RADIATIVE BUDGET FROM ScaRaB DATA

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1 Introduction

Two models of the ScaRaB radiometer (Scanner for Radiation Budget) have operated in space aboard the Russian satellites Meteor-3-7 (February 1994 to March 1995) and Resurs 1-4 (August 1998 to April 1999). These missions are the result of a co-operative project between France, Russia and Germany, with the following main contributions: instrument design development, construction and data processing by France (LMD/CNRS and CNES) with flight calibration module supplied by Russia; infrared ground calibration by France; satellite launch and data reception by Russia; solar ground calibration by Germany. As for the NASA ERBE scanners (Barkstrom et al., 1989) and CERES (Wielicki et al., 1996), ScaRaB estimates the solar reflected flux and the longwave emitted flux of the Earth. It looks for the maximum accuracy both in the measurement and in the data processing (angular and space and time averaging). These estimations are fundamental parameters of the Earth environment and climate, and their regional and monthly means have been determined with great accuracy by ERBE and ScaRaB (mean Earth albedo =0.297, global annual mean of the outgoing longwave radiation = 238 Wm^{-2}). The main objectives of ERBE/ScaRaB missions are 1) to contribute to the long time series of regional observations of radiative fluxes at TOA 2) to check or correct models (radiative transfer, thermodynamic processes, climate). Comparisons between experimental and theoretical determinations have led to refine assumptions of climate models, specifically the radiative properties of clouds (Ramanhathan et al., 1989, Bony et al., 1995,...).

The keys to the ERB determination are:
1 broadband channels with well determined spectral response (covering SW and LW domain)
2 accurate radiometric calibration, 1% LW, 2% SW (compared to 5%, for most other space SW radiometers vicarious method)
3 need of a robust and qualified secondary -level 2 & 3 - processing to solve the triple sampling issue (angular, space and time averaging)
4 scene identification (for 3 and cloud forcing studies)

Brief descriptions of missions and instrument are given in section 2. Principles of calibration and data processing are described in sections 3 and 4. The accuracy of the flux estimates at different time scales is discussed in section 5. Then the monthly regional, zonal and global estimates of SW, LW and net fluxes are compared to ERBE and CERES estimates (section 6).

2 ERB Missions and Instruments

2-1 Missions

Table 1 positions ScaRaB among other ERB scanner missions. It can be seen that the ERBE provided the major contribution with at least two instruments in space for more than four years (1985-89) and three instruments during December 1986. It also shows that we are entering the EOS/CERES epoch. However, CERES/TRMM suspended its observation in September 1998 due to instrument problems. It is planned to be re-activated when CERES/EOS-AM will be launched. Meanwhile, EOS/CERES was working for short periods of intercalibration with ScaRaB/Resurs (Haeffelin et al., 1999).

Instrument	Satellite	Altitude (km)	Resolution nadir (km)	Inclination (°)	Precessing Period	From	To
ERB	Nimbus 7	955	90	99.3	Sunsync.	Nov 78	Jun 80
ERBE	ERBS	610	30	57	72 days	Nov 84	Feb 90
„	NOAA 9	812	45	99	Suns. 14:30	Feb 85	Jan 87
„	NOAA10	830	45	99	Suns. 07:30	Oct 86	May 89
ScaRaB	Meteor	1200	60	82.6	209 days	Feb 94	Mar 95
„	Resurs	830	≈45	99	Suns 22 :15	Aug 98	Apr 99
CERES	TRMM	350	10	35		Dec 97	
„	EOS-AM	705	≈25	99	Suns. 10:30		
„	EOS-PM	705	≈25	99	Suns. 13:00		
ScaRaB	MeghaTrop	820	≈45	20			

Table 1 : Main ERB scanner missions.

