STRATEGIES FOR DETERMINING CLEAR SKY FLUXES FROM GERB DATA

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ABSTRACT

The Geostationary Earth Radiation Budget (GERB) instrument on MSG-1 (Meteosat-8), measures the outgoing longwave and reflected solar energy every 15 minutes for the whole of the MSG region. These data, which are the first high accuracy broadband measurements at such high temporal resolution, will be presented both as instantaneous radiances and fluxes and averaged into monthly means for all data points and for each 15 minutes time period.

In order to use these fluxes to study cloud forcing and to aid in climate model validation studies, the calculation of associated clear sky fluxes is required. Here we compare various strategies for determining clear sky fluxes for the GERB data, and investigate if the unique temporal sampling of the GERB instrument warrants a different approach to that used to derive clear sky fluxes for low Earth orbit radiation budget instruments. The study includes consideration of the relative merits of spatial and temporal averaging and the optimum use of imager data. A comparison with clear sky model data is also shown.

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.

2. 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. In flight calibration is updated via measurements of an internal black body and a solar integrating sphere.

GERB obtains a measure for the whole Earth disc in both a 'total' and 'shortwave' channel in a little over 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. The final GERB data products consist of reflected solar and emitted thermal radiances and fluxes (Dewitte et al. 2000) for the MSG region presented on a 50km grid centered at 0° longitude, 0° latitude. An example of approximately 15 minutes of GERB data is shown in figure 1 below. The left hand image in this figure shows the result of averaging three shortwave channel measurements, the centre image is the average of three total channel measurements and the right hand image is a difference of these two weighted to account for the transmission of the quartz filter.

As well as providing radiances and fluxes at a temporal resolution of 15 minutes, it is intended to produce monthly means and monthly time-step means of the fluxes. The high time sampling of the data mean that these products can be produced for the measurements without having to rely on interpolation to account for unobserved periods, a problem that is inherent in the sampling afforded from low earth orbit platforms.

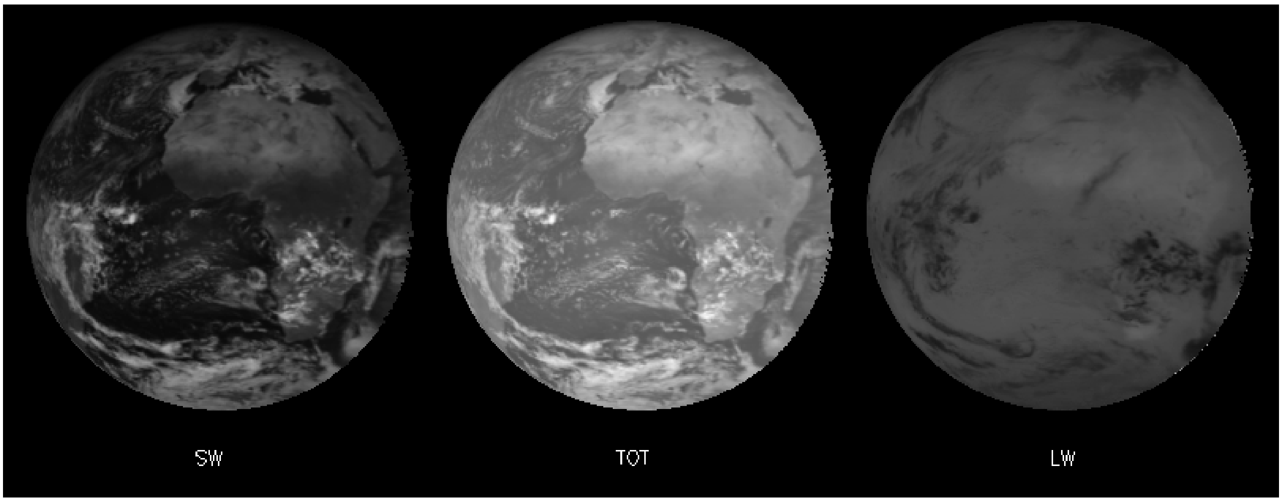

Figure 1. Approximately 15 minutes of GERB data (level 1.5 ARG product) showing measurements made in the shortwave (left hand) and total (centre) channels and the longwave (right hand) radiance obtained by subtraction of the shortwave from the total measurement.

