CGMS-XXVII EUM-WP-36
Prepared by EUMETSAT
Agenda Item: III.4

EXPLOITATION OF THE METEOSAT ARCHIVE FOR CLIMATE MONITORING: EXPECTATIONS AND LIMITATIONS

This document discusses the potential of the Meteosat archive to support climate studies and presents the reprocessing environment that has been developed at EUMETSAT. This paper has been presented at the 1999 EUMETSAT Meteorological Satellite Data Users' Conference, Copenhagen, Denmark, 6 – 10 September 1999.

Exploitation of the Meteosat Archive for Climate Monitoring: Expectations and Limitations

Y.M. Govaerts

EUMETSAT, Am Kavalleriesand 31
D-64295 Darmstadt, Germany

Abstract

The Meteosat archive contains more than 15 years of observations. Potential contributions of this unique data set to climate studies are discussed. Such studies require however (i) the documentation of the actual radiometric quality of the data, (ii) the re-calibration of these data with state-of-the-art vicarious techniques, (iii) the application of stable and robust algorithms for the extraction of products. To take the best advantage of this archive and to control its quality, a reprocessing environment has been set up at EUMETSAT. This facility permits the re-extraction of meteorological products as well as the hosting of new algorithms, specifically dedicated to climate studies.

1 INTRODUCTION

The Meteosat satellite system was designed nearly 30 years ago, essentially for real-time operational imagery purposes. The primary objective of this Programme is the acquisition of Earth atmosphere images and their dissemination to the users community. The potential value of Meteosat data for climate monitoring should however not be underestimated. During the late seventies and early eighties, space-borne observations of the Earth were very scarce, essentially limited to geostationary meteorological observations and a few polar platforms. The extent of the Meteosat observations, acquired every half an hour in almost identical conditions during more than 15 years, represents a potentially valuable input to climate monitoring. This paper discusses promising contributions of Meteosat data to climate studies in the light of the actual archive state.

The utilisation of this archive for such purpose, however, raises several technical and scientific issues about radiometric quality, geometric rectification and finally data calibration. The various Meteosat sensors exhibit small technical differences between themselves, and radiometric anomalies occurred on several instruments. Additionally, calibration and retrieval techniques have been improved, in particular during the late eighties. As a result, the archived calibration coefficients, if any, and the meteorological products cannot be used in a straightforward way for long time series analysis. Their utilisation for climate monitoring would first require the reprocessing of the Meteosat archive with state-of-the-art calibration schemes and retrieval algorithms. To this end, EUMETSAT has established a reprocessing facility, which also allows the hosting of new retrieval algorithms dedicated to climate and environment monitoring. The output of such algorithms should increase the intrinsic value of the Meteosat archive and provide feedback on the actual archived data quality. In this context, a new algorithm, designed for the surface albedo estimation, has already been implemented in this new reprocessing environment. This algorithm has been developed by the Space Applications Institute of the EC Joint Research Centre in the framework of a bilateral collaboration between the two organisations. First results of this algorithm are presented elsewhere in this conference (Pinty et al. 1999).

2 POTENTIAL SUPPORT TO CLIMATE INVESTIGATIONS

Space-borne observations support an increasing number of climate investigations and thereby contribute directly to our knowledge and understanding of the Earth as a global and integrated system. Over the last two decades, most of these space-based data have been acquired by operational meteorological satellites which have, in general, not been designed for this objective. These observations, however, represent a unique data set whose exploitation for climate monitoring is worthwhile, as already demonstrated by the Pathfinder Programme, initiated jointly by NASA and NOAA.

Climate observation can be categorised into two fundamental approaches. The first one aims at *understanding* climate processes and their variability. The second one addresses the *detection* of climate change. The International Satellite Cloud Climatology Project (ISCCP) represents a typical example of the first approach. It was the first project of the World Climate Research Programme (WCRP) tasked to produced a global data set on cloud parameters that should ultimately promote research to improve the understanding of the Earth's radiation budget and the hydrological cycle (Schiffer and Rossow 1983). The possibility of detecting trends from these data is essentially constrained by the magnitude of the expected change, which defines the required calibration accuracy. So far, it has not been possible to detect any climate trends from geostationary satellite observations.

Geostationary satellites do not provide a global view of the Earth and their performance in terms of spatial resolution and radiometric noise generally lags behind those of polar orbiting satellites. They are actually designed for the monitoring of synoptic events and their orbital position is precisely maintained. These features, in conjunction with their programme duration, represent a clear advantage in *understanding* regional climate processes better and their variability. Most relevant parameters that can be extracted from the Meteosat archive to study regional climate processes are listed below.

