THE GLOBAL SPACE-BASED INTER-CALIBRATION SYSTEM

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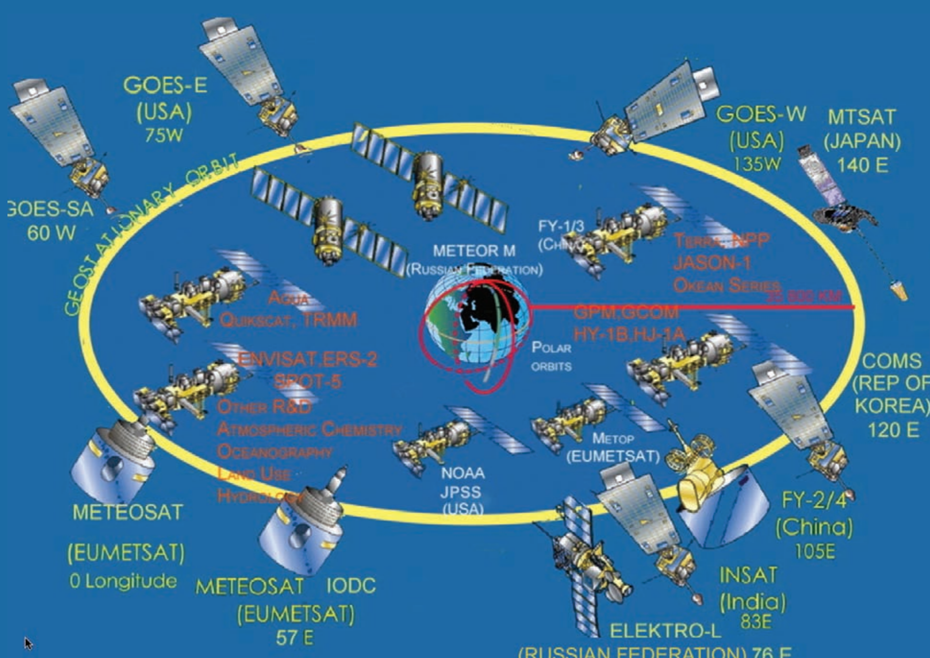
An international project will tie observations from operational low-earth-orbiting and geostationary environmental satellites to those from in-orbit sensors that serve as calibration standards.



The satellite component of the Global Observing System

Improved calibration of space-based Earth-observing instruments is a fundamental, urgent scientific need. There is an increasing demand for more accurate measurements and intercalibration of observations from different instruments in response to such issues as interoperability within the Global Earth Observation System of Systems (GEOSS), data assimilation in numerical weather prediction (NWP), climate change detection, and near-real-time operational applications. For example, as NWP models become more reliable, their appetite for more accurate data input steadily grows. As the requirements for monitoring global climate become clearer (Ohring et al. 2005)—temperature changes as tiny as a few tenths of a degree per decade, ▶

ozone trends as small as 1% decade^{-1}—the accuracy of the measurements becomes more critical.

Calibration is the process of quantitatively defining the satellite sensor responses to known signal inputs that are traceable to established standards [preferably the International System (SI) of Units]. This allows for the measurement of absolute radiances in Earth observations. By comparison, validation is the process of assessing, by independent means, the quality of the data products derived from the measured radiances. Calibrated radiances are the fundamental building blocks for all satellite products, including the radiances for data assimilation in NWP and fundamental climate data records. The quality of calibration directly affects the fidelity of satellite measurements as well as derived satellite products.

Calibration is required for the life cycle of the instrument. Prior to launch, instruments are calibrated in laboratories against known sources of radiant energy or other standards maintained at the national laboratories, such as the National Institute of Standards and Technology (NIST) in the United States. Prelaunch calibration is critical to instrument performance because it verifies the radiometric performance of onboard calibrators, determines filter in-band and out-of-band spectral response, detector linearity, stray light, instrument thermal response, and other performance attributes that are difficult to determine and correct postlaunch. Unfortunately, prelaunch calibrations may become invalid postlaunch because of suboptimal prelaunch characterization, changes during launch, and degradation on orbit.

