P4.10

SHORTWAVE RADIATIVE FLUX MONITORING OVER SOUTH AMERICAN AREA USING GOES VIS IMAGERY

Juan Carlos Ceballos (*) and Marcus Jorge Bottino (*)
Centro de Previsão de Tempo e Estudos Climáticos
Instituto Nacional de Pesquisas Espaciais - Brazil

ABSTRACT (*). Mean daily solar irradiance is assessed at CPTEC/INPE (Brazil) based on GOES VIS channel imagery, covering a region which includes South America and neighboring oceanic areas with space resolution of about 12 km. It is a simplified physical model, considering two broad bands for solar spectrum (visible+ultraviolet, and infrared). Version GL1.2 considers an atmosphere with low aerosol optical depth. Monthly means of solar irradiance show performance compatible with the proposal of bias lower than 10 $W.m^{-2}$ and standard deviation lower than 25 $W.m^{-2}$ in regions without influence of burning mass forests/cultures or urban industrial pollution.

1. INTRODUCTION

Solar irradiance at ground level has been assessed using satellite VIS data since the end of '70 years. Geostationary satellites are especially useful for this task due to the higher rate of daily images and the large area coverage. Pioneering works like the statistical model of Tarpley (1979) and the physical one of Gautier et al. (1980) have been followed by a number of variants up to present days. Physical models are at least formally able of taking detailed atmospheric characteristics into account. Although they need some information about regional physical parameters and atmospheric profile (ground reflectance, water vapor content, visibility or aerosol load, for instance), their definite advantage is the use of factor reflectance only as local variable; "ground truth" data is used only for model quality monitoring. These advantages make them useful for solar radiation assessment throughout large areas (Stuhlmann *et al*., 1990; Stackhouse *et al*., 2001).

Cloud parameterizations account for main variability effects on solar radiation at ground level. Careful modeling of solar radiation transfer allows to expect a quasi-linear relationship between shortwave net fluxes at the top of the atmosphere (TOA) and ground level, the key variable being cloud cover *C* (Schmetz, 1993; Ramaswamy and Freidenreich, 1998). Global irradiance *G* would follow an equation close to $G = a + b\ C$, where coefficients *a* an *b* can be deduced from clear air and full-cloudy model calculations, and cloudiness *C* is assessed from simple hypotheses concerning VIS reflectance factor (Stuhlmann *et al*., 1990). Another approach may be of multiband type (Pinker and Laszlo, 1992), considering an atmosphere with a "mean" stratiform cloud for which an equivalent optical depth is assessed from factor reflectance observed in VIS channel. Surface solar radiation is then calculated in several broad bands and *G* is obtained by addition. Observing the spectral location of distinctly different physical behaviors, solar radiation may be split up into two main broadband intervals: a) ultraviolet and visible, b) solar infrared, each of them allowing for specific simplifying assumptions. This is the basic idea of the GL model running operationally at CPTEC/INPE, which uses GOES VIS imagery for daily monitoring of solar radiation over a large region including South America and neighboring ocean areas. High impact applications of the model are currently in course, such as input for soil moisture assessment for agricultural/ hydrological purposes and for modeling of sea-atmosphere interaction in the Atlantic basin.

2. GL 1.2 VERSION STRUCTURE

The model uses 4 km resolution GOES VIS imagery (up to two images in one hour). Global irradiance is assessed for that pixel, and the average of a 3×3 pixel results is adopted, in order to account for mean lifetime of cloud evolution within a pixel and about half an hour ("ergodic hypothesis"). The mean irradiance within one day is obtained by the usual trapezoidal integration during the whole diurnal cycle, divided by 24 hours.

Basic considerations are the following (full description is found in Ceballos et al., 2004):

- Ultraviolet radiation (UV: 0.2-0.4 μm) incident on TOA is mainly absorbed in the stratosphere (z >17 km). The use of radiative codes as SBDART (Ricchiazzi et al., 1998) makes evident that UV1 radiation (0.2-0.28 μm) is almost completely depleted in the stratosphere, while for UV2 radiation (0.28-0.4 μm)

* Corresponding address: Divisão de Satélites e Sistemas Ambientais – CPTEC/INPE – 12630 Cachoeira Paulista, SP – Brazil. E-mails: ceballos@cptec.inpe.br, bottino@cptec.inpe.br

only 1.4 $W.m^{-2}$ or less would be depleted in the troposphere in clear-sky conditions. Also, Rayleigh scattering is low in the stratosphere.