For many applications, such as radiative forcing studies of cloud or aerosol and model comparison, it is desirable to separate the clear sky measurements from the all-sky. It is intended to include cloud flags, derived from SEVIRI visible and infrared channel data, in the instantaneous products to allow cloud to be identified and aid in the scientific interpretation of the data. For the monthly average products, in addition to the all sky averages, a separate average of the clear sky will be made. For the purpose of calculating radiative forcing or comparing with a model derived clear sky average, it is necessary to try and correct the averaged clear sky data for biases due to 'missing' clear sky measurements, that is measurements that are not available because of cloud. Previous radiation budget data sets have used reductions in temporal and spatial resolution as well as interpolation (Young et al 1998) to help remove the problem of incompletely sampled data. Here we consider the benefits of these for this application and also consider the benefit of utilizing higher resolution imager data in conjunction with the broad band measurements to provide a better estimate of the average clear sky fluxes.

3. IDENTIFYING CLEAR SKY

For the operational GERB products cloud flags will be developed specifically for the purpose of defining clear sky fluxes. In the development of these flags, the problem of varying detection efficiency with time of day and from day to night will be addressed. At this time these flags are still under development. This study makes use of available cloud flags based on SEVIRI visible and thermal data. The visible flag is that used within the GERB data processing at RMIB for scene identification (Dewitte et al 2000) and the thermal flag, is the first implementation of the SEVIRI MPEF cloud product flag available from EUMETSAT. During daylight, both these flags are available and a measurement is considered clear only if both flags show no cloud. At night, only thermal data are available and therefore only the thermal flag can be used to identify clear sky. Both these cloud flags are still undergoing validation and know issues exist in both of them, however they are considered reasonable starting points for these preliminary studies.

4. SAMPLING ERRORS IN CLEAR SKY AVERAGES

Figure 2 shows, for four different times of day for each GERB grid box, the number of days in the month during which the 50 km grid point is completely clear as defined by the visible and thermal cloud flags. A clear geographical variation is seen, with clear points on most days of the month over the Sahara and southern Africa and very few or no measurements over the ocean and tropical convective region. A variation in the amount of clear sky is also seen between the different times of days, some of which may be associated with the diurnal variation in cloud cover but which may also be due to the varying efficiency of the cloud flags with time of day.