Postlaunch calibration often relies on onboard calibration targets, such as blackbodies in the infrared and microwave and solar diffusers or lamps in the UV/visible/near infrared. For those instruments without onboard calibrators—for example, visible and near-infrared imagers on most operational satellites—changes from prelaunch calibration can be monitored by viewing relatively stable Earth targets, such as deserts, Antarctic plateau snow cover, deep convective clouds, the sun, moon, and stars. Also valuable to the process of instrument calibration are special calibration sites, such as those of the Department of Energy (DOE)'s Atmospheric Radiation Measurement program (ARM), aircraft underflight campaigns, highly accurate radiosonde and ozonesonde measurements, and other in situ databases.

Intercalibration of satellite instruments involves relating the measurements of one instrument to those of another with a stated uncertainty. Instruments can be intercalibrated when they are viewing the same scenes at the same times from the same viewing angles. Or, for satellite time series data in an archive, the overlapping records of two satellite instruments can be compared after a number of effects, such as diurnal cycle, are taken into account. Intercalibration allows us to achieve relative consistency among satellites and remove biases between them. However, intercalibration without traceability to stable standards is subject to drift over time, and such drifts may obscure the climate trend over several decades. Therefore, calibration traceability to the SI units is highly desirable.

To meet these requirements for improved calibration and intercalibration of satellite sensors—in particular, operational instruments—the World Meteorological Organization (WMO) and the Coordination Group for Meteorological Satellites (CGMS) initiated the Global Space-based Inter-Calibration System (GSICS) in 2005. The overarching goal of GSICS is to ensure the comparability of satellite measurements taken at different times and locations by different instruments operated by different satellite agencies, and then tie the measurements to SI units. The operational objectives of GSICS are as follows:

- Ensure that instruments meet specification, prelaunch tests are traceable to SI standards, and the on-orbit satellite instrument observations are well calibrated by means of careful analysis of

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instrument performance, satellite intercalibration, and validation with reference sites
- Improve the use of space-based global observations for weather, climate, and environmental applications through the intercalibration of the space component of the WMO's Global Observing System (GOS) and GEOSS
- Provide for the ability to recalibrate archived satellite data using GSICS procedures to enable the creation of stable long-term climate datasets

The GSICS program builds on concepts pioneered in the World Climate Research Programme's (WCRP's) International Satellite Climatology Project (ISCCP) (Brest et al. 1997) and by many individual research groups. Efforts to intercalibrate geostationary and polar-orbiting satellite radiance observations have been pursued for many years. Menzel et al. (1981), for example, used *National Oceanic and Atmospheric Administration 6* (*NOAA-6*) High-Resolution Infrared Radiation Sounder (HIRS) observations to assess the radiometric calibration of the Visible Infrared Spin-Scan Radiometer Atmospheric Sounder (VAS), the first sounding instrument in geostationary orbit, in the early 1980s. Several research groups within universities and government agencies have subsequently performed various satellite radiance and reflectance intercalibrations on a routine basis. The need to provide timely cloud and radiation properties to the DOE ARM necessitated satellite intercalibrations (Minnis et al. 1995) that evolved into an ongoing intercalibration program at the National Aeronautics and Space Administration (NASA)'s Langley Research Center (LaRC) to support near-real-time satellite cloud property retrievals (Minnis et al. 2008) and the NASA Clouds and the Earth's Radiant Energy System (CERES) program (Minnis et al. 2002a,b; Doelling et al. 2006). Efforts to intercalibrate the operational satellites were further stimulated by the 1997 CGMS action for its member agencies to commence satellite intercalibration activities. This led to a number of studies at individual agencies (see, e.g., König et al. 1999; Cao and Heidinger 2002; Gunshor et al. 2004).

Agencies currently participating in the GSICS program include the Centre National d'Études Spatiales (CNES), China Meteorological Administration (CMA), European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), Japan Meteorological Agency (JMA), Korea Meteorological Administration (KMA), NASA, NIST, and NOAA.

