Satellite Instrument Calibration for Measuring Global Climate Change
Report of a Workshop

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Is the earth's climate changing? If so, at what rate? Are the causes natural or human induced? What will the climate be like in the future? These are critical environmental and geopolitical issues of our times. Increased knowledge, in the form of answers to these questions, is the foundation for developing appropriate response strategies to global climate change. Accurate global observations from space are a critical part of the needed knowledge base.

Measuring the small changes associated with long-term global climate change from space is a daunting task. For example, the satellite instruments must be capable of observing atmospheric and surface temperature trends as small as 0.1°C decade^{-1}, ozone changes as little as 1% decade^{-1}, and variations in the sun's output as tiny as 0.1% decade^{-1}.

The importance of understanding and predicting climate variation and change has escalated significantly in the last decade. In 2001, the White House requested that the National Academy of Sciences (NAS) National Research Council (NRC) (NRC 2001a) review the uncertainties in climate change science. One of the three key recommendations from the NRC's report is to "ensure the existence of a long-term monitoring system that provides a more definitive observational foundation to evaluate decadal- to century-scale changes, including observations of key state variables and more comprehensive regional measurements." To accelerate federal research and reduce uncertainties in climate change science, in June 2001, President George W. Bush created the Climate Change Research Initiative (CCRI).

WORKSHOP ON SATELLITE INSTRUMENT CALIBRATION FOR MEASURING GLOBAL CLIMATE CHANGE

WHAT: About 75 scientists specializing in satellite calibration and researchers who develop and analyze long-term satellite data met to recommend instrumentation improvements to accurately measure Earth's changing climate.
WHEN: 12–14 November 2002
WHERE: College Park, Maryland

To develop recommendations for improving the calibration of satellite instruments to meet the challenge of measuring global climate change, the National Institute of Standards and Technology (NIST), the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Program Office (IPO), the National Oceanic and Atmospheric Administration (NOAA), and the National Aeronautics and Space Administration (NASA) organized a workshop at the University of Maryland Inn and Conference Center, College

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Park, Maryland, 12–14 November 2002. Some 75 scientists, including researchers who develop and analyze long-term datasets from satellites, experts in the field of satellite instrument calibration, and physicists working on state-of-the-art calibration sources and standards, participated in the workshop. Workshop activities consisted of keynote papers, invited presentations, breakout groups, and the preparation of draft input for a workshop report. The keynote papers and invited presentations provide extensive background information on issues discussed at the workshop and are posted on the NIST Web site at http://physics.nist.gov/Divisions/Div844/global/mgcc.html. (Please note that to access this site, you have to input user name, mgccoutline, and password, div844mgcc.) The workshop organizing committee consisted of R. Datla, Chair, NIST; G. Ohring, Consultant; M. Weinreb, NOAA; S. Mango, NPOESS IPO; J. Butler, NASA; and D. Pollock, University of Alabama (UAH).

The workshop had a single clearly defined goal: develop requirements and recommend directions for future improvements in satellite instrument characterization, calibration, intercalibration, and associated activities to enable measurements of global climate change that are valid beyond a reasonable doubt. Although many of the recommendations are directed at the NPOESS program, the nation's converged future civilian and military polar-orbiting operational environmental satellite system, most also apply to sustained space-based climate change observations in general. To achieve this goal, the workshop first defined the absolute accuracies and long-term stabilities of global climate datasets that are needed to detect expected trends. These accuracies and stabilities were then translated to the required satellite instrument accuracies and stabilities. The workshop then evaluated the ability of the current observing systems to meet these requirements.

The focus was on passive satellite sensors that make observations in spectral bands ranging from the ultraviolet to the microwave. The climate change variables of interest include the following:

- solar irradiance, earth radiation budget, and clouds (total solar irradiance, spectral solar irradiance, outgoing longwave radiation, net incoming solar radiation, cloudiness),
- atmospheric variables (temperature, water vapor, ozone, aerosols, precipitation, and carbon dioxide), and
- surface variables (vegetation, snow cover, sea ice, sea surface temperature, and ocean color).

