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Satellite Instrument Calibration for Measuring Global Climate Change

(Report of a Workshop at the University of Maryland Inn and Conference Center, College Park, MD, November 12-14, 2002)

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NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
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Satellite Instrument Calibration for Measuring Global Climate Change

Report of a Workshop Organized by
National Institute of Standards and Technology
National Polar-orbiting Operational Environmental Satellite System-Integrated Program Office
National Oceanic and Space Administration
National Aeronautics and Space Administration

At the University of Maryland Inn and Conference Center, College Park, MD,
November 12-14, 2002

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Abstract

Measuring the small changes associated with long-term global climate change from space is a daunting task. The satellite instruments must be capable of observing atmospheric temperature trends as small as 0.1 ° C/decade, ozone changes as little as 1%/decade, and variations in the sun's output as tiny as 0.1%/decade. To address these problems and recommend directions for improvements in satellite instrument calibration, the National Institute of Standards and Technology (NIST), National Polar-orbiting Operational Environmental Satellite System-Integrated Program Office (NPOESS-IPO), National Oceanic and Atmospheric Administration (NOAA), and National Aeronautics and Space Administration (NASA) organized a workshop at the University of Maryland Inn and Conference Center, College Park, MD, November 12-14, 2002. Some 75 scientists, including researchers who develop and analyze long-term data sets from satellites, experts in the field of satellite instrument calibration, and physicists working on state of the art calibration sources and standards, participated.

The workshop defined the absolute accuracies and long-term stabilities of global climate data sets that are needed to detect expected trends, translated these data set accuracies and stabilities to required satellite instrument accuracies and stabilities, and evaluated the ability of current observing systems to meet these requirements. The workshop's recommendations include a set of basic axioms or overarching principles that must guide high quality climate observations in general, and a roadmap for improving satellite instrument characterization, calibration, inter-calibration, and associated activities to meet the challenge of measuring global climate change. It is also recommended that a follow-up workshop be conducted to discuss implementation of the roadmap developed at this workshop.

Importance of Sustained, Long-Term Monitoring of Earth's Climate Emphasized in Declaration of the 2003 Earth Observation Summit

We, the participants in this Earth Observation Summit held in Washington, DC, on July 31, 2003:

Recalling the World Summit on Sustainable Development held in Johannesburg that called for strengthened cooperation and coordination among global observing systems and research programmes for integrated global observations;

Recalling also the outcome of the G-8 Summit held in Evian that called for strengthened international cooperation on global observation of the environment;

Noting the vital importance of the mission of organizations engaged in Earth observation activities and their contribution to national, regional and global needs;

Affirm the need for timely, quality, long-term, global information as a basis for sound decision making. In order to monitor continuously the state of the Earth, to increase understanding of dynamic Earth processes, to enhance prediction of the Earth system, and to further implement our environmental treaty obligations, we recognize the need to support:

(1) Improved coordination of strategies and systems for observations of the Earth and identification of measures to minimize data gaps, with a view to moving toward a comprehensive, coordinated, and sustained Earth observation system or systems;

(2) A coordinated effort to involve and assist developing countries in improving and sustaining their contributions to observing systems, as well as their access to and effective utilization of observations, data and products, and the related technologies by addressing capacity-building needs related to Earth observations;

(3) The exchange of observations recorded from in-situ, aircraft, and satellite networks, dedicated to the purposes of this Declaration, in a full and open manner with minimum time delay and minimum cost, recognizing relevant international instruments and national policies and legislation; and

(4) Preparation of a 10-year Implementation Plan, building on existing systems and initiatives, with the Framework being available by the Tokyo ministerial conference on Earth observations to be held during the second quarter of 2004, and the Plan being available by the ministerial conference to be hosted by the European Union during the fourth quarter of 2004.

To effect these objectives, we establish an ad hoc Group on Earth Observations and commission the group to proceed, taking into account the existing activities aimed at developing a global observing strategy in addressing the above. We invite other governments to join us in this initiative. We also invite the governing bodies of international and regional organizations sponsoring existing Earth observing systems to endorse and support our action, and to facilitate participation of their experts in implementing this Declaration.

Extended Summary

I. Introduction

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 temperature trends as small as 0.1° C/decade, ozone changes as little as 1%/decade, and variations in the sun's output as tiny as 0.1%/decade.

The importance of understanding and predicting climate variation and change has escalated significantly in the last decade. In 2001, the White House requested the National Academy of Sciences (NAS) National Research Council (NRC) (NRC, 2001a) to review the uncertainties in climate change science. One of the three key recommendations from the NRC's report is "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).

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), National Polar-orbiting Operational Environmental Satellite System-Integrated Program Office (NPOESS-IPO), National Oceanic and Atmospheric Administration (NOAA), and National Aeronautics and Space Administration (NASA) organized a workshop at the University of Maryland Inn and Conference Center, College Park, MD, November 12-14, 2002. Some 75 scientists, including researchers who develop and analyze long-term data sets 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 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 website: http://physics.nist.gov/Divisions/Div844/global/mgcc.html. (Please Note: To access this site, you have to input user name: mgccoutline, and password: div844mgcc)

This workshop report has a single clearly defined goal:

- Recommend directions for future improvements in satellite instrument characterization, calibration, inter-calibration, and associated activities, to enable measurements of global climate change that are valid beyond 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, must also apply to sustained space-based climate change observations in general.

To achieve this goal, the report first:

- Defines the required absolute accuracies and long-term stabilities of global climate data sets
- Translates the data set accuracies and stabilities to required satellite instrument accuracies and stabilities, and
- Evaluates the ability of current observing systems to meet these requirements

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

- 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)
- 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 there have been a number of previous reports that have also discussed accuracy and stability measurement requirements for long term climate data sets (for example, Hansen et al., 1993; Jacobowitz, 1997; NPOESS, 2001) and calibration issues (Guenther et al., 1997; NRC, 2000; NRC, 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, inter-instrument calibration and associated activities to meet the requirements. This general roadmap 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 concepts of accuracy and stability of time series. Accuracy is defined as the “closeness of the agreement between the result of the measurement and the true value of the measurand” (ISO, 1993). It may be thought of as the closeness to the truth and 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 data set.

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

According to the resolution adopted by the 20th Conference Generale des Poids et Measures (CGPM) - the international standards body in Paris - “that those responsible for studies of Earth resources, the environment and related issues ensure that measurements made within their programmes are in terms of well-characterized SI units so that they are reliable in the long term, be comparable world-wide and be linked to other areas of science and technology through the world’s measurement system established and maintained under the Convention du Metre” (CGPM, 1995).

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

It should be pointed out that achieving the instrument measurement requirements does not guarantee determining the desired 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.

II. 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, 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 roadmap for calibration improvements will ensure that satellite observations are of sufficient accuracy and stability not only to indicate any climate change that 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.

SATELLITE SYSTEMS

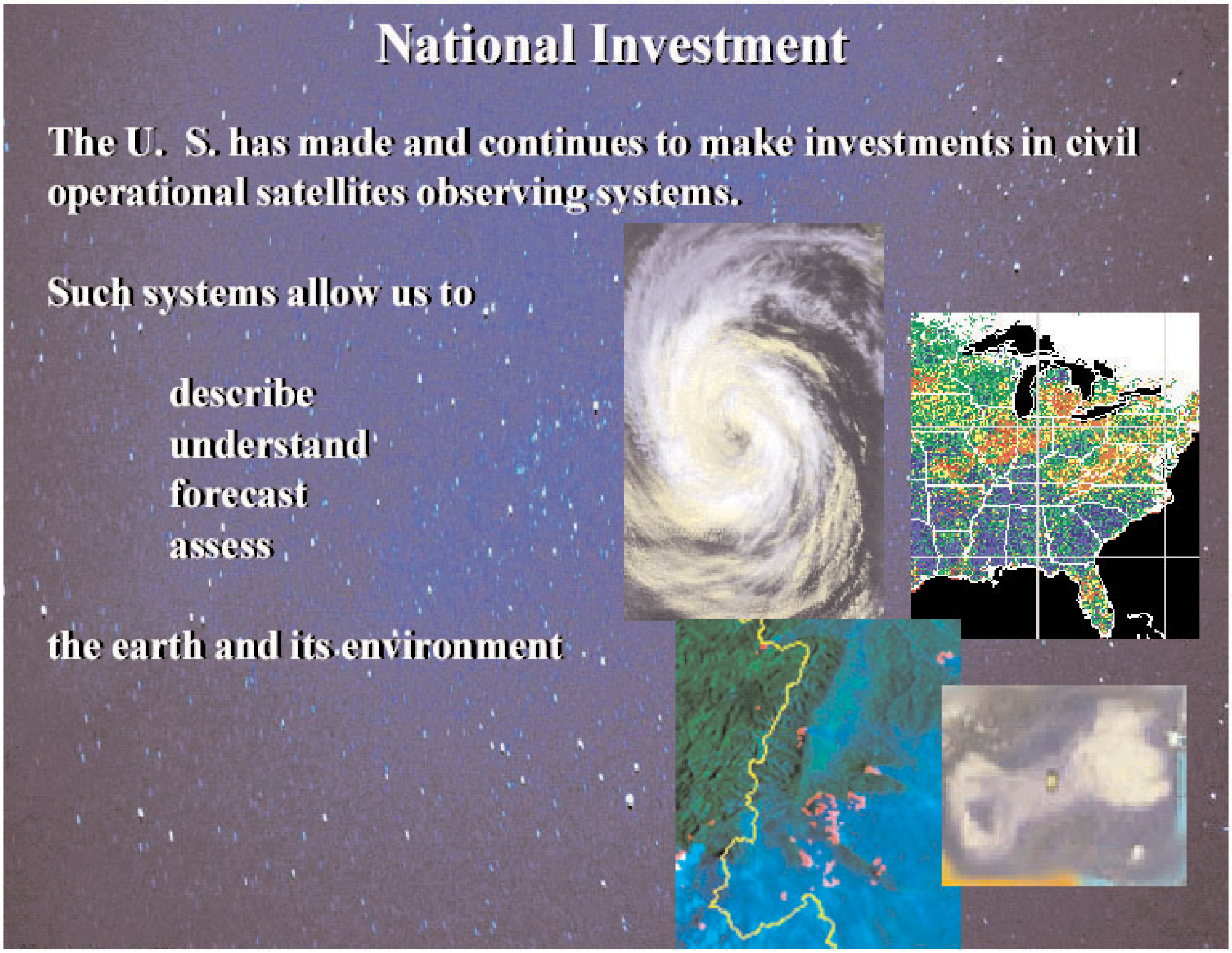
- Establish clear agency responsibilities for the U.S. space-based climate observing system
- Acquire multiple independent space-based measurements of key climate variables
- Ensure that launch schedules reduce risk of a gap in the time series to less than 10% probability for each climate variable
- Add highly accurate measurements of spectrally resolved reflected solar and thermal infrared radiation to NPOESS Environmental Data Record (EDR) list
- Increase U.S. multi-agency and international cooperation to achieve a rigorous climate observing system

CALIBRATION

- Elevate climate calibration requirements to critical importance in NPOESS
- Develop characterization requirements for all instruments and insure that these are met
- Conduct pre-launch calibration round robins (calibrations of different instruments using the same SI traceable scale) for most NPOESS and Geostationary Operational Environmental Satellite - R (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.

CLIMATE DATA RECORDS (CDRs)

- Define measurement requirements for CDRs
- Establish clear responsibility and accountability for 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.



National Investment

The U. S. has made and continues to make investments in civil operational satellites observing systems.

Such systems allow us to

describe
understand
forecast
assess

the earth and its environment

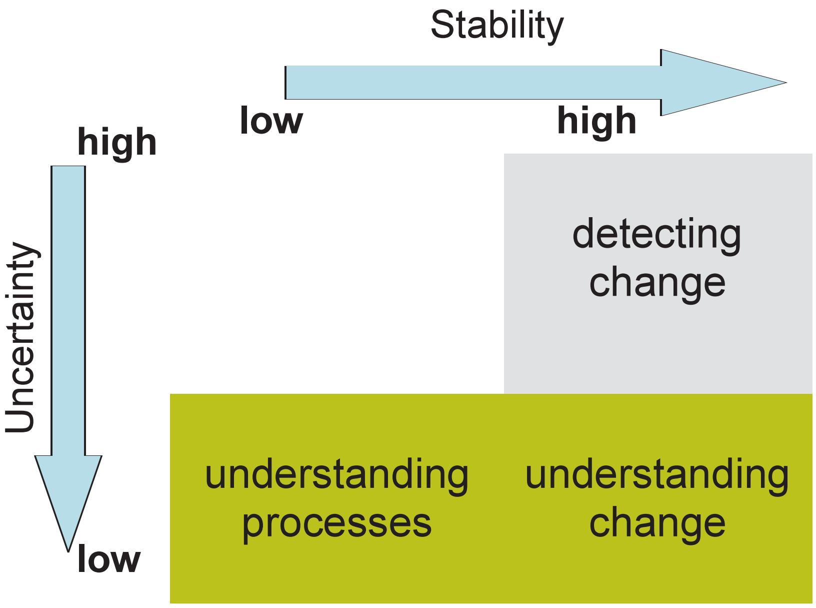
Operational environmental satellites can provide sustained long-term climate observations, but clear agency responsibilities must be established (Withee, Workshop Invited Presentation).

III. Required accuracies and stabilities for climate variables

The required accuracies and stabilities of the climate variable data sets were established with consideration of changes in important climate signals based on current understanding and models of long-term climate change. Such signals include:

- 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)
- 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 data set to permit detection of the signal. Excellent absolute accuracy in the measurement of the climate variable is vital for understanding climate processes and changes. However, it is not as necessary for determining long-term changes or trends as long as the data set 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

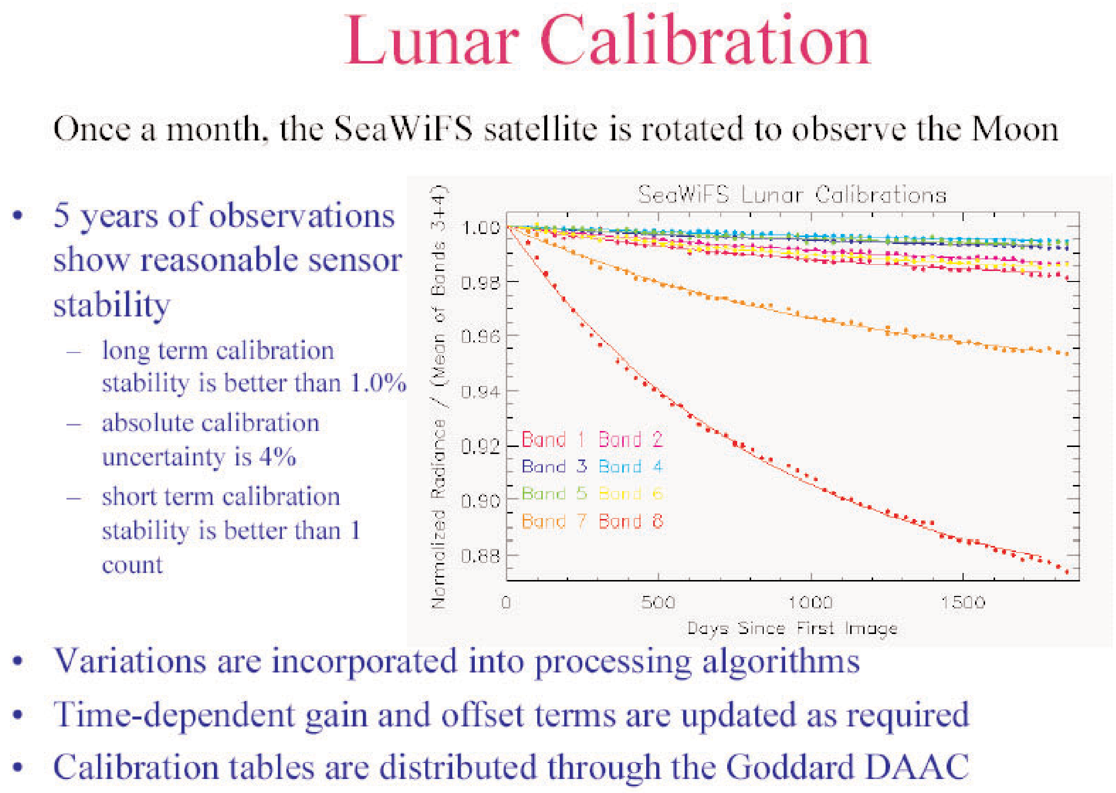


Desired characteristics of a climate observing system (After G. Stephens, 2003)

Excellent absolute accuracy (a component of uncertainty, which also depends on precision, or random error) in the measurement of climate variables is vital for understanding climate processes and changes. However, it is not as necessary for determining long-term changes or trends as long as the data set has the required stability.

ground to establish its absolute accuracy and transfer and monitor the calibration on 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 data sets is long-term stability. The required stability is some fraction of the expected signal, assumed to be 1/5 in this report. 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 factor 1/5, 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 to 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 K to 5.8 K, or factor of about 4, in the change in global temperature by 2100 (IPCC, 2001). Thus, a stability of 20% should lead to a considerable narrowing of the possible climate model simulations of 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.



Lunar Calibration

Once a month, the SeaWiFS satellite is rotated to observe the Moon

- 5 years of observations show reasonable sensor stability
  - long term calibration stability is better than 1.0%
  - absolute calibration uncertainty is 4%
  - short term calibration stability is better than 1 count
- Variations are incorporated into processing algorithms
- Time-dependent gain and offset terms are updated as required
- Calibration tables are distributed through the Goddard DAAC

The moon is a stable light source that can be used to monitor and correct for changes in satellite sensor stability (McClain, Workshop Invited Presentation).

Although excellent absolute accuracy is not critical for trend detection, which was the subject of the workshop, it is crucial for understanding climate processes and changes. Continuous efforts should be undertaken to constantly improve the accuracy of satellite instruments.

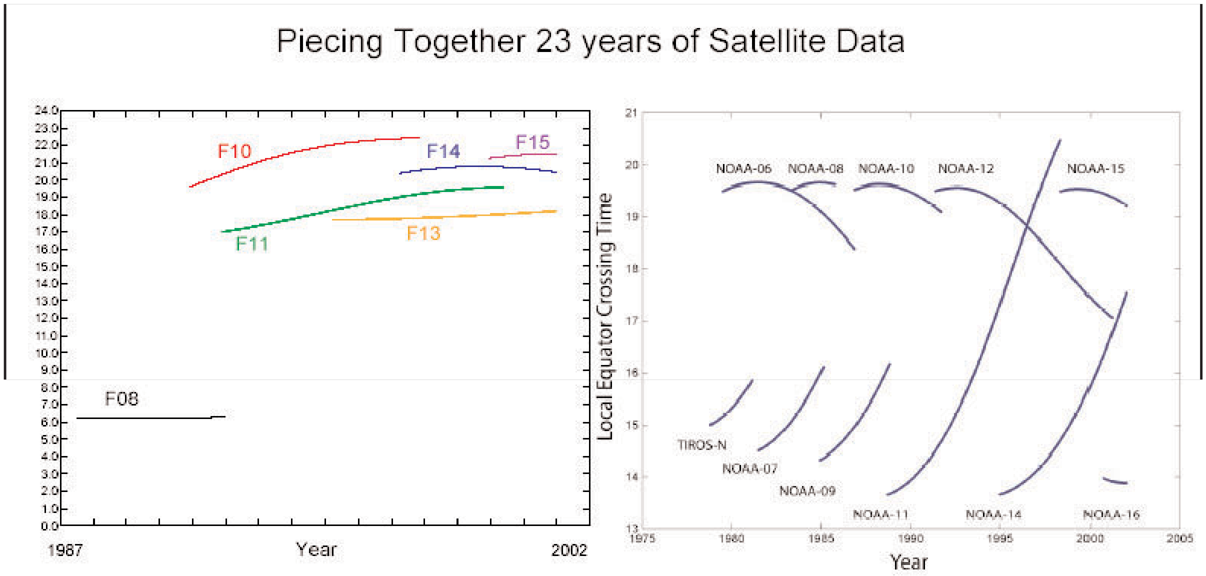
Table 1 summarizes the required accuracies and stabilities of the data sets for the solar irradiance, Earth radiation budget, and cloud variables; the atmospheric variables; and the surface variables. The table also indicates which one of the above climate signals - climate changes, climate forcings,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

IV. Translation of climate data set accuracies and stabilities to satellite instrument accuracies and stabilities

The requirements for the data sets must be translated into required accuracies and stabilities of the satellite measurements. In some cases, for example, solar irradiance and top of the atmosphere 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 data set accuracies/stabilities into satellite accuracies/stabilities.

Because of the difficulties in achieving necessary accuracies (exo-atmospheric total solar irradiance is one example, (Quinn and Frohlich, 1999)), a key attribute for the satellite instruments is long-term stability. This may be achieved by either having an extremely stable instrument or by monitoring the instrument's stability, by various methods, while it is in orbit. An ideal external calibration source is one that is nearly constant in time and able to 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 far more stringent than given in this report. 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 (Kieffer et al., 2003). The required lunar data are being supplied by a dedicated ground based facility (Anderson et. al., 1999)

Since satellites and their instruments are short-term - NPOESS satellites and instruments have design lives of about 7 years - satellite programs launch replacement satellites to continue the observations. Thus, the long-term data record for any climate variable will consist 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. Acquiring multiple independent



Time series of climate variables have been constructed by stitching together observations from series of overlapping operational satellite observations (Defense Meteorological Satellite Program F (DMSP F) series and NOAA series). Among the problems: satellite drift causing a change in the local time of the observations during each satellite's lifetime, especially for the NOAA satellites (Wentz, Workshop Invited Presentation).

space-based measurements of key climate variables - one of the climate observing principles listed above - would also help insure maintenance of stability in the event of a single instrument failure.

One proposed instrument that may have very high accuracy and may not require overlap periods is the proposed spectrally resolved radiance spectrometer (Anderson et al., 2003). 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.

V. 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 the 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?) 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 data sets 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 have been major efforts requiring a team of researchers that includes calibration and instrument experts and geophysicists to carefully examine the satellite radiances, re-evaluate 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 don't know whether current systems are adequate, and studies are needed to answer the question.

This three part process of going from requirements for climate variables to the ability of current systems to meet these requirements can be illustrated with the case of sea surface temperature (SST). Climate models predict an SST increase of about 0.2 K/decade due to global warming (see Section 3.3.2). The data set stability required to detect this change is 1/5 of 0.2 K, or 0.04 K/decade. For infrared imager observations, SSTs vary approximately as 2.5 x the difference in thermal infrared brightness temperatures, which leads to a required stability of about 0.01 K/decade in brightness temperature (Section 4.3.2). Currently, none of the available satellite infrared imagers can meet this requirement (Section 5.3.2)

Table 1. Required accuracies and stabilities for climate variable data sets. 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	02. 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%
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/hr	0.003 mm/hr
Carbon dioxide	Forcing/Sources-sinks	10 ppmv/10 ppmv	2.8 ppmv/1 ppmv

Table 1. (continued)

	Signal	Accuracy	Stability (per decade)
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 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/IR radiometer	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	Broad band 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	Broad band solar	1 W/m^2	0.3 W/m^2
Outgoing longwave radiation: Top of atmosphere	Broad band IR	1 W/m^2	0.3 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 to temperature	See cloud optical thickness and cloud to 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

	Instrument	Accuracy	Stability (per decade)
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%	0.8%

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

	Accuracy	**Stability**
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

VI. Roadmap for future improvements in satellite instrument calibration and inter-calibration 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, inter-calibration, and associated activities, and these are summarized here. 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.

Solar Irradiance, Earth Radiation Budget, And Cloud Variables

Solar irradiance

- Schedule a 1-year overlap in observations of both solar irradiance and spectral solar irradiance
- Conduct two independent series of observations to verify accuracy and stability

Surface albedo

- Implement satellite observations of the moon for monitoring visible/near infrared instrument stability
- Maintain the same satellite orbits in sequential missions

Downward longwave radiation and downward short wave radiation at the surface

- Perform studies to assess the sensitivity of downward longwave radiation to boundary layer temperature and water vapor changes, and downward short wave radiation to cloud optical depth, cloud particle size, and aerosol optical depth
- Evaluate the capability of 4-D data assimilation models to constrain boundary layer temperature and humidity, and active instruments, such as Geoscience Laser Altimeter System (GLAS), Cloudsat, and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (Calipso), to constrain cloud base for determination of downward longwave radiation
- Assimilate aerosol profile data from active instruments, such as GLAS and Calipso, into 4-D NWP models to constrain aerosol effects on downward short wave radiation
- Expand the Baseline Surface Radiation Network (BSRN) from the current 20 land sites, especially to ocean locations

Net solar radiation and outgoing longwave radiation at top of the atmosphere (Earth radiation budget)

- Plan minimum satellite overlap periods of three months for net solar radiation and one month for outgoing longwave radiation
- Fully characterize NPOESS Earth radiation budget detectors (Total and Short Wave channels) for stability with solar exposure as well as time in vacuum
- Conduct a 2nd set of Earth radiation budget observations independent of NPOESS Earth radiation budget measurements. One possibility is full broadband spectrometers for observations of Earth reflected solar radiation and Outgoing Longwave Radiation (OLR)
- Enhance NIST spectral sources and transfer radiometers to cover the full reflected solar and emitted thermal IR spectra of the Earth

Cloud base height

- Pursue the development and application of active instruments such as satellite lidar and cloud radar appear to be the only methods currently capable of meeting the cloud base height requirements

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 data set requirements into instrument accuracy/stability requirements
- Verify Moderate Resolution Imaging Spectroradiometer (MODIS) cloud measurements against GLAS, Calipso and Cloudsat observations
- Evaluate NIST standards at 1.6 µm, 2.1 µm, 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 on-orbit stability of VIS radiometers

Cloud top height, cloud top pressure, and cloud top temperature

- Insure sufficient overlap to meet 0.2 K/decade stability requirement
- Verify zero radiance levels for IR radiometers using deep space scanning
- Develop on-board black body radiation sources whose temperature can be varied over a controlled range

Spectrally resolved outgoing longwave radiation

- Establish a spectrally resolved absolute IR radiance scale by laboratory comparisons of "source-based" radiance scales (the SI traceable standard is a blackbody source) and "detector-based" radiance scales (the SI traceable standard is the cryogenic radiometer that measures optical power in terms of electrical power in Watts)
- Conduct similar measurements independently with instruments that use different technologies

<u>Atmospheric Variables</u>

Atmospheric temperature

- Plan for satellite overlap periods of (optimally) one year

Microwave instruments

- Characterize more accurately the nonlinear response of microwave radiometers by pre-launch measurements
- Maintain on-orbit temperature differences across the black body target to less than or equal to 0.1 K
- Reduce effects of extraneous microwave radiation reaching the detector by performing more accurate pre-launch measurements of feedhorn spillover off the antennas and calibration targets
- Maintain spatial and temporal temperature changes of radiometer sub-components to less than 0.3 K
- Determine earth incidence angle of observation to accuracy of 0.3 degrees

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 accuracy of on-orbit radiances of the ICT
- Accurately characterize in the laboratory non-linearities of instrument response as functions of instrument and scene temperatures
- Avoid scan angle effects on instrument throughput by intelligent instrument design and/or on-orbit processing

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

Ozone

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

Aerosols

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

Precipitation

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

Carbon dioxide

- Assess the capability of hyperspectral IR instruments such as Atmospheric Infrared Sounder (AIRS) to detect CO_2 variations
- Implement an extensive validation program, including airborne, tall tower, and ground based Fourier Transform 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.

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:

Sea Surface Temperature (SST)
- Characterize more definitively the accuracy of satellite SST measurements by initiating an on-going validation program using radiometric measurements of ocean skin temperature from ships and other platforms as ground truth

Ocean color
- Increase confidence in ocean color measurements by expanding the Marine Optical Buoy (MOBY) type surface validation program to more ocean sites

Normalized Difference Vegetation Index (NDVI)
- Explore the validation of satellite based observations of surface Normalized Difference Vegetation Index (NDVI) by ground based observations of NDVI using VIS/IR instruments similar to the satellite instruments

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

1. Background, Goal, and Scope

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 science 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.

Observing the small signals of long-term global climate change places enormous stress on satellite observing systems. Global temperature changes of tenths of a degree Centigrade per decade, ozone changes of 1%/decade, and solar irradiance variations of 0.1%/decade are typical of the kinds of signals that must be extracted from noisy time series. Measuring these signals will require much improved calibration of satellite instruments, and inter-calibration of similar instruments flying on different satellites. Ability to observe these small signals of decadal scale climate change will also give us the capability of measuring the larger signals associated with shorter-term climatic variations, such as those associated with El Nino.

This report has a single clearly defined ultimate goal:

- Recommend directions for future improvements in satellite instrument characterization, calibration, inter-calibration, and associated activities, to enable measurements of global climate change that are valid beyond reasonable doubt.

This report summarizes the requirements and general directions for improvements; future meetings should be planned to address the specific instrument calibration issues associated with the requirements. Although some of the recommendations are directed at the NPOESS program, the nation's converged future civilian and military polar environmental satellite system, they also apply to space-based climate change observations in general.

