THE GEOSTATIONARY EARTH RADIATION BUDGET (GERB) EXPERIMENT: SCIENCE AND APPLICATIONS

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ABSTRACT

When the first Meteosat Second Generation satellite (MSG-1) was launched in August 2002, it carried an additional instrument, chosen through an Announcement of Opportunity. Named the Geostationary Earth Radiation Budget (GERB) experiment, this instrument will measure the long and shortwave components of the Earth's radiation budget for the first time from geostationary orbit. This vantage point permits much higher time sampling than is possible from polar orbiting spacecraft, allowing a number of rapidly varying climate processes (e.g. diurnal convection over Africa) to be resolved. GERB data, in combination with the Spinning Enhanced Visible and Infra Red Imager (SEVIRI) and earth radiation budget measurements from polar orbiting instruments will provide a new understanding of the climate system and allow models to be tested in new ways. This paper gives some background about the GERB instrument and data products, presents some of the results from the instrument calibration commissioning and initial data validation phases and provides an introduction to some of the studies that are planned for these unique data

1. INTRODUCTION

Understanding the processes that control the natural stability and variability of the climate system, and which dictate how human activities might modify the climate balance is one of the most difficult and challenging, yet critically important, scientific problems facing humankind today. The Earth's Radiation Budget (ERB) is the balance between the incoming energy from the sun and the outgoing reflected and scattered solar radiation plus the thermal infrared emission to space. Clouds, water vapour, atmospheric gases, aerosols and surface properties affect the radiation budget according to how they interact with the solar and terrestrial radiation streams. In turn, the input of energy at the surface affects the dynamics of the atmosphere and cloud formation.

Studies of the ERB have been carried out using satellite data for about three decades, but before GERB all such measurements have been made from satellites in low earth orbit (LEO). These data provide global coverage, but at the cost of temporal resolution, as these orbits allow the instruments to view a given location just once or twice a day. Being the first ERB instrument to be mounted on a geostationary satellite means that GERB can provide the first ever measurements of the variations in the ERB at shorter timescales. By measuring the reflected solar and emitted thermal energy from the Earth's disc below every 15 minutes, GERB data will give new insights into atmospheric processes which vary rapidly, such as clouds and aerosol events and the diurnal cycle. As well as contributing to our understanding and ability to model these individual processes, these data will provide a new opportunity to test the large scale climate models used to predict the Earth's climate for the future.

The GERB instruments mounted on the MSG series of spacecraft can provide almost continuous 15 minute coverage over much of Europe, Africa and the Atlantic ocean and parts of Asia, South America and the Indian Ocean. The region covered by MSG is of particular interest in understanding many important climate processes. It covers not only regions of deep continental convection which is a direct response to surface heating and is therefore strongly dependent on the diurnal cycle of solar insolation, but also maritime convection over the tropical oceans and the important area of stratocumulus over the South Atlantic. In addition these data will allow the impact of aerosols on the radiation budget to be studied, something that is difficult to capture with measurements from low Earth orbit (LEO) because of the sporadic nature of aerosol events. Of particular interest in this region are wind-blown dust from the Sahara and other arid regions, aerosols from biomass burning over tropical Africa and sulphate and other pollution aerosols from populated areas.

In addition to the study of the processes discussed above, GERB can be used in synergy with the SEVIRI sensor on MSG which has the same coverage and temporal sampling as GERB in a number of narrow wavebands. GERB data is also complementary to measurements from similar instruments mounted on LEO satellites, such as Clouds and the Earth's Radiant Energy System (CERES) instruments, which provide global coverage but rely on interpolation to compensate for the lower temporal resolution of their measurements. GERB data will also provide new ways of testing large scale climate models, allowing a single time step comparison for a large region, analysis of the diurnal cycle and the study of individual processes. The continuous temporal coverage will also provide ERB information for field studies, whether at the land surface or within the atmosphere.

GERB was first turned on in December 2002, since then a series of instrument commissioning tests have been made, in addition to normal observations of the Earth. After a brief description of the GERB instrument and data products, this paper summarises some results of the instrument commissioning tests and initial intercomparison between GERB and CERES measurements. It also introduces four studies which plan to use GERB data. Two of the studies concentrate on using GERB data to provide a better understanding of specific climate processes, in this case tropical convection and aerosol effects, the other two plan to use GERB data to test large scale forecasting and climate models.

2. INSTRUMENT CHARACTERISTICS AND DATA PRODUCTS

GERB is a broadband radiometer, measuring the outgoing energy emitted and reflected from the Earth atmosphere system in two wavebands. The total channel is sensitive to radiation from 0.32μm to beyond 100μm, a shortwave channel covering the range 0.32 to 4μm is obtained via the insertion of a quartz filter. A longwave measurement (from 4 to beyond 100μm) is derived by subtraction of the shortwave from the total measurement. Mounted on the MSG satellite, which is spin stabilised and rotates once every 0.6 s, GERB uses a 'de-spin' mirror to hold the image of the Earth stationary for 40 ms whilst it acquires its measurement of the outgoing energy. For each rotation, the de-spin mirror directs the energy from a thin strip of the Earth's disc onto an array of 256 detector pixels. On the subsequent rotation the time of data acquisition within the rotation is altered slightly so that the strip of the Earth observed is moved and over a series of 250 rotations a measurement of the full Earth disc is obtained. On each rotation the detectors also view the internal black body for calibration purposes and the response of the shortwave channel is monitored using the shortwave calibration solar integrating sphere. Figure 1 shows a schematic cutaway of the GERB instrument indicating some of the primary components, including the 'de-spin' mirror, the detector array, the quartz filter and internal black body and shortwave calibration monitor.

