3.2

AN IMPROVED LAND/OCEAN DUST ENHANCEMENT APPLICABLE TO MODIS

Steven D. Miller
Naval Research Laboratory, Monterey

1. INTRODUCTION

Navy operations over data-denied parts of the world rely necessarily upon model and remote sensing meteorological guidance in making critical tactical decisions. Unexpected environmental conditions in the operating arena can lead to any number of undesirable outcomes, ranging from aborted missions to mishaps. The former translates to potentially millions of dollars lost (e.g., in dumped munitions, operations costs, etc.), and the latter including the possibility of lives lost. In compiling major Naval aviation mishap statistics over a nine-year period between 1990-1998, Cantu (2001) finds 54% percent of these were associated with visibility problems, and with annual losses averaging ~$50 million per year. Furthermore, the study indicated that provided sufficient forecasting and observational tools, 56% of these mishaps were considered avoidable. These potential savings underscore the Navy's motivation for seeking to gain a better handle on visibility-impacting phenomena.

Central to the meteorological challenges confronted during Operation Enduring Freedom (OEF) were frequent, ubiquitous, and persistent desert dust storms. These extreme aerosol events, spanning over both land and ocean, posed considerable problems to operations in terms of visibility reduction. In the most extreme events, visibility may be reduced to levels on the order of tens of meters. While conventional satellite infrared window (IR; e.g., 11.0μm) and visible (VIS: e.g., 0.65μm) imagery techniques for identifying dust storms are useful in some cases, there are degrees of freedom not spanned by these observations which result either in ambiguity or missed features. These problems are germane particularly to the often laminar and highly reflective desert backgrounds, where detection of dust is as relevant to OEF operations as it is difficult.

The current research builds upon previous efforts to enhance dust-over-water by way of multi-spectral Sea-viewing Wide Field-of-view Sensor (SeaWiFS) data; it extends this capability to dust-over-land by virtue of the additional spatial and spectral information available from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument flying aboard the Earth Observing System (EOS) Terra and Aqua satellites. The method, which is composed of two separate algorithms for treatment of dust over water and over land, goes a step beyond previous VIS/IR methods in discriminating elevated dust from cloud features, and thin dust from bright backgrounds, by incorporating previously unavailable spectral information from MODIS. The technique leverages several principles of dust detection drawn from the literature in forming a unified product.

The primary advantage of this product is in its ability to distinguish dust from cloud over water and land through its use of multiple MODIS channels in the visible part of the spectrum. It is an extension to the algorithm first presented by Miller and Lee (2001), applied to SeaWiFS data (a method that was applicable exclusively over water bodies). The results are presented in a way that attempts to preserve the appearance of the enhancement across coastal (and algorithmic) interfaces. The new product remains applicable only to daytime imagery, and has its own collection of caveats that will be discussed. Examples shown in this paper attempt to highlight the strengths and point out the weaknesses of the new method.

2. BACKGROUND

2.1 *Physics of Detectability*

In examining the spectral absorption behavior for silicates (one of the primary constituents of desert dust), Patterson *et al.* (1977) find that they display an increasing imaginary part of the complex index of refraction (n_i) with

---

Corresponding author address: Steven D. Miller, Naval Research Laboratory, Monterey, CA 93943-5502;e-mail: miller@nrlmry.navy.mil

decreasing wavelength. Because n_i is proportional to particle absorption, this results in the colorization of dust (in contrast to clouds which do not display a marked change in n_i across the visible and hence appear to our eyes as gray or white). Simply stated, dust appears as shades of yellow due to preferential absorption of blue light. Provided sufficient channel resolution in the visible band of the spectrum, this property can be exploited to highlight dust over certain backgrounds.

An additional property of mineral dust that allows for its detection in the infrared is the positive split-window difference (defined here as 12.0 – 11.0µm) it produces in contrast to the negative differences observed for clouds such as cirrus (owing to relatively higher 11.0µm absorption by dust, resulting in reduced transmission of warm surface radiation and correspondingly depressed brightness temperatures). Dust emissivity differences among the infrared window channels have been exploited successfully by several researchers in the enhancement of dust, as outlined below.

2.2 *Methods of Detection*

Considering channels in the infrared part of the optical spectrum can provide more information about dust. Shenk and Curran (1974) and Lee (1989) both demonstrate ways in which dust storms may be enhanced over both land and ocean backgrounds by combining visible and infrared imagery. The methods involve visible channel brightness contrasts over water bodies, and depressed infrared window brightness temperatures produced of elevated dust against relatively warm land backgrounds. Because the gross signatures of clouds under these criteria are similar (and in fact stronger), an implied requirement for detection of dust by these methods is visual discrimination on the basis of structural differences (which may not always be obvious, especially for the case of thin cirrus clouds).

