NPOESS

Next-Generation Operational Global Earth Observations

by Thomas F. Lee, Craig S. Nelson, Patrick Dills, Lars Peter Riishojgaard, Andy Jones, Li Li, Steven Miller, Lawrence E. Flynn, Gary Jedlovec, William McCarty, Carl Hoffman, and Gary McWilliams

In the next decade, the National Polar-orbiting Operational Environmental Satellite System will provide Earth science data and global environmental monitoring to weather forecasters, climate researchers, and global decision makers.

This article that describes NPOESS was completed and accepted for publication prior to the White House decision in February 2010 ordering a major restructuring of the NPOESS program. NOAA will now assume primary responsibility for the afternoon polar-orbiting operational environmental satellite orbit and DoD will take primary responsibility for the early morning orbit. However, NPP, as described in this article, is still scheduled to be launched in 2011. Several of the instruments and program elements described in this article are also likely to be carried forward into future U.S. polar-orbiting operational environmental satellite missions.

The National Polar-orbiting Operational Environmental Satellite System (NPOESS) is managed by the tri-agency Integrated Program Office (IPO), which is composed of the Department of Commerce's (DOC) National Oceanic and Atmospheric Administration (NOAA), the Department of Defense (DoD), and the National Aeronautics and Space Administration (NASA). The IPO is working with prime contractor Northrop Grumman Aerospace Systems (NGAS), principal teammate Raytheon, and their instrument subcontractors to jointly develop and acquire the next-generation operational weather and environmental satellite system. NPOESS will replace NOAA's current Polar-orbiting Operational Environmental Satellites (POESs) and the DoD's Defense Meteorological Satellite Program (DMSP) spacecraft, which have provided global data for weather forecasting and environmental monitoring for nearly 50 years. NPOESS will acquire and deliver critical Earth observation measurements to NOAA and DoD central processing facilities through an innovative global SafetyNet™ communications network of 15 unmanned ground stations that will provide significantly reduced global data latency. NPOESS will enable more timely and efficient assimilation of high-quality satellite data into numerical weather prediction (NWP) models for improved environmental forecasts and warnings. NPOESS will employ platforms and instruments that incorporate technological advances from NASA's Earth Observing System (EOS) satellites in an integrated mission serving the nation's civilian and military needs for space-based, remotely sensed environmental data. This article summarizes ▶

Detail of NASA's AQUA MODIS (2055 UTC) using dust enhancement to distinguish between dust and smoke plumes. For more information see Fig. 4.

the current status of the development of NPOESS; describes the expected capabilities; outlines the NPOESS Preparatory Project (NPP) satellite; highlights selected applications of NPOESS data; and introduces some user training resources, which are already preparing users for NPP and NPOESS.

STATUS OF NPOESS DEVELOPMENT. The NPOESS constellation will consist of four satellites (C1–C4) in two orbital planes [828-km altitude, sun-synchronous orbits with 1330 and 1730 local time at ascending node (LTAN; at LTAN, the satellite crosses the equatorial plane moving from the Southern Hemisphere to the Northern Hemisphere)] to meet the operational needs of NOAA and DoD. As a precursor to NPOESS, NPP (Murphy 2006) is scheduled for launch in 2011. NPP will test the on-orbit performance of the primary NPOESS sensors and will validate the ground system design for receiving, processing, and distributing data and products. The first operational NPOESS spacecraft (C1) is now scheduled for launch in 2014. The final satellites (C3 and C4) in the two-orbit NPOESS constellation are expected to be operational well into the 2023–26 time period.

C1 will be launched into an afternoon orbit (1330 LTAN) to replace the last of the NOAA POESs. Atmospheric temperature and moisture profiles and surface data collected from imaging and atmospheric sounding instruments in this afternoon orbit are critical for global NWP models. NOAA and DoD depend on data from the afternoon orbit for critical input into global and regional weather forecast models. The afternoon NPOESS spacecraft will carry advanced-technology visible, infrared, and microwave imagers and sounders to deliver higher spatial- and spectral-resolution data, enabling more accurate short-term weather forecasts, nowcasts, and warnings. The second operational NPOESS spacecraft (C2) is slated for launch in 2016 to replace the last of the DMSP spacecraft that currently occupy either early- or midmorning orbits to support military operations worldwide. In addition to benefiting NOAA weather forecast models, the optical- and microwave-spectrum imagery and atmospheric data from this orbit support the DoD's global NWP/cloud forecast models as well as short-term local and regional forecasts used to support tactical operations (e.g., air, sea, and ground operations). While supporting operational weather forecasting as a primary mission, NPOESS will also carry other instruments to continue and extend important legacy measurements of atmospheric ozone, Earth radiation budget, and solar irradiance that have been made from NOAA and NASA spacecraft over the last three decades.

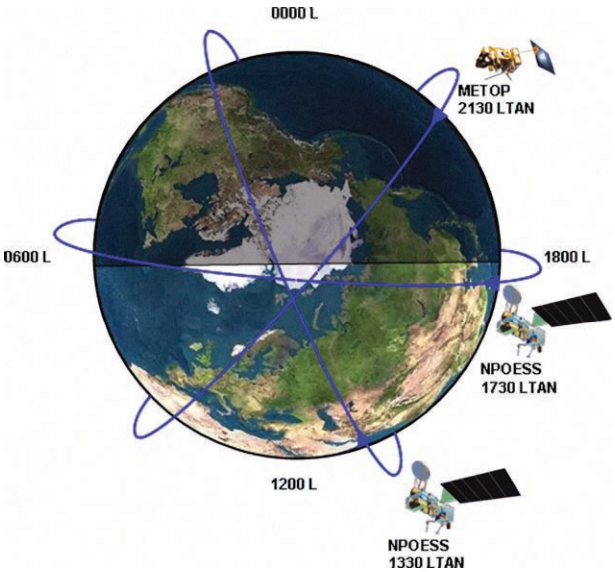

Fig. 1. Configuration of polar-orbiting operational satellites in the NPOESS/MetOp era. Times shown for satellite passes are in equatorial LTAN.

The NPOESS program was restructured in 2006 as a result of technical problems with new sensor development, associated cost growth, and schedule delays. NPOESS is now a two-orbit pro-

AFFILIATIONS: Lee and Li—Naval Research Laboratory, Monterey, California; Nelson—Riverside Technology Inc., Silver Spring, Maryland; Dills—Cooperative Program for Operational Meteorology, Education and Training, Boulder, Colorado; Riishojgaard—Joint Center for Satellite Data Assimilation, NOAA Science Center, Camp Springs, Maryland; Jones and Miller—Cooperative Institute for Research in the Atmosphere, Ft. Collins, Colorado; Flynn—NOAA/NESDIS/Center for Satellite Applications and Research, Camp Springs, Maryland; Jedlovec—Global Hydrology and Climate Center and Short-Term Prediction Research and Transition Center, NASA Marshall Space Flight Center, Huntsville, Alabama; McCarty—Global Modeling and Assimilation Office, NASA Goddard Space Flight Center, Greenbelt, Maryland, and Goddard Earth Sciences and Technology Center, University of Maryland, Baltimore County, Baltimore, Maryland; Hoffman and McWilliams—NPOESS Integrated Program Office, Silver Spring, Maryland
CORRESPONDING AUTHOR: Thomas F. Lee, Naval Research Laboratory, 7 Grace Hopper Ave., Stop 2, Monterey, CA 93943-5502
E-mail: thomas.lee@nrlmry.navy.mil

DOI:10.1175/2009BAMS2953.1

In final form 8 December 2009
©2010 American Meteorological Society

gram rather than a three-orbit program as originally planned. The midmorning orbit (2130 LTAN) will be occupied by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Meteorological Operation (MetOp) satellites that carry advanced instruments similar to those that will fly on NPOESS. EUMETSAT successfully launched the first in the series of MetOp satellites in October 2006 (Klaes et al. 2007) to permanently replace the NOAA POES in the midmorning orbit as part of the NOAA–EUMETSAT Initial Joint Polar-orbiting Operational Satellite System (IJPS). The future joint configuration of NPOESS and MetOp polar-orbiting operational satellites (Fig. 1) will provide global coverage with a data refresh rate of approximately four hours for most observations. Use of data from EUMETSAT's MetOp satellite will augment the global coverage and refresh rate of the U.S. polar-orbiting satellite system. In addition, the European meteorological community will receive valuable data from instruments on both the MetOp and NPOESS series of satellites.

