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# An infrared desert dust index for the Along-Track Scanning Radiometers

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ABSTRACT

A new aerosol index for the Along-Track Scanning Radiometers (ATSRs) is presented that provides a means to detect desert dust contamination in infrared SST retrievals. The ATSR Saharan dust index (ASDI) utilises only the thermal infrared channels and may therefore be applied consistently to the entire ATSR data record (1991 to present), for both day time and night time observations. The derivation of the ASDI is based on a principal component (PC) analysis (PCA) of two unique pairs of channel brightness temperature differences (BTDs). In 2-D space (i.e. BTD vs BTD), it is found that the loci of data unaffected by aerosol are confined to a single axis of variability. In contrast, the loci of aerosol-contaminated data fall off-axis, shifting in a direction that is approximately orthogonal to the clear-sky axis. The ASDI is therefore defined to be the second PC, where the first PC accounts for the clear-sky variability. The primary ASDI utilises the ATSR nadir and forward-view observations at 11 and 12 μm (ASDI2). A secondary, three-channel nadir-only ASDI (ASDI3) is also defined for situations where data from the forward view are not available. Empirical and theoretical analyses suggest that ASDI is well correlated with aerosol optical depth (AOD: correlation r is typically >0.7) and provides an effective tool for detecting desert mineral dust. Overall, ASDI2 is found to be more effective than ASDI3, with the latter being sensitive only to very high dust loading. In addition, use of ASDI3 is confined to night time observations as it relies on data from the 3.7 μm channel, which is sensitive to reflected solar radiation. This highlights the benefits of having data from both a nadir- and a forward-view for this particular approach to aerosol detection.

## 1. Introduction

Infrared satellite observations of sea surface temperature (SST) have become essential for many modern day applications in meteorology, climatology and oceanography. Several data sets are now made routinely available to users, for example from the Along-Track Scanning Radiometers (ATSRs; ESA, 2002), Advanced Very High Resolution Radiometers (AVHRRs; Kilpatrick et al., 2001) and the Spinning Enhanced Infrared and Visible Radiometer (SEVIRI; Brisson et al., 1998). The accuracy of these data, which are estimated from satellite top of atmosphere (TOA) radiance observations, is dependent upon several factors, such as the radiometric accuracy of the sensor, the retrieval algorithm, and the ability to correctly identify cloud. A number of studies have shown that SST retrievals may be biased by up to several tenths of a degree in the presence of tropospheric mineral dust aerosol (Donlon & Robinson, 1998; Merchant et al., 2006; Noyes et al., 2006; Vazquez-Cuervo et al., 2004). An area particularly affected by this problem is the Atlantic Ocean between West Africa and the Caribbean, where dust is lofted and blown west from the Sahara. These so-called Saharan dust events may occur at any time during the year, but are strongest and most frequent during the northern hemisphere summer months (Carlson & Prospero, 1972). Satellite SST observations where the dust loading is very high are often incorrectly flagged as cloud. However, apparently cloud-free, dust-contaminated SST retrievals are still prevalent enough to warrant the implementation of a specific strategy to either remove these observations, or develop a bias correction method, as the magnitude of the bias induced by the aerosols may exceed the accuracy requirement for many SST applications.

The objective of this study is to develop a method to detect tropospheric mineral dust in ATSR observations over the oceans that may cause SST biases.

Aerosol detection methods using visible wavelengths are well established (e.g. Brindley & Ignatov, 2006; Grey et al., 2006; Tanré et al., 1997; Thomas et al., 2007; Veefkind & de Leeuw, 1998) and have been used previously to detect the presence of aerosols in infrared SST data (e.g. Noyes et al., 2006; Vazquez-Cuervo et al., 2004). However, these data have two main limitations for this type of application. Firstly, the aerosol data are restricted to day time observations only, whereas SSTs are retrieved both at night and during the day. Secondly, the effects of aerosol at infrared wavelengths are not uniquely determined from observation of aerosol effects at visible wavelengths. For example, small-particle aerosols, such as those originating from biomass burning, are often readily detected at visible wavelengths,

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but usually have very little effect on retrieved SSTs. Given these limitations, it is desirable to develop a method of dust detection for the ATSRs that uses only infrared data that can be used both during the day and at night.

Aerosol detection using infrared satellite observations has been reported elsewhere in the literature, for example by Merchant et al. (2006), Brindley and Russell (2006) and Thomas et al. (2009). In this study, we adopt the approach of Merchant et al. (2006), who developed a Saharan dust index (SDI) for use over oceans using the thermal channels of the SEVIRI using a principal component analysis (PCA). This paper describes the development and evaluation of an ATSR equivalent to the SDI, which is hereafter referred to as the ATSR SDI, or ASDI. We begin in Section 2 by describing the study area and data sets used in this analysis and outlining Merchant et al.'s (2006) technique. In Section 3, the effects of Saharan dust on ATSR TOA infrared observations are investigated both theoretically and empirically. Using the results of these experiments, the ASDI is defined in Section 4. In Section 5, we explore the behaviour of the ASDI when applied to empirical data, and validate the dust index with other independent aerosol data sets.

## 2. Study area and data sets

The objective of this study is to define the ASDI, a Saharan dust index that uses only infrared ATSR observations. Key to this process is the use of SEVIRI SDI data, which are used as an independent measure of aerosol in the ATSR data and as a basis for defining the ASDI. Using SDI data in this way is convenient because 1) SDI is a thermal infrared dust index so should be indicative of aerosol effects in the infrared, and 2) being on a geostationary platform, SEVIRI observations are frequent and therefore provide the opportunity to obtain a good temporal match with the ATSR overpass time where empirical investigations are performed.

