Bias correction of satellite data at ECMWF

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1. Introduction

The Variational Bias Correction (VarBC) is an adaptive bias correction system developped at NCEP by Derber and Wu (1998) and implemented more recently at ECMWF (Dee, 2005) and JMA. The bias coefficients (or parameters) are updated during the assimilation simultaneously with the meteorological variables. The resulting solution minimizes the distance (*e.g.* in terms of Root-Mean Square error) to all available information. This information includes the Numerical Weather Prediction (NWP) model background, the satellite radiances and all "conventional" observations.

Auligne *et al* (2007) has shown that the observations not corrected adaptively (*e.g.* radiosondes) act as a constraint upon the VarBC. A NWP model error will mainly be attributed to analysis increments and not to radiance observation bias in order to optimize the fit to conventional observations. This provides the VarBC with some skill to discriminate observation biases from systematic NWP model errors. This property is used here to assess which regression predictors are relevant for the bias correction.

2. Performance of the VarBC

2.1 Response to an instrument problem

From previous reanalyses (Uppala *et al.*, 2005) there are a number of well documented cases where a satellite instrument has suddenly degraded or been contaminated by an extreme event (i.e. volcanic emissions). If the event is not known about in advance, this can result in a serious contamination of the analysis. If the event is known about and expected, blacklisting the affected channel can still disturb the time consistency of the analysis. The VarBC has demonstrated an ability to handle sudden systematic changes to the data and minimize damage to the analysis. An example is shown in figure 1 for November 1986 when a cosmic storm event changed the response of the microwave (MSU channel 3) detector on the NOAA-9 satellite. This case is also discussed in Dee (2005).

The sudden shift in values initially results in almost all of the observations being rejected from the analysis. However, as the VarBC system is progressively exposed to more of the shifted data, it automatically adjusts the bias correction by more than one Kelvin (the black line of figure 1).

After a few days a completely new bias correction is established allowing all the radiance data to be used again with very little disruption to the analysis system. This is seen in the lower panel of figure 1 by very little change in the fit to radiosonde temperature data at 200 hPa (near the peak of MSU channel 3 weighting function).