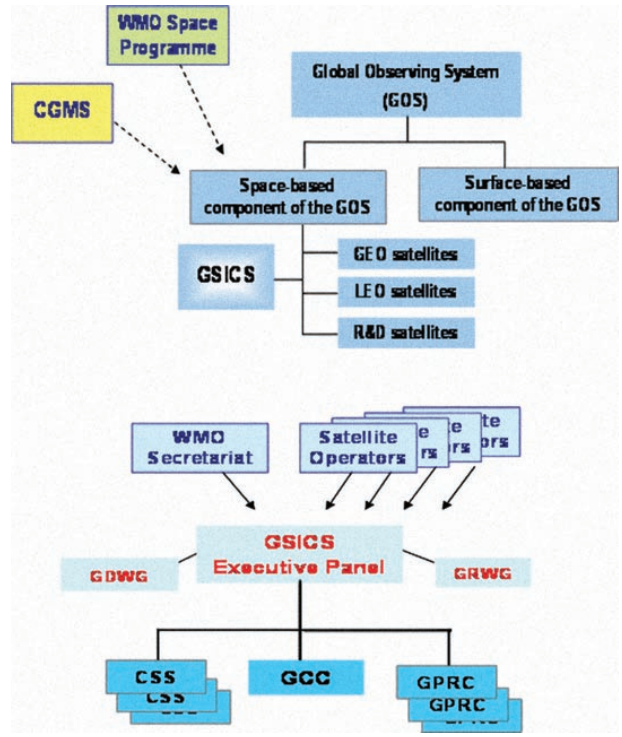

Fig. 1. GSICS within the (top) WMO GOS and (bottom) organizational structure of GSICS.

COMPONENTS OF GSICS. The major components of GSICS are the GSICS Executive Panel, GSICS Coordination Center (GCC), GSICS Processing and Research Centers (GPRCs), GSICS Research Working Group (GRWG), GSICS Data Working Group (GDWG), and Calibration Support Segments (CSSs). The relationships of GSICS with the WMO Global Observing System and the GSICS organizational structure are shown in Fig. 1.

The GSICS Executive Panel is appointed by the WMO and consists of representatives of the participating agencies. It sets strategic priorities and monitors and evaluates the evolution and operations of the GSICS.

The GCC is located at the NOAA National Environmental Satellite, Data, and Information Service (NESDIS) facility in Maryland. The GCC coordinates the development of methodologies, technical specifications, and criteria for satellite instrument intercomparisons and associated software tools; data exchange formats and reporting times; and archiving strategies for collocated data and intercalibration results. For this purpose, GCC personnel work closely with scientists and data managers from the GRWG and GDWG. The GCC is also the main communication hub for GSICS. The GCC archives, distributes, and responds to requests for GSICS calibration information, including all relevant data and results obtained by the program. The GCC also designs and hosts the central GSICS Web site and a collaborative data server, and it is responsible for publishing the newsletter *GSICS Quarterly*.

The GSICS Processing and Research Centers, one at each operational satellite agency, are responsible for prelaunch calibration, intercalibration of their own agency's sensors with other satellite sensors, and support of research activities.

The GSICS Research and Data Working Groups coordinate, plan, and implement GSICS research and data management activities, developing methodologies and technical specifications for satellite instrument intercomparisons, formats and specifications for data archives, and associated software tools. The GRWG consists of scientists and the GDWG of data management experts, representing the participating agencies.

GSICS Calibration Support Segments consist of ongoing or collaborative activities at various institutions that GSICS leverages to enhance its program. These calibration support activities are conducted at satellite agencies, national standards laboratories, major NWP centers, national research laboratories, and universities, and include the following:

- Performing in situ observations at Earth reference targets (e.g., stable desert and perpetual snow areas), long-term specially equipped ground sites, and special aircraft and field campaigns to monitor satellite instrument performance
- Observing stable extraterrestrial calibration sources—such as the sun, moon, and stars—for on-orbit monitoring of instrument calibration
- Comparing radiances computed from NWP analyses of atmospheric conditions with those observed by satellite instruments
- Analyzing the results of GSICS intercalibrations to diagnose why sensor calibrations change in orbit
- Championing and supporting benchmark missions of the highest accuracy to serve as calibration standards in space for postlaunch calibration of the operational sensors
- Developing calibration "best practices" procedures
- Supporting efforts to make satellite instruments SI traceable

IMPLEMENTATION. GSICS is initially focusing on intercalibrating current operational satellite data. Three initial scientific priorities have been identified: the development of a GSICS virtual library, on-orbit intercalibration and verification of operational satellite observations, and development of satellite instrument calibration science and standards (WMO 2006).

The GSICS virtual library will contain data and model output associated with satellite instrument calibration and validation opportunities and analyses, product documentation, meeting announcements and minutes, and general program information. It will be logically structured, easy to use, and readily accessible to GSICS partners and the user community.