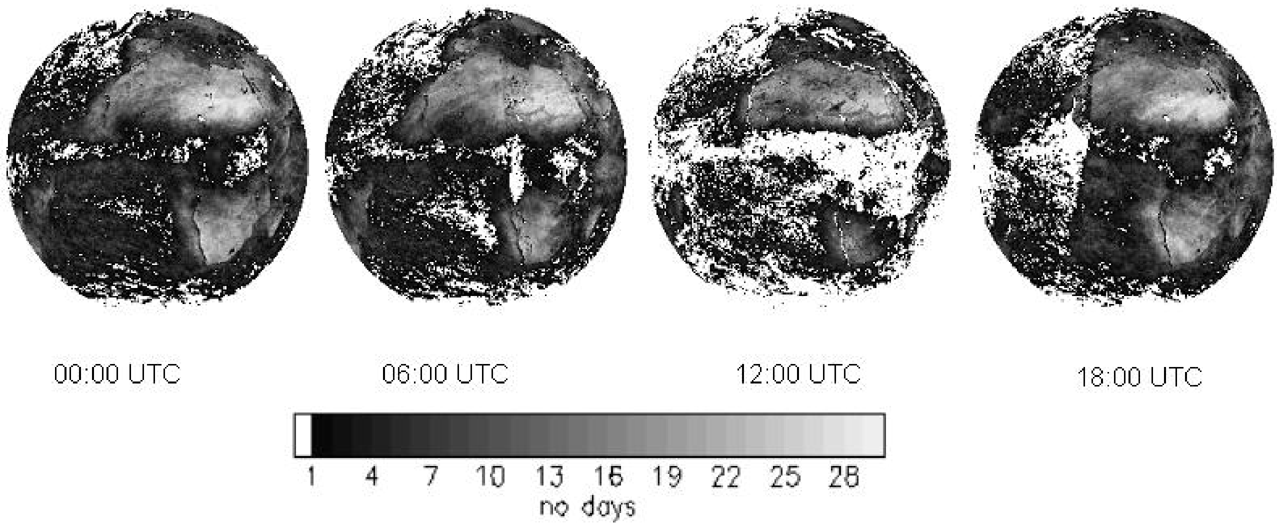

Figure 2. An example for April 2004 of the number of days for which completely clear GERB scale (50 km) measurements are available over the course of the month at four time-steps each representing a 15 minute period of the day. Clear sky was identified by a combination of visible and thermal cloud flags during the day and thermal flags only at night.

Whilst averaging the actual measured clear sky points would seem a viable way to derive a clear sky average, for radiative forcing studies and many model comparison studies what is really required is an estimate of the average clear sky flux for all days, including days on which cloud is present. It should also be borne in mind that a pixel flagged as containing cloud may only be partially covered by cloud. Whether a pixel is completely clear is a scale dependent quantity and averaging the available completely clear data points will not provide an a good estimate of the actual clear sky contribution to the outgoing flux unless it attempts to account for the clear sky portions of the partially cloudy pixels. Thus the problem of providing an estimate of the average clear sky flux to aid in the scientific use of the averaged all sky data requires some means of avoiding biases due to the limited amount of clear sky data available and the incomplete sampling of the day to day variation of the clear sky fluxes.

5. STRATEGIES FOR FILLING 'MISSING' CLEAR SKY POINTS

One way of gaining a greater, more representative, sample from which to calculate the monthly average flux, is to degrade the spatial and / or temporal resolution of the dataset. The strategy used for the ERBE radiation budget dataset and continued in the CERES products is to use as a starting point, any measurement within a 1 hour period and a 1 by 1 degree, or 2.5 by 2.5 degree grid box as an estimate for that time period and region (Young et al., 1998). For these data sets, the procedure is applied to both the clear and all sky products as the all sky measurements suffer from sparse sampling due to the lower temporal resolution available from low earth orbit. Remaining missing data is then interpolated with the aid of models where appropriate. Another approach used to aid the temporal interpolation problem for the CERES data-set is the combination of geostationary narrow band measurements with the CERES data. The narrow band measurements are used to aid the determination of the diurnal cycle and the much more infrequent broad band measurements from the CERES instruments are used as an absolute reference to anchor the more poorly calibrated narrow band data (Young et al, 1998).

As already mentioned, the sampling of the CERES instrument requires the issue of sparse data to be addressed for both the all-sky and clear sky average products. Because, the GERB all-sky data is very well sampled in time, the all sky average can be derived directly from the measurement without interpolation or degradation to the resolution. However similar approaches applied to the clear sky data may allow a more representative estimate of the clear sky average.

It can be shown that reducing the temporal and / or spatial resolution of the GERB clear sky data can indeed result in an increase to the number of clear sky estimates available over a month, although the increase is not dramatic. However, this approach will incur errors due to variations over the spatial and temporal sampling period, and either results in an inconsistency between the clear sky and all sky averages or requires an unnecessary reduction to the resolution of the all-sky product.

