Global Analysis and Characterization of AIRS/MODIS Cloud-Clearing

Hong Zhang, Hung-Lung Huang, Jun Li, Elisabeth Weisz, Kevin Baggett, and Chian-Yi Liu

Cooperative Institute for Meteorological Satellite Studies, Space Science and Engineering Center, University of Wisconsin, Madison, WI USA

ABSTRACT

The Atmospheric Infrared Sounder (AIRS) and MODerate-Resolution Imaging Spectroradiometer (MODIS) on board the EOS Aqua spacecraft measure the upwelling infrared radiance used for numerous remote sensing and climate related applications. AIRS provides high spectral resolution infrared radiances while MODIS provides collocated high spatial resolution radiances at sixteen broad infrared bands. An optimal algorithm for cloud-clearing has been developed for AIRS cloudy soundings at the University of Wisconsin-Madison where the spatially and spectrally collocated AIRS and MODIS data has been used to verify this algorithm. A global analysis and characterization of the AIRS cloud-clearing using the bias and the standard deviation between AIRS cloud-cleared brightness temperature and the nearby clear brightness temperature are studied. Both bias for daily and 45 days have been analysised.

Keywords: Cloud-Clearing, AIRS, and MODIS

INTRODUCTION

The Atmospheric Infrared Sounder (AIRS) and the MODerate Resolution Imaging Spectroradiometer (MODIS) on National Aeronautics and Space Administration’s Earth Observing System (EOS) Aqua satellite enable improved global monitoring of the distribution of global clear and clouds. AIRS is a high spectral resolution ($\nu/\Delta\nu = 1200$, where $\nu$is the wavenumber and $\Delta\nu$ is full-width half maximum of a channel) infrared (IR) sounder with 2378 channels. AIRS measures radiances in the IR range 3.74-15.4 μm, which can be used to estimate the atmospheric vertical temperature and water vapor profiles from the Earth’s surface to an altitude of 40km with a horizontal spatial resolution of 13.5km at nadir (Aumann, et al., 2003). Due to its relatively coarse spatial resolution, the chance of an AIRS footprint to be completely clear is usually less than 10% statistically (Huang and Smith, 2004). It has been demonstrated that for any satellite infrared sounders with relatively wide fields of view (IFOV size > 10 km) that the probability of entirely cloud-free observation is surprisingly low. The direct infrared only cloudy retrieval and assimilation of IR cloudy radiances are currently difficult if not impossible. The difficulty lies in the efficient and accurate modeling and treatment of the cloud signal part of the IR measurements. Some efforts have just begun to model the microphysical complexity of clouds and their radiative responses (Zhibo et al, 2006). The parameterization of cloud properties to deliver much needed improvements in speed and accuracy of forward radiative transfer models is still under development. Indirect use of cloud contaminated radiance by way of cloud-cleared radiances has since received great attention, as a interim, to improve both the spatial and spectral yields of useful satellite infrared radiances and sounding products. One of the important questions is how to effectively perform cloud-clearing (CC) for the AIRS cloudy footprints, while still retaining the single footprint sounding gradient information for numerical weather prediction. Smith *et al.*(2004) combine Moderate Resolution Imaging Spectroradiometer (MODIS) IR clear radiances and AIRS cloudy for CC using the traditional single band N* approach. In our study, an optimal CC method is developed to retrieve the AIRS clear column radiances by combing the multiband MODIS IR clear radiance observations and the AIRS cloudy radiances on a two-single footprint basis. The optimal CC methodology (Li et al., 2005) has been used in the multi-sprectral bands CC technique in this study.

In this paper, AIRS and MODIS collocated global dataset has been generated. The characteristics of these cloud-cleared brightness temperatures are analyzed. Daily and 45 days results are shown to discuss the unique characteristic and deficiencies of this synergy approach. Both bias and RMS error for daily and 45 days will be extended to further confirm and refine the findings reported in this paper.

OVERVIEW OF OPTIMAL CLOUD CLEARING METHODOLOGY

Collocation between AIRS and MODIS

AIRS spatial coverage is provided by the scan head assembly, containing a cross-track rotary scan mirror and calibrators. The AIRS spatial distribution is used in the collocation between the MODIS and AIRS measurement, which is the first step for the optimal MODIS/AIRS cloud-clearing. The MODIS pixels with 1-km spatial resolution are collocated within an AIRS footprint. With a set of AIRS earth-located observation, the footprint of each AIRS observation describes a figure that circular at nadir, quasi-ellipsoidal at intermediate scan angles, and ovular at extreme scan angles. The diameter of the AIRS footprint at nadir is approximately 13.5 km. Depending on the angular difference between the AIRS and MODIS slant range vector, a weight (ω) is assigned to each MODIS pixel collocated to AIRS: 100% if the MODIS pixel lies at the center of the AIRS oval, and 0 if at the outer edge. The collocation is modeled correctly and the algorithm provides an accuracy better than 1 km, provided the geometry information from both instruments is accurate.

AIRS Cloud Masking Using MODIS

Once the MODIS pixels are collocated with the AIRS footprints, the cloud properties within the AIRS subpixel can be characterized using the MODIS cloud mask (Ackerman et al., 1998). The cloud mask, cloud phase mask as well as the cloud-layer information mask, can be generated from MODIS products with 1-km spatial resolution (Li *et al.*, 2004). For each AIRS footprint, a clear coverage (0 ~ 1) is created by accounting for the percentage of MODIS pixels with confident clear and probably clear within the footprint. Detailed optimal cloud clearing methodology has been described in Li, et al. (2005).

GLOBAL AIRS/MODIS CLOUD-CLEARING

AIRS Global Cloud Clearing

It has been demonstrated that for any satellite infrared sounders with relatively wide fields of view (IFOV size > 10 km) that the probability of entirely cloud-free observation is surprisingly low. Figure 1 shows the frequency of AIRS clear FOV for all granules on January 1st, 2004, the average of global has about 5 to 15% true clear.