The overarching goal of GSICS is to achieve intercomparability of operational satellites. The GSICS program has selected reference sensors that have relatively high spectral resolution and accuracy to serve as on-orbit calibration standards for operational satellite instruments. These include the NASA Earth Observing System (EOS) *Aqua* Atmospheric Infrared Sounder (AIRS) and the EUMETSAT–CNES Meteorological Operation (MetOp) Infrared Atmospheric Sounding Interferometer (IASI) as references for IR instruments, and the NASA EOS Moderate Resolution Imaging Spectroradiometer (MODIS) as a reference for solar reflectance instruments. The IASI is of particular value, since it is an operational instrument and copies will be flown on *MetOp-B* and *MetOp-C*. When true benchmark instruments [e.g., Climate Absolute Radiance and Refractivity Observatory (CLARREO); Anderson et al. 2008] that cover Earth's emission and reflectance spectrum are launched into space, they can be used as the reference instruments for GSICS intercalibrations. Currently, GSICS performs low-earth-orbit (LEO)/geostationary earth-orbit (GEO), and LEO/LEO, instrumental measurements and conducts an ongoing program to develop and implement intercomparison methodologies. Each GPRC is performing intercalibration of its own geostationary satellite against reference LEO instruments using a common algorithm baseline. Partnerships are being formed with institutions to carry out satellite radiance validation and calibration based on lunar and stellar irradiance measurements; observations of stable surface areas, such as deserts; field site and airborne instrument in situ measurements; and radiative transfer modeling based on NWP model and in situ sounding data.

GSICS will also advance satellite instrument calibration science and standards by developing calibration and intercalibration best practices; collaborating with national standards laboratories to perform calibration tests of instrument components to develop a model for sensor performance; conducting end-to-end system-level measurements based on SI-traceable standards to validate the sensor performance model; creating technology transportable to sensor test sites to perform SI-traceable measurements; and radiometric characterizing of extraterrestrial sources—such as the sun, moon and stars—as stable sources of radiant energy to calibrate or monitor the stability of on-orbit optical sensors. For example, NIST has prepared a report for GSICS on best practices for optical sensors (Datla et al. 2009).

THE GSICS CORRECTION. GSICS will provide coefficients to the user community to adjust satellite observations to a common reference. The first major deliverable is the GSICS correction algorithm for the geostationary infrared imagers. The correction adjusts the geostationary data to be consistent with IASI and AIRS. The user applies the correction to the original data using GSICS-supplied software and coefficients. The coefficients will be a function of channel and time and will have the form $R_C = a_0 + a_1 R_O$, where R_C is the corrected radiance, a_0 and a_1 are the coefficients, and R_O is the observed radiance. The period used to determine the coefficients is one month, with much shorter times in cases of spikes in the geostationary observations. The coefficients for the geostationary imagers are derived from their collocations with IASI/AIRS.

GSICS will work with the user community to integrate the GSICS correction into weather and climate operations, and research projects, and it will assess the impacts of the improved observations. The detailed specifications of GSICS deliverables will evolve in consultation with representative user groups.

EXPECTED BENEFITS. The improved calibration and intercalibration of operational satellite sensors resulting from GSICS is designed to lead to more accurate sensor observations and instrument-to-instrument measurement intercomparability. Benefits will be realized in applications of satellite data to weather prediction, assessing global climate change, testing climate model predictions, near-real-time operational applications, and achieving the societal goals of the GEOSS.

The WMO plans to make use of the GSICS results at its recently initiated global network of Sustained, Co-Ordinated Processing of Environmental Satellite Data for Climate Monitoring (SCOPE-CM) as shown in Fig. 2. The overall objective of these SCOPE-CM centers is the continuous and sustained provision of high-quality essential climate variables satellite products on a global scale, which are specified in the Global Climate Observing System (GCOS) Implementation Plan (WMO 2004).

EXAMPLES OF INITIAL RESULTS FROM GSICS. *LEO/GEO IR instrument calibrations.* Many GSICS members have contributed to the baseline algorithm for GSICS GEO/LEO IR instrument intercalibration, which uses the AIRS and IASI hyperspectral instruments as references (e.g., Wang et al. 2010). It incorporates the gap-filling algorithm developed by JMA (Tahara and Kato 2009) that is critical in using AIRS data. The algorithm collocates GEO and LEO data in time (within five minutes), viewing geometry (difference in the optical path of the two satellites is less than 1%) and space (accurate to both instruments' geolocation uncertainty). It then spatially averages the GEO pixels within each LEO pixel and spectrally convolves the LEO hyperspectral radiances with GEO's spectral response function (SRF). These results, as well as all the original measurements and ancillary data (e.g., collocation uniformity and relative azimuth angle) that may be used in the data selection step, are archived in network Common Data Form, version 4 (NetCDF 4) format. This algorithm has been implemented operationally at NOAA for Geostationary Operational Environmental Satellite (GOES) Imager IR data, at JMA for Multifunctional Transport Satellite (MTSAT) Imager IR data, and experimentally at KMA using the MTSAT in preparation for Korea's Communication, Ocean and Meteorological Satellite (COMS) program.