Regarding ScaRaB, its history is here summarised

Flight Model 1

Launch of Meteor-3/7 at Plesetsk	25 January 1994
Start of Earth Observations	24 February 1994
Scanner failure	6 March 1995

Flight Model 2

Launch of Resurs-01/4 at Baikonour	10 July 1998
Failure of satellite data transmitter #1	August 1998
Data reception	November 1998 to March 1999
Failure of satellite data transmitter #2	7 April 1998

The failure of flight model 1 was due to an electrical slip ring. This component was improved for flight model 2, and the instrument worked perfectly well during the lifetime of the Resurs satellite. Considering both missions, 16 months of ERB data were obtained with ScaRaB, and they partly fill the gaps of the 15-year series of ERB determination (see on figure10). However, it can be seen that major climatic events (Pinatubo 1991, El Nino 1982, 1997) were not observed with scanner instruments (they were observed only with large field-of-view radiometers on Nimbus-7 and ERBS).

2-2 Instruments

The instrument has been described earlier (Monge *et al.* 1991, Kandel *et al.* 1998). ScaRaB is a 4-channel cross-track scanning radiometer. The earth scanning angle is 100°. Scanning is obtained by rotation of a cylinder (the rotor) carrying the optics, filters, detector, choppers and analog-digital conversion electronics about an axis parallel to the direction of motion of the spacecraft, within a cylinder (stator, figure 1) mounted on the spacecraft. The four channels (Table 1) include two broad spectral bands (figure 2) from which the reflected SW and emitted LW radiances are derived, and two narrower bands, one corresponding to the infrared atmospheric window, the other to the visible (green to red) portion of the solar spectrum.

General designs of the ERBE and ScaRaB scanners are quite different: DC thermistor bolometer for ERBE, AC pyroelectric detector with 16 Hz frequency chopping against an internal blackbody for ScaRaB; telescope with two mirrors for ERBE and one for ScaRaB.

Channel no.	**Description**	**Wavelength range**	**Filter Type**
1	Visible (VIS)	0.55 — 0.65 µm	Interference
2	Solar (SW)	0.2 — 4 µm	Fused silica
3	Total (TW)	0.2 — 50 µm	Unfiltered
4	IR window (IRW)	10.5 — 12.5 µm	Interference

Table 1 : ScaRaB channels

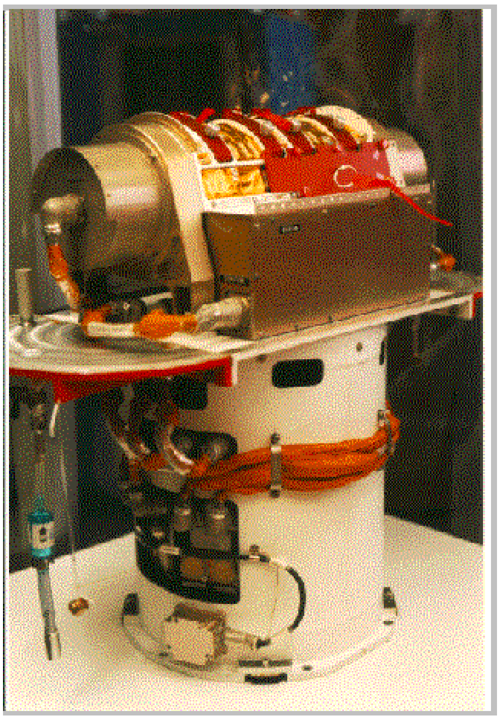


Figure 2 : Spectral Response of ScaRaB/Meteor · Main Channels

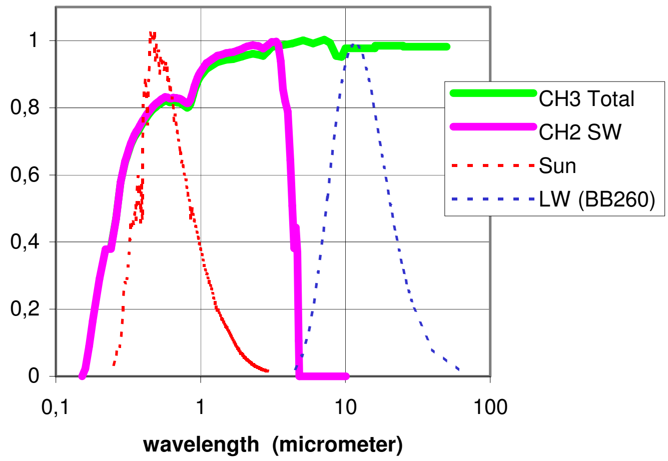


Figure 1 (right) : ScaRaB instrument. In the upper part: the stator with the 4 channel windows looking to the Earth, the rectangular calibration module on the left. In the lower part, the cylindrical structure contains the electronic parts. Weight: about 40 kg.

