

The Use of Hyperspectral Infrared Radiances In Numerical Weather Prediction

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Introduction

In 2002, the Atmospheric Infrared Sounder (AIRS), the first of the hyperspectral sounders able to provide real time data for operational and research meteorology was launched. Several of these new generation advanced sounders will subsequently be launched as part of an upgrade to the current Global Observing System. These instruments include the US Cross-track Infrared Sounder (CrIS) and the European Infrared Atmospheric Sounding Interferometer (IASI). Demonstration of the benefits of hyperspectral data on Numerical Weather Prediction (NWP) has been a high priority. Observing System Experiments (OSEs) designed to examine effective methods to use hyperspectral radiances in NWP are summarized here. Experiments showing the benefit of using hyperspectral radiance data, available in real-time from the AIRS instrument are reviewed. Effective methods of data thinning and noise reduction are noted. The importance of the spatial resolution of the data used is documented. The importance of channel selection for NWP is also discussed. Note is made of the current use of variable hyperspectral emissivity over the entire globe. Finally, note is also made of the benefits to be gained by the enhanced use of hyperspectral data in NWP.

Background

After the launch of the AIRS in 2002 and the subsequent six months calibration period the AIRS was able to provide operational data. The improved spectral resolution it provided has led to a significant increase in vertical resolution and accuracy in determining thermal and moisture fields, and increased accuracy in determination of the concentrations of absorbers such as ozone. The methods used to provide improvements in NWP from the use of radiance observations taken by this instrument are documented in the impact studies below.

Data Assimilation Studies

In mid 2004 the Joint Center for Satellite Data Assimilation (JCSDA) demonstrated significant impact from AIRS data in both the Northern and Southern Hemispheres (Le Marshall et al.,

2005a and b). This was achieved using an enhanced spatial and spectral AIRS observational data set in conjunction with an analysis methodology that paid additional attention to the possible presence of clouds. Experiments demonstrating the benefits of AIRS data assimilation and the contribution of enhanced spatial and spectral resolution data are described below.

Assimilation of Full Spatial Resolution (All Footprints) AIRS Data

To examine the impact of adding full spatial resolution AIRS radiance observations to the US National Centers for Environmental Prediction (NCEP) operational data base (without AIRS), the NCEP operational T254 64 level version of the Global Forecast System (GFS) (November, 2004 version) was employed. All fields of view (*fovs*) from the AIRS instrument on the AQUA satellite were processed into BUFR format. This provided 281 channels of AIRS data at each footprint of which 251 were suitable for assimilation. These particular channels describe most of the variance of the 2,378 AIRS channels (Susskind et al., 2003). The NCEP operational GFS (Derber and Wu, 1998, Derber et al, 2003) using the full operational data base, available within real-time cut-off constraints and without AIRS data, was employed as the *control* (“Ops”). The data base included all available conventional data and also the satellite data listed in Table1. The radiances from the AQUA Advanced Microwave Sounding Unit –A (AMSU-A) instrument were not included in the control or experimental data base. Radiative transfer calculations were performed using the JCSDA Community Radiative Transfer Model (CRTM), (Kleespies et al., 2004) The *experimental* system also employed the GFS with the full operational database (i.e. the control data base) plus full spatial resolution AIRS radiance data (“Ops + AIRS”), available within operational time constraints.

The global analysis was modified to include the use of these AIRS data and the experimental system designed to determine the impact on real time operations of the hyperspectral AIRS radiance data.

Table1: The satellite data used by the *control* forecasts

HIRS sounder radiances	TRMM precipitation rates
AMSU-A sounder radiances	ERS-2 ocean surface wind vectors
AMSU-B sounder radiances	Quikscat ocean surface wind vectors
GOES sounder radiances	AVHRR SST
GOES, Meteosat	AVHRR vegetation fraction
atmospheric motion vectors	AVHRR surface type
GOES precipitation rate	Multi-satellite snow cover
SSM/I ocean surface wind speeds	Multi-satellite sea ice
SSM/I precipitation rates	SBUV/2 ozone profile and total ozone

The analysis methodology is described in Le Marshall et al.(2005a and b). In a typical six hour global assimilation cycle approximately 200 million AIRS radiances (i.e. [200x10⁶ / 281] fields of view), were input to the analysis system. From these data about 2,100,000 radiances (281 radiances (channels) in approximately 7450 analysis boxes) were selected

for possible use, and result in about 850,000 radiances free of cloud effects being used in the analysis process. That is effective use is made of approximately 41% of the data selected for possible use. The data volumes are shown in Table 2.