To achieve its goal, the report first:

- Defines the required absolute accuracies and long-term stabilities of global climate data sets
- Translates the data set accuracies and stabilities to required satellite instrument accuracies and stabilities, and
- Evaluates the ability of current observing systems to meet these requirements

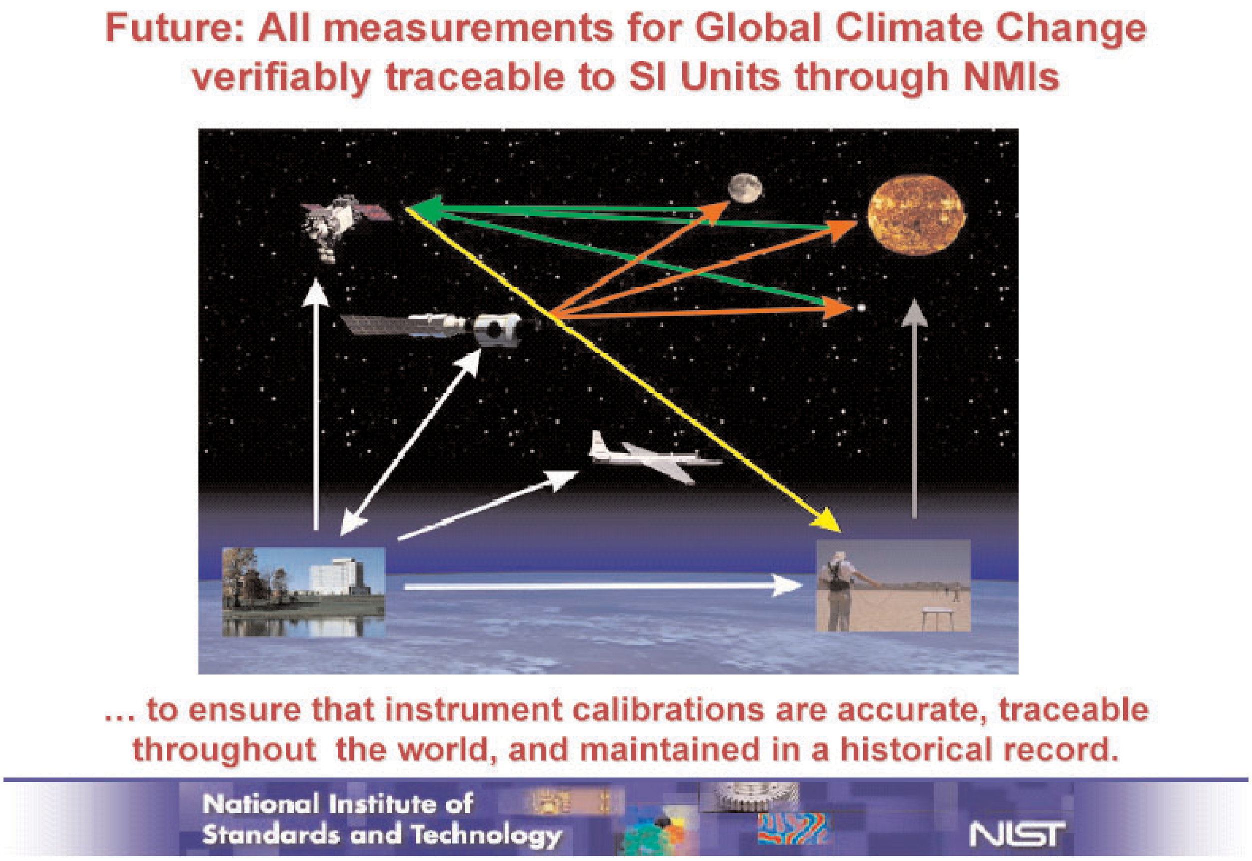
The report focuses on passive satellite sensors that make observations in spectral bands ranging from the ultraviolet to the microwave. The climate change variables of interest include:

- 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 of satellite-based climate data records, and 3) measurability from passive satellite sensors.

The report is based on a workshop held at the University of Maryland Inn and Conference Center, College Park, MD, November 12-14, 2002. NIST, NPOESS-IPO, NOAA, and NASA organized the workshop; the NPOESS-IPO and NIST provided financial support. Some 75 scientists, including researchers who develop and analyze long-term data sets 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.

The workshop agenda included a series of invited lectures followed by panel sessions. Keynote speakers Richard Goody, Professor Emeritus, Harvard University, and Tom Karl, Director, National Climatic Data Center, NOAA, led off the workshop with discussions of Issues with Space Radiance Monitoring, and Improving the Climate Contribution of Operational Satellites: A Data Perspective, respectively. Steve Mango, NPOESS-IPO, presented an overview of NPOESS/NPOESS Preparatory Program (NPP) Status/Plans Calibration/Validation. Viewpoints of two of the organizing agencies were contained in papers by Greg Withee, NOAA Assistant



Future: All measurements for Global Climate Change verifiably traceable to SI Units through NMIs

... to ensure that instrument calibrations are accurate, traceable throughout the world, and maintained in a historical record.

"those responsible for studies of Earth resources, the environment and related issues [should] ensure that measurements made within their programmes are in terms of well-characterized SI units so that they are reliable in the long term, be comparable world-wide and be linked to other areas of science and technology through the world's measurement system established and maintained under the Convention du Metre" (CGPM, 1995) (Semerjian, Workshop Invited Presentation).

Administrator for Satellite and Information Services (presented by Tom Karl) on the NOAA Perspective on a Global Observation System, and Hratch Semerjian, Director, Chemical Science and Technology Laboratory, NIST, on NIST Activities related to Global Climate Change. Invited speakers discussed current knowledge of long term variations of each climate variable, data set accuracy and stability needed to measure long term changes in the variable, translation of these requirements into accuracies and stabilities for satellite instruments, current state of the art of satellite instruments, and required improvements in instrument characterization, calibration, intercalibration, and associated activities. The invited presentations, a rich resource, are on the NIST web site, http://physics.nist.gov/Divisions/Div844/global/mgcc.html. (Please Note: To access this site, you have to input user name: mgccoutline, and password: div844mgcc)

Following the invited presentations, three panels met in parallel sessions:

- Solar irradiance, Earth radiation budget, and clouds. Chair: Bruce Wielicki, Scribe: Marty Mlynczac
- Atmospheric variables. Chair: Roy Spencer, Scribe: Gerald Fraser
- Surface Variables. Chair: Bill Emery, Scribe: Dan Tarpley

Each panel included experts on climate data sets and satellite instrument calibration issues. Panels discussed workshop issues, drafted material for a workshop report, and reported to plenary sessions. After the workshop, panel leaders prepared draft chapters for the workshop report. The Workshop agenda and list of participants are included in Appendices A and B, respectively.

While there have been a number of previous reports that have also discussed accuracy and stability measurement requirements for long term climate data sets (for example, Hansen et al., 1993; Jacobowitz, 1997; NPOESS, 2001) and calibration issues (Guenther et al., 1997; NRC, 2000; NRC, 2001b), this report not only provides the latest thinking on measurement requirements but also *provides general directions to improve satellite instrument characterization, calibration, vicarious calibration, inter-instrument calibration, and associated activities to meet the requirements*. This general roadmap provides guidance to the national agencies concerned with the development of the space system and associated satellite instrument calibration program to measure global climate change: NPOESS-IPO, NOAA, NIST, and NASA.

Measuring small changes over extended time periods necessarily involves the concepts of accuracy and stability of time series. Accuracy is defined as the “closeness of the agreement between the result of the measurement and the true value of the measurand” (ISO, 1993). It may be thought of as the closeness to the truth and 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 data set.

It is to be understood that the methods to establish the true value of a variable (the measurand) should be consistent with the internationally adopted methods and standards, thus establishing System of Units (SI) traceability (BIPM, 1998, NIST, 1995). According to the resolution adopted by the 20th Conference Generale des Poids et Measures (CGPM) - the international standards body in Paris - "that those responsible for studies of Earth resources, the environment and related issues ensure that measurements made within their programmes are in terms of well-characterized SI units so that they are reliable in the long term, be comparable world-wide and be linked to other areas of science and technology through the world's measurement system established and maintained under the Convention du Metre" (CGPM, 1995).

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

It should be pointed out that achieving the instrument measurement requirements does not guarantee determining the desired 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.

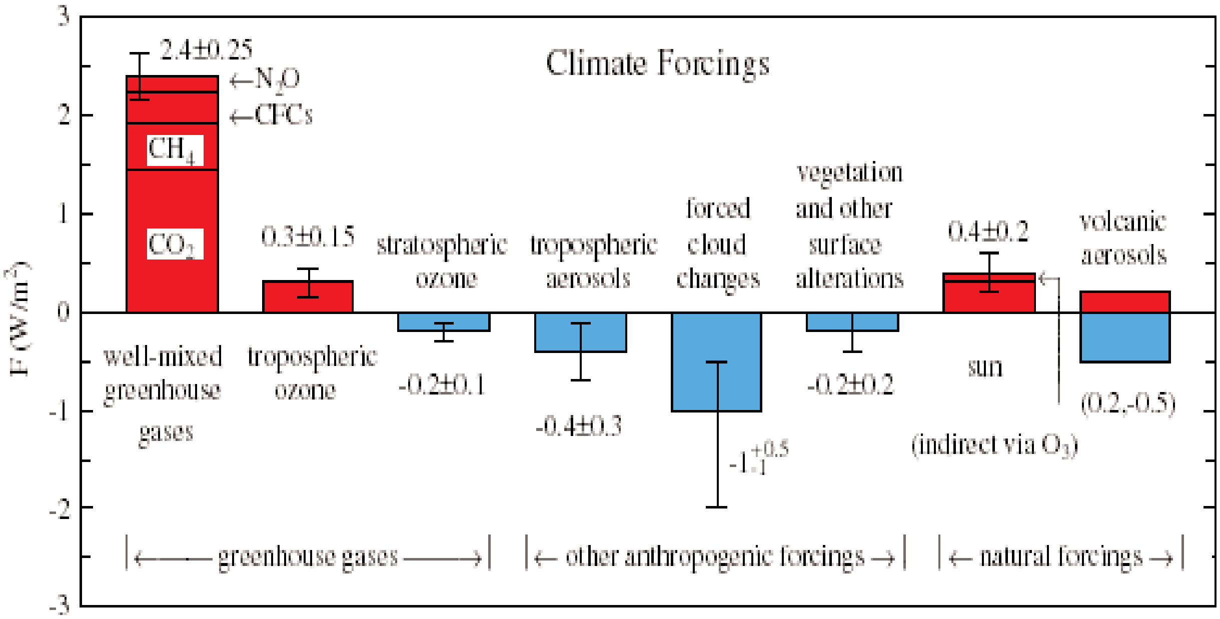
The remainder of the report is structured as follows:

Section 2 presents overarching principles that must guide high quality satellite climate observations in general. Adherence to these principles and implementation of the roadmap for calibration improvements will ensure that satellite observations are of sufficient accuracy and stability not only to indicate any climate change that has occurred, but also to prove it beyond reasonable doubt and permit evaluation of climate forcing and feedbacks.

Section 3 develops the requirements for accuracy and stability of the individual climate variables. Various rationales are used to determine these requirements including ability to measure:

- 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)
- Trends similar to those observed in past decades

Anthropogenic and Natural Forcings



Significant changes in climate forcing or feedback of a variable (comparable to that of greenhouse gases) is one criterion for determining measurement requirements (Cairns, Workshop Invited Presentation).

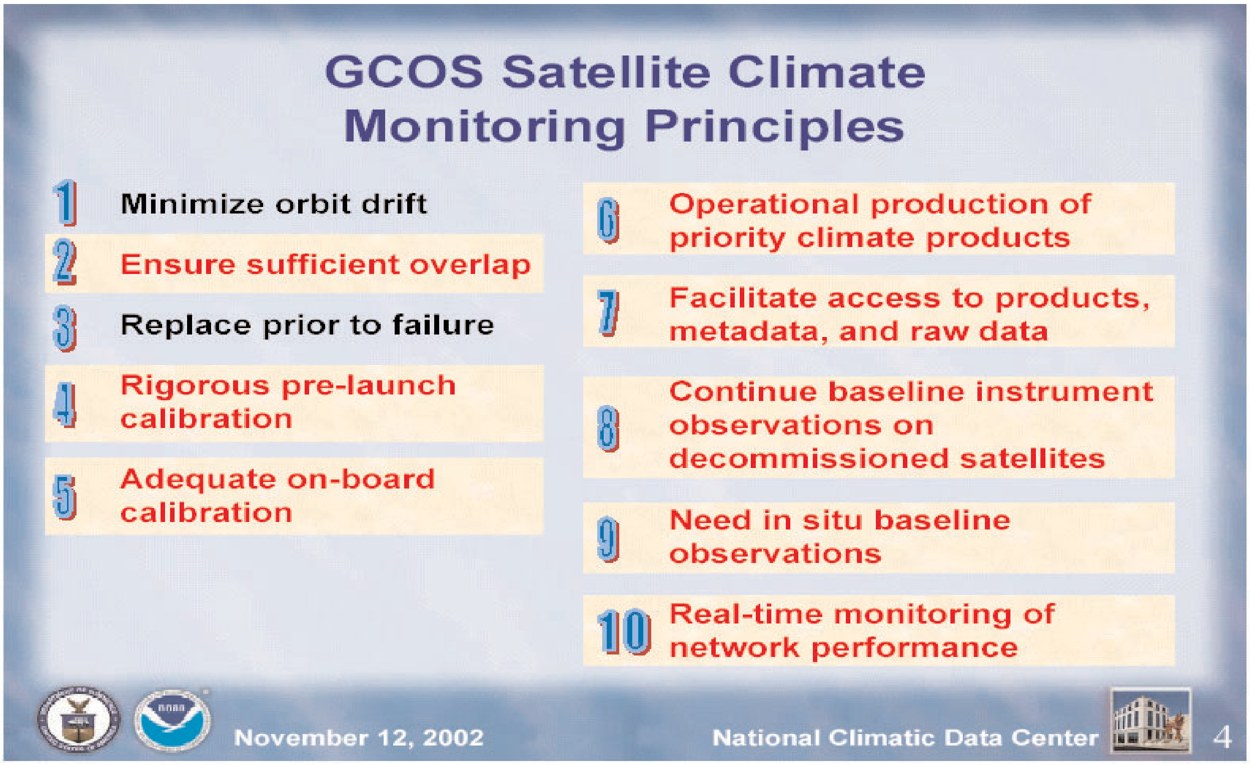
The values for stability are given per decade. The required accuracies and long-term stabilities in the NPOESS IORD II (NPOESS, 2001) were a resource for the workshop panels.

Section 4 discusses the satellite instrument accuracy and stability requirements for meeting the data set requirements of section 3. For top of the atmosphere radiation budget variables and for variables that are linearly related to the satellite measurements, there is a one to one correspondence with the data set requirements. For variables that are related to the satellite measurements in a non-linear way, translation of data set requirements into satellite instrument requirements is more complex.

Section 5 reviews the ability of current observing systems to meet the instrument requirements of section 4.

Based on the instrument requirements of section 4 and the current state of the art in section 5, section 6 presents recommendations, or a roadmap, for future improvements in satellite instrument characterization, calibration, inter-calibration, and associated activities to meet the requirements.

Almost all of the illustrations in the report are relevant figures from the workshop's invited presentations.



GCOS Satellite Climate Monitoring Principles

1. Minimize orbit drift
2. Ensure sufficient overlap
3. Replace prior to failure
4. Rigorous pre-launch calibration
5. Adequate on-board calibration
6. Operational production of priority climate products
7. Facilitate access to products, metadata, and raw data
8. Continue baseline instrument observations on decommissioned satellites
9. Need in situ baseline observations
10. Real-time monitoring of network performance

November 12, 2002

National Climatic Data Center

4

The workshop's overarching principles include many of the climate monitoring principles in NRC (1999) and GCOS (2003), but in some cases go beyond these (Karl, Workshop Invited Presentation).

2. 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, 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 roadmap 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.

SATELLITE SYSTEMS

1. **Establish clear agency responsibilities for the U.S. space-based climate observing system.** A major challenge to achieving a climate observing system is the current diffusion of responsibility across many agencies in the U.S. No single agency has the responsibility, fund-

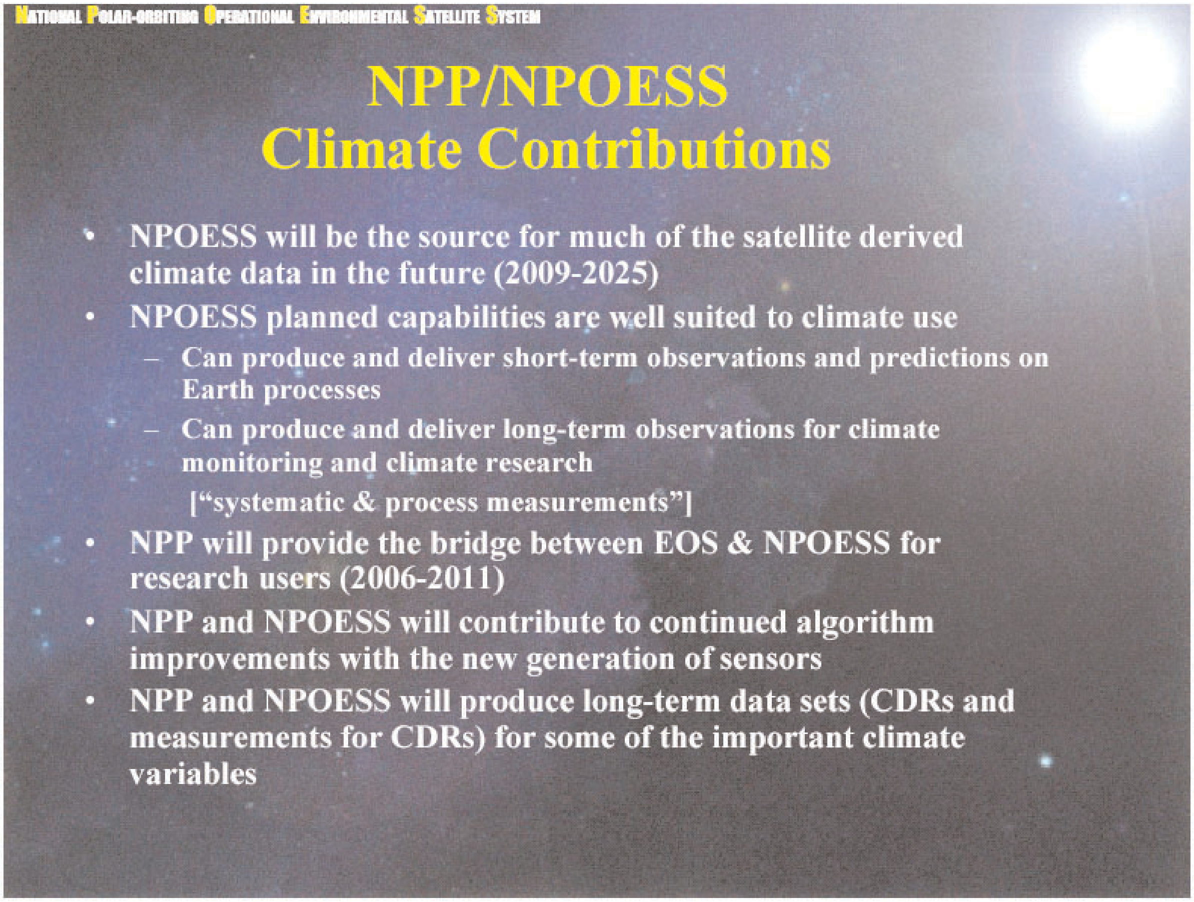
ing, and full accountability for success in the climate change "mission." This leads to great difficulties in an observing system required to be diverse and yet accurate and complete enough to cover oceans, land, biosphere, cryosphere and atmosphere. At this point we have to conclude that a rigorous climate observing system is not yet in place, nor is a plan in place to create one with a high confidence of success. The current climate observing system is an informal arrangement of research (e.g. NASA Earth Observing System (EOS) and operational satellites (e.g. NOAA polar orbiters) managed by U.S. and international agencies. It has been "collected" more than "designed". It has a high risk of critical data gaps and calibration shortcomings that will seriously degrade the confidence with which climate assessments can be made. Clear agency responsibilities must be established to insure the success of the national climate change mission.

2. **Acquire independent space-based measurements of key climate variables.** Independent instrument measurements from space of each key climate variable are required to verify accuracy. This requirement is based on the experience of NIST and other national standards laboratories. Extensive theoretical and laboratory work is done to establish the uncertainty levels of NIST calibration standards. But when multiple nations compare their standards, usually the differences exceed the predicted uncertainty. This is a fundamental lesson for climate data, which, like NIST standards, pushes the capability of instrument calibration. When climate change surprises are observed with one instrument, confidence is increased dramatically if the signal can be confirmed with an independent measurement. This is basic scientific practice. The measurements should be from different technological approaches. Some examples already exist: SST from satellite passive infrared, microwave, and in-situ buoys. Surface wind speed from satellite scatterometer, passive microwave, and in-situ buoys. Air temperature from satellite passive microwave and infrared. But many climate parameters do not currently have independent observation approaches. Cloud amount and layering should be measured both by active lidar and radar as well as passive imagers. Radiation budget should be measured both by simple broadband radiometers as well as high spectral resolution spectrometers that cover the entire (at least 99%) spectrum of earth emitted and reflected radiation. Current infrared spectrometers observe less than 50% of the emitted radiation.

3. **Ensure that launch schedules reduce risk of a gap in the time series to less than 10% for each climate variable.** Most climate measurements require overlapping (in time) observations to assure the calibration record at climate accuracy. This is an especially difficult requirement since it requires intercalibration of two instruments before the old instrument fails. In general it implies the need for hot

spares in orbit. The current NASA and NPOESS plans do not include hot spares. As a minimum, a risk analysis for instrument and spacecraft failure with time should be completed to ensure that launch schedules reduce gap risk to under 10% for each climate variable. Launch on failure, as currently planned by NPOESS will assure unacceptable gaps and insufficient overlap of climate records from space-based observations. There are also likely gaps between the end of NASA's responsibilities for climate variables and the beginning of the NPOESS measurements. Two examples are solar irradiance and radiation budget. NASA radiation budget data from CERES ends nominally in 2008, while the NPOESS follow-on ERB instrument begins in 2011. The risk of a gap is currently estimated at 50%, too high for a climate observing system. We recommend that the solar radiation and radiation budget gaps be addressed using the NPP mission planned for flight in 2006, or by flying small spacecraft in appropriate orbits.

4. **Add highly accurate measurements of spectrally resolved reflected solar and thermal infrared radiation to NPOESS EDR list.** Some key climate vari-


NATIONAL POLAR-ORBITING OPERATIONAL ENVIRONMENTAL SATELLITE SYSTEM

NPP/NPOESS
Climate Contributions

- NPOESS will be the source for much of the satellite derived climate data in the future (2009-2025)
- NPOESS planned capabilities are well suited to climate use
  - Can produce and deliver short-term observations and predictions on Earth processes
  - Can produce and deliver long-term observations for climate monitoring and climate research
    ["systematic & process measurements"]
- NPP will provide the bridge between EOS & NPOESS for research users (2006-2011)
- NPP and NPOESS will contribute to continued algorithm improvements with the new generation of sensors
- NPP and NPOESS will produce long-term data sets (CDRs and measurements for CDRs) for some of the important climate variables

The NPOESS Preparatory Program (NPP) and NPOESS programs will provide climate observations from 2006 – 2025 (Mango, Workshop Invited Presentation).

ables are missing from the EDR list. While beyond the scope of this workshop to do a comprehensive list, two examples are given. First, highly accurate and high spectral resolution (sometimes referred to as hyperspectral) radiances that cover the entire solar and thermal infrared spectrum of earth reflected and emitted radiation. Such radiances would be a data source independent of the broadband radiation data represented by CERES and Earth Radiation Budget Experiment (ERBE). They would likely use coarser spatial resolution (50 km to 100 km) and limited angle sampling (nadir or a few fixed viewing zenith angles) in order to achieve high spectral resolution with high accuracy linear detectors. In the infrared, such radiances would also represent independent confirmation of the temperature and humidity profile data extracted from the global imaging spectrometers such as Cross Track Infrared Sounder (CrIS). If placed in precessing orbits, they could also achieve intercalibration with all other solar and thermal infrared passive sensors, including the ability to match any spectral response function and to enable orbit-crossing intercalibration over a complete range of latitudes from equator to polar regions. A second example of a missing CDR is cloud emissivity in the major infrared window from 8μm to 12μm. Spectrally resolved thermal radiation from the climate system is an important and versatile climate variable that can be very accurately observed from space (Goody and Haskins 1998). This infrared radiance records both the radiative *forcing* of the atmosphere resulting from greenhouse gas emissions and aerosols and the resulting *response* caused by the adjustment of the atmosphere to this radiative forcing. The Intergovernmental Panel for Climate Change (IPCC) predicts increases in greenhouse gas concentrations and changes in atmospheric aerosols, which will manifest themselves as a significant reorganization of the spectral distribution of outgoing longwave radiation (OLR). The different predictions of future temperature, water vapor, and cloud amount forecasted by different climate models will also cause dramatic differences in the spectral characteristics of the OLR. Diagnostic signatures that can decide issues of model performance and eliminate competing scenarios of climate change can be revealed from the spectrum of accurately observed OLR. The information provided by spectral resolution allows us to study individual forcings and their responses, including those in cloud formation, which give rise to much of the variation in model forecasts of future climate.

5. **Increase U.S. multi-agency and international cooperation to achieve a rigorous climate observing system.** This report effectively focuses concern on the U.S. ability to produce the CDRs required for a successful climate research program. Currently, this situation is symptomatic of a climate research effort that is doing the best it can with limited resources. Many risky tradeoffs are justified not by climate requirements but by resource and time limi-

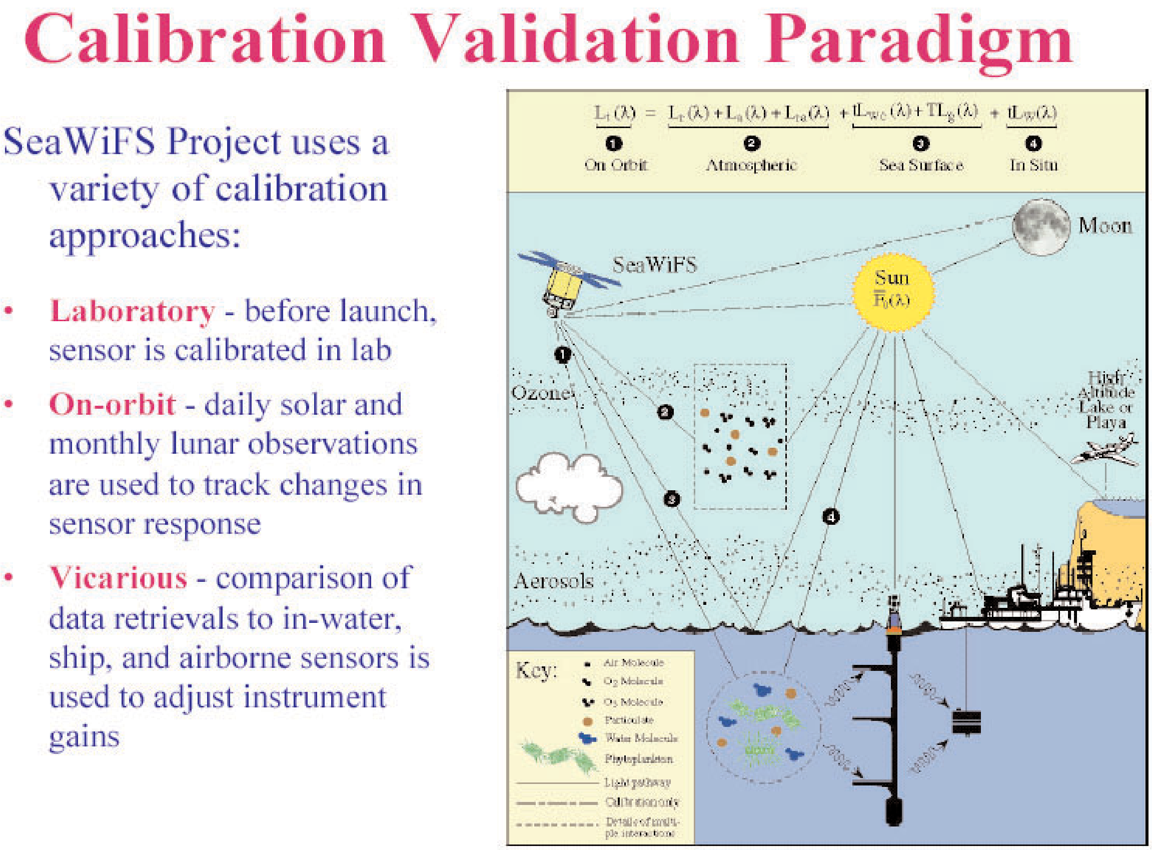
tations. As climate change is likely to continue, there may come a time when the U.S. and/or the international community decide to attack climate in an "Apollo"-like mission mode where requirements drive the process. It is instructive to imagine what could be quickly improved or changed in this scenario. Computational capacity for modeling could be increased 100 fold in a few years by purchasing additional capacity. Additional scientific expertise would require longer to transition from other fields: perhaps 5 years. But achieving the required highly accurate decadal time series of climate data would take much longer: 5 years for a crash observation system construction, and another 20 years to collect its first 2 decades of data. This suggests that the calibration discussions in this report should be considered very carefully and given a high priority to drive improvements in the next decade of observations from NASA, NOAA, and NPOESS space-based systems. It also suggests that increased U.S. multi-agency as well as international cooperation through Committee on Earth Observation Satellites (CEOS), Integrated Earth Observing Strategy (IGOS), and the 10-year program adopted at the Earth Observations Summit in Washington in July 2003 will be required to bring the resources to bear to achieve a rigorous climate observing system with a high probability of success. Interagency and international cooperation should extend across satellite missions, instruments, instrument calibration, CDR production, CDR validation, and archive and distribution.