3 Radiometric Calibration

Radiometric performances are first estimated on the ground (Sirou et al., 1997). In a vacuum chamber, ScaRaB was tested with an actively-controlled-temperature blackbody. These operations established the linearity of response and provided radiometric calibration of the temperature and emissivity of the on-board calibration blackbodies, and calibration of the temperature dependence of detector gains. On-board shortwave sources were calibrated at high-altitude sites (Mueller et al, 1997) against sun-illuminated diffusor with incoming solar flux measured by high-standard calibrated pyrheliometer and in laboratory against calibrated integrating sphere.

In flight, the temperature of the reference blackbody (emissivity = 0.993) for channel 3 is measured by a platinum resistance thermometric sonde and included in the scientific telemetry. For the SW domain, the calibration system was designed with 3 sets of preaged incandescent lamp source (Tremas et al.,1997).

Because of the channel stability (0.1% stability was measured in flight on channel 3), the inter-channel consistency can also be used for complementary cross-checking operations. Analysis of very cold bright daytime cloud scenes over tropical convective regimes, for which the TW signal is dominated by SW reflection and the LW component can be estimated independently from the IRW radiance, yields agreement at the 1% level (Duvel, private communication).

Finally intercomparisons between ScaRaB and ERBE WFOV (Bess *et al.* 1997) and between ScaRaB and CERES (Haeffelin, 1999) also have been carried out.

According the results of all these operations the accuracy of the radiances is estimated to be 1% in the longwave and 2% in the shortwave domains.

4 Data processing

The archive A1 files contain geographically located pixel radiances in physical units. From A1 files, the inversion processor produces the archive A2 file equivalent to the ERBE-CERES S8 product containing estimated SW and LW radiant fluxes as well as scene identifications. Each A1 and A2 file (about 10 and 20 Mbytes respectively) contains a full day's data from one satellite. Then using the same geographical grid as ERBE, the radiant fluxes are space-averaged over areas of 2.5 by 2.5 degrees in latitude and longitude. For each region, daily and monthly mean radiant fluxes are computed, using the same model for time interpolation as ERBE. The result is the family of A3 products: A3-MRI (Instantaneous Regional averaging) and A3-MRJ, A3-MRH, A3-MRMJ: daily regional means, the monthly regional mean diurnal cycles, and the monthly regional means obtained from the daily means.

The ERBE-like version is based on ERBE algorithms according to published descriptions: Smith *et al.* (1986), Wielicki and Green (1989), and Suttles *et al.* (1988a, 1988b) for Inversion, Brooks *et al* (1986) for the Monthly Time Space Averaging. However, the spectral corrections have had to be adjusted (Viollier et al, 1995) to the ScaRaB characteristics. An advanced version is proposed based on different studies (Stubenrauch et al.,1993, Standfuss et al. 1998). A second paper in these proceedings discusses the ScaRaB data processing in more details.

5 Accuracy

The accuracy of the ERB determination is difficult to assess because there is no 'ground-truth' comparison ! Any attempt must rely on independent error simulation and various cross-checking operations. The accuracy of the raw radiances has already been discussed in 3. The accuracy of the flux estimates are discussed in detail by Viollier et al. (this issue) and can be summarised in what follows.

Large errors occur first for instantaneous estimates due to uncertainty in angular correction. Individual misclassification of scenes can result in erroneous angular corrections. Extreme errors may occur when a scene is classified partly cloudy for both observations, one due to sun glint and the other due to limb brightening. Morever, even if the scene classification is correct, angular correction uses a model (in particular a bi-directional reflectance distribution function or BRDF in the SW) which is valid at best only statistically. There is a trend of increasing error with increasing view zenith angle, due to bigger pixel size and geometrical effect (non-observed gaps, shadowing, limb effects).