- Interaction with the troposphere is nearly conservative for visible radiation (VIS: 0.4-0.7 μm), when considering the influence of clouds and atmospheric gases like H_2O and CO_2. The model assumes an atmosphere with aerosol optical depth typical of rural areas (lower than 0.2).
- Solar infrared (IR: 0.7-3.0 μm) has negligible Rayleigh scattering, so that depletion by atmospheric gases (H_2O, CO_2) operates only on direct beam. A cloud exhibits high reflectance and negligible diffuse transmittance, thus blocking the infrared direct beam.
- These simplifying assumptions are compatible with inaccuracy inherent to accept isotropic reflectance of Earth-atmosphere system and a clear separation between cloud-contaminated and of cloudy pixels (in order to assess cloudiness *C*).

Total global irradiance is assessed adding VIS+UV and IR components *Gvisuv* and *Gir*. With these assumptions, and given that cloud reflectance is similar in UV2 and VIS intervals, a simple balance equation can be stated for the troposphere in order to assess global radiation *Gvisuv*:

$$\mu_o\, S(\text{uv2+vis})\; .\; T3(\mu_o) =$$
$$= \mu_o\, S(\text{uv2+vis})\; .\; Rp/T3(\mu_s) + (1 - Rg)\, Gvisuv \quad (1)$$

Here, *S* describes flux density of solar beam incident on TOA, $T3(\mu_o)$ represents transmittance due to ozone in the stratosphere and $T3(\mu_s)$ introduces the correction in VIS interval for an emerging beam towards satellite (μ is cosine of zenithal angle); *Rp* is planetary reflectance as assessed by VIS channel. Ground reflectance in this interval is given by *Rg*.

Solar global irradiance in infrared *Gir* implies in stating

$$Gir = \mu_o\, (Sir - \Delta S)\, (1 - C) / (1 - Rgiv.\, C\, Rc) \qquad (2)$$

ΔS accounts for gas absorption of direct beam, parameterized as a function of total precipitable water, CO_2 total column content and solar zenith angle. Denominator describes a correction due to multiple reflection between ground and cloud base (reflectances $Rgiv \approx Rc \approx 0.4$).

Cloudiness is assessed assuming that reflectance observed in VIS channel is a weighted value between extreme values of clear-sky and cloudy pixels (Stuhlmann *et al.*, 1990), which implies

$$C = (Rp - Rclear)/(Rcloud - Rclear). \qquad (3)$$

Nevertheless, *Rcloud* does not refer to the maximal reflectance observed in an image, but to the transition between cumulus-contaminated and stratiform pixel. A classification procedure for South American images suggests the threshold value *Rcloud* = 0.465 (Ceballos *et al*., 2004).

3. GL 1.2 PERFORMANCE

Figure 1 illustrates comparison of modeled mean daily irradiances with measurements of pyranometers in three environments: Florianópolis (urban, island near continent), São Paulo (urban, industrial) and Cachoeira Paulista (rural), October 2002. It is seen that clear-sky and full-cloudy values are correctly retrieved. Overestimation for lower cloudiness in São Paulo is due to polluted atmospheric conditions. Excellent fitting for lower irradiances gives support to hypotheses concerning cloud properties in infrared spectrum. Deviations for intermediate values of irradiance suggest that the threshold *Rcloud* may exhibit regional and seasonal values.

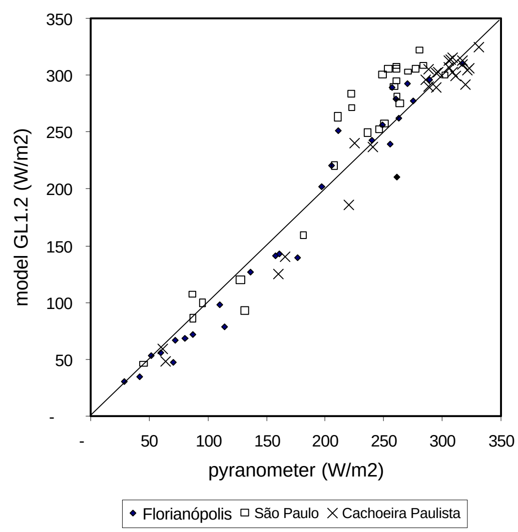


Figure 1*.* Daily mean irradiance, October 2002, for Florianópolis, São Paulo and Cachoeira Paulista sites. Ground data: pyranometers. Source: Ceballos *et al.* (2004)

Figures 2 illustrate monthly mean irradiance and standard deviation of daily values obtained for March 2004. Daily and monthly figures are released in the site http://satelite.cptec.inpe.br/htmldocs/radiacao/radsol/portal/radiacao_new.htm since September 2002. Although solar irradiance is being assessed for 0.04 degree resolution, corresponds to a mean over 3×3 pixels (about 0.12 degree) in order to account for half an hour fluctuations of irradiance and better daily integration.