- Water vapour feedback plays a crucial role in the amplification of the warming effect induced by the greenhouse gas increase as already confirmed by satellite data (*e.g.*, Rind et al. 1991). Meteosat satellites offer the advantage of observing diurnal variations of convective processes (Schmetz et al. 1997) and **Upper Troposphere Humidity** (UTH). The derivation of UTH can benefit from coordination efforts among the various geostationary satellites (Schmetz et al. 1995) and recent improvements in the calibration of the water vapour band (van de Berg et al. 1995).
- **Outgoing Long wave Radiation** (OLR) (*e.g.*, Schmetz and Liu 1988) reflects the response of the Earth to solar diurnal forcing. It and the UTH, they represent relevant parameters for model validation over diurnal, seasonal and inter-annual cycles over regions such as the Saharan desert, the intertropical convergence zone or the Atlantic ocean.
- The possibility of retrieving cloud properties from Meteosat observations is limited, but the derivation of **cloud cover**, temperature and motion could benefit from Meteosat Second Generation (MSG) algorithmic developments (*e.g.*, Lutz 1999).
- **Surface albedo** represents an important parameter that controls the Earth radiation budget. Recent progress in fast radiative transfer modelling permits the operational extraction of this parameter, accounting for the surface anisotropy and atmospheric effects (Pinty et al. 1998).
- **Land surface temperature** is subject to important diurnal variations that can be correctly sampled only with geostationary satellites. Limitations in calibration and radiometric accuracy would probably prevent the detection of any long-term trend. Nevertheless, daily variation amplitude conveys useful information on soil moisture (*e.g.*, Wetzel and Woodward 1987).
- **Aerosols** play a major role in the Earth radiative forcing mechanism. Moulin et al. (1997) have demonstrated the possibility of deriving aerosol load over ocean using the Meteosat solar

channel data. These authors claimed that the seasonal variability of atmospheric dust exported from North Africa over the Atlantic Ocean and Mediterranean Sea is well correlated with the climatic variability defined by the North Atlantic Oscillation.

The feasibility to derive these parameters has been demonstrated and they can potentially contribute to an understanding of both atmospheric and surface processes and their variability. Their extraction over a long period of time should provide valuable information for the *validation* of climate models or for the support of reanalysis efforts.

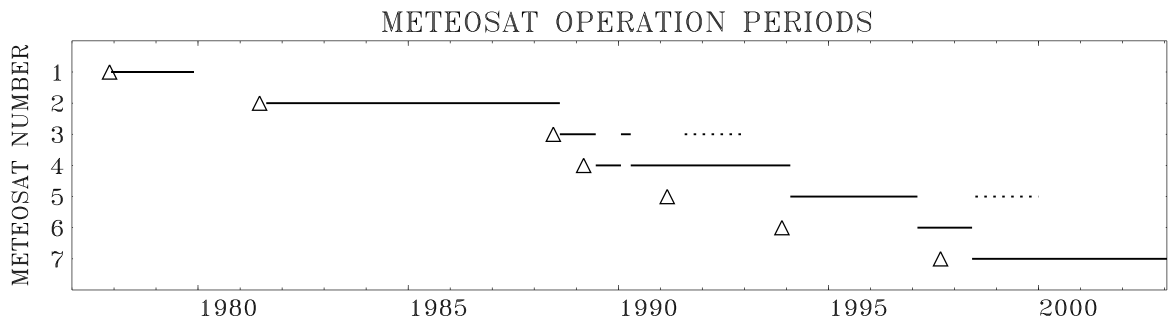

Figure 1: Meteosat launch dates (△ symbol) and operation periods (horizontal solid lines). Dashed lines correspond to operation at 50°W for Meteosat-3 and 65°E for Meteosat-5. Meteosat-7 is expected to be operational until 2003.

3 THE METEOSAT ARCHIVE

The Meteosat archive is essentially composed of image data acquired in three bands (visible (VIS) 0.4–1.1μm, water vapour (WV) 5.7–7.1μm and infrared (IR) 10.5–12.5μm) and real-time meteorological products. This data set originates from seven different spacecraft as can be seen in Figure (1), divided into three different periods: pre-operational (Meteosat-1 to -3), operational (Meteosat-4 to -6) and a transition phase to MSG (Meteosat-7). The image format, which has evolved, contains the raw data in digital count, deformation matrices used for the geometric rectification, and finally ancillary information such as the sensor configuration and orbital parameters.