Table 2: AIRS Data Usage per Analysis Cycle

Total Data Input to Analysis	~200x10 ⁶ radiances
Data Selected for Possible Use	~2.1x10 ⁶ radiances
Data Used in 3D VAR Analysis (Clear Radiances)	~0.85x10 ⁶ radiances

Assimilation of Full and Reduced Spatial Resolution AIRS Data

In order to examine the importance of using the full spatial resolution AIRS data as opposed to the one in eighteen fields of view often used for NWP, results from a data assimilation experiment for August/September 2004 have been examined. Here, forecasts which used radiances from the currently available thin (one in eighteen fovs) real time AIRS data set in addition to the full operational data base (*1/18 fovs AIRS*), have been compared to forecasts from the use of a full spatial resolution (*all fovs AIRS*) AIRS data set in addition to the operational data base. In these cases the operational data base *included AQUA AMSU-A*. The trial used the NCEP operational T254, 64 level GFS (November, 2004 version).

Assimilation of Full and Reduced Spectral Coverage

The full NCEP operational data base *including AQUA AMSU-A*, for the period 2 January – 15 February, 2004, has been used to provide a series of *control* analyses and forecasts from the operational NCEP operational T254 64 level GFS (June, 2005 version). The analyses and forecasts have been repeated using the full operational data base plus full spatial resolution AIRS data from the 115 AIRS channels whose central wavelength is between 3.7 and 9.3 μ m (*short AIRS*). In a third series of analyses and forecasts, the full operational database has been used with 152 channels of AIRS data i.e., full spatial resolution, including 152 of the 281 channels currently available for real time NWP covering the full spectral range, 3.7 - 15.4 μ m (*AIRS – 152 ch*). In a fourth series of analyses and forecasts, the full operational database has been used with all (251 channels) of AIRS data (*AIRS – 251 ch*) i.e., full spatial resolution, including 251 of the current 281 channels available for real time NWP covering the full spectral range, 3.7-15.4 μ m.

The Forecasts

Full Spatial Resolution (All Footprints) AIRS Data

In the impact studies using full spatial resolution AIRS data with the NCEP GFS, cloud free AIRS radiance data were identified and used via the methods described previously (Le Marshall et al., 2005a and b). The verification statistics were derived using the NCEP

operational verification scheme. A summary of the results is seen in Figure 1. This shows

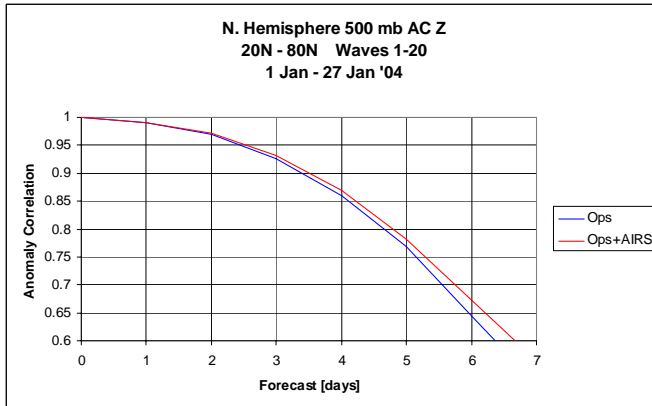


Figure 1 500hPa Z Anomaly Correlations for the GFS with (Ops.+AIRS) and without (Ops.) AIRS data, Northern hemisphere, January 2004

the geopotential height Anomaly Correlations (AC) for the GFS at 500 hPa over the Northern Hemisphere for January 2004, at one to five days, with and without AIRS data. It is clear the AIRS data have had a beneficial effect on forecast skill over the Northern Hemisphere during this period. Forecasts for the 500 hPa AC over the Southern Hemisphere for January 2004, also showed significant improvement in forecast skill.