Whilst the GERB data already has very high temporal resolution and thus temporal interpolation using narrow band data is neither feasible nor helpful, the use of higher spatial resolution narrow band SEVIRI data can be used to aid in the determination of a clear sky estimate. Cloud detection is performed on the SEVIRI pixel scale, with a GERB pixel consisting of approximately 15 by 15 SEVIRI pixels, thus a GERB pixel that is partially cloudy may contain up to 224 completely clear SEVIRI pixels. Part of the GERB processing involves the determination of an intermediate enhanced resolution product, at a spatial resolution of 3 by 3 SEVIRI pixels ($^1/_5$ of the nominal GERB pixel resolution), which is a combination of the SEVIRI and GERB measurements. A broad band flux is estimated from the narrow band SEVIRI measurements, the ratio of the SEVIRI estimate and GERB determined broad band flux is then found at the GERB pixel scale and used to correct the SEVIRI estimate for calibration inaccuracy or modelling errors. These correction factors are then smoothly interpolated to the higher spatial resolution.

For this preliminary study, completely clear GERB sub-pixels have been used to provide an estimate of the clear sky flux for the whole GERB pixel. In the future, if necessary, the correction of the SEVIRI based estimates will be optimised for clear sky by interpolation of only the correction factors derived from completely clear GERB scale pixels to the clear sub-pixels within the partially cloudy GERB grid box.

Figure 3 shows the number of days for which a clear sky estimate can be made if 1 (or more) out of the 25 sub-pixels are used to estimate the clear sky for the full GERB grid point. Comparison of this figure with figure 2 shows the potential improvement in the number of days contributing to the average that this approach can yeild.

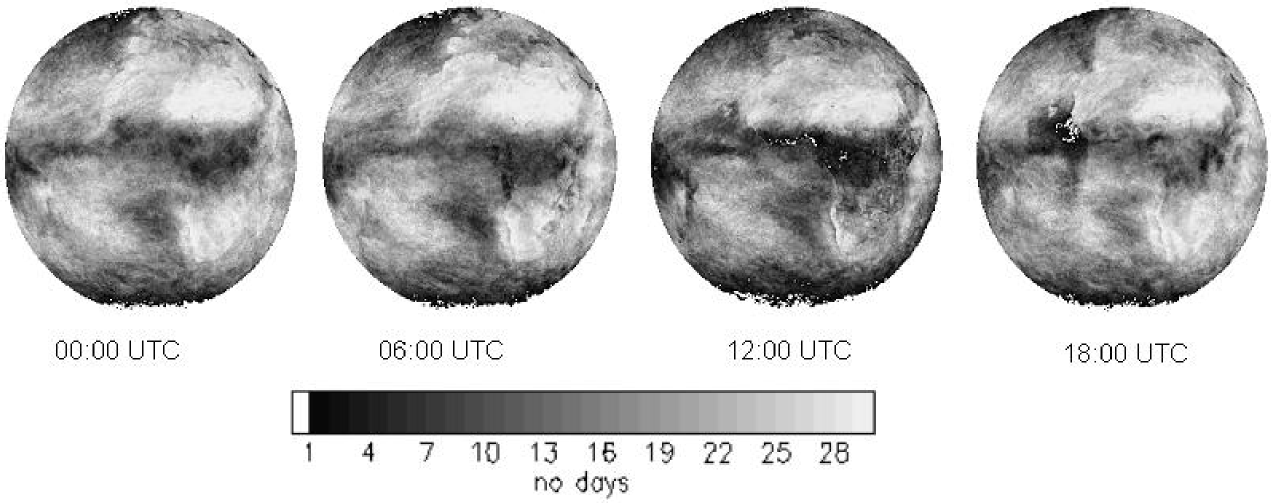

Figure 3. An example for April 2004 of the number of days during the month for which a clear sky estimate can be made if higher resolution imager data for clear regions of a partially cloudy GERB pixel is used.

Using higher resolution data obviously has the potential of increasing the number of days which contribute to the monthly average estimate, but may lead to errors due both to spatial inhomogeneity over the GERB grid box not being fully sampled or because of modelling errors inherent in the method. When including estimates from the higher resolution data there is a trade-off between the error incurred due to incomplete sampling of the spatial variation and the reduction in the error from temporal variability that results from the increase in the number of days contributing to the average. Studies of the relative contributions of these errors show that in general the benefit of the greater number of days sampled outweighs the effect of any errors due to sampling only a part of the region. In the long wave this is true for all scene types even if data representing only 1/25 of the regions is used. In the shortwave, the most highly variable land scenes, such as dark desert, indicate that slightly lower errors may result in the average if at least 5 out of 25 clear sub-pixels are required to provide the large area estimate. The effect of the modelling assumptions and the error due to these in the monthly average remains to be evaluated.

