Dust emission response to climate in southern Africa

Robert G. Bryant,1 Grant R. Bigg,1 Natalie M. Mahowald,2 Frank D. Eckardt,3 and Simon G. Ross1

Received 22 December 2005; revised 12 October 2006; accepted 3 January 2007; published 9 May 2007.

[1] The processes which act in mineral dust source regions and factors which contribute to interannual variability within dust plumes emanating from them are poorly understood. In this case study, we focus on processes modulating emissions of atmospheric mineral aerosols from a large ephemeral lake. We focus on one key ephemeral lake source in southern Africa, the Makgadikgadi Pans of Botswana. A range of satellite [for example, Total Ozone Mapping Spectrometer (TOMS), Moderate Resolution Imaging Spectrometer (MODIS)] and climate data (from meteorological stations and reanalysis data sources) are extracted and compared, highlighting initial problems (for example, data quality, calibration, record length) associated with long-term (10–20 years) monitoring of dust with regional sources in this and other dryland regions. Nevertheless, comparisons of satellite-retrieved inundation, mineral aerosols, vegetation abundance, and climate data for the 1980–2000 period suggest that desert dust loadings are intermittently influenced by the extent and frequency of lake inundation, sediment inflows, and surface wind speed variability. In addition, a significant proportion of the observed variability in the dust and hydrological cycle of this source could also be attributed to El Niño-Southern Oscillation (ENSO) and Indian Ocean sea surface temperature anomalies. Both are known to have an important role in modulating rainfall variability in southern Africa.


1. Introduction

[2] Recent research [e.g., Prospero et al., 2002; Washington et al., 2003a, 2003b] has demonstrated that most significant dust sources are associated with topographic lows in drylands that contain contemporary or old ephemeral lakes, and that complex relationships may exist between surface water, hydrology, and these desert dust sources. Generally, however, while the identification of dust source areas has been made possible through use of available remote sensing data [for example, the Total Ozone Mapping Spectrometer (TOMS)], gaining an understanding of processes acting within the dust sources themselves has not been straightforward. This has largely been the result of uncertainties associated with interpretation of the data and a general lack of field verification [e.g., Middleton and Goudie, 2001]. Where some field verification and experimentation has been possible [e.g., Washington et al., 2006], improvements in the broad understanding of processes affecting emission and transport of mineral aerosols can be made. However, for most dust sources, little data of this nature exist. This has implications for the generation and testing of dust emission models [e.g., Mahowald et al., 1999; Tegen and Fung, 1994; Tagen, 2003; Cakmur et al., 2006] and for estimating the relative impacts of natural and anthropogenic dust emission processes at regional and global scales [e.g., Mahowald and Luo, 2003; Luo et al., 2004; Grini et al., 2005; Zender and Kwon, 2005]. To address these issues, research here involves the study of processes occurring within a single dust source that has been highlighted in previous research as an important regional source, the Makgadikgadi Pans, Botswana [Prospero et al., 2002; Washington et al., 2003a, 2003b]. These pans are situated in southern Africa and are directly associated with a complex of large ephemeral lakes which experience extensive inundation on an intermittent basis.

[3] Fundamental dust emission studies at Owens (Dry) Lake, USA [e.g., Gill, 1996; Reheis, 1997; Niemeyer et al., 1999] have demonstrated that gross changes in the surface hydrology of an ephemeral lake can lead to significant (and sometimes extreme) changes in regional dust emissions. Within this and similar sources, the predominant mechanism highlighted for the liberation of dust particles is the bombardment of fine-sediment surfaces by coarse saltating particles, effectively a sandblasting of the surface [e.g., Gillette and Chen, 2001]. The key factors affecting the process of emission were seen to be (1) wind speed, (2) surface roughness (influenced by surface crust type and presence/absence of vegetation), and (3) surface soil

1Department of Geography, University of Sheffield, Sheffield, UK.
2National Center for Atmospheric Research, Boulder, Colorado, USA.
3Department of Geography, University of Cape Town, Cape Town, South Africa.

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0148-0227/07/2005JD007025
moisture content and fine sediment availability. Recent work by Zender and Kwon [2005] and Grini et al. [2005] using both observed and modeled data highlight the direct effects that variability in some of these factors may have on dust emission from this and similar large regional sources. They find that changes in the frequency and extent of natural inundation occurring within large ephemeral lake systems may lead to significant fluctuations in dust loadings for some regional sources on a seasonal and interannual basis. However, Luo et al. [2004] also highlighted that for a number of global sources not dominated by significant inflows, correlations between dust variability and soil moisture are not as well constrained as with surface wind and frictional velocities. Generally, the lack of detailed observations of processes within dust sources hampers validation of these and similar observations. Working with restricted data sets, Mahowald et al. [2003] and Bryant [2003] highlighted methods and approaches to better understand the role of ephemeral lake hydrology within dust sources that do receive significant inflow. However, while these studies highlighted links between specific inundation events on African ephemeral lakes and perturbations in the dust cycle, they fell short of being able to explain most of the variability in the dust plumes associated with these sources. This was largely a consequence of using a limited time series of climate and remote sensing data (<10 years). The number and intensity of inundation events recorded (<3 events for each source) was therefore not sufficient to fully understand observed variability in the dust plumes.

We therefore aim to use extended time series of remote sensing and climate observations for the Makgadikgadi Pans, Botswana, with three objectives. First, we will seek to comment on the relative reliability of available data that have been widely used to characterize dust sources and to explore the extent to which the seasonal and annual cycle of mineral aerosol emissions at this location can be determined. Second, we will determine the relationships between ephemeral lake inundation events detected using reflectance changes in Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectrometer (MODIS) data and vegetation greening [using Fourier-Adjusted, Sensor and Solar zenith angle corrected, Interpolated, Reconstructed (FASIR) and Fraction of Absorbed Photosynthetically Active Radiation (FAPAR)] and dust emissions detected by TOMS absorbing aerosol index (AAI)/aerosol optical depth (AOD) and MODIS (AOD) data sets. Finally, we wish to isolate key regional climate controls on lake inundation. A number of studies [e.g., Nicholson and Kim 1997; Nicholson et al., 2001] have highlighted links between interannual rainfall variability within southern Africa and associated El Niño-Southern Oscillation (ENSO) phases and related sea surface temperature (SST) anomalies over the Indian and South Atlantic Oceans. However, direct links between regional climate and the dust cycle for major sources of this kind have not yet been made. Here we will also attempt to place the dust emission and inundation cycles within the Makgadikgadi Pans within a regional context.