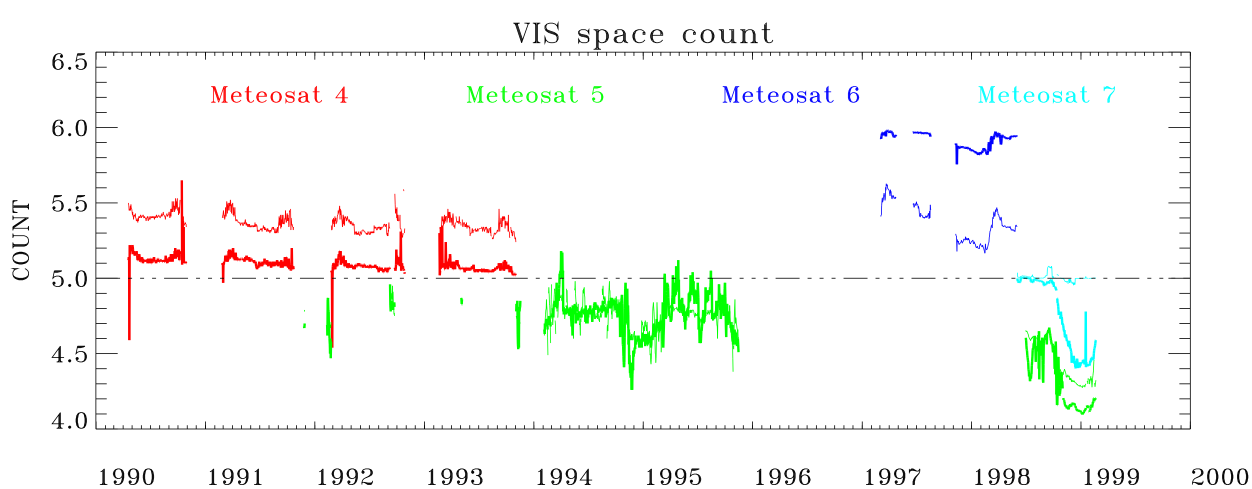

Figure 2: Mean space count values (slot 24) of the VIS 1 (thin line) and VIS 2 (thick line) detectors on board Meteosat-4 to -7. Theoretical value is 5 counts.

Meteosat sensors exhibit slightly different characteristics in terms of digitisition, scanning mode, black body calibration device and radiometric quality. Figure (2) illustrates for instance differences in the VIS band space count values from Meteosat-4 to -7. The quality of real-time thermal band vicarious calibration and retrieval algorithms has been significantly improved since the early eighties. All these changes need to be fully understood and documented before any attempt to exploit the archive for climate applications can be endeavoured. This section reviews our current knowledge of the actual Meteosat archive state.

Meteosat-1 was launched on 23 November 1977 as an experimental spacecraft. Its radiometer originally included only the VIS and IR bands. The WV channel was added only lately in the sensor design. As the downlink rate did not support this additional band, a special scanning mode was used, where the VIS_N and WV detectors were alternated during daytime, *i.e.*, from 06:00 UT to 18:00 UT. During night time, the WV channel was permanently selected. Both VIS and WV bands were coded on 6 bits (64 levels) and the IR one on 8 bits (256 levels). VIS and WV bands are expanded to 8 bits in the archive, adding noise to the last two digits. On 25 November 1979, the Meteosat-1 radiometer failed prematurely due to a fault in a tiny resistor. During its two years lifetime, no radiometric anomalies occurred, except that the signal-to-noise ratio (SNR) of the WV band was higher than expected. The rectification technique was very similar to the current one but not as accurate. It relied on the detection of the Southern horizon, *i.e.*, edge of the Earth disk, and orbital parameters. The operational extraction of meteorological products starts in 1978 with the Cloud Motion Wind (CMW) extracted at 12:00 UT and 24:00 UT and Sea Surface Temperature (SST). Calibration of the IR band was performed using the black body mechanism, one cold (space) including the full optical chain and one hot which accounts only of the inner one. A vicarious calibration, based on surface temperature observations, was also performed for the thermal bands. At that time, only a six month rolling archive was foreseen. Fortunately, and thanks to the effort of few individuals at ESA, data in this rolling archive has never been deleted, and so the Meteosat archive was born. The format used to archive the images is, unfortunately, poorly documented, and data are still on the original tapes. Important orbital information is missing.