6. EFFECT ON MONTHLY AVERAGES AND COMPARISON WITH MODEL ESTIMATES

Figure 4 shows the effect on the monthly mean clear sky longwave (upper panel) and shortwave (lower panel) flux of including estimates obtained from clear sky regions of partially cloudy GERB pixels.

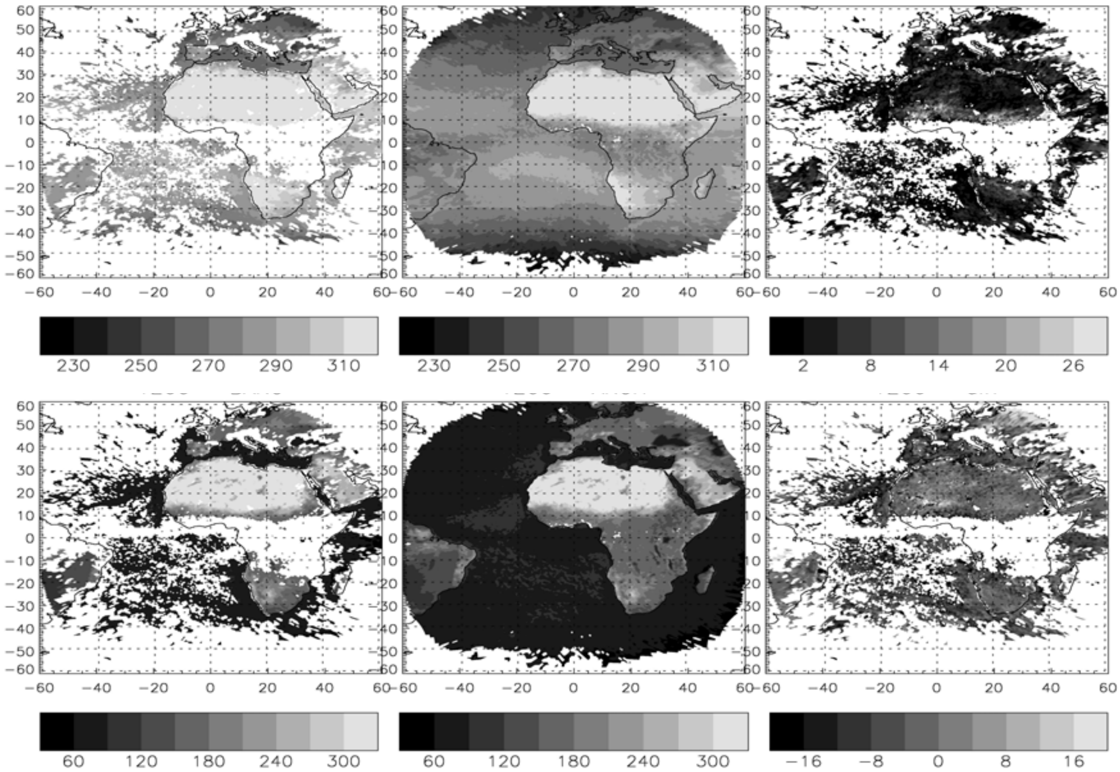

Figure 4. Longwave (top) and shortwave (bottom) monthly average clear flux for the 12:00 UTC time slot for April 2004 determined from completely clear GERB scale pixels (left hand plot), all completely clear sub-pixels (centre) and the difference between the two averages (right hand plot).