NPOESS SPACE SEGMENT. User requirements for atmospheric, oceanic, terrestrial, climatic, and solar–geophysical parameters have guided the development and design of the NPOESS program. Advanced-technology visible, infrared, and microwave imagers and sounders on NPOESS will provide enhanced capabilities to users and improve the accuracy and timeliness of observations. Critical space and ground segment components are being readied to transform raw data into processed, value-added products that will be delivered easily and quickly to end users on the ground. Prime contractor NGAS is responsible for delivering the "end to end" system, consisting of the spacecraft; sensors and instruments on the spacecraft; launch support capabilities; the command, control, communications, and data routing infrastructure; and data processing hardware and software. Major components of the command and control and data processing systems that are needed to support the NPP mission have already been delivered and tested.

In recent years, the demand for environmental satellite observations from the operational weather forecasting and climate science communities has increased significantly, in part as a result of NASA's successful EOS missions. NPOESS instruments will observe significantly more environmental parameters simultaneously from space than their POES and DMSP predecessors. NPOESS will deliver more accurate and timely measurements at higher spatial (horizontal and vertical) and spectral resolution to support operations and research. User demands for faster delivery of data are driving the space- and ground-based architectures for data routing and retrieval that will dramatically reduce data latency (time from observation by the satellite to availability of processed data). NPOESS will deliver data to users at higher data rates with more frequent space-to-ground data communications. NPOESS is expected to deliver a total data volume of approximately 8 terabytes per day, vastly exceeding the throughput of the current POES and DMSP systems (~2 to 6 gigabytes per day) and approximately 2–3 times greater than the data volume delivered by the NASA EOS missions. This substantial increase in data volume will necessarily increase demands on the front-end processors and data assimilation systems used to initialize and update global and regional NWP models, and it will also demand major upgrades to the satellite data archive and distribution systems currently operated by NOAA.

NPOESS payloads will include instruments to profile the atmosphere; probe the near-Earth space environment; monitor the Earth's radiation budget; and observe atmospheric, terrestrial, and oceanic phenomena globally. Instrument payloads for the two NPOESS orbits and for NPP are shown in Table 1. The afternoon (1330 LTAN) NPOESS spacecraft will carry the following four primary instruments: Visible/Infrared Imager Radiometer

Table 1. NPOESS and NPP instrument payloads by orbit.

NPOESS afternoon orbit	NPOESS morning orbit	NPP
1330 LTAN	1730 LTAN	1330 LTAN
VIIRS	VIIRS	VIIRS
CrIS	—	CrIS
ATMS	—	ATMS
MIS (C3)	MIS	—
OMPS (nadir)	—	OMPS
SEM-N	—	—
CERES (C1)	—	CERES
TSIS (C1)	—	—
SARSAT	SARSAT	—
A-DCS	A-DCS	—

Suite (VIIRS), Cross-track Infrared Sounder (CrIS), Advanced Technology Microwave Sounder (ATMS), and Ozone Mapping and Profiler Suite (OMPS). In addition, the afternoon NPOESS spacecraft will carry the Microwave Imager/Sounder (MIS; C3 only), Space Environment Monitor-NPOESS (SEM-N), Clouds and the Earth's Radiant Energy System (CERES; C1 only), and Total Solar Irradiance Sensor (TSIS; C1 only). Currently, the early-morning spacecraft (1730 LTAN) will fly with a reduced complement of instruments: VIIRS and MIS (C2 and C4). The NPP spacecraft will carry VIIRS, CrIS, ATMS, OMPS, and CERES. Both early-morning and afternoon NPOESS spacecraft will also be equipped with the Advanced Data Collection System (A-DCS) and the Search and Rescue Satellite Aided Tracking System (SARSAT) payload consisting of the Search and Rescue Repeater (SARR) and Search and Rescue Processor (SARP) subsystems. Flight units for ATMS, OMPS, and CERES have been delivered and integrated onto the NPP spacecraft. The flight unit for VIIRS has successfully completed testing and is ready for delivery. The flight unit for CrIS is undergoing final testing, calibration, and characterization in preparation for shipment to Ball Aerospace and Technologies Corp. for integration onto the NPP spacecraft.

The 22-channel (29 channels, counting 7 dual-gain bands) VIIRS (Murphy et al. 2006) will collect calibrated visible/infrared radiances to produce about 20 different environmental data records (EDRs) including imagery, cloud and aerosol properties, albedo, land surface type, vegetation index, ocean color, land surface temperature, and sea surface temperature (SST), similar to the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's EOS *Terra* and *Aqua* missions. The swath width on VIIRS will be approximately 700 km wider than on MODIS, providing more complete daily global coverage over the visible, short/medium infrared, and longwave infrared spectrum at horizontal spatial resolutions of 370 and 740 m at nadir. VIIRS will image at a near-constant horizontal resolution (Johnson et al. 1994; Lee et al. 2006b) across its ~3000-km swath (i.e., from 370 m at nadir to ~800 m at edge of scan), a significant improvement over the Advanced Very High Resolution Radiometer (AVHRR) and MODIS instruments. VIIRS also has a day/night band (DNB) to detect low levels of visible/near-infrared radiance at night from sources on or near the Earth's surface, such as low clouds, fog, and snow cover illuminated by moonlight and lightning flashes. VIIRS will produce low-light imagery at a much higher horizontal spatial (~740 m across the scan) and radiometric resolution (Lee et al. 2006a) than the Operational Linescan System (OLS) on DMSP (Elvidge et al. 1998). The VIIRS DNB marks a significant advance over current environmental visible/infrared imagers. For the first time, there will be calibrated visible observations of clouds and other phenomena at night. Real-time radiances from the DNB will be available to all users, not just to DoD users, as is generally the case now with DMSP OLS nighttime data.

The VIIRS flight sensor for NPP has successfully completed long-duration thermal vacuum testing, during which the instrument demonstrated very good radiometric performance. Instrument performance has recently been assessed by comparing VIIRS calibration and characterization sensor data records (SDRs) to equivalent level 1 products from MODIS. Predictions indicate that cloud products, land EDRs (land surface temperature, surface type, surface albedo, and vegetation index), and SST from VIIRS will be equivalent in quality to products from MODIS. Aerosol EDRs (aerosol optical thickness, aerosol particle size parameter, and suspended matter) may be degraded with respect to MODIS performance partly due to reliance on MODIS-based algorithms in testing and to optical crosstalk in the filter assemblies on the first VIIRS flight sensor. However, it is expected that VIIRS aerosol EDR performance will be comparable to MODIS and certainly will be significantly better than can be obtained from the current operational AVHRR system. VIIRS will provide the first operational U.S. ocean color capability. Ocean color/chlorophyll products from VIIRS on NPP may be degraded with respect to MODIS performance because of optical crosstalk in the filter assemblies on the first VIIRS flight sensor. However, some of these problems may be resolved through ground processing. NPOESS ocean color/chlorophyll products will not be degraded with respect to MODIS performance because the crosstalk problems will be corrected on the second VIIRS flight sensor.

