Climate Change and Sounder Radiometric Stability

Thomas S. Pagano*[a], Hartmut H. Aumann[a], Evan Manning[a]
[a]California Institute of Technology, Jet Propulsion Laboratory,
4800 Oak Grove Dr. Pasadena, CA 91109

ABSTRACT

Satellite instrument radiometric stability is critical for climate studies. The Atmospheric Infrared Sounder (AIRS) radiances are of sufficient stability and accuracy to serve as a climate data record as evidenced by comparisons with the global network of buoys. In this paper we examine the sensitivity of derived geophysical products to potential instrument radiometric stability issues due to diurnal, orbital and seasonal variations. Our method is to perturb the AIRS radiances and examine the impact to retrieved parameters. Results show that instability in retrieved temperature products will be on the same order of the brightness temperature error in the radiances and follow the same time dependences. AIRS excellent stability makes it ideal for examining impacts of instabilities of future systems on geophysical parameter performance.

Keywords: Atmosphere, Sounding, AIRS, Aqua, Climate, Temperature, Stability

1. INTRODUCTION

The Atmospheric Infrared Sounder (AIRS) is a hyperspectral infrared instrument on the EOS Aqua Spacecraft, launched on May 4, 2002. AIRS has 2378 infrared channels ranging from 3.7 μm to 15.4 μm and a 13.5 km nadir footprint. The AIRS is a "facility" instrument developed by NASA as an experimental demonstration of advanced technology for remote sensing and the benefits of high resolution infrared spectra to science investigations[1]. The AIRS, in conjunction with the Advanced Microwave Sounding Unit (AMSU), produces temperature profiles with 1K/km accuracy on a global scale, as well as water vapor profiles and trace gas amounts for CO_2, CO, SO_2, O_3 and CH_4. AIRS data are used for weather forecasting, climate process studies and validating climate models[2]. For more information see http://airs.jpl.nasa.gov.

2. AIRS RADIOMETRIC ACCURACY AND STABILITY

We first demonstrate that the AIRS instrument is highly stable making it useful for demonstrating the effects of potential instability on geophysical radiances of other future systems. If AIRS were not radiometrically stable, then these instabilities would manifest themselves in the geophysical products. If dynamic tuning of radiances were applied, they would not apply to a future instrument perturbation, again making it not useful for investigating sensitivities. No dynamic tuning or correction of any kind is applied to the AIRS radiances.

The AIRS instrument was radiometrically calibrated during pre-flight testing while viewing a Large Area Blackbody (LABB) with a 57 degree wedge angle. The output of the LABB was NIST traceable through NIST calibrated temperature sensors. For the transfer of this calibration to the AIRS Onboard Blackbody Calibration source (OBC) the LABB was stepped through a sequence of temperatures between 220 K and 340 K. The procedure allowed us to fit the radiometric response of the AIRS instrument to the known temperature and emissivity of the LABB. The coefficients of the radiometric transfer equations derived from these pre-flight tests are still used in routine radiance calibration today, almost seven years after the AIRS data became operationally available. The resulting calibration accuracy is 0.2K three sigma at a scene temperature of 265K[3].

Radiometric stability is of critical importance for long term climate trending for two reasons. 1) A long-term data record can be established, if the operational sounders IASI (Infrared Atmospheric Sounding Interferometer), CrIS (Cross-track Infrared Sounder) and AIRS have an order of magnitude better stability than absolute accuracy. Based on the analysis of AIRS and IASI data, this requires a minimum of a full year of operational data[4]. 2) Changes in the thermal environment can introduce large changes in the calibration accuracy. A data record may thus be extremely accurate as a one year average, but large systematic orbital and seasonal patterns are averaged out. Day/night, zonal and seasonal variations are

key climate signals. The common practice of tuning out these systematic effects based on a preconceived knowledge of the "true" climate variability undermines the use of the data for critical climate research.