The left hand plots in this figure show the average calculated from completely clear GERB scale pixels, obviously for this calculation a limited number of days, shown in the upper panel of figure 3, are available from which to compute an average. Regions shown as white have no days during the month on which a GERB scale pixel is completely clear. The middle plots show the average obtained including estimates from one or more completely clear sub-pixels, this average will include more days over the month as indicated from figure 3. The right hand plot show the difference between the two averages (full pixel – sub pixel).

In the longwave the difference is either zero or positive, indicating that the average obtained by including the clear sky estimates from the sub-pixels results in a lower average clear sky flux for the month. The lowering of the average may in part be due to some wetter days being included when measurements from partially cloudy pixels are used, whilst averaging over only completely clear GERB scale regions results in a bias towards abnormally dry, and therefore warm, points. The large differences in the longwave seen at the edge of the convective region at the border of the Sahara and southern Africa are in regions where very few days of data were originally contributing to the average.

In the shortwave over much of the land differences between the two averages are close to zero, as may be expected. The ocean generally shows a negative difference, indicating that the average constructed from the clear sub-pixels is brighter than the average obtained from the completely clear GERB pixels. This may be a problem with the cloud flags and an indication of greater cloud contamination in the second average, or it may be related to an increased ocean roughness in the sub-pixels or even scattering into the beam from cloud edges. Alternatively it could be a problem with the method and deserves further investigation.

As a comparison, clear sky estimates obtained from the met-office unified model run to simulate GERB data as part of the SINERGEE project (Allan et al. 2004) were calculated for April 2004 for the 12:00 UTC model time-step. Two different clear sky averages were made, the first is the average of only model grid points that contain no cloud (type I sampling); the second is the average clear sky flux calculated for all columns including those that actually contain cloud (type II sampling). The two averages and the difference between them are shown in figure 5.

