Trends in atmospheric haze induced by peat fires in Sumatra Island, Indonesia and El Niño phenomenon from 1973 to 2003

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[1] Visibility was used as a long-term indicator of atmospheric haze caused by peat fires on the peat land area of the island of Sumatra, Indonesia. Visibility and the anomalies of sea surface temperature in the Niño 3.4 region from 1973 to 2003 were analyzed. A significant linear relationship existed between the visibility and time, and the two signals shared two periodic components of 45 months (3.7 yr) and 61 months (5.1 yr), corresponding with the El Niño-Southern Oscillation (ENSO) variability. Visibility decrease occurred about 3 months earlier than peak ENSO, suggesting fires initiated during the ENSO onset stage. The study demonstrated the connection of inter-annual climate variability, biomass burning, and air quality in the region. The study could facilitate the prediction of change in fire occurrence and air quality from ENSO monitoring data. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 9320 Information Related to Geographic Region: Asia; 4522 Oceanography: Physical: El Nino; 3210 Mathematical Geophysics: Modeling; 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305); 4801 Oceanography: Biological and Chemical: Aerosols (0305). **Citation:** Wang, Y., R. D. Field, and O. Roswintiarti (2004), Trends in atmospheric haze induced by peat fires in Sumatra Island, Indonesia and El Niño phenomenon from 1973 to 2003, *Geophys. Res. Lett.*, *31*, L04103, doi:10.1029/2003GL018853.

1. Introduction

[2] Atmospheric haze is a serious consequence of biomass burning in Indonesia. On the Sumatra Island, haze is frequently caused by peat fires [*Levine*, 1999; *Page et al.*, 2002; *Cochrane*, 2003], particularly on the southern half of the island [*Bowen et al.*, 2001]. The fires occur mainly during the dry season from June to September and intensify during El Niño years [*Chandra et al.*, 1998; *Wooster et al.*, 1998; *Siegert and Hoffmann*, 2000; *Roswintiarti and Raman*, 2003], during which convection activity over Indonesia is reduced [*Heil and Goldammer*, 2001]. The global significance of emissions from Indonesian peat fires is well established [*Herman et al.*, 1997; *Levine*, 1999; *Thompson et al.*, 2001; *Page et al.*, 2002; *Cochrane*, 2003], as are the local impacts, particularly on human health [*Kunii et al.*, 2002; *Sastry*, 2002].

[3] *Kita et al.* [2000] and *Thompson et al.* [2001] provided the characterizations of the haze phenomenon using the total ozone of troposphere as proxy between 1980 and 1990, and between 1993 and 1998. They found that major haze events over Indonesia occurred in concert with the ENSO phenomenon, specifically during 1982–1983, 1991, 1994 and 1997. They used remotely sensed data from the Total Ozone Mapping Spectrometer (TOMS) (http://jwocky.gsfc.nasa.gov/) as an indicator of biomass burning; the TOMS sensor is sensitive to aerosols primarily at higher altitudes [*Herman et al.*, 1997; *Duncan et al.*, 2003]. Peat fires burn at a relatively low intensity; concentrated emissions will not be vertically transported by convection near the fire location, but rather through gradual dispersion and diffusion. Hence, the TOMS sensor may not capture the full magnitude of peat burning, because a significant portion of emissions remains at too low an altitude to be detected.

[4] We used visibility as an alternative haze indicator to the TOMS data, and hence have developed a continuous long-term indicator of in-situ air quality. Visibility observations were used to characterize the 1997/1998 haze event in Indonesia [*Husar et al.*, 2000; *Heil and Goldammer*, 2001], but have not been yet employed as a long-term haze indicator. Here, we used visibility data from 1973 to 2003 to examine the relationship between haze episodes over Sumatra and the ENSO phenomenon, and determined the long-term haze trend and the synchronization between haze and ENSO data.

2. Data Source and Analysis

[5] Visibility observations were obtained from the National Climatic Data Centre (NCDC) (http://www.ncdc.noaa.gov), with the data originating from the Indonesian Bureau of Meteorology and Geophysics' synoptic station network. The main fire prone areas in Sumatra are the peat lands distributed along the island's eastern coast from 3°N to 5°S (Figure 1) [*Bowen et al.*, 2001]. Four weather stations were located along the eastern coast and at the west edge of the peat land areas. As easterly winds prevail in the lower troposphere over Sumatra during the dry season [*Kita et al.*, 2000], the haze produced along the eastern coast could be transported westwards, and so two stations located on the western coast were also included. World Meteorological Organization (WMO) identifications and locations of the stations were depicted in Figure 1.