AIRS radiances have undergone extensive checks for stability based on (obs-calc), where "obs" is the observed brightness temperature in an AIRS channel, and "calc" is the brightness temperature expected to be observed. In general "calc" requires the independent knowledge of the surface temperature and emissivity, and temperature and water vapor profiles, which can be obtained from the ECMWF or NCEP analysis. For the window channels available to a hyperspectral sounder only the Sea Surface Temperature needs to be known for the daily evaluation of (obs-calc) under clear conditions. Based on the first three years of data the AIRS radiances have been demonstrated to be stable to better than 16 mK/year[5] using the 2616 cm^{-1} AIRS superwindow channel. This result is confirmed by results from six years of data and zonal day/night analysis. Figure 1 shows the anomaly of (obs-calc) for the 1231 cm^{-1} window channel. We show the 1231 cm^{-1} channel results since this channel is available to IASI and CRIS. Each point in Figure 1 represents the anomaly of the mean(obs-calc) from typically 5000 clear night spectra from the non-frozen oceans. The red trace is a sliding 32 day mean. The six year trend in the anomaly is +3 ± 4 mK/yr, where the trend uncertainty is 2 sigma, i.e. the trend is statistically not significant. The analysis of trends in window channels at 2616 cm-1, 2508 cm-1, 1128 cm-1, 961 cm-1, 900 cm-1, 790 cm-1 and 781 cm-1, day/night and 20 degree wide ocean latitude zones produce similar results.

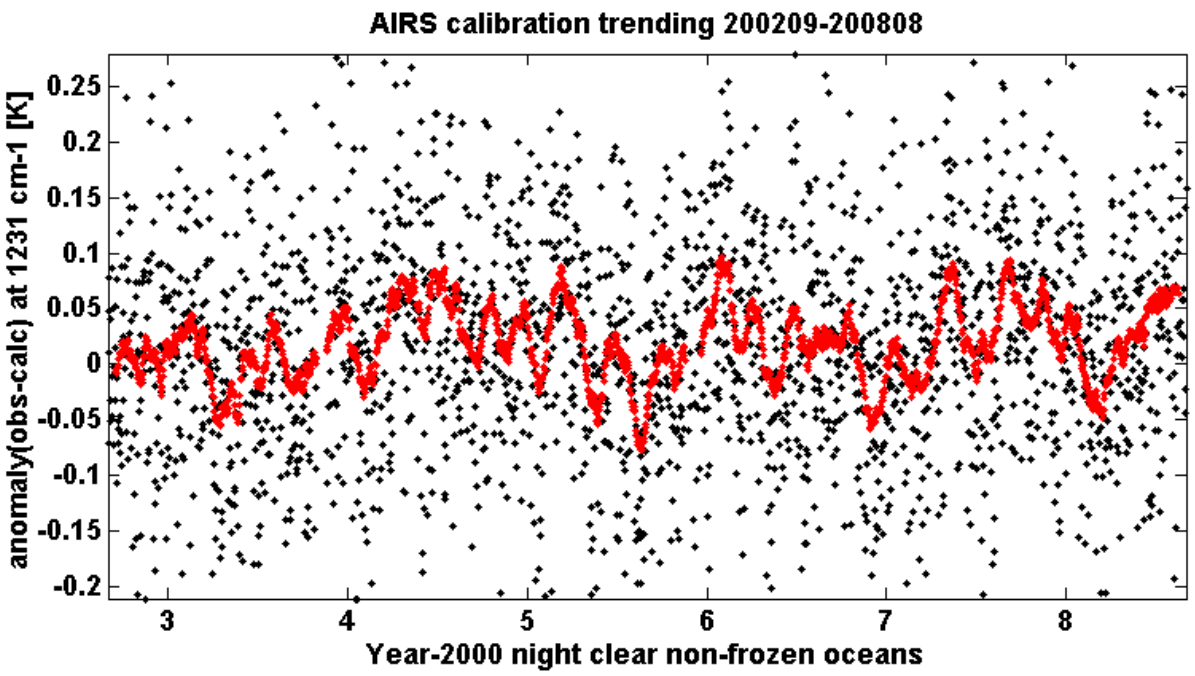

Figure 1. Observed zonal trend of the AIRS brightness temperatures relative to Sea Surface Temperature.