2. Study Area

Covering approximately 37,000 km², the Makgadikgadi Basin, situated in semi-arid central Botswana (20°–21.50°S and 24.5°–26.50°E), represents a range of fluvial, lacus-
trine, and aeolian surface morphologies (Figure 1). This basin forms part of the Lake Paleo-Makgadikgadi or Makgadikgadi-Okavango-Zambezi rift depression and represents one of the largest paleo-lake systems in Africa [Shaw et al., 1997; Ringrose et al., 2005; White and Eckardt, 2006]. The Makgadikgadi Basin is currently occupied by a complex of large ephemeral lakes [Goudie and Wells, 1995], most notably the regional sump of Sua Pan (890 m a.s.l.), with an area of approximately 3000 km² and the slightly larger Ntwetwe Pan (approximately 900 m a.s.l.) [Ringrose et al., 2005; Thomas and Shaw, 1991].

The Makgadikgadi Basin has consistently been identified as being one of the 10 most important global dust sources in a number of recent studies [Prospero et al., 2002; Washington et al., 2003a, 2003b; Zender and Kwon, 2005]. The Makgadikgadi ephemeral lakes themselves are therefore recognized as one of the principal dust sources in southern Africa (e.g., Resane et al. [2004]; the other being Etosha Pan, Namibia [Bryant, 2003]) and possibly an important source of Fe-rich mineral aerosol to the Indian Ocean (IO) [Piketh et al., 2000, 2002]. In addition, Wood et al. [2005] also identified a mantle of evaporite minerals derived from the Makgadikgadi Basin up to 150 km from the source area, outlining the long-term activity of this source and its regional importance [White and Eckardt, 2006]. Both dust sources therefore have well-defined and persistent dust plumes which also demonstrate high-annual and interannual variability [e.g., Prospero et al., 2002; Bryant, 2003; Mahowald et al., 2003; Luo et al., 2004]. Dust emissions from these lakes have been assumed to be both synchronous [Prospero et al., 2002] and “sediment-supply limited” [Washington et al., 2003a, 2003b; Gillette and Chen, 2001]. Zender and Kwon [2005] classified this source as having strong moisture and vegetation constraints over multiple timescales, but their relationships do not necessarily elucidate process. Consequently, very little is known about what actually controls sediment supply and availability for dust emission at this and other similar locations, although it has been assumed that inundation processes may play a significant role. Importantly, most of the data used here and elsewhere to characterize dust emission from this source chronicle the period after which flow from the Boteti River into Ntwetwe Pan has ceased, and therefore represent a period in which the surface sedimentary and hydrological regime has undergone significant change.

3. Data and Methods

3.1. Mineral Aerosol Data

The long-term mean TOMS AAI value for this source [e.g., Washington et al., 2003a, 2003b] is generally greater than 0.8. Atmospheric mineral aerosol loadings for the Makgadikgadi Basin were therefore initially derived from both the TOMS AAI [Torres et al., 1998] and AOD data sets [Torres et al., 2002]. Because of the low variability in UV surface reflectance, TOMS AAI can be used to detect aerosols over land as well as oceans, and thus it has been used for studies of mineral aerosol source areas [e.g., Prospero et al., 2002; Washington et al., 2003a, 2003b]. TOMS AAI is proportional to the amount of absorbing aerosols, the refractive index in the UV range, and the aerosol height; however, the large 1° × 1.25° latitude/longitude grid of the TOMS AAI means that the presence of clouds or scattering aerosols will interfere with TOMS’ ability to detect absorbing aerosols [Torres et al., 1998]. TOMS AAI is available from 1979 to 1993 and 1996 to 2004 (http://toms.gsfc.nasa.gov/c0) with the recent implementation of the version-8 processing algorithm significantly improving the calibration between these two time series up to and including 2000. Because of the dependence of TOMS AAI values on aerosol height [a function of the planetary boundary layer height (PBLH)] and the strong seasonal cycle in the height of desert dust plumes [Mahowald and Dufresne, 2004], the monthly mean seasonal cycle of the TOMS AAI is thought not to be linearly proportional to monthly mean mineral aerosol loading [e.g., Hsu et al., 1999]. However, the anomalies of the monthly mean TOMS AAI (i.e., monthly mean – climatology monthly mean = anomalies) are likely to be proportional to significant increases or decreases in aerosol loading. This assumes that there are no strong fluctuations in the vertical mixing between different years [e.g., Cakmur et al., 2001]. Torres et al. [2002] created a TOMS AOD product by combining TOMS AAI with model output for different aerosol types. These data (http://toms.gsfc.nasa.gov/aerosols/aot.html) have a 1° × 1° latitude/longitude grid over both the oceans and the continents. In this study, we show the results of comparative analyses run using both TOMS AOD and TOMS AAI. Working from the criteria used to identify the possible dust source within the Makgadikgadi Basin outlined by a number of workers [Prospero et al., 2002; Washington et al., 2003a, 2003b; Zender and Kwon, 2005], five adjacent TOMS cells were selected to represent the dust signal from this source as it spread in a downwind direction from Sua Pan. For the 2000–2005 period, MODIS Level-3 Atmosphere Monthly Global data (http://modis-atmos.gsfc.nasa.gov/MOD08_M3/index.html) were also collated. These data have 1° × 1° latitude/longitude grid on an equal-angle grid that spans a (calendar) monthly interval which is then summarized over the globe [Kaufman and Tanre, 1998; Remer et al., 2005; Kaufman et al., 2005]. Generally, these data do not perform well when collected over surfaces that have very bright backgrounds (for example, the Sahara), and therefore have not been used widely to characterize large dust source regions [Chu et al., 2002]. In this instance, we find that the MODIS AOD data do not saturate over the Makgadikgadi Pans, and we therefore evaluate the data alongside the TOMS time series. In addition, we also evaluate daily gridded Ozone Monitoring Instrument (OMI) aerosol data (http://toms.gsfc.nasa.gov/omi/), which represent the application of the TOMS v8 algorithm to OMI data (2004–present) to provide a data set which is directly comparable to TOMS AAI (i.e., with the same 1° × 1.25° latitude/longitude grid). We also include monthly mean PBLH calculated using the Model of Atmospheric Transport and Chemistry (MATCH) driven by National Center for Environmental Prediction (NCEP) winds [Luo et al., 2003; Mahowald et al., 2003]. The boundary layer height is calculated based on either surface buoyancy-induced mixing (usually during sunny days) or mechanical mixing (at night) as described in Holtslag and Boville [1993]. Boundary layer mixing was calculated every time step (40 min) from values of the
vertical temperature and humidity profiles and surface heating fluxes interpolated from 6 hourly values taken from the NCEP data set.