Ackerman (1989) examines the brightness temperature difference between 3.7 and 11.0µm as a method for monitoring dust outbreaks. Predicated on the enhanced absorption of dust at 11.0µm, the technique is found to work best for daytime observations although it is also shown to be applicable in a limited capacity at night. The split window difference technique has been used successfully to detect and track both dust and volcanic aerosols (e.g., Ackerman, 1997). The signature diminishes for optically thick dust (where transmission is minimized) and for dust at very low levels (where temperature contrasts between the surface and that of the bulk dust cloud may be lower). For elevated dust, however, this decrease in split window sensitivity is usually offset by an increase in thermal contrast between the dust and the underlying surface, as mentioned earlier.

Miller (2001) demonstrates with the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) one way to take advantage of these physics using multiple narrow-band channels in the visible spectrum to enhance dust. The enhancement replaces the red channel of the standard true color enhancement with a normalized difference between the reflective-infrared (865 nm) and blue (443 nm) channels, such that dust produces a large positive difference while clouds produce relatively smaller differences (having less spectral variability across this part of the spectrum). Depressing the cloud signal in the red color gun leaves them with a cyan appearance, while the enhanced dust component assumes shades of red and bright pink.

Other techniques include computation of the principle components (PC) of a collection of mulitspectral imagery, and the inference of dust based on reduction of feature contrast in high-resolution visible channels. Both methods are well suited for application to MODIS data. Hillger (2002) demonstrates the impressive ability of PC to identify dust and smoke plumes over complex terrestrial backgrounds. Interpretation of enhancements generated by this method are challenged by their changing appearance as a function of inherent spectral variability in the scene (something that can vary with domain size or changing weather situation). For this reason, PC techniques may ultimately be better suited for research applications rather than as the basis for an operational product. Contrast reduction (or “adjacency effects”) have been used successfully to detect dust over land from geostationary platform (e.g., Tanré and Legrand, 1991), although the method may face challenges over more laminar desert backgrounds (where contrasts are inherently smaller). It is likely that no single enhancement method, including the one currently proposed, will produce a consistently superior result over all different dust event scenarios. The current work is therefore not intended to supplant previous methods, but rather to innovate upon them with the new ability to distinguish dust from any clouds present in the scene.

The fundamental shortcoming with the method outlined above is that land bodies will also be enhanced in red tones since their spectral properties at visible wavelengths are of course the same as the airborne dust. In order to enhance dust over land, additional information from the beyond the visible, and into the infrared part of the spectrum, is required. For this reason, the SeaWiFS dust enhancement is applicable only over water bodies, and will also fail in sediment-laden waters, since SeaWiFS has only shortwave channels. Combining SeaWiFS with another platform that includes infrared measurements is limited almost exclusively to geostationary satellites whose spatial resolutions are considerably coarser and therefore less desirable for quality products. In the case of MODIS, all requisite channels are available on the same platform and at very high spatial resolution. For convenience, only MODIS examples are given here, with the understanding that the algorithm is extendable to multi-platform observations.

3. MODIS

3.1 *Instrument Capabilities*

The Moderate Resolution Imaging Spectroradiometer (MODIS; e.g., King *et al.*, 1992) instruments flying aboard the Earth Observing System (EOS) Terra and Aqua platforms offers 36 narrowband spectral channels between 0.4 to 14.4 μm. All infrared channels are available at 1km sub-satellite resolution, a selection of visible and shortwave infrared channels exist at native resolutions of either 500m (channels 3-7) or 250m resolutions (channels 1 and 2). Included in this suite of channels are spectral bands of particular relevance to enhancing dust. Those channels selected for the current enhancement are similar to of studies mentioned above, with the innovation being in the combining of these techniques together with unprecedented spatial resolution.

The EOS-Terra platform, launched into sun-synchronous orbit in December of 2001, provides a local equatorial crossing time of 1030 (on a descending node). Hence it is referred to as the “AM” component of the Aqua/Terra constellation. The Aqua platform, launched in May of 2002, provides a 1330 ascending node and assumes the “PM” component. Based on the diurnal cycles driving dust outbreaks in the Middle East (instability and frictional winds increasing throughout the day), it is anticipated that Aqua will observe a higher number of fresh dust outbreaks. Synoptic flow patterns, and particularly migratory baroclinic systems, also play significant roles in generating dust storms that are less dependent on time of day. Together with SeaWiFS, which provides a 1200 descending node, the Terra-SeaWiFS-Aqua trio will enable a limited looping capability. At a fixed location, exact crossing times for each satellite will vary according to latitude (e.g., higher latitudes receive higher frequency of overpasses) and orbit (e.g., early coverage on the western side of the swath, or later coverage on the eastern side of the swath). Procurement of these data in near real time has been a focal point of Navy Satellite METOC efforts since the onset of the current conflict.

3.2 *Data Source and Latency*

A topic of high relevance to Navy operations, in addition to obtaining high quality satellite observations, is the latency of these data. The expression “being inside the decision loop” is a metaphor often used in Navy operations to underscore the importance of contributing the right information at the right time. METOC guidance, however important, is only a single component of a greater decision protocol. If timely information cannot be supplied, missions may still be carried out, albeit at a greater risk to those involved. For these reasons, considerable efforts have been made to transition MODIS from research to operational charter in support of the Department of Defense and the ongoing war on terrorism.