During a similar series of impact studies using full spatial resolution AIRS data, an examination was undertaken of the moisture field in the lower troposphere. An example of the Forecast Impact is seen in Figure 2 where *Forecast Impact* estimates which forecast (with or without AIRS) is closer to the analysis at forecast verification time.

$$Forecast\ impact = 100 * \sqrt{\frac{Err(Cntl)^2 - Err(AIRS)^2}{Err(Cntl)^2}}$$

where the first term on the right is the error in the Control forecast. The second term is the error in the AIRS forecast.

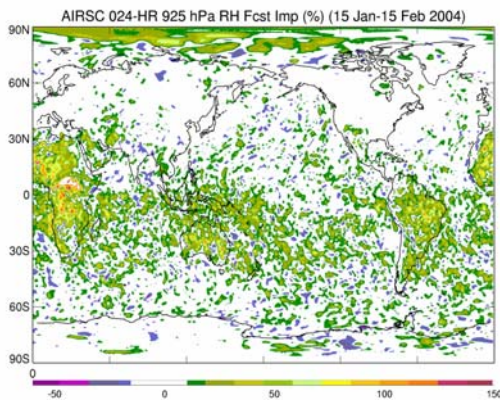


Fig 2. Forecast Impact improvement/ degradation (%) of the 12 hr Relative Humidity forecast at 925 hPa

Dividing by the error in the control forecast and multiplying by 100 normalizes the results and provides a percent improvement or degradation. A positive Forecast Impact means the forecast is better with AIRS data included. Fig.2 shows a degree of improvement over a significant area in the 925hPa relative humidity in the 12 hour forecast with AIRS. Significant areas of improvement were also seen in the 850 hPa Relative Humidity and the Total Precipitable Water at 12 hours.

Full and Reduced Spatial Resolution AIRS Data

In an experiment to illustrate the importance of using the full spatial resolution AIRS data as opposed to the one in eighteen fields of view often used in NWP, results for an assimilation

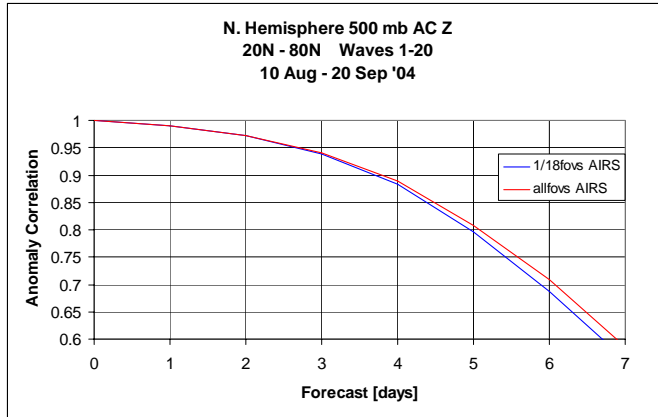


Figure 3. 500hPa Z Anomaly Correlations for the GFS with thinned – one AIRS fov in 18 (1/18 fovs AIRS) and for the GFS using all AIRS fovs (all fovs AIRS), Northern Hemisphere, August/September, 2004

experiment in August/September 2004 are provided. In this study, forecasts which used radiances from the currently available thinned (*1/18 fovs AIRS*) real time AIRS dataset in addition to the operational data base, were compared to results from the use of a full spatial resolution (*all fovs AIRS*) data set in addition to the operational data base. In these cases the operational data base included *AQUA AMSU-A*. Identical versions of the GFS were used in both cases. It is clear (see fig. 3), the increased information related to atmospheric temperature and moisture, contained in the full

spatial density data set (*all fovs AIRS*), has resulted in improved analyses and forecasts.

Full and Reduced Spectral Coverage

Results from a comparison of forecasts from i) the *control* (full operational database, including *AQUA/ AMSU-A*), ii) using the full operational data base plus full spatial resolution AIRS observations from the 115 AIRS channels whose central wavelength is between 3.7 and 9.3 μm (*short AIRS*), iii) a third series of analyses, where the full operational database has been used with 152 AIRS channels (central wavelengths 3.7 to 15.4 μm) of AIRS data (*AIRS-152 ch*) i.e., full spatial resolution, including 152 of the 281 channels currently available for real time NWP, a subset presently used for operational NWP, and iv) a series of analyses and forecasts, where the full operational database has been used with all 251 AIRS channels, central wavelengths 3.7 to 15.4 μm (*AIRS-251 ch*), i.e., full spatial resolution, including 251 of the 281 channels currently available for real time NWP, are displayed in Figure 4.