CALIBRATION

1. **Elevate climate calibration requirements to critical importance in NPOESS.** Calibration must be done to absolute international standards similar to NIST standards both prelaunch and postlaunch. Also, adopt current international protocols, definitions, guidelines, and principles in metrology, including uncertainty assessments for calibration. Calibration must be of such a high priority that it is capable of driving instrument cost and schedule. Currently, instrument calibration and characterization are done at the end of instrument build when schedule and budget pressure to finish is very high. The calibration objective must be high enough priority to drive this final stage. It typically is not, and many corners are cut at the end of instrument build and calibration. This includes solving instrument problems that first appear during calibration. This will be a particular challenge for the NPOESS satellite system. NPOESS will fly a suite of new sensors that, while they all have considerable heritage, will require careful pre- and post-launch calibration/validation. Painful experience has taught us that careful in-lab calibration of the sensor avoids many problems that come up after the launch and on-orbit operation. Another important lesson learned is that independent "vicarious" calibration/validation is something that can't be done only once early in the life of the new sensor but must continue periodically throughout the life of the sensor. Only in this way can we obtain an independent estimate of the drift of

the instrument over time. Climate calibration is not as high a priority as the weather observation mission, and so given schedule and budget pressures that are already appearing, climate quality calibration and, hence, the credibility of long-term CDRs, are at very high risk. It is also important to establish the veracity of ancillary data (aerosol networks, radiosondes, etc.) and measurement systems for vicarious calibration. In essence, the foundation of CDRs is a three-legged stool: pre-launch calibration, post-launch instrument calibration/corrections, and use of correlative data for validation of the CDRs.

2. **Develop characterization requirements for all instruments and insure that these are met.** Instrument characterization remains basic to calibration and to the quality of the climate data records. At a minimum, instrument artifacts in the data sets, such as residual striping, banding, or scattered light in the images, detract from the users' confidence in the overall quality of the measurements - even if these artifacts are within the accuracy specifications for the instruments. More fundamentally, instrument artifacts may conceal important geophysical changes or may be misinterpreted as geophysical properties, themselves.



Calibration Validation Paradigm

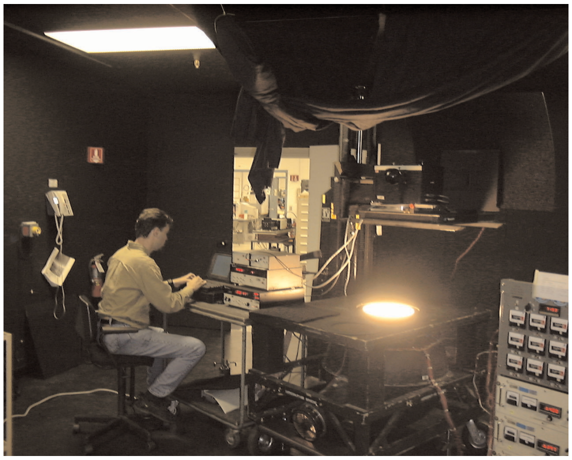
SeaWiFS Project uses a variety of calibration approaches:

- **Laboratory** - before launch, sensor is calibrated in lab
- **On-orbit** - daily solar and monthly lunar observations are used to track changes in sensor response
- **Vicarious** - comparison of data retrievals to in-water, ship, and airborne sensors is used to adjust instrument gains

Satellite instrument calibration begins in the laboratory, continues on-orbit, and includes vicarious calibration (McClain, Workshop Invited Presentation).

Spectral Radiance Comparisons

- Spectral range: 250 nm to 2500 nm
- Protocol: Assess accuracy of user calibration of working standard radiance sources using calibrated transfer radiometers (blind study)
- Key Participants: NIST, University of Alabama, NASA
- Comparisons held: Multiple, since 1993
- Characterizations: spatial and angular uniformity, temporal stability, repeatability
- Typical agreement: ~3% (visible), 4% to 10% (near infrared)



Assessing the accuracy of standards for satellite instrument calibration is an important component of an overall calibration program (Johnson, Workshop Invited Presentation).

Thus, there is the requirement for insight into the characterization plan and reviews of the characterization data while the instruments are in the lab to ensure the adequacy of the climate data sets. Once the instruments are out of the lab and on orbit, the characterization of instrument parameters, such as polarization for example, can be difficult and expensive, if possible at all. During the instrument fabrication, the insight should come from a real time parallel or collaborative analysis with data provided to a government maintained cal/val archive. (This is the basic procedure planned for the government's procurement of data for the Landsat Data Continuity Mission (LDCM)).

3. **Conduct and verify prelaunch calibration of NPOESS and GOES-R instruments using NIST transfer radiometers.** Pre-launch calibration involving most NPOESS and GOES R instruments should be conducted using NIST transfer radiometers, when available, for appropriate spectral wavelength ranges and at climate relevant accuracies. If transfer radiometers are not available, conduct and verify the accuracy of the pre-launch radiometric calibration and the adequacy of the characterization of flight sensors by direct measurement and in conjunction with available SI traceable transfer standards from national measurement institutes such as NIST for the U.S.

4. **Simplify the design of climate monitoring instruments.** Instruments designed for climate monitoring should be simple to calibrate and maintain calibration in orbit. Other objectives such as high spatial resolution may need to be sacrificed to attain this goal.

5. **Implement redundant calibration systems.** Redundant calibration systems are critical: both pre-launch laboratory calibration as well as post-launch on-orbit calibration. Such systems allow much more rigorous estimates of calibration uncertainty. Redundancy can take the form of independent on-board systems, intercalibration of similar instruments on different satellites, and vicarious calibration against lunar or earth targets.

6. **Establish means to monitor the stability of the sensors.** As the stability of the sensors is an essential requirement, their pre-flight stability is to be monitored during the time interval between pre-launch calibration and launch. Also, where possible, stable extra-terrestrial sources proven for their stability (sun, moon, stars) are to be incorporated for studies of in-flight sensor degradation and sensor inter-comparison.

CLIMATE DATA RECORDS (CDRs)

1. **Define requirements for CDRs.** In NPOESS nomenclature, EDRs (Environmental Data Records) are designed for use at short time/space scales for applications such as weather forecasting. CDRs will typically have different requirements than EDRs, with more stringent calibration accuracy, stability, and requirements for overlapping records. Current NPOESS EDR specifications have tried to add stability requirements for many EDRs that are meant to respond to CDR concerns. This is an improvement but does not fully reach climate requirements in many cases. This workshop report attempts to clarify these problems, where appropriate, for each NPOESS EDR. Both EDR and CDR requirements need definition. Clear priorities cannot be assigned when they are mixed in one set of requirements as in the current EDRs. We recommend that CDRs be generated for all key climate variables that can be measured from space. It is unlikely that the current NPOESS EDR data products will be sufficiently accurate for climate use. There are two primary reasons for this assessment. First, EDRs are designed primarily for weather forecasting, so that data products must be produced within a few hours of a measurement taken by satellite. CDRs can lag observations by months without serious impact on long-term climate research. Second, the weather accuracy requirements are typically easier to meet than the more stringent climate accuracy (e.g. 1 K instantaneous temperatures versus 0.1 K time averaged temperature). This mismatch of space/time/accuracy for weather and climate data products will naturally lead to simpler and faster analysis algorithms for EDRs than for CDRs. CDRs will be required to verify calibration stability and accuracy over many months of analysis, and will commonly require reprocessing to

remove small artifacts that are not an issue for weather applications but are critical to climate use. The optimal CDR data products have historically lagged spacecraft launch by 3 to 4 years. Steps should be taken to assure that the operational products will blend seamlessly with EOS and other mission sensors. EDRs can potentially meet CDR objectives through improved algorithms, careful analysis by potential users, and rigorous use of validation data. The NPOESS Preparatory Project (NPP) will be evaluating the use of EDRs, or enhanced EDRs, as CDRs suitable for climate research.

2. **Establish clear responsibility and accountability for generation of climate data records.** Clear responsibility and accountability must be established for each climate variable as a function of time. This has not yet been achieved for the full range of climate variables either nationally or internationally. This is particularly a challenge for the multi-agency nature of satellite climate data sets, with NASA, NOAA, and DoD all playing major roles.

3. **Arrange for production and analysis of each CDR independently by at least two sources.** Each CDR should be analyzed and produced by at least two independent sources. Not only instruments, but also analysis algorithms and code require validation and independent confirmation. Scientific remote sensing algorithms and supporting code to produce climate quality data sets can vary from 10,000 to 500,000 lines of code. For large code developments the question is not whether code errors exist, but rather how many. The most robust method to discover and eliminate both algorithm and coding problems in a rigorous fashion is independent algorithms and coding. Climate signals are often subtle and require exceptional efforts to attain a high degree of confidence in results. A recent example is the difference in Microwave Sounding Unit (MSU) analysis results among different research groups.

4. **Organize CDR science teams.** Given the differences in time/space/accuracy of EDR and CDR data products there will be a requirement to organize CDR Science Teams whose purpose will be to oversee, develop, validate, and carry out the production of CDRs at climate accuracy. They will most likely be required to return to level 0 raw instrument data and re-calibration to assure climate accuracy of the products. The algorithms must also focus on physically based algorithms that will likely require more processing time than the EDR analysis algorithms. Finally they will have to account for diurnal cycles to enable daily mean and monthly mean data products merging data from multiple satellites and instruments. Experience with past satellite climate data products indicates that the CDR Science Teams will require extensive participation of climate data users (e.g. climate modelers) as well as algorithm and instrument science specialists. Typically, these teams would be some combination of agency and

university scientists. These teams should be started prior to launch with sufficient input to assure adequate instrument calibration and characterization are done pre-launch. The teams must be able to review instrument progress as well as to affect schedules and costs if climate accuracy is to be obtained. Post launch team activities would focus on validation and algorithm improvement. NPOESS currently has Operational Algorithm Teams (OATS) to carry out a review function for EDRs, but no equivalent for CDRs. There is no current plan to form CDR teams, or to produce/validate/archive CDR NPOESS data products. However, two recent initiatives are dealing with this issue. NOAA, with the assistance of the National Academy of Sciences/National Research Council, is developing a plan for generating CDRs from operational satellite observations. This plan will include recommendations on science teams. NASA has formed a science team for NPP to assess the utility of the EDRs for use as CDRs and to determine additional work that may need to be done. *It is clear that one of the early functions of the multi-agency Climate Change Science Program (CCSP) effort should be to build upon these initiatives*

5. **Develop archive requirements for NPOESS CDRs.** CDRs that achieve validated and science-ready state will require permanent archive, even when they are superceded by improved versions. This is needed to enable rigorous scientific comparison of results and conclusions in the published scientific literature over the decadal time scale of climate research. While it might seem sufficient to archive the computer code for generating the CDRs, computer hardware, operating systems, and compilers change too dynamically to achieve a high degree of confidence that code run 10 years ago can be made to run on today's systems without a major effort and high code maintenance costs. It also may not be possible to recreate the same versions of all input data products used in the CDR product. This is another fundamental difference between EDRs and CDRs. EDRs can use the most recently available and best "current" processing software with little concern about consistency with 5 or 10 year old products: the application of such data is over the time scale of days. This also is a challenge for the NPOESS system. Weather requirements will likely lead to a system with a running archive of the last 3 to 6 months of data easily available, plus a level 0 raw data archive of all data. There is not yet a clear NPOESS requirement for CDR products, their permanent archive, or easy access to earlier versions that may have been produced 5 or 10 years earlier. Note that the archive includes not only the data products themselves, but also data and documentation on the instrument, calibration, algorithm, intermediary data products used for validation, and validation for each CDR.

Why do we need absolute calibration?

Some possible answers:

A. It is required by a rigorous, physics-based error analysis flow down.
B. We want to force the contractors to do the best they can.
C. We don't, really: we only need long term stability, but feel that this is the best way to guarantee it.
D. We don't: the satellite instrument only interpolates. The Kelvin comes from the radiosondes (or buoys, or other vicarious).
E. We haven't decided yet what we will rely on, so we need it just in case.
F. We don't: we just want pictures.
G. All of the above.
H. None of the above.

Tongue in cheek (Rice, Workshop Invited Presentation).

3. Required Absolute Accuracies and Long Term Stabilities for Climate Variables

This section discusses the required accuracy and stability for each climate variable data set. These are the accuracies and stabilities needed to detect a climate signal. For present purposes, the climate signal is a change in the climate variable over time and the time scale of interest is a decade.

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 data set to permit detection of the signal. Excellent absolute accuracy in the measurement of the climate variable is vital for understanding climate processes and changes. However, it is not as necessary for determining long-term changes or trends as long as the data set 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 ground to establish its absolute accuracy and transfer and monitor the calibration on 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 data sets is long-term stability. The required stability is some fraction of the expected signal, assumed to be 1/5 in this report. 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 factor 1/5, 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 to 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 K to 5.8 K, or factor of about 4, in the change in global temperature by 2100 (IPCC, 2001). Thus, a stability of 20% should lead to a considerable narrowing of the possible climate model simulations of 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.

Although excellent absolute accuracy is not critical for trend detection, which was the subject of the workshop, it is crucial for understanding climate processes and changes. Continuous efforts should be undertaken to constantly improve the accuracy of satellite instruments.

3.1 Solar Irradiance, Earth Radiation Budget And Clouds

How Were the Requirements Set?

Overall, the variables in this section are linked in their role in the energetics of the climate system. The sun is the dominant source of energy for the earth's climate. For a long time thought of as being a steady, constant energy source - hence, the term "solar constant" to express the amount of solar radiation reaching the Earth - we now know that it can vary on the decadal time scales of present interest. Accurate measurements of solar irradiance are key to defining climate radiative forcing, and its accuracy requirements are specified in that context. Changes in surface albedo can represent both changes in climate forcings - due to human caused land-cover change - and climate feedbacks - due to changes in ecosytems and in snow and ice cover resulting from climate changes. Cloud feedback remains the largest single factor in the current large uncertainty in climate sensitivity (IPCC, 2001). Cloud properties are critical to understanding and defining the role of clouds as feedback mechanisms in the climate system. Earth radiation budget is the final integral of energetics in the climate system, and is a key diagnostic for a wide range of climate forcings (aerosol), feedbacks (clouds, ice/snow), and climate responses (heat transport). Accuracies for clouds and radiation budget are defined at levels sufficient to be at or above estimates of unforced natural climate variability in current climate models; these accuracies must also be sufficient to directly observe decadal changes in clouds and radiation budget that would constrain potential cloud feedback mechanisms in climate models.

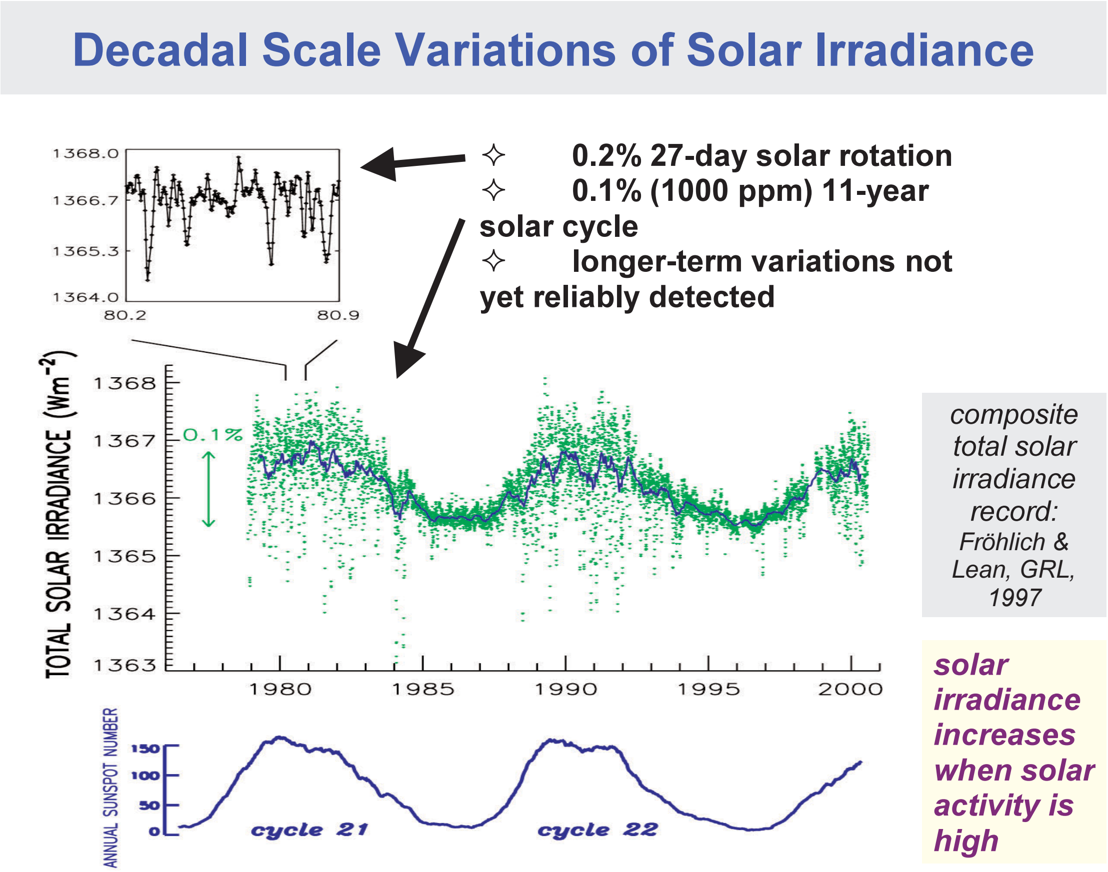
The largest time and space scales will drive the accuracy and stability requirements. For solar irradiance and surface albedo, climate radiative forcing drives the requirements. For clouds and radiation budget, climate feedbacks drive the requirements. Recent studies of the last two decades of cloudiness (International Satellite Cloud Climatology Project (ISCCP)) and radiation budget data (ERBE, Scanner for Radiation Budget (ScaRaB), CERES) from satellites have indicated significant interannual to decadal variability in the tropics from latitude 20S to latitude 20N. This variability is not shown in current climate model simulations and is representative of changes that are critical to assess accurately from observations, and to be able to predict from climate models. A climate observing system that cannot rigorously observe such changes with high confidence is very unlikely to be able to constrain and verify cloud feedbacks within climate prediction models.

Accuracy requirements can also be determined by considering the amount of climate change likely over the next few decades. For example, many climate change models use a 1%/year increase in carbon dioxide to simulate a nominal doubling of CO_2 in 70 years. This doubling is a radiative forcing of the climate system of about 4 Wm^{-2}, or about 0.6 Wm^{-2} per decade. A change in global average cloud fraction sufficient to offset this radiative forcing would be about 0.015 if all other cloud properties remained fixed. This would be a cloud feedback so strong that climate change due to greenhouse forcing would become negligible. We suggest that a minimum signal to noise of at least 5 is needed to detect such change, suggesting a requirement for stability per decade in global cloud cover of 0.003. This would be sufficient to detect a cloud feedback. This approach essentially follows that used by Hansen et al. (1993) in a workshop report that summarized accuracies required for long-term monitoring of global climate forcings and feedbacks. The accuracy requirements in this section are in general similar to those in Hansen et al. where the same climate variable was evaluated. As in that report, this workshop concluded that the appropriate scaling for climate requirements is the radiative flux changes that can potentially alter climate: either forcing or feedback.

The NPOESS project convened a workshop to assess climate measurement requirements for the Integrated Operational Requirements Document (IORD) variables (Jacobowitz, 1997). The report influenced the IORD to add or change stability requirements, but had little effect on other IORD requirements, which were focused on instantaneous observations and, often, high spatial resolution. Climate space scales run from 50 km through global, and climate time scales from a few weeks to centuries for current global change concerns. The requirements in this report and in Hansen et al. (1993) for clouds and radiation budget are often more stringent than in the NPOESS climate workshop. The NPOESS workshop does not appear to have used a consistent radiative definition of the forcings and feedbacks. Many of its threshold stability values would not be able to detect the decadal changes expected for forcings and feedbacks. Following Hansen et al. (1993) the current report tries to address the requirements in a consistent radiative forcing or feedback metric. It also assumes that the forcing or feedback must be detected accurately enough to assess decadal change at the level of 20% of the anticipated greenhouse gas forcings per decade. If four forcing and/or feedback mechanisms are found to be significant at this level and the data verify that a future climate model predicts them to this accuracy, then in the simplest sense the uncertainty in future predictions by the climate model is composed of four likely independent errors, each of which is 20% of the base greenhouse forcing. We might anticipate in this scenario that the uncertainty in future predictions would be 20% (square root (4)) = 40%. This would be a dramatic improvement over the current factor of 4 or larger uncertainty. But it also suggests that the stricter stability requirements in the current document and in Hansen et al. (1993) are to be thought of as thresholds or minimum values, not as desired objectives. The objectives should be set even tighter by a factor of 2 to 4 (10% to 5% of the greenhouse forcing).

The current report does not discuss in depth spatial, angular, and time sampling requirements, since the focus of the workshop was on calibration. But Climate Data Record (CDR) accuracy includes these issues as well. For an observing system with fixed sunsynchronous orbits such as NPOESS, angular and time sampling biases are primarily a function of the orbit. Time sampling for many of the cloud and radiation variables can be augmented by incorporating the geostationary satellite data sets (imager and sounder), especially where they can be routinely intercalibrated with the climate instruments to provide consistent data. Angle sampling errors are being markedly reduced through the efforts of the new multi-angle POLarization and Directionality of the Earth's Reflectances (POLDER), Multiangle Imaging SpectroRadiometer (MISR), and CERES observations. Spatial sampling errors become significant for instruments that only view nadir such as the new active lidar and radar systems. This primarily limits their climate-monitoring role to zonal and global means, but in some cases they can be sufficiently accurate for 1000 km scale annual mean regional values.

Regional climate change signals will be larger than zonal or global climate signals. But internal climate system noise will also be larger on these regional scales. The tradeoff of the internal climate noise versus signal has yet to be clearly defined for all of the variables in this report. There should be a continuing effort in the future to estimate climate noise for each variable at a range of time and space scales. This information can then be used to refine the observing system



Decadal Scale Variations of Solar Irradiance

- ✧ 0.2% 27-day solar rotation
- ✧ 0.1% (1000 ppm) 11-year solar cycle
- ✧ longer-term variations not yet reliably detected

composite total solar irradiance record: Fröhlich & Lean, GRL, 1997

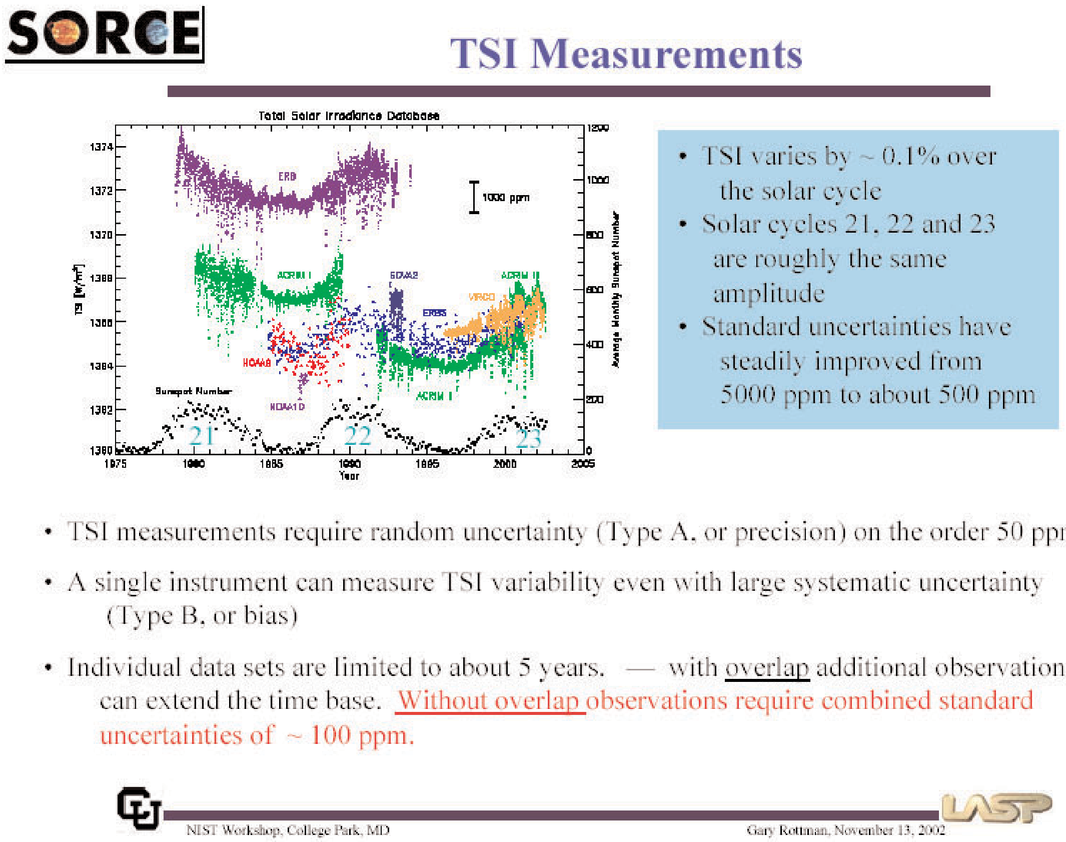
solar irradiance increases when solar activity is high

At least a one-year overlap of solar irradiance observations is needed to remove instrument differences in absolute calibration (Lean, Workshop Invited Presentation).

requirements. There is little justification to measure more than a factor of 2 more accurately than the background climate noise. In the current analysis, we have used climate model noise estimates to help set requirements for several climate variables.

3.1.1 Solar Irradiance

The IORD-II (NPOESS, 2001) requirements were reviewed and were endorsed for both total irradiance and spectral irradiance accuracy and stability. The threshold for absolute accuracy of total irradiance is 1.5 Wm^{-2} (0.1%), and for stability 0.02%/decade. As for many instruments, the stability of the active cavity radiometers greatly exceeds the absolute accuracy. At least a one-year overlap of observations is needed to remove instrument differences in absolute calibration. A 0.02%/decade stability requirement is sufficient to detect a 0.3 Wm^{-2} change in solar irradiance over a decade. This stability will constrain solar radiative forcing of the Earth's climate to within (0.3)(0.25)(0.7) = 0.05 Wm^{-2} per decade. The factor of 0.25 converts solar constant to the global average insolation over the Earth's surface, while the factor of (0.7) is the approximate fraction of energy absorbed by the Earth. This stability requirement will also allow rigorous tests of decade to century time scale variability in solar output as the length of the data record grows. The system would be capable of



TSI Measurements

- TSI varies by ~ 0.1% over the solar cycle
- Solar cycles 21, 22 and 23 are roughly the same amplitude
- Standard uncertainties have steadily improved from 5000 ppm to about 500 ppm

- TSI measurements require random uncertainty (Type A, or precision) on the order 50 ppm
- A single instrument can measure TSI variability even with large systematic uncertainty (Type B, or bias)
- Individual data sets are limited to about 5 years. — with overlap additional observations can extend the time base. Without overlap observations require combined standard uncertainties of ~ 100 ppm.

NIST Workshop, College Park, MD

Gary Rottman, November 13, 2002

Each color in the above graph represents a time series of total solar irradiance measured by an individual satellite instrument. The total solar irradiance time series in the previous figure (Lean, Workshop Invited Presentation) is based on exploiting the overlapped observations to adjust for the differing absolute accuracies of the individual instruments (Rottman, Workshop Invited Presentation).

detecting 0.5 Wm^{-2} per century change in solar forcing. Even this subtle change would be a significant fraction of anticipated greenhouse gas forcing over the next century.

Spectral irradiance requirements are in general about a factor of 10 less stringent, but details vary with wavelength as indicated in the IORD-II. The spectral irradiance measurements are crucial for properly specifying the way that the solar radiative energy enters the climate system. Absorption scattering, and reflection (in the atmosphere, at the surface and in the mixed layer of the ocean), all depend on wavelength. Solar radiation at different wavelengths has different variability. As an example, the UV radiation that is deposited in the stratosphere, and influences ozone, varies by one to two orders of magnitude more than the visible radiation that reaches the earth's surface. The IR radiation varies least. So solar radiation at different wavelengths is deposited in different ways depending on geography and altitude. The measurements of total irradiance alone provide no information about the spectral content of the irradiance variability so a physical understanding of the processes by which climate responds to solar forcing requires the measurements of the spectral irradiance. Spectral irradiance observations are also important for verifying solar physics models.

3.1.2 Surface Albedo

Land use change is a potential climate radiative forcing, while ecosystem response and snow/ice changes are climate feedbacks. The goal is monitoring global average surface albedo change to an equivalent radiative forcing change of 0.1 Wm^{-2} per decade, or about 1/5 of the expected rate of CO2 forcing. Since one-quarter of the Earth is covered by land, and about half of the land is cloud free, this equates to an 0.8 Wm^{-2} change in the average land surface reflected flux for a 24-hour average insolation of 342 Wm^{-2}. The resulting change in land albedo would be 0.8/342 = 0.002. The global average land albedo is roughly 0.2, so that the stability requirement of 0.002 albedo units per decade is a relative change of 1%/decade of the broadband solar energy reflected by the surface. This 1%/decade will drive the instrument requirements. Accuracy can be a factor of 5 less, or 0.01 albedo units. For climate applications, 25 km would be sufficient horizontal resolution.

3.1.3 Downward Longwave Radiation at the Surface

Ideally, we would require surface LW flux accuracy of 1 Wm^{-2} and stability of 0.2 Wm^{-2} per decade, similar to those for TOA (Top of Atmosphere) LW flux. See section 3.1.6 for the determination of these values. The TOA flux changes determine energy input to the entire column of land/ocean and atmosphere. The surface radiative fluxes are important in understanding the vertical redistribution of changes in TOA flux. Further climate modeling studies are needed to estimate the internal climate system noise in surface radiative fluxes analogous to that done for TOA fluxes. Recent studies of an 18-year record of surface LW flux estimates from the ISCCP (International Satellite Cloud Climatology Project) have indicated possible large fluctuations in downward LW radiation at the surface (Zhang and Rossow, 2002).

