True Color Earth Data Set Includes Seasonal Dynamics

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Space exploration has changed our visual perception of planet Earth. In the 1950s, satellites revolutionized weather forecasting. Astronaut photography in the early 1970s showed us the Earth in color, the so-called 'Blue Marble' (Figure 1, left). Since 1972, satellite sensors have been acquiring atmosphere, land, ice, and ocean data with increasing spectral and spatial resolution. Satellite remote sensing systems such as the NASA Earth Observing System (EOS) help us to understand and monitor Earth's physical, chemical, and biological processes [*Running et al.,* 1999].

The false-color Earth image shown in the center of Figure 1, named Blue Marble, was created in 2000 with data from the Advanced Very High Resolution Radiometer (AVHRR), the Geostationary Operational Environmental Satellite (GOES 8), and the Sea-viewing Wide Field-of-view Sensor (SeaWiFS). New sensors such as the Moderate-Resolution Imaging Spectroradiometer (MODIS), aboard NASA Terra and Aqua satellites, allow the derivation of a wide range of geophysical parameters from measured radiances of a single sensor.

By R. Stöckli, E. Vermote, N. Saleous, R. Simmon, and D. Herring

While false-color visualizations are artificially colorized from single- or multispectral data, true-color images are based on data which closely reflect the full spectral range of our visual perception: things in true-color images appear the way we would see them. In 2002, the authors of this article created the true-color Earth image on the right side of Figure 1. This image consists of separate layers created from the underlying MODIS land, ocean, sea ice, and atmosphere science products. Both (2000 and 2002) Blue Marble images have been widely used in museums, print media, and television documentaries, by mapping agencies, and in NASA's public communications about its missions and research initiatives.

The wide public use of the Blue Marble imagery motivated the authors to continue the project. The Blue Marble: Next Generation (BMNG) is a true-color and normalized difference vegetation index (NDVI) data set that displays land surface state at 500-meter spatial resolution and monthly temporal resolution. The BMNG was created using Terra MODIS science data collected in 2004; cloud disturbances were removed with a discrete Fourier technique.

Whereas cloud-free Earth imagery is commercially available, the BMNG aims to provide freely available imagery as a product complementary to the standard MODIS science datasets. Although the spatial resolution of the BMNG true color data is comparable to other data sets, seasonal variations have not been shown before in seamless true-color composites. Visualizations of snowfall, droughts, wet seasons, spring greening, and so forth, can be applied in formal and informal education. Visual perception of Earth system dynamics can foster interest to further explore the underlying science. Furthermore, the BMNG can help to increase public understanding (and therefore acceptance) of satellite missions and awareness of causes and effects of changes in Earth's climate system.

How to Create Cloud-Free Global Imagery

Seamless cloud-free spatial and temporal compositing of the Earth's surface is not a trivial task. It is dependent on sophisticated atmospheric corrections (e.g., water vapor, ozone, and aerosol absorption and scattering [*Vermote et al.,* 1997]) and cloud screening. Even then, cloudy pixels and remote sensing artifacts such as heavy dust and smoke, calibration errors, and illumination conditions [*Los et al.,* 2000] can disturb satellite data. Temporal compositing can be used to remove such irregularities.

For the BMNG data set, a temporal adjustment based on second- and third-order discrete Fourier series was used. This method is

Fig. 1. *Earth views: (left) Apollo 17 astronaut photograph (1972); (center) Blue Marble false-color composite (2000), see http://rsd.gsfc.nasa.gov/rsd/bluemarble/; (right) MODIS Blue Marble true-color composite (2002), see http://earthobservatory.nasa.gov/Newsroom/BlueMarble/BlueMarble_2002.html*