The detector array builds up a measurement of the Earth's disc as a series of strips observed over consecutive MSG rotations. It takes a little over two and half minutes to make a measurement for the full disc in one of its channels and obtain some space measurements for calibration; after this time the position of the quartz filter is swapped and a complementary measurement is made in the second channel. In this way GERB obtains a measure for the whole Earth disc in both a 'total' and 'shortwave' channel in a little over

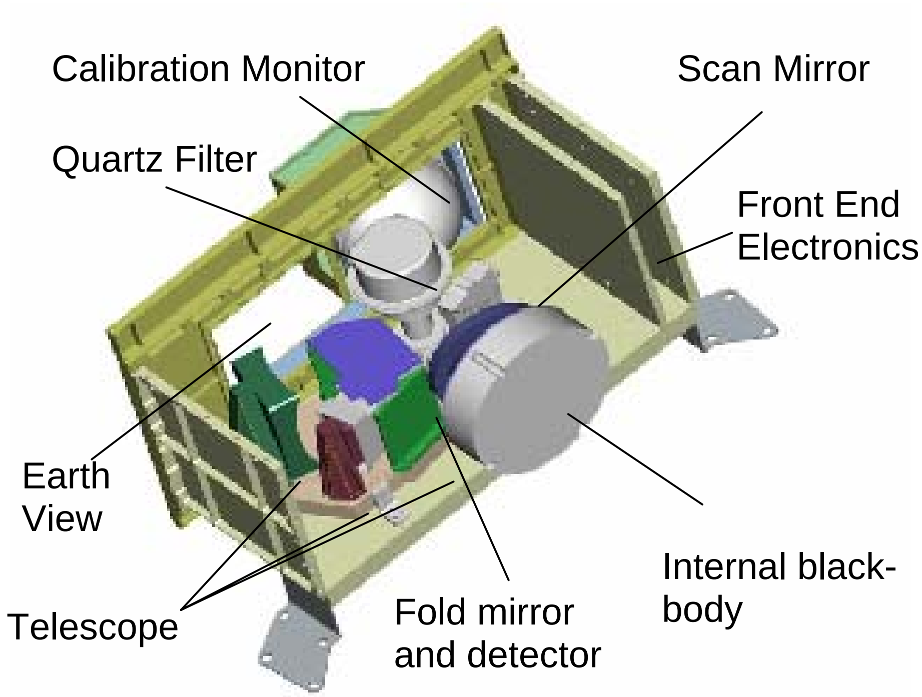

Figure 1. A cutaway of the GERB instrument showing the main instrument components.

five minutes. Three such scans are averaged together as part of the data processing, to improve signal to noise and provide optimal synergy with the 15 minute time resolution data from the SEVIRI instrument, which is the primary instrument on MSG and whose measurements are used in some of the GERB data processing.

For calibration the instrument gain is calculated every five minutes from measurements of the internal black body and deep space. These gains are used by the GERB ground segment processing system (GGSPS) at the Rutherford Appleton Laboratory[1] to convert the raw counts into filtered radiances. The images are then geolocated using information from the MSG satellite regarding its position, orientation and spin rate. The resulting geolocated filtered radiances in the two channels comprise the GERB level 1.5 Non-Averaged Non-Rectified Geolocated (NANRG) product shown in figure 2. Further processing at Royal Meteorological Institute of Belgium averages three such scans together, corrects for the instrument response, and, using a scene identification based on SEVIRI data and angular distribution models derived from CERES, derives the associated longwave and shortwave fluxes (Dewitte et al. 2000).

3. INSTRUMENT COMMISSIONING RESULTS

GERB made its first in orbit measurements on 12 December 2002. During the first year of operation, in addition to making normal measurements of the Earth, a series of instrument commissioning tests have been carried out to evaluate the instrument performance and stability. In addition initial intercomparisons between the radiances measured by GERB and those obtained by the similar CERES instrument have been made. Here we summarise some of the results of these studies.