The Bar graph shows the 1000 hPa and 500 hPa geopotential height (Z) five day forecast Anomaly Correlations for the Northern and Southern Hemispheres. It was apparent in this trial that addition of the shortwave channels (*short AIRS*) to the operational observation database generally provided a positive increment at five days with a larger improvement being seen in the Southern Hemisphere 1000hPa fields. It was also clear for this period, that *addition* of longwave channels (channels whose central wavelength is greater than 9.3 μm , *AIRS-152 ch*, *AIRS 251ch*)

generally provided improved forecasts in each of the categories. The clear advantage from using the full spectral range with 251 channels of AIRS data was also apparent in these experiments for this period.

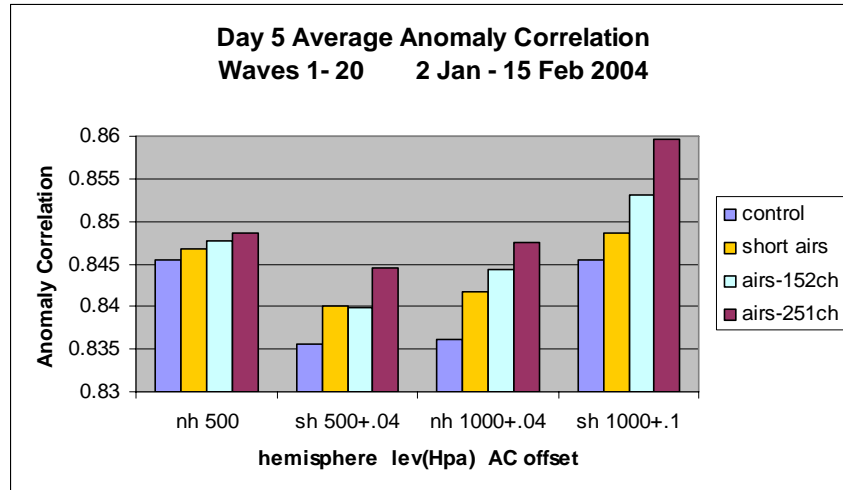


Figure 4. 1000 and 500hPa Z Anomaly Correlations for the GFS for the Control, Short AIRS (using 115 AIRS shortwave channels), AIRS-152ch using 152 out of the 281 channels available for real time NWP and AIRS-251ch using 251 out of the 281 channels available for real time NWP, Northern and Southern Hemisphere, January/February, 2004. An Anomaly Correlation offset has been added to each Channel set to allow display on a common graph.

Further Experiments

Experiments relating to the use of AIRS data in the analysis of the stratosphere and also to the use of hyperspectral surface emissivities in the analysis have also been undertaken and are summarised here. In relation to the use of AIRS data in the stratosphere, averaging of the AIRS radiances has been undertaken to reduce noise in the stratospheric channels. Sixty stratospheric channels have been averaged over each AMSU field of view (i.e. a 3 x 3 average). Figure 5 shows the average fit to the background/six hour forecast and the average fit to the final analysis, for the control and also for the experimental runs with radiances averaged over an AMSU footprint. As expected, the averaged radiances have resulted in a better fit to the six hour forecast and also to the final analysis.

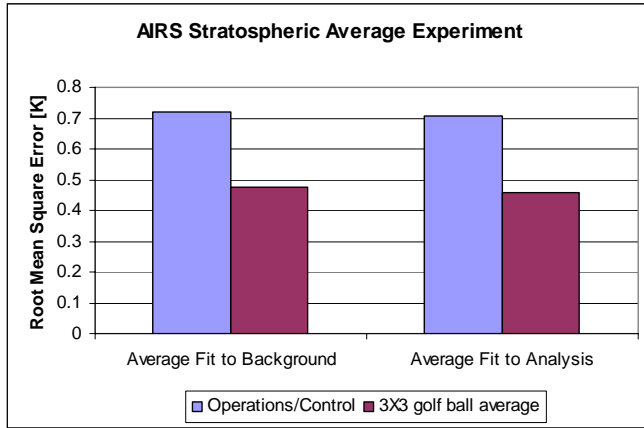


Figure 5: Average fit of AIRS stratospheric radiances (control) and averaged stratospheric radiances (3 x 3 average over an AMSU fov) to the background analysis and final analysis

improvement of this emissivity data base, emissivities have been calculated from cloudfree AIRS radiances using the minimum variance method (e.g. Knuteson, 2003). The variance is calculated by summing the emissivity differences between spectrally close on-line (water vapour emission line) and off-line channel pairs as surface temperature is varied. The optimum surface