3.1.4 Downward Shortwave Radiation at the Surface

Ideally, we would require surface SW flux accuracy of 1 Wm^{-2} and stability of 0.3 Wm^{-2} per decade, values similar to those for TOA SW flux. See section 3.1.5 for the determination of these values. In general, surface SW fluxes and TOA SW fluxes are closely coupled. The exception is when atmospheric absorption changes. This can be the case with strongly absorbing aerosols, but only small variations are expected for cloud phase, optical depth, particle size and height. Liquid and ice water cloud particles absorb at similar wavelengths to water vapor absorption, so that to first order clouds change the vertical distribution of solar absorption in the atmosphere.

3.1.5 Net Solar Radiation at the Top of the Atmosphere

Climate noise represents the unforced natural variations in the climate system. Climate models indicate that tropical annual mean (20S to 20N) shortwave (SW) reflected flux climate noise is roughly 0.3 Wm^{-2}. This estimate is taken from the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) and United Kingdom Meteorological Office (UKMO) climate model simulations used in a recent study of decadal tropical variability (Wielicki et al., 2002). The previous two decades of Earth radiation budget measurements of SW reflected flux at very large time/space scales indicate that changes of 1 Wm^{-2} to 3 Wm^{-2} are possible. From both these perspectives, a stability requirement/decade is chosen as 0.3 Wm^{-2} per decade to be able to resolve changes over a decade to within current estimates of climate noise, and to be consistent with potential climate variability. Accuracy is not required at the same level, and 1 Wm^{-2} should be adequate.

3.1.6 Outgoing Longwave Radiation at the Top of the Atmosphere (TOA)

Climate models (see 3.1.5) indicate that annual tropical mean (20S to 20N) longwave (LW) flux climate noise is roughly 0.2 Wm^{-2}. Studies of potential decadal changes in LW flux at very large time/space scales indicate that changes of 1 Wm^{-2} to 3 Wm^{-2} are possible. From both these perspectives, a stability requirement/decade is chosen as 0.2 Wm^{-2} to be able to resolve changes over a decade to within current estimates of climate noise. Accuracy is not required at the same level, and 1 Wm^{-2} should be adequate.

3.1.7 Cloud Base Height

Cloud base height is not directly observed from space unless active cloud lidar and cloud radar are used to rigorously cover a full range of cloud thickness and cloud overlap. Estimates from passive imagers use cloud top height and a parameterization of cloud thickness as a function of cloud optical depth or cloud liquid/ice water path. The accuracy in cloud base height should be sufficient to achieve a surface cloud radiative effect in downward LW flux of 1 Wm^{-2}, similar to the TOA flux absolute accuracy. The primary effect is from low clouds (the opposite of TOA flux), which are present about 1/4 of the time. This suggests an accuracy of 4 Wm^{-2} in downward LW flux when these low clouds are present. Using a radiative model, this equates to a knowledge of global average cloud base height to roughly 0.5 km. Stability requirements would be 0.1 km per decade using a similar scaling for cloud effects on downward LW flux, and assuming the same 0.2 Wm^{-2} per decade global mean analogous to outgoing LW flux at the TOA (3.1.5).

3.1.8 Cloud Cover

For climate change, cloud feedbacks should be monitored to a global average radiative effect similar to climate model noise in LW and SW fluxes (3.1.5 and 3.1.6). Cloud cover affects both SW and LW fluxes. But the largest effect will be for SW fluxes and therefore should meet a similar 0.3 Wm^{-2} decadal change stability. The current global average SW cloud radiative effect (all-sky reflected flux minus clear-sky reflected flux) is about 50 Wm^{-2}. Using the average global cloud fraction of 0.5, this indicates an average overcast SW cloud radiative effect (overcast minus clear skies) of about 100 Wm^{-2}. The global average effect of a change in cloud cover alone (all other properties constant) would then be 100 Cf, where Cf is cloud fractional coverage in units from 0 to 1. Since cloud radiative effect is roughly linear in cloud cover, the final stability threshold requirement for cloud cover is 0.3/100 = 0.003 stability/decade. Accuracy is not required at this level, and 0.01 accuracy should be sufficient to be consistent with the 1 Wm^{-2} accuracy of TOA fluxes in 3.1.5 and 3.1.6). Note that as clouds become optically thin, the accuracy of the cloud cover requirement becomes less stringent proportional to the SW cloud radiative effect of the thin cloud. For example, a thin cirrus with a SW radiative effect of only 10 Wm^{-2} would have a stability requirement of 0.03/decade for cloud fraction of these thin clouds. Therefore cloud fraction accuracy for hard to detect very thin clouds can be relaxed from the average value.

3.1.9 Cloud Particle Size Distribution

No stability or accuracy recommendations are made at this time because of uncertainties in the effect of cloud particle size distribution on radiative fluxes. For climate applications, cloud particle size distribution is less critical than cloud effective radius. This is also true for aerosols (3.2.4). Since most cloud particles are much larger than the wavelength of visible radiation, geometric optics govern, and variations in the size distribution have little effect on SW reflected fluxes. For infrared fluxes, effective particle size can be used to predict the changing absorption optical depth or emissivity with infrared wavelength. The one exception to this may be thin to moderate optical depth ice cloud where particle size is of the order of the wavelength for the far infrared rotation band of water vapor at 17 μm to 100 μm wavelengths. About half of the thermal emission of the earth originates in this spectral band, and most of the water vapor greenhouse effect is in this spectral band. Typical ice crystal effective radii for thin to moderate thickness ice clouds are 20 μm to 50 μm, so that a simple effective radius may not sufficiently characterize the LW radiative effect of these clouds in the far infrared. Further analysis of far-infrared radiative modeling as a function of cloud particle size distributions is required to clarify this requirement for climate applications.

3.1.10 Cloud Effective Particle Size

Cloud effective particle size plays a potential role in both radiative forcing and climate sensitivity. The radiative forcing role is known as the indirect effect of aerosol forcing. In the simplest sense, increasing aerosols increase cloud condensation nuclei, which results in smaller cloud particle size for a given amount of liquid water condensed during rising motion. Cloud liquid water path (LWP) is the vertical column amount of liquid water in a cloud layer. For a given LWP, decreased effective radius Re results in larger cloud optical depth Tau and therefore larger cloud albedo and reflected SW flux. We use the same simple relation in 3.1.12 of LWP = K x Tau x Re, where K is a constant, to relate these three key cloud variables. The driver for this requirement will be the radiative forcing accuracy desired for the indirect radiative effect of aerosols. The nominal requirement is to understand the potential indirect aerosol radiative forcing at 0.1 Wm^{-2} per decade: equivalent to the changes in land albedo radiative forcing discussed in 3.1.2, and a factor of two less stringent than solar forcing. This stability is also consistent with the 0.12 Wm^{-2}/decade requirement for direct aerosol radiative forcing in 3.2.4. Boundary layer water clouds that are considered susceptible to modification by aerosols cover only about 1/4 of the earth. Therefore, the most stringent effective particle size limit will be for liquid water clouds (without overlying thick ice cloud) and will be a stability requirement of 4(0.12) = 0.5 Wm^{-2} change in SW cloud radiative forcing for these clouds, when present. The relationship of LWP, Tau, and Re indicates that for constant LWP, a +2% change in Re causes a -2% change in cloud optical depth. Using the discussion in section 3.1.13 for Tau, we conclude that the stability requirement for water cloud Re is 2% per decade. The absolute accuracy is 10%. For ice clouds, instead of the more stringent radiative forcing limits, we use the less stringent cloud feedback SW radiative flux changes of 0.3 Wm^{-2} used in 3.1.5 and 3.1.13. We also assume that these ice clouds cover roughly 1/4 of the Earth. The resulting ice cloud effective radius absolute accuracy requirement is then 20%, and stability requirement is 4% per decade. Note that as for cloud optical depth, these accuracies can be relaxed for optically thin clouds, proportional to their SW cloud radiative effect.

3.1.11 Cloud Ice Water Path

Cloud ice water path (IWP) and liquid water path (3.1.12) are similar variables. The major difference is that the vertical variation in particle size can commonly be a factor of 10 in ice clouds versus a factor of 2 for water clouds. This complicates simple relationships such as IWP = K x Tau x Re, where K is a constant, Tau is cloud visible optical depth, and Re is cloud particle effective radius. But such simple relationships remain useful for scaling observing requirements, and relating radiative flux changes to cloud IWP. Following the logic in 3.1.12 for LWP, the IWP absolute accuracy requirement is 25% and the stability requirement is 5%/decade.

3.1.12 Cloud Liquid Water Path

Cloud liquid water path (LWP) is the vertical column amount of liquid water in a cloud layer. LWP is related to cloud effective particle size (Re) from 3.1.10 and cloud optical depth (Tau) from 3.1.13 by the simple approximation LWP = K x Tau x Re, where K is a constant. It is clear then that cloud liquid water path is a link between the water cycle and the energy cycle. But the time average total amount of liquid and ice water in clouds is only a very small fraction of the time integral of precipitation, or of the column amount of water vapor. For example, a typical liquid water cloud with Re = 10 micron, and Tau = 10, has a LWP of about 0.06 mm of water. Global average column water vapor is about 30 mm equivalent, 500 times larger. Annual average precipitation is about 1 m, or 15,000 times larger. This makes it clear that while there is a link between the water and energy cycles, large changes in cloud LWP could occur with little or no changes in precipitation. For this reason, cloud LWP is more closely linked to the energy cycle than to the water cycle. But cloud LWP is closely related to the dynamics of the cloud system through the moist and dry adiabatic lapse rates. Therefore it is important to evaluate independently of cloud optical depth and effective radius. Changes in the vertical distribution of particle size within cloud layers (factor of 2) complicate the simple approximation of LWP = K x Tau x Re. The key role of cloud dynamics in cloud radiative feedbacks indicates that LWP accuracy and stability goals should be sufficient to allow direct comparison of independent measurements of LWP, Tau, and Re. As a result, we use the cloud radiative effects discussed in 3.1.13 and 3.1.10, and the simple approximation discussed above to set the LWP absolute accuracy requirement at 15%, and the stability requirement at 3%/decade, if all clouds were water clouds. Using roughly half of the radiatively important clouds as liquid water, the final requirement becomes 25% absolute accuracy and 5%/decade stability in LWP. The average cloud water content is about 0.1 mm; hence the required accuracy and stability are 0.025 mm and 0.005 mm.

3.1.13 Cloud Optical Thickness

For climate change, cloud feedbacks should be monitored to a global average radiative effect similar to climate model noise in TOA LW and SW fluxes. Cloud optical thickness is primarily relevant to SW fluxes and therefore should meet a similar 0.3 Wm^{-2} decadal change stability. Global average SW cloud radiative effect (all-sky minus clear-sky reflected flux) is about 50 Wm^{-2}. Cloud effects on SW fluxes, however, are highly nonlinear in optical depth. But using a broadband radiative transfer model, we can convert accuracy in TOA SW flux to approximate accuracy in cloud optical depth. For an average cloud cover of 50%, a stability of 0.3 Wm^{-2} equates to a 0.6 Wm^{-2} change in cloudy regions. Table 4 shows the percentage stability in cloud optical depth (equivalent to a TOA change of 0.3 Wm^{-2}) as a function of cloud optical depth, as predicted by a radiative model.

Table 4. Required cloud optical depth stability as a function of cloud optical depth

Cloud Optical Depth	0.1	0.5	2	8	32	128
Cloud Optical Depth stability (%)	20	5	2	2	3	6

Since the majority of clouds have optical depths between 2 and 32, the requirement is selected at 2% stability/decade. Absolute accuracy is not required at this level, and 10% accuracy should be sufficient. Three-dimensional cloud effects may dominate cloud optical depth absolute accuracy while instrument visible channel stability will control the stability requirement. At very low or high cloud optical depths, less accuracy and stability are required in cloud optical depth.

3.1.14 Cloud Top Height

Cloud top effective radiating temperature is used to set the height requirements. Temperature is mapped to height through the temperature profile retrieved by other EDRs and CDRs. For climate, the cloud top temperature is the more fundamental parameter (3.1.16), and the height is a property derived for convenience. Some degradation of accuracy from temperature to height is expected because of temperature profile errors, especially in polar regions with strong temperature inversions. Use of a typical temperature lapse rate in the atmosphere allows conversion of the cloud temperature requirement (3.1.16) to a cloud top height requirement. For a typical value of 6 K/km lapse rate, the 1 K accuracy requirement for cloud temperature converts to 150 m in global average cloud height. The stability requirement converts to 0.2/6 = 0.03 km or 30 m per decade.

3.1.15 Cloud Top Pressure

Similar to cloud height, the cloud top pressure is typically converted from cloud top temperature using vertical temperature profiles. In the lower half of the troposphere, 100 hPa is roughly 1 km in height. Therefore lower troposphere global accuracies of 15 hPa in cloud top pressure, and stability of 3 hPa per decade are required. For upper tropospheric clouds such as cirrus, however, these values will be scaled down by the decreased change in pressure with height (not linear) and will be scaled up by the 1/Ce cloud emissivity dependence discussed in 3.1.16 for Cloud Temperature.

3.1.16 Cloud Top Temperature

For climate change, cloud feedbacks should be monitored to a global average radiative effect similar to climate model noise in TOA LW and SW fluxes. Cloud top temperature is most relevant to LW TOA fluxes and therefore should meet a similar 0.2 Wm^{-2} decadal change stability. We use a rough approximation to relate cloud radiative effect on LW flux CFlw, cloud fraction Cf, cloud emissivity Ce, cloud temperature Tc, and surface temperature Ts. The approximation is given by CFlw = 2 x Cf x Ce x (Tc-Ts). This approximation leads to a requirement of about 0.2 K/decade stability in cloud top temperature, assuming 50% global average cloud fraction. Note that for climate, the cloud top effective radiating temperature is most appropriate and is the most directly measured quantity by imager or interferometer retrieval techniques. This is the "cloud top" temperature referred to in these climate requirements. To match accuracy with outgoing LW flux (3.1.6) at the top of atmosphere, accuracy in cloud top temperature should be 1 K for optically thick cloud. For optically thin clouds, to maintain similar cloud radiation feedback accuracy, cloud top accuracy should be 1 K/Ce: e.g. 2 K for cloud emissivity = 0.5, 5 K for cloud emissivity = 0.2. The same dependence on cloud emissivity also applies to the stability requirement, which can be stated as 0.2 K/Ce per decade. For thin cirrus of infrared emissivity 0.2, the stability requirement would be 1 K/decade.

3.1.17 Spectrally Resolved Longwave Radiation

Climate models indicate a lower range of temperature change of 0.1 K/decade (Holton *et al*. 1995). Analysis of the Global Cloud Imagery (GCI) dataset (Salby and Callaghan, 1997) of 11 µm radiation indicates typical interannual variability over climatic spatial scales (22.5° x 22.5° grid boxes) of 0.3 K (Kirk-Davidoff et al., 2003). The radiation at 11 µm represents a worst-case in both total variability and diurnal cycle, representing a sound basis for determining overall dataset requirements. An absolute accuracy of 0.1 K in a data set of spectrally resolved longwave radiation will allow the detection of these low range climate changes as they become distinct from the interannual fluctuations. A stability of 0.04 K/decade is required to resolve estimated 0.2 K/decade global warming.

3.2 Atmospheric Variables

How Were the Requirements Set?

The expected decadal changes in a variety of atmospheric variables were used to determine accuracy and stability requirements. This usually involved utilizing the expected response to global warming estimated from general circulation model experiments. As in the previous section, we assume that a signal-to-noise of at least 5 is required to reliably detect these changes from an instrument stability standpoint. The instrument accuracy, as has been discussed above, is less of an issue. As long as overlapping satellite records can be constructed to determine the calibration offsets between instruments, we can relax the absolute accuracy requirements to what is expected (and indeed already achievable) from a variety of sensor technologies in the coming decade. This is not to minimize the importance of understanding the sources of absolute accuracy errors, since some of these sources could conceivably affect the stability we require for climate monitoring. For many of the passive microwave or infrared technologies, instrument absolute accuracies of 0.5° C can meet our requirements, as long as these accuracy numbers are dominated by a systematic bias that can be removed during satellite overlap periods.

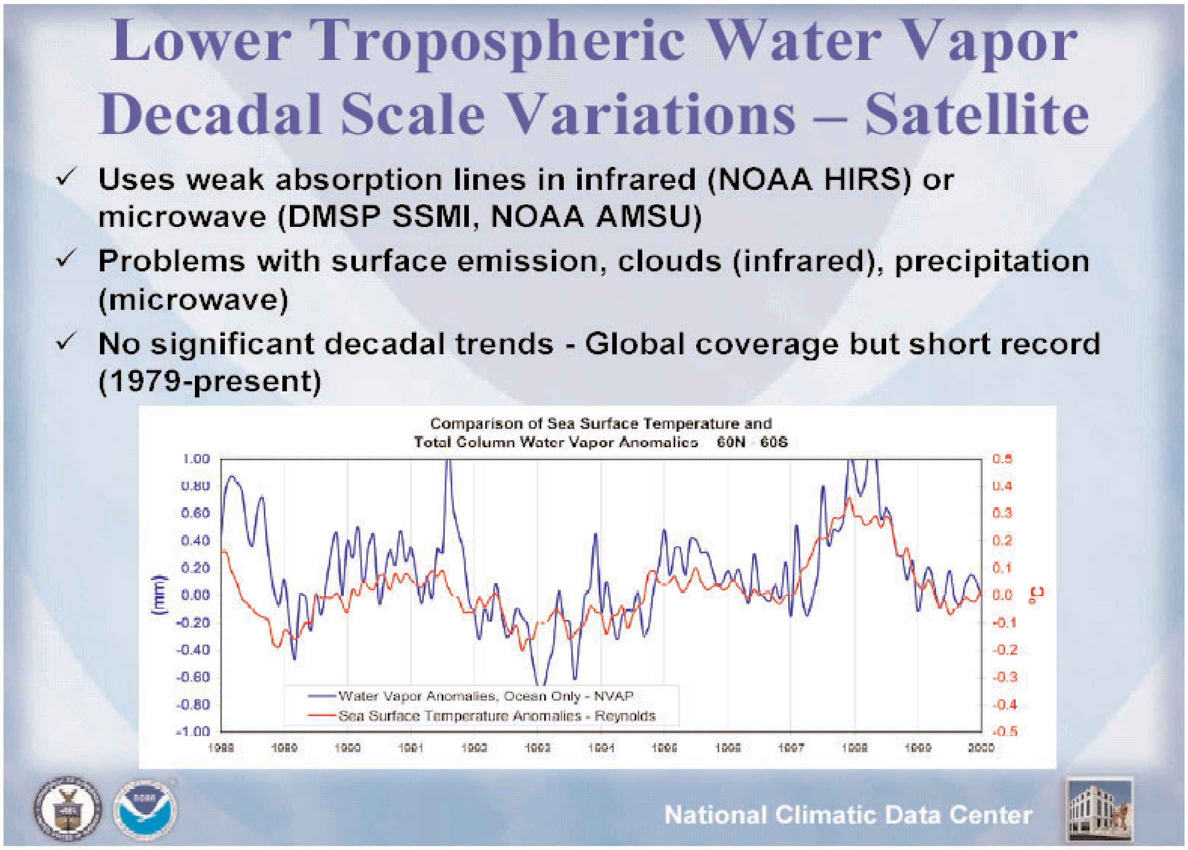
3.2.1 Atmospheric Temperature

The most stringent climate-monitoring requirement for atmospheric temperature would be the observation of the expected average global warming signal, which, based on climate model estimates, is about 0.20° C/decade over the next century for deep-layer tropospheric temperature, depending somewhat upon latitude. Expected cooling of the stratosphere is about 0.40° C/decade, also depending somewhat upon latitude (IPCC, 2001).

Absolute accuracies of about 0.5° C are now realistic and achievable, assuming we are talking about deep-layer averages, which are probably more pertinent for climate monitoring work. The expected global warming signal of 0.20° C/decade in the troposphere, assuming the 1/5 factor discussed above, leads to a long-term stability requirement of 0.04° C/decade.

3.2.2 Water Vapor

Again, the accuracy (bias) associated with the measured humidity is less important that the long-term stability of that measurement. We somewhat arbitrarily assume a 5% accuracy requirement, which for deep-layer averages or vertically integrated water vapor is already being achieved from SSM/I. This is considerably more stringent that listed in IORD II (20-25%), primarily because of large uncertainties in the retrieval of humidity *in shal-*



Lower Tropospheric Water Vapor Decadal Scale Variations – Satellite

- ✓ Uses weak absorption lines in infrared (NOAA HIRS) or microwave (DMSP SSMI, NOAA AMSU)
- ✓ Problems with surface emission, clouds (infrared), precipitation (microwave)
- ✓ No significant decadal trends - Global coverage but short record (1979-present)

National Climatic Data Center

No significant water vapor trends have been detected since 1979 (Bates, Workshop Invited Presentation).

low layers to meet NPOESS weather forecasting requirements.

Assuming that constant relative humidity is maintained during global warming, at least in the lower troposphere, then an absolute humidity (or total water vapor) increase of about 1.3%/decade would be expected (global average) for a warming of +0.20° C/decade. Again, very substantial regional deviations from this average value would be expected. Utilizing a factor of (1/5) leads to a 0.26%/decade long-term stability requirement. This is substantially more stringent than the 2% threshold stability requirement in the NPOESS IORD II (2001). Again, this is the requirement to observe the global moistening of the atmosphere associated with global warming-regional changes could be much larger and would have a much less stringent stability requirement.

3.2.3 Ozone

Over the next 50 years, stratospheric ozone should return to its levels of 25 years ago. Thus, the changes one expects to see are increases at about half the rate of the observed decreases. The *WMO CEOS* Report on Ozone (WMO, 2001) gives trend detection goals by atmospheric levels consistent with detecting these trends: 5%/decade for the troposphere, 3%/decade for the stratosphere, and 1% per decade for the total column. To detect these trends requires data set stabilities of 1/5 of the above values: total column: 0.2%/decade, stratosphere: 0.6%/decade, and troposphere: 1%/decade. Required accuracies are 3% for total column ozone, 5% for stratospheric ozone, and 10% for tropospheric ozone.

The NPOESS IORD II (NPOESS, 2001)) gives threshold long-term stability requirements of 1% per 7 years for total ozone and 2% per 7 years for profile ozone and objective requirements of half these amounts. These long-term requirements are on single-instrument stability, not absolute accuracy. The IORD has threshold requirements only for the total column and stratosphere, not for the troposphere. The OMPS will have a capability to derive tropospheric ozone from its observations and pre- and post-launch instrument calibration should be considered for reducing errors in this atmospheric parameter since it is important to climate science.

3.2.4 Aerosols

The most realistic approach to defining the required accuracy and long-term stability requirements for aerosols is with respect to the rate of increase of forcing by well-mixed greenhouse gases. This is because of the considerable uncertainties in modeling studies (Haywood and Boucher, 2000) and poor knowledge of historical changes in this variable. Unlike greenhouse gases, aerosols can cause either warming or cooling depending on their single-scattering albedo. The magnitude of the aerosol radiative forcing is principally dependent on the aerosol optical depth, but is also affected by the vertical distribution of the aerosols, their size distribution and refractive index. The expected rate of increase of forcing by well-mixed greenhouse gases is assumed here to be roughly 0.6 W/m^2 per decade. The 0.2 stability factor leads to a stability requirement of 0.12 W/m^2 per decade. We estimate that required accuracies will be approximately 0.01 for aerosol optical depth (AOD) measurements, 0.02-0.03 for single scattering albedo, the greater of 0.1 μm or 10% for effective radius, and the greater of 0.3 or 50% for effective variance. Here it is assumed that the aerosol size distribution is bimodal since this is typical of aerosol sampling measurements (when optically irrelevant Aitken nuclei are neglected) and of the majority of AeroNet retrievals (except when stratospheric aerosol yields a trimodal distribution). For aerosols, as before, we define the necessary long term stability as 0.2 of the change in forcing by well mixed greenhouse gases, which means that the long term stability requirements are about 50% smaller than the absolute accuracy requirements over a decade. These requirements are consistent with IORD-II (NPOESS, 2001), since the required accuracy and long term stability for aerosol measurements used a similar radiative definition of the aerosol climate signal. Although the refractive index only has a small effect on the radiative forcing of aerosols, it is a crucial diagnostic of the aerosol species and therefore represents an important constraint on aerosol transport models and, consequently, the prediction of aerosol forcing. It should therefore be measured with sufficient accuracy to discriminate between broad classes of aerosols. An accuracy of 0.02 provides this discrimination and a long-term stability requirement of 0.01 per decade is consistent with the radiatively defined parameters.

Episodic events (e.g., eruption of Mt. Pinatubo) can inject large aerosol optical depths into the stratosphere and cause a substantial cooling on a 1-3 year time scale. The radiative effect of stratospheric aerosols is less dependent on the aerosol single scatter albedo than that of tropospheric aerosols, because of the significant thermal radiative forcing, and so is defined principally by the AOD and secondarily by the aerosol size distribution. We estimate that the required accuracy, using the same radiative definition as for tropospheric aerosols, is 0.01 for optical depth, 0.1 µm for effective radius and 50% for effective variance, where it is assumed that the stratospheric aerosols are monomodal. As before, long-term stability requirements on a decadal time scale are 50% tighter than the accuracy requirements.

3.2.5 Precipitation

The globally averaged precipitation rate is about 3 mm/day, which is 0.125 mm/hr. It is estimated that only about 5% or less of the earth is covered by precipitation at any given instant. Thus, we can say that, where it is raining, the average rain rate is (1/0.05) x (0.125 mm/hr) = 2.5 mm/hr. The consensus of a variety of climate model simulations suggests that this average precipitation rate is expected to increase about 3% per degree C of warming. Thus, for an expected decadal warming trend of 0.2° C, there should be a 0.6%/decade increase in the precipitation rate. This amounts to 0.015 mm/hr increase in the 2.5 mm/hr average rain rate. Utilizing the 0.2 factor as before, this requires a measurement stability of about 0.003 mm/hr when observing rain. An absolute accuracy of about 5% of the mean is somewhat arbitrarily assumed here, which results in 0.125 mm/hr absolute accuracy requirement where it is raining. Again, we keep in mind that this accuracy refers to a systematic bias over many measurements, as this level of accuracy is probably not attainable for even the best rain gauges for individual measurements.

3.2.6 CO2

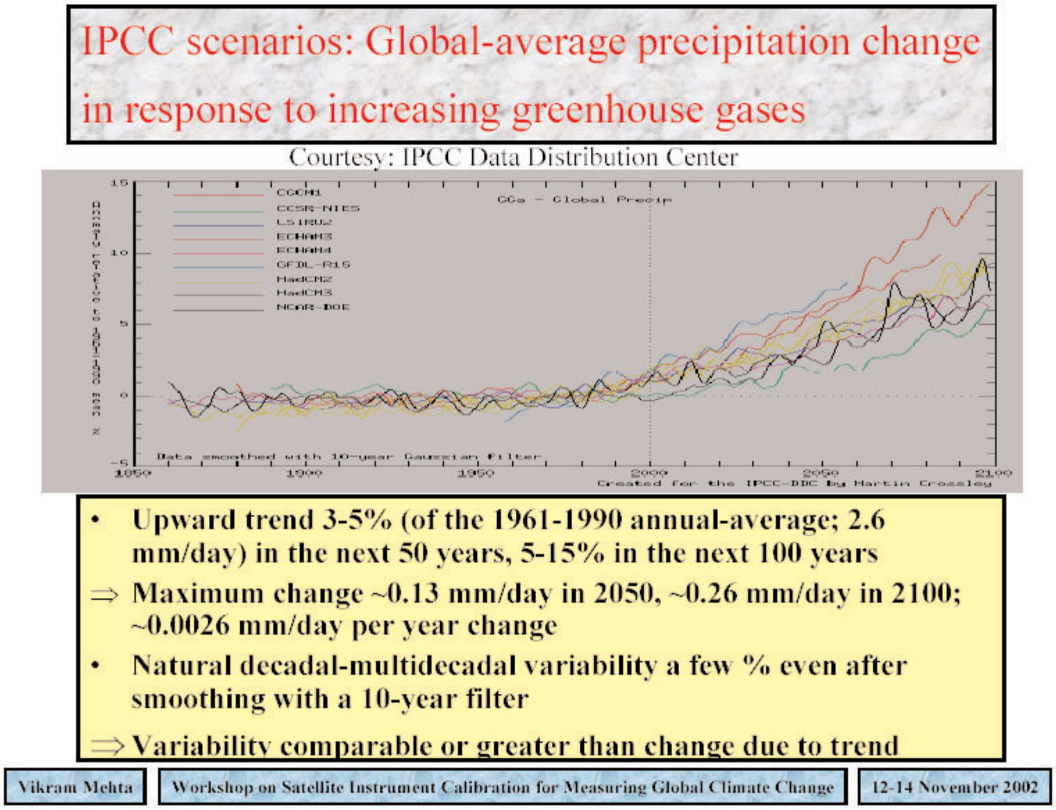
The secular trend in CO_2 is currently about 1.4 ppmv yr^{-1}, or about 4% per decade. This variation can easily be detected by a single in-situ station (e.g., Mauna Loa), and is therefore uninteresting for satellite applications.

Much more important for climate projection is the behavior of sources and sinks on these time scales. The in-situ data can be inverted to allow the integrated source or sink to be estimated at continental or ocean basin scale, but these estimates will be of little use for understanding mechanisms or improving predictive models. Satellite data can supplement in-situ data in determining sources and sinks.