3.2. Surface Hydrology

The last 100 years, recorded flow into the Makgadikgadi Basin has occurred primarily via the Boteti River to the west and, to a lesser extent, the Nata River to the east. However, the balance of flow and sediment supply from these two river systems with contrasting source areas and flow pathways has changed dramatically in the last 30 years. Human interference coupled with a series of drought years meant that flow from the Okavango River/Delta system to the Boteti River has been negligible since the mid-1970s [Thomas and Shaw, 1991; McCarthy et al., 2003; Bauer et al., 2006]. This change in flow regime has been further underlined by the recent diversion of Boteti flow at the Mopipi Dam, intended to provide water for the Orapa diamond mine, but now itself devoid of any flow. Generally, inflow to the basin is now almost exclusively from the Nata catchment, which has its source in the highlands of Zimbabwe. Flow in this river currently results in occasional flooding of Sua Pan and significant groundwater recharge which often results in partial flooding of the neighboring Ntwetwe Pan. Mining of salts (sodium carbonate and sodium chloride) via pumping and evaporation of groundwater from northern Sua Pan by the Botswana Ash (Botash) Company from 1988 onwards also represents important human intervention into the surface hydrological cycle of these ephemeral lakes. However, it is unlikely that short-term water abstraction has, to date, impacted significantly on the inundation cycle [Eckardt et al., 2007].

Measure of lake inundation were derived using satellite retrievals of standing water within ephemeral lake basins. AVHRR data were obtained from either the GES (GSFC Earth Sciences) Distributed Active Archive Center (http://daac.gsfc.nasa.gov/) or Satellite Active Archive (http://www.saa.noaa.gov/). Pathfinder 10-day composites (8-km resolution) and Noontime, cloud-free local area coverage (LAC) or high-resolution picture transmission (HRPT) images (4- and 1-km resolution) were collected. A continuous time series (1980–2001) was extracted for Sua Pan on the basis of 2–4 images per month [Bryant and Rainey, 2002; Bryant, 2003]. Images were initially georectified and reprojected to a suitable latitude/longitude coordinate system. A time series of near-infrared (NIR) reflectance variability (augmented with lake areas measured in square kilometers for the 1996–2004 period) was extracted (for details of the methods used, see Bryant and Rainey [2002]) and was subsequently smoothed to attenuate remnant cloud noise. The same method was used to extend the time series for the period 2001–2005 using NIR reflectance values from MODIS 32-day composites (500-m resolution) obtained from the Global Land Cover Facility (GLCF; http://glcf. umiacs.umd.edu/data/modis/500m32day.shtml).

The inundation periods identified were predominantly controlled by inflow from the Nata River for which monthly flow data were available for the period 1980–1999. The contributing catchment was derived from the HYDRO1K catchment database (http://lpdaac.usgs.gov/gtopo30/hydro/), and this area was used to derive the total monthly precipitation in a 0.5° grid-box. Measures of lake inundation were derived using satellite retrievals of standing water within ephemeral lake basins. AVHRR data were obtained from either the GES (GSFC Earth Sciences) Distributed Active Archive Center (http://daac.gsfc.nasa.gov/) or Satellite Active Archive (http://www.saa.noaa.gov/). Pathfinder 10-day composites (8-km resolution) and Noontime, cloud-free local area coverage (LAC) or high-resolution picture transmission (HRPT) images (4- and 1-km resolution) were collected. A continuous time series (1980–2001) was extracted for Sua Pan on the basis of 2–4 images per month [Bryant and Rainey, 2002; Bryant, 2003]. Images were initially georectified and reprojected to a suitable latitude/longitude coordinate system. A time series of near-infrared (NIR) reflectance variability (augmented with lake areas measured in square kilometers for the 1996–2004 period) was extracted (for details of the methods used, see Bryant and Rainey [2002]) and was subsequently smoothed to attenuate remnant cloud noise. The same method was used to extend the time series for the period 2001–2005 using NIR reflectance values from MODIS 32-day composites (500-m resolution) obtained from the Global Land Cover Facility (GLCF; http://glcf. umiacs.umd.edu/data/modis/500m32day.shtml).

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The 10-m surface wind data for speed and direction were derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-40 Reanalysis Project archived online at the British Atmospheric Data Centre (BADC; http://badc.nerc.ac.uk/data/ecmwf-e40/). A complete time series at 6-hourly intervals with 1° resolution for the period 1980–2001 were extracted. The winds reported here are median wind speeds cubed and then averaged over a month. To augment these data, we have also extracted comparable and overlapping surface wind speed time series from both the Francistown and Sua meteorological stations (Figure 1) alongside records of surface visibility extracted from DS464.0 archived at the US National Center for Atmospheric Research.

Sea surface temperature anomalies were extracted from the Climate Diagnostics Centre (CDC) online archives (http://www.cdc.noaa.gov/ClimateIndices/) and the Indian Ocean dipole (IOD) site maintained by the Frontier Research System for Global Change (FRSGC)/Japan Agency for Marine-Earth Science and Technology (JAMSTEC) Climate Variations Research Program (http://www.jamstec.go.jp). FASIR FADAR data were kindly provided by Los et al. [2000] and can be obtained from http://islscp2.sesda.com/. The time series used here represent average FASIR profiles for the key vegetation zones within the Makgadikgadi Basin.