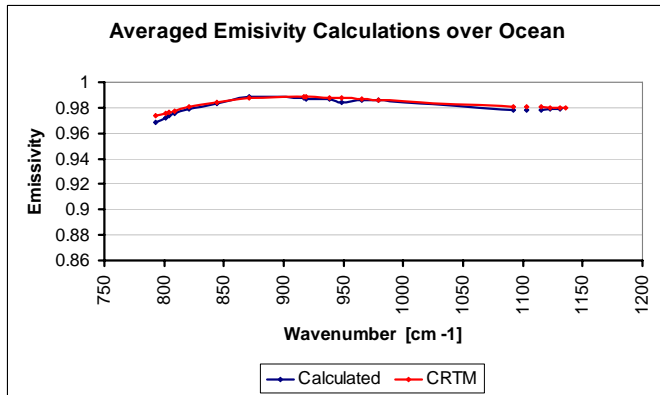


Figure 6 Hyperspectral emissivity over the sea, calculated using the JCSDA CRTM and calculated from observed AIRS radiances.

has been used to verify the technique. The method is currently being used over ice and land in combination with emissivity studies using MODIS observations and is intended to be used to update the CRTM data base. In combination with this approach, the estimation of emissivity using an eigenvector approach is being pursued.

A series of studies has also been undertaken using; hyperspectral emissivities from the JCSDA CRTM, hyperspectral emissivities estimated from observed radiances and a regression relation based on synthetic radiance calculations, and hyperspectral radiances based on observed cloud-free AIRS radiances. The JCSDA CRTM provides geographically tabulated hyperspectral emissivities which are used by the new 3D-Var. Gridpoint Statistical Interpolation (GSI) analysis, which is expected to be introduced into operational use by NCEP in 2007. To aid in the

improvement of this emissivity data base, emissivities have been calculated from cloudfree AIRS radiances using the minimum variance method (e.g. Knuteson, 2003). The variance is calculated by summing the emissivity differences between spectrally close on-line (water vapour emission line) and off-line channel pairs as surface temperature is varied. The optimum surface temperature leads to the minimum variance in the emissivities. The surface temperature can then be used to estimate hyperspectral emissivities. The methodology has been tested by comparing computed emissivities over the sea with those predicted by the CRTM (Van Delst, 2003). Figure 6 shows a typical comparison between average CRTM modelled hyperspectral emissivity and the averaged AIRS estimated emissivity. The agreement between modelled and calculated emissivities (and also the angular variation of these emissivities)

Conclusions

The introduction of AIRS hyperspectral data into environmental prognosis centers was anticipated to provide improvements in forecast skill. Here we have noted results where AIRS hyperspectral data, used within stringent operational constraints, have shown significant positive impact in forecast skill over both the hemispheres for January 2004. The magnitude of the improvement is quite significant and would normally take several years to achieve at an operational weather center. We have also noted the improvement gained from using AIRS at a spatial density greater than that used generally for operational NWP. In addition we have completed some studies to look at the impact of spectral coverage and found for the period studied, use of a fuller AIRS spectral coverage and the full AIRS spectral range, namely 3.7 to 15.4 μm , provided superior forecasts.

In conclusion, given the opportunities for future enhancement of the assimilation system and the resolution of the hyperspectral data base, the results indicate a considerable opportunity to improve current analysis and forecast systems through the application of hyperspectral data. It is anticipated current results will be further enhanced through use of higher spectral and spatial resolution data. Further improvements may also be anticipated through use of cloudy data and the use of complementary data such as Moderate Resolution Imaging Spectroradiometer (MODIS) radiances for determining cloud characteristics. Improvements are also expected from the effective exploitation of the new hyperspectral data which will become available from the IASI, CrIS and geostationary instruments such as the Geostationary Imaging Fourier Transform Spectrometer (GIFTS).