This list is not exhaustive. The variables were selected on the basis of the following criteria: 1) importance to decadal-scale climate change, 2) availability or potential availability of satellite-based climate data records, and 3) measurability from passive satellite sensors. The workshop breakout groups were aligned with the above three groups of climate variables.

While previous workshops have also discussed accuracy and stability measurement requirements for long-term climate datasets (e.g., Hansen et al. 1993; Jacobowitz 1997; NPOESS 2001) and calibration issues (Guenther et al. 1997; NRC 2000, 2001b), the present document is an end-to-end report. It not only covers the latest thinking on measurement requirements but also *provides general directions to improve satellite instrument characterization, calibration, vicarious calibration, interinstrument calibration, and associated activities to meet the requirements.* This general road map provides guidance to the national agencies concerned with the development of the space system and related calibration program to measure global climate change—NPOESS IPO, NOAA, NIST, and NASA.

Measuring small changes over extended time periods necessarily involves the accuracy and stability of time series. Accuracy is measured by the bias or systematic error of the data, that is, the difference between the short-term-average measured value of a variable and the truth. The short-term average is the average of a sufficient number of successive measurements of the variable under identical conditions, such that the random error is negligible relative to the systematic error. Stability may be thought of as the extent to which the accuracy remains constant with time. Stability is measured by the maximum excursion of the short-term-average measured value of a variable under identical conditions over a decade. The smaller the maximum excursion, the greater the stability of the dataset.

The methods to establish the true value of a variable (the measurand) should be consistent with the internationally adopted methods and standards, thus, establishing the International System of Units (SI) traceability (BIPM 1998; Taylor 1995).

The spatial scale of interest to the workshop is generally that of global averages. This is not to say that regional climate change is not important. On the contrary, just as all politics are local, all climate changes are regional [e.g., desertification, monsoonal changes, ocean color (coral death), and snow/ice cover (retreating snow lines and decreasing sea ice cover/receding glaciers)]. Because trends in globally averaged data will generally be smaller than those of regional averages, meeting global average requirements will ensure meeting regional climate-monitoring requirements.

OVERARCHING PRINCIPLES. The workshop developed a set of basic axioms, or overarching principles, that must guide high-quality climate observations in general. The principles include many of the 10 climate observing principles outlined in the NRC report on climate-observing systems (NRC 1999), and the additional principles for satellite-based climate observations that were adopted by the Global Climate Observing System (GCOS; GCOS 2003). But; in some cases, they go beyond both of those recommendations, especially relative to the NOAA, NASA, and NPOESS satellite systems.

Adherence to these principles and implementation of the road map for calibration improvements will ensure that satellite observations are of sufficient accuracy and stability not only to indicate that climate change has occurred, but also to prove it beyond reasonable doubt and permit evaluation of climate forcing and feedbacks.

These key climate observation principles are given below. (Some of these, while specifically directed at NPOESS, a major future contributor to the nation's climate-monitoring program, are also applicable to all satellite climate-monitoring systems):

1) Satellite systems
   - Establish clear agency responsibilities for the U.S. space-based climate-observing system.
   - Acquire multiple independent space-based measurements of key climate variables.
   - Ensure that launch schedules reduce the risk of a gap in the time series to less than 10% probability for each climate variable.
   - Add highly accurate measurements of spectrally resolved reflected solar and thermal infrared radiation to the NPOESS Environmental Data Record (EDR) list.
   - Increase U.S. multiagency and international cooperation to achieve a rigorous climate-observing system.
2) Calibration
   - Elevate climate calibration requirements to critical importance in NPOESS.
   - Develop characterization requirements for all instruments and ensure that these are met.
   - Conduct prelaunch calibration round robins for most NPOESS and Geostationary Operational Environmental Satellite (GOES)-R instruments using NIST transfer radiometers.
   - Simplify the design of climate-monitoring instruments.
   - Implement redundant calibration systems.
   - Establish means to monitor the stability of the sensors.
3) Climate data records (CDRs)
   - Define measurement requirements for CDRs.
   - Establish clear responsibility and accountability for the generation of climate data records.
   - Arrange for production and analysis of each CDR independently by at least two sources.
   - Organize CDR science teams.
   - Develop archive requirements for NPOESS CDRs.