3.4. Data Reliability

3.4.1. Climate Data

As mentioned above, wind speed data extracted from ERA-40 Reanalysis products and two local meteorological stations have been processed to provide data reflecting median wind speeds cubed and then averaged over a month. As surface winds are highly variable, averaged data of this nature may not appropriately represent the true variability in observations [e.g., Tegen, 2003]. However, dust model studies suggest that monthly averaged cubed wind fields correlate well with dust source strength in regions with little fluctuation in soil moisture [Luo et al., 2003, 2004]. For most periods in which the Makgadikgadi Basin is in a dry or drying state, we would therefore expect these data to be associated with surface mineral aerosol emissions. Close examination of the wind speed data from the Sua and Francistown stations did reveal some periods of erroneous records in which the data may have been compromised either by operator error or the unrecorded relocation of anemometers. Careful quality control of these data therefore necessitated the removal of a number of years of data from each station and careful cross-checking with station records.

A number of researchers [e.g., Engelstaedter et al., 2003; Tegen et al., 2002] have shown that it is possible to use dust storm frequency (DSF) derived from station meteorological data (collected when visibility is reduced below a specified level because of the presence of dust in...
the boundary layer) in order to gain a qualitative understanding of the activity of dust sources, and the location and size of associated dust plumes. A record of surface visibility was therefore derived from the Francistown and Sua meteorological station records, located in close proximity to the pans (but on its eastern and northern border). These data were found to record very few low-visibility events (i.e., when visibility was <1 km) during the 1980–2005 period. Since these events are often seen by remote sensing, this disparity was explained by location of these meteorological stations in relation to the normal westward trajectories of dust emanating from the pans, and highlights one of the difficulties in using visibility from station data to characterize surface dust emissions for all source areas.

3.4.2. Optical Remote-Sensing Data

[15] Using a principally remote-sensing approach to the synergistic monitoring of the dust and hydrological cycle of the Makgadikgadi Pans (or other large ephemeral systems) over a 20- to 30-year period requires access to a wide range of land and atmosphere data archives, an approach which is not without problems and pitfalls. Observing mineral aerosols over land using remotely sensed data is commonly affected by poor contrast between the aerosols themselves and the naturally high albedo of many desert surfaces [e.g., Miller, 2003; Kaufman et al., 2002]. In the case of the Makgadikgadi Pans, which is a relatively discrete dust source surrounded by vegetated semiarid rangelands, this effect is less apparent. Certainly, in the last 10 years, moderate resolution optical remote-sensing data with a low return period [e.g., MODIS and Sea-Viewing Wide Field-of-View Sensor (SeaWIFS)] have been used to some extent in the monitoring of daily source activity. Figures 2a and 2b represent MODIS and SeaWIFS images of two separate dust events from this source in July 2001. These data both record a plume emanating from the Sua/Ntwetwe Pans and spreading westward over Rakops and Orapa. However, even though these unenhanced data can highlight periods in which a plume is clearly visible, it is still difficult to use these data to pinpoint the exact source location of each event. In this case, it is possible to infer from the data that the southern part of Sua Pan may be the principal source region, but the evidence is not conclusive. Nevertheless, these observations help explain the lack of a significant proportion of low-visibility observations coincident with dust plumes at either the Sua or Francistown meteorological stations (see above). By comparison, detection of shallow surface water on the pan surface is less problematic, both being a longer-term phenomena (weeks/months) and a more easily detectable spectral signature [Bryant and Rainey, 2002]. In this case, a Landsat Enhanced Thematic Mapper (ETM) image is used to characterize surface water cover in May 2000, shortly after a major inundation event (Figure 2c). These data show that despite significant inflow reaching only the basin via the Nata River, both Sua Pan and Ntwetwe Pan can become inundated as a result of regional shallow groundwater recharge.

3.4.3. Satellite Aerosol Retrievals

[16] In November 2000, the Earth Probe (EP)-TOMS instrument underwent a wavelength-dependent calibration drift which ultimately affected the absorbing aerosol index calculation. This has been noted by a number of workers [e.g., de Graaf et al., 2005], and we can see the drift in these data from a plot of global averages of TOMS AAI (v8; Figure 3). It is clear that, from 2000 onwards, the increase in global AAI is unlikely to be the results of global increases in mineral aerosol concentrations. We therefore chose not to use EP-TOMS AAI data beyond 2000 in any time series analyses for this source. To assess temporal stability in aerosol retrievals within the 1980–2005 period (and also for some events in the post-2000 period), we made a direct comparison of monthly and seasonal averages of TOMS AAI, AOD, and MODIS AOD data for identical plume
locations (Figure 4). From these data, we found that the recorded aerosol data are not completely synchronous. In particular, TOMS AOD data were found to have a counter-intuitive seasonal trend in which peak AOD is recorded in the wet season, a period in which increased aerosol emissions from either mineral (which seem to peak in the August–October period) or biomass (which peak in June/July [Swap et al., 2003]) sources are extremely unlikely. This may be an artifact resulting from the intensive reprocessing these data have undergone in recalibration to AOD [Torres et al., 2002]. On the basis of these observations, it is suggested here that, although the calibrated TOMS AOD

Figure 3. Global average EP-TOMS AAI (v8) values for the 1996–2004 period which show a significant overall increase in AAI values (and standard deviation) from 2001/2002 onwards, which is consistent with the reported period of calibration drift and is unlikely to be the result of increased mineral aerosol emissions. Solid lines represent mean values, and dashed lines represent ±1 standard deviation.

Figure 4. Comparing the complete time series of N7 and EP TOMS AAI (v8) and TOMS AOD data for the Makgadikgadi plume, the gross interannual trends are comparable. We can clearly see from these data an increase in TOMS anomalies up to 1988, and then a sharp decline followed by another steady increase in the 1989–1993 period. However, the N7-TOMS AOD/AAI data demonstrate a clear temporal shift when compared to EP-TOMS data. MODIS AOD data overlap both time series in 2000 and compare well with the seasonal cycle of TOMS AAI.
data set has significant advantages over TOMS AAI for understanding absolute aerosol concentration in many locations, the data may not at present be completely reliable in recording temporal variability in aerosol concentrations for this source, or for other similar sources in the Southern Hemisphere. Nevertheless, for comparison, we include TOMS AOD data for this source in our subsequent data analysis.