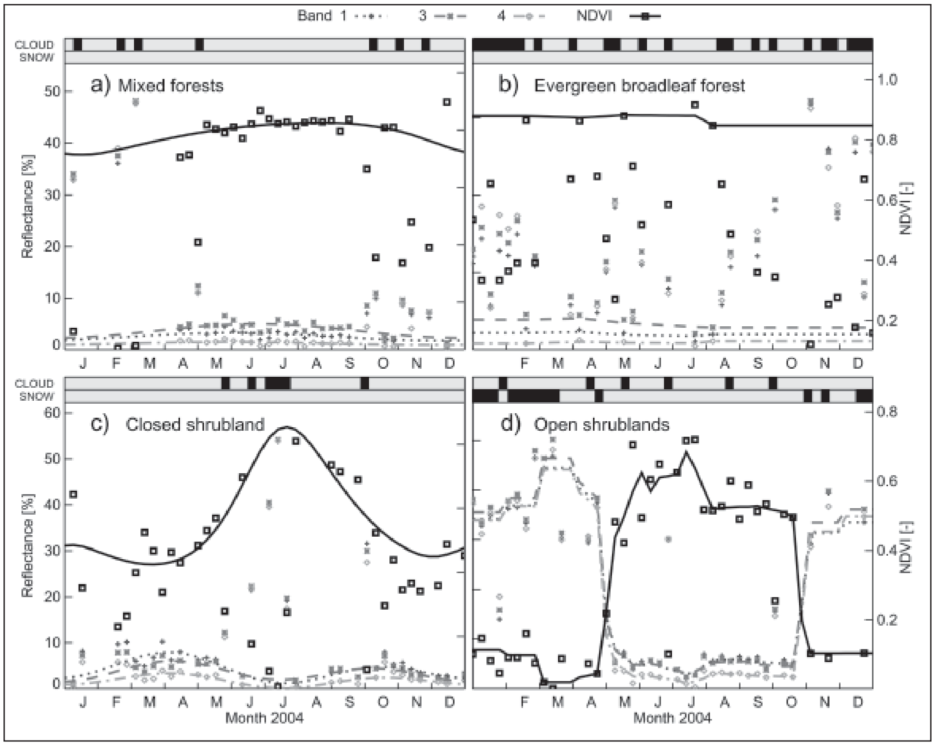

Fig. 2. *Yearly time series of uncorrected (symbols) and Fourier-adjusted (lines) land surface reflectances and NDVI: (a) Swiss alpine mixed forest; (b) tropical rainforest in Sumatra, Indonesia; (c) shrubland in the Tibetan Plateau; (d) shrubland in Utah, U.S.*

well suited to create consistent NDVI time series from AVHRR data [*Los et al.,* 2000; *Stöckli and Vidale,* 2004] but has not been applied to true-color imagery until now. The method assumes that the snow-free land surface changes on a seasonal timescale with a yearly periodicity and ignores short-term disturbances (e.g., clouds, aerosols).

Eight-day composites of MODIS land surface reflectances (MOD09A1) from 2004 [*Justice et al.,* 2002] were used. First, individual MODIS bands were quality-checked to identify high aerosol concentrations, clouds, and snow, followed by a snow-free Fourier adjustment. Some areas do not show substantial seasonal change (such as lakes, oceans, and permanently snow covered areas), or do not have sufficient temporal coverage due to cloud cover or persistent aerosols (e.g. tropical rainforests). For those areas, weighted temporal averaging was applied. As a last step, reflectance values for snow-covered areas were added to the snow-free data set, and then the data were transformed into true-color imagery and NDVI maps. A technical and scientific overview of the processing methodology is given at http://www.iac.ethz.ch/staff/stockli/bmng

Resulting Time Series

Figure 2 shows time series of original (MOD09A1, symbols) and Fourier-adjusted (BMNG, dashed/solid curves) MODIS reflectances. The Alpine mixed forest (Figure 2a) has a long growing season. The NDVI, which yields high values for lush vegetation because of strong near-infrared reflectance off green plants, is slightly lower in winter, when the deciduous part of vegetation has lost its leaves. The MODIS cloud flag (indicating where the MODIS cloud-masking algorithm detects clouds; Figure 2, at the top of each graph) captures cloud-disturbed pixels well, except for one at the beginning of October 2004, which is then corrected by our Fourier adjustment algorithm.

Significantly heavier cloud contamination is seen in reflectances of a tropical rainforest in Sumatra, Indonesia (Figure 2b). However, the situation there can be overcome since the cloud mask in combination with the weighting scheme used allows the reconstruction of the constantly high NDVI time series and a low albedo (reflective power) of 2–5% in the visible bands. NDVI slightly decreased after July 2004 during the dry season. A few tropical pixels are cloudy during the whole year, which results in cloud-contaminated BMNG time series.

High-altitude vegetation, such as shrubs in the Tibetan Plateau (Figure 2c), only grows during a short period, being limited by temperature. Clouds obscure observations during the monsoon season, but the short peak in NDVI has been reconstructed by the use of discrete Fourier series. Snow cover changes surface albedo from 10–50% within one eight-day period, as shown in a time series over the western United States (Figure 2d). The snow-free Fourier adjustment provides summer reflectance time series, and snow is patched in winter based on a snow flag (where MODIS detects snow; Figure 2, at the top of each graph).

However, the beginning and end of snow cover are not clear. The MODIS snow flag shows snow from January to March and at the end of December, whereas observed reflectances suggest snow from January to April and during November and December. Discriminating snow cover from the snow-free reflectances is one of the main problems in the BMNG algorithm. The uncertainty of ±1 month in the timing of snow cover affects the visual appearance of areas with seasonal snow cover.

