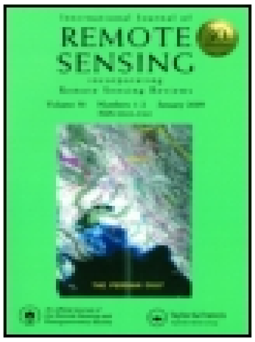

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Research Article

MODIS provides a satellite focus on Operation Iraqi Freedom

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Extreme weather conditions over southwest Asia posed significant challenges to military operations conducted during the 2003 Operation Iraqi Freedom (OIF) campaign. This paper describes an effort to provide improved environmental characterization by way of a suite of value-added satellite imagery tools leveraging moderate resolution imaging spectroradiometer (MODIS) data. Available from the National Aeronautics and Space Administration (NASA) Terra and Aqua platforms, these research-grade data were made available to operational users in 2 to 3 hours turn-around time via a near real-time processing effort (NRTPE) interagency collaboration between the National Oceanographic and Atmospheric Administration (NOAA), NASA, and the Department of Defense (DoD). Derived products were packaged into a centralized online graphical user interface, Satellite Focus, which provided a one-stop resource for satellite information over the southwest Asia domain. A central goal of Satellite Focus was to expedite information gathering while augmenting the capabilities of users tasked to synthesize a wide variety of environmental information in support of time-critical decisions impacting operational safety and mission success. Presented herein are several examples illustrating the unprecedented capabilities available to Coalition Force users during OIF enabled by near real-time access to Terra/Aqua MODIS.

1. Introduction

Geostationary and polar-orbiting satellite observing systems provide a unique and valuable source of global knowledge pertaining to atmospheric and terrestrial environmental conditions, particularly in areas where in situ information is unavailable. The space platform is of particular value to military operations conducted in data-sparse or access-denied regions of the world. With the rapid evolution toward very high spatial/spectral resolution capabilities of next-generation

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satellite sensors, and their associated high data rates/volumes, the hardware and computational overhead required for remotely deployed users to process data in the field is becoming increasingly prohibitive.

One solution to this problem is the 'reach-back' concept, whereby remote users may connect to centralized sites that synthesize large volumes of data into compact, salient information. The concept implies an end-to-end system capable of (1) gaining rapid access to all available satellite data, (2) quickly deriving useful applications, and (3) effectively distributing/communicating the results to remote users, e.g. via Internet protocols. Military weather analysts require environmental information that is timely, intuitive, pertinent to mission objectives, and easily accessed. Successful products tailored to this user must minimize interpretation time while maximizing information content. Through multi-spectral, multi-sensor, and model-fusion algorithms designed to exploit the underlying physics and isolate specific parameters of interest, large amounts of information from a potentially complex scene must be converted into a few readily interpretable applications. The 'Satellite Focus' effort described herein was developed by the Naval Research Laboratory as an attempt to accomplish the reach-back task within the scope of its research and development framework.

Stephens and Matson (1993) detail the use of National Oceanic and Atmospheric Administration (NOAA) advanced very high resolution radiometer (AVHRR) (from the operational Polar Orbiting Environmental Satellite (POES) system) data in observing from space some aspects of the 1991 Persian Gulf War. The current work provides an analogous application for the 2003 Operation Iraqi Freedom (OIF) conflict, based on new and improved research-grade satellite data from the moderate-resolution imaging spectroradiometer (MODIS, King *et al.* 1992) carried aboard the National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) program. MODIS is regarded as a heritage sensor to the future visible/infrared imaging radiometer suite (VIIRS) instrument to fly aboard the National Polar-orbiting Operational Environmental Satellite System (NPOESS) in ~2010. This paper describes the Satellite Focus system in terms of MODIS data acquisition, value-added application development, automated processing, and end-product distribution, used in the context of operational weather support to coalition forces during OIF.