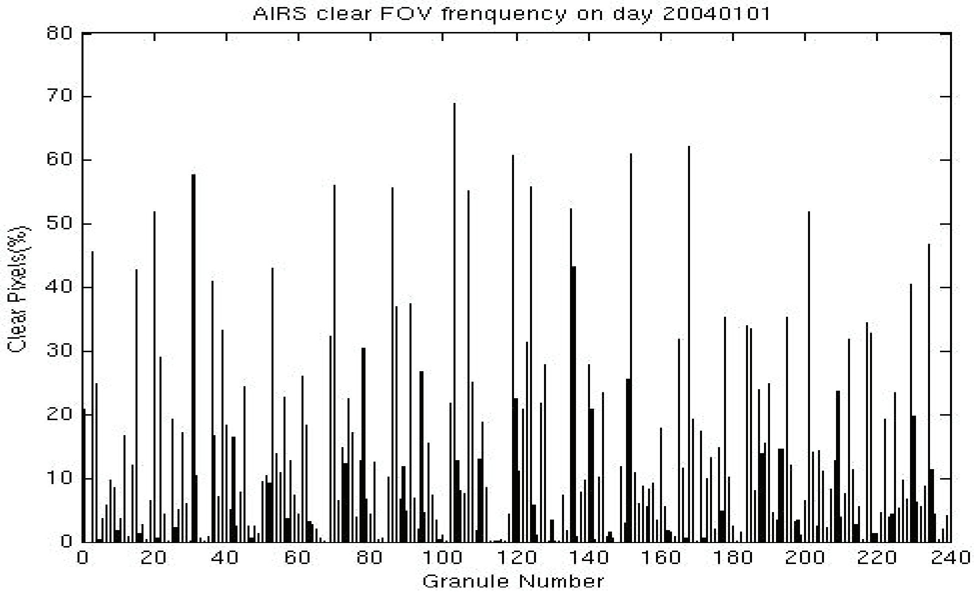
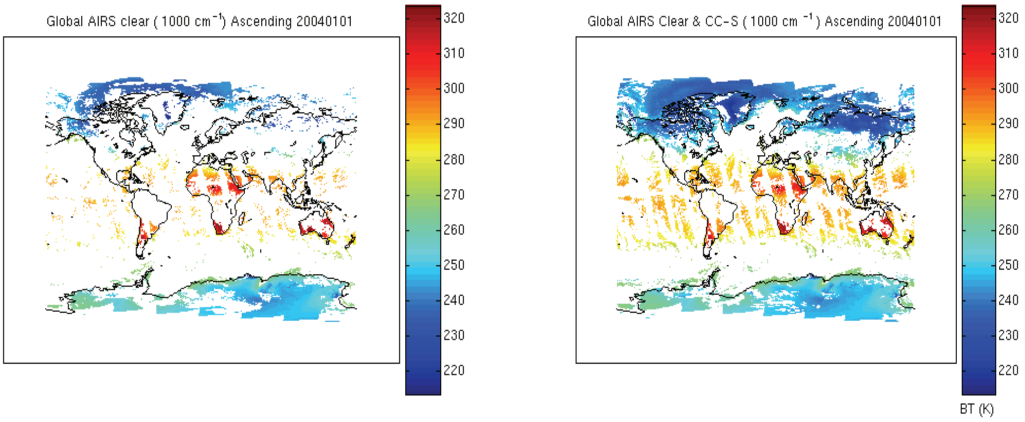
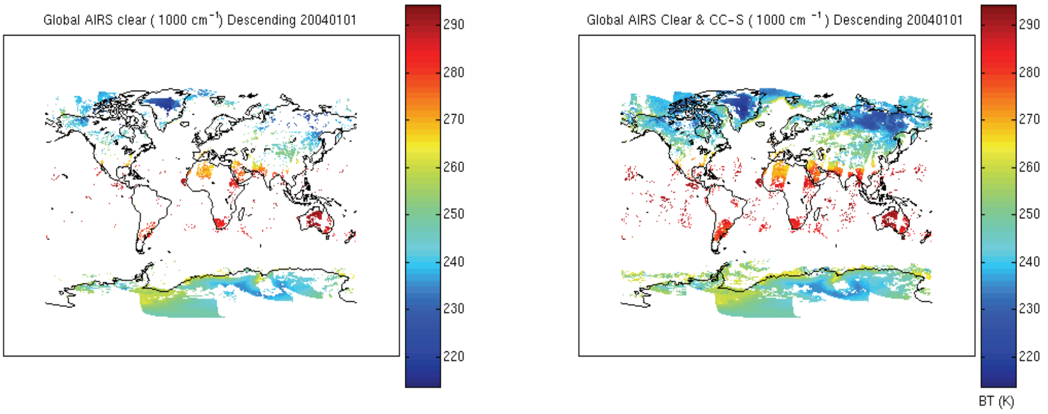


Figure 1: AIRS Global clear FOV frequency on January 1, 2004.

The optimal cloud clearing method is applied to all AIRS footprints that are partly cloudy. The optimal cloud clearing will not be performed if the AIRS FOV is determined as fully cloudy. There are four categories in the AIRS cloud clearing FOVs: clear, cloud clearing successful (CC-S), cloud clearing fail (CC-F), and cloudy. Figure 2 is an example of AIRS cloud clearing for both descending and ascending granules on January 1, 2004. Figure 2(a) is the clear only FOV brightness temperature (BT) of ascending granules at AIRS wavenumber 1000 cm^{-1}, Figure 2(b) is the BT of both clear and cloud clearing successful of ascending granules, Figure 2(c) shows the clear FOV BT of descending granules, and Figure 2(d) is the BT of both clear and cloud clearing successful of descending granules.