The direct validation of the stability of all AIRS channels using (obs-calc) using the ECMWF T(p), q(p) is in process. The results are more difficult to analyze because the temperature sounding channels are sensitive to the increase in the CO_2 mixing ratio. The results of a four year (obs-calc) analysis for the 791.7 cm^{-1} channel were published by Strow and Hannon (2007)[6]. The observed trend in (obs-calc) at 791.7 cm-1 in the tropical oceans is consistent with a 2.21±0.24 ppmv/year increase in the co2 abundance, compared to the Mauna Kea value of 1.99+/-0.05 ppmv/year. The sensitivity of this channel to co2 is -30 mK/ppmv. Assuming that the entire difference and one sigma uncertainty on the trend is due to a unrecognized trend in the radiances, the trend would be (-0.22±0.24)*(30) =-6±7 mK/year. This is consistent with our results for the 1231 cm-1 surface channel.

3. SIMULATION

In the prior section, we showed that the AIRS radiances are extremely stable. The question remains as to what would be the impact of any radiance instability on the geophysical products. Geophysical products, e.g. Temperature Profiles, Water Vapor Profiles, are widely used by scientists since they are directly relatable to processes in nature and directly comparable to model parameters allowing improvement in climate processes and model parameterization respectively. Trending of the geophysical parameters will only be possible if two conditions are met: a) the AIRS instrument is stable, and b) the retrievals do not introduce artifacts that would create instabilities. The former is readily understandable, however the latter may require further explanation. For example, if the retrieval of temperature relies on a consistent level of CO_2 in the atmosphere, as the CO_2 changes, the retrieval will introduce a trend in the temperature, water vapor, or clouds. The AIRS retrieval includes a global increase in the level of CO_2 so this is not likely to produce major trends.

We can examine the impact on temperature profiles resulting from changes in instrument radiometry through simulation. In this simulation we apply an artificial time dependent radiometric bias to the AIRS radiances and see what the corresponding impact is to the 100 mb and surface air temperatures (1000 mb) retrieved. The time dependent perturbation applied has a radiance error that scales with scene temperature. This would be the case if the radiometric error were caused by an uncorrected reflection of background energy on the internal blackbody calibration target. The radiance error is scaled by the scene temperature relative to the radiance of the calibration target (in this case a 287K blackbody). We then apply a sinusoidal oscillation of that error with orbit and season according to the equation

$$\delta L\ (t) = \delta L_{287K} \frac{L_{Tscene}}{L_{287K}} \left[\cos(2\pi f_1 t + \phi_1) + \cos(2\pi f_2 t + \phi_2)\right]$$

δL_{287K} = Nominal radiance perturbation of the internal blackbody calibration target at 287K

$1/f_{1,2}$ = 1 orbit (98.8min), 1 year

ϕ_1 = Minimum at equator night side, maximum at equator day side

ϕ_2 = Minimum in winter (December 31), max in summer (June 30)

Rather than choose an arbitrary level of radiometric error, we use expected values of radiometric instability from the Cross-track Infrared Sounder (CrIS) on NPP assuming no correction applied. Using realistic values is important as there may be a spectral dependence to the instability that would impact the retrieval. Figure 2 shows the modulation amplitude, $dL_{287K} \times L_{250K} / L_{287K}$ expressed in temperature at 250K used for the simulation. These values were calculated by analysis of the internal calibration target blackbody emissivity and expected temperature fluctuations in the baffles surrounding the internal blackbody[7]. It represents a worst case instability in the temperature surrounding the internal blackbody of 5K that modulates with orbit and season. This energy is reflected off the internal blackbody into the instrument aperture causing the radiometric error. The relatively low emissivity blackbody on CrIS causes the spectral dependence shown. CrIS does not have channels below above 2500 cm^{-1} so the errors are extrapolated in order to fill the AIRS channel space necessary for the simulation. It should be noted that algorithms will be incorporated in the CrIS Sensor Data Record (SDR) algorithm to correct for this modulation based on model simulations, but the efficacy of this correction has yet to be demonstrated. With that, we can treat the perturbations applied as "hypothetical".

The amplitude of the radiance instability is assumed to be time dependent according to the above equation. We assume an orbital and seasonal dependence to the fluctuation of equal magnitude. We show the total time dependent radiance perturbation for an example channel at 1290 cm^{-1}.