2. MODIS data acquisition

The MODIS instruments carried aboard EOS Terra (1030 local equatorial crossing, descending node) and Aqua (1330 local equatorial crossing, ascending node) satellites offer high spatial resolution, multi-spectral observations and onboard calibration. MODIS features 36 narrow-band channels within in the optical (0.4–14 micrometer wavelength) part of the electromagnetic spectrum of high value in characterization of the surface and atmosphere. MODIS spatial resolutions range from 1000 m (infrared bands 8 to 36) and 500 m (visible bands 3 to 7) to as high as 250 m (red and reflective infrared, bands 1 to 2).

A growing list of universities (e.g. University of Wisconsin-Madison, University of Miami, Oregon State University) and research organizations (e.g. Goddard Space Flight Center (GSFC) and the United States Geological Survey (USGS) Earth Resources Observation & Science (EROS)) are making their direct broadcast capture of MODIS available online, and the Space, Science, and Engineering Center (SSEC; located at University of Wisconsin-Madison) has spearheaded the effort to augment direct broadcast capabilities worldwide via the International MODIS/AIRS Processing Package (IMAPP; e.g. Strabala *et al.* 2003). Prior to the events of 11 September 2001, however, no conduit or protocols existed to provide global observations from MODIS (a research satellite) to operational processing facilities in near real-time. It was the sudden need for improved observational capabilities in support of responding forces in the Middle East that catalysed the near real time processing effort (NRTPE; e.g. Haggerty *et al.* (2003)). Co-ordinated between NOAA, NASA, and the DoD, the NRTPE was designed to enable turn-around of calibrated MODIS data in a timeframe relevant to operational users. Figure 1 depicts the flow of the MODIS data stream through the NRTPE framework—from raw sensor (rate-buffered) data to calibrated Level-1B radiances/brightness-temperature sensor data records (SDRs). For the Terra-MODIS telemetry, downlink contacts with the Tracking and Data Relay Satellite System (TDRSS; a geostationary-based communications satellite constellation) were increased from once to twice-per-orbit. In the ground-processing segment, software upgrades, dedicated hardware acquisition, and installation of optical fibre communication lines resulted in significant latency reductions. Aqua (which does not have TDRSS connectivity) data were down-linked to Svalbard, Norway, once per orbit and followed a subsequent processing flow similar to Terra. During the active military phase of OIF, average Terra/Aqua global data latencies were less than 3 hours—a vast improvement in comparison to pre-NRTPE MODIS latencies of 1–2 weeks.

3. The Satellite Focus system

To handle the computational burden of processing high volumes of data (totalling approximately 50 gigabytes/day for the southwest Asia domain alone), a multi-processor portable batch system (PBS) queuing architecture with an onboard 300 GB raid storage system was implemented. The PBS operates as a load-balanced cluster, wherein jobs are distributed and processed in a serial fashion across any of the available free or lowest-tasked nodes (each having dual 2.8 GHz processors with 4 GB memory cards). Local storage of the large satellite datasets (a single MODIS 5-minute daytime granule set containing all 36 spectral channels at native

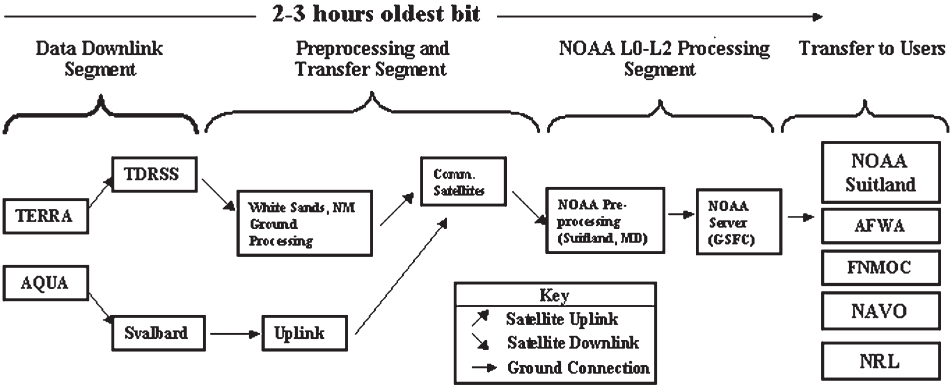

Figure 1. Schematic flowchart describing the transmission and preprocessing of Terra/Aqua MODIS digital data to operational centres via the near real-time processing effort.