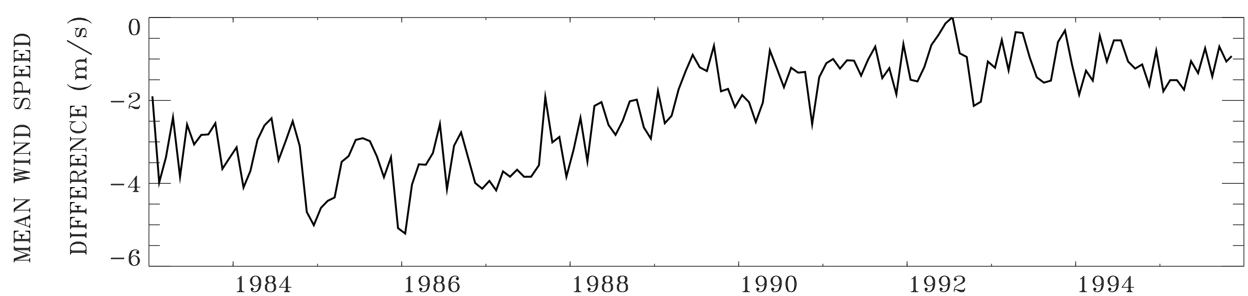

Figure 3: Wind speed difference (m/s) between collocated radiosondes and high infrared cloud motion winds.

Meteosat-2, launched on 19 June 1981, had the longest operational lifetime, *i.e.*, from 1981 to 1988. Retrieval algorithm quality has progressed significantly during that period. These modifications concern essentially IR and WV band calibration, image rectification, on-line radiative transfer computation, quality control, cloud tracking mechanisms and new products, such as for example water vapour and high resolution winds (*e.g.*, Schmetz 1989; Schmetz et al. 1993). The overall impact of these improvements included a 2 m/s reduction of the mean wind speed bias derived from the infrared band (Figure 3). Vicarious calibration of the VIS band has been performed by Koepke (1982) by means of radiative transfer computation over well documented sites as well as aircraft observations.

The estimated mean accuracy of the rectification is about 2.5 IR pixels with respect to the reference grid and 0.7 IR pixels root mean square error for slot to slot (de Aragon 1986). This accuracy is limited by seasonal variations of the Earth apparent contour. Meteosat-2 images were archived using the so-called IMAG1TG image format. Important ancillary data, essentially orbital parameters, are missing in this format. This information would be necessary to recompute the deformation matrices using the latest version of the algorithm, or to redefine the eclipse periods. Data archiving has been conducted as an operational activity since Summer 1983. The possibility of exploiting data before this date remains to be determined.

Meteosat-3, an engineering model refurbished in the mid-eighties, was the last satellite of the pre-operational phase. It was launched on 15 June 1988, when the sensor was already 12 years old. The scanning mode and coding mechanism is similar to Meteosat-1. The quality of the rectification was stable. There is no known major radiometric anomaly. The black body calibration device failed, but, hopefully, the real-time vicarious technique of the cold bands was already operational. Vicarious calibration of the VIS channels revealed a high sensor degradation (Moulin et al. 1996). In August 1991, Meteosat-3 was moved to 50°W in anticipation of a gap in the coverage normally provided by USA satellites. These observations were archived but no product extraction took place. Meteosat-3 data were archived using the IMAG2TG format, which is quite similar to the current archive format.

Meteosat-4, launched on 6 March 1989, is the first satellite of the Meteosat Operational Programme (MOP). Major differences with respect to the pre-operational radiometers are: (1) all channels are coded on 256 levels, (2) the three channels are always scanned in full resolution and (3) the on-board black body calibration mechanism of the thermal channels is composed of two black bodies, one cold and one warm, which share the same inner optical chain. For technical reasons, it was not possible to use this mechanism. One major radiometric anomaly is known for the Meteosat-4 radiometer, referred to as "fish". This anomaly is due to a premature aging problem on the analogue-to-digital convertor and shows a well identified signature that can be minimised using neighbouring pixels. Luckily, this problem did not occur simultaneously on both convertor so that it was possible to switch from one detector to the other one. During the development of that correction scheme, Meteosat-3 was imaging from the backup position of 10°W. The computation of the deformation matrices used by the rectification process was improved to account for the seasonal variations of the North-South apparent horizon, providing a mean rectification absolute accuracy of about one IR pixel. Moreover, a ground control point (land marks) technique was implemented to monitor the quality of the rectification.