[6] Data existed between 1950 and 2003, but there was a serious missing data problem for visibility before 1973;

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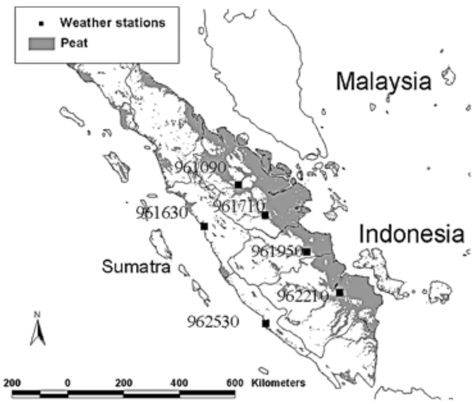

Figure 1. Sumatra with peat areas and weather stations. The WMO codes and locations of the stations are 961090 (0.47°N, 101.45°E), 961630 (0.83°S, 100.35°E), 961710 (0.47°S, 102.32°E), 961950 (1.63°S, 103.65°E), 962210 (2.90°S, 104.70°E), and 962530 (3.88°S, 102.33°E).

therefore, only the data from January 1973 to July 2003 were analyzed. The visibility was observed several times per day; however, only the records from 07:00 to 19:00 local time were used in deriving monthly signals. Additionally, observations with non-zero rainfall were excluded to help ensure that low visibility values could be attributed exclusively to smoke-haze.

[7] The raw visibility was taken as visual range in kilometer, and it was transformed into extinction coefficient (EC), which is a simple inverse function of the visual range [*Husar et al.*, 2000]. EC results from scattering and absorption of gases and aerosols in the path of the observation, and it would refine and allow a better removal of rain, cloud, and fog events from the data set. As *Husar et al.* [2000] suggested, EC = 1.9/visibility was used in this study.

[8] For both visibility and EC, monthly mean was defined as the mean of all observations in the month for each station. As a measure robust to outliers, monthly median was also calculated. Totally, four monthly signals were derived for each station: (1) monthly mean visibility, (2) monthly median visibility, (3) monthly mean EC, and (4) monthly median EC. The four signals from the six stations were averaged to produce regional monthly signals across the study area, which were regional mean visibility, regional median visibility, regional mean EC, and regional median EC.

[9] A regional daily TOMS Aerosol Index signal was obtained by averaging daily 1 × 1.25 degree gridded values over the study area. The result, similar to that of *Thompson et al.* [2001], was used to derive a monthly mean signal. The data suffer from a data gap from 1993 to 1997, which included the significant 1994 fire [*Bowen et al.*, 2001], and is known to be problematic after 2001. The Niño 3.4 index was used to quantify ENSO conditions [*Trenberth*, 1997; *Trenberth and Stepaniak*, 2001].

[10] Periodogram analysis was conducted to the visibility and ENSO signals, assuming the data were a composition of many periodic components at known Fourier frequencies [*Chatfield*, 1984]. The amplitude corresponding to the frequency was plotted against period to form periodograms. The amplitude can be interpreted as the contribution of the harmonic frequency to the total sum of squares, in the analysis of variances sense [*SAS Institute Inc.*, 1999]. Linear regression was used to detect long-term trends in both signals.

3. Results and Discussion

[11] There was a strong association between high Niño 3.4 index and low visibility (or high EC) (Figure 2). The mean and median visibilities for each station were similar, and they all captured the steep visibility decreases. The two EC signals for each station were also very similar, and they were not shown.

[12] The Niño 3.4 index peaked in January 1983, August 1987, February 1992, December 1994, November 1997, and November 2002, which were El Niño years [*Trenberth*, 1997]. Correspondingly, the six markedly steep visibility decreases occurred in September 1982, October 1987, November 1991, October 1994, September 1997, and October 2002. Generally, poor visibility took place about 3 months ahead of the Niño 3.4 index peaks, except for 1987. The visibility and EC variability appeared to be a strong function of the ENSO onset, or the steepest visibility decrease (or the steepest EC increase) occurred at the onset of increased sea surface temperature.