It is worthwhile to note that reflectance *Rvis* obtained for GOES 8 imagery were corrected for degradation of VIS sensor, according to calibration proposed by NOAA-NESDIS. *Rp* values obtained for GOES 12 are not yet being corrected since May 2003, in despite of sensor degradation suggested by systematic deviation from observed ground truth. Comparison of GOES 8- based assessments with pyranometers made evident a mean deviation and standard deviation of about 5 $W.m^{-2}$ for daily values, or about 2.5% for typical mean irradiances of 200 $W.m^{-2}$. In general, a possible error of 5% might be accepted.

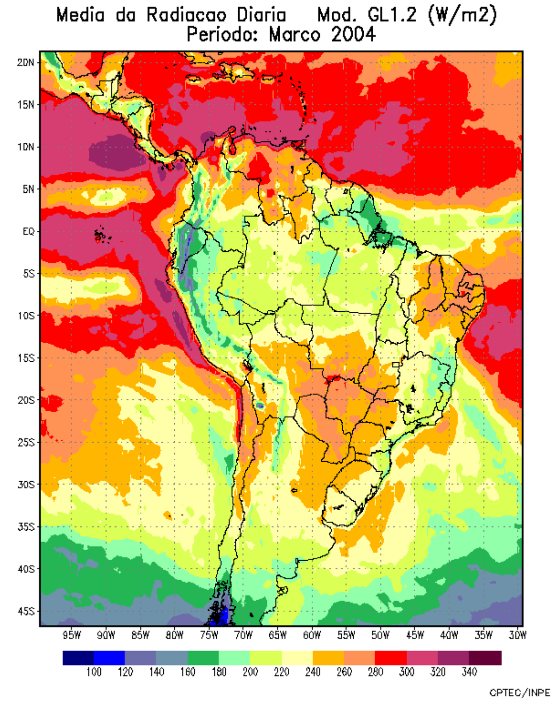
Monthly comparison with ground truth makes use of a network of more than 100 automatic stations throughout Brazil. Although solarimeters (LiCor) may not have the accuracy of second class pyranometers, they show a satisfactory behavior if proper maintenance is held. Standard error is lower than 20 $W.m^{-2}$ when daily values are averaged within 2.5x2.5 degrees cells (Ceballos *et al*., 2004); comparison with this network suggests an annual cycle of mean bias ranging from +10 to –10 $W.m^{-2}$, with amplitude of about 10 $W.m^{-2}$. These values are close to proposed requirements of 10 $W.m^{-2}$ for mean deviation and 25 $W.m^{-2}$ for standard deviation (Whitlock *et al*., 1995). The cycle may be induced by cloudiness assessment, affected by regional and seasonal values of *Rmax*.

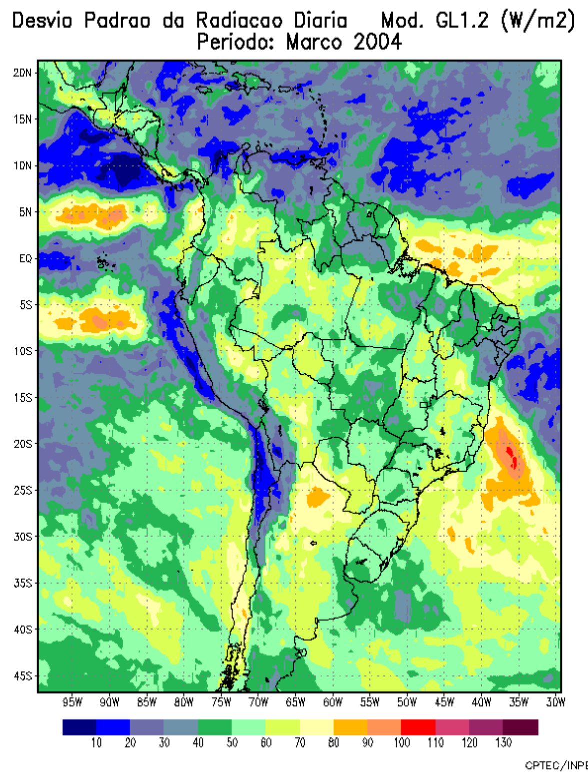
Figures 3 below show mean monthly deviations for March 2004, using GOES 12 data. It is seen that they are typically lower than 10%. The comparison makes evident a fairly good performance of GL1.2 model. On the order hand, observation of higher deviations allow for detection of problems concerning automatic station themselves (labeled with red symbols), generating an alert for maintenance services (removing dust deposition from the sensor is usually enough).