The CrIS and ATMS instruments will provide vertical profiles of atmospheric temperature, humidity, and pressure from the surface to the top of the atmosphere. CrIS and ATMS are complementary; together, they comprise the Cross-track Infrared Microwave Sounding Suite (CrIMSS). CrIS senses upwelling infrared radiances from 3 to 16 μm at very high spectral resolution (~1300 spectral channels) to determine the vertical atmospheric distribution of temperature and moisture from near the surface to the top of the atmosphere across a swath width of 2200 km. CrIS will succeed the Atmospheric Infrared Sounder (AIRS), which is on NASA's EOS *Aqua*

spacecraft, and will fly in a complementary orbit to the Infrared Atmospheric Sounding Interferometer (IASI) on the EUMETSAT MetOp satellites. Details on CrIS and AIRS are available in Susskind (2006). ATMS is the next-generation cross-track microwave sounder that will combine the functionality of the Advanced Microwave Sounding Unit (AMSU-A/B) and Microwave Humidity Sounder (MHS) instruments in an energy-efficient, lightweight, compact package (Goldberg and Weng 2006). ATMS has 22 microwave channels in the 23–183-GHz range to provide vertical temperature and moisture soundings across a swath width of 2300 km. In comparison to heritage instruments, ATMS has an extended off-nadir view angle, which will result in no gaps between successive orbits. Data from CrIMSS will be used to construct atmospheric temperature profiles at 1 K accuracy for 1-km layers and moisture profiles accurate to 15% for 2-km layers to approximate the accuracy of data obtained from radiosondes. Direct radiance assimilation of data from these types of instruments is discussed in the section on data assimilation and NWP. ATMS will also be capable of retrieving surface precipitation rates, water path estimates for rain and snow, and peak vertical wind. Recent studies demonstrate that ATMS will perform better than AMSU for these retrieved precipitation parameters (Surussavadee and Staelin 2008).

The IPO has defined a less complex passive microwave radiometer sensor to replace the Conical-scanning Microwave Imager/Sounder (CMIS) that was originally planned for NPOESS. The MIS will fly on NPOESS C2–C4 to perform key "all weather" measurements, including soil moisture; sea surface temperature; ocean surface wind vectors; and other environmental parameters, including atmospheric temperature and moisture profiles and integrated atmospheric moisture and precipitation. MIS will be the primary instrument for satisfying 16 EDRs. The design for MIS is based on conically scanning microwave radiometers that are currently flown on DMSP spacecraft and on the Naval Research Laboratory's (NRL) WindSat/Coriolis mission (Gaiser et al. 2004). MIS will use a 1.8-m rotating main reflector to cover a 1700-km swath width while measuring over a frequency range of 6–183 GHz. MIS will produce operational ocean surface wind vectors using methodology developed for WindSat (e.g., Bettenhausen et al. 2006) with validated wind speeds up to about 25 m s^{-1}.

The OMPS consists of two separate instruments that view nadir and limb, respectively (Flynn et al. 2006). The nadir instrument that will be flown on NPOESS and NPP has two detectors: the nadir mapper and the nadir profiler. The nadir mapper has a wide field of view and will make measurements of backscattered solar ultraviolet radiance (BUV) to provide estimates of the global daily total ozone field. These measurements will continue the record started with the NASA Total Ozone Mapping Spectrometer (TOMS) and currently provided by the Ozone Monitoring Instrument (OMI) on EOS *Aura* and the Global Ozone Monitoring Experiment-2 (GOME-2) on MetOp. The nadir profiler measures shorter-wavelength BUV along a suborbital swath. These measurements will be used to generate estimates of the ozone vertical profiles to continue the current products from the operational Solar Backscatter Ultraviolet Radiometer (SBUV/2) instrument series on the NOAA POES. The OMPS limb profiler measures three vertical slits of UV, visible, and near-infrared radiances scattered by the Earth's atmosphere. These will be used to retrieve estimates of the ozone vertical profiles with 3-km vertical resolution in the middle and lower stratosphere, much better than the 7–10-km resolution of the SBUV/2 (and OMPS nadir profiler). The OMPS will continue monitoring the recovery of the ozone layer with the phase out of chlorofluorocarbons and will do so with much-improved measurements of ozone profiles in the stratosphere, where these changes are occurring. Long-term stability of data products from both nadir and limb sensors will be maintained through periodic solar irradiance measurements. Currently, the OMPS limb profiler is only manifested on NPP.

NPOESS will carry SEM-N, a multichannel, charged particle spectrometer to measure the population of low-, medium-, and high-energy particles in the near-Earth space environment and the particle precipitation phenomena resulting from solar activity. Measurements from the SEM-N will provide five of the NPOESS space EDRs, including the auroral boundary, auroral energy deposition, suprathermal through auroral energy particles, medium-energy charged particles, and energetic ions. SEM-N will be a newly designed version of the SEM payload that is currently flying on NOAA's POES and EUMETSAT's MetOp.

The CERES instrument consists of three broadband radiometers, covering the spectral regions from 0.3 to >50 μm, that scan the Earth from limb to limb. CERES flight model 5 will fly on NPP (a follow-on unit will be carried on NPOESS C1) to provide measurements of the space and time distribution of the Earth's radiation budget (ERB) components (Wielicki et al. 1996). CERES will continue a nearly 30-yr record

of measurements of the Earth radiation budget by instruments on NASA spacecraft. Data from CERES will be used in conjunction with VIIRS to observe variations in the Earth's energy balance and its sensitivity to changes in clouds and aerosols.

The TSIS will measure variability in the sun's solar output, including total solar irradiance. TSIS consists of two instruments: the Total Irradiance Monitor (TIM; Kopp and Lawrence 2005), which measures the total light coming from the sun at all wavelengths, and the Spectral Irradiance Monitor (SIM; Harder et al. 2005), which will measure how the light from the sun is distributed by wavelength. TSIS is an important climate sensor that will help maintain continuity of the climate data record (CDR) for space-based solar irradiance measurements that now span more than three decades.

NPOESS is designed to deliver more than 35 essential measurements (Fig. 2) for operational weather and ocean nowcasting and forecasting, land use, and space weather while providing continuity of data for 14 of 26 essential climate variables. Although several NPOESS climate sensors were demanifested as a result of program restructuring in 2006, the NPOESS spacecraft is designed to accommodate all demanifested sensors, including climate monitoring sensors, should the opportunity arise. In fact, as a result of tri-agency (DOC, DoD, and NASA) decisions during 2008 in response to recommendations from the National Research Council (2007), CERES was added to NPP and both CERES and TSIS will be flown on NPOESS C1. CERES, TSIS, and OMPS are important climate sensors that will now be flown on an operational platform to maintain continuity of CDRs for space-based measurements that currently span more than three decades. Preflight characterization of instruments, enhanced onboard instrument calibration, and stable orbits will significantly contribute to high-quality CDRs from NPP and NPOESS. NOAA and NASA continue to review and evaluate options to meet requirements for long-term climate monitoring from space. As recommended by the National Research Council (2007), these options may include additional leveraging of NPOESS.

NPOESS spacecraft are being designed for precise orbit control to maintain altitude and nodal crossing times to within ±10 min throughout the mission lifetime and repeat ground tracks. These design criteria are particularly important for climate measurements from CrIS and ATMS. For example, drift in the orbits of the 20-plus-yr series of afternoon NOAA POES spacecraft coupled with issues of merging and intercalibrating multiple Microwave Sounding Unit (MSU) and AMSU instruments on these satellites have resulted in controversial results with respect to long-term trends in tropospheric temperatures (e.g., Christy et al. 2003; Mears and Wentz 2005). These types of spacecraft and instrument attributes that add uncertainty to the measurements will now be remedied on NPOESS.