resolutions is on the order of 1 GigaByte) minimizes data transfer delays, and the system is self-contained to minimize network file system (NFS) mounting and maximize system stability. Mirrored system discs and a dual power supply provide additional fail-safes. The system is fully scalable, accepting additional processing nodes as computational demands increase.

Upon receipt of new data (e.g. a 5-minute MODIS 'granule'), a series of pre-processing steps performs quality checks, converts the data into standard formats and units, and removes sensor artefacts (e.g. a de-striping correction applied to MODIS thermal infrared and 1.38 μm channels using software developed by SSEC, following the empirical distribution function normalization method described by Weinreb *et al*. 1989). Then, a series of science algorithms (examples provided below) convert the digital data into a suite of value-added products mapped to common earth projections over specific areas of interest (e.g. based on user requests). Finally, these products are transferred to the globally deployable Satellite Focus web page interface for immediate user access.

To accommodate requirements for information at a variety of spatial scales, Satellite Focus adopts a hierarchical data storage structure (figure 2). In the top three levels of this structure, Earth is partitioned into a set of nested domains, enabling users to zoom into any available area while observing environmental conditions on a variety of scales. The product-centric design appeals to users who are interested primarily in the information itself as opposed to the means used to obtain it (i.e. several independent observing systems may be capable of rendering the same product). Dotted lines in figure 2 denote pattern continuity, implying that an

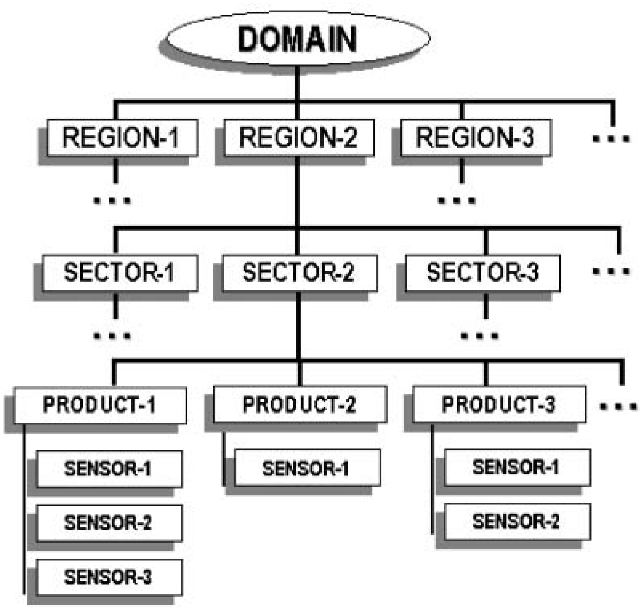

Figure 2. The general architecture of product storage on Satellite Focus, wherein Earth is partitioned into an arbitrary number of nested domains containing co-registered products produced from a variable collection of satellite observing systems.

arbitrary number of domains (of arbitrary spatial scale) containing any number of products and sensors may contribute to those general product categories.

Satellite Focus operates at the interface between research, application development, and operations—providing a previously unavailable conduit between cutting-edge satellite products and operational users far in advance of conventional technology-transfer time frames. While this is a potentially powerful system for communicating information in the net-centric environment, it is only as useful as the clarity of materials being presented. Due to the broad scope of backgrounds and levels of expertise held by military users, and particularly in light of the novelty of many of the products being shown, information displayed on Satellite Focus needed to be communicated in as simple, direct, and comprehensive terms as possible. To this end, online tutorials explaining the purpose, utility, and limitation of each satellite application presented were included on the website. The tutorials, written at a sufficiently high level to ensure comprehension by laypersons and experts alike, included multiple examples taken from the specific geographic areas of relevance. These built-in user guides, including tutorials for how to navigate the page itself, were intended to provide users of Satellite Focus with the basic familiarity and proficiency necessary to integrate with confidence the new satellite products as part of their standard operating procedures.

