is aerosol-affected NDVI.

[12] The results of this normalization were tested to see whether the EDF procedure does not distort the data. In our earlier research it was shown that the AVHRR based vegetation health (VH) indices correlate strongly with crop yield in different parts of the world including Brazil [*Salazar et al.*, 2007; *Liu and Kogan*, 2002]. Therefore, corn yield data during 1985–1995 were collected from the aerosol affected Minas Gerais (MG) state of Brazil. For the major corn area of MG (46°W–47°W, 16°S–17°S), the average spatial values of the NDVI-based Vegetation Condition Index (VCI) [*Kogan*, 1997] were calculated for each week of the 1985–1995 period (two datasets: aerosol affected and normalized). Then, end of season MG corn yield deviation from technological trend was correlated with weekly VCI of the 1985–1995 period.

[13] Figure 3 displays test results. As seen, during silking, which is the critical period of corn development, correlation between corn yield deviation from 1985–1995 trend and weekly VCI for both data is increasing from near zero in the pre-silking time to 0.45 at the peak of the silking and drops to zero in post-silking time. The improved data show higher correlation than the aerosol distorted. Although the differences are not larger than 0.1 still this test confirm utility of the normalization procedure.

[14] Finally, Figure 4 shows NDVI for week 40 (October) over part of the aerosol affected South America and central Africa in pre- (1989) and post-eruption (1991) time and normalized 1991 NDVI. As seen, the NDVI is higher (greener) in 1989 (Figure 4a) without stratospheric aerosols than in 1991 (Figure 1b) 3–4 months after the Mount Pinatubo eruption. The normalization procedure returns NDVI back to pre-eruption period. The normalization (Figure 4c) NDVI increased considerably (0.03 to 0.18) and was in general similar to the October NDVI in 1989.

4. Conclusions

[15] In this article we presented a statistical method that uses the EDF approach to reduce the effect of stratospheric aerosols from the volcanic eruptions of El Chichon and Mount Pinatubo on AVHRR derived NDVI. In this scheme we bypass possible corrections made to VIS and NIR channels normalizing NDVI directly. The extent of the affected area was determined from several sources: a) differences between benchmark and post-volcanic NDVI images, b) images of aerosol optical thickness after the volcanic events, c) the latitudinal profiles of the benchmark NDVI and post-volcanic NDVI, and d) numerical differences between the benchmark EDF's NDVI and the affected EDF's

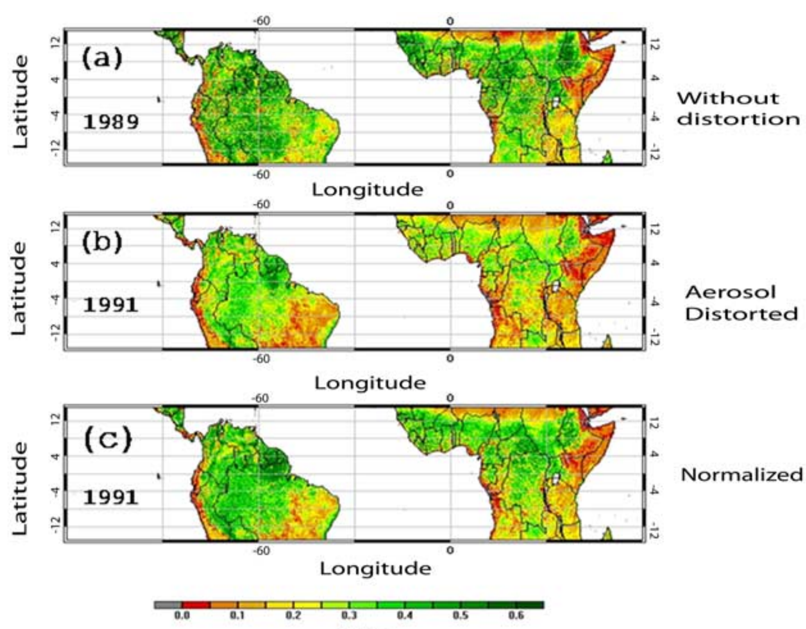

Figure 4. NDVI week 40, October (a) 1989 without volcanic aerosol distortion, (b) 1991 aerosol distorted (after Mt. Pinatubo eruption in June 1991), and (c) 1991 normalized by EDF.

NDVI. The results show that this method enhances the NDVI that had been distorted by the volcanic aerosols. There is no consensus in the effect of volcanic aerosols in photosynthetic activity. Several studies emphasize that the volcanic aerosols actually reduce the photosynthetic activity by reducing the amount of sunlight reaching the vegetation [*Oliveira et al.*, 2007; *Krakauer and Randerson*, 2003], whereas others show that volcanic aerosols enhance solar radiation scattering that ultimately increase the terrestrial carbon sink by increasing plant productivity [*Roderick et al.*, 2001; *Gu et al.*, 2003; *Matsui et al.*, 2008]. Therefore, it is possible that our normalization method in some cases enhances NDVI where the reduction in NDVI was actually caused by reduction in photosynthetic activity (NDVI reduction greater than the NDVI threshold for normalization). The normalization improves the vegetation health products derived from the NDVI dataset and will allow us to construct more consistent time series for climate studies.

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