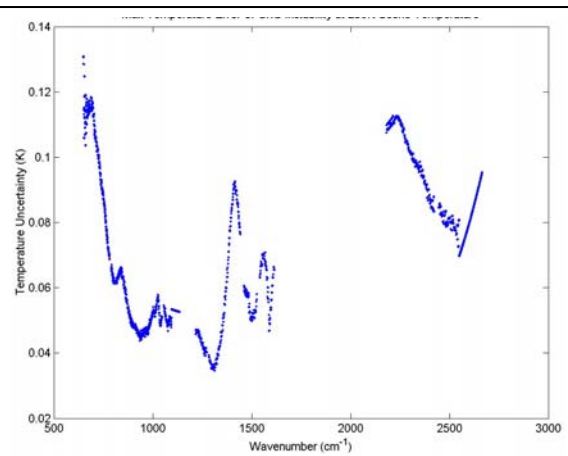

Figure 2. Amplitude of hypothetical radiometric instability used in the sensitivity study of radiances to geophysical products.

The perturbations were applied to four cases. 1) Winter Ascending, December 31, 2002, 2) Winter Descending, December 31, 2002, 3) Summer Ascending, June 30, 2003 and 4) Summer Descending, June 30, 2003. The perturbations were applied directly to the AIRS radiances for the entire day (and night) cases. The radiances were then run through the Level 2 Product Generation Executable (PGE) to generate products. The resulting difference between the unperturbed and the perturbed retrievals were then generated.

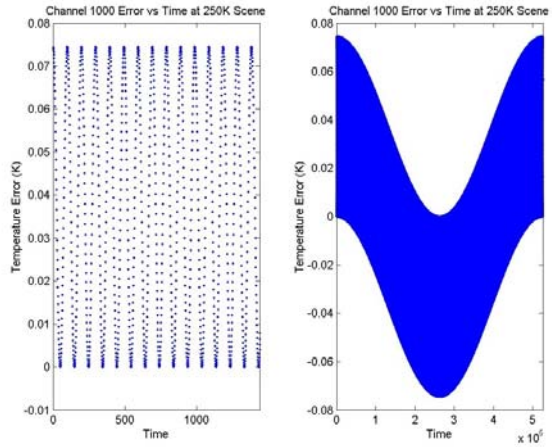

Figure 3. Time dependence of the radiometric instability for 1290 cm^{-1}. All channels in the simulation have the same time dependence, with amplitude corresponding to the values in Figure 2.

4. RESULTS

Figures 4 and 5 show the results at 100 mb. We see that the winter ascending and summer descending have the smallest errors, primarily because the radiances have the lowest differences. The summer ascending and winter descending show errors on the order of 100 mK or more. We also see that the errors in the polar regions are opposite those of the mid latitudes (high when the mid latitudes are low, and low when the mid latitudes are high). This is due to the orbital oscillation in the temperatures. Figures 6 and 7 show a similar oscillation in the surface air temperatures but with a significantly higher magnitude than the radiance errors. This could be due to several effects including the warmer temperatures at the surface (higher perturbation applied), the higher errors in the shortwave used for temperature retrievals in AIRS, and possible cloud clearing effects.

5. CONCLUSIONS

The results of this analysis indicate that instability in the retrieved temperature product would be directly related to instability in the radiance products. Instabilities are on the order of the brightness temperatures of the radiances themselves. Instabilities of this magnitude are not expected from AIRS since the radiance product is stable to 10-20 mK/year. Future operational sounders should take care in design of the internal calibration blackbodies and employ effective temperature control to ensure radiometric stability of the geophysical products.

ACKNOWLEDGMENTS

The authors would like to acknowledge the AIRS Science Team for the development of the AIRS Product Generation System used in the analysis. The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

[1] Pagano, T.S., "Improving Weather and Climate Prediction with the AIRS on Aqua", Proc. SPIE 7452-15, August, 2009

[2] J. Le Marshall, J. Jung, M. Goldberg, C. Barnet, W. Wolf, J. Derber, R. Treadon and S. Lord, "Using cloudy AIRS fields of view in numerical weather prediction". Aust. Meteorological Magazine, 2008, vol. 57, pp. 249-254

[3] T. S. Pagano, H. Aumann, R. Schindler, D. Elliott, S. Broberg , K. Overoye, M. Weiler, "Absolute Radiometric Calibration Accuracy of the Atmospheric Infrared Sounder", Proc SPIE, 7081-46, San Diego, Ca, August 2008

[4] D. Elliott, H. Aumann, L. Strow, Global comparison of radiances from the Atmospheric Infrared Sounder (AIRS) and the Infrared Atmospheric Sounding Interferometer (IASI), Proc SPIE, 7456-32, San Diego, Ca, August 2009.