4. Selected applications from OIF

The high spatial and spectral resolution MODIS data provide superior capabilities to contemporary operational radiometers in characterizing the diverse and often complex southwest Asian environment. The following examples illustrate a subset of MODIS capabilities in the context of weather events observed during the OIF campaign.

4.1 *True colour*

To novice interpreters of satellite imagery, making sense of a complicated Earth/atmosphere scene using grey-scale or false colour imagery can be a very difficult task. True colour imagery (depicting the scene in a similar fashion to a colour photograph) allows users to make sophisticated interpretations of meteorological phenomena with relatively little training. True colour imagery is created by combining atmospherically corrected (subtraction of the molecular atmosphere signal as a function of solar/sensor geometry, as provided here from radiative transfer simulations) narrowband red, green, and blue light information (from MODIS bands 1, 4, and 3, respectively) into a signal that approximates how human vision would perceive the same scene. The resultant imagery portrays blue oceans, brown soils, tan deserts, white clouds, green vegetation, grey smoke (or black, in the case of oil fires). Figure 3 demonstrates these high spatial resolution true colour capabilities over Iraq. In figure 3A, dark smoke plumes (designated by yellow arrows) over the city of Baghdad are more clearly delineated from other dark features of the scene (e.g. vegetation). In figure 3B a dust front passes over the northern Arabian Gulf, while shallow/turbid water near the coast and river outlets produces a cyan/green appearance. It is readily apparent in this example how true colour facilitates the distinction of land properties, ocean turbidity features, and cloud/dust discrimination over water. Readers interested in viewing additional high-quality true colour examples from MODIS are encouraged to visit the GSFC MODIS Rapid Response System (http://rapidfire.sci.gsfc.nasa.gov).

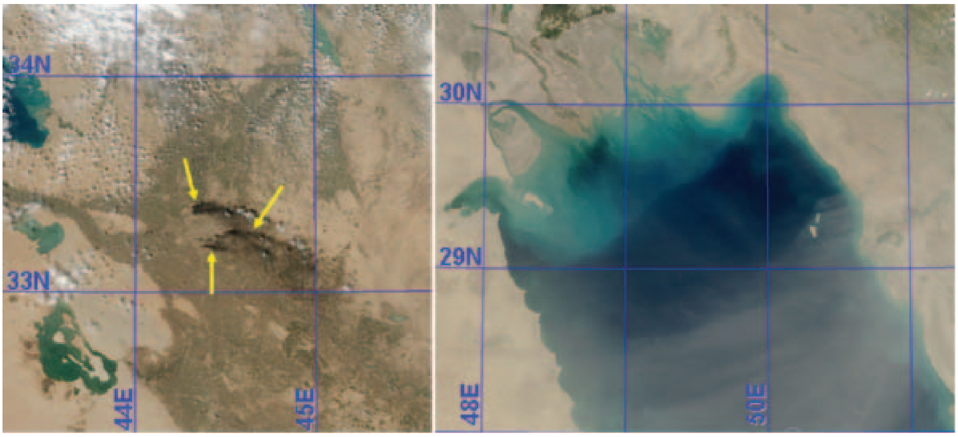

Figure 3. MODIS 250 m true colour examples revealing black smoke plumes (yellow arrows) over Baghdad (left, 27 March 2003, 1000 UTC) and tan dust plume over the northern Arabian Gulf (right, 17 April 2003, 1015 UTC).