REQUIRED ACCURACIES AND STABILITIES FOR CLIMATE VARIABLES. The required accuracies and stabilities of the climate variable datasets were established with the consideration of changes in important climate signals based on current understanding and models of long-term climate change. Such signals include the following:

- climate changes or expected trends predicted by models,
- significant changes in climate forcing or feedback variables (e.g., radiative effects comparable to that of increasing greenhouse gases), and
- trends similar to those observed in past decades.

The first step in the process is specifying the anticipated signal in terms of expected change per decade. The second step is determining the accuracies and stabilities needed in the dataset to permit detection of the signal. Excellent absolute accuracy in the measurement of the climate variable is vital for understanding climate processes and changes. Continuous efforts should be undertaken to constantly improve the accuracy of satellite instruments. However, such accuracy is not as necessary for determining long-term changes or trends as long as the dataset has the required stability, and, when it comes to building satellite instruments, stability appears to be less difficult to achieve than accuracy. The difficulty arises because of the many known and unknown systematic uncertainties that are to be accounted for in the calibration of the instrument on the ground to establish its absolute accuracy and transfer and monitor the calibration in orbit. Stability, on the other hand, is the measure of repeatability and reproducibility of the metrological characteristics of the instrument with time. Thus, a key attribute for the climate datasets is long-term stability. The required stability is some fraction of the expected signal, assumed to be 0.2 by the workshop participants. If we cannot achieve the above stability, for example, if we can only achieve a stability of 0.5 of the signal, there would be an increased uncertainty in the determination of the decadal rate of change.

The stability factor 0.2, or 20%, is somewhat arbitrary. It should be periodically reevaluated. If the climate signal is one unit per decade, a ±20% stability would imply an uncertainty range of 0.8–1.2, or a factor 1.5, in our estimate of the signal. One basis for choosing such a factor is related to the uncertainty in climate model predictions of climate change. Thirty-five climate model simulations yield a total range of 1.4–5.8 K, or a factor of about 4, in the change in global temperature by 2100 (IPCC 2001). Thus, an observational stability of ±20% should lead to a considerable narrowing of the possible model simulations of climate change. Achieving the stability requirement does not guarantee determining these long-term trends. Superimposed on these trends is climatic noise—short-term climate variations—that may mask the signal we are trying to detect or reduce our confidence in the derived trend.

Table 1 summarizes the required accuracies and stabilities of the datasets for the solar irradiance, earth radiation budget, and cloud variables; the atmospheric variables; and the surface variables. The table also indicates which one of the above climate signals—climate changes, climate forcings, climate feedbacks, or trends similar to those in recent trends—forms the basis for the requirement.

TRANSLATION OF CLIMATE DATASET ACCURACIES AND STABILITIES TO SATELLITE INSTRUMENT ACCURACIES AND STABILITIES. The requirements for the datasets must be translated into required accuracies and stabilities of the satellite measurements. In some cases, for example, solar irradiance and top-of-the-atmosphere (TOA) earth radiation budget, there is a one-to-one correspondence. For other climate variables, this translation is more complex, and for a few of the variables, additional studies are needed to determine the mapping of dataset accuracies/stabilities into satellite accuracies/stabilities.

Long-term stability may be achieved by either having an extremely stable instrument or by monitoring the instrument's stability while it is in orbit. An ideal external calibration source is nearly constant in time and can be viewed from different orbit configurations. If there is scientific evidence regarding the degree of stability of such a source, and it is believed to be at an acceptable level for long-term climate studies, then the stability of the satellite sensor can be assessed independent of other reference standards. With such monitoring, instrument readings can be corrected for lack of stability. However, this brings up a measurement challenge for establishing the degree of stability of the external reference source. Obviously, the methods and instruments testing the stability of those sources must have stability requirements that are far more stringent than those given in this summary. One method that has been successfully implemented for the reflected solar spectral interval is lunar observations, from orbit, with the sensor. One example is the ocean color satellite Sea-viewing Wide Field-of-View Sensor (SeaWiFS), which used lunar observations to correct for degradation in the near-infrared channels (Barnes et al. 2004). The required reference lunar reflectance data are being supplied by a dedicated ground-based facility (Anderson et al. 1999).