The second type of error is related to the diurnal extrapolation and concerns the daily and monthly means. The diurnal cycle indeed is generally inadequately sampled: a scanner on a polar satellite observes the tropical zone only twice in 24 hours. The gaps before and after the observations have to be filled with the diurnal interpolation extrapolation procedure (DIEP). This was the reason why ERBE and ScaRaB were originally planned as multi-satellite missions. Unfortunately, launch delays and instrument or satellite failure reduce the number of available datasets. If the errors (angle and time sampling) are statistically indépendant (often but not always the case), then the error in the regional and global means (resulting from processing 5×10^7 elementary measurements) should be considerably reduced. This is the case of global means, calibration errors in the range -2 to 2 % yielding an almost linear impact on the computations of global means (Viollier et al., 1999). However the errors are not always random, and may depend systematically on the observation time and therefore on orbit characteristics and they may persist in the regional means. About time-averaged quantities, one must distinguish regions where the extent and properties of clouds undergo pronounced systematic and coherent diurnal variations: e.g. morning low clouds in marine areas west of continents, afternoon convective activities over continents. According to some of our simulations and data found in the literature (Barkstrom et al., 1989, Diekmann and Smith, 1989, Harrison et al., 1990, Wielicki et al, 1995, Ye and Coakley, 1996, Dlhoplsky et al. 1994,..), some basic figures are given in table 2. It can be seen that errors are more important in the SW than in the LW domain.

Level		Resolution Space	 Time	Accuracy SW rms	 peak	Accuracy LW rms	 peak
1	Radiance	40-100 km	Instant	2%		1%	
2	Flux	40-100 km	Instant	37 Wm^{-2}		12 Wm^{-2}	
3	Instantaneous Regional Means	2.5° 2.5°	1 mn	15 Wm^{-2}	50 Wm^{-2}	5 Wm^{-2}	
4	Monthly Regional Means	2.5° 2.5°	month	5 Wm^{-2}	42 Wm^{-2}	3 Wm^{-2}	14 Wm^{-2}
4	Monthly Global Means	Globe	month	2% 2 Wm^{-2}		1 % 2.5 Wm^{-2}	

Table 2 : Error Estimates at different time-space-scales.

6 Results.

6.1 ScaRaB/Meteor

The flux estimates from ScaRaB/Meteor have been published earlier (Kandel *et al.* 1998). In summary, distributions exhibit no significant global bias in SW, and a possibly significant intrinsic increase in outgoing LW flux (1%) when compared to ERBE results The annual global mean net radiative flux is found to be +2.5 Wm^{-2}, closer to zero than found by ERBE, however small compared to the above uncertainties. Figures 3,4 and 5 show the SW, LW and net global monthly means estimates of ScaRaB (March 94- February 95) compared to the five years of ERBE scanners.

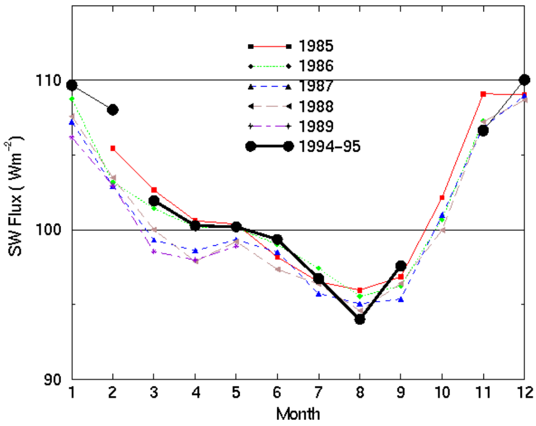


Figure 3 Annual cycle of the global means SW flux for the 5 ERBE scanner years and ScaRaB/Meteor.