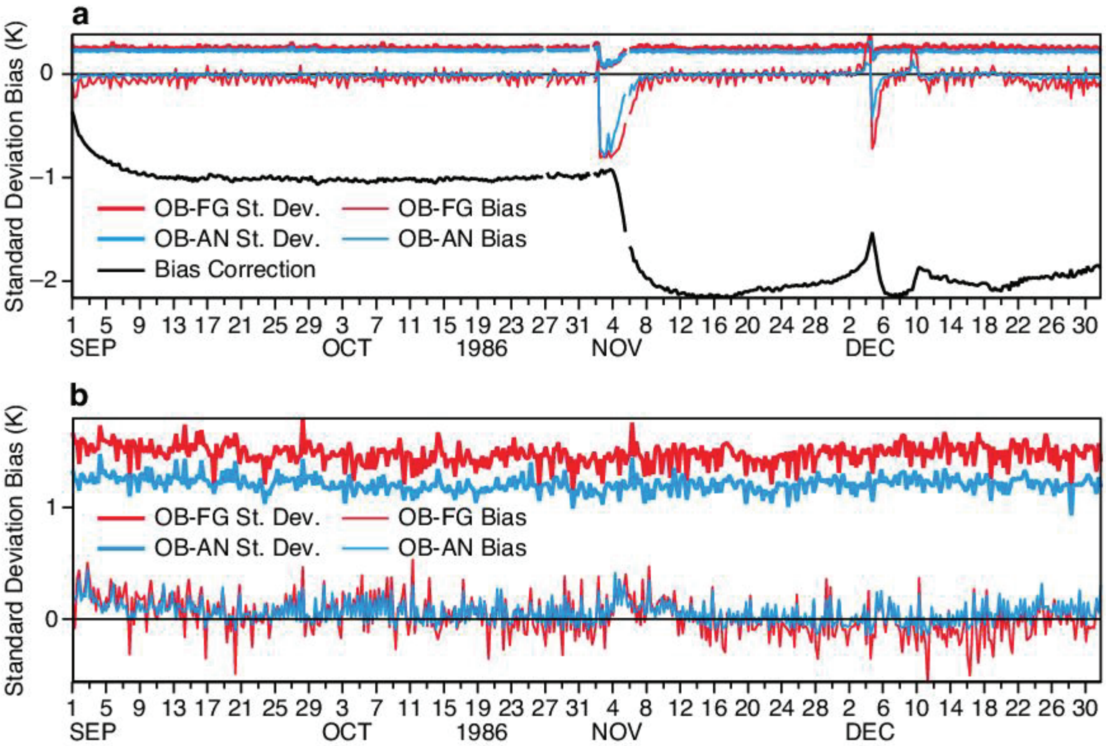

Figure 1: Standard deviation and bias of observed minus background (red) and observed minus analysis fit (blue) for NOAA-9 MSU channel 3 temperatures (a) and 200 hPa radiosonde temperatures (b) in the Tropics. The bias correction is represented with the black line.

2.2 Response to a systematic NWP model error

Figure 2 shows the mean fit to radiosonde temperature data for two different assimilation systems. The red line corresponds to a system using a static bias correction from ECMWF CY30R1 operations. The radiosonde temperature data suggest there is a cold bias in the assimilation (short-range forecast and analysis) in the lower stratosphere. Similar statistics for radiances from the AMSU-A in channels sensitive to the lower stratosphere show no such disagreement. However, the radiances are only unbiased by virtue of their bias correction towards the model. This situation has been known about for some time, and an obvious interpretation is that the forecast model does have a cold bias in the lower stratosphere, which is sustained in the analysis by the assimilation of wrongly bias corrected radiances. Attempts in the past to manually resolve this problem - {*e.g.* by completely removing bias corrections from some of the upper AMSUA channels - have failed to achieve an appropriate balance between different overlapping AMSUA channels (Kelly, personal communication).

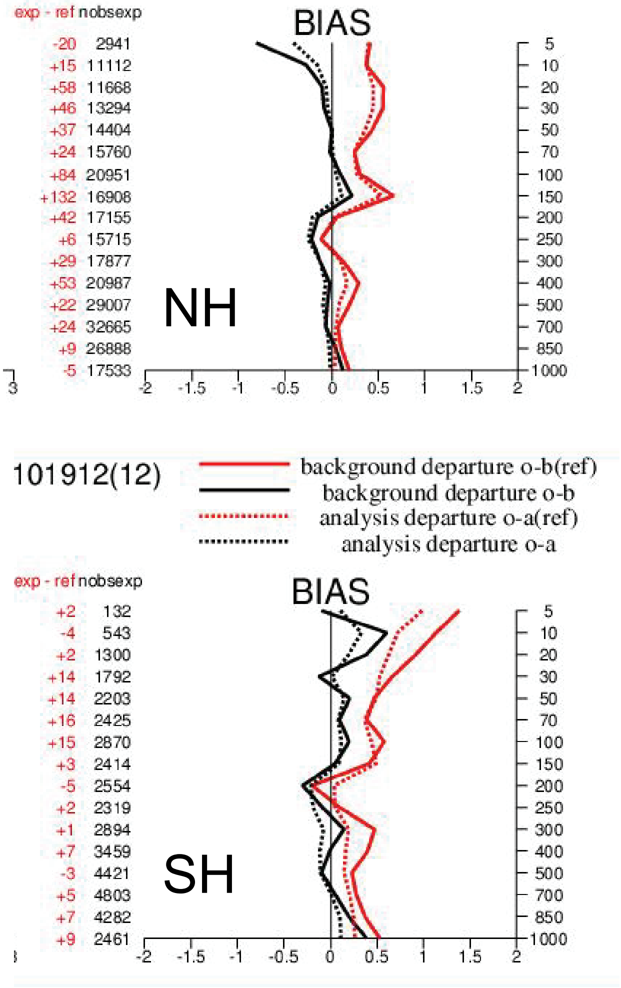

Figure 2: Standard deviation and bias of observed minus background (solid) and observed minus analysis fit (dashed) for radiosonde temperatures over (a) the Northern Hemisphere and (b) the Southern Hemisphere. Two experiments are shown that use the Static bias correction (red) and the VarBC (black) respectively.