Because satellites and their instruments are short term—NPOESS satellites and instruments have design lives of about 7 yr—the long-term data record consists of contributions from a series of satellite instruments, some using different techniques. To assess the reproducibility of the measurement results, to assist in understanding the differences that arise even with instruments of similar design, and to create a seamless data record, it is essential that the satellites be launched on a schedule that includes an overlap interval of the previous and the new instrument. This cannot be achieved if the policy is to "launch on failure" of the existing satellite. Acquiring multiple independent space-based measurements of key climate variables—one of the climate-observing principles listed above—would also help ensure maintenance of stability in the event of a single instrument failure.

One instrument that may have very high accuracy and may not require overlap periods is the proposed spectrally resolved radiance spectrometer (Anderson et al. 2004). Sequential flights of copies of this instrument might maintain the climate record without overlapping measurements.

Table 2 summarizes the required accuracies and stabilities of the satellite instruments for solar irradiance, earth radiation budget, and cloud variables; the atmospheric variables; and the surface variables. The table also indicates the types of satellite instruments used for the measurements.

TABLE 1. Required accuracies and stabilities for climate variable datasets. Column labeled "signal" indicates the type of climate signal used to determine the measurement requirements.

	Signal	Accuracy	Stability (per decade)
Solar irradiance, earth radiation budget, and cloud variables			
Solar irradiance	Forcing	1.5 W m^{-2}	0.3 W m^{-2}
Surface albedo	Forcing	0.01	0.002
Downward longwave flux: surface	Feedback	1 W m^{-2}	0.2 W m^{-2}
Downward shortwave radiation: surface	Feedback	1 W m^{-2}	0.3 W m^{-2}
Net solar radiation: top of atmosphere	Feedback	1 W m^{-2}	0.3 W m^{-2}
Outgoing longwave radiation: top of atmosphere	Feedback	1 W m^{-2}	0.2 W m^{-2}
Cloud-base height	Feedback	0.5 km	0.1 km
Cloud cover (fraction of sky covered)	Feedback	0.01	0.003
Cloud particle size distribution	Feedback	TBD	TBD
Cloud effective particle size	Forcing: water Feedback: ice	Water: 10% Ice: 20%	Water: 2% Ice: 4%
Cloud ice water path	Feedback	25%	5%
Cloud liquid water path	Feedback	0.025 mm	0.005 mm
Cloud optical thickness	Feedback	10%	2%
Cloud-top height	Feedback	150 m	30 m
Cloud-top pressure	Feedback	15 hPa	3 hPa
Cloud-top temperature	Feedback	1 K/cloud emissivity	0.2 K/cloud emissivity
Spectrally resolved thermal radiance	Forcing/climate change	0.1 K	0.04 K
Atmospheric variables			
Temperature			
Troposphere	Climate change	0.5 K	0.04 K
Stratosphere	Climate change	0.5 K	0.08 K
Water vapor	Climate change	5%	0.26%
Ozone			
Total column	Expected trend	3%	0.2%
Stratosphere	Expected trend	5%	0.6%
Troposphere	Expected trend	10%	1.0%
Aerosols			
Optical depth (troposphere/ stratosphere)	Forcing	0.01/0.01	0.005/0.005
Single scatter albedo (troposphere)	Forcing	0.03	0.015
Effective radius (troposphere/ stratosphere)	Forcing	greater of 0.1 or 10%/0.1	greater of 0.05 or 5%/0.05
Precipitation		0.125 mm h^{-1}	0.003 mm h^{-1}
Carbon dioxide	Forcing/Sources–sinks	10 ppmv/10 ppmv	2.8 ppmv/1 ppmv
Surface variables			
Ocean color		5%	1%
Sea surface temperature	Climate change	0.1 K	0.04 K
Sea ice area	Forcing	5%	4%
Snow cover	Forcing	5%	4%
Vegetation	Past trend	3%	1%

TABLE 2. Required accuracies and stabilities of satellite instruments to meet requirements of Table 1. The instrument column indicates the type of instrument used to make the measurement.