Mechanisms for current sinks on land are believed to include CO_2 fertilization, nitrogen deposition, re-growth of previously cleared forests, fire suppression, and a longer growing season at high latitudes due to the warming climate. Of these mechanisms, only CO_2 fertilization is expected to strengthen over coming decades. Most terrestrial sink mechanisms are expected to saturate or even reverse their signs over time, so huge variations in sources and sinks are expected over the next 30 years. The uncertainty in the future behavior of these sinks is one of the primary drivers of uncertainty in future climate.

Since carbon dioxide is measured to a high level of accuracy at a number of sites around the globe, any biases in spaceborne measurements will likely be removable, and so we arbitrarily assume an absolute accuracy requirement of 10 ppmv, which is approaching 3% of the average carbon dioxide concentration of the atmosphere. The 0.2 factor applied to the current global trend of 14 ppmv/decade yields a stability requirement of 2.8 ppmv/decade.

For estimating sources and sinks on large spatial (10° by 10°) and temporal (month) scales, stabilities of about 2 ppmv would provide information comparable to that of the current in-situ network. However, the stability requirement is 1 ppmv (Peylin et al., 2002; Gurney et al., 2002). Accuracy is not critical since it is the spatial and temporal gradients that are important for this problem.



IPCC scenarios: Global-average precipitation change in response to increasing greenhouse gases

Courtesy: IPCC Data Distribution Center

- Upward trend 3-5% (of the 1961-1990 annual-average; 2.6 mm/day) in the next 50 years, 5-15% in the next 100 years

⇒ Maximum change ~0.13 mm/day in 2050, ~0.26 mm/day in 2100; ~0.0026 mm/day per year change

- Natural decadal-multidecadal variability a few % even after smoothing with a 10-year filter

⇒ Variability comparable or greater than change due to trend

Vikram Mehta | Workshop on Satellite Instrument Calibration for Measuring Global Climate Change | 12-14 November 2002

Climate model predictions of precipitation trends as a result of greenhouse warming can be used to determine the precipitation measurement requirements (Mehta, Workshop Invited Presentation).

3.3 Surface Variables

Surface variables include land vegetation, snow cover, sea ice, ocean color, and temperature. One problem with defining the requirements for the satellite measurements of the Earth's surface is the wide range of surface types covered. Under the final "roadmap" section we will also discuss the various concerns that the group had relative to the future of these satellite measurements. A fundamental concern is the need for both accurate pre-launch calibration and post-launch validation of all satellite instruments. By their very nature satellite measurements do not directly sense the parameter of interest and it is only through these calibration and validation efforts that we can develop methods to estimate the desired parameters from the satellite data. These concerns apply both to the present and future satellite measurements.

3.3.1 Ocean Color

About 90% of the signal received by satellite instruments measuring reflected visible radiation is contributed by the atmosphere rather than the ocean. Thus, it was clear that it will never be possible to compute accurate "water leaving radiances" from ocean color sensors without some method of in-situ calibration. Atmospheric correction methods alone cannot yield sufficiently accurate ocean color measurements and it will always be necessary to have comparisons with in-situ measurements to derive the appropriate algorithm coefficients. Any future satellite system must be coupled with in-situ measurements that can be used to calibrate and validate the satellite sensor data. With these caveats the requirements for ocean color measurements are set at 5% for accuracy and 1% for stability.

3.3.2 Sea Surface Temperature (SST)

Climate models predict air temperature increases of about 0.2 K per decade due to greenhouse warming. Sea surface temperatures can be expected to increase at about the same rate. To measure this change requires a data set stability of 1/5 of 0.2 K/decade or 0.04 K/decade. Accuracy of 0.1 K is considered adequate.

Ocean buoys measure the SST at 1m to 2 m below the surface representative of the "bulk SST" that were also measured by ship buckets prior to the 1950s and ship injection SSTs since then. Satellite measured SSTs are sensitive to the topmost skin layer of the ocean, but they are generally corrected to bulk SSTs. The Surface Panel recommends that the satellite SST program include an in-situ program of calibration/validation measurements that combine both skin and bulk SSTs.

3.3.3 Sea Ice

Changes in sea ice area represent potential changes in climate forcing due to the sea ice- albedo feedback mechanism. We specify the sea ice area measurement requirement using the same rationale as for land surface albedo. We must determine the change in sea ice area needed to cause a change in mean global reflected solar radiation of 0.1 W/m^2 (about 1/5 of expected greenhouse forcing in a decade). Since clouds cover sea ice about half the time, the change in sea ice area has to be doubled to achieve the 0.1 W/m^2 value.

$$0.2 \text{ W/m}^2 = (\delta A_{\text{sea ice}}/\text{earth surface area}) \times (\alpha_{\text{sea ice}} - \alpha_{\text{ocean}}) \times (\text{Insolation}) \qquad (1)$$

where $\delta A_{\text{sea ice}}$ is the required change in sea ice area, earth surface area is the total surface area of the earth, $(\alpha_{\text{sea ice}} - \alpha_{\text{ocean}})$ is the difference in albedo between sea ice and open ocean, and Insolation is the average solar radiation at high latitudes. Taking 0.5 as the difference in albedo between sea ice and open ocean and 200 W/m^2 as the insolation at high latitudes, we obtain a required sea ice cover change of 10^6 km^2 per decade. With current average sea ice cover of about 23x10^6 km^2, this represents a change in total sea ice cover of about 4% per decade. Thus, stability of the sea ice cover data set should be about 4% per decade. Absolute accuracy of 5% would be sufficient.

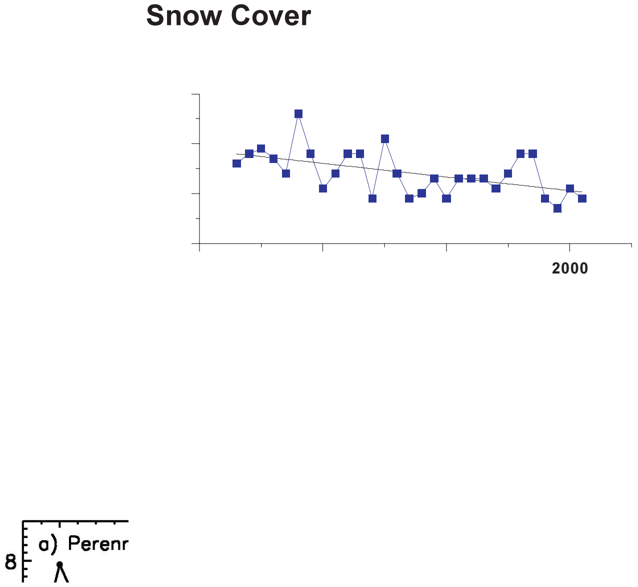
3.3.4 Snow Cover

Changes in snow cover represent potential changes in climate forcing due to the snow- albedo feedback mechanism. We specify the snow cover measurement requirement using the same rationale as for sea ice area. We must determine the change in snow cover needed to cause a change in mean global reflected solar radiation of 0.1 W/m^2 (about 1/5 of expected greenhouse forcing in a decade). Since clouds cover snow about half the time, the change in snow cover has to be doubled to achieve the 0.1 W/m^2 value.

$$0.2 \text{ W/m}^2 = (\delta A_{\text{sea ice}}/\text{earth surface area}) \text{ x } (\alpha_{\text{sea ice}} - \alpha_{\text{ocean}}) \text{ x } (\text{Insolation}) \qquad (2)$$

where dAsnow is the required change in snow cover, (asnow - aland) is the difference in albedo between snow and snow-free land, and Insolation is the average solar

Yearly Perennial Sea Ice Cover and
Average North American Snow Cover



Satellite observations indicate that both snow cover and sea ice are decreasing (Tarpley and Comiso, Workshop Invited Presentations).

radiation at high latitudes. Taking 0.5 as the difference in albedo between snow and snow-free land and 200 W/m^2 as the insolation at high latitudes, we obtain a required snow cover change of 10^6 km^2 per decade. With current average snow cover of about 25x10^6 km^2, this represents a change in total snow cover of 4% per decade. Thus, stability of the snow cover data set should be about 4% per decade. Absolute accuracy of 5% would be sufficient.

Experience with over more than 30 years of photo-interpretive snow mapping by human analysts show what current capabilities are. We think that automated snow mapping to be implemented in the near future would achieve snow cover accuracy of 5% and stability of 1.5%. These are limits presently met by the human analyst system and should be the expectations for the future automated systems.

3.3.5 Vegetation

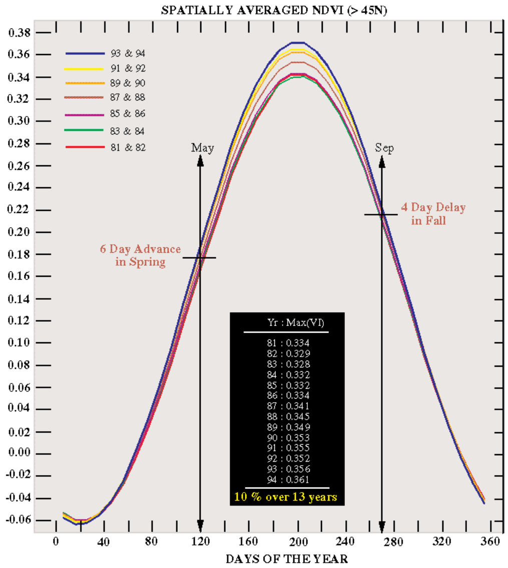
The type and distribution of vegetation native to a geographic region are diagnostic of the area's climate. This is because vegetation integrates the effects of precipitation and temperature over all time frames longer than a few days. In addition the vegetation feeds back into climate because of the plant species contribution to the surface energy and moisture balance and its impact on surface roughness and albedo. For these reasons, observing vegetation changes in the seasonal to interannual time frame and over long term is important to climate monitoring.

The quantity usually derived from satellite observations is normalized difference vegetation index (NDVI). NDVI is usually defined as (NIR -VIS)/(NIR + VIS), where VIS and NIR are albedo measurements at a visible and near infrared wavelength. More physically meaningful quantities such as

Northern Latitude Greening Trends

Our analysis shows that during the years 1981 through 1994 for the Northern high latitudes

- NDVI averaged over boreal growing season months of May to September increased by about 10%,
- the timing of spring green-up advanced by about 6 days.



Greening trend?
Orbital drift?
Inter-sensor variation?
Noise in the channel data?

AVHRR observations suggest that the growing season increased between 1981 and 1994, but questions remain, mainly with respect to calibration and inter-calibration of sequential satellite instruments (Knyazikhin, Myneni, and Shabanov, Workshop Invited Presentation).

green vegetation fraction and leaf area index can be derived from NDVI. Because NDVI is a relatively robust quantity, that is, it minimizes some of the noise introduced by viewing and illumination conditions, we recommend that it be the basic vegetation parameter for climate monitoring. There are related ground truth measurements such as leaf area index (LAI) that can be measured and compared with the NDVI estimates. One could also make direct spectral measurements near the ground that can be used to directly compute an NDVI for comparison with the satellite estimates. These would have to be averaged up to a size that would be relevant to the satellite data.

The needed accuracy and stability for NDVI for monitoring vegetation at climate time scales is not clear. There is no ground truth for NDVI, so translating vegetation changes as seen from the surface into equivalent NDVI has not been done. Likewise, there is no modeled result that would tell us what kind of vegetation changes could be expected with global warming or CO_2 doubling. Several researchers have reported increases in the Advanced Very High Resolution Radiometer (AVHRR) NDVI products over decadal or longer time spans. Such results have been controversial because of difficulty in calibration of the AVHRR and problems introduced into the data record by change in observation times caused by orbit drift. However decadal changes in average NDVI of 5 to 10% at high latitudes have been reported. In light of these reports, an accuracy requirement of 3% and a stability requirement of 1% per decade are suggested for NDVI.

4. Translation of Climate Dataset Accuracies and Stabilities to Satellite Instrument Accuracies and Stabilities

The requirements for the data sets must be translated into required accuracies and stabilities of the satellite measurements. In some cases, for example, solar irradiance and top of the atmosphere 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 data set accuracies/stabilities into satellite accuracies/stabilities.

Because of the difficulties in achieving necessary accuracies (exo-atmospheric total solar irradiance is one example, (Quinn and Frohlich,1999)), a key attribute for the satellite instruments is long-term stability. This may be achieved by either having an extremely stable instrument or by monitoring the instrument's stability, by various methods, while it is in orbit. An ideal external calibration source is one that is nearly constant in time and able to 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 far more stringent than given in this report. 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 SeaWiFS, which uses lunar observations to correct for degradation in the near infrared channels (Kieffer et al., 2003). The required lunar data are being supplied by a dedicated ground based facility (Anderson et. al., 1999).

Since satellites and their instruments are short-term - NPOESS satellites and instruments have design lives of about 7 years - satellite programs launch replacement satellites to continue the observations. Thus, the long-term data record for any climate variable will consist 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. Acquiring multiple independent space-based measurements of key climate variables - one of the climate observing principles listed above - would also help insure maintenance of stability in the event of a single instrument failure.

One proposed instrument that may have very high accuracy and may not require overlap periods is the proposed spectrally resolved radiance spectrometer (Anderson et al., 2003). Sequential flights of copies of this instrument might maintain the climate record without overlapping measurements.

4.1 Solar Irradiance, Earth Radiation Budget, and Clouds

4.1.1 Solar Irradiance

Accuracy requirements map directly into instrument requirements. No conversion is required.

4.1.2 Surface Albedo

From section 3.1.2, the absolute accuracy requirement of surface albedo is 0.01 and the stability requirement is 0.002/decade. Using global average surface albedo of roughly 0.2, these requirements are 5% in absolute accuracy and 1% per decade in stability of the radiometer used to determine surface albedo.

4.1.3 Downward Longwave Radiation at the Surface

Surface radiative fluxes from satellites are inherently much less accurate than TOA fluxes, especially for downward LW flux. The downward LW flux is a function of near surface air temperatures, water vapor, and mid to low-level cloud base heights. Whereas high altitude clouds have the largest effect on TOA fluxes, low-level clouds are most important for downward LW flux at the surface. Estimates for surface LW flux are typically made using radiative modeling approximations that use near surface atmospheric temperature and moisture, cloud base temperature, and cloud fraction. These parameters will therefore control the downward LW flux accuracy, and continuous verification against a global network of surface validation sites (e.g. BSRN and Atmospheric Radiation Measurement (ARM) program) is essential. Absolute accuracy at global scale is estimated at about 5 Wm^{-2} for current state of the art (e.g. CERES on Tropical Rainfall Measurement Mission (TRMM) or Terra). Stability will depend primarily on the stability of satellite estimated lower atmosphere temperature, water vapor, and cloud base altitudes. For the values from section 3.2, an air temperature stability of 0.05 K/decade translates to roughly 0.2 Wm^{-2} change in downward LW flux. Water vapor stability of 0.3% per decade would cause a 0.1 Wm^{-2} change in downward LW flux. To first order, cloud base = cloud top - cloud thickness. Cloud thickness is roughly proportional to cloud optical depth for a given cloud type. Using the stability requirements in sections 3.1.13 to 3.1.16, we predict a rough stability of 0.3 K/decade in cloud base temperature or 0.25 Wm^{-2} in downward LW flux at the surface. We conclude that the required accuracy and stability requirements for downward LW flux at the surface will be achieved, if the instrumental requirements for air temperature, water vapor, cloud base temperature, and cloud fraction are met. Examples of the sensitivity of surface LW flux to these parameters can be found in Gupta (1989).

4.1.4 Downward Shortwave Radiation at the Surface

In general, downward SW surface flux can be predicted as equal to TOA net solar radiation (3.1.5) minus within-atmosphere SW absorption. Within-atmosphere solar absorption is dominated by water vapor, cloud water droplet, and cloud ice particle absorption: these are thought to sum to roughly 20% of TOA incident solar radiation, and can be estimated with sufficient accuracy by meeting the instrumental requirements in 4.1.5 (net solar radiation at TOA), 4.1.10 (effective cloud particle size), 4.1.13 (cloud optical depth), 4.1.14 (cloud top height) and 4.2.2 (water vapor). But additional absorption can be present from aerosols with black carbon and organic carbon. Unknown aerosol absorption complicates the determination of clear-sky surface SW fluxes and potentially cloudy sky SW fluxes as well for low clouds embedded in absorbing aerosol layers. The instrumental requirement for aerosol single scatter albedo (4.2.4), however, should be sufficient to satisfy this requirement. Given the difficulty of measuring aerosol absorption from space, a combination of aerosol assimilation models and satellite aerosol optical depth, particle size, and composition will likely be required to constrain aerosol absorption. In addition, a global network of aerosol and surface SW measurements that covers ocean, land, and cryospheric climatic regions and observes varying aerosol types (biomass burning, industry, dust, etc) will be a key complement to the satellite observing system, both for independent assessment as well as for validation.

4.1.5 Net Solar Radiation at the Top of the Atmosphere

Accuracy and stability requirements for net solar radiation are directly related to the accuracy in TOA SW reflected flux. 1 Wm^{-2} absolute accuracy is 1% of the average broadband reflected flux and is a 1% instrument calibration requirement. 0.3 Wm^{-2} per decade stability equates to 0.3% per decade calibration stability for the broadband SW radiance.

4.1.6 Outgoing Longwave Radiation at the Top of the Atmosphere

Absolute accuracy of 1 Wm^{-2} is equivalent to 0.5% in broadband global average radiance level for calibration. Stability of 0.2 Wm^{-2} is equivalent to 0.1% per decade.

4.1.7 Cloud Base Height

As indicated in 3.1.7, cloud base height estimates with the NPOESS instruments will be dependent on estimates of cloud top height and cloud optical depth or LWP and IWP. Sensitivity studies should be done to verify the changes in cloud base height estimates with changes in the imager channels used to determine these parameters. It is expected that the primary factor will be cloud top height, which is in turn specified by cloud top temperature. This suggests a requirement for imager infrared window channel calibration of 1 K absolute and 0.2 K/decade stability as in 4.1.16. These cloud base heights, however, are only indirect estimates. Direct estimates of cloud base will require active lidar and cloud radar sensors for global conditions, especially for polar clouds where cloud detection is difficult against bright snow and ice surfaces during daylight and against small thermal contrasts and large temperature inversions in polar night.

4.1.8 Cloud Cover

Cloud cover is estimated in the NPOESS system by the cloud imager. The basic method is to classify each imager field of view (350 m or 700 m in diameter) as cloudy or clear. Requirement for global average cloud cover is 0.01 absolute accuracy and stability of 0.003 per decade (in units of cloud fraction between 0 and 1). Cloud detection is usually achieved via a multi-channel algorithm that detects cloud as changes from expected clear-sky spectral reflectance and thermal emission values at a range of spectral wavelengths. In some cases ratios of reflectances or differences in brightness temperature of thermal emission are used. Because of the complicated decision trees in these algorithms, there is no easy mapping of this requirement to individual channels. In order to better understand this requirement, sensitivity studies should be performed using the MODIS data and MODIS cloud mask algorithm to determine the sensitivity to each channel's calibration and stability. In most algorithms, however, application of the calibration requirements for cloud optical depth (4.1.13) to all solar reflectance channels, and for cloud top temperature (4.1.16) to all thermal infrared channels will result in sufficient stability and accuracy for cloud fraction determination.

4.1.9 Cloud Particle Size Distribution

There are no current recommendations for particle size variance accuracy and stability.

4.1.10 Cloud Effective Particle Size

A radiative transfer adding doubling model used to derive look up tables for cloud remote sensing algorithms was used to convert the cloud particle size requirements into equivalent instrument gain accuracy and stability for two of the Visible and Infrared Scanner (VIRS) spectral channels key to particle size retrievals: 3.7 µm and 1.6 µm. The results indicate the following requirements for water and ice clouds at 1.6 µm and 3.7 µm:

Table 5. Instrumental stabilities and accuracies at 3.7 µm and 1.6 µm for water and ice clouds

	Stability (%/decade)		Accuracy (%)	
Wavelength	3.7 µm	1.6 µm	3.7 µm	1.6 µm
Water cloud	1	0.5	5	2.5
Ice cloud	2	1	10	5

4.1.11 Cloud Ice Water Path

At this time it is not clear that IWP can be measured accurately enough to meet the requirements in section 3.1.11. The major difficulty is the large vertical variation in ice particle size within a single cloud layer (up to a factor of 10), while the satellite remote sensing techniques only derive particle size up to an optical depth of 2 or 3 into the cloud. Since the same channels are used for ice particle and water particle size retrieval, and since the water particle requirements are tighter than for ice, the calibration requirements in 4.1.10 are sufficient for any future applications to cloud ice water path, if the vertical cloud particle size variations can be handled. The cloud optical depth requirements in section 4.1.13 are also sufficient to meet any future applications to IWP. In the future advanced methods will likely be required for IWP climate measurements including cloud radar and/or sub-mm wavelength radiometers.

4.1.12 Cloud Liquid Water Path

There are two methods applicable to measuring LWP using current and near future satellite instruments. The first was discussed in section 3.1.12 and relies on the simple relationship LWP = K x Tau x Re. The LWP requirement is set to be consistent with the imager Tau and Re requirements and therefore is met by the requirements 4.1.13 and 4.1.10. The second method is use of a passive microwave imager. This is a multi-channel, multi-polarization retrieval of LWP, which is usually combined with a simultaneous retrieval of surface wind speed and column water vapor. The major challenge for microwave LWP is poor accuracy for liquid water clouds with optical depths less than about 6, and poor spatial resolution for fair weather cumulus cloud that are a factor of 10 smaller than the microwave field of view. The advantage of the microwave is that it does not depend on any assumptions of the vertical distribution of cloud particle size within the cloud layer. The required accuracy of 0.025 mm and stability of 0.005 mm in the cloud liquid water path translate into a microwave instrument accuracy of 0.75 K and stability of 0.2 K.

4.1.13 Cloud Optical Thickness

The relationship of cloud optical depth to imager visible channel reflectance is nonlinear. As earlier, we use a radiative transfer model to determine the relationship at a range of optical depths. On average, a 2% change in cloud optical depth results from a 1% change in visible imager radiance. The sensitivity to radiance change is very large at high optical depths, and small at low optical depths. We conclude that 1%/decade stability and 5% absolute calibration is required for the visible wavelength channel on the cloud imager.

4.1.14 Cloud Top Height

As discussed in 3.1.14, cloud height requirements are derived from cloud temperature requirements. As a result, the instrument requirements in 4.1.16 for cloud top temperature apply for cloud top height as well.

4.1.15 Cloud Top Pressure

As discussed in 3.1.15, cloud pressure requirements are derived from cloud temperature requirements. As a result, the instrument requirements in 4.1.16 for cloud top temperature apply for cloud top pressure as well.

4.1.16 Cloud Top Temperature

Absolute accuracy of 1 K in cloud temperature converts to a 1 K temperature accuracy for the infrared imager and spectrometer atmospheric window channels used to determine cloud top temperature. Stability of 0.2 K/decade also converts directly to a 0.2 K/decade requirement for the same infrared window channels. These levels are less stringent in stability than the surface temperature determined from the same channels during clear-sky conditions.

4.1.17 Spectrally Resolved Longwave Radiance

Absolute accuracy of 0.1 K is equivalent to 0.21% of the radiance of a 250 K (the average temperature of the atmosphere) blackbody at 11 μm (910 cm^{-1}). The decadal stability requirement of 0.4 K translates to a 0.1% decadal stability for the spectrally resolved longwave radiance instrument. To insure adequate sampling throughout the diurnal cycle, the instrument orbit should be chosen so that annual average radiance spectra are sampled to an accuracy of 0.1 K or better at large spatial scales over a maximum of the globe, with special attention given to the tropics because of their importance to the climate heat engine. An analysis of the Global Cloud Imagery dataset (GCI), which provides gridded top-of-the-atmosphere (TOA) radiances at 11 μm (910 cm^{-1}) at 3-hour intervals (Salby and Callaghan 1997) has been performed to evaluate the sampling accuracies of various possible satellite orbits (Kirk-Davidoff et al. 2003). This study indicates that for a single satellite in low earth orbit, either a true polar orbit or low-precessing orbit is required to obtain sampling accuracies of 0.1 K or better over a majority of the tropics. A satellite in sun-synchronous orbit, even with cross-track scanning, obtains this accuracy over less than one-quarter of the tropics.

4.2 Atmospheric Variables

4.2.1 Atmospheric Temperature

Tropospheric temperature is profiled by using atmospheric molecules that are assumed to be well mixed throughout the troposphere. In the infrared, carbon dioxide lines near 4.2 μm and 14 μm are used. In the microwave, molecular oxygen lines in the 50-60 GHz region are used. For sensing near surface temperature, the same radiative transfer issues noted with sensing near surface water vapor apply. That is, the radiative contrast tends to be small in the infrared since the surface emissivity is generally near unity over land and ocean and there is relatively more contrast in the microwave. Again, the microwave weighting functions are stable but the infrared weighting functions are a function of the temperature profile itself. Radiance is also a non-linear function of temperature, proportional to T^4 at 15 µm and T^{12} at 4 µm. The temperature data set accuracy and stability requirements described in 3.2.1 are 0.5° C accuracy and 0.04° C/decade stability for the troposphere, and 0.5° C accuracy and 0.08° C/decade stability for the stratosphere.

For both microwave and infrared sounders, a 1° C change in deep-layer atmospheric temperature corresponds to on order of a 1° C change in the instrument measured brightness temperature (T_b). Thus, the temperature data set accuracy and stability requirements translate into similar instrument accuracy (0.5° C) and stability (0.04° C/decade) for the troposphere, and 0.5° C accuracy and 0.08° C/decade stability for the stratosphere. These stability requirements, which were arrived at independently, closely agree with those from the NPOESS IORD II (NPOESS, 2001).

4.2.2 Water Vapor

Weak water vapor absorption lines in the infrared (on the wings of the 6.7 µm band or in the water vapor continuum at 11µm - 12 µm) or the microwave (around the 22 GHz water vapor line) are used to observed emission from the lower atmosphere. Discrimination of water vapor in the lower troposphere is dependent on the relative contrast between the surface emission and the atmospheric emission. In the infrared, both ocean and land surfaces have emissivities near 1.0, creating a low sensitivity to lower tropospheric water vapor. In the microwave near 22 GHz, the ocean emissivity ranges from 0.5-0.6 but the land emissivity is near 1.0. Because of this, there is good contrast in the microwave and a greater sensitivity to changes in lower tropospheric water vapor over the ocean versus infrared techniques. In the microwave, the water vapor weighting function (i.e., change in transmittance with change in logarithm of pressure) is stable and the radiance is linearly related to brightness temperature. In contrast, in the infrared, the weighting function is more highly variable (and is a function of the water vapor profile) and the radiance is a non-linear function of temperature (about T^8 near 6.7 µm).

Both microwave and infrared water vapor measurements operate at frequencies where the expected increase in vapor accompanying, say, a 1 K warming, leads to a larger instrument response than 1 K, i.e., from a 2 K increase at microwave frequencies to 0 K to 4 K decreases at infrared wavelengths, depending upon the channel frequency. Thus, the signal magnitude of increased humidity might be expected to be larger than the expected global warming signal, by a factor of 2 to 4. Unfortunately, since water vapor is not a uniformly mixed gas like oxygen (for microwave temperature) or carbon dioxide (for infrared temperature), there are significant data interpretation problems when trying to retrieve water vapor in the atmosphere from passive measurements.

In the microwave, total column vapor can be measured near the 22.235 GHz water vapor line, while tropospheric profiles of vapor can be retrieved with several frequencies near the 183.3 GHz water vapor line. Using a 2:1 instrument response factor just described, we can double the temperature requirements, i.e. 1.0° C absolute accuracy and 0.08° C/decade stability requirement for microwave water vapor measurements.

In the infrared, the response of individual channels varies widely, but we can assume an average response factor of around 2 to 4. For the global warming case in which relative humidity remains approximately constant, the global average brightness temperature also remains approximately constant. This is because the radiative impact of the warmer temperature profile offsets the effect of increased specific humidity in the free troposphere. The approximate simple relation between an infrared channel brightness temperature and upper tropospheric humidity is

$$a + bT_b = \ln(\mathrm{UTH}\ P_{ref}) \tag{3}$$

where T_b is brightness temperature, UTH P_{ref} is upper tropospheric humidity at P_{ref}, a reference pressure level, and b = -0.115. Although UTH depends on both water vapor mixing ratio and atmospheric temperature, observations indicate that the main variations are due to the water vapor. This equation indicates that to detect a 0.3% change in water vapor requires a stability of 0.03 K in brightness temperature.

4.2.3 Ozone

Estimates of atmospheric ozone can be obtained from satellite instrument measurements of scattered, reflected and emitted signals from a wide range of the electromagnetic spectrum. This section provides details only on instruments that measure scattered sunlight in the UV and visible parts of the spectrum. The principal measurements of these instruments are ratios of Earth radiances to solar irradiances, called albedos or top-of-atmosphere reflectivities (TOAR).

Total column ozone (TOZ)

The OMPS algorithms will use Total Ozone Mapping Spectrometer (TOMS)-style retrievals even though the OMPS has spectral measurements. The Differential Optical Absorption Spectroscopy (DOAS) retrievals require a very high Signal to Noise ratio (SNR) (not provided by OMPS) and spectral coverage. They are used in retrievals for the Global Ozone Monitoring Experiment (GOME) series of sensors. EOS Aura Ozone Monitoring Instrument (OMI) will have both algorithms applied.

The TOMS-style algorithms use combinations of BUV measurements at two or three individual wavelengths (called pairs or triplets) with at least one wavelength having significant ozone absorption for the viewing conditions and a second wavelength with much smaller absorption.

Three types of error contribute to the total instrument error: wavelength-dependent error, wavelength-independent error, and wavelength scale error (NPOESS, 2000). To achieve the required 0.2% stability in the ozone data, the sum of the contributions of these three errors must be less than 0.2%.