[5] H.H. Aumann, et al., Three years of Atmospheric Infrared Sounder radiometric calibration validation using sea surface temperatures, Journal of Geophysical Review, VOL. 111, D16S90, doi:10.1029/2005JD006822, 2006

[6] Strow, L. L., and S. E. Hannon (2008), "A 4-year zonal climatology of lower tropospheric CO_2 derived from ocean-only Atmospheric Infrared Sounder observations", J. Geophys. Res., 113, D18302, doi:10.1029/2007JD009713

[7] Pagano, T.S., Broberg, S., Aumann, H., Elliott, D., Schindler, R., "CrIS Radiometric Accuracy and Stability Compliance Review: ICT Effects", NPP Science Team Technical Memorandum, February 4, 2009.

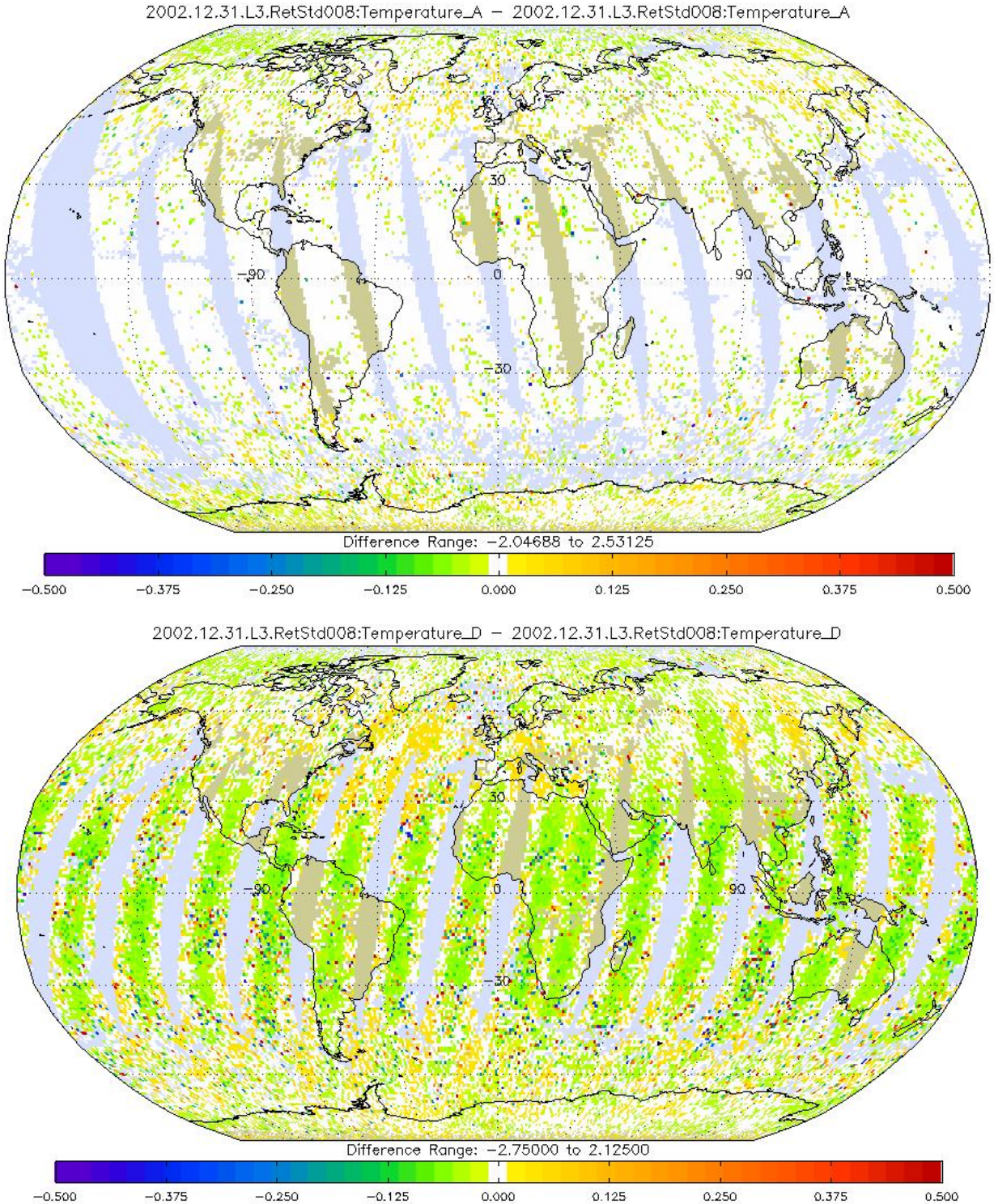

Figure 4. 100 mb Temperature errors for Winter Ascending (Top), and Descending (Bottom) orbit position after hypothetical perturbation of radiances according to the prescription in Figures 2 and 3.

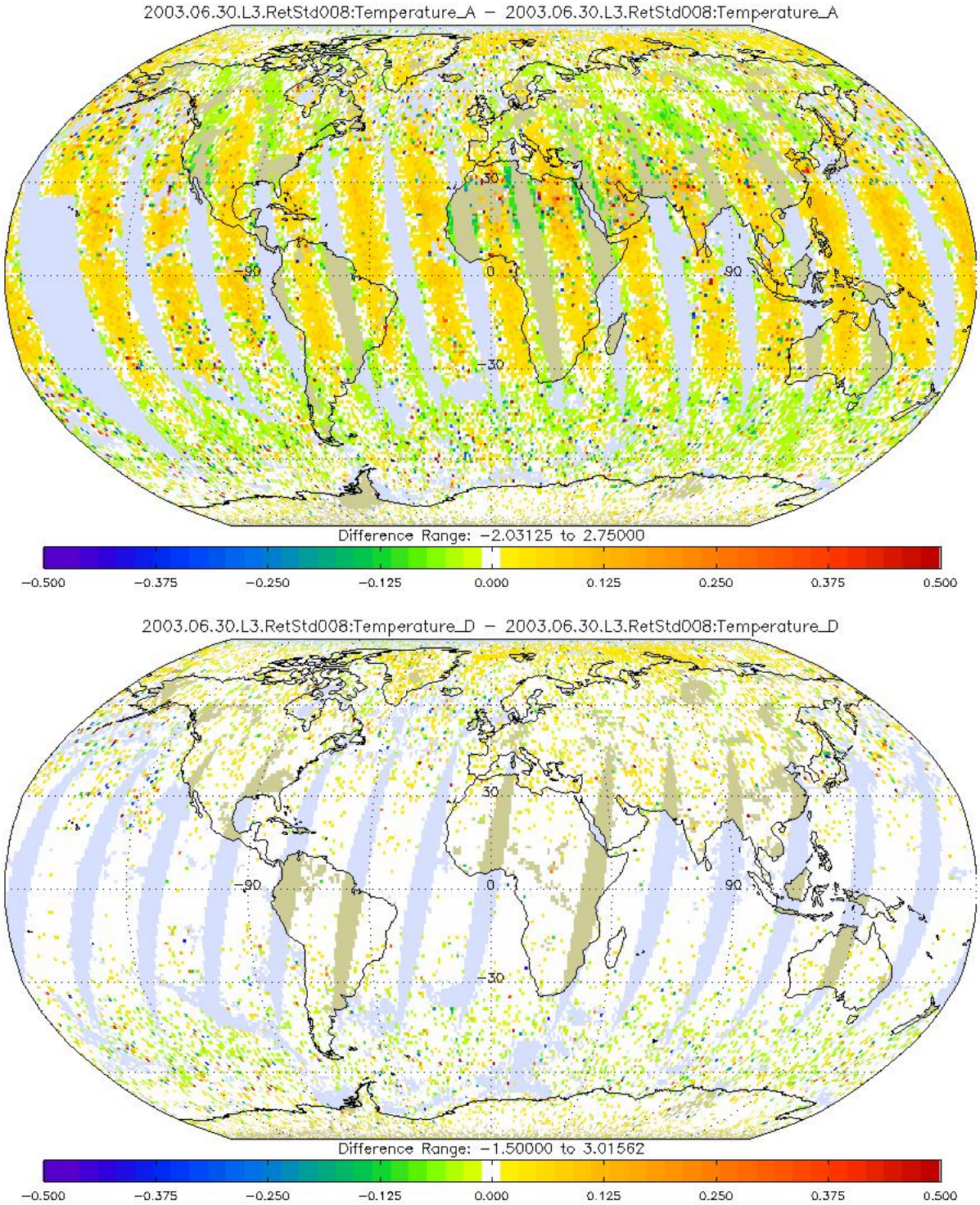

Figure 5. 100 mb Temperature errors for Summer Ascending (Top), and Descending (Bottom) orbit position after hypothetical perturbation of radiances according to the prescription in Figures 2 and 3.