Some considerations must be pointed out.

a) GOES 12-based results during 2004 suggest errors of about 0-30 $W.m^{-2}$ over Eastern Brazil. A closer observation of time series suggests a systematic deviation of about +20 $W.m^{-2}$ over the region, which could be due to VIS sensor degradation.

b) Version 1.2 of the model does not include the effect of aerosols. This fact induces higher values of irradiance. The effect is particularly strong during dry season in Amazon region (August-October), due to intense burning for agricultural of deforestation reasons. Daily deviations between model and ground truth may usually attain 50 $W.m^{-2}$ and more over stations located at hundreds of kilometers of intense fires. High deviations for this region are observed in other models, even with 2.5 degree grid mean values (Pinker *et al.*, 1995).





Figures 2*.* Mean solar irradiance assessed by GL 1.2 model for March 2004. Bottom: standard deviation of daily values.

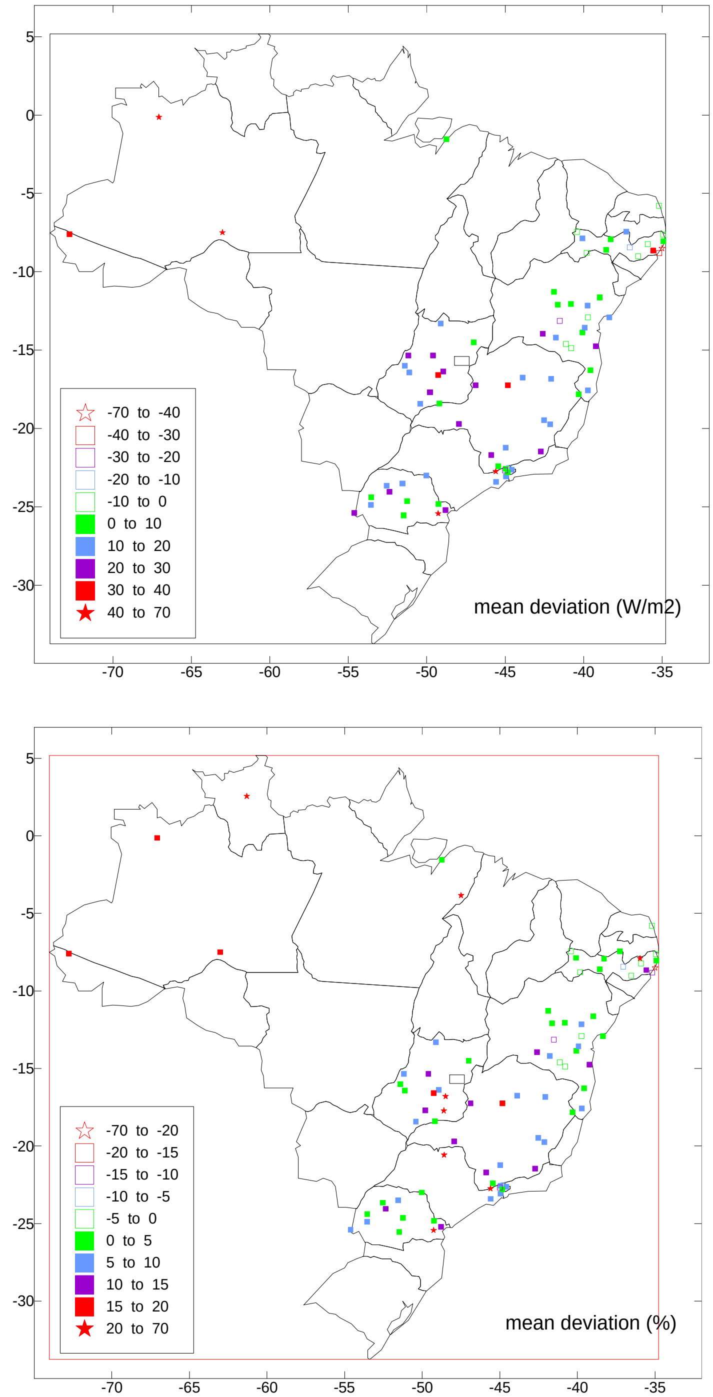


Figure 3. Monthly mean deviation for March 2004 (top: values in $W.m^{-2}$; bottom: percentage of monthly mean irradiance). Analysis of station data labeled in red suggests problems in maintenance, rather than micrometeorological or modeling reasons.