	Instrument	Accuracy	Stability (per decade)
Solar irradiance, earth radiation budget, and cloud variables			
Solar irradiance	Radiometer	1.5 W m^{-2}	0.3 W m^{-2}
Surface albedo	VIS radiometer	5%	1%
Downward longwave flux: surface	IR spectrometer and VIS/IRradiometer	See tropospheric temperature, water vapor, cloud-base height, and cloud cover	See tropospheric temperature water vapor, cloud-base height, and cloud cover
Downward shortwave radiation: surface	Broadband solar and VIS/IR radiometer	See net solar radiation: TOA, cloud particle effective size, cloud optical depth, cloud-top height, and water vapor	See net solar radiation: TOA, cloud particle effective size, cloud optical depth, cloud-top height, and water vapor
Net solar radiation: top of atmosphere	Broadband solar	1 W m^{-2}	0.3 W m^{-2}
Outgoing longwave radiation: top of atmosphere	Broadband IR	1 W m^{-2}	0.2 W m^{-2}
Cloud-base height	VIS/IR radiometer	1 K	0.2 K
Cloud cover (fraction of sky covered)	VIS/IR radiometer	See cloud optical thickness and cloud-top-temperature	See cloud optical thickness and cloud-top-temperature
Cloud particle size distribution	VIS/IR radiometer	TBD	TBD
Cloud effective particle size	VIS/IR radiometer	3.7 μm: water, 5%; ice, 10% 1.6 μm: water, 2.5%; ice, 5%	3.7 μm: Water, 1%; Ice, 2% 1.6 μm: Water, 0.5%; Ice, 1%
Cloud ice water path	VIS/IR radiometer	TBD	TBD
Cloud liquid water path	Microwave and VIS/IR radiometer	Microwave: 0.3 K VIS/IR: see cloud optical thickness and cloud-top height	Microwave: 0.1 K VIS/IR: see cloud optical thickness and cloud-top height
Cloud optical thickness	VIS radiometer	5%	1%
Cloud-top height	IR radiometer	1 K	0.2 K
Cloud-top pressure	IR radiometer	1 K	0.2 K
Cloud-top temperature	IR radiometer	1 K	0.2 K
Spectrally resolved thermal radiance	IR spectroradiometer	0.1 K	0.04 K
Atmospheric variables			
Temperature			
Troposphere	MW or IR radiometer	0.5 K	0.04 K
Stratosphere	MW or IR radiometer	1 K	0.08 K
Water vapor	MW radiometer IR radiometer	1.0 K 1.0 K	0.08 K 0.03 K
Ozone			
Total column	UV/VIS spectrometer	2% (λ independent), 1% (λ dependent)	0.2%
Stratosphere	UV/VIS spectrometer	3%	0.6%
Troposphere	UV/VIS spectrometer	3%	0.1%
Aerosols	VIS polarimeter	Radiometric: 3% Polarimetric: 0.5%	Radiometric: 1.5% Polarimetric: 0.25%
Precipitation	MW radiometer	1.25 K	0.03 K
Carbon dioxide	IR radiometer	3%	Forcing: 1%; Sources/sinks: 0.25%
Surface variables			
Ocean color	VIS radiometer	5%	1%
Sea surface temperature	IR radiometer	0.1 K	0.01 K
	MW radiometer	0.03 K	0.01 K
Sea ice area	VIS radiometer	12%	10%
Snow cover	VIS radiometer	12%	10%
Vegetation	VIS radiometer	2%	0.80%

ABILITY OF CURRENT OBSERVING SYSTEMS TO MEET REQUIREMENTS.