4.2 *Desert dust storms*

Beyond simple enhancements such as true colour, Miller (2003) demonstrates the capability of MODIS to distinguish airborne dust from the surface and other atmospheric features, resulting in a revised enhancement useful in observing and tracking the dust storms frequent to southwest Asia. The algorithm takes advantage of several well-established physical principles of dust detection, providing reflectance contrast in visible and near infrared, and thermal contrasts in infrared. The enhancement is created by replacing the red channel of the true colour composite with a multispectral term derived from seven channels from the visible, shortwave and thermal infrared spectrum. Assigning dust regions a bright orange/pink tonality in contrast to cyan clouds and dark green land, the enhancement applies to significant dust concentrations (having visible optical depths greater than about 0.5, or corresponding roughly to horizontal visibility below 6 km when assuming a 1 km thick dust layer) over both land and water backgrounds. An example of this application is shown in figure 4, compared with the corresponding true colour rendition to demonstrate the conventional over-land detection challenges. The intent of the dust product was to provide a quick-look of the dust-obscured portions of the scene, particularly in moderate-to-heavy dust conditions over smooth desert backgrounds. When available, low-level winds from numerical weather prediction models were overlaid to provide a superior nowcasting tool for dust location and short-term advection.

4.3 *Aircraft contrails*

Aircraft condensation trails (contrails; e.g. Minnis *et al.* 2004) form when warm, moist jet exhaust mixes with the cold and dry upper troposphere environment. Depending on the upper tropospheric humidity (UTH), contrails may either dissipate rapidly or persist and spread over time (forming extensive cirrus shields). Contrails are of special interest to military analysts from the standpoint of air traffic monitoring and conducting flight operations. Several papers (e.g. Lee 1989 and Weis *et al.* 1998) illustrate the ability to detect contrails from space, based on the

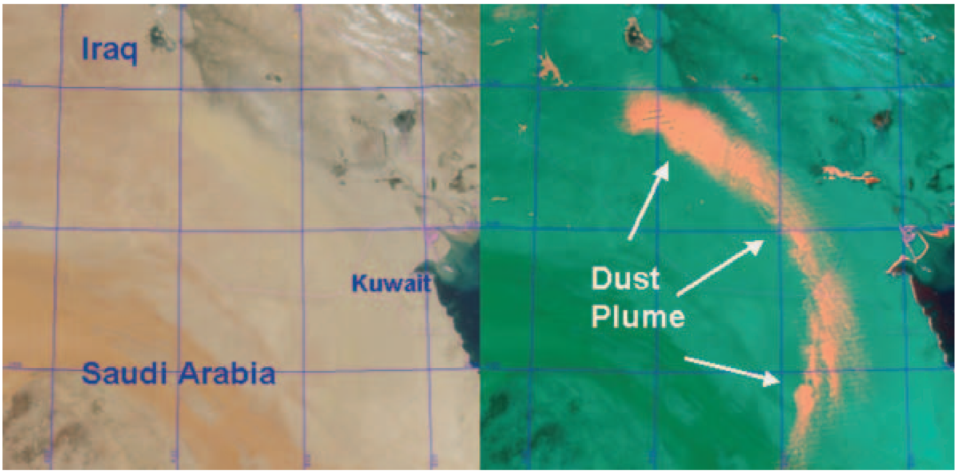

Figure 4. MODIS dust enhancement (right) reveals dust plumes over land difficult-to-detect using true colour or conventional imagery (left). Data collected on 10 June 2003 at 1010 UTC, and latitude/longitude grid spacing is 2°.

'split-window' 11.0–12.0 μm brightness temperature difference (e.g. Inuoe 1985) available from existing operational platforms such as the Geostationary Operational Environmental Satellites (GOES), Meteosat-8, and the advanced very high resolution radiometers (AVHRR). The MODIS contrail enhancement, shown in figure 5, combines the split window method with a cloud phase detection technique (8.5–12 μm difference, e.g. Strabala *et al.* 1994). Since contrails are subject to drift and wind shear, their appearance at any single point in time may be displaced and distorted with respect to the actual aircraft flight trajectories.