c) Better definition of parameters like precipitable water and ground reflectance may improve model performance. Present version assumes typical ground reflectance *Rg*= 0.06 in VIS spectrum, and constant values of precipitable water over extended regions. Daily distribution will be introduced in a next future, based on NWP models output at CPTEC.
d) Better parameterizations of water vapor absorption may improve performance for low cloudiness situations, yet limited to less than 10 $W.m^{-2}$ (Ceballos *et al.*, 2004).
e) Availability of high frequency imagery is a critical aspect for model performance. This can be a seasonal serious problem for latitudes South from 20°S for GOES images.

4. FINAL CONSIDERATIONS

The GL 1.2 model exhibits a behavior compatible with usual performance required for this kind of model. It has a simplified but physically clear structure which allows to introduce further improvements in a simple manner. In particular, seasonal and regional atmospheric and surface variables will be introduced in a near future. Low optical depths of aerosol do not introduce high errors, if considered those associated to water vapor content fluctuations and cloudiness assessment. Introduction of aerosol physics in the case of high optical depth is in progress.

5. REFERENCES

Ceballos, J.C., M.J. Bottino, and J.M. d Souza (2004), A simplified physical model for assessing olar radiation over Brazil using GOES 8 visible imagery, J. of Geophys. Res., vol. 109, D02211, doi:10.1029/ 2003JD003531.

Gautier, C., G. Diak, and S. Masse (1980), A simple physical model to estimate incident solar radiation at the surface from GOES satellite data, *J. Appl. Meteorol.*, 19, 1005–1012.

Pinker, R. T., and I. Laszlo (1992), Modeling surface solar irradiance for satellite applications on global scale, J. Appl. Meteorol., 31, 194– 211.

Pinker, R. T., R. Frouin, and Z. Li (1995), A review of satellite methods to derive surface shortwave irradiance, *Remote Sens. Environ.*, 51, 108–124.

Ramaswamy, V., and S. M. Freidenreich (1998), A high-spectral resolution study of the near-infrared solar flux disposition in clear and overcast atmospheres, *J. Geophys. Res.*, 103, 23,255–23,273.

Ricchiazzi, P., S. Yang, C. gautier, D. Sowle. SBDART: A research and teaching software tool for plane-parallel radiative transfer in the Earth's atmosphere. **Bulletin of the American Meteor. Soc.**, v. 79, 2101-2114, 1998.

Schmetz, J. (1993), Relationship between solar net radiative fluxes at the top of the atmosphere and at the surface*, J. Atmos. Sci*., 50, 1122– 1132.

Stackhouse, P. W., S. K. Gupta, S. J. Cox, M. N. Chiacchio, and J. C. Mikovitz (2001), The WCRP/GEWEX Surface Radiation Budget Project release 2: An assessment of surface flux at 1 degreeresolution, in *IRS2000: Current problems in Atmospheric Radiation, pp. 485-488*, A. Deepak, Hampton, Va.

Stuhlmann, R., M. Rieland, and E. Raschke (1990), An improvement of the IGMK model to derive total and diffuse solar radiation at the surface from satellite data, *J. Appl. Meteorol*., 29, 586– 603.

Tarpley, J. D. (1979), Estimating incident solar radiation at the surface from geostationary satellite data*, J. Appl. Meteorol*., 18, 1172–1181.

Whitlock, C. H., T. P. Charlock, W. F. Staylor, R. T. Pinker, I. Laszlo, A. Ohmura, H. Gilgen, T. Konzelman, R. C. Di Pasquale, C. D. Moats, S. R. LeCroy, and N. A. Ritchey (1995), First global WCRP shortwave surface radiation budget dataset*, Bull. Am. Meteorol. Soc*., 76, 905– 922.

Acknowledgments. This work was partially supported by CNPq, Brazil. We thank automatic stations data provided by SIMEPAR for Brazilian Paraná State.