Instrument noise

Under normal scanning conditions each scan of the Earth's disc contains several deep space columns, which are used for instrument calibration. One of the commissioning tests was to use a deep space scanning mode which considerably extends the amount of space data acquired during each scan. These data allow the stability of the instrument gain to be evaluated under conditions of varying internal black body temperature and can also be used to determine the instrument noise level. An analysis was made of the distribution of instrument gain calculated for each deep space column for 12 hours worth of deep space data for each of the GERB pixels. Although the gain is calculated every five minutes, so gain stability over a

[1] After further validation the GERB data will be made available at the GGSPS website: http://ggsps.rl.ac.uk

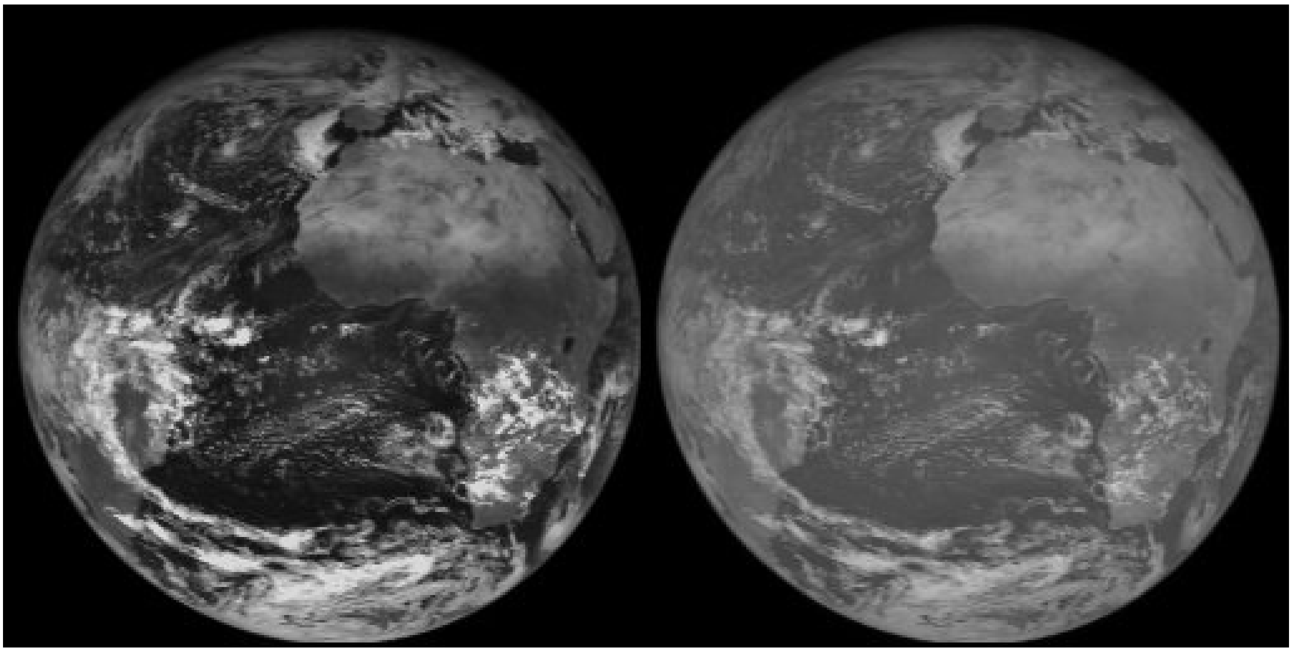

Figure 2. Two out of the six scans contained within the level 1.5 NANRG product. The left hand image is for the shortwave channel and the right hand image from the total channel for 1st Feb 2003 12:55 GMT.

twelve hour period is not a requirement for accurate calibration, in practice it is found that the gain is stable over this time. The spread of these distributions can, therefore, be considered indicative of the instrument noise level. For most GERB pixels, the distributions are relatively narrow and sharply peaked with standard deviations around 0.3%. One GERB pixel was found to have a noise level three times this value and one other pixel shows no usable signal, effects which will be flagged within the data. These distributions are derived from single column measurements, whilst in practice the gain for each scan is averaged over all space columns (at least 15), and the final GERB data products are the average of three scans. These results show that the noise on the filtered radiances are well within the specified requirements.

Short wave calibration monitoring

A known issue with using a quartz filter on a space mission is deterioration of the filter transmission due to extended exposure to solar radiation. Any degradation of the GERB quartz filter is monitored by the use of a solar integrating sphere (IS). Initial characterisation of the reflective properties of the IS in flight is necessary to determine the optimal timing for illumination of the sphere. In order to do this, the response of the IS to solar input over the daily cycle was measured as part of the commissioning activities. Routine monitoring of the quartz filter consists of measurements made at points throughout the year when the illumination conditions are expected to be the same, *i.e.* at constant relative IS-solar angle. Three such measurements have been made in this series to date. Results so far have shown that the sphere is thermally stable during this test, which is a necessary condition for its use as a calibration source. This is an ongoing calibration mode and measurements for the same angular conditions (i.e. time of year) will be compared to provide monitoring of the shortwave response of the instrument. The calibration parameters will be adjusted to account for any significant change in the filter response.