The hyperspectral total ozone algorithms use small scale variations in the observed albedos corresponding to small scale features in the ozone absorption cross section. They are even less sensitive to wavelength-independent errors and can adjust for some wavelength scale errors automatically, but require higher SNR measurements and usually better wavelength resolution. They are more sensitive to wavelength-dependent calibration errors, unless the errors are smooth functions of wavelength, but only need such smoothness over a limited wavelength interval.

Vertical ozone profiles

This discussion will cover two measurement techniques: systems that measure backscattered ultraviolet radiances (BUV) and systems that measure limb-scattered ultraviolet/visible radiances (LUVV). The discussion material is broken into stratospheric and tropospheric subsections.

Stratospheric ozone

For BUV instruments, the types of error are calibration errors at a wavelength (dependent or independent) and wavelength scale error (NPOESS, 2000; Bhartia, et al., 1996).. The sum of the contributions of these errors to the total error must be less than 0.6% to achieve 0.6% stability for the stratospheric ozone profiles.

For limb-scattered uv-visible measurements, the following error types apply: wavelength-dependent error, wavelength-independent error, wavelength scale error, and pixel-to-pixel error (NPOESS, 2000). The pixel-to-pixel error is the spatial error of measurements of limb-scattered uv-vis radiation. The sum of the contributions from these four error types must be less than 0.6% to meet the 0.6% stability requirement for stratospheric ozone profiles. These inequalities assume that satellite pointing and other errors do not have significant contributions to the accuracy. Pixel-to-pixel errors are important in the height normalization step of the algorithm. Improperly characterized detector nonlinearity could be an additional source of pixel-to-pixel errors.

Tropospheric ozone

Systems using BUV and LUVV measurements have difficulty determining tropospheric ozone directly. Estimates may be obtained by "tropospheric residual" techniques in which one subtracts stratospheric column estimates from total column estimates. Since the ozone in the troposphere may be as little as 10% of the total column, the differences will magnify any errors, e.g., a 0.5% error in the total column could produce a 5% error in a tropospheric estimate. The 1% stability requirement on tropospheric ozone imposes stability requirements on the total column ozone and stratospheric column ozone of about 0.1%, and, hence, instrument stabilities of this order. There are additional problems with the lack of efficiency of BUV methods in detecting TOZ changes in the lower troposphere. For the systems considered in this section, monitoring tropospheric changes independently is problematic.

4.2.4 Aerosols

Satellite sensors should be capable of measuring aerosol optical depth and the aerosol microphysical parameters (single scattering albedo, refractive index, effective radius and effective variance) to the absolute accuracies defined in section 3.2.4. The absolute accuracies derived there are based on an evaluation of the radiatively significant perturbations in the aerosol parameters.

For a multi-spectral polarimeter making measurements over the spectral range of 400 nm-2500 nm, with multi-angle views of the same location, the instrumental accuracy that is implied by the required accuracy with which the aerosol parameters must be determined is better than 3% radiometric accuracy and better than 0.5% polarimetric accuracy. A relative spectral accuracy of better than 1% and a relative angular accuracy of better than 1% are also required. Other instruments (MODIS, MISR, POLDER, and A-band spectrometers) may be capable of meeting the aerosol parameter accuracies defined in section 3.2.4 over some surface types, but the requirements given here are relevant to the NPOESS Aerosol Polarimetry Sensor (APS) sensor. Since this sensor provides a complete sampling of the spectral and angular, polarized signature of aerosols in the atmosphere it is expected that the required instrumental accuracies for other sensors would be more challenging.

The satellite sensor must be inter-calibrated and validated using AeroNet, and other networks of surface-based sun photometers. AeroNet has provided aerosol estimates since about 1993 that meet the present state of the art regarding accurate AOD retrievals with an accuracy of approximately 0.01. The major deficiency with

AeroNet is the sparseness of its global coverage. Other complementary relatively dense sun photometer networks with limited coverage also exist and are useful for aerosol validation over land (e.g., DoE ARM Southern Great Plains (SGP) Multi-Filter Rotating Shadowband Radiometer (MFRSR) network and NASA's Solar Irradiance Research Network (SIRN) network).

4.2.5 Precipitation

The most physically direct passive measurements of precipitation come from microwave radiometers. The physics underlying this capability is more straightforward and accurate over the ocean than over land. The frequency range most often utilized for this is 10-90 GHz, although lower and higher frequencies also have utility. Unfortunately, it is difficult to validate these instruments' measurements of precipitation since *in-situ* validation data for rainfall (rain gauges and radars) are probably not accurate to better than 5-10%. Instead, the errors involved in the measurement of rainfall from these satellites can be estimated with an error model, but the results will vary widely depending on the assumed sizes of individual error components and assumptions about whether any of these errors are inter-correlated.

Because of the problems inherent in the validation of rainfall retrievals to better than 5% to 10%, the (arbitrary) absolute accuracy requirement of 5% we assumed in section 3.2.5 really refers in this case to potential biases in our retrieved rain rate statistics. An accuracy of 5% applied to the average rain rate (where it is raining) of 2.5 mm/hr, leads to an accuracy requirement of 0.125 mm/hr. The sensitivity of several microwave frequencies to rain rate approaches 10° C for each 1 mm/hr in rain rate, transforming the instrument accuracy requirement into 1.25° C, which is now being met with spaceborne window frequency microwave radiometers.

Of greater importance, again, is the requirement for sufficient long-term radiometric stability to allow us to determine climate time-scale fluctuations in precipitation, even though we may not know what average bias (accuracy) exists in the satellite data record. The measurement stability of about 0.003 mm / hr when observing rain (from section 3.2.5), multiplied by the instrument sensitivity to rain (10° C per 1 mm / hr) leads to an instrument stability requirement of 0.03° C/decade. As we will see later, even though this is a stringent requirement, it is possible that existing technology could meet it.

4.2.6 CO_2

The retrieval of variations in dry-air mixing ratio of atmospheric CO_2 from spaceborne instruments is very challenging, requiring spectroscopic measurements of 0.25 to 0.5% (1-2 ppmv) of the background values (375 ppmv). The measurements must be sensitive to variations in the Atmospheric Boundary Layer (ABL). The estimation of surface sources and sinks from such data is even more challenging, yet the potential benefits for carbon cycle science and concomitant climate effects makes it imperative to try.

4.3 Surface Variables

4.3.1 Ocean Color

The ocean color data set requirements in 3.3.1 translate directly to the satellite requirements. Since it is clearly not possible to have a satellite-only parameter retrieval any retrieval requirement will depend on in-situ calibration measurements. Thus, a requirement for this application is the addition of a greater number of in-situ measurement systems such as the MOBY-type buoy system. The satellite requirements are 5% in accuracy and 1% for stability.

4.3.2 Sea Surface Temperature

The required SST stability and accuracy are 0.04 K/decade and 0.1 K. Sea surface temperatures (SST) are generally measured at IR window wavelengths. The relevant equation is of the form

$$SST = T_1 + 2.5(T_1 - T_2) \tag{4}$$

where T_1 and T_2 are IR brightness temperatures at two IR window wavelengths.

Error analysis of this equation assuming that T_1 and T_2 have the same absolute errors leads to a stability requirement of about 0.01 K for each window wavelength brightness temperature. Required accuracy for the measurements is 0.1 K. For sensors with additional channels, such as the Visible/Infrared Imager/Radiometer Suite (VIIRS) and MODIS, other SST algorithms may be more effective. The proposed SST algorithm for VIIRS is a “dual split window” which uses a brightness temperature difference at the shorter 4 micron channels together with the longer 11 micron channel difference to give a more stable SST estimate. But the above error analysis should hold for any split window type of SST measurement.

Microwave observations at 6.9 GHz can also be used to measure SST. A 1 K change in SST causes about a 0.33 K change in observed brightness temperature. The reduction in sensitivity is due to the low microwave ocean emissivity of about 0.5 and wind roughening effects. Thus, to maintain a stability of 0.04 K in SST requires about a 0.01 K microwave instrument stability. Required accuracy is 0.03 K.

These values ignore the influence of sensor pointing angle on SST accuracy for the passive microwave sensors. Both the passive microwave and the thermal infrared sensors will require an in-situ calibration/validation program to insure that these requirements are met. This in-situ program must include both skin and bulk measurements of SST and should be continuous.

4.3.3 Sea Ice

Results of sensitivity studies with the NOAA automated snow cover algorithm (see 4.3.4) can also be applied to sea ice. Visible channel accuracy of 12% and stability of 10% would be required to achieve the required sea ice area data set accuracy of 5% and stability of 4%.

4.3.4 Snow Cover

It is recognized that if the satellite sensor requirements for ocean color, SST and sea ice are met the requirements for snow cover will also be fulfilled. It was also acknowledged that snow cover computation is transitioning from a “human in the loop” snow cover product to an automated system and it was not clear that the automated system would be able to produce the same accuracy as the man in the loop system.

Sensitivity studies with the NOAA automated snow cover mapping algorithm indicate that visible channel accuracy of 12% and stability of 10% would be required to achieve the required snow cover area data set accuracy of 5% and stability of 4%.

4.3.5 Vegetation

Specifying the tolerable error in NDVI requires that the albedos from the individual bands be within certain bounds. Errors in channel albedo, a_i , propagate into the NDVI in a way that is dependent on the value of NDVI itself. The equation below gives the relation between relative uncertainty in NDVI (shortened to N in the equation) and uncertainty in the channel calibration:

$$(\Delta N / N) = [(1 - N^2) / 2N] (\Delta a_i / a_i) \qquad (5)$$

The accuracy and stability of the albedo observations needed to achieve the specified relative accuracy of 3% and stability of 1% per decade in the NDVI data set is dependent on NDVI itself. The average global vegetation index is about 0.35. This value leads to a needed stability of 0.8% per decade and accuracy of 2% for the albedo measurements and, hence, for the visible and near infrared measurements upon which the albedo observations depend. The stability value of 0.8% per decade assumes that the bands used in derivation of NDVI generally drift in the same direction, which is practically always the case. Study of desertification would entail looking at low values of NDVI, so would require greater accuracy and stability in ($\Delta a_i / a_i$). Studies of changes in vegetation, such as of the greening of the boreal forests, require less stringent requirements on ($\Delta a_i / a_i$).

5. Ability of Current Observing Systems to Meet Requirements

5.1 Solar Irradiance, Earth Radiation Budget, And Clouds

5.1.1 Solar Irradiance

Current Total Solar Irradiance measurements meet the climate stability requirements but not the absolute accuracy requirements. Current spectral irradiance measurements do not meet the absolute accuracy or the stability requirements. NPOESS IORD II (NPOESS, 2001) threshold requirements will meet climate needs, but absolute accuracy of current and near-term instruments are such that overlap of at least a year is essential to meet the climate stability threshold requirement.

5.1.2 Surface Albedo

AVHRR absolute accuracy in the visible and near IR is estimated at 5 to 10%, and MODIS and MISR at 3 to 5%, just meeting the goal of 5%. Stability of AVHRR after correction using earth viewing targets (no on board calibration) is estimated to be 3 to 5% per decade (Rossow and Schiffer, 1999), well short of the goal of 1%/decade. MODIS and MISR instruments have only been in space for 3 years, too soon to assess long-term stability. These instruments do carry diffuser plates, and comparisons to these have shown changes of 1-2% per year. But direct MISR/MODIS comparisons show systematic differences of +/-3% for bright and dark earth targets in the two instrument's radiances for matched time/space/viewing angle comparisons. These differences have not yet been resolved, but may indicate nonlinear response in one or both of the instruments.

MODIS has used partial lunar calibration throughout its mission, and both MISR and MODIS began full lunar calibration in March 2003 using a Terra spacecraft maneuver to scan the moon. The moon provides a constant low albedo target in the dynamic range of ocean and land surfaces. While snow albedo is high, the solar zenith angles for polar conditions are typically low, so that radiance signals from snow can be lower or larger than tropical land and ocean values. Lunar calibration using orbital maneuvers, and overlap of instrument time series appear to be critical for obtaining multi-decade accurate surface albedo records. Further analysis is needed in this area, and experience from the routine SeaWiFS lunar calibration record over several years should assist in estimating stability achievable using spacecraft pitch maneuvers to scan the lunar surface at constant libration and phase angles, assuring a view of the same surface, illumination, and scattering angles.

5.1.3 Downward Longwave Radiation at the Surface

Current downward LW flux measurements do not meet the climate requirement of 1Wm^{-2} absolute accuracy and 0.2 Wm^{-2} stability per decade. Analysis from recent EOS CERES data products show absolute accuracy of about 3 to 5 Wm^{-2} for global average when compared against a range of tropical and mid-latitude ARM, BSRN, Surface Radiation Budget Network (SURFRAD), and NOAA/ Climate Monitoring and Diagnostic Laboratory (CMDL) surface reference sites. Stability has not yet been established, as the data products have only been available for about a year and a long time record is not yet available. The analysis discussed in section 3.1.3, however, indicates that if the stability and accuracy goals for 4.2.1, 4.2.2, 4.1.7, and 4.1.8 (temperature, water vapor, cloud base height, cloud cover) can be met, then the stability and accuracy for downward LW flux may also be met.

5.1.4 Downward Shortwave Radiation at the Surface

Current downward SW flux measurements do not meet the climate requirement of 1 Wm^{-2} absolute accuracy and 0.2 Wm^{-2} stability per decade. Analysis of recent EOS CERES data products indicates absolute accuracy of about 10 Wm^{-2} (24 hr average) when compared to a range of tropical and mid-latitude ARM, BSRN, SURFRAD, and NOAA/CMDL surface reference sites. The majority of the surface sites are over land, with a few on islands. Aerosols are thought to cause at least half of the problem over land sites, and island-effect cloudiness may play a similar role over most island stations. Given that oceanic aerosols are lower in optical depth than over land, bias errors over ocean are likely much less than 10 Wm^{-2}, and global average may be closer to 5 Wm^{-2}. But oceanic buoy and ship-based observations are required to assess global satellite data accuracy. Improvements in aerosol measurements over most land surfaces are now becoming available with the EOS MODIS and MISR instruments, but issues remain for aerosol absorption. Stability of this estimate is not currently known but will rely most heavily on the stability of top of the atmosphere SW reflected flux, and on aerosol optical depth and absorption determination.

5.1.5 Net Solar Radiation at the Top of the Atmosphere

Current CERES observations of Net Solar Radiation at the TOA meet the absolute accuracy requirement of 1 Wm^{-2} (1% in instrument calibration, Priestley et al., 2000) but the instruments have not been in orbit long enough to fully verify stability at 0.3 Wm^{-2} or 0.3% per decade. Early results from 3 years of Terra observations by two CERES instruments indicate less than 0.3% change in SW channel gain against on-board calibration sources. Most of the change occurred during the first year on orbit, but at least a 5-year record of the new data will be needed to predict decadal stability values.

The absolute accuracy of these radiometers, however, cannot meet the stability requirement without at least a 3-month overlap of observations. The TRMM and Terra mission CERES overlap demonstrated the ability to intercalibrate to within 0.5 Wm^{-2} using 1 month of data (95% confidence) by rotating one of the CERES scanners to align its scan plane with the other during satellite orbit crossings. This technique could achieve the 0.3 Wm^{-2} matching requirement for decadal stability with a 3-month overlap for 95% confidence. The NPOESS system will fly a copy of CERES called ERB starting in 2011. CERES on the recently launched Aqua spacecraft nominally will remain in orbit until the Aqua mission is de-orbited in 2008. Risk of a data gap from Terra/Aqua CERES to the NPOESS ERB is estimated at 50% probability, including all known international mission possibilities (Geostationary Earth Radiation Budget Experiment (GERB), Megha-Tropique). NASA is hoping to close the gap by adding the final CERES instrument in storage onto the joint NASA/NPOESS NPP gap-filling mission planned for launch in 2006.

5.1.6 Outgoing Longwave Radiation at the Top of the Atmosphere

Current CERES observations of outgoing LW flux at the TOA meet the absolute accuracy requirement of 1 Wm^{-2} (0.5%, Priestley et al., 2000, 2002) but the instruments have not been in orbit long enough to verify their ability to achieve 0.2 Wm^{-2} (0.1%) per decade. Instrument gain changes of 0.1% to 0.2% per year early in the mission have been corrected using on-board blackbody sources. But, as for the net solar radiation at the TOA, overlapping satellite observations are required to meet the decadal stability requirement. Gaps between missions will leave 1 to 2 Wm^{-2} uncertainty in decadal signals (similar to 5.1.5). See the discussion in 5.1.5 concerning the 50% probability gap between EOS and NPOESS in 2008 to 2011.

5.1.7 Cloud Base Height

Current estimates of cloud base height do not meet the accuracy requirements. Cloud base height stability is unknown. Largest problems are for multi-layer cloud systems and for polar clouds.

5.1.8 Cloud Cover

Current estimates of cloud cover absolute accuracy do not meet the climate requirement of 0.01. Accuracy of recent CERES and MODIS cloud analysis of the MODIS imager is estimated to be about 0.05. Largest uncertainties are amounts of very thin cloud, which remain hard to detect because of small solar and infrared signals. Polar clouds present a similar problem. But the radiative climate effect of very thin cloud is less significant, so that the uncertainty relative to cloud feedback effects is smaller than 0.05 would imply. Frequency distributions of optical depth for cirrus and trade cumulus, two common cloud types are peaked at optical depth zero, and decrease monotonically with increasing optical depth. These clouds have no modal or "typical" optical depth. Further work is needed to determine a more radiatively relevant parameter than simple cloud cover for climate research. Advances should be possible with the upcoming GLAS and Calipso space-based lidar missions as well as the Cloudsat cloud radar. Calipso, Cloudsat, MODIS, and CERES flying in formation together in the A-train (starting in 2005) should be capable of assessing the accuracy much more rigorously for thin, thick, and overlapped cloud layers. Stability for current AVHRR, GOES, and MODIS cloud fraction has not been rigorously determined. Since many clouds are detected by thresholds set near clear-sky background values, it is thought that cloud fraction is not very sensitive to small changes in imager calibration. For example, a common threshold for detection of clouds over ocean is about 3% reflectivity above the ocean background value: say 5% ocean background and 8% threshold. A change in instrument gain of 5% would only change these values to 5.15% and 8.4% respectively, for a cloud "signal" of 3.25% instead of the true value of 3%. If 0.05 cloud fraction resides between 3% and 6% above background then about a 0.005 error in cloud fraction would occur. But since the albedo of these clouds is only 0.045 above background, the actual radiative effect of cloud missed is only $0.005(0.045)(342) = 0.08\ Wm^{-2}$. This is less than the 0.3 Wm^{-2} per decade SW flux stability requirement, so that for studies of cloud feedback, this would not be a problem.

But more serious problems arise if infrared window channels located at wavelengths such as 3.7 μm, 11μm, and 12 μm vary in calibration. This is because small signals of a few K in brightness temperature difference are used to detect low clouds at night when visible channels are not available, or for clouds over bright surfaces e.g. snow, ice. These low clouds would have only small effects on the TOA LW flux, but large effects on the downward LW flux at the surface, especially in the polar regions. More complete sensitivity studies are necessary. Note that lidar, which can be self calibrated against Raleigh scattering, would be a much more rigorous method to determine cloud layering and cloud fraction trends at zonal to global scales. Lidar and radar taken together is the only currently available method that could realistically provide the climate accuracy requirements for a complete range of climate regimes and cloud layering.

5.1.9 Cloud Particle Size Distribution

No accuracy requirements have been specified. Further study is needed.

5.1.10 Cloud Effective Particle Size

There has not been sufficient time in orbit to establish if the current MODIS instrument can meet the stability requirements in 4.1.10 for the 3.7 µm and 1.6 µm spectral channels. The accuracy requirements are within the MODIS radiometric design goals. Accuracy issues remain, however, with the effect of three-dimensional cloud radiative transfer on particle size retrievals, as well as sub-pixel cloudiness.

5.1.11 Cloud Ice Water Path

Current estimates of cloud IWP cannot meet the requirements for absolute accuracy of 25% or for stability of 5% per decade whether from shortwave or microwave instruments. Current algorithms use visible optical depth and effective radius to predict IWP but also include contributions from water cloud in multi-layer cloud conditions. Very limited comparisons with ARM IWP reference values show average consistency to within 20% for single level ice clouds. Multi-layer errors would be larger. Overall global mean uncertainty is likely to be a factor of 1.5 to 2. Methods exist to improve multi-layer cloud conditions over ocean backgrounds by combining passive microwave liquid water path with imager derived total cloud optical depth and ice particle size when cloud layers are overlapped. Improvements in both the ARM IWP reference data (many more cases for a wider range of cloud types and climatological regions) as well as satellite comparisons will be necessary. It is not clear yet if the Cloudsat/Calipso/MODIS space based cloud IWP will be capable of 25% accuracy and 5% stability, but it is the more physically sound approach and should provide significantly higher accuracy than current imager based approaches. Existing spaceborne microwave radiometers operating near 90 GHz and 183 GHz have substantial retrieval errors, approaching 50%, due to unmeasurable variations and uncertainties in particle size distribution and the intensity of upwelling microwave radiation at cloud base. It is hoped that additional, higher frequencies will help alleviate this problem somewhat, and these frequencies are currently being tested in aircraft experiments. A final possibility is passive sub-mm wavelength estimates using microwave scatter from ice particles. These instruments are still in aircraft demonstration stage but provide hope along with lidar/radar of providing the answer for IWP.

5.1.12 Cloud Liquid Water Path

Current estimates of cloud liquid water path have not yet demonstrated absolute accuracy of 25% and stability of 5% per decade. Estimates are made by two methods: passive microwave (SSM/I, TRMM Microwave Instrument (TMI), Advanced Microwave Scanning Radiometer (AMSR)) for ocean background only, and by cloud imager using visible optical depth and cloud particle size (land and ocean). A recent comparison using TRMM TMI passive microwave matched with VIRS cloud imager estimates showed consistency in these two methods of about 10% for monthly averaged single layer water cloud over 40S to 40N. The passive microwave observations become noisy for optically thin water clouds (small signal) and cannot provide the data over land backgrounds. However, for thicker clouds over oceans, microwave observations can meet the requirement. Optical methods become saturated at very large optical depths (greater than 50 to 100) and cannot see water clouds beneath thick ice cloud. The combination of active and passive methods, Cloudsat/Calipso/MODIS/AMSR, should be able to much more accurately determine cloud LWP for all global conditions. Imager LWP stability will be met if the instrument stability for optical depth in 4.1.13 and effective particle size in 4.1.10 are met. Current visible imagers have not yet demonstrated the 1%/decade calibration stability necessary (see 5.1.2).

5.1.13 Cloud Optical Thickness

Current AVHRR, GOES, and MODIS instruments have not yet demonstrated the ability to reach the requirements of 5% absolute accuracy and 1% per decade stability. The MODIS radiometer does appear to have achieved 5% absolute accuracy for its visible channel, but the instrument has not been in orbit long enough to demonstrate 1%/decade stability. The key will be lunar calibrations and the amount of degradation in the solar diffuser plate. Lunar calibration can in principle reach this accuracy but needs further analysis and verification (Stone et al. 2002; Kieffer et al. 2002). Recent work suggests the SeaWiFS could attain a long-term stability of 0.5% or better through periodic lunar observations (Kieffer et al, 2003). The absolute accuracy limit is the understanding of 3-dimensional cloud structure. Sensitivity of 10 to 30% in cloud optical depth is common even for stratocumulus layered clouds. The sensitivity is most obvious in the dependence of imager derived optical depth on viewing angle (Loeb and Coakley, 1998). Given the importance of three-dimensional cloud structure, this issue should be addressable using the GLAS lidar as its orbit precesses across the Terra and Aqua MODIS imager swaths. It is not clear if the absolute accuracy can be reached without adding active cloud profiling from cloud radar and/or lidar.

5.1.14 Cloud Top Height

Cloud top height is just a function of cloud top temperature. See 5.1.16.

5.1.15 Cloud Top Pressure

Cloud top pressure is just a derivative of cloud top temperature. See 5.1.16.

5.1.16 Cloud Top Temperature

Current AVHRR, GOES, and MODIS cloud top temperatures have not been verified to reach the 1 K absolute accuracy requirement at very large time and space scales. More extensive comparisons have begun with ARM site vertical lidar/radar cloud profiles that should soon provide more rigorous analysis of current capability. Early estimates show mean accuracies of about 2 K for thick clouds and about 6 K for optically thin clouds like cirrus. A much better accuracy estimate will be possible using GLAS and Calipso lidar data with MODIS. Stability of cloud height is primarily a function of stability in the imager and infrared sounder or spectrometer channel calibration. For thick clouds, the relationship will be one-to-one, so that the 0.2 K/decade requirement in cloud height would require a 0.2 K per decade calibration stability for the infrared channels used for cloud height. This will be met if the imager meets SST stability requirements and the sounder/spectrometer meets the air temperature stability requirements. Overlap will be key to assuring the stability, since absolute accuracy is often less than 0.2 K for infrared radiometers.

5.1.17 Spectrally Resolved Longwave Radiation

Spectrally resolved measurements made by the AIRS instrument (Aumann and Overoye 1996) had a planned on-orbit validation level of 3% (Chahine *et* al., 2000), equivalent to 1.4 K at 250 K and 11 µm (910 cm^{-1}). Actual validation experiments under a limited range of conditions indicate on-orbit performance may be better than this design absolute accuracy (Aumann, 2003).

5.2 Atmospheric Variables

5.2.1 Atmospheric Temperature

The Microwave Sounding Units (MSU) on the NOAA polar-orbiting satellites have yielded a 24 year record so far, made up by a total of eight satellites (e.g., Christy et al., 2000). Overlap between successive MSUs yield monthly global average standard deviations in the inter-satellite difference approaching 0.01° C - 0.03° C. The absolute accuracy of these instruments appears to be around 0.5° C, which is the same as the required accuracies stated here. Monitoring of decadal trends to an accuracy of about 0.04° C/decade - 0.08° C/decade over the 24-year period of record has been achieved. Much of this remaining uncertainty is contributed to less by uncertainty in intercalibration between instruments than it is to (1) changes in instrument temperature (causing nonlinearity-induced changes in calibration) and (2) corrections for drift of the NOAA satellite orbits through the diurnal cycle.

Clearly, to maintain this (marginal) meeting of the long term stability requirement would require continued periods of overlap (preferably at least 1 year) between successive satellites throughout the coming decades. Fortunately, the newer Advanced Microwave Sounding Units (AMSUs) appear to have much better absolute calibration than did the MSUs. Preliminary work with the NOAA-15 and NOAA-16 AMSU data suggests that their difference in calibration could be as small as 0.10° C. This level of accuracy is difficult to validate. Different satellites measure at different times of day, and so the differences between satellites are partly attributable to diurnal changes in air mass temperatures. Radiosonde measurements do not have accuracies to this level, and even if they were, large numbers of comparisons to satellite measurements would need to be averaged together to reduce spatial sampling noise. It is still too early to determine the long-term stability of the AMSUs, as the maximum overlap between successive AMSUs amounts to only three years at this writing.

The utility of the infrared sounders for climate monitoring has not been explored as much as the microwave sounders. This is partly due to a much higher data rate, leading to a much larger volume of data to be analyzed, and because of the much greater influence of clouds on the infrared radiances. The primary instruments have been the High-resolution InfraRed Sounder (HIRS), flying with the MSUs since 1979. It is still too early to tell if the stability and capability for obtaining measurements in partly cloudy regions of the new Atmospheric InfraRed Sounder (AIRS) instrument on NASA's Aqua satellite is sufficient for climate monitoring of atmospheric temperature to the required levels.

5.2.2 Water Vapor

The current microwave capability for monitoring total column tropospheric vapor comes from the Special Sensor Microwave/Imager (SSM/I) instruments, operating since mid-1987. These instruments have allowed the construction of a continuous record that has been compared to observed sea surface temperatures (SST), and suggest an increase in oceanic vapor consistent with the increase in SST during 1987-1998 (Wentz and Schabel, 2000). The existing series of SSM/Is appear to be achieving a stability of 0.2%/decade humidity stability, which is approximately equal to the 0.26% requirement from section 3.2.2.

Water vapor profiles in the troposphere depend upon measurements near 183.3 GHz, channels, which have flown on the SSM/T-2 carried by several DMSP satellites and the AMSU-B instruments flying since early 1998 on the NOAA polar orbiters. There has as yet been very little work performed to document the long-term stability or absolute accuracy of these instruments. Absolute accuracy is particularly difficult since standard methods for measuring water vapor profiles in the atmosphere are notoriously poor (e.g., Elliot and Gaffen, 1991; Garand *et al*., 1992). The most accurate ground-based methods are expensive, and it would take many match-ups with satellite measurements to provide validation.

It is still too early to tell if the stability and capability for obtaining measurements in partly cloudy regions of the new Atmospheric InfraRed Sounder (AIRS) instrument on NASA's Aqua satellite is sufficient for climate monitoring of atmospheric water vapor to the required levels.

5.2.3 Ozone

Current atmospheric ozone observing systems are not designed to meet the requirements. Two percent differences are commonly found in comparisons among TOMS, GOME and Solar Backscattered Ultraviolet instrument 2 (SBUV/2) global mean TOZ time series during overlapping periods of their records. Some of the adjustments to SBUV/2 calibrations from SSBUV underflight comparisons led to ozone profile changes greater than 5% (Hilsenrath et al., 1995). Even for a time series from the self-calibrating measurements of Stratospheric Aerosol and Gas Experiment (SAGE I, II and III), the break in the data record from SAGE I to SAGE II is viewed as a large source of uncertainty in determining long-term trends.