The same data fits after the VarBC has been allowed to adjust the satellite bias correction are also shown by the black line of figure 2. There is a striking improvement in the radiosonde agreement, achieved by the VarBC adapting the bias correction applied to the stratospheric AMSUA channels. The timeseries for AMSU-A channel 10 is shown in figure 3, where the bias correction (black line) has been adjusted from 0.22K to almost 0K. By progressively reducing the amount of bias correction applied to the radiance data, more of the information from the AMSU-A forces mean increments and warms the analysis accordingly (as seen in the timeseries of the radiosonde fit in figure 2b). Indeed, there is a gradient in the analysis cost function which indicates that the observation bias can be reduced to improve the overall fit of the system to all observations. However, the successful removal of the cold bias has not been achieved quickly. The VarBC has taken several weeks of assimilation to gradually reduce the original satellite bias correction.

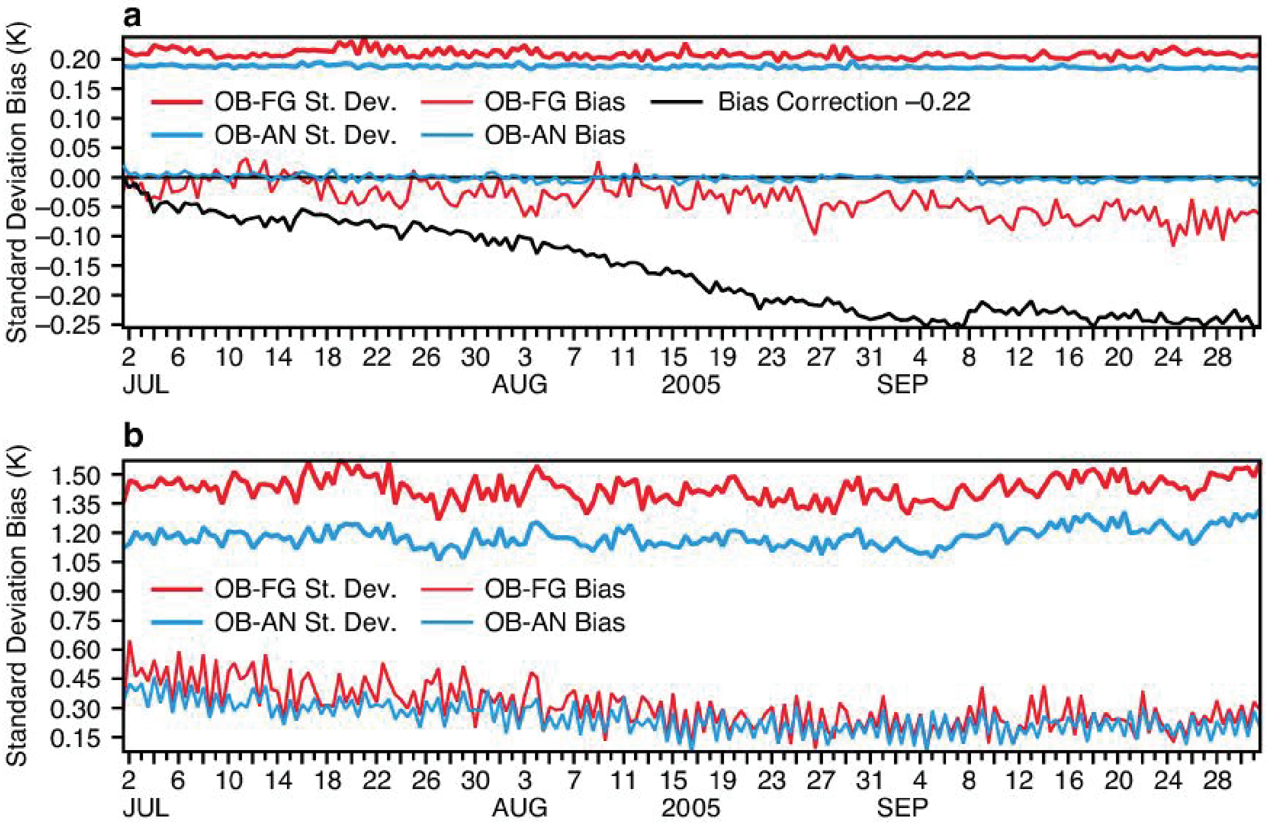

Figure 3: Standard deviation and bias of observed minus background (red) and observed minus analysis fit (blue) for NOAA-16 AMSU-A channel 10 temperatures (a) and 50 hPa radiosonde temperatures (b) in the Northern Hemisphere. The bias correction is represented with the black line (with an initial offset of 0.22 K).

While an instrument failure or contamination is usually accounted for within a couple of days, in this case the cold bias observed in the stratosphere requires several weeks to be corrected. This cannot be explained by the inertia term (as it is deliberately relaxed for stratospheric channels). The potential damping influence of the quality control is similarly a small effect for stratospheric channels and as yet the reason for the slow evolution is not understood.

3. Predictors in the operational parametric form

Observation biases are often complex and difficult to assess from the first-guess departures. The parametric form is the model that is used to represent these biases. It can be as simple as a global offset, but a popular technique consists in a linear regression based on “air-mass” predictors issued from the NWP model (Harris and Kelly, 2001). A more “physical” approach is to make assumptions on the nature of the observation bias. The $[\gamma,\delta]$ bias correction is an example where the main source of bias is assumed to be located in the radiative transfer model and a coefficient γ is used to adjust the absorption coefficient. The systematic departures with respect to the scan angle of the observations also need to be assessed. It is essential to distinguish the parametric form and the adaptivity of the bias correction. The latter