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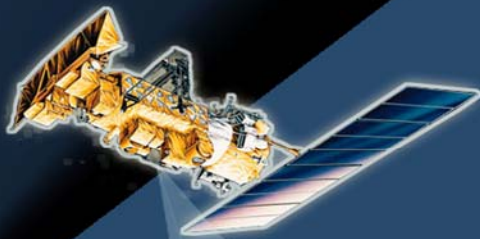
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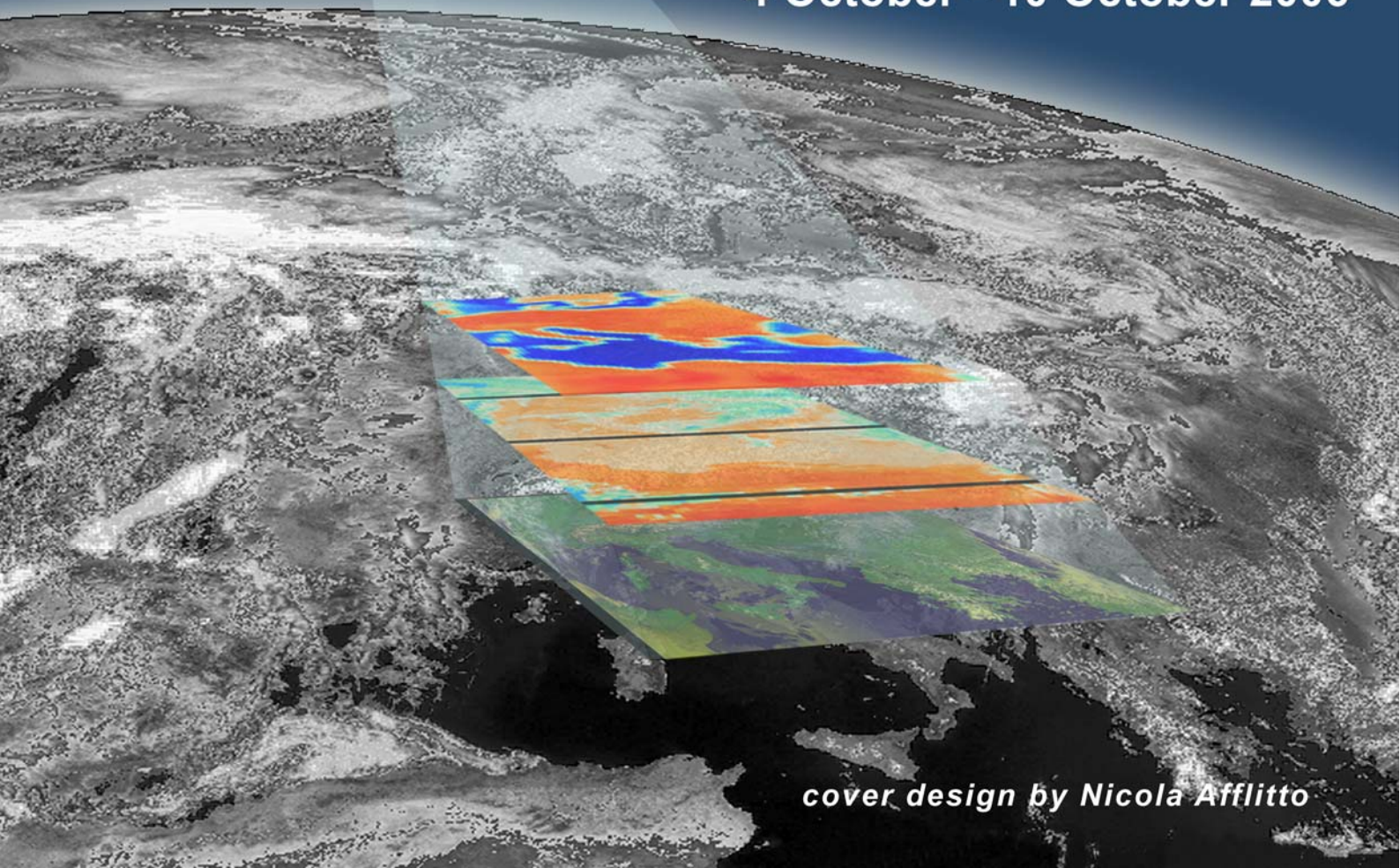
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