The spacecraft instruments are designed for autonomous operations for up to 60 days without commanding from the ground. Onboard data handling capabilities will be sufficient to store data at instrument resolution globally, so there will be no need to schedule special higher-resolution imagery products [i.e., as currently occurs with POES local area coverage (LAC) and DMSP fine mode]. Fault-tolerant designs for each of the instrument payloads will enable long mission life (up to 8 yr of storage and 7 yr of operation) to ensure mean mission durations exceeding 5 yr for each of the NPOESS spacecraft over the operational life of the program (2014 to ~2026). This is a significant improvement over the average on-orbit life of POES or DMSP spacecraft (36–48 months) and comparable to NASA's current EOS missions. Longer on-orbit life also means that fewer spacecraft will be required to provide coverage over the 10-plus-yr span of NPOESS operations. Decisions on future launches of NPOESS C3 and C4 or replacement strategies for failed sensors will be based on need to maintain continuity of operational measurements and products.

NPP. To ensure a successful transition from current research to future operations, the NPOESS IPO and NASA are partners in the NPP that is scheduled for launch in 2011. NPP will accomplish several key objectives: 1) reduce final development risks for NPOESS by providing on-orbit testing, calibration, and validation of sensors, algorithms, and ground-based operations and data processing systems prior to the launch of NPOESS-C1 in 2014; 2) provide continuity of the NASA EOS *Terra*, *Aqua*, and *Aura* global imaging and sounding observations; 3) ensure early user access to data from NPOESS sensors for evaluation and use 3 yr in advance of NPOESS; and 4) accelerate operational and research user adoption and use of NPOESS data, products, and services.

NPP will carry five NPOESS sensors (VIIRS, CrIS, ATMS, OMPS, and CERES) to provide on-orbit testing and validation of sensors, algorithms, ground-based operations, and data processing and distribution systems prior to the launch of the first operational NPOESS satellite. NPP will be launched into the 1330 LTAN orbit to reduce the risk of a data

gap between the last POES and the first NPOESS satellite. The NPP satellite will be commanded from the NPOESS Mission Management Center at the NOAA Satellite Operations Facility (NSOF) through a ground station at Svalbard, Norway. Svalbard's high latitude (78°N) will enable it to contact and downlink data from all 14 daily NPP satellite orbits. The global stored mission data from NPP will be transmitted from Svalbard within minutes to the United States via a fiber-optic cable system completed in January 2004 as a joint venture between the IPO, NASA, and the Norwegian Space Center (NSC). The Svalbard ground station and fiber-optic link will improve data latency from NPP to ~100 min compared to the ~120–180-min data latency from POES and DMSP. NPP will generate approximately 1.5 terabytes of data per day that will be processed into ~25 separate EDRs and higher-level products at the NSOF and the Air Force Weather Agency (AFWA). Raytheon Intelligence and Information Systems, NGAS's largest subcontractor and principal teammate, has delivered the ground control and data processing systems for NPP well in advance of launch. NOAA, DoD, and NASA will have immediate access to processed data from NPP for use and critical evaluation, ensuring that NPOESS products will be incorporated into operations soon after launch.

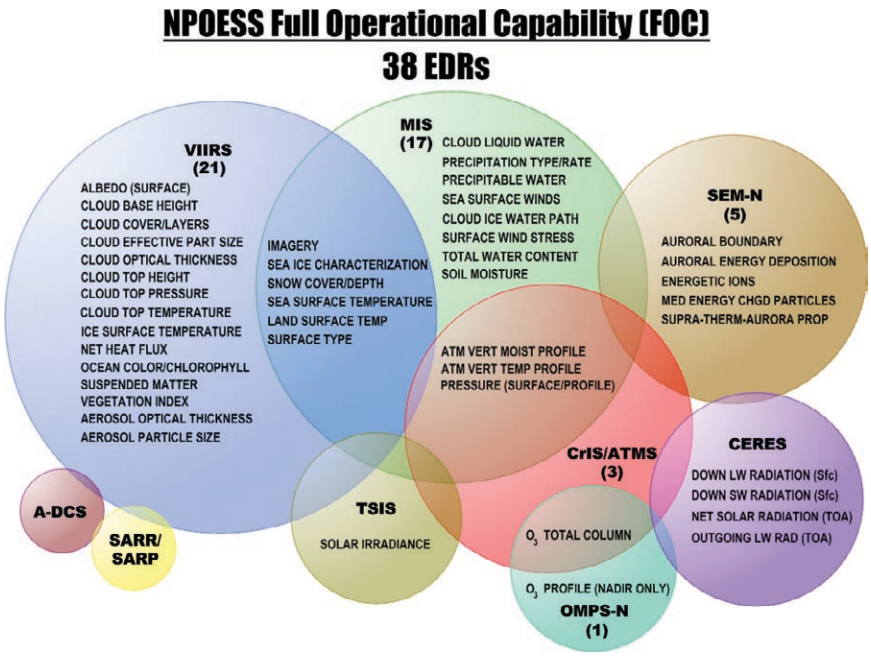

Fig. 2. EDR by instrument and mission area for full operational capability (FOC) when NPOESS C1 and C2 are in orbit. The number of EDRs produced will depend on the instruments carried on the NPOESS spacecraft and will range from 24 for NPP to 38 for NPOESS C3. Parameters shown for CERES, TSIS, and OMPS-N (O_3 profile) will be processed to the SDR level only.

NPP will also support real-time direct broadcast (DB) services via an X-band downlink. There are currently more than 150 ground stations worldwide that acquire real-time DB data (e.g., imagery) from the X-band downlinks on NASA's EOS *Terra* and *Aqua* satellites (Huang et al. 2004). Users will be able to receive real-time data from NPP by using the International Polar Orbiter Processing Package (IPOPP) developed by the IPO through a collaborative arrangement with the Direct Readout Laboratory at the NASA Goddard Space Flight Center and the Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin—Madison.

A key component of NPP is NASA's science data segment (SDS), which will be used to evaluate key NPP/NPOESS EDRs in the following discipline areas: oceans, land, ozone, atmospheric sounding, and atmospheric composition. The SDS will assess NPP EDR quality and performance and test the suitability of EDRs for climate research.

NPOESS GROUND SYSTEM. The NPOESS ground system has three key components that will ensure the timely and efficient delivery of NPOESS data once operational: the Command, Control, and Communications Segment (C3S); the Interface Data Processing Segment (IDPS); and the Field Terminal Segment (FTS). NPOESS will provide an end-to-end system to acquire, process, and deliver data to NOAA and DoD central processing facilities through a global SafetyNet™ communications network of 15 dedicated, unmanned ground stations connected through the AT&T worldwide, high-speed, highly reliable commercial fiber-optic communications network, which will provide significantly improved data latency. The NPOESS C3S will deliver global stored mission data to four U.S. operational processing centers (OPCs) for processing and distribution to end users: NOAA's National Environmental Satellite, Data and Information Service (NESDIS), which will serve

the National Centers for Environmental Prediction (NCEP); AFWA; Fleet Numerical Meteorology and Oceanography Center (FNMOC); and the Naval Oceanographic Office (NAVOCEANO).

The NPOESS ground system architecture consisting of SafetyNet™ and the IDPS is expected to deliver 95% of the data within 28 min from the time of collection. This major innovation will speed up data delivery enormously. Today, data temporarily stored on NOAA's POES are delivered to a single ground antenna once per orbit (~100-min orbital period). The ground processing system adds another delay of approximately 10 min–2 h. SafetyNet™ will employ 15 sites around the world that will download and deliver data, sometimes within 2 min of acquisition. The SafetyNet™ system can also be leveraged to accommodate other future satellite missions.

This dramatic, fourfold to fivefold improvement in data latency from NPOESS will lead to significant improvements in forecasts produced by NWP models. Dr. Louis Uccellini (2008, personal communication), director of NCEP, has stated that "lowering data latency rates ensures that we will be able to process NPOESS data quickly and deliver more timely, higher resolution forecasts to decision makers."