represents the frequency of updates for the coefficients of the parametric form. The panel of options ranges from a static bias correction (where the bias parameters are calculated once and kept constant ever after) to a fully adaptive bias correction (where the parameters are updated for each new analysis cycle). It will be shown later in this paper that a comparison of the updates from different adaptive schemes can provide significant information on the relevance of the bias parameters themselves.

The parametric form used operationally at ECMWF combines the following:

- a global offset accounting for example for any approximation in the instrument calibration,
- air-mass predictors derived from the NWP model and used in a linear regression. The sets of predictors are dependent on the instrument and summarized in Table 1,
- a scan correction consisting in a third order polynomial regression based on the nadir viewing angle for all instruments aboard polar orbiting satellites plus an offset,
- a correction to the absorption coefficient in the radiative transfert model (RTM) for AIRS and AMSU-A.

The RTM γ correction and the scan offset are fixed (static bias correction) while the global offset, the air-mass and scan parameters are updated at each analysis cycle (adaptive bias correction).

Instruments	**Predictors**
HIRS, AMSU-A AMSU-B, AIRS	1000 - 300 hPa thickness 200 - 50 hPa thickness 10 - 1 hPa thickness 50 - 5 hPa thickness
SSMI	Tskin Surface Wind Speed Total Column Water Vapor
GEOS (GOES, Meteosat, MSG)	1000 - 300 hPa thickness 200 - 50 hPa thickness Total Column Water Vapor

Table 1: Predictors from Harris and Kelly (2001) bias correction used operationally for different instruments.

4. A first diagnostic to evaluate predictors

When investigating the relevance of bias predictors, it is practically uneasy to compute the variance explained by each predictor for each channel. However, if all the predictors are normalized (*i.e.* their mean value has been subtracted and they are scaled by their standard deviation), their importance in the bias correction can be compared. There is no guarantee that a predictor associated with a large coefficient (once convergence has been reached) will be useful. On the contrary a predictor associated with a small coefficient can only correct a small portion of the systematic signal in the radiance departures. Therefore, a threshold can easily be set (*e.g.* as a fraction of the variance of the first-guess departures) to discard the predictors that have very little impact in the bias correction.

A first step of pruning (*i.e.* the process starting from a wide set of potential predictors and discarding some of them) can be applied using the absolute value of the coefficients as a diagnostic.