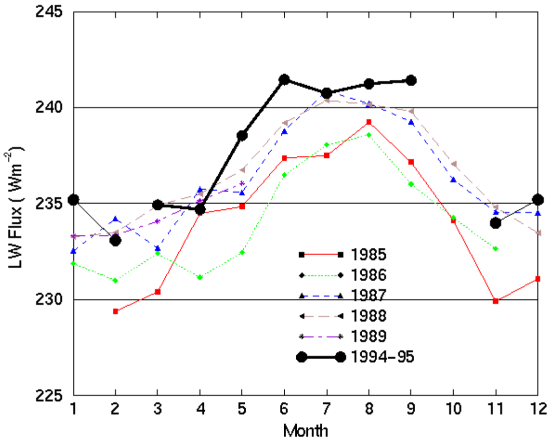
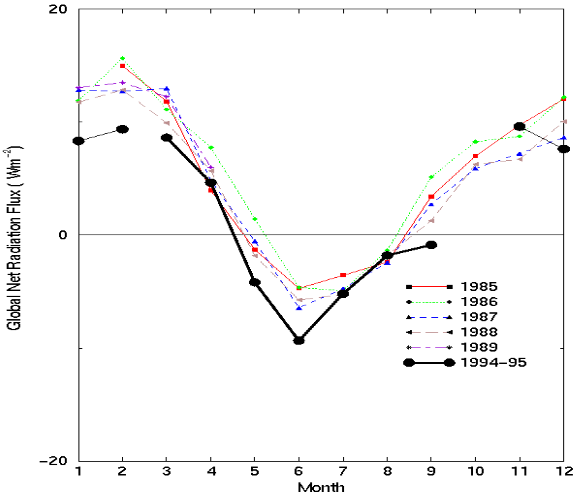


Figure 4 : same as figure 3 but for the LW reflected flux.



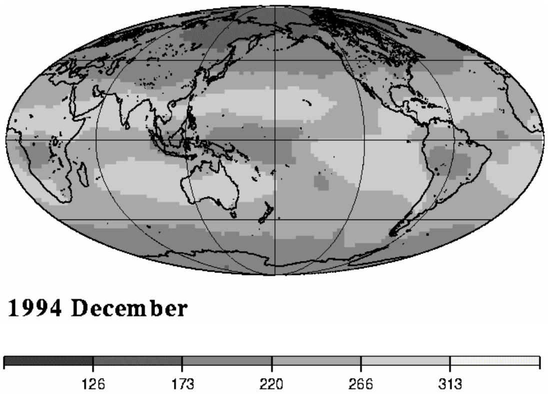
	LW CRF	SW CRF	Net CRF
ERBE 3/1985-2/1989	+29.1	-47.6	-18.5
ScaRaB 3/1994 -3/1995	+27.2	-48.2	-21.0

Table 3 Average of global means of cloud radiation forcing components.

Figure 5: same as figure 3 but for the net radiation flux.

The so-called cloud radiative forcing (CRF) is defined as the difference between the clear-sky and all-sky radiation results (Charlock and Ramanathan 1985, Ramanathan et al. 1989). Empirical evaluation of CRF may combine the rms errors of both all-sky and clear-sky quantities, so that the uncertainty may be as large as 10Wm-^{2} (Harrison et al., 1990). The LW CRF is positive (Table 3: global annual mean of order +30 Wm^{-2}) since the clear-sky LW fluxes are generally higher than all-sky fluxes: thus clouds tend to warm the surface-atmosphere system and contribute to the natural greenhouse effect. The SW CRF is negative (global annual mean of order -50 Wm^{-2}): clouds tend to cool the planet by returning to space a portion of the incident solar flux. Net CRF in the present climate (~ -20 Wm^{-2}) appears to be a cooling effect. Just as was found for the annual global mean net radiative flux, the global annual averages of the LW, SW and net CRF exhibit remarkable consistency between ScaRaB 1994 and ERBE 1985 (Table3). Such results are striking, considering that the two experiments have different specific characteristics (instrument concept, calibration procedure, pixel size, time sampling, software independently developed).

At regional scales, strong interannual variations are observed. For example in December 1994, the outgoing LW flux (figure 6) show the minimum in the Tropical Pacific centred around 160°W instead of 120° for non El-Nino years. Maximum of albedo (figure 7) is observed in the same way. This period corresponds to the maturation of the 1994-95 ENSO event, also considered as the last phase of an extended event that began in 1990.