In addition to the space-to-ground transmission of stored mission data, NPOESS will simultaneously broadcast two continuous real-time data streams, at high (X band) and low (L band) rates, to suitably equipped field terminals worldwide running a subset of the IDPS software appropriate for the type of FTS hardware. The NPOESS high-rate data (HRD) broadcast will be a complete, full-resolution dataset containing all sensor data and auxiliary/ancillary data necessary to generate all NPOESS EDRs (except some Earth radiation EDRs) and is intended to support users at fixed, regional hubs. The NPOESS low-rate data (LRD) broadcast will offer a subset of the full NPOESS sensor data and is intended for U.S. and worldwide users of field terminals (land- and ship-based, fixed and mobile environmental data receivers operated by DoD users and surface receivers operated by other U.S. government agencies, worldwide weather services, and other international users).

The NPOESS IDPS features high-speed, symmetric, multiprocessing computers that will rapidly convert and process large streams of NPP and NPOESS raw data records (RDRs; on the order of 8 terabytes per day when NPOESS is fully operational) into 38 distinct EDRs at the four OPCs. The IDPS equipment for the NSOF and AFWA is currently installed to serve the NPP mission. The IDPS equipment for NAVOCEANO and FNMOC will be installed in 2012/13 to complete the system for NPOESS operations. NOAA's NESDIS will maintain the long-term archive of NPOESS data. NESDIS will also be responsible for providing the international user community with near-real-time processed NPOESS data, products, and archives.

Key components of the NPP and NPOESS C3S have already been installed and have passed preliminary tests at the Svalbard Satellite Station (SvalSat) and at NOAA's Satellite Operations Facility. Communications capabilities from Antarctica are being upgraded to support NPOESS. NOAA and EUMETSAT are currently exploring opportunities to receive MetOp data from an Antarctic ground station, thereby substantially improving data latency in the midmorning orbit. In the future, NPOESS and MetOp will provide essential real-time data to the international community to support weather forecasting as well as continuity of critical data for monitoring, understanding, and predicting climate change.

DATA ASSIMILATION AND NWP. High (spatial and spectral)-resolution imaging and sounding instruments on NPP and NPOESS will support continuing advances in data assimilation systems and NWP models to improve short- to medium-range weather forecasts. NPP will maintain continuity of high-resolution data from NASA's EOS missions during the transition to NPOESS. NPP data will be available in a time frame consistent with the projected installation of the next-generation Advanced Weather Information Processing System (AWIPS) at National Weather Service (NWS) forecast offices.

The CrIS (heritage: AIRS and IASI) and ATMS (heritage: AMSU and MHS) instruments on NPP and NPOESS will deliver unprecedented volumes of measurements related to the state of the surface and the atmosphere. Data assimilation and NWP will translate these data into increased forecast skill and societal benefits. Good initialization requires two elements: an effective forecast model and high-quality observations about the relevant model variables with good and timely coverage of the entire model domain. Because of the speed of error propagation in atmospheric models, a global forecast domain is necessary at ranges beyond 5–6 days. The only practical way of obtaining the necessary global observational coverage is via space-based observing systems such as NPP/NPOESS.

The required input for NWP consists of the three-dimensional fields of atmospheric temperature, humidity, and horizontal wind, along with the two-dimensional surface pressure field. Advanced

infrared and microwave sensors such as CrIS and ATMS will provide excellent global coverage of the temperature and moisture fields. A single platform carrying these two instruments will provide near-global coverage every 12 h. When fully deployed, the joint constellation of NPOESS (carrying CrIS and ATMS at 1330 LTAN) and MetOp (carrying IASI, AMSU, and MHS at 2130 LTAN) will provide full global coverage of the temperature and moisture fields every 4–8 h. The launch of the AMSU in 1998 and the simultaneous adoption of radiance assimilation produced a substantial increase in NWP skill. The ATMS sensor will continue the AMSU legacy and enable the global NWP community to progress over the next decade and a half.

The NWP community entered the era of hyperspectral infrared sounding with the launch of NASA's AIRS sensor in 2002. Assimilation of high-spectral-resolution radiance data from AIRS into NWP models at NCEP has already resulted in a several-hour increase in forecast skill/range at 5–6 days in both the Northern and Southern Hemispheres, a significant improvement that normally takes several years to accomplish (Le Marshall et al. 2006b). This achievement is even more remarkable considering that the science of hyperspectral infrared data assimilation is still fairly immature and even now only a fairly small fraction of the data is being used in operations. AIRS and EUMETSAT's IASI now rank near the top of satellite instruments for NWP assimilation. Deployment of the CrIS instrument, the first U.S. operational hyperspectral infrared sensor, will enable further improvement in NWP skill.

Very low data latency is an important requirement of NPOESS, because the value of meteorological observations to real-time NWP forecast systems decreases very rapidly with time. The goal of NPOESS is to have practically all observations delivered to the NWP users within 30 min, which is consistent with the projected requirements of the National Weather Service during the operational lifetime of NPOESS. A 30-min latency for an observation will help substantially improve the generation and delivery of short-range NWP products used for watches and warnings. The SafetyNet™ system is key to meeting this goal that will transform data access for operational use.

Global NWP systems have a very important role also in providing lateral boundary conditions for regional and mesoscale NWP systems used for short-term forecasts. Thus, data latency improvements to global NWP will benefit regional and local applications. Historically, the use of satellite data in regional and mesoscale NWP applications has been indirect, namely via the use of global NWP output for initial and boundary conditions. One reason is that many of these systems are heavily resource constrained and employ only rudimentary, if any, data assimilation. The other, related reason is that the latencies of most satellite data are incompatible (i.e., too old) with respect to the data cutoff times of these models. The vastly improved latency of the NPOESS data compared to past polar-orbiting operational satellite systems will allow the regional/mesoscale NWP community to take advantage of direct assimilation into their own systems, similar to global NWP.

ANTICIPATING NPOESS: SELECTED PRODUCTS AND APPLICATIONS. In this section we describe selected products and applications from heritage sensors that anticipate the expected capabilities of new instruments on NPP and NPOESS. These examples highlight several primary sensors: CrIS, VIIRS, OMPS, and MIS.

AIRS radiance assimilation (anticipating CrIS). NASA's Short-term Prediction Research and Transition (SPoRT) Center (Goodman et al. 2004; Jedlovec et al. 2004) has been providing real-time data and products based on MODIS and AIRS data to NWS forecasters on an experimental basis to improve short-term weather forecasts. Le Marshall et al. (2006a) have demonstrated that assimilation of AIRS measurements can significantly improve medium-range forecasts within the NCEP operational Global Forecast System (GFS). To demonstrate the impact of assimilating hyperspectral data on short-term (0–48 h) weather forecasts in the NPOESS era, SPoRT has assimilated AIRS temperature and moisture profiles to initialize the Weather Research and Forecasting (WRF) model. The AIRS profiles convey detail in temperature and moisture in regions that are otherwise sparsely observed. By improving the initial analyses, the corresponding forecasts are also improved. Assimilation of direct radiances eliminates the retrieval error from the total error of the observation and strengthens the impact of the observation. The AIRS radiances were also assimilated into the NCEP operational North American Model (NAM) at SPoRT, with cooperation and resources from the Joint Center for Satellite Data Assimilation (JCSDA). Though the operational NAM runs to 84 h, the focus of verification has been on the short-term forecasts. The experiment consisted of two runs, a control run (all data operationally assimilated in the NAM data assimilation system) and a run in which AIRS radiances were used in addition to the control.