[13] The TOMS data captured the El Niño phenomena for 1983, 1992, and 1997 but missed it for 1987 and 1994 (Figure 2, bottom panel). The 1994 haze event was distinctly more severe than the 1982/83 event, despite 1994

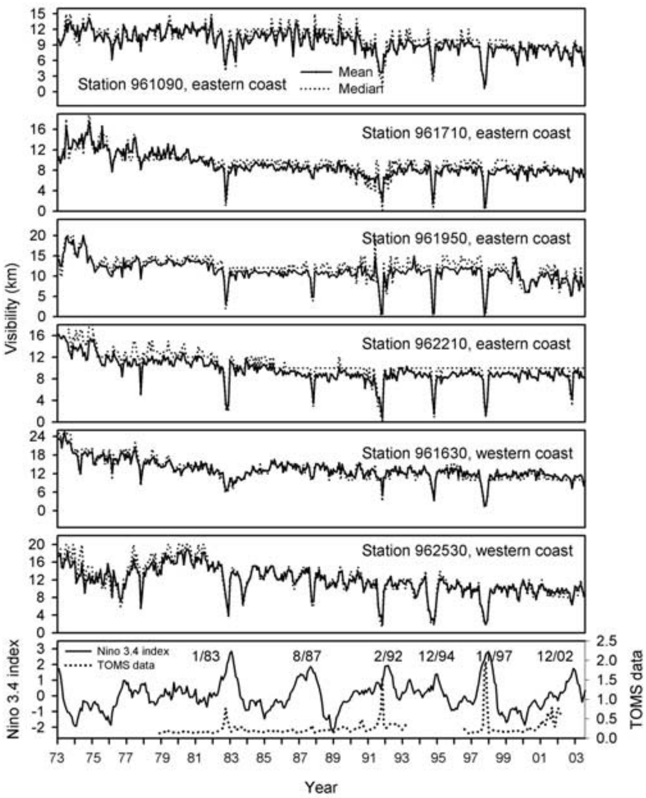

Figure 2. Monthly mean visibility, monthly median visibility, the Niño 3.4 index, and TOMS data. Labeled tick marks on horizontal axes are for January of each year.

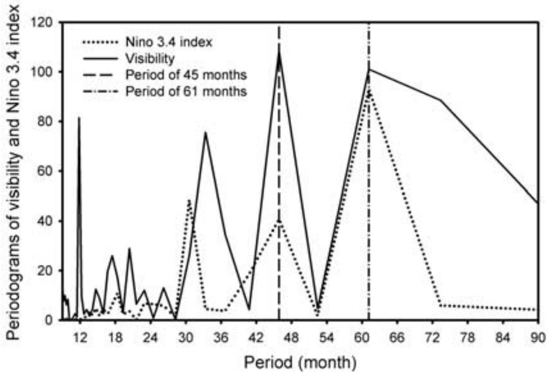

Figure 3. Periodogram of the regional mean visibility and Niño 3.4 index time series.

being a weaker El Niño than 1982/83. The 2002 haze event, however, was of smaller magnitude than the 1994 event.

[14] Periodogram revealed several periodic components in both regional mean visibility and Niño 3.4 index time series (Figure 3). Visibility shows four major periods at 12, 35, 45, and 61 months. A one-year period corresponded to the annual cycle in peat land fires, whereas the dominating components of longer periods reflected long-term periodic trends of the fires. Three periodic components could be discerned for the Niño 3.4 index with periods 31, 45, and 61 months. Notably, both visibility and Niño 3.4 signals shared two common components of periods 45 and 61 months (3.7–5.1 yr), in the range of ENSO variability. The shared components would explain the strong periodic association between the two signals in the El Niño years. Periodogram analysis of the regional median visibility and the regional mean and median EC data shows the same or similar results (not shown).

[15] The continuity and longer availability of the visibility data also allowed for a more robust trend detection than has been possible with the TOMS data, from which no conclusive trends in atmospheric haze over Indonesia have been detected [*Thompson et al.*, 2001]. Significant linear trends existed for all regional signals (Figure 4). The regional mean visibility showed a historical decreasing trend at the rate of 0.0152 km/month, and the regional median visibility decreased 0.0166 km per month. The trends found in this study could be the most precise quantification to date of the long-term decrease in air quality in Sumatra.