An example of the application of this method is shown in Fig. 3, which compares (top panel) the GOES 13.3-μm channel to both AIRS and IASI (Wang et al. 2010). The jumps in July 2008, January 2009, and April 2010 are due to a decontamination procedure that was applied to the GOES imager. Differences between AIRS and IASI, obtained by a double-differencing technique, with GOES as the transfer radiometer, are shown. The difference

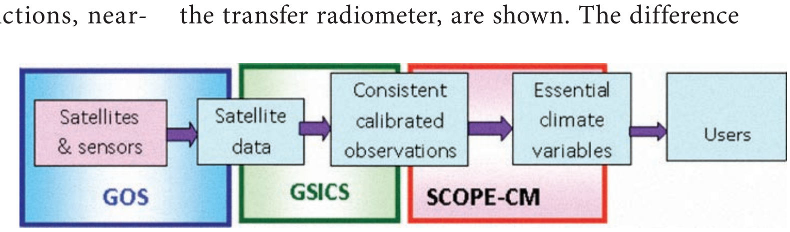

Fig. 2. The role of GSICS in the end-to-end process of creating satellite-based climate data records operationally by the WMO's SCOPE-CM program from observations of the satellite component of the GOS.

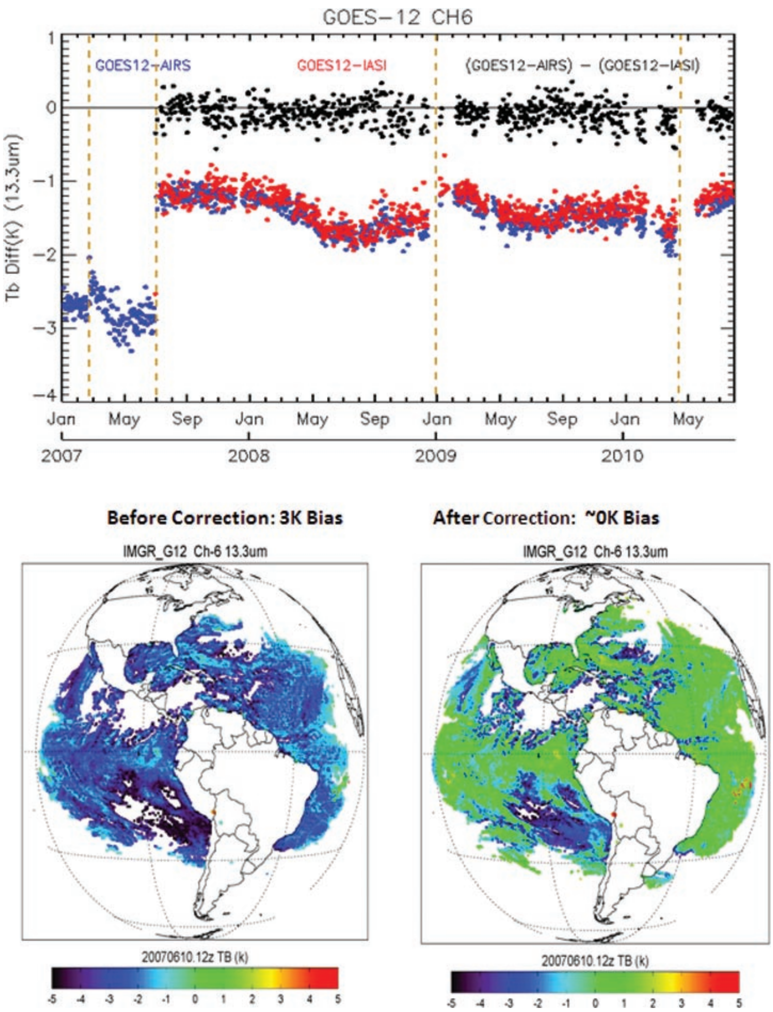

Fig. 3. (top) The time series of daytime BT differences between the *GOES-12* 13.3-μm channel and AIRS (red) and IASI (blue) from Jun 2007 to Aug 2010. The vertical dashed lines indicate the times of decontamination procedures applied to the GOES imager, which result in sudden bias changes. The black dots represent the double difference (difference between GOES and AIRS and GOES and IASI) and suggest excellent agreement between AIRS and IASI. (bottom) The difference between observed and calculated BTs for *GOES-12* 13.3-μm channel before and after the GSICS correction is applied. The GSICS correction is determined from the GOES–AIRS differences in (top).