(a) clear only ascending granules (b) clear and cloud clearing successful ascending granules



(c) clear only descending granules (d) clear and cloud clearing successful descending granules

Figure 2: AIRS global clear and cloud clearing brightness temperature on Jan. 1, 2004.

Figure 3a shows that there are about 17% CC-S for day January 1st (left) and January 4th (right), 2004, which make total clear FOV about 30% instead of 13% clear FOV, globally. Bias images for day January 4th are not shown here. 45 days global cloud clearing statistics from January 1st to February 15th, 2004 (no January 3rd due to short of data) were shown on Figure 3b and 3c, on average, there was 13.26% clear, 20.60% cloud-cleared successful, and 17.78% cloud-cleared failed.

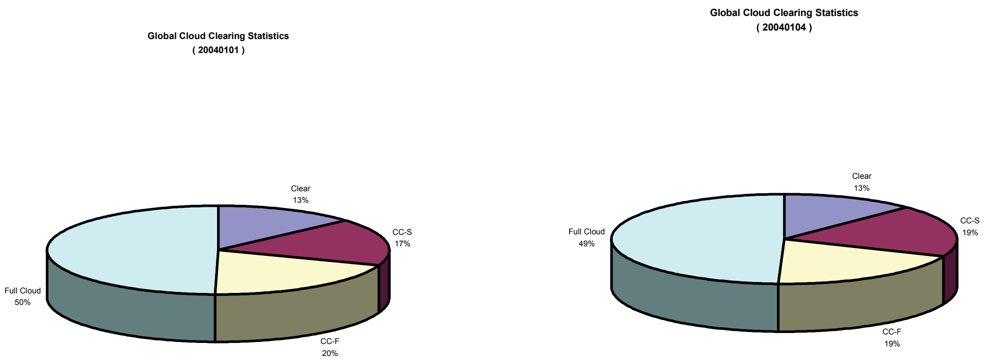


Figure 3a: Global cloud clearing statistics, Jan. 1, 2004 (left): clear (13%), CC-S (17%), CC-F (20%), and Cloudy (50%); Jan, 4, 2004 (right): clear (13%), CC-S (19%), CC-F(19%), and Cloudy (49%)

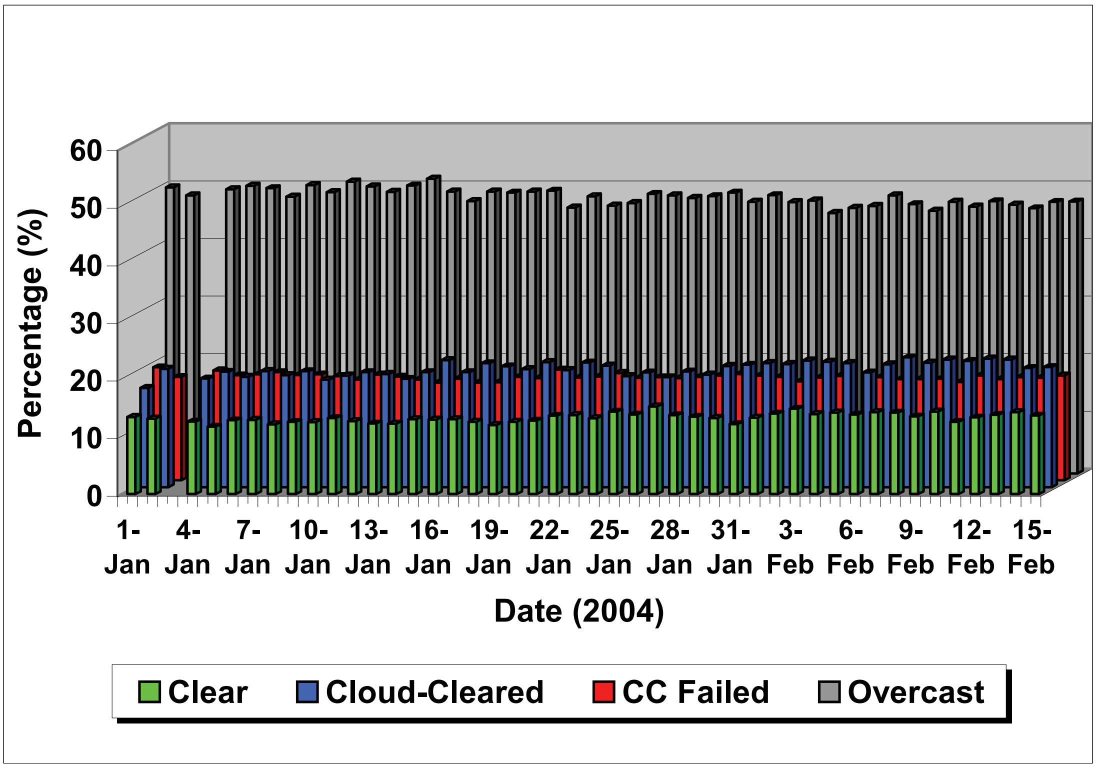


Figure 3b: 45 days global cloud clearing statistics from January 1st to February 15th, 2004 (no January 3rd due to short of data)