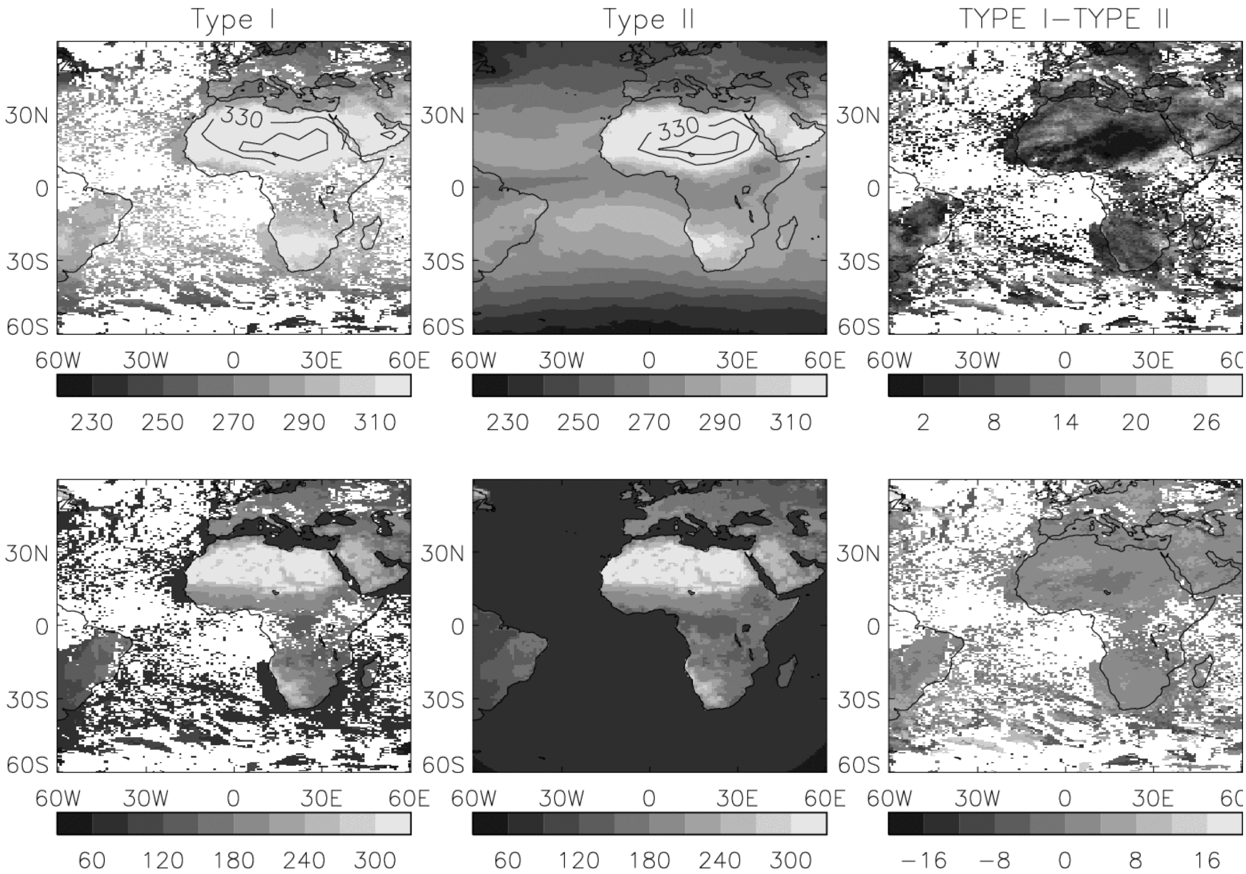

Figure 5. Model calculated longwave (top) and shortwave (bottom) monthly average clear flux for the 12:00 UTC time step for April 2004 determined by type I (left) and type II (centre) sampling. The difference between the two averages is shown are the right hand plots. (Please see proceedings CDROM for colour version of this plot).

In common with the difference between the two longwave averages obtained from the GERB data, the greater number of points included in the type II average lead to a generally lower estimate of the average longwave flux. This supports the idea that the effect of including clear estimates from partially cloudy pixels goes some way to avoiding the problem of the 'dry bias' that results from sampling unusually clear / dry days. The difference between the two longwave model averages is slightly larger than the difference between the two GERB longwave averages, as would be expected as the data can never include clear estimates from the wettest points as these will be cloudy at all scales. In the shortwave the difference between the type I and type II averages is generally small, both over the land and over the ocean as would be expected from the lower day to day variability seen in the shortwave. This contrasts with the generally negative differences seen over ocean between the two shortwave averages derived from the GERB data, the origin of these will be investigated further.

7. CONCLUSIONS

In addition to the instantaneous GERB fluxes which will be provided at a temporal resolution of 15 minutes for the whole of the MSG observing region, monthly averages of the all-sky and clear sky data- will be provided. The high temporal sampling of the GERB measurements means that the all-sky average may be calculated directly from the instantaneous data without interpolation or filling of missing points. However the infrequent occurrence of completely clear regions at the GERB spatial scales means that the clear sky average may be subject to errors due to only a few days during a month contributing to average. To avoid this it is proposed to use the higher spatial resolution of the SEVIRI data in combination with the GERB measurements to estimate the clear sky flux from the clear regions of partially cloudy GERB pixels. This approach can be shown to dramatically increase the number of days for which clear sky estimates are available.

Including clear estimates derived from the clear sub-pixels within partially cloudy GERB pixels results in a lowering of the average longwave flux. A similar lowering is also seen when clear sky averages determined from model fluxes from only completely clear model columns are compared to averages calculated for all model columns. The difference is thought to be due to completely clear regions being present on unusually dry days when outgoing longwave flux would be greater, the inclusion in the clear sky average of higher resolution estimates allows the inclusion of slightly wetter regions and goes some way to removing the problem of this ‘dry bias’.

In the shortwave the inclusion of higher resolution estimates makes very little difference over much of the land area, a result in common with the difference seen between the two differently sampled model average clear sky shortwave flux. However, in contrast to the model results the use of the higher resolution data results in an increase in the average shortwave flux over the ocean. The origin of this difference is not understood, although may be related to differences in ocean roughness, problems with cloud contamination or the assumptions of the method.

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