The National Oceanographic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Admininistration have collaborated with the United States Navy and

Airforce in making the global EOS Terra and Aqua data available to several agencies of the DoD in near real-time. The multi-tiered arrangement, which involves hand shaking between numerous facilities, has recently been optimized to include two Tracking and Data Relay Satellite Systems (TDRSS) contacts per orbit for the Terra platform, and streaming of these data from White Sands, NM to the GSFC processing center. There, the data are processed and sent automatically to various DoD facilities either via the Shared Processing Network (SPN) or the Defense Research Engineering Network (DREN). Latency of EOS Terra data since establishing dual TDRSS contacts has been on the order of 2-4 hours—latencies that place the value-added products derived from these data to reach the warfighter within the required decision loop time windows.

The data consist of calibrated radiance and brightness temperatures (so-called “Level-1B” data) for the one-kilometer (1km), half-kilometer (hkm), and quarter-kilometer (qkm) spatial resolutions. These data are identical in format to what is available from the NASA Distributed Active Archive Center (DAAC; see http://daac.gsfc.nasa.gov). Each file is packaged as a 5-minute “granule” partitioned from the ~90-minute satellite orbit. A full orbit comprises about 14.4 Gigabytes of data

Until direct broadcast capabilities come online in the regions of conflict, the current arrangement for near real-time MODIS from NOAA/NASA is an invaluable stopgap solution that has already paid operational dividends during OEF. It is anticipated that the global near real-time capability will continue to be of high priority in the capacity of supplying on-demand regional coverage to data denied or data void locations, with the latter including applications to the monitoring of tropical cyclones. Software for automated client/server requests of granule coverage is currently in development.

3.3 *Channel Selection for the Dust Product*

The MODIS dust enhancement seeks to exploit both the spectral and spatial resolution capabilities of the instrument. While the 1km datasets include the higher resolution channels (pixels combined via weighted averaging to degrade them to a common resolution), the hkm and qkm channels are utilized in the algorithm whenever the domain size allows for it.

Listed in terms of (channel index; central wavelength; native spatial resolution; units) and in order of increasing wavelength, the dust product uses the following MODIS channels: (3; 469nm; 500m; W/m2-sr-µm), (4; 555nm; 500m; W/m2-sr-µm), (2; 853nm; 250m; W/m2-sr-µm), (26; 1.38µm; 1km; W/m2-sr-µm), (31; 11.0µm; 1km; Degrees Celsius), and (32, 12.0µm; 1km; Degrees Celsius). Details on to how (and why) these channels were combined to form the dust enhancement are given in the next section.

4. PROCEDURE

4.1 *Processing Flow*

The processing of MODIS data is triggered upon receipt of the Level-1B calibrated data file upon the NRL ftp server. First, this file is converted to TeraScan Data Format (the native format of the local satellite processing/display software) and then it is distributed automatically to a suite of processing scripts that includes the dust enhancement code. Upon completion of processing, the resultant products (usually converted to jpeg formatted imagery) are hosted to both password-protected Internet and secure Internet web page interfaces for immediate use by Navy METOC personnel.

4.2 *Two Backgrounds, Two Algorithms*

To optimize the dust detection capabilities of the current enhancement, the land and water backgrounds are treated differently. Dust over a dark background such as water (apart from the cases of shallow water with bright sand bottom or water laden with a heavy suspension of alluvial runoff or biological materials) is generally easier to detect, and so a method geared toward enhancing details of optically thin dust features are more tractable. The over-water algorithm is similar to that described by Miller and Lee (2001), with appropriate Rayleigh atmosphere corrections applied to the MODIS channels. Here, MODIS channels 3 and 4 imagery are loaded into the blue and green “color guns” and the red color gun is supplied the over-water dust enhancement (DE_W)—a normalized difference between the channel 2 (“reflective infrared”) and 3 (blue) reflectivities defined as:

$$DE_W = {R_2 - R_3}\big/{R_2 + R_3}, \qquad (1)$$

where reflectance (R) at wavelength (λ) is expressed in terms of channel radiance (I) as:

$$R_\lambda = {\pi I_\lambda}\big/{\mu_\circ F_\circ}, \qquad (2)$$

μ_o and F_o are the cosine of the solar zenith angle and band-weighted solar spectral flux, respectively. The simple idea of this approach is that in the visible part of the spectrum mineral dusts preferentially absorb blue light (hence scattering yellow-tones of light) whereas clouds exhibit so such marked preference (therefore appearing white). An instrument capable of splitting white light into red, green, and blue components can exploit this difference as in Equation (1). Here, dust produces a large positive difference compared to clouds. When this expression is loaded into the red color gun, dust features produce pink/red shades while clouds appear cyan. Normalization ensures that weak dust signals over dark surfaces are also enhanced.