5. A second diagnostic to evaluate predictors

We define the Offline scheme as an adaptive bias correction scheme identical in every point to the VarBC except that the update of the bias coefficients is performed outside the meteorological analysis.

Unlike the VarBC, the Offline scheme has no knowledge of other data when fitting the radiance departures. Therefore there is no constraint to prevent the bias correction from correcting for some NWP model error. However, if the bias predictors only accounted for observation bias (and not for systematic NWP model error), the VarBC and Offline implementations should be equivalent. A comparison of the coefficients calculated by the

VarBC with the ones from an identical scheme without any constraint (*i.e.* the Offline scheme) provides an indication on the relevance of the predictors. An assimilation experiment using the VarBC is run until convergence is reached for the bias coefficients. Then at the beginning of each assimilation cycle, an Offline estimate of the bias is calculated and compared to the VarBC.

The disagreement for a given predictor of a given channel is defined as the absolute value of the difference between the coefficient from the Offline bias correction minus the coefficient from the VarBC. A small disagreement will reflect the fact that the bias predictor is relatively insensitive to the updating scheme (VarBC or Offline). If the Offline scheme gives a large update to the bias coefficient while the VarBC does not, there is a signal in the first-guess departures that is (partially) constrained in the VarBC in order to fit other observations. In this case the predictor is believed to correct for NWP model error and the corresponding disagreement will be large. If the VarBC gives a large update to the coefficient while the Offline scheme does not, the analysis has significantly evolved from the first-guess. The analysis departures indicate a change in the bias while the first-guess departures had no corresponding signal. This can happen for example in the case of a stringent first-guess check around a biased first-guess. Since the adaptive system is considered only once the convergence of the VarBC has been reached, the discrepancy between first-guess and analysis can be seen as systematic. The predictor is then sensitive to systematic NWP model error and its disagreement will be large.

The disagreement can be used as a second diagnostic for potential predictors to assess if they are mostly sensitive to observation bias or to systematic NWP model error.

6. Application of the diagnostics to the selection of predictors

The two diagnostics described above are now derived from a 12-hour assimilation including the VarBC and the AIRS instrument is used as an illustration. The results are shown in figure 4 for the four air-mass predictors from the OPER parametric form listed in Table 1. In order to isolate structures the channels are ranked vertically by the pressure of the peak of their weighting function (or Jacobian) calculated from a standard atmosphere. Three spectral bands are also separated corresponding to the Long-Wave temperature (LW), Water-Vapour (WV) and Short-Wave temperature (SW) AIRS channels. The top panels represent the first diagnostic estimating the weight of each parameter in the total bias correction. All predictors are used significantly to correct the bias of the upper stratospheric LW channels. The two tropospheric thicknesses have a non-negligeable influence on the bias correction of the tropospheric LW and SW channels. Concerning the water-vapour band, the first predictor focuses on the low level channels (peaking under 600 hPa) while the second predictor mainly corrects channels above 500 hPa. Apart from a few SW window channels, the two stratospheric thicknesses have a small influence on the bias correction for the LW and SW tropospheric channels.