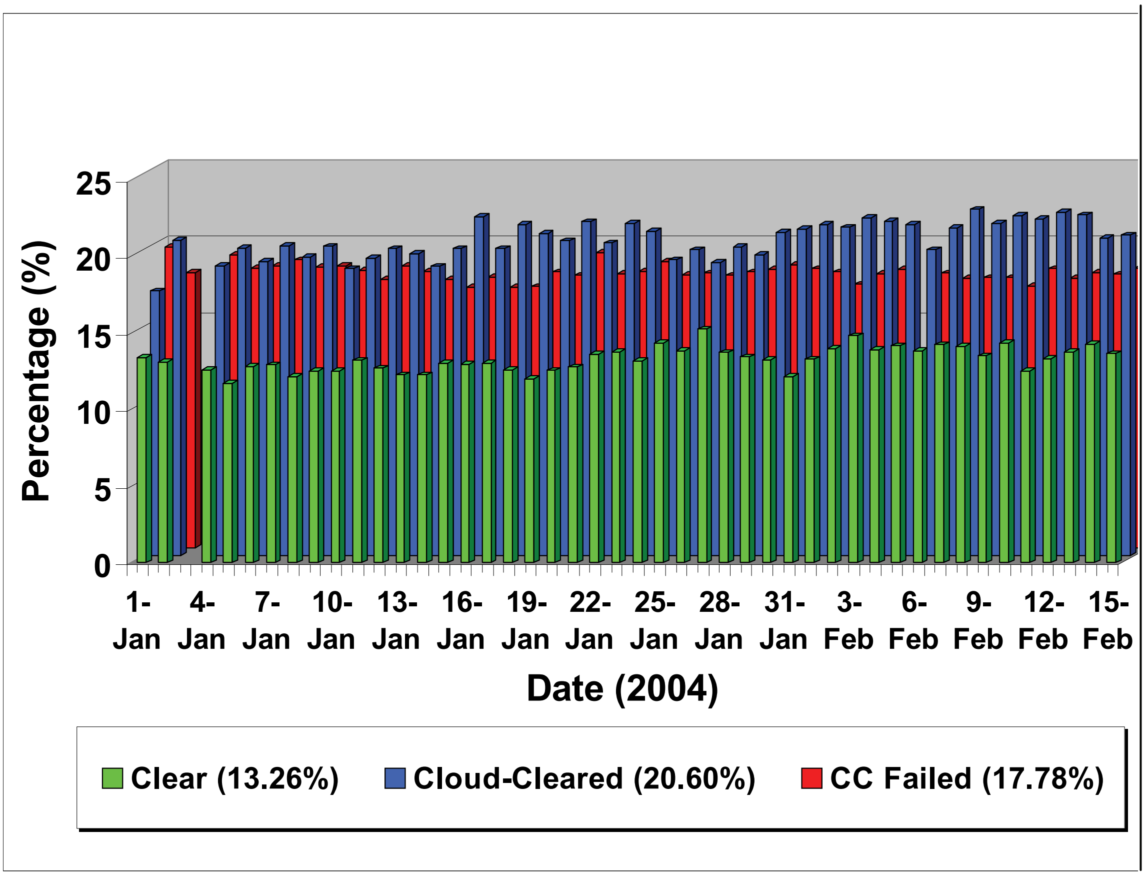


Figure 3c: 45 days global cloud clearing statistics from January 1st to February 15th, 2004 (no January 3rd due to short of data), on average, 13.26% clear, 20.60% cloud-cleared successful, and 17.78% cloud-cleared failed.

Bias and RMS error of cloud-cleared vs. nearby clear

To evaluate the performance of AIRS cloud clearing, bias, standard deviation, and the root mean square difference (RMSD) were studied. Figure 4 shows the bias (upper panel), standard deviation (middle panel), and RMSD (lower panel) between the AIRS cloud-cleared BT spectra and their nearby clear footprint BT spectra over land (Figure 4a) and water (Figure 4b) on 1 January 2004. It can be seen that the bias is less than 0.3 for the spectral region of 600 ~ 2400 cm^{-1}, a sight larger bias between 2400 to 2600 cm^{-1}. The standard deviation of AIRS cloud-cleared BTs is less than 2 K for most spectral regions. The use of the near by clear as the “truth” for validating the cloud-cleared error suffers the inherited scene inhomogeneous effect that need to be accounted for. In the subsequent analysis the scene inhomogeneous effect will be quantified and removed from the current estimate of the cloud-cleared error shown in Figure 4.

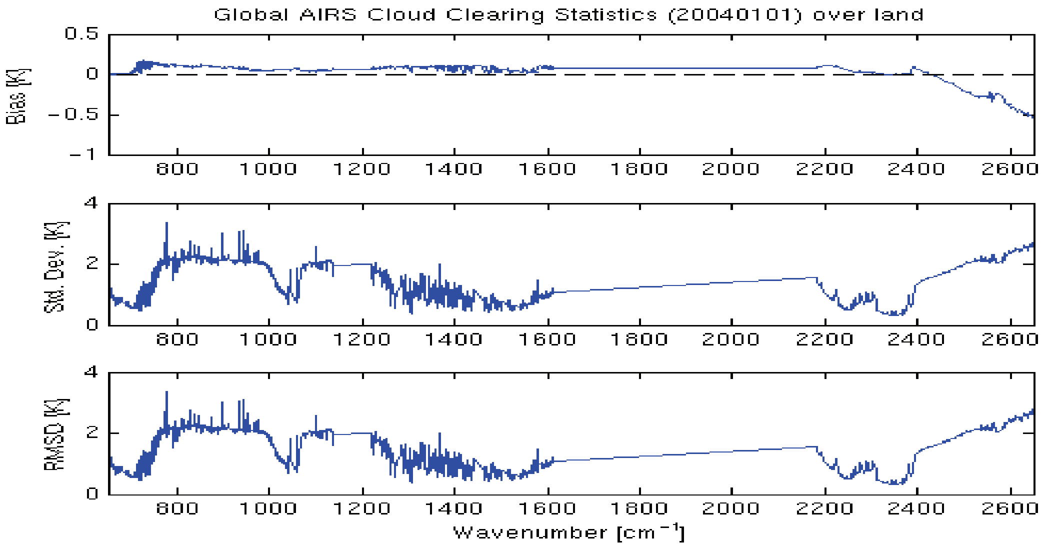


Figure 4a: Bias (upper panel), standard deviation (middle panel), and RMSD (lower panel) between the AIRS cloud-cleared BT spectra and their nearby clear footprint BT spectra over land of the granules on day Jan. 1, 2004.