The over-water enhancement has the undesireable effect of also enhancing the region of sunglint (near-specular reflection of the solar disk upon water surfaces) as dust. For this reason, an attempt to demarcate the region of potential sunglint has been included in the product, with a “glint zone” defined as any pixels whose solar/sensor geometries result in a glint angle less than 30 degrees. Because sunglint is actually a function of local windspeed and wave action, the actual zone of glint influence may be greater or less than the default region currently defined. In this glint region, MODIS Ch.2 data is substituted for the dust enhancement.

Over bright surfaces such as deserts, detection of dust is exceedingly more difficult, and requires additional spectral channels from the infrared to separate the dust signal from the other components of the scene. A land mask is used with the geolocated data to determine where to apply the over-land algorithm. The premise for the enhancement is threefold: i) elevated dust, having cooled to its environmental temperature, will produce a depressed brightness temperature against the hot skin temperature of the land background, ii) this cool layer of dust can be differentiated from a cloud having the same radiometric temperature based on its propensity for displaying larger values in the channel difference as defined in Equation (1), and iii) thin, elevated dust layers produce a positive 12.0-11.0μm difference as exemplified by Ackerman (1997). The blue and green color guns remain the same as the over-water algorithm, and the red color gun combines items (i)—(iii) to form the over-land dust enhancement (DE_L):

$$\begin{aligned} DE_L = {} & C_1(R_2 - R_3) + C_2(T_{32} - T_{31}) + \\ & C_3(1.0 - T_{31}) - C_4 I_{26}, \end{aligned} \qquad (3)$$

All components are scaled between limits determined experimentally (by statistical composites of a wide variety of dust storm case studies), and normalized. Weighting coefficients (C_1—C_4) determine the amount each component contributes to the overall enhancement. The Channel 26 scaled and normalized radiance (I_{26}; shortwave water vapor channel situated at 1.38μm) has also been introduced in an effort to further depress the signal from middle to upper-tropospheric clouds (usually cirrus) whose optical thicknesses are large enough to produce large temperature depressions (pertaining to C_3 term in Equation (3)) but remain optically thin enough to allow transmission of a component of the land signal (pertaining to C_1 term). The coefficients of Equation (3) are chosen such that upper tropospheric dust (usually optically thin and producing large 12.0-11.0μm differences) is dominated by the C_2 term. In this way dust remains enhanced at upper levels in spite of the mitigating C_4 component.

4.3 *Threshold Tuning*

Normalization of the various components in Equation (3) is done to combine quantities of differing units (what is sought is the relative strength of the dust signal in each component), and scaling is done so as not to change the appearance of the enhancement as function of spatial region considered. While this scaling provides a consistent appearance to the enhancement that is independent spatial scale, the compromise is that this may not be the optimal enhancement of dust from region to region and season to season. This point will be revisited in the discussion of caveats in Section 6.

5. EXAMPLES

This section presents several recent dust storm case studies captured by Terra MODIS. The high quality data provided by these and other true-color capable sensors are only beginning to reveal the frequency and pervasiveness of these storms on a global scale.

5.1 *Saharan Dust Case*

On May 7th, 2002, a Boeing 737 commercial aircraft operated by EgyptAir crashed on a hillside as its pilot attempted to make an emergency landing at an airstrip near Tunis, Tunisia. The accident, which began as a result of failed landing gear which forced a second approach, killed 18 of the 60 people on board. Weather in the area at the time was reported as foggy and rainy, with sand storms blowing into the area from the Saharan interior to the South.

The imagery shown in Figure 1was collected by Terra MODIS near the time of the EgyptAir crash. The top panel, a true color product created at 500m resolution, reveals the city of Tunis obscured by a squall line in advance of a baroclinic system centered over Algeria. An obvious cloud of dust is observed fanning into the Mediterannean Sea, escorted northward by the strong southerly winds associated with the storm system. Also evident, but less obvious, are indications of a diffuse cloud of dust over land to the West of the squall line.

The lower panel of Figure 1 is the corresponding MODIS dust enhancement. Areas of dust are highlighted as shades of pink. Evidence of the low level wind structure in the cloud-free regions of the baroclinic system are evidenced by the observable circulations of enhanced dust. Note that the enhancement cannot detect the presence of dust obscured by cloud (although dust-over-cloud will be detectable), and so for this example only an inference of the presence of dust near Tunis may be made based on its presence to the east and west of the squall line. These imagery were provided to cooperatives of the National Transportation Safety Board for assistance in their investigation of this accident.

5.2 *Middle Eastern Dust Case*

A second case of desert dust, highlighting the benefits of an over-land detection capability, is shown in Figure 2. The synoptic scenario responsible for this particular event was the passage of a baroclinic system to the north. Strong northerly winds associated with the advancing high pressure in the wake of this storm lifted copious dust from the deserts and dry lakebeds of Eastern Iran, Southern Afghanistan, and Pakistan. Strong “gap winds” near the shore (formed by the channeling of winds through coastal valleys) lifted additional dust as dense plumes, which are clearly visible in the top panel as they stream into the Northern Arabian Sea.