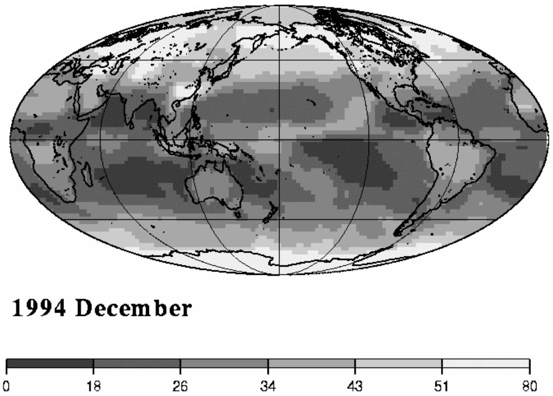


Figure 6 Map of outgoing longwave flux (Wm^{-2}) Figure 7 Map of albedo (%)-undefined in the polar night (uniform grey shade for latitude >80°N)

6-2 Time series of ERB over Tropics including preliminary results from CERES/TRMM and ScaRaB/Resurs

With many gaps due to the problems of the satellite transmitter, there are some useful Resurs data from November 1998 to March 1999. Figure 8 shows the SW flux from 3 consecutive orbits over Indian Ocean during the INDOEX experiment for 1999 January 19 (left) and 20 (right).

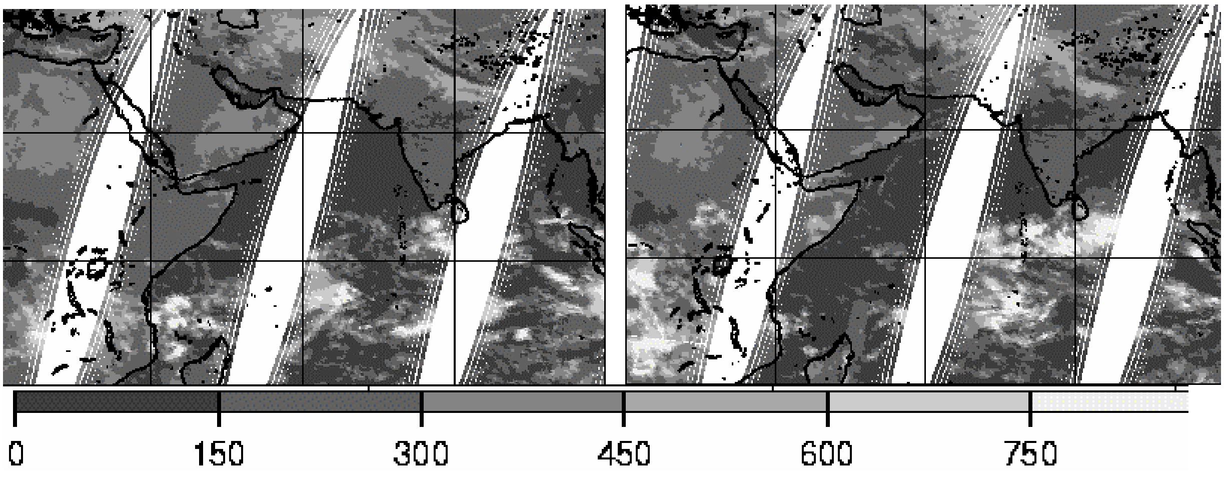
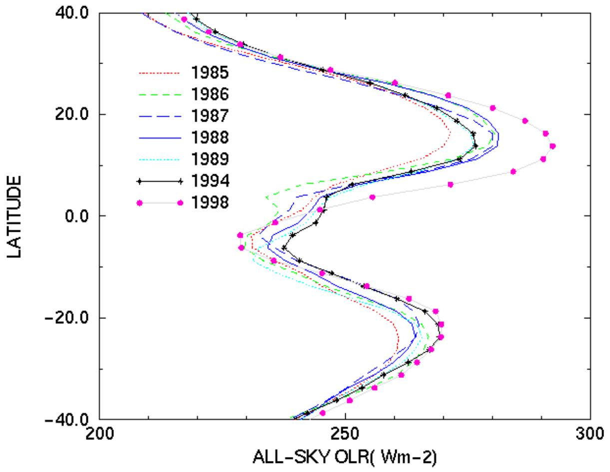


Figure 8: SW flux (Wm^{-2}) from 3 consecutive orbits of ScaRab/Resurs over Indian Ocean for 1999 January 19 (left) and 20 (right).