4.4 *Convective cloud top heights*

Strong convection poses many hazards particularly to flight operations (e.g. high winds and wind sheer, clear icing conditions, lightning, and hail), and cloud top

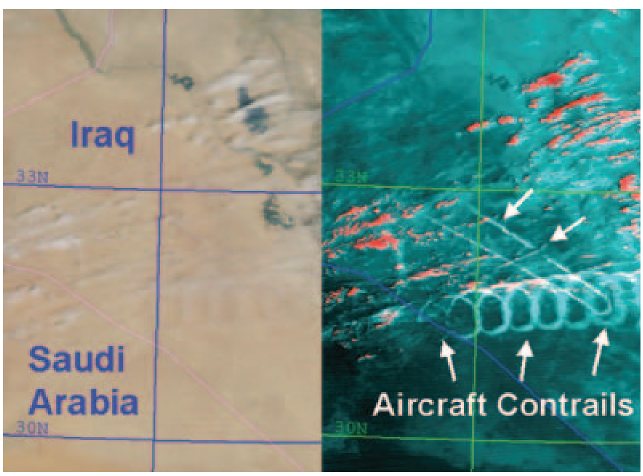

Figure 5. MODIS contrail detection (right) reveals the flight patterns of aircraft over Iraq that are otherwise poorly defined within the true colour example (left).

altitude is a useful metric for assessing the maturity and severity of these storms. We constructed a convective cloud top product through the combination of infrared window (11.0 μm) information with modelled (NOGAPS/COAMPS®) temperature profiles. Retrievals of cloud top height are valid only for opaque clouds, such that infrared brightness temperatures are assumed to be representative of the cloud top temperature. To isolate deep convection in the retrieval, we enlist a convective diagnostic outlined by Schmetz *et al.* (1997), based on a threshold difference between the 6.7 μm (water vapour absorbing) and 11.0 μm (infrared window) channels. As shown in Turk and Miller (2005), small differences of this quantity imply the presence of optically thick clouds in the upper troposphere. To conform to the convention of pilots, retrieved heights were converted to equivalent altimeter readings (i.e. pressure altitudes) for convective tops. Figure 6 demonstrates the convective cloud top heights retrieved from a line of thunderstorms entering the Arabian Gulf, revealing details of the cloud-top structure. Half-hourly resolution loops were available at reduced spatial resolution (4 km) from Metoesat-5. Aircraft carriers deployed in this region used these convection products to navigate ships safely away from the deepest cells during aircraft launch and recovery.

4.5 *Fires*

Prins *et al.* (1998) and Kaufman *et al.* (1998) demonstrate the utility of the 4.0 μm band (available from MODIS, GOES, and AVHRR) in the detection of fires. Combining 4.0 and 11.0 μm data (e.g. to avoid misclassification of cloud edges as hot-spots during the day) we produced a graphic revealing small burning/smouldering features within the scene, even in the presence of clouds or smoke.

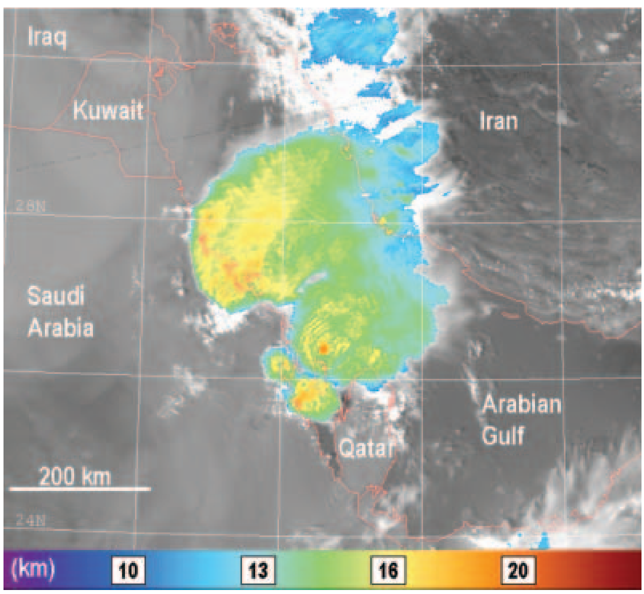

Figure 6. Squall line thunderstorms enter the northern Arabian Gulf in advance of a strong dust front (left) on 16 April 2003 at 09.35 UTC. Yellow/red line delineates a sun glint zone over the water (where the MODIS dust enhancement cannot be applied). Retrieved cloud top heights (right) associated with the deepest storm tops exceeding 18 km. Imagery is from 16 April 2003 at 0935 UTC, and latitude/longitude grid spacing is 2°.