Evaluation of the instrument pointing accuracy and point spread function

The instrument point spread function (PSF) is measured on the ground as part of the instrument ground calibration and characterisation. However, as it is not possible to replicate all the in orbit conditions the instrument experiences, most notably the 18g force that it is under on the rapidly rotating MSG spacecraft, some modelling must also be employed to derive an in flight PSF. For this reason part of the commissioning activities were aimed at validating the PSF, to validate the model and ensure that no optical distortion had occurred since the pre-launch characterisation. Four different measurements have been made to date, each consisting of fine scanning modes which increment the GERB pixel array only a fraction of the normal step between consecutive rotations. The tests performed include 24 hours of full earth disc measurements at one fifth of the normal GERB column spacing, daylight scans of the Western coast of Africa at one eighteenth column spacing and 3 days of scans of the Earth’s limb at one twenty seventh column spacing.

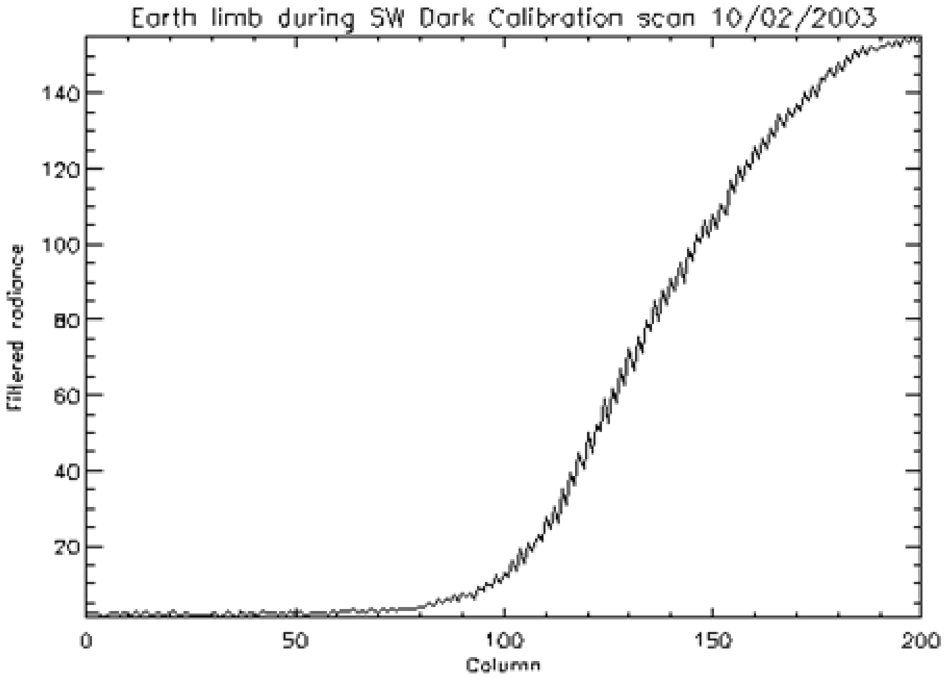

Figure 3. Filtered total channel radiance for the Earth limb scan, each column in this scan is 1/27th of the normal GERB column spacing

Full analysis of these data requires the availability of SEVIRI data for these periods and is therefore still in progress. However, analysis of the Earth limb scan has allowed identification of a difference in the pointing between the two sides of the GERB de-spin mirror. Figure 3 shows the observed filtered radiance in the total channel for the Earth limb scan. The saw tooth pattern seen in this plot is due to alternate sides of the de-spin mirror pointing at slightly different angles because the two sides are slightly non-parallel, resulting in uneven column spacing. Analysis of these data has shown that the difference in pointing between the two sides of the mirror is 0.1 of a normal GERB column spacing. The on-board software can compensate for this difference, by adjusting the time at which the Earth data is acquired according to which side of the mirror is being used. This correction was applied and the GERB pointing accuracy is now well within the 0.1 pixel accuracy required.

Intercomparison of GERB and CERES radiances

The CERES instruments are a series of broad-band radiometers, similar to GERB, mounted on LEO satellites. Unfiltered radiances from the GERB and CERES instrument for co-angular observations from the CERES FM2 instrument, mounted on the TERRA satellite, have been compared as part of the commissioning studies. Initial analysis of these results show that the unfiltered radiances from the two instruments have a mean agreement within the expected accuracy of the measurements. Further results from the intercomparison can be found in the paper by Dewitte et al. (2003) within this proceedings.

4. PLANNED SCIENCE STUDIES

In this section we outline some plans for the use of GERB data which will lead to a better understanding of various climate processes and our ability to accurately model the climate system.