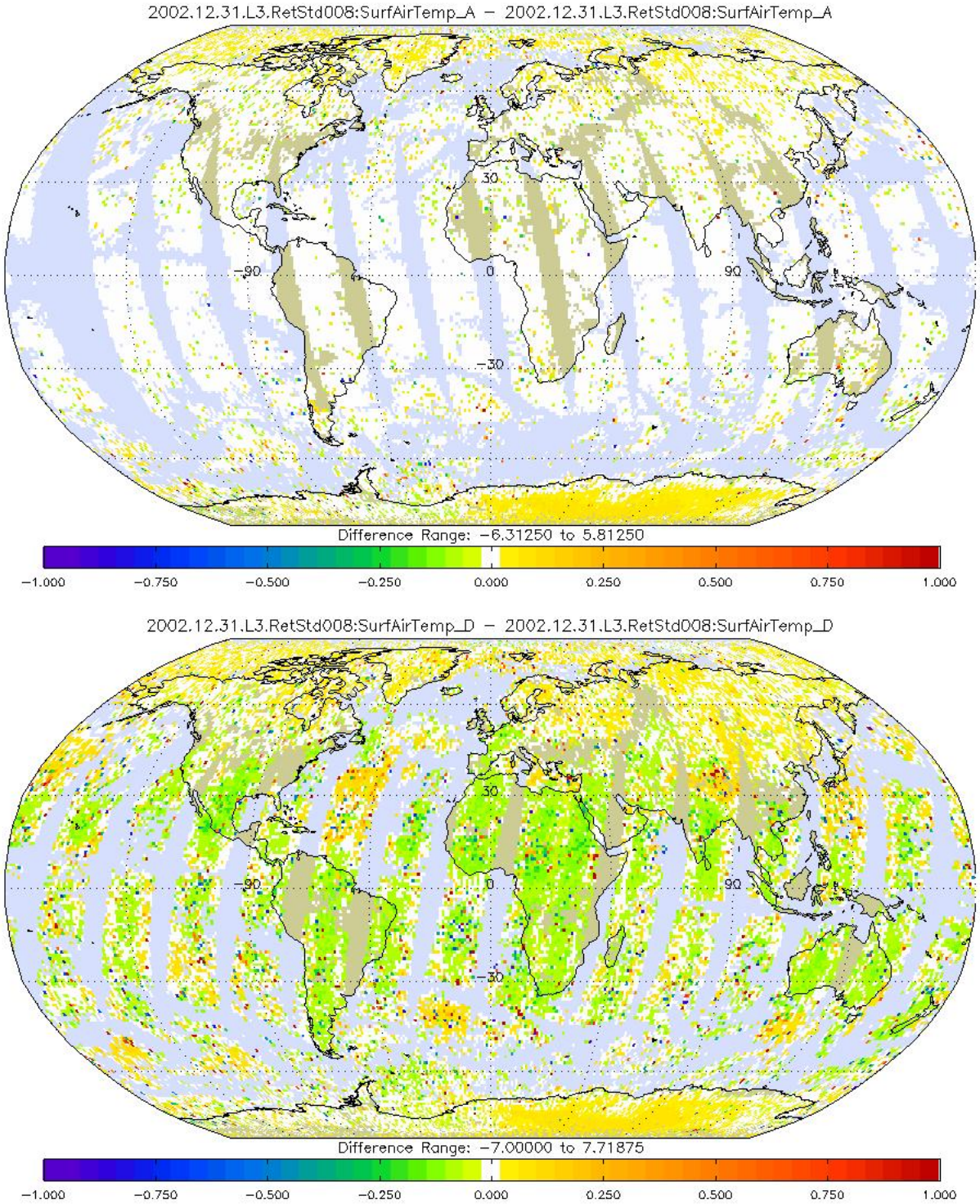

Figure 6. Surface Air Temperature errors for Winter Ascending (Top), and Descending (Bottom) orbit position after hypothetical perturbation of radiances according to the prescription in Figures 2 and 3.

