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MONITORING CLIMATE CHANGE FROM GEOSTATIONARY SATELLITES

Herbert Jacobowitz *
Short and Associates, Inc., Silver Spring, MD

Gerald J. Dittberner and James J. Gurka
NOAA/NESDIS Office of Systems Development, Silver Spring, MD

1. WHY MONITOR CLIMATE CHANGE FROM GEOSTATIONARY SATELLITES?

Geostationary satellites have the unique capability to measure the same location at frequent intervals of time (e.g. every 15 minutes). In comparison, satellites in polar orbits can measure the same location only at 12-hour intervals. Individual satellites in polar orbits are able to provide nearly global coverage in contrast to the continental scale coverage provided by a single satellite in a geosynchronous orbit. However, the frequency of the geostationary measurements is necessary to observe the important diurnal variations of the atmospheric and surface boundary layer, as well as cloud systems and precipitation. Near global coverage, similar to that of polar orbiting satellites, could be attained by a system of four or five geostationary satellites. This number of satellites already spans the globe.

An example of the importance of frequent measurements for climate can be understood by considering the absorption of solar radiation at the surface, which has both strong diurnal and seasonal cycles. Climate forcing occurs when solar heating at the surface is transferred from the surface through the atmospheric boundary layer by a number of processes. Some of these processes are also modulated diurnally and seasonally, such as the transport of convective heat and moisture and the influence of clouds on the outgoing fluxes. One must, therefore, make observations not only at seasonal scales, but at diurnal scales as well.

Characterization of the seasonal cycle is crucial to an understanding of climate, but having a better knowledge of the diurnal cycle often substantially improves the characterization of the seasonal cycle. This can be understood by imagining a situation where measurements of a parameter are made at nearly the same time each day of the year by a sun-synchronous polar orbiter. If the diurnal variation of this parameter significantly changes throughout the year, the seasonal cycle derived from the fixed-time observations would be inaccurate. Averaging measurements from a number of polar orbiters will only reduce the error, but not eliminate it.

Another major advantage of a geostationary satellite is based on its fixed location in relation to the Earth. Each viewed spot on the Earth is observed from the same single angle of view at all times, in contrast to that for a polar orbiter, where the viewed spot is observed from different angles of view as the earth rotates beneath the satellite. This advantage will yield a more accurate measurement of the diurnal variation of a parameter since one does not have to make any adjustment to a changing viewing angle. The zenith angle of the sun incident upon the spot is the only angle that varies over the day.

2. HISTORY OF CLIMATE MONITORING FROM GEOSTATIONARY SATELLITES

Operational geostationary satellites have already made a considerable contribution to data products for climate. Some of these products include snow cover, surface insolation, clouds, and precipitation, as well as vertical moisture and temperature profiles. The Global Energy and Water Cycle Experiment (GEWEX) project has extensively utilized NOAA’s Geostationary Operational Environmental Satellite (GOES) system (GOES Users Conference, NOAA, 2002). GEWEX was initiated by the World Climate Research Programme (WCRP) to observe, understand and model the hydrological cycle and energy fluxes in the atmosphere, land surface and in the upper oceans. Their goal is the prediction of global and regional climate change.

Geostationary satellites worldwide have also been used extensively (GCOS, 2001) to gather data required by the International Satellite Cloud Climatology Project (ISCCP), the Surface Radiation Budget (SRB) Project, and the Global Precipitation Climatology Project (GPCP). These geostationary satellites have all yielded global data sets over a span of 20 years. The data are being used to address several key questions on climate variations raised by the Intergovernmental Panel on Climate Change (IPCC), (Houghton, et al, 2001). While earlier GOES satellites provided monthly precipitation data on a 2.5x2.5 degree grid, the latest GOES satellites are able to provide higher resolution, daily precipitation data on a 0.5x0.5 degree grid.

3. WHAT DRIVES THE REQUIREMENTS?

Requirements for the instruments that make these important climate measurements must be determined carefully. Analysis of long-term climate change is made difficult by the small signals involved. For instance,

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* *Corresponding author address*: Herbert Jacobowitz, Short and Associates, Inc., 2308 Hidden Valley Lane, Silver Spring, MD 20904-5270; e-mail: herbjacob@comcast.net.

global temperature changes of tenths of a degree Celsius per decade, ozone changes of a percent per decade, or even variations in the solar irradiance of a tenth of a percent per decade are typical of the signals that must be extracted from long-time series. The ability to measure these signals demands that satellite instruments be developed with more accurate calibration. The long-term stability of the measurements must be even more stringent, since it is the changes in the climate signals over a longer period, such as a decade, that must be identified. If the stability is insufficient, scientists will be unable to identify real climate change.

A workshop on calibration for climate change (Ohring, 2003) attempted to answer how stable the measurements need to be by looking at climate model predictions and trends in the climate. Many climate change models simulate the doubling of carbon dioxide in 70 years by using a 1%/year increase in CO_2. The doubling of the CO_2 has been estimated to be a radiative forcing of the climate system of approximately 4 $W/m^{2,}$ which is about 0.6 W/m^2 per decade. This amount of forcing was then translated into the amount required by any given geophysical parameter to offset the forcing, so that no change in the climate signal due to the carbon dioxide doubling would be observed. For example, it was estimated that the global cloud fraction would have to change by 0.015/decade to offset the forcing. To ensure that one could measure this change, a signal-to-noise ratio of 5 to 1 would be required as suggested by Hansen et al., 1993. Therefore, a long-term stability of the global cloud fraction, equal to 0.003/decade or 1/5 of the offset, would be required.