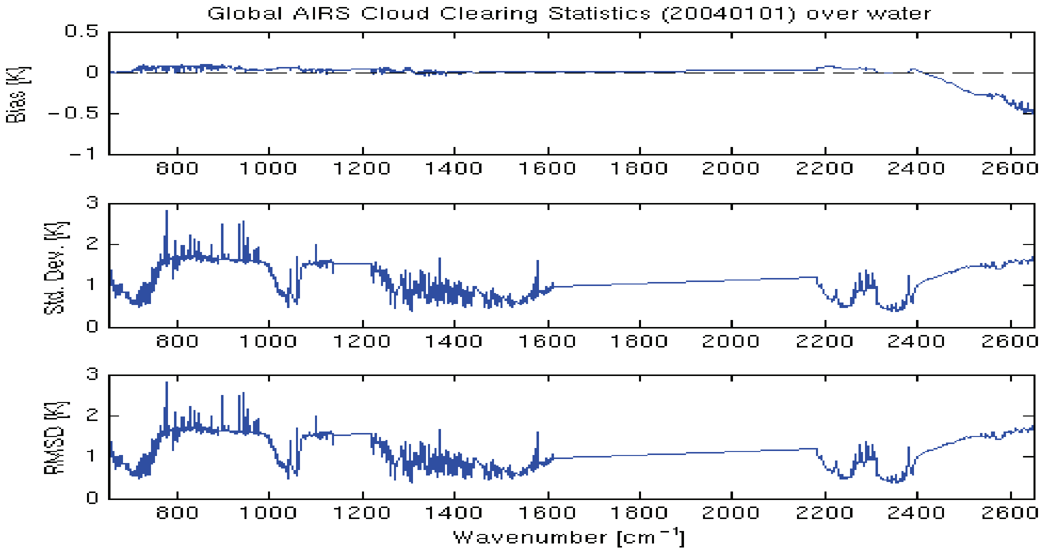


Figure 4b: the same as Figure 4a, but for granules over water on day Jan. 1, 2004

Figures 5 and 6 show the bias between the AIRS convoluted CC-S BT and the collocated MODIS clear measurements at MODIS bands on 6 February 2004 (daytime only), 21 January 2004 (nighttime only) respectively, for over land (upper panel), water (middle panel), and mixed surface (lower panel). For land surface, water surface or mixed surface type, the CC bias for MODIS bands 21 22, 23, 25, and 30 through 36 are very small (less than 1 K); the bias for bands 24 and 28 are slightly larger but still less than 0.5 K. However, bias for bands 20 and 29 are relatively large (around 2.0 K) due to the convolution bias (Tobin *et al.*, 2004). The AIRS popping channels and the AIRS spectral gap cause the convolution bias. MODIS bands 35 and 36 might also have an SRF calibration bias. The performance is also consistent at day and nighttime when MODIS cloud mask characteristic is taking into account.

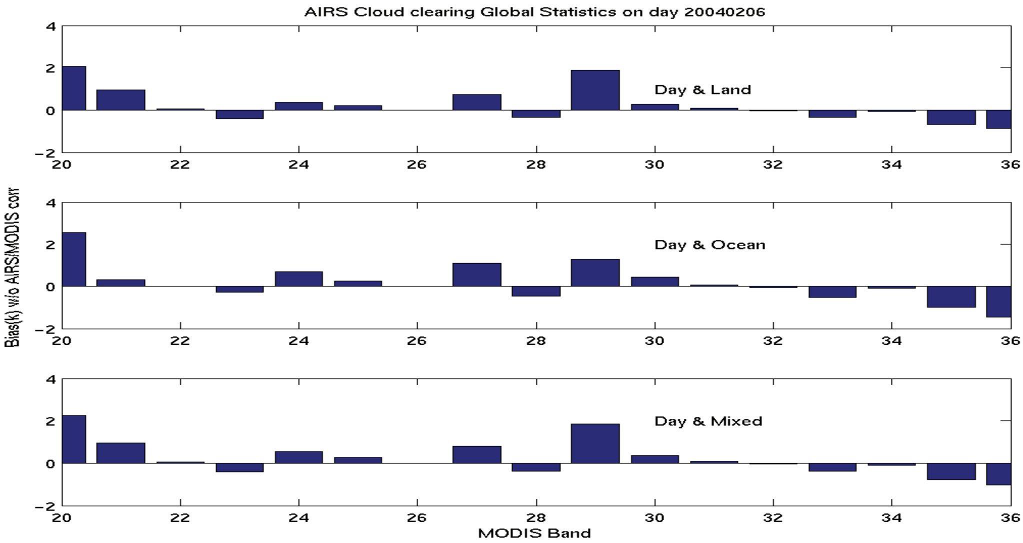


Figure 5: Global bias between the AIRS convoluted CC-S BT and the collocated MODIS clear BT on 6 February 2004(daytime only) for over land (upper panel), water (middle panel), and mixed surface (lower panel).