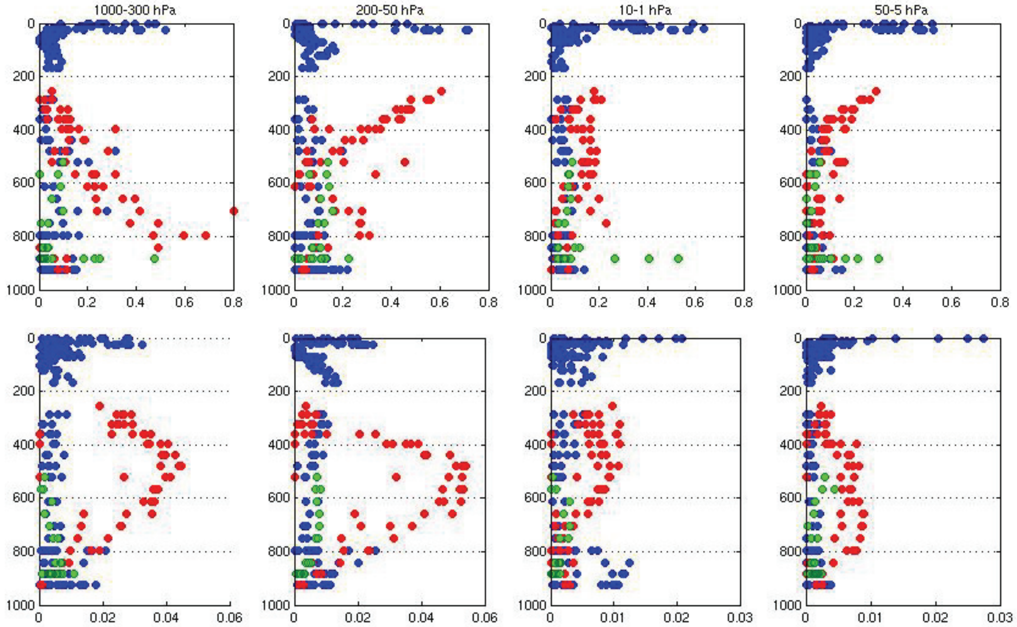

Figure 4: Diagnostics of relevance for the predictors from the OPER bias correction (listed in Table 1) applied to AIRS channels. The top panels correspond to the first diagnostic (the absolute value of the normalized parameters in the VarBC). The bottom panels show the second diagnostic (the absolute value of the difference between the estimation in the VarBC and in its equivalent scheme performed offline). The channels are ranked by the pressure of the peak of their Jacobian and separated into three spectral band (Long-Wave, Water-Vapour, Short-Wave).

The bottom panels represents the second diagnostic (*i.e.* the disagreement) assumed to provide for each parameter an approximation of its sentivity to NWP model error. All predictors for the LW upper-stratospheric channels have a strong disagreement which is probably underestimated because of the very poor constraint from conventional data on the VarBC at this altitude. The LW and SW channels show a general good agreement in the troposphere except for some low-peaking LW channels (under 800 hPa). On the other hand all predictors, especially the two tropospheric thicknesses, seem to be very sensitive to NWP model error for the WV channels with some variations on the altitude of their maximum sensitivity.

The combination of the two diagnostics gives an individual estimation of the usefulness for each parameter by quantifying its importance in the correction of the observational part of the systematic first-guess departures. In summary, none of the predictors from the OPER bias correction is appropriate for the upper-stratospheric channels and some of the LW window channels. The first two thicknesses should be used for LW and SW tropospheric channels. The WV channels peaking under 700 hPa seem to be bias corrected by the first predictor while the WV channels above 400 hPa are corrected by the second predictor (and also slightly by the last predictor). The two stratospheric thicknesses are usefull to explain biases in a few low-peaking SW channels which might be contaminated by sun-glint or non-LTE effects.

7. Conclusions

The evolution of the bias parameters within the adaptive context of the VarBC has shown very positive effects. A better consistency between the different types of observations is achieved, especially in the stratosphere where the fit the radiosonde temperatures is improved. The VarBC has shown some skill to discriminate between observation bias and systematic NWP error. However this relies on the availability of an sufficient network of observations (such as radiosondes) that are not corrected adaptively (anchoring network). A close attention needs to be devoted to forbid the system to map NWP model error into observation bias, especially in the stratosphere where the anchoring constraint is very weak. The VarBC skills are used to derive diagnostics to evaluate the relevance of the predictors in the bias correction. This should be useful to build a method to select bias predictors objectively.

References

T. Auligne, A. P. McNally and D. P. Dee (2007): ‘Adaptive bias correction for satellite data in a numerical weather prediction system’, *submitted to Q. J. Royal Met. Soc..*

D. P. Dee (2005): Bias and data assimilation, *Q. J. Royal Met. Soc.* **613,** pp 3323-3343.

J. Derber and W. Wu (1998): The use of TOVS cloud-cleared radiances in the NCEP SSI analysis system. *Mon. Wea. Rev.,* **126**, pp 2287-2299.

B. Harris and G. Kelly (2001): A satellite radiance bias correction scheme for radiance assimilation, *Q. J. Royal Met. Soc.* **127,** pp 1453-1468.