With provisional calibration, and in spite of the missing days, an attempt has been made to estimate monthly means from ScaRaB Resurs. Interannual comparison of zonal monthly means are shown in figures 9 and 10 for November with Resurs data on 1998, and for March with CERES/TRMM data for 1998. The other years are provided from ERBE and ScaRaB/Meteor. From these values the 15-year record (with large gaps) of the monthly means in the Tropical band, between 20°S and 20°N are shown on figure 11. As emphasized by the March 1998 CERES data (corresponding to the end of 1997-98 El Nino peak) a slight increasing trend is observed at the limits of the uncertainty range. Either real or due to unexpected artefact in the calibration or in the data processing, the observed trend has to be confirmed and understood.



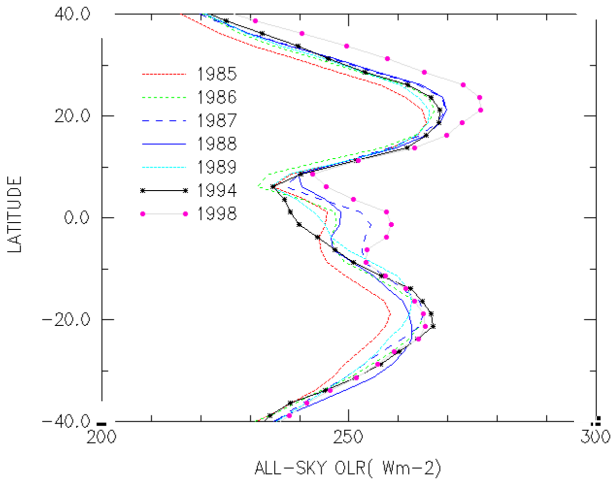


Figure 9 : latitudinal profiles of zonal means - March Figure 10: same but for November.
ERBE data from 85 to 89- ScaRaB for 1994
CERES/TRMM for March 1998, ScaRaB/Resurs for November 1998 (preliminary results).

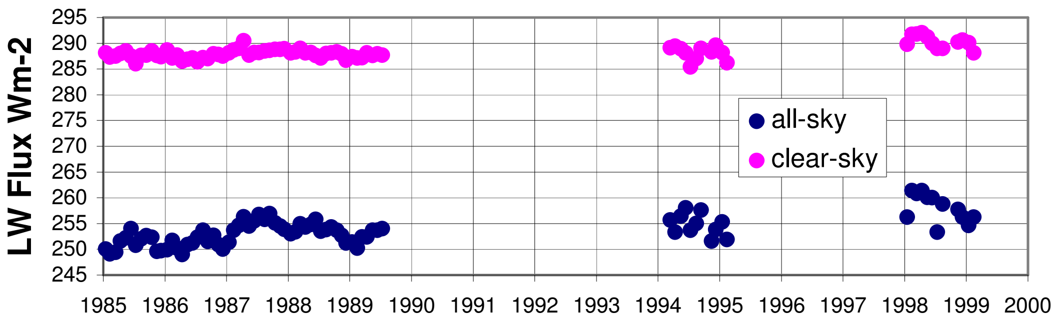


Figure 11 Record of the monthly means of the LW flux between 20°N and 20°S, all-sky (down) and clear-sky (up).

7 Conclusion

There are many reasons to determine the components of the Earth Radiation Budget from Space. They are the ultimate constraints of the Earth Environment and constitute a major contribution to monitor and to study climate (year-to-year monthly means variability). At small temporal scale, ERB measurement must help to understand meteorological processes. Furthermore they can be done only from space and they are direct radiometric measurements (in spite of the triple sampling issue). Two ScaRaB instruments have provided 16 months (11+ 5) of ERB data on 2 different payloads and they have contributed to the radiometric calibration challenge, for long time series of ERB observations and for climate model tests. In the future, the payload of the Megha-Tropiques mission might include a similar ScaRaB instrument. The objective of Megha-Tropiques is focused on the tropical zone and on processes at a scale of 100 km and between a few hours to a few days. In this context, the instantaneous flux estimates are the most important dataset, and studies related to the scene identification and to the angular corrections have to be pursued in order to improve their accuracy.

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