between AIRS and IASI is small and stable despite the fact that their differences from GOES are large and variable. The bottom panel of Fig. 3 illustrates the elimination of the GOES bias error, resulting from the decontaminations by applying the GSICS correction procedure, which is based on the differences between GOES and AIRS shown in the top panel. The bottom panel shows the difference between observed brightness temperatures (BTs) and brightness temperatures computed using a radiative transfer model and the National Centers for Environmental Prediction (NCEP) analysis atmospheric state parameters for *GOES-12* channel 6, before and after the correction, respectively. The bias is reduced from 3 K to nearly zero, a significant improvement for both weather and climate users.

LEO/LEO microwave instrument calibrations. The results of applying the simultaneous conical overpass (SCO) method to the microwave observations of rain-free tropical ocean areas by a series of Special Sensor Microwave Imager (SSM/I) instruments on Defense Meteorological Satellite Program (DMSP) satellites since 1987 are shown in Fig. 4. Collocated SSM/I measurements from a pair of satellites are obtained when they simultaneously pass over a local area. The bias between the SCO pairs is characterized over various surface conditions, relative to the *F13*, which had the longest record. If there is no direct collocation between *F13* and a satellite, then a third satellite that intercepts with *F13* is used as a transfer radiometer. This cascading approach is applied for all SSM/I sensors from *F10*, *F11*, *F13*, *F14*, and *F-15* during 1992–2006. SSM/I measures the microwave radiance at four frequencies (19.35, 22.235, 37, and 85.5 GHz) with dual polarization (except for 22.235 GHz, which has only vertical polarization). Figure 4 compares the time series of rain-free monthly-mean brightness temperature (T_b) over the tropical oceanic (20°S–20°N) areas before and after intersensor calibration for three of the SSM/I channels. The graphs clearly demonstrate that the intercalibration reduces the sensor-to-sensor biases and results in more consistent trends in brightness temperature.

As noted earlier, a key objective of GSICS is to apply the improved calibrated radiances to derive important geophysical parameters for monitoring climate change. For example, the total precipitable water (TPW) can be obtained from the intercalibrated brightness temperatures of the three channels shown in Fig. 4 using the following equation (Alishouse et al. 1990):

$$\mathrm{TPW} = 232.894 - 0.149T_b(19\mathrm{V}) - 1.829T_b(22\mathrm{V}) - 0.370T_b(37\mathrm{V}) + 0.0062[T_b(22\mathrm{V})]^2,$$

where T_b(19V), T_b(37V), and T_b(22V) are the microwave brightness temperatures for the vertical polarization 19.35-, 37-, and 22.235-GHz channels, respectively. We compute a decadal trend for rain-free tropical oceans of 0.63 mm decade^{-1}, or about 1.4% decade^{-1}. This trend is consistent with other independent TPW trends derived from the SSM/I observations (Mears et al. 2007). It should be noted that without the SSM/I intersensor adjustments, the computed trend is an erroneous 1.35 mm decade^{-1}—a factor of 2 greater than the derived trend—demonstrating the importance of intercalibration.

DISSEMINATION OF CALIBRATION RESULTS. The main GSICS data and information storage and distribution facility is located at the GCC at NOAA. The GCC is responsible for maintaining pathways of information communication and data transfer among the GSICS partners and the user community. It serves as a one-stop source for information on all satellite instruments. The GCC provides easy, near-real-time access to calibration information via its Web site. Collaborative data servers to be hosted by NOAA and EUMETSAT are to house the data produced by GSICS members. From time to time, the GCC in consultation with GPRCs will issue special assessment reports of instrument trends or other results of general interest. The GCC will also communicate with satellite agencies GSICS guidance on satellite instrument calibration. To inform and unify the satellite calibration and user community, the GCC publishes and distributes an electronic GSICS quarterly newsletter with news and notes on satellite calibration activities throughout the world.(The GSICS Web site is located at http://gsics.wmo.int/). Future plans of the GCC are to expand the storage and dissemination of GSICS data and information by establishing a GSICS virtual library. The proposed virtual library is envisioned to have many services similar to the U.K.'s National Physical Laboratory's implementation of Second Life and the Virtual Center for Decadal Climate Variability (Mehta et al. 2006).