The lower panel of Figure 2 is the corresponding dust enhancement. The plumes that were obvious in the true color counterpart are again obvious here, now as shades of pink. However, the dust enhancement identifies several additional plumes residing over land that were entirely obscured by the bright topography. These plumes were difficult to detect in the infrared-only (Ch. 31) imagery, but were brought out most prominently by the Ch. 32 – Ch. 31 (split window) difference. In situations where plumes are optically thick, the opposite effect occurs and dust remains enhanced. Had there been any clouds in the scene, the dust would be differentiated according to the Ch. 2 – Ch. 3 difference from Equation (3). Figure 3 is another Middle Eastern dust event occurring in a region just to the northeast of the area shown in Figure 2 (with similar difficulties in dust detection using true color imagery alone). Mesoscale details in these plumes are apparent that give forecasters an idea of local flow patterns.

5.3 Analysis of Source Regions and Mesoscale Structure

A priori knowledge of the likely source regions for dust given certain environmental conditions can be an invaluable asset to improving their forecast. Researchers have begun examining the utility of the MODIS products in this capacity, with the understanding that temporal resolution is limited. Shown in Figure 4 are three instances of dust emanating from the same region during three consecutive months. The source for these plumes is a series of dry lakebeds in Southwestern Afghanistan. High winds channeled into the Margow Desert basin are responsible for this variety of dust outbreak on a regular basis, especially during the summer months. As suggested in the August image of the series, some of these storms can become intense and lead to vanishingly small visibilities near the surface.

6. INTERPRETIVE CONSIDERATIONS

The MODIS dust enhancement outlined in this paper is not without its interpretive pitfalls. Listed in no particular order are the following considerations:

1) Elevated, cold topography may appear “enhanced” due to the similar visible-channel properties of dust combined with the strong inverted infrared contribution (See Eq. (3)).
2) Dry lakebeds that go undetected by the land/sea database will be enhanced as dust, since the inappropriate (over-water) algorithm is being applied here. Often these lakebeds act as sources for dust (e.g., Fig. 4).
3) The region demarcated as sunglint is specified at a fixed glint angle, when in fact the true region of glint influence is a function of sea surface state. No account for surface wind speeds that would allow for a dynamic glint zone are made in the current product.
4) Very low and optically thick dust over land (producing a small split window difference and small inverted-infrared signature) may go undetected
5) The fixed scaling of components in Equation 3 leads to a standardized enhancement at the expense of case-by-case optimization.
6) Dust on the edge of the satellite swath will exhibit a stronger enhancement than the same dust near satellite nadir. This is due to the optical path through the dust being longer at higher sensor scan angles.

7. CONCLUSION

A new method for identifying dust over water and land backgrounds has been developed for use with multispectral satellite imagery. Concepts from the literature are combined with new spectral and spatial resolution capabilities available from the MODIS sensors aboard EOS Terra and Aqua to enhance dust as shades of pink while clouds become cyan. The method is composed of two algorithms (land & water) and has been tuned to maintain a similar appearance for the enhanced dust. Navy assets have used products generated from near real time MODIS data, and preliminary feedback has been overwhelmingly positive.

Future modifications to the product include replacement of the sunglint zone with and infrared-only technique, and attempt a dynamic specification of this glint zone based on a model surface wind field. The additional infrared channels available on MODIS will be explored to determine whether innovations to current nighttime dust enhancement techniques can be made. To the maximum extent possible, maintenance of the same look and feel for such an enhancement would be desirable from the standpoint of minimization the requisite training for potential users.

8. REFERENCES

Ackerman, S. A., 1997: Remote sensing aerosols using satellite infrared observations. J. Geophys. Res. 102, 17069—17079.

Cantu, R., 2001: The role of weather in major naval aviation mishaps FY90-98, M.S. Thesis, Naval Postgraduate School, Monterey, CA, 106pp.

Hillger, D. W., and G. P. Ellrod, 2002: Detection of important atmospheric and surface features by employing principle component image transformation of GOES imagery. *J. Appl. Meteorol.*, In press.

King, M. D., Y. J. Kaufman, W. P. Menzel, and D. Tanre, 1997: Remote sensing of cloud, aerosol and water vapor properties from the moderate resolution imaging sptrometer (MODIS). *IEEE Trans. Geoscience and Remote Sensing*, **30** 2—26.

Miller, S. D., and T. F. Lee, 2001: Desert dust storms as detected by Meteosat and SeaWiFS multispectral imagery.

Proceedings of the 11th Conference On Satellite Meteorology, AMS, 43—46.

Lee, T. F., 1989: Dust tracking using composite visible/IR images: a case study. *Wea. Forecasting*, **4**, 258—262.

Patterson, E. M., D. A. Gillette, and B. H. Stockton, 1977: Complex index of refraction between 300 and 700 nm for Saharan aerosols. J. Geophys. Res., **82**, 3153—3160.

Shenk, W. E., and R. J. Curran, 1974: The detection of dust storms over land and water with satellite visible and infrared measurements. *Mon. Wea. Rev.*, **102**, 830—837.