Table 3 indicates the ability of current satellite instruments to meet the requirements for accuracy and stability that are spelled out in Table 2. Most current observing systems have not been designed to measure the small changes over long time periods that are of concern here. The Clouds and Earth's Radiant Energy System (CERES) instrument appears to be meeting the accuracy requirements for earth radiation budget, but it has not been in orbit long enough to determine whether it is meeting the stability requirements. Stability requirements are being met, or appear to be close to being met (stabilities labeled "yes" in Table 3) for solar irradiance, cloud cover, cloud temperature, cloud height, atmospheric temperature, total column water vapor, ozone, ocean color, snow cover, and sea ice measurements. Seamless long-term datasets have been assembled for many of these variables by stitching together observations from successive satellites and exploiting satellite overlap periods to account for systematic differences between successive instruments. However, these datasets have required major collaborative efforts to carefully exam the satellite radiances, reevaluate the algorithms, and consider the validation data. In all cases, more than one reprocessing was required. For most climate variables, current observing systems cannot meet both accuracies and stabilities. In some cases, we do not know whether current systems are adequate, and studies are needed to answer this question.

ROAD MAP FOR FUTURE IMPROVEMENTS IN SATELLITE INSTRUMENT CALIBRATION AND INTERCALIBRATION TO MEET REQUIREMENTS.

It is quite clear from the previous section that we are currently unable to meet the measurement requirements for most of the climate variables. Each of the three workshop panels made recommendations for improving satellite instrument characterization, calibration, intercalibration, and associated activities, and these are listed in the appendix and summarized below. Action on these recommendations and on the overarching principles listed above would permit us to detect climate change signals at a much earlier stage than is possible now.

The specific recommendations generally fall into groups that are consistent with the overarching principles. To ensure continuity and stability of climatic time series, satellite overlap periods from 1 month for outgoing longwave radiation to 1 yr for solar irradiance and atmospheric temperature are recommended. Specific independent observations of the same variable are recommended, for example, verifying Moderate Resolution Imaging Spectroradiometer (MODIS) cloud measurements against Geoscience Laser Altimeter System (GLAS), Calipso, and Cloudsat observations, and conducting full broadband spectrometer observations of reflected and outgoing longwave radiation to compare with NPOESS earth radiation budget observations. Suggested programs to validate satellite datasets include radiometric observations of ocean skin temperatures from ships to validate satellite SSTs, Marine Optical Buoy (MOBY)-type measurements for checking on satellite ocean color observations, ground-based measurements of the normalized difference vegetation index (NDVI) similar to those made from satellites, and expansion of the Baseline Surface Radiation Network for validating satellite-based surface radiation quantities. Recommended improvements in prelaunch instrument characterization include enhancement of NIST spectral sources and transfer radiometers to cover the full reflected solar and emitted infrared (IR) thermal spectra of the earth, enhanced use of NIST's portable calibrated thermal transfer radiometer, and a number of detailed recommendations for ultraviolet (UV), visible (VIS), IR, and microwave instruments. Recommendations for onboard calibration include implementing multiple calibration references—lunar measurements, calibration lamps, and solar diffusers—for monitoring the in-orbit stability of VIS radiometers.

It is recommended that a follow-up workshop be conducted to discuss implementation of the above road map developed at this workshop.

SUMMARY.

Perhaps for the first time a large group of climate dataset producers/users and instrument experts assembled to discuss the problem of measuring global climate change from space. In addition to specific recommendations, the workshop developed a set of overarching principles for satellite systems, satellite instrument calibration, and climate data records that should guide high-quality climate observations in general. The complete workshop report has been published by NIST (Ohring et al. 2004) and should serve as valuable guidance for the federal agencies responsible for implementing the nation's satellite program for monitoring global climate change. A follow-up workshop to discuss implementation of recommendations is in the early planning stages.

Table 3. Ability of current observing systems to meet accuracy and stability requirements.		
	Accuracy	**Stability**
Solar irradiance, earth radiation budget, and cloud variables		
Solar irradiance	No	Yes
Surface albedo	Yes	TBD
Downward longwave flux: surface	No	No
Downward shortwave radiation: surface	No	No
Net solar radiation: top of atmosphere	Yes	Yes?
Outgoing longwave radiation: top of atmosphere	Yes	Yes?
Cloud-base height	No	No
Cloud cover (fraction of sky covered)	No	Yes?
Cloud particle size distribution	TBD	TBD
Cloud effective particle size	TBD	TBD
Cloud ice water path	No	No
Cloud liquid water path	No	No (except thicker clouds over oceans)
Cloud optical thickness	No	TBD
Cloud-top height	No	Yes?
Cloud-top pressure	No	Yes?
Cloud-top temperature	No	Yes?
Spectrally resolved thermal radiance	No	No
Atmospheric variables		
Temperature		
Troposphere	Yes	Yes? (deep layer means)
Stratosphere	Yes	Yes? (deep layer means)
Water vapor		
Total column	Yes	Yes
Profile	?	?
Ozone		
Total column	No	Yes?
Stratosphere	No	Yes?
Troposphere	No	No
Aerosols		
Optical depth	No	No
Single scatter albedo	No	No
Effective radius	No	No
Precipitation	No	?
Carbon dioxide	?	?
Surface variables		
Ocean color	Yes	Yes?
Sea surface temperature	No	No
Sea ice area	Yes	Yes
Snow cover	Yes	Yes
Vegetation	?	No