[17] Close examination of daily satellite data of dust storm activity within the Makgadikgadi Basin from coincident MODIS and TOMS aerosol products (AAI, AOD) can often highlight significant variability in the quality of data retrieval for individual events (Figure 5). In this case, events...
from July 2001 (Figure 5a, with detail in Figure 2a) and September 2003 (Figure 5d) recorded by MODIS are contrasted with coincident MODIS AOD (Figures 5b and 5c) and EP-TOMS (Figures 5e and 5f). For the July 2001 event, the MODIS and TOMS data suffered from significant data loss because of either orbital or cloud effects. The September event is less problematic and highlights, in particular, the ability of the daily MODIS AOD product to characterize the plume. These data show that dust emission events are recorded by both TOMS and MODIS data. However, they also highlight that, when aspects affecting data retrieval are taken into account, daily records of aerosol variability from TOMS and MODIS may underestimate or spatially misrepresent the number of dust events occurring both in and around some source regions. Nevertheless, it seems that, when the data from these events are averaged over longer periods (week/month/season/year [Washington et al., 2003a, 2003b]) or filtered to remove any background noise (for example, by only recording the number of days where data were greater than a set threshold [Prospero et al., 2002]), these effects are somewhat minimized, and a reasonable indication of source location (if not absolute spatial/temporal variability) may be generated. Figure 6 shows long-term averages in TOMS AAI, TOMS AOD, and MODIS AOD data for southern Africa. What is apparent from these data sets is that they all highlight both Etosha Pan and Sua Pan as significant source regions. It is also important to highlight that MODIS AOD data retrievals for this region, which are seriously affected by bright-surface effects in the Saharan dust belt, are able to characterize these sources at least as well at the TOMS time series [Ichoku et al., 2003]. This has implications for the use of these data for successful long-term monitoring of dust sources that lie outside of the dust belt.

Figure 6. Mean annual aerosol images. (a) N7-TOMS (v8) 1980–1993, (b) TOMS-AOD (1980–2000), and (c) MODIS AOD (2000–2005). All three data sets identify the two principal source areas in southern Africa. However, because of high seasonal and interannual variability, the relative extent and magnitude of the plumes are not well characterized by these mean annual data.

4. Results
4.1. Annual and Seasonal Cycles
4.1.1. Rainfall and River Flow
[18] Data from the meteorological stations situated within the Makgadikgadi Basin (Figure 1), and extracted from a gridded rainfall product for the Nata catchment, outline the clear wet (December-February [DJF]) and dry season (June–August) observed in this region (Figure 7). Also apparent is a rainfall gradient across the basin, ranging from 500 mm y$^{-1}$ in the northeastern part (Sua, Nata) to less than 400 mm y$^{-1}$ in the west (Rakops and Orapa). High interannual variability in rainfall is also apparent, with wet season rainfall being especially variable in the western part of the basin. Recorded flow in the Nata River between 1970 and 1999 (Figure 8) shows the river discharge to be perennial/ephemeral in nature. Flow can be seen to occur principally in the wet season period, with peak flows occurring in February and low flow in the May-November period. High interannual variability in flow is also apparent with peak annual flows in wet years exceeding 300 × 10^6 m$^3$, with similar months in dry years recording little or no flow. The variability in wet/dry season in rainfall and river flow across the Makgadikgadi Basin is also reflected in clear seasonal and interannual fluctuations in vegetation greening. The time series of FASIR F$_{APAR}$ data for the basin show a clear lagged peak in vegetation greening in February-April and a minimum in September-November (SON; Figure 9). Across the basin we can also see that the response of vegetation to wet and dry periods is more marked in the drier western rangelands.

4.1.2. Wind Speed
[19] A summary of median wind speed data (m s$^{-1}$)$^2$ for Francistown (Figure 10a) and Sua (Figure 10b) both show a
peak in SON and relatively low surface winds speeds in May–July. In contrast, a comparable time series of ERA-40 10-m median wind speed data (m s$^{-1}$) for the Makgadikgadi Basin (Figure 10c) highlight some of the problems associated in using such data to characterize surface wind speed variability. These maxima and minima, although demonstrating high-seasonal and interannual variability, generally coincide with dry periods within the basin in which vegetation is partly senescent. A comparable time series of ERA-40 10-m median wind speed data (m s$^{-1}$) for the Makgadikgadi Basin (Figure 10c) also have a peak in wind speed in the same SON period, but the average wind magnitudes in this period are significantly lower than the station data for the same period, with less marked seasonal variability. This is consistent with the ERA-40 winds being modeled or simulated over a larger region than just one observational site, but highlights difficulties in knowing the fluctuations in wind speeds in source regions. For the period 1980–2002, only 2.5% of all winds were found to be above the accepted sand transport threshold of 6 m s$^{-1}$ [Fryberger, 1979]. Clearly, relative to surface observations, ERA-40 data underestimate the occurrence of erosive winds in both the mean and the variability of the time series. A comparative time series of anomalies in monthly median wind speed (m s$^{-1}$) for the 1980–2005 period (not shown here) highlights the difficulty in comparing temporal variability in these data sets. Although some extreme anomalies were broadly comparable across the time period (for example, positive anomalies in 1982, negative anomalies in 1986), there were also many instances where the data did not concur (for example, 2002). Nevertheless, anomalies in the ERA-40 record represent the only long-term

Figure 7. Seasonal and interannual variability in rainfall for the period 1950–2000 recorded at the following: (a) Gweta, (b) Orapa, (c) Nata, (d) Sua, (e) Wilmott gridded reanalysis data (1980–1999) for the Nata catchment, and (f) Rakops. All data are characterized by high interannual variability and a clear rainfall gradient across the Makgadikgadi Basin (see Figure 1 for locations). Solid lines represent mean values, and dashed lines represent ±1 standard deviation.
approach to assess wind speed control on dust emissions from most sources.

4.1.3. Mineral Aerosols

[20] To complement the inventory of seasonal averages, we have compiled a monthly time series of TOMS AAI and MODIS AOD for the Makgadikgadi source region covering the period 1980–2005. Mahowald and Dufresne [2004] highlighted some of the problems associated with interpretation of temporal variability in TOMS AAI in certain locations, in that they have shown AAI values to be significantly affected by variations in PBLH within the Saharan dust belt. Modeled PBLH for the Makgadikgadi Basin shows clear seasonal variability (Figures 11a–11d [Mahowald and Dufresne, 2004]).

[21] TOMS AAI data suggest a dust peak in the August-October (ASO) period, and MODIS AOD record a peak in SON (Figures 11a–11d). OMI data (not shown here) also concur closely with the location and seasonal aerosol variability in the Makgadikgadi plume outlined by both

Figure 8. Recorded seasonal and interannual variability in Nata River flow (10^6 m^3) for the period 1970–1999. Whiskers represent the standard deviation of flow for each month.