Radiative forcing of tropical convection

Monthly mean maps of net cloud radiative forcing (CRF) from the ERBE mission (Ramanathan et al, 1989) revealed net CRF close to zero (within ±10Wm^{-2}) in the convectively disturbed regions of the tropics, indicating near cancellation between the large longwave and shortwave forcings found in these regions. It has been debated whether this is simply a coincidence due to the height of the tropical tropopause (and hence of convective cloud) and typical anvil cloud albedos (Kiehl 1994) or whether the cancellation is in fact a property of the ensemble of cloud types associated with convection, and indicates the existence of a feedback process influencing the distribution of cloud-types (Hartmann et al, 2001)

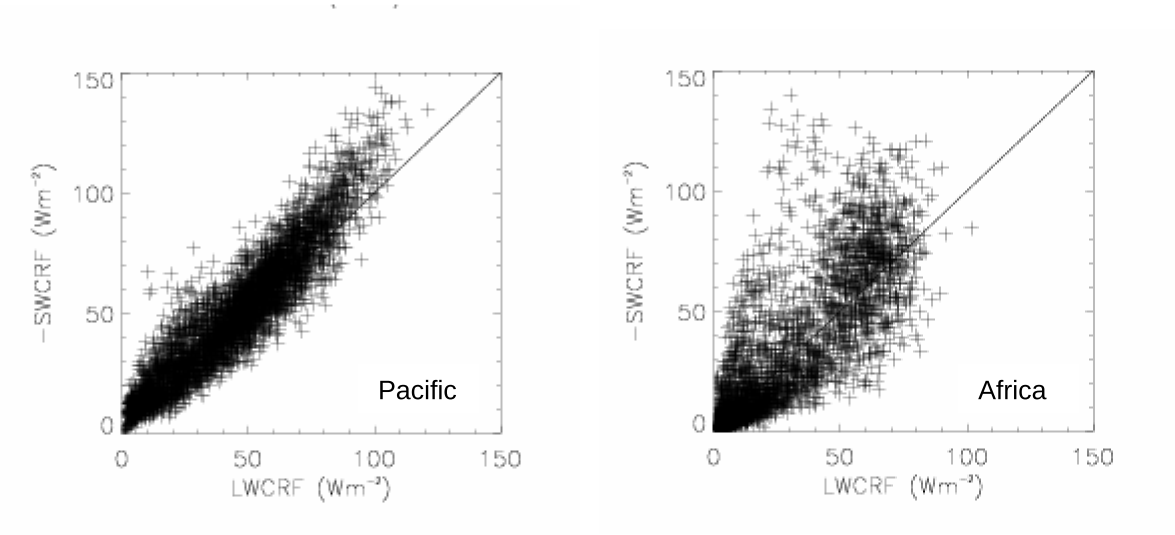

Figure 4. Scatter-plots of grid-box scale (2.5 x 2.5^o) LW and SWCRF for the tropical western Pacific (20S-20N, 110-180E) and for African land regions within 30S-20N, 30W-50E, based on ERBE-like data (ES-9, Edition 2) from CERES on the TERRA satellite

This cancellation has been assumed to occur for all tropical convective regions, although limited studies exist to confirm this. Figure 4 shows a scatter plot of the longwave and shortwave cloud radiative forcing (LWCRF and SWCRF respectively) derived from monthly mean CERES data for two regions of tropical convection. It is clear from this figure that the proportionality between the longwave and shortwave CRF is weaker over Africa than the Pacific, and substantial departures from cancellation occur. Part of this additional spread may result from variability in the surface type over the Africa land region, and part to the influence of non-convective cloud.

Monthly mean data average together the radiative effects of all clouds occurring within a grid-box during the course of a month, and hence the forcing quantities calculated are not necessarily representative of the cloud type of interest. To separate the radiative effects of convective clouds from other cloud occurring in the region requires the use of radiation budget data which resolve the individual cloud systems, and therefore requires sampling that is more frequent than the lifetimes of these clouds. The new data from the GERB instrument can provide such sampling of the radiation budget for the first time. By combining fluxes from GERB with a scene and cloud type identification from SEVIRI, it will be possible to separate the radiative effects of particular cloud regimes, and hence to make more accurate estimates of the cloud forcing due to convective clouds over the African region at monthly timescales, as well as enabling the study of the radiative effects at higher timescales. Observing the radiative effects of individual convective systems over their lifetime should help to confirm or refute the validity of proposed mechanisms for cancellation. If a feedback process such as that proposed by Hartmann et al. (2001) exists, it would be expected to act at the timescales at which convective systems develop. Observations from GERB will help determine if this is indeed the case and so allow the validity of such proposals to be tested, and lead to a greater understanding of these processes.

Studying the radiative properties of aerosol

The MSG field of view is a particularly good test bed for studying the interaction between aerosols and the climate system. Savanna burning over Africa is estimated to release 0.7 GT carbon per year, comprising around 20 % of the total global biomass burning. Although monthly mean climatologies of aerosol optical depth do exist for the region these are based on data from polar orbiting platforms and therefore suffer from the poor diurnal sampling typical of this orbit. Detailed investigations of the optical properties of biomass burning aerosols performed using ground based measurements (Eck *et al*., 2001) have indicated a large diurnal variability in the derived aerosol optical depth (AOD). GERB data will provide the first opportunity to measure the effect this variability has on the ERB over the large region that these aerosols events can cover.