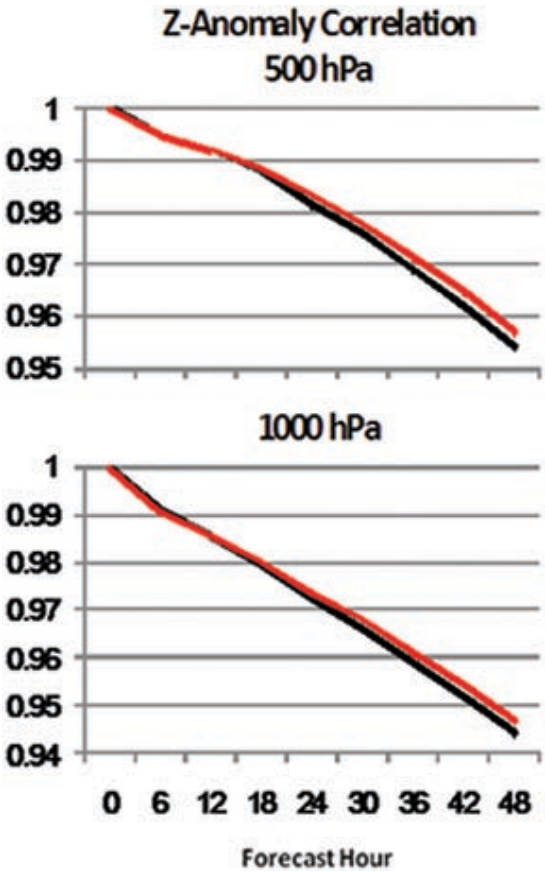

Fig. 3. Height anomaly correlations for the control (black) and the AIRS experiment (red) at (top) 500 and (bottom) 1000 hPa for forecasts spawned during 9–16 Apr 2007.

Over the United States, the addition of AIRS data (Fig. 3) to the data assimilation system produced a forecast improvement of 3 h at 500 hPa (for the 48-h forecasts). Similar improvements appear for 1,000 hPa.

MODIS dust/smoke detection (anticipating VIIRS). Multispectral techniques are being used to identify, distinguish between, and characterize various forms of atmospheric aerosols. Using blue-light absorption techniques, VIIRS dust detection capability can be simulated using MODIS data (e.g., Miller 2003; Hsu et al. 2004). Smoke plumes from an exceptional wildfire outbreak in October 2007 are readily apparent in a true color image (left panel of Fig. 4). The strong offshore winds also lofted thick plumes of dust, which are enhanced in pink/red by virtue of their enhanced blue-light absorption (right side of Fig. 4).

Ozone monitoring (anticipating OMPS). Ozone measurements from the OMPS will provide estimates of total column ozone vertical profiles for both operational and climate applications. The near-real-time products will be assimilated into NWP models to improve upper-tropospheric radiative heating profile accuracy into ozone fields to improve surface ultraviolet index forecasts and into air quality models as upper-boundary conditions establishing transport and external sources for respiratory health applications. The products will be used on medium-

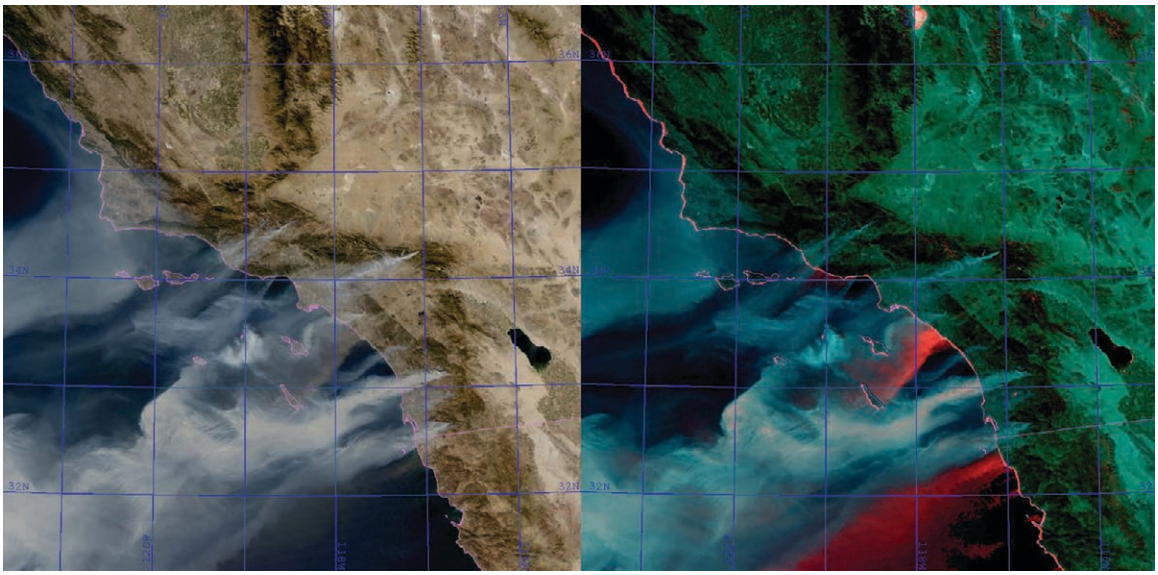

Fig. 4. Strong winds fan the flames of wildfires and blow plumes of dust and smoke off the coast of Southern California on 22 Oct 2007. Imagery from (left) NASA's *Aqua* MODIS (2055 UTC) in true color and (right) with the dust enhancement (dust in red and smoke in bluish brown) distinguishes between these plumes. NPOESS/VIIRS will offer similar capabilities on an operational platform.

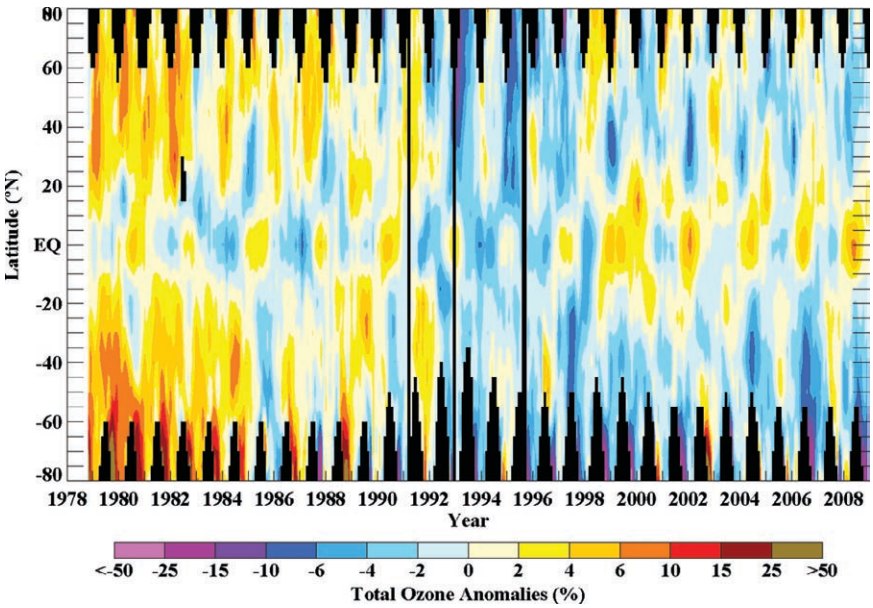

Fig. 5. Time series of monthly average anomalies (percent) of zonal mean total ozone derived from *Nimbus-7* SBUV (Nov 1979–Dec 1988), *NOAA-11* SBUV/2 (Jan 1989–Dec 1993), *NOAA-9* SBUV/2 (Jan 1994–Dec 1995), *NOAA-14* (Jan 1996–Dec 1998), *NOAA-11* (Jan 1999–Dec 2000), *NOAA-16* (Jan 2001–Dec 2005), and *NOAA-17* (Jan 2006–present). Black areas indicate insufficient sunlight to make measurements.

range time scales to monitor ozone variability in the polar regions (e.g., the seasonal development of the Antarctic ozone hole; Stolarski et al. 2005). The data will be used for longer-term assessments of the expected recovery of the ozone layer and to study the complex interactions involved in climate change. The OMPS measurements will also provide information on aerosols (based on a UV aerosol index from the nadir measurements and stratospheric aerosol profiles from the limb instrument), atmospheric SO_2, and surface and cloud reflectivity. The 30-yr time series of global ozone anomalies derived from NOAA's SBUV and SBUV/2 instruments (Fig. 5) shows the general decline at midlatitudes in both hemispheres. OMPS will maintain long-term continuity of this climate record while contributing improved measurements of ozone profiles in the stratosphere where changes in the ozone layer are occurring.