The non-linear spectral response of blackbody radiation for different emission temperatures results in the 4.0 μm atmospheric window offering exceedingly higher sensitivity to hot sources (even when present only at sub-pixel scales) compared to the infrared window band at $\sim$11.0 μm. As a result, fires that are very small compared to the detector footprint, such as gas flares (on the scale of several metres) in southern Iraq, can readily be detected in the 1 km imagery (figure 7). NWP wind fields were overlaid upon these fire products to enable short-term prediction of smoke transport. During OIF, these products assisted analysts in monitoring the oil fields of southern Iraq for possible environmental sabotage (similar to what occurred during the 1991 Gulf War, e.g. as depicted by Stephens and Matson 1993). Global fire products from MODIS, also available to the public in near real-time via the aforementioned GSFC Rapid Response website's 'Rapid Fire' application (e.g. Justice *et al.* 2002 and Justice *et al.* 2003), are being used by a number of agencies including the United Nations Global Fire Monitoring Centre (GFMC) for monitoring, planning, and disaster mitigation.

5. User impacts

During the early phase of OIF a strong low-pressure system moved across Iraq. The storm crossed the region over a three-day period spanning 25–27 March 2003. As a powerful squall line entered the Persian Gulf, northwesterly winds lifted heavy post-frontal dust throughout Iraq, bringing operations to a virtual standstill. In southern Iraq, US ground forces advancing toward Baghdad had no choice but to wait out the storm under conditions of near-zero visibility. Figure 8 chronicles, over a three-day period (25–27 May 2003), the passage of the dust storm across Iraq as depicted by MODIS products hosted on Satellite Focus. In addition to the extensive dust plume, some false dust enhancements are seen to occur over Iran (far right side of image), arising from wintertime cold-land effects as described by Miller (2003). Here, the online training modules included on Satellite Focus point out the

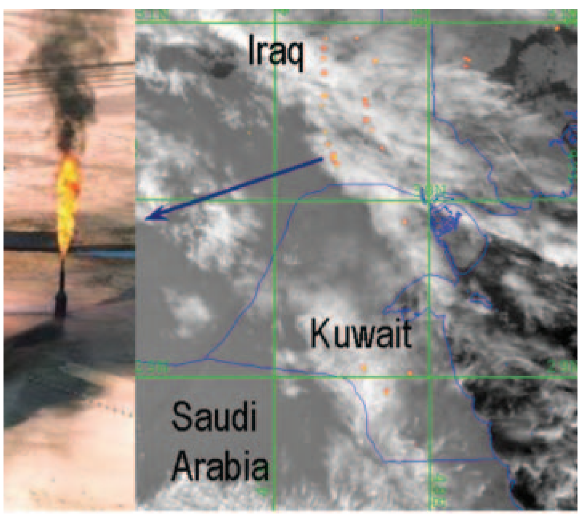

Figure 7. Fire detection showing hot spots (red/yellow points) from gas flares over southern Iraq and Kuwait whose emissions are detectable even beneath thin clouds (white). Photo inset indicates the spatial scale of the gas flare point sources responsible for the satellite-detected heat signatures. Latitude/longitude grid spacing is 1°.