In addition to biomass burning aerosols, Africa is also a rich source of mineral dust. Dust plumes are seen regularly in satellite imagery extending off the west coast of Africa (Figure 5), and can also strongly affect conditions in the Mediterranean (e.g. Ozsoy *et al*., 2001). Regionally, increased dust loading is believed to be strongly linked to the reduction in Sahel precipitation seen over recent decades providing a possible feedback mechanism between surface and atmospheric processes (e.g. Nicholson, 2000), and dust layers

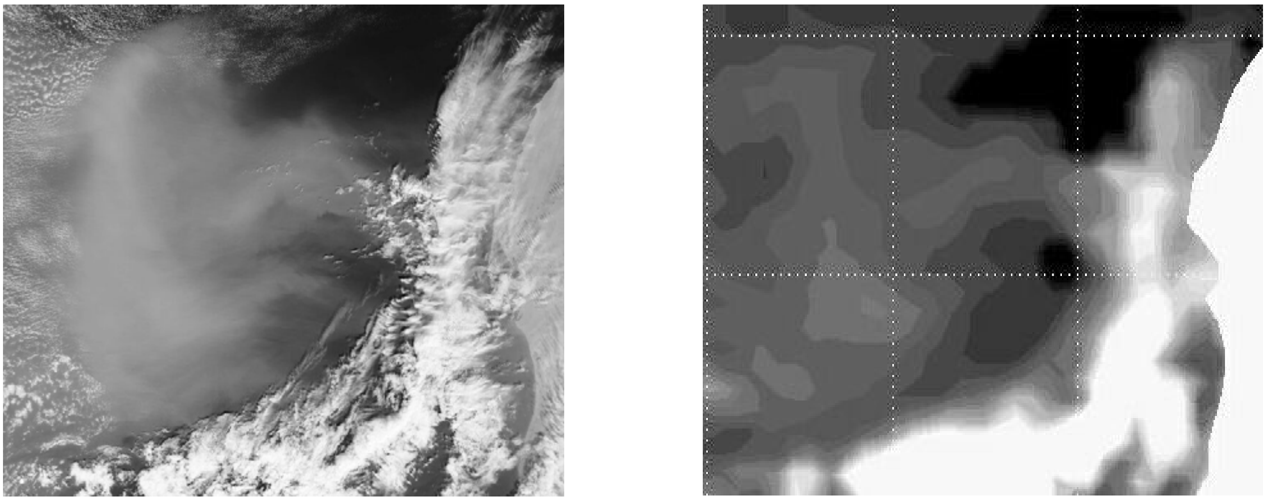

Figure 5. Left hand panel shows a MODIS image of a Saharan dust event off the coast of Senegal on 27/01/03 at 12:15 GMT. The right hand panel shows the shortwave reflected flux for the region as measured by GERB for the same time.

may also play a role in determining the strength of the African Easterly Jet and easterly wave generation (e.g. Chang, 1993). More locally, dust storms can reduce the visibility to a matter of meters. The duration of such storms is of the order days, and the temporal variability over this period is strongly dependent on the proximity to the dust source (N'Tchayi Mbourou *et al*., 1997).

The synergy of GERB and SEVIRI thus provides an ideal opportunity to investigate aerosol radiative forcing. The spectral information available from SEVIRI allows the identification of aerosol type and optical depth (e.g. Watts et al, 2000), whilst contemporaneous GERB measurements can be used to characterise the direct impact of these aerosols on the radiation field. With additional in-situ information the high temporal resolution of both instruments should also provide exciting opportunities to probe the indirect role of aerosols in modifying the atmospheric state, particularly cloud fields.

Climate model validation

The eventual long time series of radiation budget measurements from the succession of GERB instruments will be a valuable resource for evaluating the performance of climate models. GERB data will be used to assess the top-of-atmosphere radiation budget climatology, but will also enable a model's representation of the temporal variability of the radiation budget to be examined in a manner that has not previously been possible.

Data from the Earth Radiation Budget Experiment have been used extensively at the Hadley Centre and by the wider climate modelling community. Figure 6 shows a comparison of the reflected shortwave (RSW) and outgoing longwave (OLR) radiation from ERBE with a recent version of the Hadley Centre climate model (HadAM4) for the June, July, August (JJA) season. It is clear that the model produces a reliable representation of the major features of the radiation budget over this region. The comparison also identifies deficiencies in the simulation. For example, the underestimate of RSW off the west coast of southern Africa is due to a lack of marine stratocumulus cloud in the model, while the OLR field suggests that convection is too weak over continental Africa and too strong over the Atlantic ITCZ.

Recent studies (Allan et al 2002; Ringer and Allan 2003; Williams et al 2003) have demonstrated the benefits of combining satellite-derived radiation budget and cloud data sets with reanalyses to evaluate climate model performance. Figure 6 also shows a comparison of the 500 hPa vertical velocity from the new ECMWF reanalyses (ERA40) with the Hadley Centre model for the same period. There is clearly a close correspondance with features in the radiation budget fields and this can be exploited in order to assess the model cloud and radiation budget fields in terms of 'dynamical regimes'. Such techniques are particularly useful for assessing the model's physical parametrizations.

These studies are currently being developed and extended and will eventually make use of GERB data as it becomes available.