For another example of the required stability, consider the global average surface albedo. Again, using the signal to noise ratio of 5 to 1 would require an equivalent radiative forcing of approximately 0.1 W/m^2/decade to mask the expected CO_2 forcing. Since one-quarter of the Earth is covered by land, and about half of that land is cloud free, this is equivalent to requiring a 0.8 W/m^2/decade change in the average land surface reflected flux. Assuming the daily averaged insolation is approximately 342 W/m^2, the resulting change in land albedo would have to be 0.002/decade. This change is approximately 1% of the global average land albedo. Therefore, the measurements of broadband solar energy reflected by the surface must have a long-term stability of approximately 1%/decade.

4. GENERAL REQUIREMENTS

As noted in this paper, most climate signals vary little over the long-term. However, even minor changes in signals can result in major climate changes. Therefore, it is imperative that the observing system be capable of maintaining a long-term stability when measuring these changes. In recognition of the unique problems involved with observing climate change from satellites, a number of general requirements are noted below based on the GCOS Second Adequacy Report (GCOS, 2003).

4.1 *Minimize Orbit Drift*

While this is an obvious goal for sunsynchronous polar satellites, it is also important for geostationary satellites. A drift in a geostationary orbit would result in a shift in the consistent angle of view for a given viewing region, offsetting a unique advantage of these satellites, as noted earlier. However, orbit drift is not a problem for the GOES satellites since periodic N-S and E-W maneuvers are performed to maintain the position of the satellite within a half-degree box (latitude and longitude).

4.2 *Maintain Some Satellite Overlap*

When a new satellite is launched, there must be a period when the data sets of both the previous and newly launched satellites are compared. These data sets must then be adjusted to maintain long-term continuity and data stability.

4.3 *Replace Prior to Failure*

It is essential to replace older satellites prior to failure to ensure sufficient satellite overlap. Since it is almost impossible to predict when a satellite will fail, GOES maintains an on-orbit spare, which can be activated within two days to provide images. Overlapping as mentioned above can easily be accomplished when the spare is activated for station keeping or system checks. This normally happens approximately once a year for about two to four weeks.

4.4 *Conduct a Thorough Pre-launch Characterization*

The accuracy, precision, and long-term stability of the instruments are of particular importance. In addition, any factors that could affect the measurement must be included in the characterization.

4.5 *Conduct Adequate On-board Calibration*

Calibration is not a one-time occurrence, but must be performed periodically. This is absolutely necessary for long-term climate observations. For accuracy to be demonstrable in flight, redundant systems are essential. Radiances must be calibrated and cross-calibrated among all geostationary satellites in operation. Demonstrable calibration against absolute standards is fundamental to climate science.

4.6 *Plan For Product Reprocessing*

Reprocessing must be an operational priority of climate products to remove spurious trends. Reprocessing may need to be performed a number of times.

4.7 *Ensure Access to Products*

There must be ready access to products, metadata, and raw data necessary for reprocessing.

4.8 *Continue Observations On Decommissioned Satellites*

Baseline instrument observations must be continued on decommissioned satellites. When satellites have completed their operational use, it is important to continue operating any instrument from which a climate product is generated as long as it is still working. This practice will yield extended mission data.

4.9 *Include In-situ Observations*

In-situ baseline observations will permit blending research and operational products.

4.10 *Monitor Network Performance*

Real-time monitoring of network performance will help to identify errors early and facilitate reanalysis.

5. SPECIFIC REQUIREMENTS

The table below lists those climate variables that are largely dependent upon geostationary observations. The variables have a diurnal component that can be adequately observed only from a geosynchronous orbit. The variables have been separated into those particular to the atmosphere, land, or ocean.

Table 1. Climate Variables Dependent on Geostationary Observations

Atmosphere	Aerosols, clouds, precipitation, ozone, earth radiation budget, trace gases, and temperature
Land	Temperature and surface radiation budget
Ocean	Sea surface temperature, sea surface height, ice surface temperature, and ocean color

6. THE NEXT GENERATION OF U.S. GEOSTATIONARY SATELLITES (GOES-R SERIES)

The GOES-R series of satellites have been in the planning stage since 1998, with the collection of preliminary requirements from selected high-priority operational users and scientific communities. These requirements, in turn, have been translated into preliminary instrument technical documents, while initial concept, trade, and cost studies and analyses have also been conducted. The expectation is that a final validated set of system requirements will be available approximately April 2005. It is estimated that the first satellite in the series will be launched approximately 2012 and that all the satellites in the series will be operational through 2025. The current GOES-I/M and planned GOES-N series only support mission requirements through 2012.

The GOES-R series is expected to yield valuable data that will increase our knowledge of climate processes, improve on our ability to monitor climate, and yield more accurate climate model predictions.

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