Tanré, D., and M. Legrand, 1991: On the satellite retrieval of Saharan dust optical thickness over land: two different approaches. *J. Geophys. Res*., **96**, 5221—5227.

9. ACKNOWLEDGEMENTS

The support of the research sponsor, the Oceanographer of the Navy through the program office Space and Naval Warfare Systems Command, PMW-155, under program element 0603207N is gratefully acknowledged.

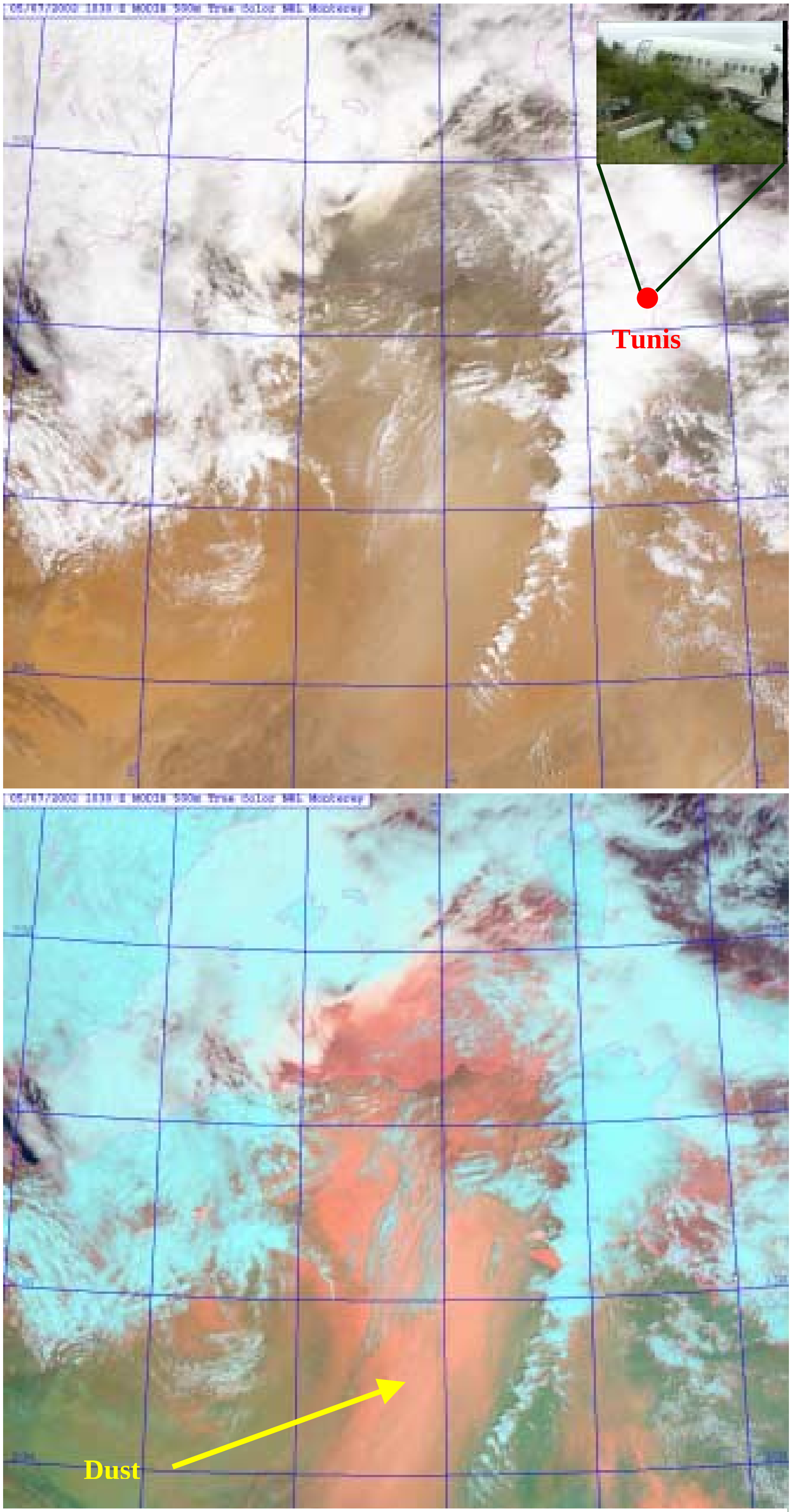

Figure 1. True color (top) and dust enhancement (bottom) imagery from Terra-MODIS corresponding to the EgyptAir Boeing 737 crash on May 7, 2002. Dust enhanced as pink.