Figure 9. Monthly average and standard deviation values as recorded by AVHRR FASIR data for the 1980–1999 period, outlining seasonal and interannual variability for the principal vegetation zones in and around the Makgadikgadi Basin. Solid lines represent mean values, and dashed lines represent ±1 standard deviation.

Figure 10. Seasonal and interannual variability in median wind speed (m s^-1)^3 for the 1980–2000 period recorded at (a) Francistown to the southeast of the Makgadikgadi Basin, (b) Sua, directly to the north of Sua Pan, and (c) comparable ERA-40 10-m median wind speed (m s^-1)^3 data for the Makgadikgadi Basin. A peak in wind speed in the October period can be seen in all data sets. Solid lines represent mean values, and dashed lines represent ±1 standard deviation.

TOMS AAI and MODIS AOD. As we have outlined earlier, the peak in TOMS AOD data has a significant temporal shift and occurs in the November-January period. We can see from these data that, in comparison to PBLH, TOMS AAI data seem unlikely to be solely a function of variations in PBLH and have a seasonal cycle which fits observed wind and rainfall cycles. Finally, in line with TOMS AAI data, MODIS AOD data variability seems to closely match observations of surface wind speed variability within the basin. Quarterly observations of respective aerosol variabil-
ity for each data set (Figures 12a–12c) also highlight the slight temporal lags in these data. When we compare the monthly time series of data for the Makgadikgadi plume (Figure 3), we can see that, for the 1980–1993 (Nimbus-7) data sets, TOMS AOD and AAI both record the same significant interannual variations in the plume strength. We can see an increase in N7-TOMS anomalies in the period up to 1988, followed by a sharp drop in anomalies and another period of increase up to and including 1993. However, in using TOMS AAI as opposed to TOMS AOD data to document variability in mineral aerosol concentrations, considerable care also has to be taken to observe only statistical anomalies in the time series, as opposed to absolute values [Mahowald et al., 2003], and to account for local variations in PBLH [Mahowald and Dufresne, 2004].

4.2. The 1980–2004 Time Series

In putting together the disparate data collected for the Makgadikgadi Basin, a synchronous time series of key variables was constructed to outline significant controls exerted on the observed dust cycle. In terms of surface hydrological variability, the time series of monthly lake inundation recorded by AVHRR (LAC and global area coverage) and MODIS between 1980 and 2005 (Figure 13a) highlight nine significant periods of surface inundation on Sua Pan (i.e., events leading to water coverage on the lake of >10%). The periods of extreme inundation and assumed sediment inflow can be directly related to periods of significant rainfall in the Nata catchment and flow on the Nata River (Figure 13b), which also coincide with major fluctuations in vegetation (Figure 13c). Anomalies in TOMS AAI and ERA-40 wind speed (m s\(^{-1}\)) are used to characterize the dust cycle in the same periods (Figure 13d). As has been shown above (Figure 12), significant interannual variability in the dust plume has been recorded. Here we can see that positive and negative anomalies from this time series loosely coincide with significant dry and wet phases within the basin. Factors which may explain variability in the dust cycle for this source are explored below.

5. Discussion

5.1. Lake Inundation and Vegetation Phenology

To outline key changes in the surface hydrology of the Makgadikgadi Pans, it is important to study in detail the key events occurring in the 1980–2005 time series (Figure 13a). Prior to 1988, no significant inflows or inundation periods were observed. For most of the 1980s, this part of Africa experienced a number of dry years associated with a persistent El Niño phase [Nicholson et al., 2001]. Event 1 occurred in the wet season of 1988 in which significant rainfall fell within the Nata catchment (474 mm; Figure 13c) in the DJF period (four times the long-term

Figure 11. Mean annual aerosol concentrations in the Makgadikgadi Basin. (a) Seasonal and interannual fluctuations in the PBLH above the Makgadikgadi Basin show relatively low variability in the ASO dust season. The seasonal and interannual variability in aerosol concentrations for the Makgadikgadi plume is documented by the following: (b) TOMS AAI, (c) TOMS AOD, and (d) MODIS AOD. All data show slightly different seasonal aerosol peaks. TOMS AOD data show a significantly different seasonality to TOMS AAI. Solid lines represent mean values, and dashed lines represent ±1 standard deviation.
average fell at both Nata and Sua) resulting in high flows on the Nata River (reaching a total of $228 \times 10^6$ m$^3$ in March; Figure 13c). This was followed by extensive inundation of both Sua and Ntwtewe Pans, beginning in late March/early May and peaking at coverage of 36% (1080 km$^2$) in June. This event coincided with a return to La Niña (Figure 13e) and negative ENSO 3.4 sea surface temperature anomalies. It is likely that high water tables resulting from this event persisted into the wet season of 1989 when a small lake (event 2) formed (peaking briefly at 450 km$^2$; 15%). Nata catchment rainfall was 315 mm in the 1989 DJF period, and flow on the Nata peaked at a modest $13.7 \times 10^6$ m$^3$ (March 1989). Event 3 occurred in January 1993 where a short-lived lake (1095 km$^2$; 36.5% coverage) formed after DJF rainfall within the catchment exceeded 327 mm and flow on the Nata River peaked at $152 \times 10^6$ m$^3$. Event 4 occurred in January 1996 when a lake of 1500 km$^2$ (50.2% coverage) formed as a result of significant DJF rainfall (529 mm) and total Nata River flows of $300 \times 10^6$ m$^3$ s$^{-1}$ in both January and February (both comparable with event 1). Again, it is assumed that high water tables resulting from this event contributed to the formation of a lake (event 5) of 1300 km$^2$ in 1997 (44% coverage peaking in April). DJF rainfall of 378 mm coupled with a Nata flow of $28.3 \times 10^6$ m$^3$ were observed. Event 6 occurred in 1999 where DJF rainfall of 366 mm and peak flow of $11.47 \times 10^6$ m$^3$ resulted in a lake of 750 km$^2$ (25% coverage). Event 7 occurred in February 2000 when La Niña conditions coupled with the landfall of tropical cyclone (TC) Eline [Reason and Keibel, 2004] caused extensive flooding in Mozambique and the eastern coast of southern Africa. Its vestiges eventually traveled inland to cause further widespread damage and flooding in the eastern provinces of Botswana. Recorded February rainfalls at Nata (316 mm) and Sua (385 mm) were between three and four times the long-term average at each location and two to three times higher than the totals for any of the other recorded events. This resulted in high flows on the Nata River (no data available here) and elsewhere in eastern Botswana and one of the largest flood events recorded in recent times on Sua Pan. The lake that formed on the surface of the Makgadikgadi Pans was in excess of 4500 km$^2$. Sua Pan itself had a lake of approximately 2400 km$^2$ (peaking in April 2000; see Figure 2c) which covered approximately 78% of the entire Pan surface to a depth of 1–2 m and which only disappeared briefly in January 2001. Event 8 followed quickly in March 2001 and can again be associated with the likelihood of high water tables remaining from event 7. The lake area peaked at 1000 km$^2$ (33.4%). No river flow or climate data were available for this event. The final significant event occurred in January 2004, with a lake of 1500 km$^2$ forming in April and drying up by September. Again, no flow or climate data are available for this event.