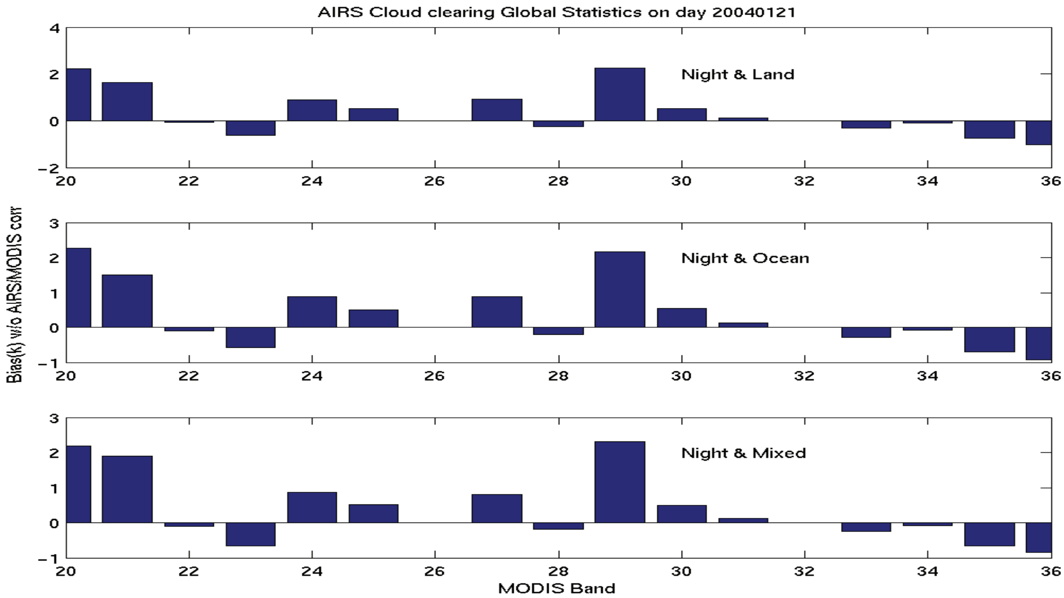


Figure 6: the same as Figure 5, but for night only on 21 January 2004.

There is smaller bias over water surface type than land surface at MODIS band 23 and 29. Those biases are removable provided that the reliable estimates are available. Global average bias of 45 days from January 1st to February 15th, 2004 (no January 3rd due to short of data) was shown on Figure 7 (daytime only) and Figure 8 (nighttime only), respectively for over land (upper panel), water (middle panel), and mixed surface (lower panel). Figure 9 represents 45 days (from January 1st to February 15th, 2004, no January 3rd due to short of data) global average bias (upper panel), standard deviation (middle panel), and RMSD (lower panel) between the AIRS cloud-cleared BT spectra and its nearby clear footprint BT spectra, red lines represent land surface, blue lines are for water surface.

The performance of daily and 45 days average are very consistent for both land and water surface when FOV to FOV scene variation is taking into account.

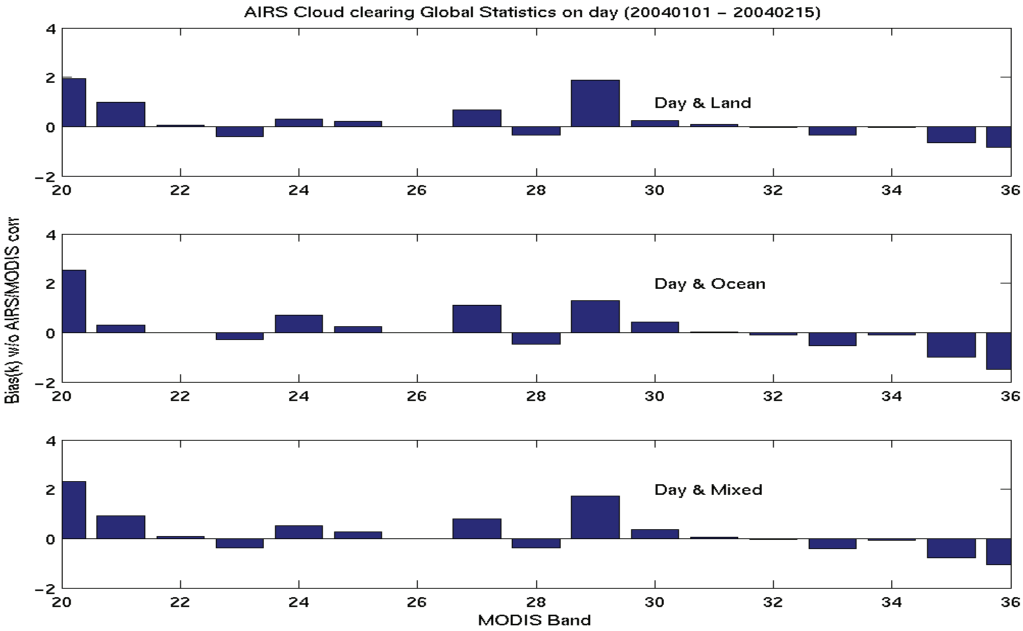


Figure 7: Global average bias of 45 days from January 1st to February 15th , 2004 (no January 3rd due to short of data) between the AIRS convoluted CC-S BT and the collocated MODIS clear BT daytime only for over land (upper panel), water (middle panel), and mixed surface (lower panel).

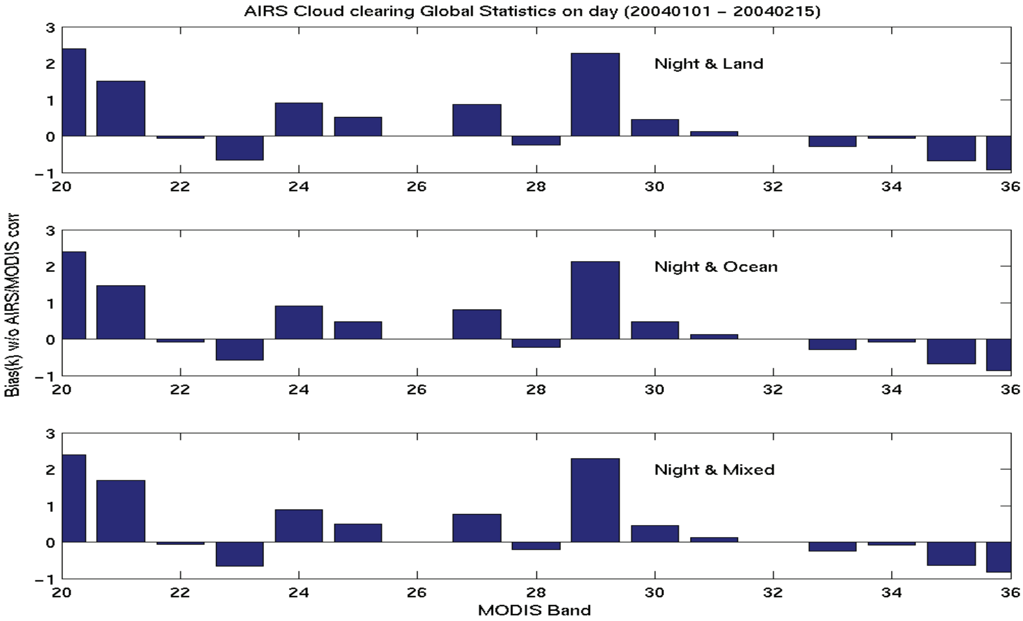


Figure 8: the same as Figure 7, but for night only.