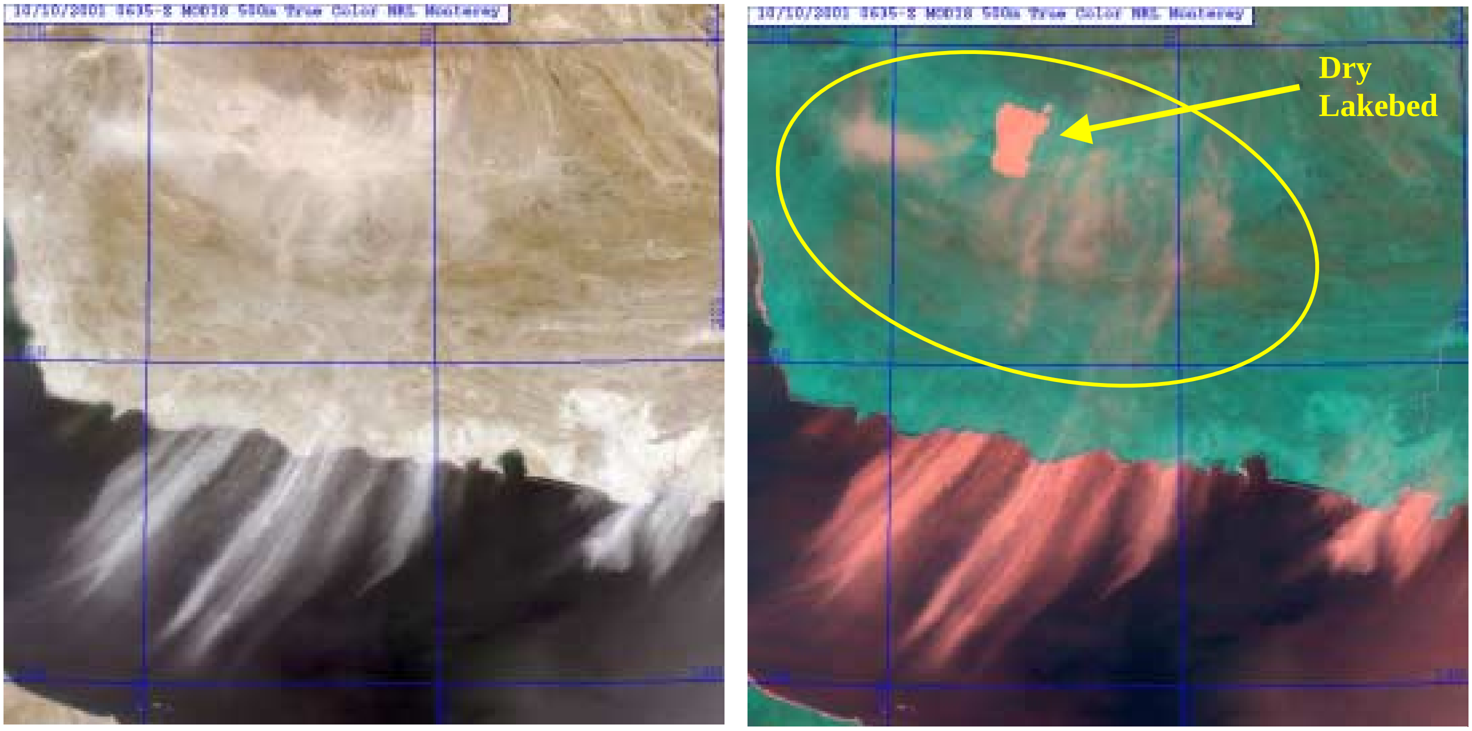

Figure 2. New information about dust coverage over land is revealed in the dust enhancement. Refer to text for discussion of dry lakebeds. Visibilities within some of the plumes offshore were less than 1 nautical mile.