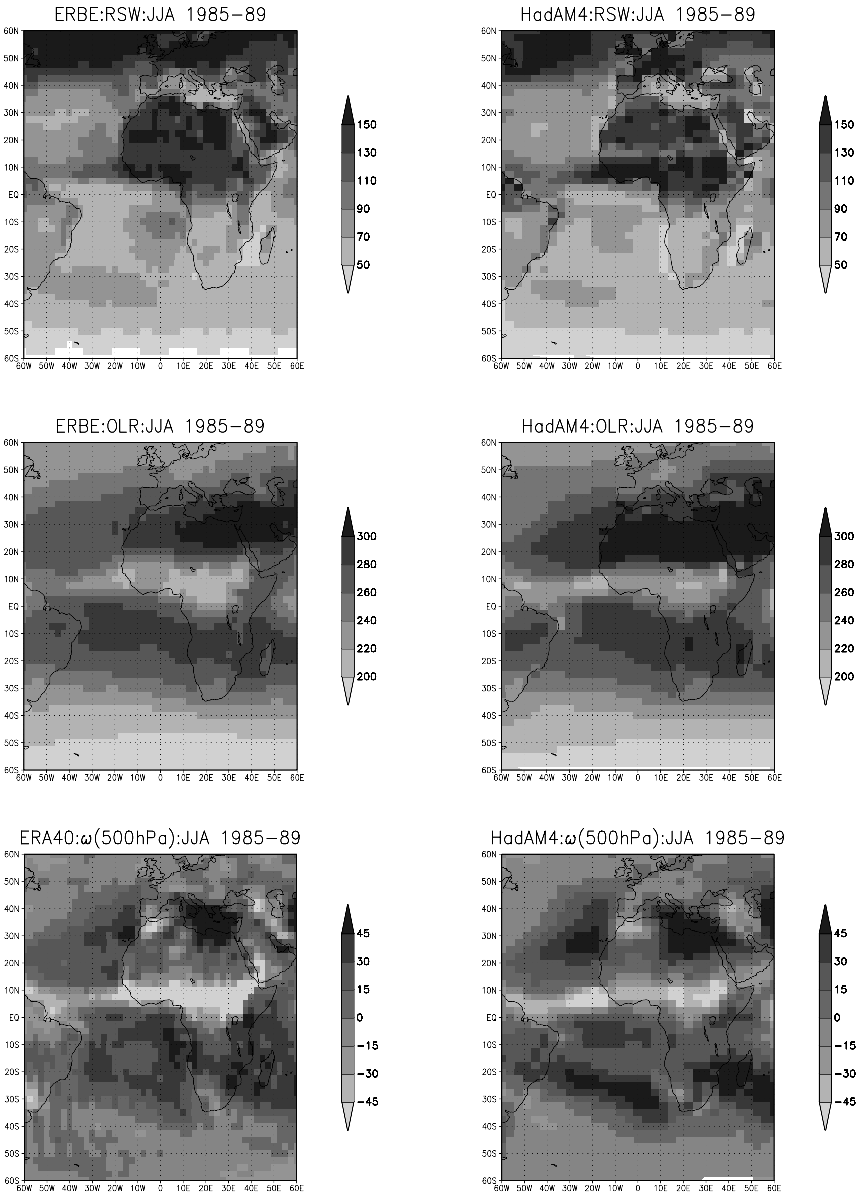

Figure 6. Upper and central panels show a comparison of ERBE RSW/OLR (Wm^{-2}) with HadAM4 for the JJA season averaged over 1985-89. Lower panels show a comparison of ERA40 vertical velocity (hPa day^{-1}) with HadAM4 for the same period.

Comparing GERB data with Met office UM forecast model

In addition to the planned use of GERB data to evaluate the Hadley centre climate model, the measurements the instrument is currently making are already being exploited to evaluate the "New Dynamics" forecast version of the Met Office Unified Model (UM) (see Bell et al. 2002) under the SINERGEE project central panels show a comparison of ERBE RSW/OLR (Wm-2) with HadAM4 for the JJA season averaged over 1985-89. Lower panels show the comparison of ERA40 vertical velocity (hPa day-1) with HadAM4 for the same period.

Experiments are conducted at each model analysis time (00, 06, 12, 18 GMT) in which diagnostics are calculated using the model analysis fields as input to a single time-step integration. Broadband radiation budget diagnostics are subsequently compared with GERB data. The comparisons allow problems with the data or the model or interesting synoptic conditions to be identified, usually within about 1 day of the measurement time. Figure 7 shows example OLR comparisons for the 9th August 2003 for the four model analysis times. The GERB data is re- gridded on the UM grid. Only data for Meteosat viewing azimuth angles less than 70 degrees (relative to the zenith-north plane) are used. To ensure a consistent comparison, only grid-points containing valid GERB data are considered. For example, missing GERB data at about 40°S in the Eastern hemisphere (Fig. 7g) are also marked as missing in the UM data (Fig. 7h). In Fig. 7, dark regions denote low OLR, generally due to low thermal emission from the cold tops of extensive cloud cover. Bright regions correspond to high longwave emission relating to cloud-free scenes of high surface temperature. For example, the highest OLR in Fig. 7e and 7f corresponds with cloud-free regions of Africa and Saudi Arabia. Because direct surface solar heating is considerable over these regions at 12z, surface temperatures and hence OLR are also large.