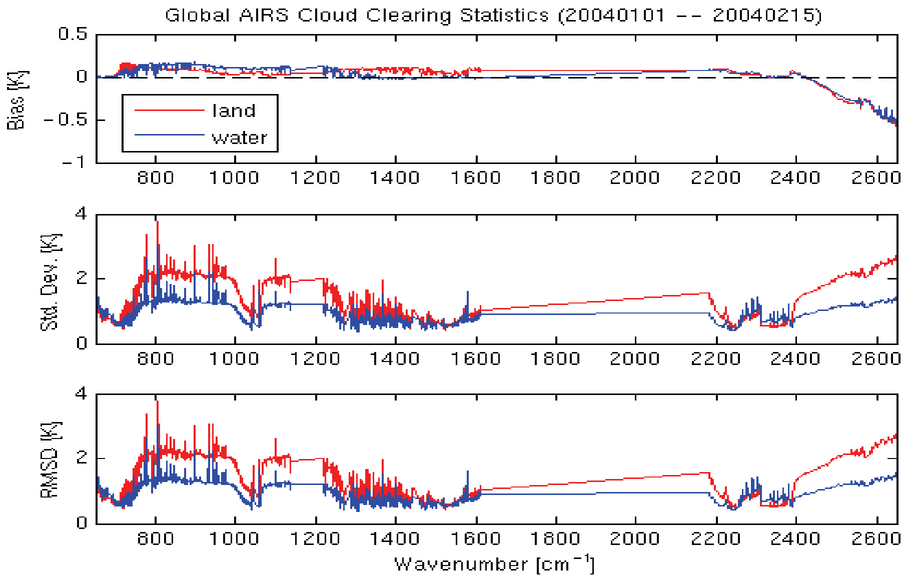


Figure 9: 45 days (from January 1st to February 15th, 2004, no January 3rd due to short of data) global average bias (upper panel), standard deviation (middle panel), and RMSD (lower panel) between the AIRS cloud-cleared BT spectra and their nearby clear footprint BT spectra, red lines represent land surface, blue lines are for water surface.

CONCLUSIONS AND FUTURE WORK

45 days (January 1st to February 15th, 2004, no January 3rd data due to short of data) of collocated AIRS/MODIS global data has been generated, the results have shown that about 21% of AIRS cloudy footprints are successfully cloud cleared, which make about 30% of FOVs are available for clear sounding. The synergistic AIRS/MODIS cloud-clearing performance in terms of bias and RMS error using collocated MODIS clear and nearby AIRS clear data has been characterized.

For future work, the cloud-cleared radiances dataset along with their associated error estimates are to be delivered to Join Center for Satellite Data Assimilation (JCSDA) and Global Modeling and Assimilation Office (GMAO), for potential assimilation of AIRS cloud-clearing radiances. The potential for numerical weather prediction and cloudy sounding applications will be studied. Also we are going to continue to refine cloud-clearing error processing procedure to include the calculate clear radiances as the “reference truth” and to remove FOV to FOV scene in-homogeneity from the errors estimate when using near-by clear as the independent reference truth, more over, reanalyze cloud-clearing characteristic using the latest version 5 of MODIS cloud mask and new AIRS/MODIS collocation routine. Upon successful implementation and validation of the AIRS/MODIS synergistic cloud-clearing, it’ll be incorporated in the future release of International MODIS/AIRS Processing Package (IMAPP) (Huang et al., 2004). Synergistic imaging and sounding cloud-clearing approach will also be adopted for the future geostationary cloud-clearing processing where high spatial resolution imaging and hyperspectral sounding data are available to improve the yield of the clear sounding probability.

ACKNOWLEDGEMENTS

This work was supported by NASA grant NNG06GC20G.

REFERENCES

Huang, H.-L., and W. L. Smith, 2004: Apperception of clouds in AIRS data. *Proc. ECMWF Workshop on Assimilation of High Spectral Resolution Sounder in NWP*, 28 Jun-1 Jul 2004, p155-169.

Huang, H.-L., L. E. Gumley, K. Strabala, J. Li, E. Weisz, T. Rink, K. C. Baggett, J. E. Davies, W. L. Smith, and J. C. Dodge, 2004: International MODIS and AIRS Processing Package (IMAPP): A direct broadcast software for the NASA earth Observing System. *Bull. Amer. Meteor. Soc.*, **85**, 159-161.

Aumann, H. H., M. T. Chahine, C. Gautier, M. D. Goldberg, E. Kalnay, L. M. McMillin, H. E. Revercomb, P. W. Rosenkranz, W. L. Smith, D. H. Staelin, L. L. Strow, and J. Susskind, 2003: AIRS/AMSU/HSB on the Aqua mission: design, science objectives, data products, and processing systems. *IEEE Trans. Geosci. Remote Sens.*, **41**, 253-264.

Li, J., H.-L. Huang, C.-Y. Liu, P. Yang, T. J. Schmit, H. Wei, E. Weisz, and W. P. Menzel, 2005: Retrieval of cloud microphysical properties from MODIS and AIRS, *J. Appl. Meteor.*, **44**, 1526-1543.

Li, J., C.-Y. Liu, H.-L. Huang, T. J. Schmit, X. Wu, W. P. Menzel, and J. J. Gurka, 2005b: Optimal cloud-clearing for AIRS radiances using MODIS, *IEEE Trans. on Geosci. Remote Sens*. **43**, 1266-1278.