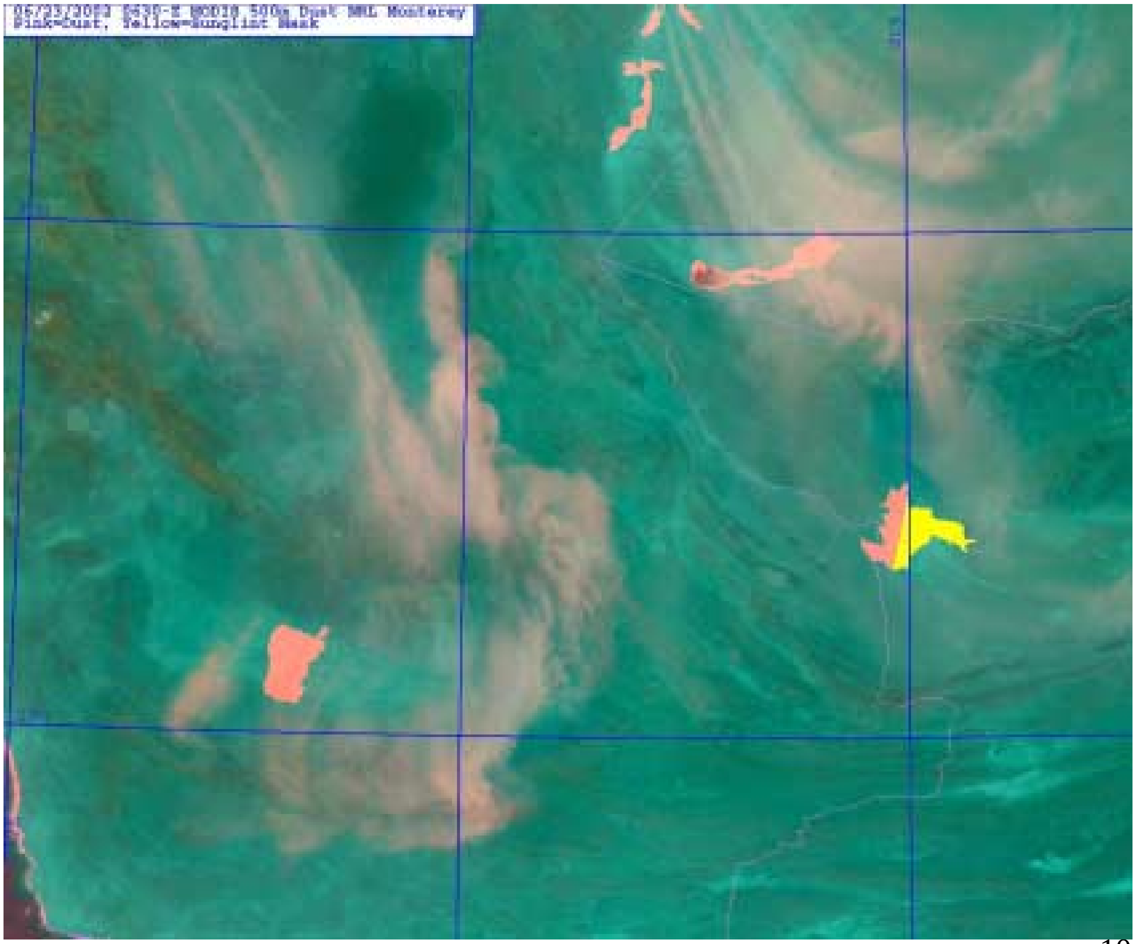

Figure 3. Example of fine detail information available from dust-over-land product.

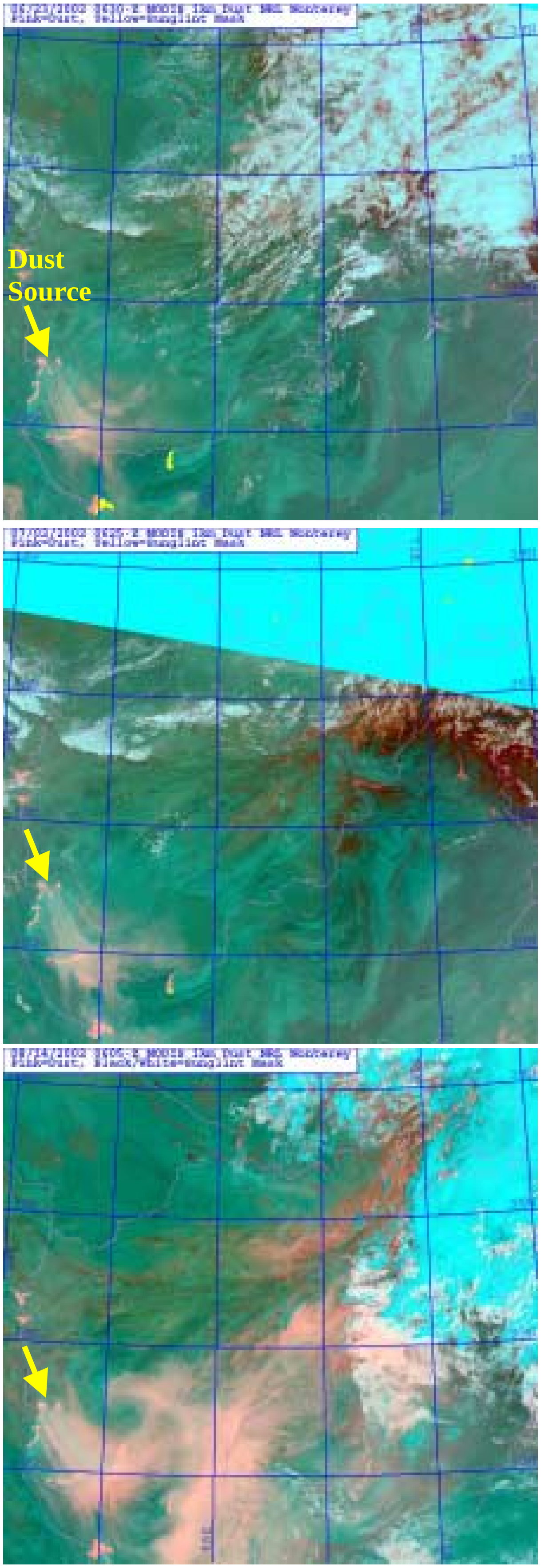

Figure 4. A series of images over a 3-month period illustrating the potential of the current product to identify persistent sources of dust. In this case, dry lakebeds in the Southwest portion of Afghanistan combine with northerly winds to produce dust.