[16] The decrease in air quality can be attributed to anthropogenic and climatic causes. Indonesia's Transmigration Program is among the largest population resettlement schemes in the world, roughly 3 million people resettling in Sumatra and Kalimantan from 1968 to 1990 [*World Bank*, 1994], which continued through the 1990s [*Fearnside*, 1997]. This resulted in an increase in agricultural and land-clearing burning in Sumatra, a substantial portion of which occurred on drained peat land. As exacerbated by unsustainable land-use and exploitative forest logging, the fire frequency and severity in the island had risen steadily [*Bowen et al.*, 2001; *Meijaard and Dennis*, 1997]. The downward visibility trend can also be attributed to climatic factors. Since the early 1980s, more frequent droughts have occurred in the region [*Bowen et al.*, 2001], owing to more frequent El-Nino episodes. Note also that the Niño 3.4 index exhibited an increasing trend at the rate of 0.0011 °C/month, which could be associated with an overall weakening of convective activity over Indonesia. We suggest that the increased frequency of haze events is due to the increased frequency of El Niño episodes, while the increased severity of haze events during the 1990s can be attributed to increased anthropogenic activity, and perhaps also to reduced rainfall. The latter proposition requires a more detailed investigation of local rainfall records.

4. Conclusion

[17] Visibility was used as a long-term indicator of biomass burning in Sumatra, providing the longest, most continuous, and most sensitive measure of haze available to date. Given the lack of reliable fire occurrence or area burnt statistics [*Bowen et al.*, 2001], the visibility observations are also useful as a proxy for fire occurrence. Haze events identified over the past three decades were strongly correlated with the El Niño phenomenon. Both visibility and ENSO signals possessed two common cycles of periods 45 months (3.7 yr) and 61 months (5.1 yr), indicating a strong synchronization between them. The variation in haze was composed of annual and lower frequency components, whereas the variation of the Niño 3.4 index was dominated by lower frequency components, with periods 31 months or

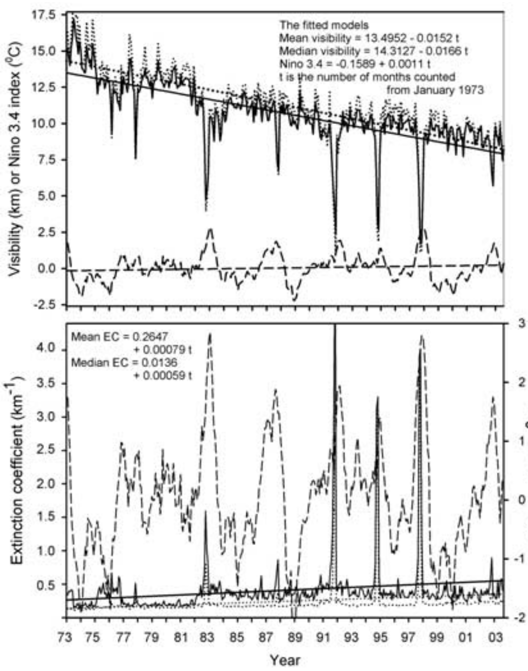

Figure 4. The observed and predicted regional signals and the Niño 3.4 index. Labeled tick marks on the horizontal axe are for January of each year. In the upper plot, solid line, dotted line, and long dashed line are the regional mean visibility, the regional median visibility, and the Niño 3.4 index, whereas the three straight lines are the linear trends corresponding to the three signals. In the lower plot, solid line, dotted line, and long dashed line are the regional mean EC, the regional median EC, and the Niño 3.4 index, whereas the two straight lines are the predicted ECs.

longer. The visibility over the analysis period decreased by 0.0152 km (mean) and 0.0166 km (median) per month. Haze episodes were more frequent and severe during the 1990s due to increasing population in the peat-areas of Sumatra and increased El Niño frequency. The extents to which the increase in haze can be attributed between natural and anthropogenic factors require further investigation, and ideally, would consider the drought effects quantified by local rainfall records. The analysis of this study would help in understanding the connections between inter-annual climate variability, biomass burning and air quality. Such understanding would facilitate the prediction of change in fire occurrence and air quality from ENSO monitoring data, and through coupling with ever-improving climate prediction models, it would also help in preventing and mitigating future haze damages in the region.

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