Uppala et al (2005): The {ERA}-40 re-analysis, *Q. J. Royal Met. Soc.* **131,** pp 2961-3012.

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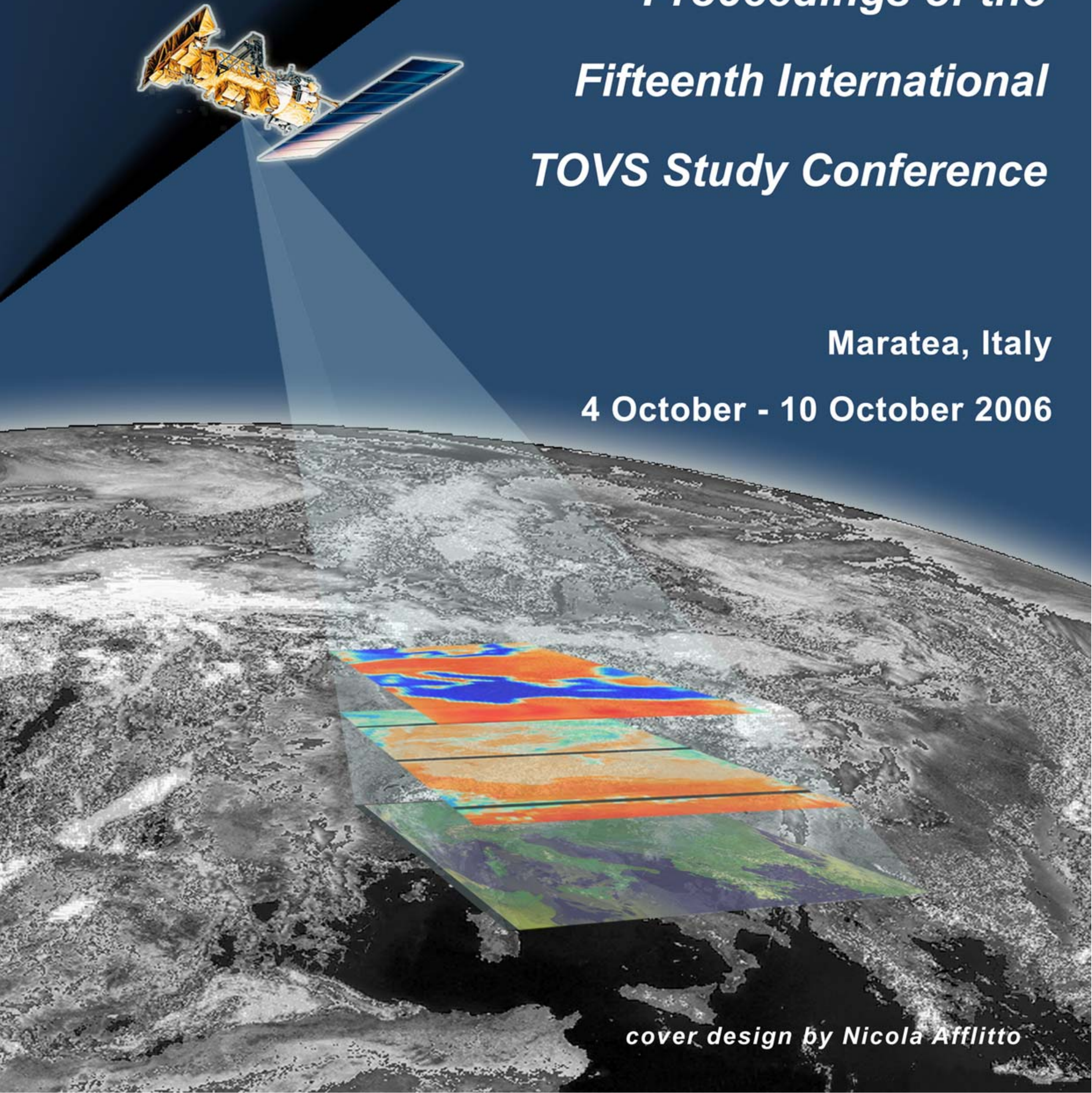

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