Figure 12. Quarterly images of mean aerosol concentration in southern Africa. Periods are optimized to emphasize the wet/dry season in this region. (a) TOMS AOD, (b) TOMS AAI, and (c) MODIS AOD. These data highlight the clear seasonal variability observed in each data set, periods of biomass burning in equatorial regions, and the contrasting quarterly maxima in the mineral aerosol record.
Fluctuations in \( F_{\text{APAR}} \) within the Makgadikgadi Basin (Figure 13c) also seem to link closely with some of the key climate cycles and associated inflow events. This is especially apparent for event 1, where vegetation abundance increases sharply in response to rainfall associated with the switch to La Niña conditions, a relationship similar (but opposite) to that observed in the dust cycle of the southwestern US by Okin and Reheis [2002]. Prior to this event, vegetation seems to have been significantly affected by prevailing drought conditions. In the 1988–1998 period, vegetation abundance is generally high and reflects a return to average rainfall inputs. The only significant dip in \( F_{\text{APAR}} \) observed is in 1994/1995 and is closely associated with below-average wet-season rainfall within the basin. Events 4 and 5 signify a return to increased vegetation abundance.

5.2. Links Between Mineral Aerosol Emissions and Inundation Events

During the dust season within the Makgadikgadi Basin (ASO), the predominant wind direction is easterly (90°–100°) [see also White and Eckardt, 2006], and events in this period (ERA-40) account for 68% of wind speeds exceeding 6 m s\(^{-1}\). Positive anomalies in the 1980–1993 time series of N7-TOMS AAI data (Figure 13c) are closely associated with the dry periods both before (1984–1987) and after (1990–1993) the Sua Pan floods of 1988–1989 (events 1 and 2). The positive anomalies in the dust seasons of 1984–1986 are closely related to variability in surface wind velocity anomalies and seem to mirror decreases in vegetation \( F_{\text{APAR}} \) associated with increased drought conditions experienced in this region. In this instance, recorded dust emissions seem largely unaffected by depletion of sediment supply. In the dust season of 1986, there were positive anomalies in TOMS AAI values associated with winds which were in excess of one standard deviation below average. Rainfall and inflow were also negligible in this period by comparison to other years, which may indicate that either the surface sediments had reached some form of optimum condition for emission in terms of either reduced roughness, or soil moisture or crust formation made fine sediment available at the surface. Negative AAI anomalies predominate throughout the 1988–1989 period in which the lake was partially filled with water (events 1 and 2). In the period 1989–1993, once the water table has lowered and the lake dried, AAI anomalies again seem to become positive and demonstrate a link to wind speed variability. A significant increase in fine sediment availability for emission in Sua Pan in the direct aftermath of events 1 and 2 is most likely to account for increases in the magnitude of AAI anomalies under unexceptional surface wind conditions and enhanced vegetation abundance around the basin (for example, 1992). The EP-TOMS time series from 1996 to 2005 also demonstrate strong negative anomalies in the period 1996–1997 (coincident with events 4 and 5) and 2000–2001 (event 7) in which the pan surface was repeatedly covered in water. In 2001, TOMS AAI dust emissions values for the dust season are extremely low and rarely exceed 1.0 AAI units (a typical figure for February–April). Very strong positive anomalies observed in the 2003 and 2004 dust seasons are most likely the result of serious calibration drift of the EP-TOMS instrument (see Figure 3).

Overall, for those months in the dust season (ASO) which were unaffected by lake inundation (or the immediate aftermath of inundation; 1984–1987, 1992–1993), ERA-40 wind speed anomalies were found to be significantly correlated with TOMS AAI anomalies (\( r = 0.40 \); sig 0.05; data not shown here). In these periods, there is also a notable decrease in vegetation \( F_{\text{APAR}} \) associated with a likely reduction in soil moisture. The data from these time series confirm the very close control that the cycle of lake inundation, drying, and associated vegetation greening/senescence has on the emission of dust from the Makgadikgadi Basin. These observations therefore confirm the general observations of Washington et al. [2003a, 2003b] and Zender and Kwon [2005], but provide significant further understanding of interannual fluctuations in sediment supply and dust emissions at this location, a factor which may influence our understanding of other similar regional sources. In particular, despite the possibility of contrasting dust regimes from Ntwetwe Pan (receiving little or no direct inflow/sediment) and Sua Pan (significant inflow/sediment), the system seems to act as a single source. This may reflect the fact that both pans still flood in a synchronous manner (as a result of coupled groundwater fluctuations) or the possibility that, relative to Sua Pan, fine surface sediments on Ntwetwe Pan have either become depleted or heavily crusted (and therefore not available for emission).