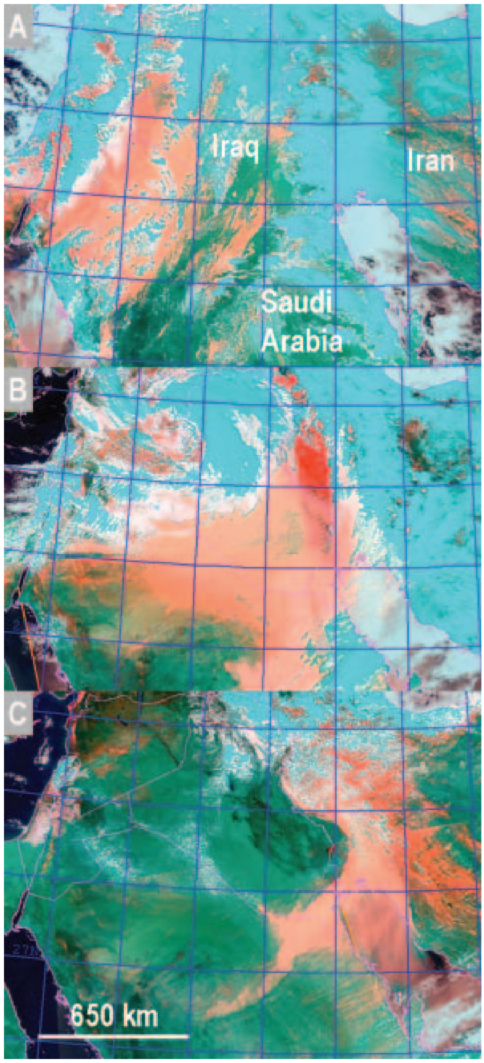

Figure 8. A powerful storm system crosses the southwest Asia domain from West to East over the period 25–27 May 2003, as viewed by MODIS Terra/Aqua true colour (left) and dust enhancement (right). Regions of heavy dust are depicted in pink.

capabilities and limitations of the dust products, providing users with the background necessary to distinguish actual dust features from common false alarms.

At the onset of this intense weather, crews aboard several US naval vessels deployed in the Arabian Gulf struggled to avoid thunderstorms crossing the Arabian Gulf while attempting to recover their aircraft in advance of the dust front:

> Navy ships are taking over all operations in support of ground troops. The Air Force has stopped operations. All ships are receiving aircraft from others as well. We are currently using the [Satellite Focus] products to determine the Abe's track to safely support the mission.
>
> *USS Abraham Lincoln* (CVN-72)

Post-deployment reports from these ships cited reduced visibility dust storms as the most significant and persistent challenge encountered throughout the southwest Asia domain during OIF. By no coincidence, the MODIS dust products were among the most widely used for a variety of applications:

> The dust product was invaluable—we were able to track the progression of dust through southern Iraq and Kuwait. […] We used model data in conjunction with the dust product to nail down the forecast in regards to the possibility of dust being advected to the [aircraft carrier].
>
> *USS Nimitz* (CVN-68)

Here, Satellite Focus MODIS dust products served to reduce the risk of aviation mishaps and potential collateral damage associated with visibility reductions. In the post-OIF era, near real-time MODIS continues to support an operational need for a wide range of applications ranging from ocean colour and global fire detection, to previewing the capabilities of NPOESS/VIIRS on the NexSat web page (Miller *et al.* 2005, www.nrlmry.navy.mil/NEXSAT.html) through real time MODIS imagery examples and supporting online tutorials.

6. Summary

Through collaboration between NASA, NOAA, NRL, FNMOC, and AFWA, multiple satellite datasets, including those of research-grade sensors such as Terra/Aqua MODIS were combined into a consolidated source for environmental products during Operation Iraqi Freedom. The resulting Satellite Focus application enables rapid production of value-added satellite products in near real-time. New satellite technologies emerging over the next decade (e.g. NPOESS), combined with an ever-growing expertise in these sensors, promise to broaden the scope of satellite applications. Through its ability to rapidly and dynamically field a large array of satellite-derived environmental information anywhere in the world from a central processing source, the end-to-end Satellite Focus system will continue to evolve in conjunction with the increasing reach-back requirements of its users.

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