Global Maps of Seasonal Variations

Such time series were automatically processed for the whole planet at 500-meter spatial resolution. The resulting monthly maps are different from previous cloud-free visualizations of the Earth in that they show seamless seasonal variations on the land surface, with one set of maps in true color and another set as NDVI. The novel atmospheric correction and cloud-masking algorithms used in MODIS land products are important for producing these composites. However, while the Fourier adjustment of snow-free reflectance data uses sound assumptions based on seasonal phenology, compositing snow reflectances on a monthly interval presents a major difficulty in this study. A solution to this problem may be the availability of a more sophisticated snow classification scheme, the compositing of multiple years of snow fall (snow climatology), or the rejection of short-term (e.g., less than 3–4 months) snow cover data.

Figure 3 displays the two seasonal opposites, January and July 2004, in 0.5° (available at 0.004667°) resolution. The algorithm used efficiently removes cloud contamination in tropical areas. Boreal forest albedo in northern latitudes is low during wintertime, since the trees project out of the snow layer, contrasted by the very high albedo of short vegetation in these areas. The brownish surface during the dry season (January) in northern India and China changes into dark green during the monsoon season (July).

These, among many other interesting features, can be discovered while exploring the data set, and the images' application in formal and informal education is especially encouraged. NASA is publicly sharing the BMNG data set at no cost at the following Web site: http://bluemarble.nasa.gov

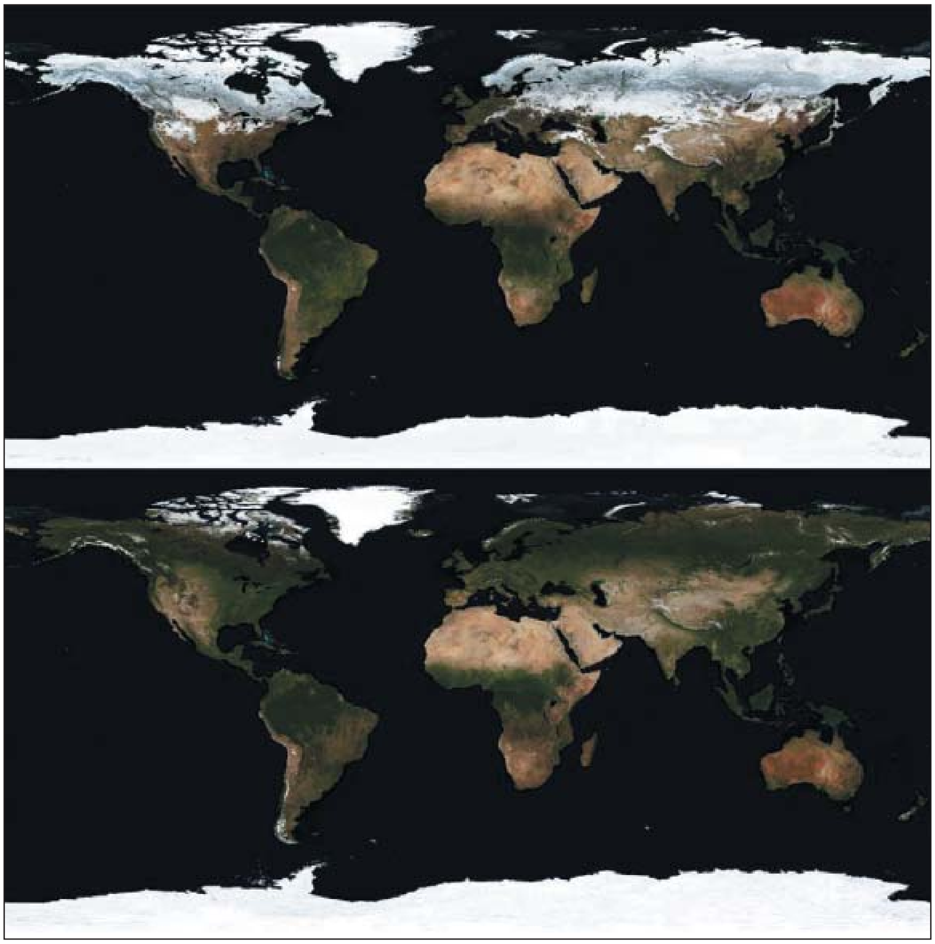

Fig. 3. Blue Marble: Next Generation—true-color, cloud-free composites during (top) January 2004 and (bottom) July 2004.

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Author Information

Reto Stöckli, Institute for Atmospheric and Climate Science, Federal Institute of Technology, Zürich, Switzerland; E-mail: rstockli@climate.gsfc.nasa.gov; Eric Vermote and Nazmi Saleous, Department of Geography, University of Maryland, College Park; Robert Simmon, NASA Earth Observatory, Goddard Space Flight Center, Greenbelt, Md.; David Herring, NASA Headquarters, Washington, D.C.