Meteosat-5 was launched on 3 March 1991 as the second operational satellite. Its instrument has one imaging problem, referred to as "rotating lens". A lens in the cold optical path was not been correctly installed and rotates in its support, affecting the accuracy of the rectification. This effect is at a maximum along the North-South direction, close to the Equator. Since the computation of the deformation matrices is based on the IR images, it affects also the WV and VIS image rectification. This problem has been progressively fixed in the rectification algorithm during the first three years of the satellite lifetime. The remaining maximum rectification error is about two IR pixels.

In November 1995, data processing and archiving were transferred from ESA/ESOC to EUMETSAT headquarters. Since July 1998, Meteosat-5 has been imaging at 65°E over the Indian ocean in support of the INDOEX experiment. Both images and meteorological products are archived.

Meteosat-6 was launched on 20 November 1993. The technical problem that prevented the use of the black body calibration on the two previous spacecraft was fixed. Nevertheless, this mechanism was useless on this spacecraft, because of a major radiometric anomaly in the IR band. The gain of this band exhibits random jumps while an image is scanned. Albeit a correction algorithm was developed to minimise the impact of this anomaly on the image quality, the operational period of Meteosat-6 was limited to one year. It has been replaced by **Meteosat-7**, launched on 2 September 1997, the current operational satellite. So far, its radiometer functionality is nominal, in particular the black body calibration. Meteosat-7 will be operational until 2003.

As can be seen from this review, the use of the Meteosat archive for climate research will depend on the possibility of controlling and documenting changes in the radiometric accuracy, image rectification and calibration.

- **Radiometric accuracy** has changed from satellite to satellite, in particular between the pre-operational and operational phase. The WV channel of the pre-operational Meteosat radiometers appears to be very noisy (de Aragon 1986). Meteosat-4 to -6 instruments had anomalies, but correction software should reduce their effect on the radiometric quality. Equalisation between the two detectors of the VIS band is far from optimal and could in principle benefit from the enhanced method developed for MSG.

- Image **rectification** is based on archived deformation matrices, whose calculation method has been improved. The re-computation of these matrices requires detailed information on orbital parameters, not available in the IMAG1TG format. This information should however still exist on separate tapes. The accuracy of the rectification can be documented thanks to a ground control point technique implemented in the rectification algorithm.

- Data **calibration** and sensor drift monitoring is certainly the most critical issue. Operational calibration of the thermal bands has been subject to constant improvement and should clearly be re-estimated using state-of-the-art techniques. Current investigation based on satellite cross-calibration highlighted discrepancies in the calibration of the WV channel of Meteosat-5 (Schmetz et al. 1999).

  The absolute calibration of the VIS band has been performed with only a very limited number of airborne campaigns (Kriebel and Amann 1993). A rigorous monitoring of the sensor drift is highly desirable, using the advanced approach developed for MSG (Govaerts et al. 1998). In addition, the pre-launch characterisation of the VIS band spectral response is doubtful for Meteosat-5 and -6 (Govaerts 1998).

4 THE EUMETSAT REPROCESSING ENVIRONMENT

Recognising the value of the Meteosat data set and the need to control and document the quality of these data, EUMETSAT set up a reprocessing chain or R-MPEF (Reprocessing Meteorological Products Extraction Facility)[1]. This environment should permit the re-calibration of the data and the generation of a comprehensive time series of the meteorological products.

R-MPEF is essentially based on the software developed for the on-line processing of real-time observations. Major modifications are: (i) input data originate directly from the Meteosat Archive and Retrieval Facility (MARF); (ii) the task scheduler is data-driven; and (iii) the product dissemination is restricted to the MARF, *i.e.*, no products from R-MPEF are sent on the Global Telecommunication System (GTS). R-MPEF allows the fully automated extraction and archiving of the products, including the monitoring of statistics on image quality, rectification accuracy, calibration coefficients and extracted products.

The reprocessing environment has already been used to generate one year of surface albedo with an algorithm developed by Pinty et al. (1998). This algorithm benefits from the latest developments in terms of fast radiative transfer modelling and inversion techniques. This collaboration has been initiated as a demonstration activity to study spatial and seasonal variations of the surface albedo in the Meteosat VIS spectral band at the full VIS pixel resolution. First results are shown in Figure (4). This new product is currently being validated.