SUMMARY AND FUTURE PLANS. The Global Space-based Inter-Calibration System (GSICS) is off to a good start toward achieving its overarching goal of ensuring the comparability of satellite measurements taken at different times, by different instruments, operated by different agencies, and tying these measurements to the International System (SI) of Units. Eight international agencies are already participating in this program of the WMO and the Coordination Group for Meteorological Satellites.

An initial GSICS strategy has been the use of selected reference sensors that have relatively high spectral resolution and accuracy to serve as in-orbit calibration standards for operational satellite instruments. Reference instruments include the NASA EOS AIRS and the EUMETSAT–CNES MetOp IASI for IR sensors, and the NASA EOS

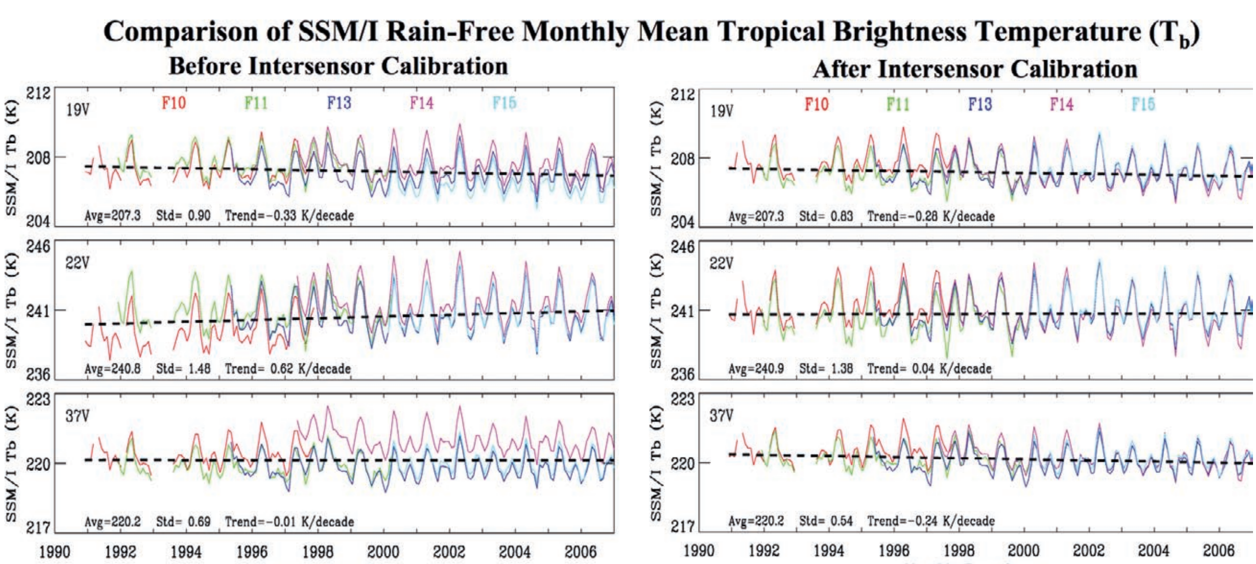

Fig. 4. The time series of the SSM/I T_b over tropical oceans at (top) 19V-, (middle) 22V-, and (bottom) 37V-GHz channels (left) before and (right) after intersensor calibration.

MODIS for solar reflectance measurements. Once benchmark instruments covering Earth's emission and reflectance spectrum—for example, Climate Absolute Radiance and Refractivity Observatory (CLARREO) (Anderson et al. 2008)—are in space, they can be used as the reference instruments for GSICS intercalibrations.

Future plans include establishing closer ties with the climate and NWP communities. GSICS plans to recalibrate historical instrument records and work with the climate community to generate climate data records. GSICS also intends to engage the NWP centers in the evaluation of the impact of improved satellite calibration on weather forecasts. In summary, the GSICS program will provide stable, intercalibrated, unbiased satellite observations that will improve weather prediction, facilitate the detection of climate change, permit the testing of climate model predictions, improve the near-real-time operational use of the data, and help the Global Earth Observation System of Systems (GEOSS) achieve its societal goals.

A follow-up article that will include the results of the GSICS program and their applications is planned.

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