Fortunately, through a combination of good in-flight monitoring of long-term instrument changes, overlapping missions and well-managed ground-based observations (see discussions in WMO, 2001 and Hilsenrath et al., 1998), the existing ozone data are able to provide researchers with information on trends at close to the desired accuracy (WMO, 1998). For in-flight calibration of BUV instruments, the two most important techniques were those developed to maintain the radiance/irradiance calibration and the wavelength scale calibration. The first technique uses multiple diffuser (used to measure the solar irradiance and normalize the radiances which remove some instrument throughput errors in the TOAR) working together to better characterize both changes in the instrument throughput and their own degradation. The second uses solar Fraunhofer lines or calibration lamp line sources to track the wavelength scale. The current and planned instruments will not meet absolute accuracy requirements for determining trends. But by using overlap periods with other satellite instruments and intercomparisons with well-calibrated ground stations, their long-term stability should allow their products to be components of multi-instrument atmospheric ozone data records of climate quality.

The current state-of-the-art for satellite-based BUV ozone measurements is the result of over 30 years of research and analysis. Efforts need to be implemented to ensure that post-launch calibration is of high accuracy to establish climate quality data sets. A short list of some of the most important areas of development includes:

1. On-board calibration (e.g., diffusers for solar measurements and lamp lines sources);
2. Vicarious calibration (*e.g.*, ice radiances and spectral discrimination);
3. Algorithmic and internal consistency checks (*e.g.*, pair justification and ascending/descending comparisons);
4. Algorithms with low sensitivity to measurement errors (*e.g.*, height normalization, triplets and DOAS);
5. Inter-instrument comparisons with similar instruments (*e.g.*, SSBUV underflights);
6. Inter-instrument comparisons with other satellite instruments (*e.g.*, matchup data sets, methods using trajectory mapping with sparse but accurate occultation-instrument estimates);
7. Comparisons with ground-based networks (*e.g.*, Dobson and Umkehr); and
8. Comparison to other solar measurements (*e.g.*, SOLSTICE and Mg II Index work).

5.2.4 Aerosols

Current satellite sensors (e.g., AVHRR, MODIS, MISR, VIIRS) have difficulty with aerosol retrievals over land due to backscattered photons through the target aerosol from the surface, which causes a noise proportional to albedo and are therefore predominantly used to retrieve aerosols over the ocean or dense dark vegetation. These sensors are also unable to adequately retrieve the required aerosol model from measurements alone and must therefore make prior assumptions about aerosol refractive indices and the range and mixtures of size distributions. The lack of surface noise for upward-looking sun photometers allows this type of measurement to have excellent accuracy in retrieving aerosol optical depth and reasonable accuracy in the inversions that are required to derive aerosol microphysical model parameters. It is therefore important that satellite sensors be calibrated and validated against these surface measurements to allow “AeroNet-like” accuracies to be approached on a global scale. It should however be emphasized that the inability of a satellite instrument to measure a particular aerosol parameter does not mean that the parameter can be fixed using AeroNet measurements and then used in aerosol retrievals globally without any reduction in accuracy.

5.2.5 Precipitation

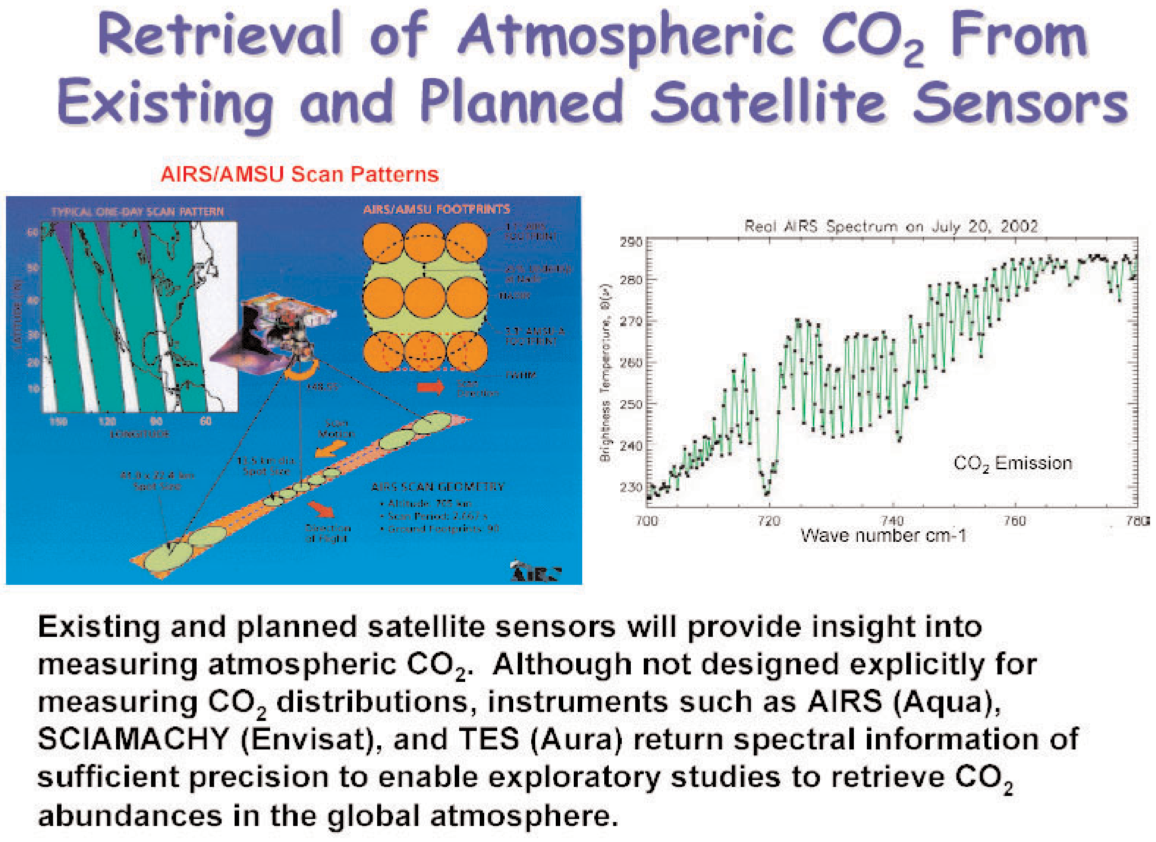
Our current state of the art in precipitation measurement from space with radiometers is represented by the Microwave Imager (TMI) on the Tropical Rain Measurement Mission (TRMM), and the SSM/I series of instruments on the DMSP weather satellites. Unfortunately, it is not known how well any of these instruments measures precipitation because in-situ validation data for rainfall (rain gauges and radars) are probably not accurate to better than 5% to 10% at best. Instead, the errors involved in the measurement of rainfall from these satellites can be estimated with an error model, but the results will vary widely depending on assumptions regarding sizes of individual error components and whether any of the error sources are correlated. Despite these uncertainties, the SSM/I and TMI data records clearly reveal climate-scale changes in rainfall on the order of ± 10% due to the El Nino and La Nina phenomena. The SSM/I data record (since mid-1987) is still not sufficiently long to reveal a global warming-related increase in precipitation, partly due to the large interannual variability in the record, and the drift of the DMSP satellites through the diurnal cycle.

5.2.6 CO_2

Atmospheric CO_2 products derived from thermal emission spectra (AIRS/AMSU, Tropospheric Emissions Spectrometer (TES), Infrared Atmospheric Sounding Interferometer (IASI), and operational follow-ons) will probably be quite useful in conjunction with the in-situ data for estimating seasonal and interannual variation in total CO_2 sources and sinks at continental scales. These data will likely be effective for detecting gross changes in the carbon cycle, but the resolution of the retrieved sources and sinks will not be sufficient for mechanistic interpretation or modeling.

Passive Near InfraRed (NIR) spectroscopy (Orbiting Carbon Observatory (OCO), SCanning Imaging Absorption spetroMeter for Atmospheric ChartographY (SCIAMACHY)) is expected to allow sub regional source/sink estimation, and in conjunction with other carbon-relevant remote sensing (vegetation, biomass, and ocean color) will probably facilitate a revolution in verifiable process-based models.

Active NIR spectrometry by laser absorption and/or LIDAR will resolve diurnal and seasonal biases, provide vertical profiling, and allow rigorous source/sink modeling and model evaluation at high spatial resolution. In an assimilation system along with other satellite and in-situ data,


Retrieval of Atmospheric CO_2 From Existing and Planned Satellite Sensors

AIRS/AMSU Scan Patterns

Existing and planned satellite sensors will provide insight into measuring atmospheric CO_2. Although not designed explicitly for measuring CO_2 distributions, instruments such as AIRS (Aqua), SCIAMACHY (Envisat), and TES (Aura) return spectral information of sufficient precision to enable exploratory studies to retrieve CO_2 abundances in the global atmosphere.

Although not designed for measuring CO_2, some current and planned satellite instruments could provide useful information. (Denning, Workshop Invited Presentation).

these measurements will allow fluxes to be estimated from process-based models at the native resolution of the land and ocean remote sensing, yet be consistent with atmospheric mass balance.

5.3 Surface variables

5.3.1 Ocean Color

The following current satellite sensors are capable of making ocean color estimates: SeaWiFS, MODIS, MEdium Resolution Imaging Spectrometer Instrument (MERIS), and POLDER. Some of these may be meeting the accuracy requirement of 5% for visible measurements. SeaWiFS, using MOBY for vicarious calibration, is achieving 5% accuracy, and, using the moon as a stable reference, it may be meeting the stability requirement of 1%/decade. Even with a good instrument, ocean color requirements will not be met without in-situ and lunar supplemental measurements.

5.3.2 Sea Surface Temperature

The following existing satellite sensors make measurements that can be used for SST estimation: AVHRR, MODIS, Along Track Scanning Radiometer (ATSR) (including Advanced Along Track Scanning Radiometer AATSR)), GOES, AIRS, TMI, AMSR. In spite of this wealth of satellite sensors presently flying, none of the available SST products can meet the requirements set out in this report. If ATSR data were to be reprocessed, it may be possible to approach these requirements. ATSR has unique “dual-look” capability to correct for atmospheric water vapor attenuation. Likewise, MODIS should be reprocessed to determine its capability for long-term SST observations.

5.3.3 Sea Ice

Currently available visible and microwave radiometers appear capable of meeting the sea ice requirements.

5.3.4 Snow Cover

Currently available visible radiometers appear capable of meeting the snow cover requirements.

5.3.5 Vegetation

MODIS and MISR provide sufficient information to make a good estimate of LAI and Fraction of Photosynthetically Active Radiation (FPAR). These estimates are close to an accuracy requirement of 3% and a stability requirement of 1% set forth in this document.

6. Roadmap for Future Improvements in Satellite Instrument Calibration and Inter-Calibration to Meet Requirements

6.1 Solar Irradiance, Earth Radiation Budget, And Clouds

6.1.1 Solar Irradiance

Major requirements are to assure a 1-year overlap of total and spectral solar irradiance measurements, to improve accuracy of spectral measurements, and to plan for at least two independent instruments to allow verification of accuracy and stability in orbit.

6.1.2 Surface Albedo

Routine lunar calibration appears to be the only viable current method to assure the long-term stability requirement. This will require spacecraft to perform calibration maneuvers that allow the spectral imagers to scan the lunar surface at scheduled times to obtain constant lunar phase angle and libration. Analysis of the SeaWiFS lunar calibration experience and comparisons to the new Terra lunar calibration should be used to assess the accuracy achievable, the frequency of lunar calibration required, and the level of constant libration and phase angle required to reach a given stability measure. The linearity of the radiometers is also critical to verify. Sensitivity studies should be carried out using current MODIS data to verify the level of linearity and lunar calibration required to meet the stability requirement.

Another approach to improve calibration is to constrain the imager derived surface albedo to agree with estimates using a more accurately calculated broadband radiometer (CERES, ERB). For either narrowband or broadband approaches, aerosol scattering and absorption can cause significant errors in surface albedo estimates. Aerosol scattering estimates are improving rapidly with MODIS, MISR, and POLDER observations. Aerosol absorption remains highly uncertain and is a significant issue for surface albedo estimates. All surface albedo estimates use radiances to estimate reflected flux. Recent advances in multi-angle observations from MISR, POLDER, and CERES appear to be approaching the accuracy required.

It is also key to keep the same orbit sampling for successive missions: both to improve intercalibration as well as to eliminate errors from changed solar zenith, viewing azimuth, and viewing zenith causing anisotropy changes to be interpreted as surface albedo change. Studies using the new Terra surface bidirectional reflectance models and comparing surface albedo estimates from Terra and Aqua can be used to assess this sensitivity to orbit. Uncertainties in aerosol absorption need to be assessed for the impact on the stability and accuracy of surface albedo estimates.

6.1.3 Downward Longwave Radiation at the Surface

Sensitivity studies are needed to more rigorously assess the sensitivity to boundary layer temperature and water vapor profile changes. Weather prediction accuracy requirements are for 1 km vertical layers in temperature and 2 km in water vapor. These will be too coarse by themselves to bound downward LW flux change. 4-D assimilation models using AIRS/AMSU/Humidity Sounder for Brazil (HSB) are beginning and when verified against radiosonde boundary layer temperature and water vapor profiles, may be sufficient to constrain the boundary layer temperature and water vapor by combining improved model surface and boundary layer physics with the constraint of the satellite spectral radiances. Finally, the ability to constrain cloud base height must be addressed using the new EOS algorithms as well as new GLAS, Cloudsat, and Calipso active sounding data.

Satellite measurements of downward longwave radiation are validated against measurements at surface stations. Recently, some of the longer time records from the stations of the Global Energy and Water Cycle Experiment (GEWEX) surface radiation budget (SRB) project have extended beyond a decade in length, but as yet there is limited overlap with the new reference Baseline Surface Radiation Network (BSRN). Even with this overlap in the future, accuracy of the BSRN network will need to be improved to 1 Wm^{-2}, and stability to 0.2 Wm^{-2}, if full verification of climate trends and accuracy is to be achieved. Current instruments are estimated to be accurate to 2-5 Wm^{-2} in both absolute accuracy and stability. The BSRN network also needs to be extended from the current 20 or so primarily land based sites. Observations are needed in ocean regions, from oceanographic research vessels, ships of opportunity, and ocean platforms, and in polar regions.

The international BSRN needs to be expanded into a true global network with stable institutional support clearly defined, as opposed to the current essentially volunteer network. Site locations need to be driven by climate regime sampling, not convenience.

6.1.4 Downward Shortwave Radiation at the Surface

Rapid improvements in TOA SW flux constraints, cloud optical depth, cloud particle size, and aerosol optical depth (MODIS, MISR, ASP) are being made, but further advances are needed in aerosol absorption. Sensitivity studies are needed to map calibration accuracy/stability effects of each of these parameters (and their instrument approaches) into downward SW flux at the surface. It is likely that the CERES, MODIS, MISR, and APS calibrations may be sufficient to meet all but the aerosol absorption. These instruments, together with aerosol 4-D assimilation models may be capable of constraining aerosol absorption and optical depth with sufficient accuracy in the future, but they cannot today. This is primarily a key issue for clear-sky downward SW fluxes, but may also have a very significant role for boundary layer cloud as well when the aerosol layer is over or within the cloud layer. This suggests that the GLAS and Calipso ability to vertically profile both aerosols and clouds are very likely to be critical components both the improve 4-D aerosol assimilation where vertical layering is the key to tying aerosols to source regions using back-trajectory analysis, as well as the large difference in aerosol absorption from an aerosol layer placed above or below a thick cloud layer. Finally, as for LW surface fluxes, improvements in the surface validation network and data are required. Accuracy and stability of the surface radiometers need improvement, especially for diffuse SW fluxes. Greatly improved sampling over oceans is also required on ships, buoys, and ocean platforms. The vast majority of current surface data is at land and island sites: both of which differ substantially from open ocean conditions. Polar regions are also inadequately covered. While climate regimes should dominate the selection of LW surface sites, the number of SW sites needs to include additional sites to cover major aerosol types. Each of these sites must have Aeronet class aerosol data available with the surface SW radiation data. The international BSRN and Aeronet programs would provide the obvious starting point for expansion.

6.1.5 Net Solar Radiation at the Top of the Atmosphere

The NPOESS ERB instrument needs to at least meet the current CERES absolute accuracy and to exceed it in stability. Since the ERB instrument will use new detectors: these must be characterized for stability with solar exposure to UV (TOTAL and SW channels) as well as time in vacuum. Overlapping observations are key to achieving the stability requirement and the risk of this must be reduced from the current 50% between NASA Aqua and NPOESS ERB observations. The NPP mission is timed correctly to cover the gap (late 2006 launch), and NASA has a spare copy of the current CERES instrument in storage. A 3-month overlap of observations is required to meet the stability requirement.

There currently is only one planned continuous time series of broadband radiation data: CERES to ERB. There is a European Organisation for the Exploitation of Meteorological Satellites EUMETSAT geostationary broadband instrument (GERB) on Meteosat Second Generation, but its current instrument lifetime is estimated at 1 to 2 years. There are plans to place GERB on 3 future Meteosat platforms, but the platform life is nominally 7 years, so that large gaps in the data record are likely. A second and independent set of broadband radiation is needed to allow independent verification of the CERES/ERB time series. Absolute accuracy should be at least 1%. The technology should differ from CERES/ERB, the time series should be overlapped and continuous, and space/time sampling should be sufficient to allow continuous inter-calibration with the CERES/ERB record. The optimal method would be a full broadband spectrometer (0.3 µm to 4 µm) that covers at least 99% of the earth reflected solar spectrum and is linear to better than 0.2%.

NIST spectral calibration sources and transfer radiometers are needed to cover the full reflected solar spectrum from the Earth.

6.1.6 Outgoing Longwave Radiation at the Top of the Atmosphere

The discussion on NPOESS ERB instrument requirements and the NPP mission requirements in section 6.1.5 applies to outgoing longwave radiation measurements also except a 1-month overlap of observations is sufficient instead of 3 months overlap to meet the stability requirement.

Again as discussed in Section 6.1.5, a second and independent set of broadband radiation data is needed allow independent verification of the CERES/ERB time series. Again the absolute accuracy should be at least 1%. As noted before the technology should differ from CERES/ERB, the time series should be overlapped and continuous, and space/time sampling should be sufficient to allow continuous inter-calibration with the CERES/ERB record. The optimal method would be a full broadband spectrometer (4 µm to 100 µm) that covers at least 99% of the earth emitted thermal spectrum and is linear to better than 0.2%. Aircraft and balloon instruments to cover the full longwave spectrum at very high accuracy exist and are being tested and improved. This development should continue and evolve into an independent verification of longwave flux measurements using global scanners like CERES and ERB. Sampling must be sufficient to allow intercalibration to 0.2% at 95% confidence in no longer than 6 months of overlapping data.

Again NIST spectral calibration sources and transfer radiometers are needed to cover the full emitted thermal infrared spectrum from the Earth.

6.1.7 Cloud Base Height

Lidar and cloud radar are the only methods that currently appear capable of meeting the cloud base height requirements. But GLAS was just launched, and Cloudsat and Calipso launch in 2004. These data, together with the MODIS estimates of cloud base, are critical to assess this accuracy and stability capability. Even lidar and radar, however have their challenges. Lidar does not penetrate to the base of the lowest cloud layer in about 20 to 30% of cases globally. Lidar can, however, be self calibrated against Raleigh scattering, and the lidar vertical resolution is less than 50 m in the boundary layer. Cloud base for water clouds, however suffers from multiple scatter stretching which needs further evaluation for accuracy in determinations of cloud base from lidar. Cloud radar has much less of an attenuation problem and will observe most of the multi-layered cloud that the lidar misses due to attenuation. Cloud radar challenges are: low sensitivity to small particle water clouds, absolute calibration, and a relatively coarse 500 m vertical resolution. Accurate assessment of cloud base data from space will rely on a network of surface site lidars. Such an international network is now in development but exists at very few sites (Welton et al., 2001). These sites need to be expanded to include all significant climate regimes as defined by cloud height distributions. In particular, ocean and polar cloud regions will need to be rigorously sampled. Early sites are focused on traditional mid-latitude and tropical land sites. These will not be typical of open-ocean or polar regions.

6.1.8 Cloud Cover

Sensitivity studies are needed to map cloud cover requirements into instrument requirements. The recently developed MODIS cloud algorithms could be used in these studies. A key issue is the wide variability of cloud optical depth and cloud detection/masking over bright or highly variable backgrounds. Results must be converted into equivalent SW and LW cloud radiative effects to avoid unrealistic requirements. For example, very thin high may be difficult to detect but may have very little radiative effect. The accuracy and stability metrics for TOA and surface fluxes can be used as a guide to determine cloud cover accuracy and stability requirements for different cloud types. The larger the radiative impact, the tighter the accuracy constraint.

A second key study is verification of the MODIS derived cloud cover and layering against the GLAS, Calipso, and Cloudsat active cloud measurements. Calipso and GLAS should provide the most accurate cloud cover determinations. It is likely that meeting the climate accuracy and stability at large time/space scales (zonal to global) will require both lidar and radar active instruments. If this is the conclusion, then the lidar and radar will be required as a routine part of the climate observing system.

6.1.9 Particle Size Distribution

Sensitivity studies are required to further assess this climate requirement, its instrument requirements, and any further developments that might be necessary.

6.1.10 Cloud Effective Particle Size

Sensitivity studies are required to further assess this climate requirement. This may be one of the most stringent calibration requirements for imagers like MODIS and VIIRS to meet. NIST standards at wavelengths near 1.6 µm, 2.1µm, and 3.7 µm may need improvement to meet this calibration and stability requirement.

6.1.11 Cloud Ice Water Path

Several new methods to derive cloud Ice Water Path need further assessment: the use of only the MODIS imager, a combination of passive microwave (AMSR or TMI) and passive imager (MODIS, VIRS) over ocean backgrounds, lidar/infrared window channels (Icesat, Calipso) for thin ice cloud layers, lidar/radar/visible channel/near-IR channel (Calipso, Cloudsat, MODIS) for moderate to thick ice cloud layers, and finally sub-mm/far-infrared radiometers and spectrometers for moderate to thick ice cloud layers. The best reference for validation of these approaches will be ARM-like lidar, doppler cloud radar, and radiometer approaches verified in turn against in-situ aircraft microphysical data. Further work is needed to cover a complete range of ice cloud types, especially for optically thick clouds. The international community should also work to expand the ARM surface site network into missing climate regimes such as tropical land where deep convection is much stronger than over ocean backgrounds and is likely to change cloud IWP and microphysics. It is likely that only a combined instrument approach (Cloudsat, Calipso, MODIS) will achieve climate accuracy and stability from satellite observations. Further work is also needed to assess and verify that cloud radar calibration (ARM sites and Cloudsat) has sufficient accuracy and stability to meet the requirement. Improved approaches to calibration of space-based radar systems may be required.

6.1.12 Cloud Liquid Water Path

Imager calibration needs for cloud liquid water path are the same as those for visible optical depth and cloud effective particle size (6.1.13 and 6.1.10). Further work on imager channel stability is needed using lunar calibration. But imagers alone are unlikely to meet the climate requirements. Passive microwave (SSM/I, TMI, AMSR) is an independent method over ocean backgrounds that should be capable of the accuracy and stability for moderate to thick water clouds. But recent instruments (TMI, AMSR) have shown worse calibration accuracy than SSM/I and further improvements are needed in the future NPOESS versions. Further sensitivity studies are needed to tie the LWP accuracy/stability goals to passive microwave calibration values. This is required because a wide range of channels is used in LWP derivation from these instruments. Combining passive microwave for moderate to thick LWP, and imager for low LWP cases should have the accuracy potential over ocean backgrounds. Over land, additional cloud radar data is likely to be required to replace the passive microwave, which is ineffective over land backgrounds. Extensive validation will be required to assess if the imager plus cloud radar can meet accuracy over land backgrounds. The r^6 sensitivity of radar to particle size means that combination with imager data will be critical for LWP over land. Validation of any of these retrievals requires up looking passive microwave. Additional sites are required to validate over a complete range of water cloud types and boundary layer conditions. In particular, additional data are required over ocean from ships and platforms, and in the tropics over land. The four ARM sites are the current reference for this validation but do not cover all climate regions.

6.1.13 Cloud Optical Thickness

Further assessments of the SeaWiFS and MODIS attempts at lunar calibration are key to verifying the ability to reach the climate stability requirement. Further assessment is also required for linearity of response for current imagers. This will be especially key if lunar calibration is used as the stability reference. Zero levels can be verified from nighttime observations, and low reflectivity levels from lunar calibration. But high reflectivity cloud is only verified through linearity of the sensors. Independent calibration with diffusers and lamps are key contributions, but may not achieve the 1%/decade stability. Current diffusers degrade with exposure, and lamps degrade with use. Improved stability lamps and solar diffusers or other solar calibration sources should also be examined. Multiple calibration references are critical for stability. Lunar, lamps, and diffusers used in conjunction may be sufficient to reach the stability goal. Another option that should be assessed is flight in inclined orbit of a highly calibrated spectrometer that could be used to intercalibrate the imager data. This could provide key independent calibration of a wide range of imager reflectance channels if it covered the range from 0.4 µm to 2.5 µm. Overlapping observations will be required to maintain the stability requirement, since absolute accuracy is insufficient.

6.1.14 Cloud Top Height

This is a function of cloud top temperature and is discussed in 6.1.16.

6.1.15 Cloud Top Pressure

This is also a function of cloud top temperature and is discussed in 6.1.16.

6.1.16 Cloud Top Temperature

Overlapping observations will be required to meet the 0.2 K/decade stability of infrared window and sounder channels used to determine cloud top temperature. For infrared sounder multi-channel retrievals, sensitivity studies need to verify the interchannel calibration consistency required to maintain accuracy and stability. This should be straightforward with current MODIS and AIRS algorithms. One of the limitations in calibration of current instruments is the inability of the blackbody to vary its temperature over a controlled range. This ability would allow more direct verification of channel gain, linearity, and separation of gain from offset or zero level. Scanning mirrors can be a problem because of scan angle dependent emissivity of the mirror (MODIS).

In many cases, deep space calibration is needed to verify zero levels. This is especially important for thermal instruments since they in essence have “stray light” emitted from the instrument itself. The instruments in turn vary in temperature through the orbit as a result of varying amounts of solar heating. Unlike solar reflectance channels, they cannot use the night side of the earth to verify zero radiance levels. We recommend that all thermal instruments be capable of verifying zero radiance levels using deep space scanning. This type of spacecraft maneuver has been carried out by ERBS, TRMM, and SeaWiFS in the past, and will soon be initiated on the EOS Terra mission.

6.1.17 Spectrally Resolved Longwave Radiation

The NPOESS CrIS instrument has design accuracies of 0.45% between 650 cm^{-1} - 1095 cm-1, 0.6% between 1210 cm^{-1} - 1750 cm^{-1}, and 0.8% over 2155 cm^{-1} - 2550 cm^{-1}. These design accuracies correspond to an absolute accuracy in equivalent temperature of 0.29 K - 0.18 K between 650 cm^{-1} - 1095 cm^{-1},0.22 K - 0.15 K between 1210 cm^{-1} -1750 cm^{-1}, and 0.16 K- 0.14 K between 2155 cm^{-1} - 2550 cm^{-1}.

To meet the spectrally resolved longwave radiation at 910 cm^{-1}, the absolute accuracy of CrIS would need to improve by about a factor of 2. Additionally, the diurnal sampling requirements of this CDR are severely impaired by sun synchronous orbit (Kirk-Davidoff *et al*. 2003)-either a true polar orbit or a low precessing orbit is preferable to meet to the goal of achieving annual average radiance accuracy of 0.1 K over large spatial scales, over majority of the tropics and a large fraction of the rest of the globe.

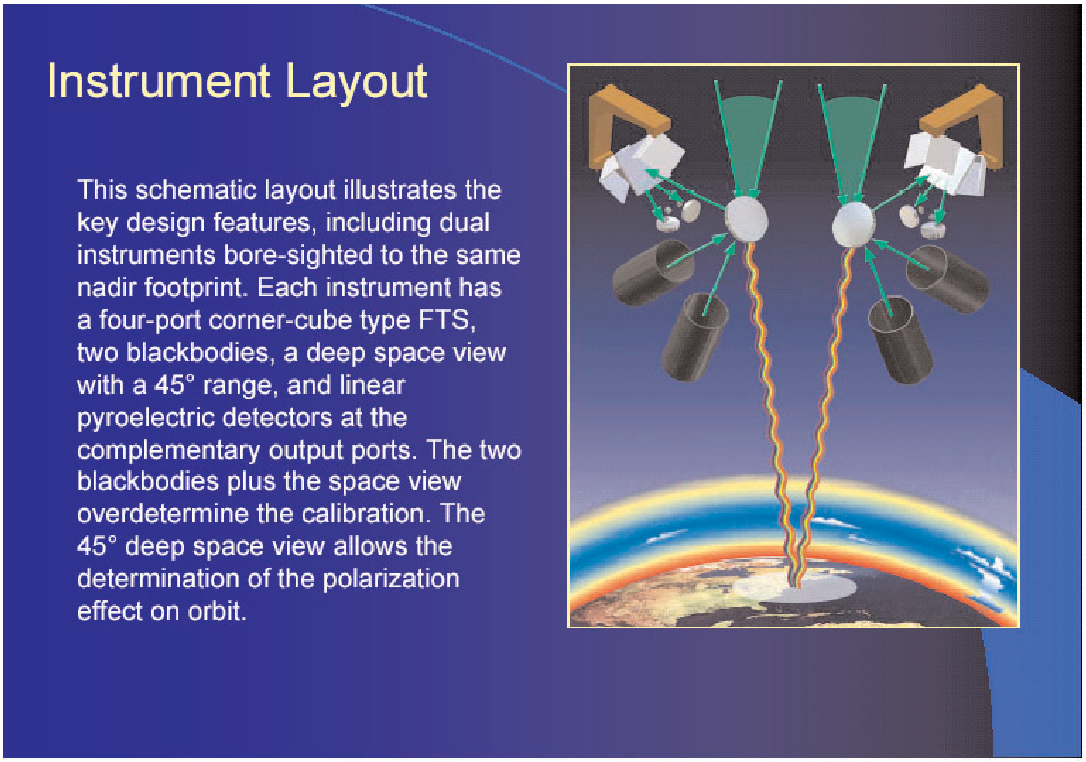
To meet the absolute accuracy calibration requirements in the pre-launch phase, a program of laboratory comparisons between so-called "source-based" radiance scales (Fowler *et al*. 1995) and "detector-based" radiance scales (Brown *et al*. 2000) from NIST is necessary to establish the spectrally resolved absolute infrared radiance scale and evaluate the instrument's "native" radiance scale. An instrument designed to meet the CDR should then provide a means of on-orbit evaluation of the drift of the instrument native scale from its pre-launch value. An inter-calibration with a second spectrally resolved instrument based on different sensor technology and meeting the same standards of pre-launch calibration and on-orbit diagnostics would provide the maximal demonstration of accuracy achieved on-orbit, in accordance with one of the overarching principles listed in Section 2 above: Acquire independent space-based measurements of key climate variables.