APPENDIX: LIST OF DETAILED WORKSHOP RECOMMENDATIONS.

1) Solar irradiance, earth radiation budget, and cloud variables
   - i) Solar irradiance
     - Schedule a 1-yr overlap in observations of both solar irradiance and spectral solar irradiance
     - Conduct two independent series of observations to verify accuracy and stability
   - ii) Surface albedo
     - Implement satellite observations of the moon for monitoring visible/near-infrared instrument stability
     - Maintain the same satellite orbits in sequential missions
   - iii) Downward longwave and shortwave radiation at the surface
     - Perform studies to assess the sensitivity of downward longwave radiation to boundary layer temperature and water vapor changes, and downward shortwave radiation to cloud optical depth, cloud particle size, and aerosol optical depth
     - Evaluate the capability of 4D data assimilation models to constrain boundary layer temperature and humidity, and active instruments, such as GLAS, Cloudsat, and Calipso, to constrain cloud base for determination of downward longwave radiation
     - Assimilate aerosol profile data from active instruments, such as GLAS and Calipso, into 4D NWP models to constrain aerosol effects on downward shortwave radiation
     - Expand the Baseline Surface Radiation Network (BSRN) from the current 20 land sites, especially to ocean locations
   - iv) Net solar radiation and outgoing longwave radiation at top of the atmosphere (Earth radiation budget)
     - Plan minimum satellite overlap periods of 3 months for net solar radiation and 1 month for outgoing longwave radiation
     - Fully characterize NPOESS Earth radiation budget detectors (total and shortwave channels) for stability with solar exposure as well as time in vacuum
     - Conduct a second set of Earth radiation budget observations independent of the NPOESS Earth radiation budget measurements. (One possibility is full broadband spectrometers for observations of earth-reflected solar radiation and outgoing longwave radiation.)
     - Enhance NIST spectral sources and transfer radiometers to cover the full reflected solar and emitted thermal IR spectra of the earth
   - v) Cloud-base height
     - Pursue the development and application of active instruments, such as satellite lidar and cloud radar, because they appear to be the only methods currently capable of meeting the cloud-base height requirements
   - vi) Cloud cover, cloud particle size distribution, cloud effective particle size, cloud ice water path, and cloud liquid water path
     - Perform additional studies to translate cloud dataset requirements into instrument accuracy/stability requirements
     - Verify MODIS cloud measurements against GLAS, Calipso, and Cloudsat observations
     - Evaluate the NIST standard at 1.6, 2.1, and 3.7 μm to determine if improvements are needed to meet accuracy/stability requirements for cloud effective particle size
     - Assess the various instrumental approaches—VIS/IR, microwave, and active systems—to meet cloud requirements
     - Implement multiple calibration references—lunar measurements, calibration lamps, and solar diffusers—for monitoring the in-orbit stability of VIS radiometers
   - vii) Cloud-top height, cloud-top pressure, and cloud-top temperature
     - Ensure sufficient overlap to meet 0.2°C decade^{-1} stability requirement
     - Verify zero radiance levels for IR radiometers using deep space scanning
     - Develop onboard blackbody radiation sources whose temperature can be varied over a controlled range
   - viii) Spectrally resolved outgoing longwave radiation
     - Establish a spectrally resolved absolute IR radiance scale by laboratory comparisons of "source based" radiance scales and "detector based" radiance scales
     - Conduct similar measurements independently with instruments that use different technologies