[1]The elaboration of this reprocessing facility was triggered by a request from the European Centre for Medium-Range Weather Forecasts to support their ERA-40 re-analysis project.

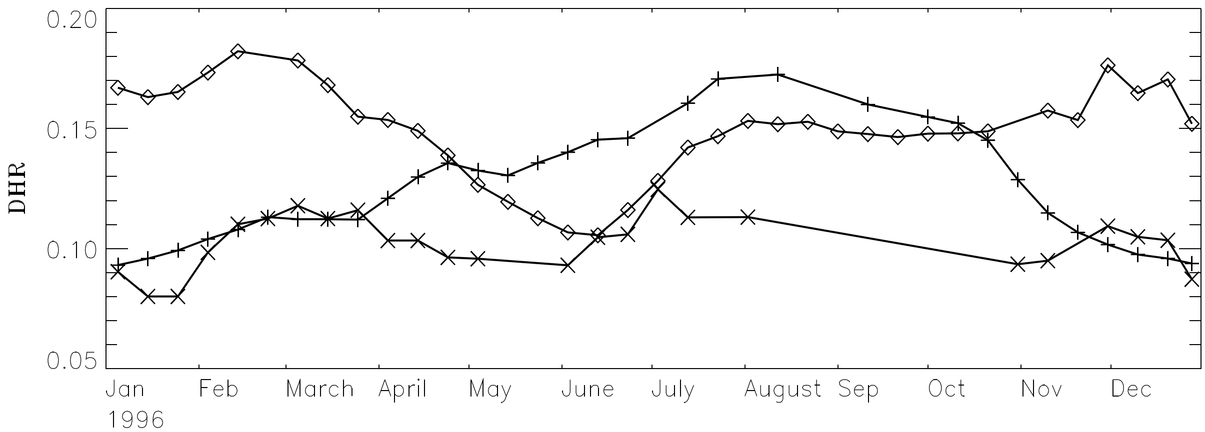

Figure 4: Seasonal variations of the Meteosat surface albedo (Directional Hemispherical Reflectance, DHR) in 1996 over three different regions: tropical forest ($\times$), Nile river delta ($\diamond$) and a semi-arid area in Senegal (+).

From this first exercise, the reprocessing environment has proven to be very robust, requiring only limited maintenance. It has demonstrated the possibility to implement and run new retrieval algorithm, dedicated to climate and environment applications. Such physically-based algorithms provide a useful feedback on the actual archive quality. This reprocessing lasted for four months, which means that, on the average, three days of Meteosat observations were processed per calendar day. The extraction and rectification of images from the MARF represented the main limiting factor. Future reprocessing of long period will clearly require a faster retrieval rate in order to keep the duration of the process within acceptable limits. This issue may be critical when old data are reprocessed. Not all the archive has been transcribed to modern storage devices, and data prior to 1984 are still on their original tapes. Reading these tapes often requires lengthy and costly recovery procedures.

5 CONCLUSIONS

Geostationary observations offer various advantages for climate investigations. In particular, the Meteosat archive can contribute to the analyse of *regional* climate processes and their variability, as already demonstrated by studies based on ISCCP data. The possibility of detecting climate trends has however not been demonstrated so far, essentially because of the limited calibration accuracy. Typical parameters that can be extracted from the Meteosat archive are, among other, UTH, cloud cover, wind vorticity, aerosol load, surface temperature and its diurnal variation, and, finally, surface albedo. The extraction of these products can benefit from coordination efforts between the various geostationary platforms' operators.

The exploitation of this data set is not straightforward due to data inhomogeneity. A reprocessing environment as been set up at EUMETSAT to control the archive quality, provide state-of-the-art calibrated data and generate consistent products to support climate research. An initial data reprocessing consisting of the extraction of surface albedo for 1996 has already demonstrated the potential of this environment.

The main role of EUMETSAT is to document the data quality and to calibrate the observations as accurately and precisely as possible. Analysing the temporal and spatial consistency of products extracted with physically-based algorithms provides the ultimate verification of the archive quality. Finally, through this reprocessing activity, EUMETSAT is acquiring experience in processing large data sets.

References

de Aragon, A. M. (1986). A contribution to the quality analysis of Meteosat image data. In EUMETSAT (Ed.), *6th METEOSAT Scientific Users' Meeting*, Amsterdam, The Netherlands.