Li J., W. P. Menzel, F. Sun, T. J. Schmit, and J.Gurka, 2004: AIRS sub-pixel cloud characterization using MODIS cloud products*, J. Appl. Meteor.* **43**, 1083-109.

S. A. Ackerman, K. I. Strabala, W. P. Menzel, R. A. Frey, C. C. Moeller, and L. E. Gumley, 1998: Discriminating clear sky from clouds with MODIS. *J. Geophys. Res.-Atmospheres*, **103**, 32141-32157.

Smith, W. L., et al., 2004: Extraction of profile information from cloud contaminated radiances. *Proc. ECMWF Workshop on Assimilation of High Spectral Resolution Sounder in NWP*, 28 Jun-1 Jul 2004, p145-154.

Tobin, D. C., H. E. Revercomb, C. C. Moeller, R. O. Knuteson, F. A. Best, W. L. Smith, et al., 2004: Validation of Atmospheric InfraRed Sounder (AIRS) spectral radiances with the S-HIS aircraft instrument. Remote Sensing of Cloud and the Atmosphere IX, *Proceedings of SPIE* 5571, 13-15 September 2004, Maspalomas, Gran Canaria, Spain.

Zhibo, Z., P. Yang, G. Kattawar, H-L Huang, T. Greenwald J. Li, B. Baum, D. K. Zhou, and Y. Hu, 2006: A Fast Infrared Radiative Transfer Model Based on the Adding-Doubling Method for Hyperspectral Remote Sensing Applications. Accepted for publication in *J. Quant. Spectro. Rad. Transfer*.

INTERNATIONAL ATOVS WORKING GROUP

Sharing ideas, plans and techniques

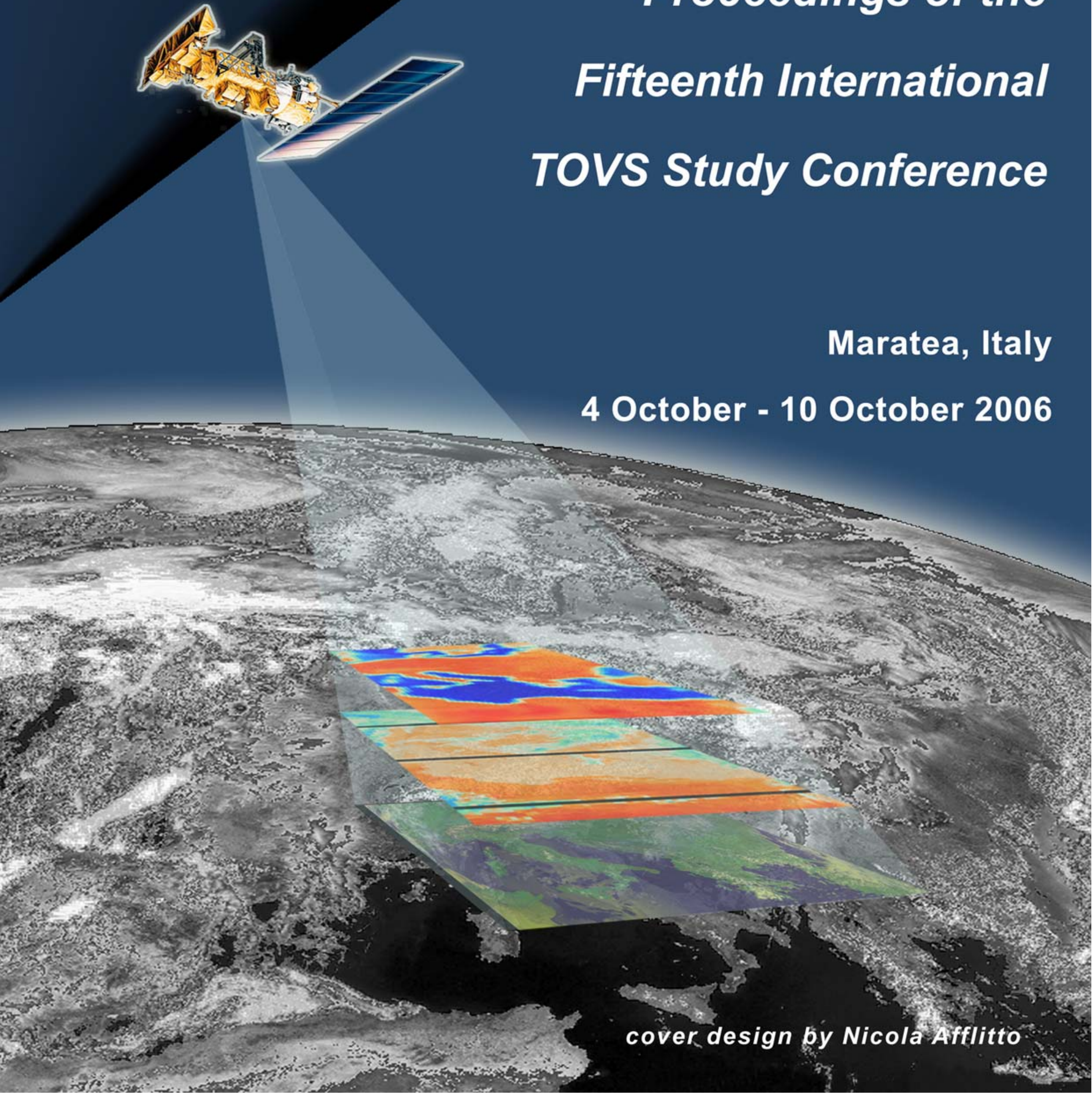
to study the earth's weather

using space-based observations

Proceedings of the Fifteenth International TOVS Study Conference

Maratea, Italy

4 October - 10 October 2006



cover design by Nicola Afflitto