The OLR simulation at high latitudes is excellent compared to GERB. The progression of mid-latitude weather systems during the day are also well captured. Although the model assimilates humidity information, the excellent OLR agreement in Fig. 7 indicates two points. Firstly the assimilated humidity field is well constrained by the model dynamics. Secondly, the model cloud parameterizations effectively convert the humidity information into a realistic cloud field. Agreement between model and data is less good over tropical regions. In particular, at 12z, the model appears to overestimate the extent and spatial variability of convective cloud cover compared with GERB. Some of these model errors stem from inaccuracies in the diurnal cycle of convection in the model (e.g. Slingo et al. 2003).

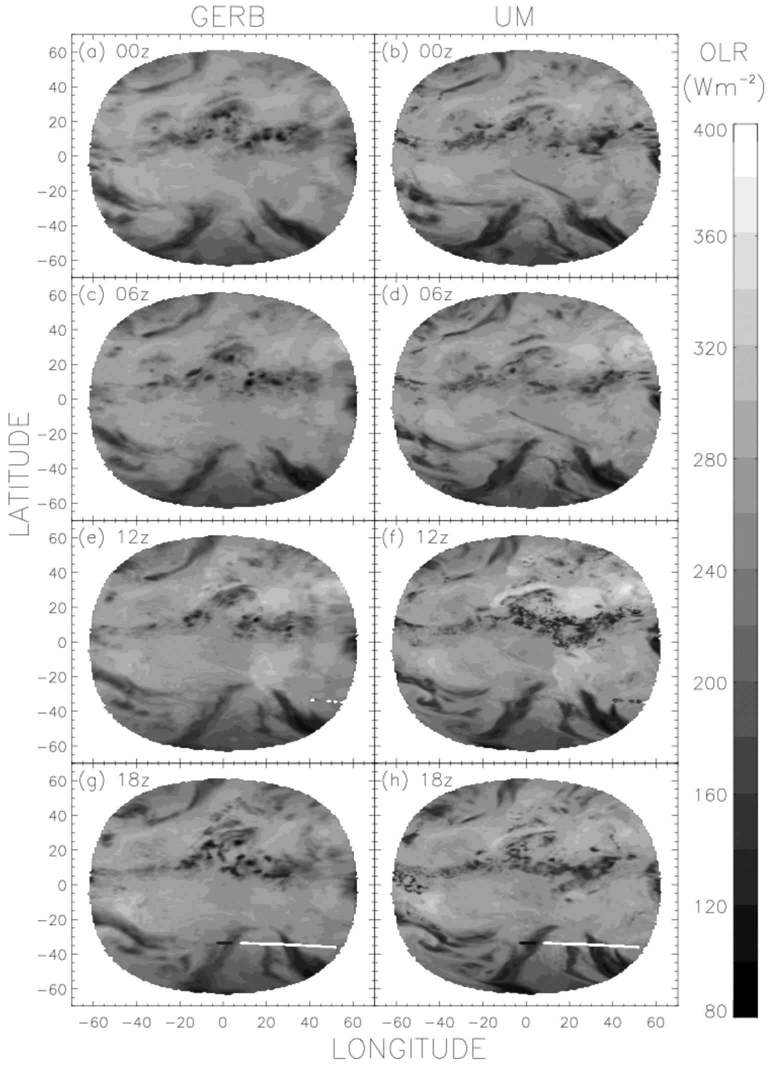

Figure 7: Comparison between UM model and GERB (ARG) longwave flux at four different model times steps.

At present, SINERGEE comparisons are restricted to the model analysis times and for OLR and Albedo comparisons only[2]. In future work, the simulation of narrow-band radiances within the model (e.g. Ringer et al. 2003) and comparisons with SEVIRI data are expected to aid the analysis of model errors and will be used in conjunction with the comparisons between the model and GERB data. Also, the use of model forecasts, in addition to model analyses, will allow comparisons to extend across the entire diurnal cycle.

5. SUMMARY

The GERB instrument made the first ever measurements of the Earth's radiation budget from a geostationary orbit in December of last year. This paper has presented a summary of the commissioning tests which have been performed during the first year of the instruments operation. These results demonstrate the instrument is stable, performing well and providing measurements with low noise levels. Initial comparisons between the GERB data and similar instruments in LEO indicate good mean agreement and are now being analysed in more detail as part of the ongoing validation activities. Proposed studies outlined here will use GERB measurements to provide a better understanding of the radiative effects of clouds and aerosols. In addition the data are currently being used to evaluate the Met office UM forecast model and the Hadley centre climate model by members of the GERB science team. Formal release of the GERB data products are expected by

[2] For example comparisons see http://www.nerc-essc.ac.uk/~rpa/GERB/gerb.html

the middle of next year, after further validation. These data will be made available via the GGSPS website (http://ggsps.rl.ac.uk) and distributed generally through the BADC.

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