Soil moisture monitoring (anticipating MIS). Soil moisture is a key environmental variable in the global water, energy, and carbon cycles and in environmental assessment and prediction. It greatly affects a broad range of scientific and operational applications in hydrology, climate studies, and agriculture. Soil moisture is also a desired input parameter to NWP models because it controls the land–atmosphere interaction, such as dust emission and heating/moistening of the lower atmosphere. Microwave radiometry offers the direct sensing of surface soil moisture through the large contrast of dielectric constant between soil and water at microwave frequencies. The NPOESS MIS will have the needed 6–37-GHz channels as previewed by the WindSat radiometer launched in 2003 (Gaiser et al. 2004). The NPOESS MIS will be the first operational satellite sensor capable of a soil moisture product.

The prototype WindSat algorithms were validated against multitemporal- and multispatial-scale data of soil moisture climatology, ground in situ network data, precipitation patterns, and vegetation data from AVHRR and MODIS sensors. The WindSat soil moisture retrievals agree very well with the in situ data, with an uncertainty of about 4%, a bias of 0.4%, and a correlation coefficient of 0.89. At the global scale, the soil moisture retrievals in Fig. 6 are very consistent with the dry/wet patterns of climate regimes, capturing well the deserts and arid regions,

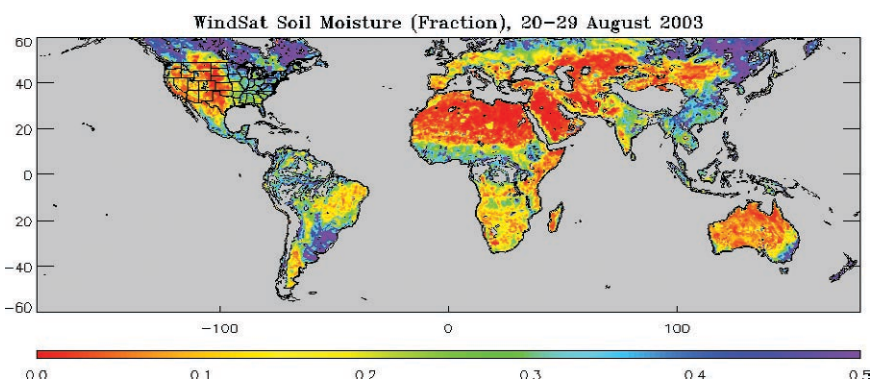

Fig. 6. WindSat global soil moisture retrievals for 20–29 Aug 2003.

as well as the two distinct patterns of continental climate in the United States: the humid east and the arid west. At the synoptic scale, the spatial distribution of retrieved soil moisture is consistent with major precipitation patterns following extreme short-term drought conditions. A temporal two-dimensional variational (2DVAR) soil moisture retrieval system is in development to extend these retrievals to depths greater than 1 m (Jones et al. 2004, 2008).

USER TRAINING. In the past, lack of available training for users has hindered the understanding, acceptance, and use of products from new sensors on recently launched satellites. In some cases, important applications were overlooked for a year or more simply because users did not understand the purpose and capabilities of the new sensors. To promote rapid use of data and products from NPP and NPOESS shortly after launch, the NPOESS program has been supporting the development of education and training modules that simulate NPOESS-era products well ahead of launch. Over the past six years, the Cooperative Program for Operational Meteorology, Education and Training (COMET) has developed satellite training on the capabilities, applications, and relevance of NPP and NPOESS to operational weather forecasters and other communities (Lee et al. 2007). Complementary training resources are hosted on the NRL Next Generation Weather Satellite Demonstration Project (NexSat) Web site (available online at www.nrlmry.navy.mil/NEXSAT.html), which displays real-time imagery from current operational (e.g., POES and DMSP) and research (e.g., NASA's EOS *Terra* and *Aqua*) satellites. The site highlights the expected capabilities of comparable sensors on the future NPP and NPOESS spacecraft (Miller et al. 2006). The goal is to ensure that forecasters and other users will be prepared to use data and products from NPP and NPOESS on "day 1" of operations.

To this end, imagery and radiance data from MODIS on NASA's EOS *Terra* and *Aqua* satellites are being used to simulate the expected capabilities and performance of VIIRS on NPOESS. Current users of the multispectral features on MODIS are paving the way for VIIRS. Multispectral MODIS products now routinely support military operations in the Middle East and Southwest Asia. Products issued by NRL, FNMOC, and AFWA aid in the detection of dust storms, observation of low clouds at night, and monitoring of convective storms.

CONCLUSIONS. In the next decade, NPOESS will be the principal U.S. operational, polar-orbiting, space-based observing system for weather forecasting and climate monitoring. Consistency of radiometric measurements from NPOESS instruments and similar instruments on EUMETSAT's MetOp spacecraft will help improve present NWP weather forecasting capabilities and allow forecasters to extend the range of forecasts for the United States. Weather satellites currently provide more than 99% of the data that are assimilated into NWP models and increase the accuracy of the models as much or more than data from all other observing systems combined. NPOESS will continue this role and will provide timely measurements needed to derive critical quantitative weather products. Use of NPOESS data will extend beyond NWP centers to regional and local weather forecast offices to support specialized forecast products. NPOESS spacecraft, flying in controlled, stable orbits, will carry well-calibrated instruments suitable for long-term monitoring of essential climate variables, including sea and land surface temperature, water vapor, cloud properties, ozone, aerosols, and winds.

NPOESS will support the operational needs of the civilian meteorological, oceanographic, environmental, climatic, and space environmental remote sensing programs, and it will provide global military environmental support, including geophysical and near-Earth space weather support. In addition, NPOESS data will be available to more than 120 different nations around the world. The advanced-technology visible, infrared, and microwave imagers and sounders that will fly on NPOESS will deliver higher spatial- and spectral-resolution oceanic, atmospheric, terrestrial, climatic, and solar–geophysical data, enabling more accurate short-term weather forecasts and severe storm warnings. These data will be assimilated into NWP models to improve short- to medium-range weather forecasts.

The NPOESS architecture will enable data to be used faster and more frequently in numerical weather prediction models for improved environmental forecasts and warnings. Shortly after NPOESS becomes operational, NOAA will also be implementing the Geostationary Operational Environmental Satellite-R (GOES-R) program with the first satellite launch in ~2015. NPOESS and GOES-R will carry similar advanced-technology, high-resolution visible/infrared imagers to provide the weather forecasting community with highly complementary data. Together, NPOESS and GOES-R will serve as the basis of the U.S. contribution to build the Global Earth Observation System of Systems (GEOSS) supporting the "nine societal benefits areas." A global network of observing systems, combined with improvements

in NWP models and weather information processing and display systems, will allow scientists to improve weather forecasts, predict energy needs months in advance, monitor forest fires and volcanic ash, issue timely warnings of air quality effects, and anticipate outbreaks of environment-related diseases. NPOESS and GOES-R will provide essential real-time data to the international community to support weather forecasting, as well as continuity of critical data for monitoring, understanding, and predicting climate change and assessing the impacts of climate change on seasonal and longer time scales. The return on investments in NPOESS and GOES-R will benefit the general public in the United States and the international community for decades to come.