5.3. Controls on Rainfall Variability and Mineral Aerosol Emissions

Rainfall variability within Botswana has been strongly linked with ENSO cycles [e.g., Nicholson et al., 2001; Nicholson and Kim, 1997; Fauchereau et al., 2003], Indian Ocean SST anomalies [e.g., Rocha and Simmonds 1997a, 1997b; Landman and Mason, 1999; Goddard and Graham, 1999], and changes in the Indian Ocean Dipole [e.g., Saji et al., 1999; Reason, 2002; Saji and Yamagata, 2003; Washington et al., 2003b; Washington and Preston, 2003, 2006]. In line with these observations, significant correlations \( (r = -0.3; p < 0.05; \text{Table 1}) \) for the 1980–2000 time series are observed between wet season (DJF) rainfall in the Nata catchment and subtropical Indian Ocean dipole (SIOD) values for January-March (JFM) of the same year. Rainfall within the Nata River catchment (DJF) has a strong positive

Figure 13. Time series of observations for the Makgadikgadi Basin. (a) Lake inundation data at Sua Pan derived from AVHRR and MODIS data, a time series of NIR reflectance and the percent of the lake area covered by surface water. Key flood events are highlighted; (b) rainfall within the Nata River catchment derived from reanalysis climate data (0.5°) and flow on the Nata River; (c) average and anomalies in FASIR \( F_{\text{APAR}} \) data for the Makgadikgadi Basin; (d) monthly normalized anomalies (monthly mean minus the mean of the monthly means normalized to 1 standard deviation) for TOMS AAI v8 (NIMBUS7 and Earth Probe) 1980 through 2005 and wind speed data derived from the ECMWF ERA-40 reanalysis climate product (1°); (e) sea surface temperature anomalies for the SIOD and Pacific (ENSO 3.4) regions. The landfall of tropical cyclones on the m coast of southern Africa is also noted (L).
correlation ($r = 0.72, p < 0.01$) with the flow in the Nata River itself over the same time period (December-March). However, there are some dangers associated with general treatment of such a short time series of data in this manner. In particular, there also seem to be some significant leads and lags in the relationship between rainfall and SST variability. Nevertheless, we can confirm that variations in rainfall entering the Nata catchment are broadly consistent with regional SST controls reported elsewhere. These data highlight the possibility of close and relatively low-lag relationships between extreme regional rainfall events, flow in the Nata River catchment, and subsequent flooding events on the surface of Sua Pan. Such events are also thought to be strongly associated with ENSO 3.4 and SIOD SST anomalies and are linked with the associated landfall of significant Indian Ocean TCs during La Niña (Figure 13e). 

Reason and Keibel [2004] suggested that less than 5% of the southwest Indian Ocean tropical cyclones actually make landfall on the east coast of southern Africa and that even fewer significantly penetrate into the interior. In the case of TC Eline, they argue that the precursor synoptic conditions together with large-scale circulation and SST anomalies over the Indian Ocean associated with a strengthening La Niña were highly favorable in this instance. Washington and Preston [2006] also look closely at extreme rainfall years within southern Africa and target cold SST anomalies in the Maserene region which they suggest induce anomalous anticyclonic circulation, which in turn drives anomalous low-level easterly moisture flux along $10^\circ$–$20^\circ$S into eastern southern Africa. They found that these conditions result in enhanced moist convective uplift and enhanced rainfall over a large part of southern Africa. Consequently we suggest that it is likely that those Indian Ocean tropical cyclones which do make landfall in this region (Figure 13e) have an important impact in strengthening extremes in rainfall inputs to the Nata River catchment under La Niña conditions (for example, 1988, 1996, 2000), resulting in associated negative TOMS AI anomalies in subsequent dust seasons. Given the links between rainfall, inundation, and TOMS AI anomalies within the Makgadikgadi Basin, it is also interesting to note direct relationships which exist between ASO dust anomalies and SST variability within the 1980–2005 period (Figure 13e 2). For this period, as with

### Table 1. Quarterly Correlations Between DJF Rainfall in the Nata Catchment and SST Anomalies Covering Yearly Positive and Negative Lags for the 1980–2000 Period

<table>
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<th>MEI</th>
<th>DMI</th>
<th>SIOD</th>
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$^a$sig 0.01. $^b$sig 0.05.

### 6. Conclusions

This study has looked in detail at the climate controls on dust emissions from a large regional source in southern Africa. 

1. In terms of commenting on the reliability of available and widely used data, we show that the careful combination of readily available Earth observation data and climate data/methodologies used here (i.e., combinations of daily/monthly seasonal aerosol observations, lake flooding records, local/regional meteorological data, etc.) represents essential and important steps toward elucidating how key controls on dust emissions from other large regional dust sources might be determined. However, the detailed approach used here also highlighted known problems with the use and interpretation of other existing and widely used data (for example, wind speed and visibility/DSF) and possible further data issues that had not previously been encountered (for example, the use of TOMS AOD).

2. In exploring links between gross hydrological changes and perturbation in the observed dust cycle we find that annual and interannual variabilities in dust emissions (as recorded by TOMS AAI) from the Makgadikgadi Basin in the 1980–2005 period are significantly influenced by the extent and frequency of lake inundation, which exerts a primary control on sediment availability for deflation. However, for periods in which the pan is dry and sediment is available for deflation on the pan surface, it is likely that wind speed variability is the dominant factor influencing observed dust loadings. Clearly, this system is therefore likely to be sensitive and responsive to changes in regional climate and hydrological disturbance (for example, via water extraction and damming of rivers).

3. In terms of understanding and isolating key regional controls on lake inundation, we find that the hydrology of the Makgadikgadi Basin is significantly influenced by variations in IO SST anomalies and enhanced

### Table 2. Quarterly Correlations Between ASO TOMS Dust Anomalies and SST Anomalies Covering Yearly Positive and Negative Lags for the 1980–2000 Period

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$^a$sig 0.05.
by associated IO tropical cyclone/storm landfall occurring within periods of La Niña. Data here concur with our understanding of the known drivers of regional rainfall and extreme rainfall events in this part of southern Africa.

[31] Importantly, we expect that other regional Southern Hemisphere dust sources focused on ephemeral lake basins will operate with similar constraints. Clearly, some understanding of the complex interactions that can lead to fluctuations in rainfall in each region must be taken into account when trying to understand the dust cycle. In addition, other aspects of natural and human interaction with the hydrological cycle of these sources need to be both understood and quantified for a full picture of the causes of temporal variability in dust emissions to be understood.

[32] Acknowledgments. The manuscript was greatly improved by the helpful comments of Richard Washington. This research was funded in part by Natural Environment Research Council (NERC) Grant NER/B/S/2003/00221. HYDRO1K data were kindly provided by Kristine Verdin of the United States Geological Survey (USGS). Graham Davis (Oxford) obtained and processed some of the original AVHRR LAC data for Sua Pan. Paul Coles and Graham Allsopp drew the figures, and Paul Shaw provided useful comments on earlier drafts of the manuscript.

References