6.2 Atmospheric Variables

6.2.1 Atmospheric Temperature

Microwave instruments

For microwave instruments, it is possible that the current AMSU design is sufficient in both long-term stability and absolute accuracy to meet the climate requirements. This, however, is difficult to determine either empirically (due to a lack of sufficient data analysis) or through engineering



Instrument Layout

This schematic layout illustrates the key design features, including dual instruments bore-sighted to the same nadir footprint. Each instrument has a four-port corner-cube type FTS, two blackbodies, a deep space view with a 45° range, and linear pyroelectric detectors at the complementary output ports. The two blackbodies plus the space view overdetermine the calibration. The 45° deep space view allows the determination of the polarization effect on orbit.

Proposed dual interferometer for very accurate spectrally resolved longwave radiation observations (Goody, Invited Workshop Presentation).

analysis. Although not driven by climate requirements, the AMSUs had a very carefully thought out calibration design. In any event, the AMSU observations will likely end in another ten years, at which point the Conically-Scanning Microwave Imager Sounder (CMIS) and the Advanced Technology Microwave Sounder (ATMS) will take over the microwave temperature-monitoring task. It is not clear whether engineering analysis has been done to determine if any of these instruments have sufficient accuracy and stability designed into them to meet the climate monitoring requirements.

Some of the instrument issues that need to be addressed are discussed in the following sections.

6.2.1.1 Microwave instrument linearity

Microwave radiometers are slightly non-linear devices. These non-linearities need to be accurately measured prior to launch, at a range of *instrument temperatures*. While, the pre-measurements of the MSUs were insufficient (Christy *et al*., 2003), the measurements of the AMSU instruments were much more extensive. Multi-point (as opposed to two-point) calibration strategies might need to be explored. Better understanding of the causes of radiometer nonlinearity is needed.

6.2.1.2 Target temperature gradients

Calibration targets need better thermal stability as well as a better understanding and characterization of the combined thermal and electrical (emissivity or complex reflection coefficient) properties. On orbit, it is absolutely essential that the hot calibration target be maintained at a uniform - less than 0.1° C variation - temperature throughout its extent. A sufficient number of precision thermistors need to be embedded at the surface and at various depths within the target to characterize the calibration targets thermal field. New techniques for maintaining target temperature uniformity (e.g. microwave transparent, but infrared-and solar-opaque enclosures) should be explored.

6.2.1.3 Microwave antenna patterns, illumination, and feedhorn spillover

The amount of feedhorn energy that does not come from reflection off the antenna (during Earth observations and cold space observations), or from the warm load (during warm calibration target viewing), leads to substantial uncertainty in absolute calibration. Pre-launch measurements of feedhorn spillover off the antennas and calibration target(s) must be more accurate than have been achieved to date. The feedhorn spillover needs to be measured to an accuracy of 0.2% in order to meet the absolute accuracy requirement. New methods of virtually eliminating spillover in the antenna design should be explored.

6.2.1.4 Radiometer sub-component temperatures

Accurate temperature measurements of subcomponents in the radiometer are needed. The subcomponents should be enclosed in a thermally uniform and stable environment with spatial and temporal gradients less than 0.2 K.

6.2.1.5 Instrument pointing accuracy

Better pointing angle characterization is required. The Earth incidence angle needs to be precisely known, i.e., to an accuracy of about 0.03 degrees.

Infrared instruments

Calibration issues for the infrared sounders are more complex than those in the microwave region, and will require substantial work to meet the absolute accuracy and long-term stability requirements.

There are numerous potential calibration problems affecting infrared sounders that may hinder creation of climate-quality datasets. Many of them can be avoided or minimized with intelligent design and careful construction of the sounder instruments. Residual problems still necessitate careful, complete instrument characterization before launch, corrective algorithms in the calibration processing, and continual performance monitoring and frequent validation on orbit.

The importance of the calibration and characterization activities before launch cannot be overstated. Too often budget and schedule shortfalls are made up by curtailing the effort at the end of the instrument procurement contract, which is, as luck would have it, the calibration and characterization activity. It is rare enough that calibration and characterization are actually given their pre-planned level of effort. It is almost unheard of that the level of effort for calibration and characterization could actually be increased if unexpected problems cropped up (and unexpected problems almost always do) and more time was needed to understand and rectify them. Yet, without such dedication, we pay a penalty in accuracy and stability of the observations throughout the lifetime of the sensor in orbit.

From our experience with current sounders, we have found that the following are major issues that need to be considered for climate datasets:

1. Lack of knowledge, stability, and consistency of spectral response. Application of sounder data requires knowledge of the spectral response in all sounder channels. Errors in spectral response functions cause errors in calculated radiances, leading in turn to errors in derived products. Users often invoke empirical corrections for such errors, but empirical corrections usually do not accurately reproduce the scene-dependencies of Spectral Response Function (SRF) associated errors. SRF errors may also be quite different on different satellites, and this will introduce discontinuities in time series spanning a sequence of satellites. To avoid these problems, the SRF must be carefully measured before launch. If the instrument vendor provides SRF measurements, an independent institution should make corroborative measurements. Finally, we usually assume that for a given instrument, the SRF remain invariant on orbit. If that were not true, the resulting data set will contain spurious drifts. Therefore, development of filters known to remain stable under conditions encountered in space, as verified by testing under simulated conditions in the laboratory, is essential. In addition, development of on-orbit techniques to measure spectral response should be considered. It is likely that SRF errors will be smaller for the new generation of hyperspectral sounders than they are for the current generation of filter radiometers.

2. Errors in on-board blackbody radiances: The calculated radiance of the internal blackbody is one of the anchor points of the on-orbit calibration. During pre-launch testing, the calibration of a laboratory blackbody is transferred to the internal blackbody. Therefore, the radiances of the laboratory blackbody must be known extremely accurately. Up to very recently, those radiances were computed from the temperatures, measured by embedded thermistors,

inside the laboratory blackbody. Traceability to NIST was through the calibration of the thermistors, but there was no guarantee that the radiances were known accurately. Possible non-blackness, poorly known thermal gradients, and scattered radiation could affect the laboratory blackbody and reduce confidence in the accuracies of the calculated radiances. Now, however, NIST has developed the capability to transfer the NIST radiance scale to a laboratory blackbody with a portable calibrated radiometer, the Thermal Transfer Radiometer (TXR). This will improve the calibration of the laboratory blackbody and thus that of the internal blackbody as well.

Despite an accurate pre-launch calibration, the accuracy of the radiances of the ICT on orbit can be compromised by phenomena such as scattered radiation from solar-heated components of the sounder during the calibration process, and thermal lag within the blackbody during periods of rapid heating and cooling. These phenomena, which are worst in polar orbiters near the terminator and in geostationary satellites near local midnight, should be minimized in the design of the sensor, as they are extremely difficult to correct for after the fact.

3. Inadequate treatment of nonlinearities in response (Response here means the increment in instrument output [e.g. counts] resulting from a unit increment in incident radiance): Nonlinearities introduce observation errors whose magnitudes vary with scene temperature. It would be best if sounders were built with small or negligible nonlinearities. Failing that, the nonlinearities must be accurately characterized as functions of instrument and scene temperature in pre-launch testing and that information should be applied during on-orbit calibrations.

4. Dependence of instrument throughput on scan angle (e.g. polarization-induced dependence of reflectance of scan-mirror on cross-track scan angle): This phenomenon can cause significant systematic calibration errors when calibration sources (and Earth scenes) are not all at the same scan position. Best avoided by intelligent design, it can also be accounted for in on-orbit processing. Best results require data from both pre-launch measurements and occasional large-angle scans of space on orbit. The latter may require special, and possibly inconvenient and/or dangerous, spacecraft maneuvers.

5. Random effects-e.g., noise and striping: Normally, effects of noise and random detector-to-detector striping are reduced to insignificance by averaging, and averaging is usually appropriate with data intended for construction of long-term or global datasets. However, extremely high noise for long periods of time (as has affected the GOES-8 sounder) and systematic biases (often resulting from failure of a sounder component), cannot be overcome by averaging and thus present a more serious difficulty.

6.2.2 Water Vapor

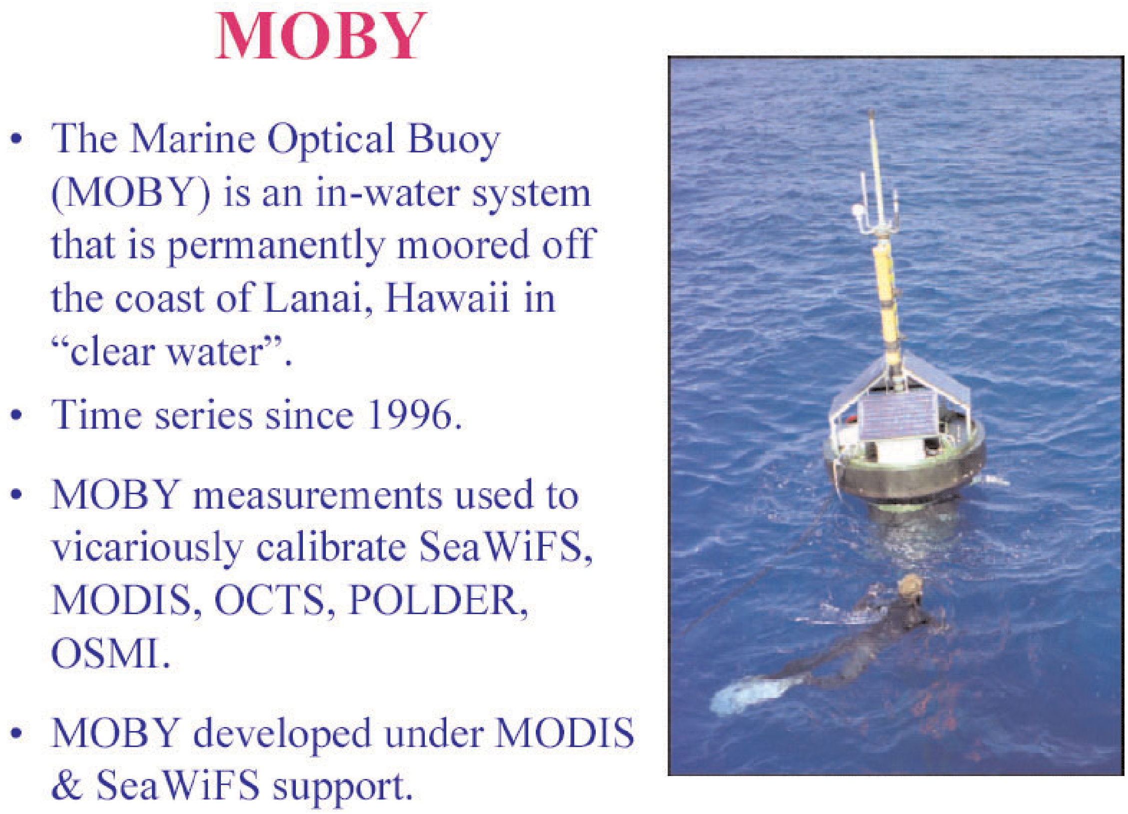
The microwave radiometer issues for water vapor are not quite as stringent as for temperature, but the instrument design issues remain the same as those described above for temperature. Design issues for infrared sounders for water vapor measurements are similar to those for temperature observations.

6.2.3 Ozone

While current and planned BUV and LUVV instrument calibration tests make use of lamps, spheres, and diffusers traceable to NIST standards (Hilsenrath et al., 1998), there is need for improved consistency from test to test whether for a single instrument, a series of instruments or instruments with different designs. In other words, standard and well-documented practices need to be employed. This is particularly applicable to other instruments employing BUV techniques such as GOME-2 flying on MetOp. Data from this instrument are likely to be compared or even incorporated into the long-term ozone record; therefore, common calibrations are essential. There is also a need for increased accuracy beyond the current capability at the less than 3% level of radiance/irradiance calibration to 1%. Accurate determination is also needed for characterization of the 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. Much can be learned about BUV and LUVV instrument performance when it used to view the zenith sky from the laboratory. This procedure should become part of standard instrument prelaunch testing. Tropospheric residual techniques (differences between total column and stratospheric column ozone estimates) require accurate intercalibration of the instruments or wavelength ranges producing the two estimates. In particular, the generation of accurate tropospheric residuals from the differences between TOZ from BUV and stratospheric columns from IR instruments will require improved characterization of the physical quantities for ozone absorption and emission.

New instruments such as OMPS, which have more advanced technologies, must be further calibrated over what has been done in the past for TOMS and SBUV/2. These include full calibration and instrument characterization in vacuum with a measure of temperature sensitivity of wavelength and radiometric stability. Because of the advanced algorithms, instrument characterization should include a measure of instrument response when viewing a gas cell containing known amounts of ozone.

The use of new detector technologies in the form of Charge-Coupled Device (CCD) and linear array detectors poses additional challenges for instrument calibration and characterization work. Instead of a single shared photomultiplier tube for all the measurements, different pixels are used for the different wavelengths. Characterizing thousands of pixels and monitoring their behavior in space will require new techniques. The new technology will also introduce new problems, *e.g.*, the need to monitor CCD charge transfer efficiency.



MOBY

- The Marine Optical Buoy (MOBY) is an in-water system that is permanently moored off the coast of Lanai, Hawaii in “clear water”.
- Time series since 1996.
- MOBY measurements used to vicariously calibrate SeaWiFS, MODIS, OCTS, POLDER, OSMI.
- MOBY developed under MODIS & SeaWiFS support.

To provide more confidence in satellite ocean color observations, more Marine Optical Buoys (MOBYs), or similar systems with successor technologies, should be deployed at additional ocean locations (McClain, Workshop Invited Presentation).

In addition to direct calibration of the satellite instruments, ground-based instruments providing measurements for comparisons of radiances or atmospheric ozone estimates need calibration and standards. For the Dobson network, stations trace their calibration to Instrument #83, the world standard. A triad of instruments in Toronto, Canada monitors the stability of the Brewer network. NIST regularly participates in very useful workshops and intercomparison campaigns for surface UV measurements. Methods to use surface measurements to validate satellite-measured radiances are under development.

Instruments on NASA’s Earth Observing System (EOS) satellites will break new ground in providing space-based measurements. The Spectral Irradiance Monitor (SIM) of the Solar Radiation and Climate Experiment (SoRCE) will provide highly accurate solar spectra. These measurements can be used to assist in tracking the performance of BUV and LUVV instruments.

6.2.4 Aerosols

Although relative spectral and relative angular calibration is important in the retrieval of many of the required aerosol parameters (size distribution and refractive index, respectively), the optical depth retrieval from intensity measurements is dominated by absolute radiometric calibration. The calibration issues described for other solar backscattering observational instruments are therefore also directly applicable to aerosol requirements (e.g., VIIRS, SBUV, SAGE). The future use of polarization measurements requires accurate polarimetric calibration and characterization on the ground with consequent needs for characterization of any instrumental birefringence and instrumental polarization and effective methods to polarimetrically calibrate on orbit.

6.2.5 Precipitation

The microwave radiometer issues for precipitation are the same as those for temperature discussed in Section 6.2.1.

6.2.6 CO_2

Any spatially coherent bias in the CO_2 retrieval will be misinterpreted by the assimilation system as a source or sink, so it is crucial that any such biases be extremely well characterized and documented through calibration/validation activities. Expected sources of such biases are land-sea or vegetation contrasts in surface spectral reflectance, atmospheric aerosol, cloud effects, and solar and viewing geometry. Each of these potential sources of bias must be characterized by vigorous in-situ measurement campaigns that are designed to account for the vertical weighting function of the satellite retrieval. Temporal biases associated with diurnal and seasonal cycles and cloud vs. cloud-free columns will also need to be characterized and documented so that they can be accounted for in the assimilation system.

Measurements necessary to fully characterize these spatial and temporal biases in the satellite retrievals will include airborne campaigns to measure vertical structure and spatial variations, continuous high-precision measurements from tall towers to characterize diurnal and seasonal cycles and cloud effects, and upward-looking ground-based FTIR spectrometry which can retrieve column CO_2 simultaneously with the satellite instrument. Orbiting Carbon Observatory (OCO) includes a “stare mode” of operation, which will allow the instrument to observe the column over these fixed stations for on-board calibration and validation. Airborne campaigns and FTIR spectrometer siting must be designed to span possible sources of potential bias (geographic, solar zenith angle, aerosol, land/sea placement).

It cannot be emphasized too strongly that the error characteristics of the satellite CO_2 retrievals must be reported and documented in as much detail as possible! Data assimilation and transport inversions of these data will have to balance spatially dense satellite retrievals with sparse but extremely accurate in-situ data. This will be done by specifying an error covariance matrix for all CO_2 data, and simply filling this matrix with a spatially and temporally uniform value (e.g., CO_2 retrievals are uncertain at +/- 2 ppmv) will render the data nearly useless for the source retrieval. Atmospheric inversions and CO_2 assimilation calculations will be improved by reporting of spectroscopic errors, vertical weighting functions and averaging kernels, and cloud masking in every column retrieval, not just the global or time mean. These error characteristics as estimated in retrieval algorithms should be considered a crucial part of the “product” suite from any CO_2 instrument.

Because of the great difficulties in measuring CO_2 with passive instruments, active systems (e.g., lidar) should be developed.

6.3 Surface Variables

All the surface variables are measured by visible/infrared and microwave radiometers. Recommendations for improving calibration and characterization of these instruments have already been discussed in sections 6.1 and 6.2. However, some surface variables have several unique validation issues.

Both the IR and microwave measurements are sensitive to a very thin layer of the ocean's surface - in the case of IR to a microns thin skin layer and for microwave to a layer of centimeters in thickness. But as discussed earlier, the richest source of ground truth comes from ships and buoys, which measure not the skin layer temperature but the ocean temperatures at a depth of about a meter or more. The satellite techniques are adjusted to account for the normal difference between these two temperatures, but the adjustments are not perfect. To more accurately validate the performance of satellite radiometers measuring SST, an on-going program of radiometric observations of ocean skin temperatures from ships and other platforms should be initiated.

The ocean color signal in satellite observations is masked by the atmospheric contribution, which accounts for 90% of the observed radiance over the oceans. Ocean color observations have been validated by intensive in-situ radiometric measurements from a specially designed ocean buoy (MOBY). To provide more confidence in satellite ocean color observations, more MOBYs, or similar systems with successor technologies, should be deployed at additional ocean locations.

The satellite observed Normalized Difference Vegetation Index (NDVI) is a measure of density and vigor of surface vegetation, but no ground truth exists to validate this measurement. Some algorithms used for processing these satellite observations correct for the atmosphere to derive a value of the NDVI at the earth's surface rather than that observed from space. Consideration should be given to validation programs using VIS/IR radiometers similar to those in space to measure NDVI in areas with different vegetation conditions.

7. Concluding Remarks

Perhaps for the first time a large group of climate data set producers/users and instrument experts assembled to discuss the problem of measuring global climate change from space. The group attacked the problem using an end-to end process: establishing accuracy and long-term stability requirements for key climate data sets; translating the data set requirements into satellite instrument requirements; evaluating the capabilities of current satellite instruments to meet the observing requirements; and developing requirements and recommendations for improving satellite instrument calibration and associated activities. 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. This workshop report 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.

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Appendix A. Workshop Agenda

Workshop on Satellite Instrument Calibration for Measuring Global Climate Change, November 12 - 14, 2002
Inn and Conference Center, University of Maryland, College Park, MD

Time	Day 1 Nov 12, 2002	Day 2 Nov 13, 2002	Day 3 Nov14, 2002
7:30	Refreshments (Continuous from 7:30 AM to 11:00 AM and from 1:00 PM to 4:30 PM) Registration/ Help Desk (open from 8:20 AM to 5 PM)	Refreshments (Continuous from 7:30 AM to 11:00 AM and from 1:00 PM to 4:30 PM) Registration/ Help Desk (open from 8:20 AM to 5 PM)	Refreshments (Continuous from 7:30 AM to 11:00 AM and from 1:00 PM to 4:30 PM) Registration/ Help Desk (open from 8:20 AM to 5 PM)
8:20	Registration – No fee	2nd day Opening Remarks - Hratch Semerjian, Director, CSTL, NIST	Breakout groups meet: – Report writing – Rough draft of workshop report
8:40	Registration – No fee		
9:00	Introductions, Wkshp Objectives Opening Remarks - Greg Withee, NOAA/NESDIS	Jim Anderson, Harvard U.; IR	
9:20	Keynote – Richard Goody, Professor Emeritus, Harvard U.	Joe Rice, NIST; IR - Absolute Calibration	
9:40	Keynote – Tom Karl, NOAA / NESDIS / NCDC	Frank Wentz , RSS; Microwave	
10:00	NPOESS Plans – S. Mango, NPOESS-IPO	Gary G. Rottman, U. Colorado; Total/Spectral Solar Irradiance	
10:20	Judith Lean, NRL; Total and Spectral Solar Irradiance	Kory Priestly, NASA/LaRC; Earth Reflected Solar Radiation, and Earth Emitted Radiation	
10:40	Bruce Wielicki, NASA/LaRC; Earth Radiation Budget	Charge to breakout groups	
11:00	Roy Spencer, NASA/MSFC; Atmospheric Temperature	Breakout groups meet: 1. Solar irradiance, ERB, and clouds 2. Atmospheric variables 3. Surface variables Appropriate climate scientists and instrument scientists on each team – Can we meet requirements?	
11:20	Andy Harris, NOAA/NESDIS/ORA; Sea Surface Temperature		
11:40	Chuck McClain, NASA/GSFC; Ocean Color		

Time	Day 1 Nov 12, 2002	Day 2 Nov 13, 2002	Day 3 Nov14, 2002
12:00	Lunch	Lunch	Plenary: Breakout group – Summaries of wkshp report
12:20			
12:40			
1:00	John Bates, NOAA/NESDIS/NCDC Atmospheric Water Vapor	Breakout groups meet: – Roadmap to meet requirements	Wkshp Adjourns
1:20	Richard Stolarski, NASA, GSFC; Ozone		
1:40	Chris Brest, NASA,GSFC,GISS; Cloudiness		
2:00	Vikram Mehta, NASA, GSFC; Precipitation	– Writing assignments	Editing committee reviews/edits wkshp report and produces first draft
2:20	Scott Denning, U. Colorado; CO_2 and other GH Gases		
2:40	Brian Cairns, NASA, GSFC, GISS; Atmospheric Aerosols		
3:00	Dan Tarpley, NESDIS/ORA; Snow Cover		
3:20	Josefino Comiso, NASA, GSFC; Sea Ice		
3:40	Juri Knyazikhin, Boston U.; Vegetation		
4:00	Ernie Hilsenrath/ Scott Janz, NASA, GSFC; UV		
4:20	Carol Johnson, NIST; Visible and Near IR – absolute calibration		
4:40	Bob Evans, RSMAS, U. Miami; Visible and near IR	Plenary: Breakout group progress reports	
5:00			
5:20	Reception : Starts at 5:30 PM	Adjourn	Editing committee adjourns

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List of Acronyms and Abbreviations

AATSR	Advanced Along Track Scanning Radiometer
ABL	Atmospheric Boundary Layer
AOD	Aerosol Optical Depth
AIRS	Atmospheric InfraRed Sounder
AMSU	Advanced Microwave Sounding Unit
APS	Aerosol Polarimetry Sensor
ARM	Atmospheric Radiation Measurement program
ATBD	Algorithm Theoretical Basis Document
ATMS	Advanced Technology Microwave Sounder
AATSR	Advanced Along Track Scanning Radiometer
AMSR	Advanced Microwave Scanning Radiometer
ATSR	Along Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
BIPM	Bureau International des Poids et Measures
BSRN	Baseline Surface Radiation Network
BUV	Backscattered UltraViolet - radiances or technique
CALIPSO	Cloud-Aerososl Lidar and Infrared Pathfinder Satellite Observations
CCD	Charge-Coupled Device
CCSP	Climate Change Science Program
CEOS	Committee on Earth Observation Satellites
CGPM	Conference Generale des Poids et Measures
CDR	Climate Data Record
CERES	Clouds and the Earth's Radiant Energy System
CMDL	Climate Monitoring and Diagnostic Laboratory
CMIS	Conically-Scanning Microwave Imager
CrIS	Cross Track Infrared Sounder
DMSP	Defense Meteorological Satellites Program
DOAS	Differential Optical Absorption Spectroscopy
DoE	Department of Energy
EDR	Environmental Data Record
EOS	Earth Observing System
ERB	Earth Radiation Budget
ERBE	Earth Radiation Budget Experiment
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FPAR	Fraction of Photosynthetically Active Radiation
FTIR	Fourier Transform InfraRed
GAW	Global Atmosphere Watch
GCI	Global Cloud Imagery
GCOS	Global Climate Observing System
GERB	Geostationary Earth Radiation Budget Experiment
GEWEX	Global Energy and Water Cycle Experiment
GLAS	Geoscience Laser Altimeter System

GOES	Geostationary Operational Environmental Satellite
GOME	Global Ozone Monitoring Experiment
GOMOS	Global Ozone Monitoring by Occultation of Stars
GPS	Global Positioning System
HALOE	HALogen Occultation Experiment
HIRDLS	High Resolution Dynamic Limb Sounder
HIRS	High-resolution InfraRed Sounder
HSB	Humidity Sounder for Brazil
IASI	Infrared Atmospheric Sounding Interferometer
ICT	Internal Calibration Target
IGOS	Integrated Global Observing Strategy
IGACO	Integrated Global Atmospheric Chemistry Observations
IORD	Integrated Operational Requirements Document
IPO	Integrated Program Office (for NPOESS)
IPCC	Intergovernmental Panel for Climate Change
ISCCP	International Satellite Cloud Climatology Project
IWP	Ice Water Path
IR	InfraRed
LAI	Leaf Area Index
LW	Longwave
LWP	Liquid Water Path
LIDAR	Light Detection and Ranging
LUVV	Limb-scattered Ultraviolet and Visible radiation
MERIS	MEdium Resolution Imaging Spectrometer Instrument
Meteosat	European Geostationary Meteorological Satellite
MetOp	Meteorological Operational satellite
MFRSR	Multi-Filter Rotating Shadowband Radiometer
MISR	Multiangle Imaging SpectroRadiometer
MLS	Microwave Limb Sounder
MOBY	Marine Optical Buoy
MODIS	Moderate Resolution Imaging Spectroradiometer
MSU	Microwave Sounding Unit
MW	Microwave
NASA	National Aeronautic and Space Administration
NDSC	Network for the Detection of Stratospheric Change
NDVI	Normalized Difference Vegetation Index
NIR	Near InfraRed
NIST	National Institute for Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Program
NRC	National Research Council
NWP	Numerical Weather Prediction
OATS	Operational Algorithm Teams

OCO	Orbiting Carbon Observatory
OLR	Outgoing Longwave Radiation
OMI	Ozone Monitoring Instrument
OMPS	Ozone Mapping and Profiler Suite
POAM	Polar Ozone and Aerosol Measurements
POLDER	POLarization and Directionality of the Earth's Reflectances
SAGE	Stratospheric Aerosol and Gas Experiment
SBUV	Solar Backscattered Ultraviolet instrument
SCIAMACHY	SCanning Imaging Absorption spetroMeter for Atmospheric CHartographY
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
ScaRaB	Scanner for Radiation Budget
SGP	Southern Great Plains
SIM	Spectral Irradiance Monitor
SIRN	Solar Irradiance Research Network
SOLSTICE	SOLar STellar InterComparison Experiment
SoRCE	Solar Radiation and Climate Experiment
SPARC	Stratospheric Processes and their Role in Climate
SNR	Signal to Noise Ratio
SRB	Surface Radiation Budget
SRF	Spectral Response Function
SBUV	Space shuttle SBUV
SSM/I	Special Sensor Microwave/Imager
SSM/T	Special Sensor Microwave/Temperature sounder
SSM/T-2	Special Sensor Microwave/Water Vapor sounder
SST	Sea Surface Temperature
SURFRAD	Surface Radiation Budget Network
SW	Short Wave
TES	Tropospheric Emissions Spectrometer
TMI	TRMM Microwave Instrument
TOA	Top of Atmosphere
TOAR	Top-Of-Atmosphere Reflectivity
TOMS	Total Ozone Mapping Spectrometer
TOZ	Total column Ozone
TRMM	Tropical Rainfall Measuring Mission
TSI	Total Solar Irradiance
TXR	Thermal Transfer Radiometer
UTH	Upper Troposphere Humidity
UV	UltraViolet
VIRS	Visible and Infrared Scanner
VIIRS	Visible/Infrared Imager/Radiometer Suite
VIS	Visible
WMO	World Meteorological Organization
WOUDC	World Ozone and Ultraviolet Data Center

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