The main area chosen for this study lies between 0° and 30°N and 50° and 0°W. This area was selected firstly, because strong Saharan dust events occur frequently in the region, and secondly, because this area falls within the SEVIRI field of view (FOV) at view zenith angles for which reliable SDI can be obtained. The analysis carried out here is mostly based on data for the year 2005. The following sections describe the ATSR and SEVIRI data used in this study.

### 2.1. The Along-Track Scanning Radiometers

The ATSR series to date comprises three instruments. The first, ATSR-1, was launched in 1991 on board the European Space Agency's (ESA) polar-orbiting European Remote Sensing satellite-1 (ERS-1). This was followed by the launch of ATSR-2 in 1995 on board ERS-2, and most recently, the Advanced ATSR (AATSR) in 2002 on ESA's Envisat platform. At the time of writing, the AATSR is still fully operational.

The primary objective of the ATSR missions is to provide accurate SST retrievals on a global scale. All ATSR instruments share a common design that facilitates SST retrieval with an accuracy that is currently unmatched by any other space borne sensor. A unique feature is the conical scan mechanism that allows the surface of the earth to be viewed at both nadir and approximately 55° from zenith, enabling an improved atmospheric correction. The ATSR instruments also have exceptional infrared radiometric accuracy ($\ll 0.1$ K) and stability (specified drift of the on board calibration system is less than 0.03 K over a nominal sensor lifetime of 5 years). This is achieved through the use of two onboard calibration black bodies and actively-cooled detectors (Llewellyn-Jones et al., 2001; Mason, 1991; Smith et al., 2001). All the ATSR instruments carry three infrared channels, at approximately 3.7, 11 and 12 μm for SST retrieval, together with a channel at 1.6 μm for cloud detection. ATSR-2 and AATSR also have additional visible channels at 0.56, 0.66 and 0.87 μm for remote sensing of chlorophyll and vegetation, and for cloud detection over land.

Owing to these design features, the orbit stability and temporal consistency of the ERS and Envisat platforms, and the existence of sufficient overlap periods, the ATSR mission provides a unique opportunity to generate a global long-term, high accuracy, homogeneous SST record independently of *in situ* observations. This is the objective of the ATSR Reanalysis for Climate (ARC) project, which aims 'to reduce regional biases in retrieved SST to less than 0.1 K for all global oceans, while creating a homogenous record that is stable in time to within 0.05 K decade$^{-1}$' (Merchant et al., 2008). The ASDI developed here was formulated within the framework of the ARC project and will be used to identify the presence of dust in the ARC SST data sets and to flag SST retrievals that may be biased as a result.

The ATSR data used in this study were obtained from the NERC (Natural Environment Research Council) Earth Observation Data Centre (NEODC: see http://www.neodc.rl.ac.uk/). We use Level 1b 1-km gridded brightness temperature (BT) data, processed using software developed at the University of Leicester. The geolocation (i.e. pixel to geographical latitude and longitude) of these data has been performed as in the AATSR Frequently Asked Questions (FAQ), Appendix A (document ref: AEP.REP.001 (2005)—download from http://envisat.esa.int/instruments/aatsr/faq/AATSR/FAQ/issue1.pdf). For each ATSR data set used here, an alignment correction has been applied following Corlett (2009), where the forward view is shifted relative to the nadir view by −2 pixels in the along track direction, and +2 pixels in the across-track direction. For AATSR, 0.2 K has been added to both forward and nadir 12 μm BTs following the work of Nightingale and Birks (2004), who report a BT deficit of approximately this magnitude, which is likely to be a result of an incorrect pre-launch measurement of the spectral response function (Smith, 2007). (Note: this problem is unique to AATSR; ATSR-1 and ATSR-2 are not affected).

Operational ATSR SST data are not used in this study. However, the effects on SST retrievals are predicted from the results of the radiative transfer modelling by applying the operational retrieval coefficients for 2005, specified in the file ATS_SST_AXVIEC20051205_102103_20020101_000000_20200101_000000.N1 (download from http://earth.esa.int/services/auxiliary_data/aatsr/).

#### 2.1.1. ATSR SST retrievals

ATSR SST estimates, $x$, are retrieved using a linear function of top of atmosphere brightness temperatures (BT—this is the equivalent black body temperature that produces the observed channel radiances):

$$x = a_0 + \sum_{i=1}^{n} a_i y_i \tag{1}$$

where $n$ is the number of observations used, $y_i$ is the BT obtained from channel $i$ (either from the nadir-view only or both the forward- and nadir-views) and $a_0$ and $a_i$ are retrieval coefficients. Four different SST retrievals, can be performed: dual three-channel (D3), which use all three thermal infrared channels from both views, nadir three-channel (N3), which again uses all three channels but only in the nadir-view, and the dual and nadir two-channel coefficients (D2 and N2), which do not include the 3.7 μm channel and are used during the day when the 3.7 μm channel is contaminated by reflected solar radiation. See Table 1 for terminology.

The retrieval coefficients are derived theoretically using a radiative transfer model (RTM), by regressing the simulated BTs against the SSTs used in the model for a large number of atmospheric scenarios (Merchant et al., 1999; Závody et al., 1995). Previous validation of the operational ATSR SST retrieval against in situ observations suggests that most of the data meet the required 0.3 K (one standard deviation) accuracy under cloud-free conditions (Corlett et al., 2006; Noyes et al., 2006; O'Carroll et al., 2006; O'Carroll et al., 2008). Following the work