ACKNOWLEDGMENTS. The support of the research sponsors 1) the National Polar-orbiting Operational Environmental Satellite System Integrated Program Office located in Silver Spring, Maryland; 2) the Office of Naval Research under Program Element PE-0602435N; and 3) the Oceanographer of the Navy through the program office at the Space and Naval Warfare Systems Command, PEO C4I and PMW-120 under Program Element PE-0603207N, is gratefully acknowledged. We thank Jeffrey Hawkins from NRL and John Furgerson from the IPO for several insightful suggestions.

REFERENCES

Bettenhausen, M. H., C. K. Smith, R. M. Bevilacqua, N.-Y. Wang, P. W. Gaiser, and S. Cox, 2006: A nonlinear optimization algorithm for WindSat wind vector retrievals. *IEEE Trans. Geosci. Remote Sens.,* **44,** 597–608.

Christy, J. R., R. W. Spencer, W. B. Norris, W. D. Braswell, and D. E. Parker, 2003: Error estimates of version 5.0 of MSU–AMSU bulk atmospheric temperatures. *J. Atmos. Oceanic Technol.,* **20,** 613–629.

Elvidge, C. D., K. E. Baugh, V. R. Hobson, E. A. Kihn, and H. W. Kroehl, 1998: Detection of fires and power outages using DMSP-OLS data. *Remote Sensing Change Detection: Environmental Monitoring Methods and Applications*, R. S. Lunetta and C. D. Elvidge, Eds., Ann Arbor Press, 123–135.

Flynn, L., C. Seftor, J. Larsen, and P. Xu, 2006: The ozone mapping and profiler suite. *Science and Instruments,* J. J. Qu et al., Eds., Vol. 1, *Earth Science Satellite Remote Sensing,* Springer, 279–296.

Gaiser, P. W., and Coauthors, 2004: The WindSat spaceborne polarimetric microwave radiometer: Sensor description and early orbit performance. *IEEE Trans. Geosci. Remote Sens.,* **42,** 2347–2361.

Goldberg, M. D., and F. Weng, 2006: Advanced technology microwave sounder. *Science and Instruments,* J. J. Qu et al., Eds., Vol. 1, *Earth Science Satellite Remote Sensing,* Springer, 243–253.

Goodman, S. J., W. M. Lapenta, G. J. Jedlovec, J. C. Dodge, and J. T. Bradshaw, 2004: The NASA Short-term Prediction Research and Transition (SPoRT) Center: A collaborative model for accelerating research into operations. Preprints, *20th Conf. on Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology,* Seattle, WA, Amer. Meteor. Soc., P1.34. [Available online at http://ams.confex.com/ams/pdfpapers/70210.pdf.]

Harder, J., G. Lawrence, J. Fontenla, G. Rottman, and T. Woods, 2005: The spectral irradiance monitor: Scientific requirements, instrument design, and operation modes. *Sol. Phys.,* **230,** 141–167.

Hsu, N. C., S.-C. Tsay, M. D. King, and J. R. Herman, 2004: Aerosol properties over bright-reflecting source regions. *IEEE Trans. Geosci. Remote Sens.,* **42,** 557–569.

Huang, H.-L., and Coauthors, 2004: International MODIS and AIRS Processing Package (IMAPP): A direct broadcast software package for the NASA Earth Observing System. *Bull. Amer. Meteor. Soc.,* **85,** 159–161.

Jedlovec, G. J., S. L. Haines, R. J. Suggs, T. Bradshaw, C. Darden, and J. E. Burks, 2004: Use of EOS data in AWIPS for weather forecasting. Preprints, *20th Conf. on Weather Analysis and Forecasting/16th Conf. on Numerical Weather Prediction,* Seattle, WA, Amer. Meteor. Soc., 2.2. [Available online at http://ams.confex.com/ams/pdfpapers/69955.pdf.]

Johnson, D. B., P. Flament, and R. L. Bernstein, 1994: High-resolution satellite imagery for mesoscale meteorological studies. *Bull. Amer. Meteor. Soc.,* **75,** 5–33.

Jones, A. S., T. Vukicevic, and T. H. Vonder Haar, 2004: A microwave satellite observational operator for variational data assimilation of soil moisture. *J. Hydrometeor.,* **5,** 213–229.

——, and Coauthors, 2008: An NPOESS feasibility study to retrieve deep soil moisture using WindSat data and a temporal variational data assimilation method. Preprints, *Fourth Symp. on Future National Operational Environmental Satellite Systems,* New Orleans, LA, Amer. Meteor. Soc., P1.16. [Available online at http://ams.confex.com/ams/88annual/techprogram/paper_135607.htm.]

Klaes, K. D., and Coauthors, 2007: An introduction to the EUMETSAT polar system. *Bull. Amer. Meteor. Soc.,* **88,** 1085–1096.

Kopp, G., and G. Lawrence, 2005: The Total Irradiance Monitor (TIM): Instrument design. *Sol. Phys.,* **230,** 91–109.

Lee, T. F., S. D. Miller, C. Schueler, and S. Miller, 2006a: NASA MODIS previews NPOESS VIIRS capabilities. *Wea. Forecasting,* **21,** 649–655.

——, ——, F. J. Turk, C. Schueler, R. Julian, S. Deyo, P. Dills, and S. Wang, 2006b: The NPOESS VIIRS day/night visible sensor. *Bull. Amer. Meteor. Soc.,* **87,** 191–199.

——, and Coauthors 2007: NPOESS online satellite training for users. *Bull. Amer. Meteor. Soc.,* **88,** 13–16.

Le Marshall, J., and Coauthors, 2006a: Improving global analysis and forecasting with AIRS. *Bull. Amer. Meteor. Soc.,* **87,** 891–894.

——, J. Jung, T. Zapotocny, J. Derber, R. Treadon, S. Lord, M. Goldberg, and W. Wolf, 2006b: The application of AIRS radiances in numerical weather prediction. *Aust. Meteor. Mag.,* **55,** 213–217.

Mears, C. A., and F. J. Wentz, 2005: The effect of diurnal correction on satellite-derived lower tropospheric temperature. *Science,* **309,** 1548–1551.

Miller, S. D., 2003: A consolidated technique for enhancing desert dust storms with MODIS. *Geophys. Res. Lett.,* **30,** 2071, doi:10.1029/2003GL018279.

——, and Coauthors, 2006: NexSat: Previewing NPOESS/VIIRS imagery capabilities. *Bull. Amer. Meteor. Soc.,* **87,** 433–446.

Murphy, R. E., 2006: The NPOESS Preparatory Project. *Science and Instruments,* J. J. Qu et al., Eds., Vol. 1, *Earth Science Satellite Remote Sensing,* Springer, 182–198.

——, P. Ardanuy, F. J. Deluccia, J. E, Clement, and C. F. Schueler, 2006: The visible infrared imaging radiometer suite. *Science and Instruments,* J. J. Qu et al., Eds., Vol. 1, *Earth Science Satellite Remote Sensing,* Springer, 199–223.

National Research Council, 2007: *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond.* The National Academies Press, 456 pp.

Stolarski, R. S., R. D. McPeters, and P. A. Newman, 2005: The ozone hole of 2002 as measured by TOMS. *J. Atmos. Sci.,* **62,** 716–720.

Surussavadee, C., and D. H. Staelin, 2008: NPOESS precipitation retrievals using the ATMS passive microwave spectrometer. *Proc. Int. Geoscience and Remote Sensing Symp. (IGARSS),* Boston, MA, IEEE, Vol. 5, 570–573.

Susskind, J., 2006: Introduction to AIRS and CrIS. *Science and Instruments,* J. J. Qu et al., Eds., Vol. 1, *Earth Science Satellite Remote Sensing,* Springer, 254–278.

Wielicki, B. A., B. R. Barkstrom, E. F. Harrison, R. B. Lee III, G. L. Smith, and J. E. Cooper, 1996: Clouds and the Earth's Radiant Energy System (CERES): An Earth Observing System experiment. *Bull. Amer. Meteor. Soc.,* **77,** 853–868.