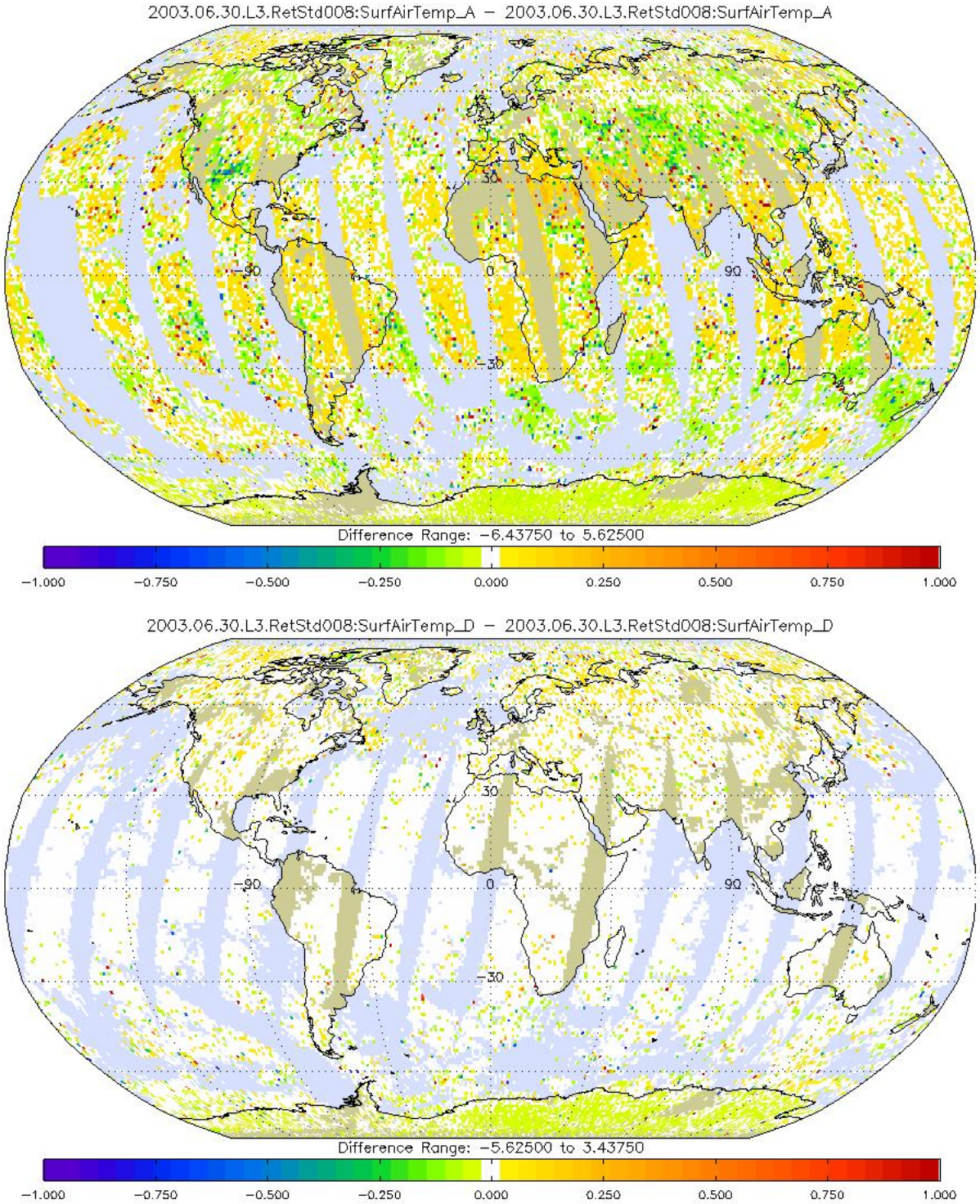

Figure 6. Surface Air Temperature errors for Winter Ascending (Top), and Descending (Bottom) orbit position after hypothetical perturbation of radiances according to the prescription in Figures 2 and 3.