Govaerts, Y. M. (1998). Correction of the Meteosat-5 and -6 VIS band relative spectral response with Meteosat-7 characteristics. *Int. J. Remote Sensing In print.*

Govaerts, Y. M., B. Pinty, M. M. Verstraete, and J. Schmetz (1998). Exploitation of angular signatures to calibrate geostationary satellite solar channels. In IEEE (Ed.), *IGARSS'98*, Seattle, USA, pp. 327–329.

Koepke, P. (1982). Vicarious satellite calibration in the solar spectral range by means of calculated radiances and its application to Meteosat. *Applied Optics 21*, 2845–2854.

Kriebel, K. T. and V. Amann (1993). Vicarious Calibration of the Meteosat visible channel. *J. Atm. Ocean Techn. 10*, 225–232.

Lutz, H. J. (1999). Scenes and cloud analysis for Meteosat Second Generation. EUMETSAT Tech. report 4 In preparation, EUMETSAT.

Moulin, C., C. E. Lambert, F. Dulac, and U. Dayan (1997). Control of atmospheric export of dust from North Africa by the North Atlantic Oscillation. *Nature 387*, 691–694.

Moulin, C., C. E. Lambert, J. Poitou, and F. Dulac (1996). Long term (1983-1994) calibration of the Meteosat solar (VIS) channel using desert and ocean targets. *Int. J. Remote Sensing 17*, 1183–1200.

Pinty, B., F. Roveda, M. M. Verstraete, N. Gobron, and Y. Govaerts (1999). Estimating Surface Albedo from the Meteosat Data Archive: a Revisit. In EUMETSAT (Ed.), *The EUMETSAT Satellite Data Users' Conference*, Copenhagen, Denmark, In print.

Pinty, B., F. Roveda, M. M. Verstraete, N. Gobron, Y. Govaerts, N. Gianni, and J. Verdebout (1998). Meteosat Surface Albedo Retrieval: Algorithm Theoretical Basis Document. JRC Publication No. EUR 18130 EN, Space Applications Institutes.

Rind, D., E.-W. Chiou, W. Chu, J. Larsen, S. Oltmans, J. Lerner, M. P. McCormick, and L. McMaster (1991). Positive water vapour feedback in climate models confirmed by satellite data. *Nature 349*, 500–503.

Schiffer, R. A. and W. B. Rossow (1983). The Internation Satellite Cloud Climatlogy project (ISCCP): The first project of the World Climate Research Programme. *Bulletin of the American Meterological Society 64*, 779–784.

Schmetz, J. (1989). Operational calibration of the Meteosat water vapour channel by calculated radiances. *Applied Optics 28*, 3030–3038.

Schmetz, J., K. Holmlund, J. Hoffman, B. Strauss, B. Mason, V. Gaertner, A. Koch, and L. Van De Berg (1993). Operational cloud-motion winds from Meteosat infrared images. *J. Appl. Meteo. 32*, 1206–1225.

Schmetz, J. and Q. Liu (1988). Outgoing longwave radiation and its diurnal variation at regional scales derived from Meteosat. *J. Geophys. Res. 93*, 11192–11204.

Schmetz, J., B. J. Sohn, M. Koenig, S. Tjemkes, H. Lutz, and A. Arriaga (1999). Satellite intercalibration of the Meteosat water vapour channel. In EUMETSAT (Ed.), *The EUMETSAT Satellite Data Users' Conference*, Copenhagen, Denmark, In print.

Schmetz, J., S. A. Tjemkes, M. Gube, and L. van de Berg (1997). Monitoring deep convection and convective overshooting with METEOSAT. *Adv. Space Res. 19*, 433–441.

Schmetz, J. P., P. Menzel, C. Velden, X. Wu, L. van de Berg, S. Nieman, C. Hayden, K. Holmlund, and G. Carlos (1995). Monthly mean large scale analyses of upper tropospheric humidity and wind field divergence derived from three geostationary satellites. *Bull. Amer. Met.er Soc. 76*, 1578–1584.

van de Berg, L. C. V., J. Schmetz, and J. Whitlock (1995). On the calibration of the Meteosat water vapor channel. *J. Geophys. Res. 100*, 21069–21076.

Wetzel, P. J. and R. Woodward (1987). Soil moisture estimation using GOES-VISSR infrared data: a case study with a simple statistical model. *J. Clim. Applied Meteor. 26*, 107–117.