2) Atmospheric variables
   i) Atmospheric temperature
      - Plan for satellite overlap periods of (optimally) 1 yr

      a) Microwave instruments
         - Characterize more accurately the nonlinear response of microwave radiometers by prelaunch measurements
         - Maintain in-orbit temperature differences across the blackbody target to less than or equal to 0.1 K
         - Reduce effects of extraneous microwave radiation reaching the detector by performing more accurate prelaunch measurements of feedhorn spillover off of the antennas and calibration targets
         - Maintain spatial and temporal temperature changes of radiometer subcomponents to less than 0.3 K
         - Determine the Earth incidence angle of observation to accuracy of 0.3°

      b) Infrared instruments
         - Perform careful laboratory measurements of spectral response functions and develop filters that remain stable in space
         - Calibrate laboratory blackbody target radiances with the NIST portable calibrated radiometer, the Thermal Transfer Radiometer (TXR)
         - Minimize scattered radiation from solar-heated components of the IR sounder and thermal gradients within the internal calibration target (ICT) to increase the accuracy of in-orbit radiances of the ICT
         - Accurately characterize in the laboratory nonlinearities of the instrument response as functions of instrument and scene temperatures
         - Avoid scan angle effects on the instrument throughput by intelligent instrument design and/or in-orbit processing

   ii) Water vapor
      - Microwave radiometer issues for water vapor are not as stringent as for temperature, but the recommendations above carry through for water vapor
      - IR instrument recommendations for temperature carry through for water vapor

   iii) Ozone
      - Improve the consistency of the preflight calibrations of all UV/VIS ozone instruments and employ standard and well-documented procedures
      - Increase the accuracy of preflight calibration of albedo (radiance/irradiance) measurements of UV/VIS ozone instruments
      - Improve preflight characterization of wavelength scales, bandpasses, fields of view uniformity, nonlinearity of responses, out-of-band and out-of-field stray light contributions, imaging and ghosting, and diffuser goniometry
      - Add zenith sky viewing to prelaunch instrument testing
      - Calibrate and characterize new instruments [those with advanced technologies such as Ozone Mapping and Profiler Suite (OMPS)] more fully in a laboratory vacuum, including the temperature sensitivity of wavelength and radiometric stability, and the instrument response to different ozone amounts
      - Develop methods to validate satellite-measured radiances using ground-based measurements

   iv) Aerosols
      - Aerosol optical depth measurements are derived from solar spectral reflectance observations, thus, the recommendations concerning VIS/NIR instruments listed above are applicable
      - Develop methods for accurate preflight laboratory calibration and characterization of polarimetric instruments
      - Develop methods for the in-orbit calibration of polarimeters

   v) Precipitation
      - Precipitation measurements are derived from microwave radiometer observations, thus, recommendations concerning microwave radiometers listed above are applicable

   vi) Carbon dioxide
      - Assess the capability of hyperspectral IR instruments, such as the Atmospheric Infrared Sounder (AIRS), to detect CO_2 variations
      - Implement an extensive validation program, including airborne, tall tower, and ground-based Fourier transformed infrared (FTIR) spectrometric measurements

to fully characterize spatial and temporal biases in satellite CO_2 measurements

- Report and fully document error characteristics of satellite CO_2 measurements to facilitate effective data assimilation techniques
- Develop new active techniques (e.g., lidar) to measure CO_2 in the atmosphere

3) Surface variables

The surface measurements are derived from VIS/IR and microwave radiometers, thus, recommendations concerning VIS/NIR and microwave radiometers listed above are applicable. In addition, the following recommendations apply to individual surface variables:

i) SST
- Characterize more definitively the accuracy of satellite SST measurements by initiating an ongoing validation program using radiometric measurements of ocean skin temperature from ships and other platforms as ground truth

ii) Ocean color
- Increase confidence in ocean color measurements by expanding the MOBY buoy-type surface validation program to more ocean sites

iii) Normalized difference vegetation index
- Explore the validation of satellite-based observations of surface NDVI by ground-based observations of NDVI using VIS/IR instruments similar to the satellite instruments

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