INVESTIGATION OF RADIANCE CALIBRATION, CLOUD PROPERTIES, AND ATMOSPHERIC PROFILES WITH MODIS

FINAL REPORT

Paul Menzel, Steve Ackerman, Bryan Baum, Richard Frey, Liam Gumley, Dan LaPorte, Jun Li, Jeff Key, Chris Moeller, Suzanne Seemann, Kathy Strabala, Tom Rink, and Hong Zhang
CIMSS at the University of Wisconsin-Madison
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Abstract

UW assessed Terra and Aqua MODIS L1B thermal infrared band radiometric accuracy using ER-2 based observations collected during several field experiments over the past years. After overcoming problems associated with PC band cross-talk, reflective changes with scan angle, thermal leakage into reflective band measurements, and detector to detector differences, it was found that most Terra and Aqua MODIS bands are performing within or very near specification. UW developed and tuned the algorithms for cloud mask, cloud top properties, and atmospheric profiles (MOD35, MOD06, and MOD07); periodic updates incorporated post-launch instrument characterizations, improved radiance bias adjustments, expanded training data sets, better treatment of surface emissivity and skin temperature, more efficient algorithm coding, mitigation of day-night product differences, and adapting Terra code for Aqua applications. ATBDs for each of the three products areas were written and updated several times. The EOS Data Products Handbook was updated several times to include more current references and product examples. Conference papers were given in a multitude of venues and training classes were held internationally to promote use of the MODIS data in earth science studies. Twenty three peer reviewed publications were the direct (or indirect) result of this work.

I. MODIS Radiance Calibration

UW has participated in pre-launch and post-launch evaluation of the Terra and Aqua MODIS sensors. For both sensors, these efforts included evaluating pre-launch test data sets, assessing instrument performance impact on science products, formulating recommendations for mitigating instrument performance issues, participating in the MODIS assessment and evaluation post launch, monitoring data routinely to detect on-orbit performance issues, developing correction algorithms that mitigate identified performance anomalies, and validating MODIS L1B radiances. In all activities, close interaction with the MODIS Characterization Support Team (MCST) was maintained.

Contributions to the MODIS calibration effort include:

- Pre- and post-launch evaluation of PC band cross-talk, development and implementation of cross-talk correction algorithm,
- Post-launch evaluation and correction of MODIS scan mirror RVS characterization,

- Pre-launch evaluation of MODIS relative spectral response (RSR) characterization including assessment of filter accuracy and correction for ground support equipment influences,
- Pre- and post-launch evaluation of the 5.3 um thermal influence on S/MWIR bands, including correction algorithm development,
- Post-launch mitigation of detector striping and out of band (OOB) influence in the MODIS thin cirrus detection band at 1.38 um (band 26), including correction algorithm development,
- Post-launch evaluation and adjustment of PC band radiometric calibration coefficients,
- Post-launch assessment and validation of MODIS L1B thermal band radiometric accuracy performance.

A few of these are highlighted in the following paragraphs.

Pre-launch testing of MODIS proto-flight model (PFM) on Terra revealed a light leak from the infrared window band 31 (at 11 μm) into atmospheric bands 32-36 (from 12.5 to 14.3 μm). The leak included both spatial and spectral components. The radiometric impact for typical radiances in these bands ranged from less than 1% in band 32 to more than 10% in band 36. The MODIS radiometric accuracy specification of 0.5% for band 32 and 1% for bands 33-36 was jeopardized. A simple linear correction algorithm was developed to reduce the contamination in these bands. At-launch correction coefficients based on pre-launch test data sets were updated based on on-orbit moon view and earth view data. Removal of 80 to 90% of the contamination was realized; an example of the correction in band 36 is presented in Figure CCM1.

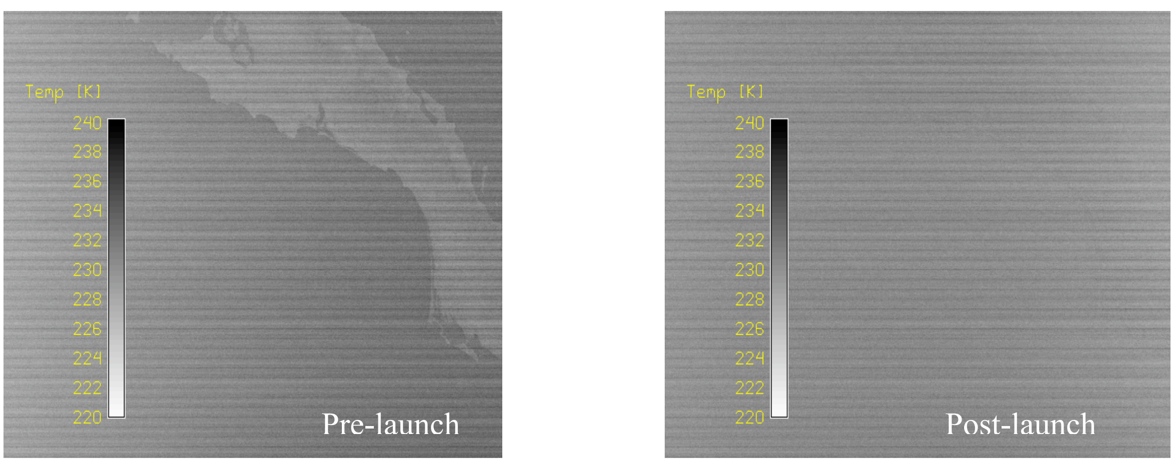


Figure CCM1. MODIS band 36 (14.3 μm) using PC band correction coefficients (left) based on pre-launch test data, and using updated correction coefficients (right) based on earth view data. The appearance of Baja in the left image demonstrates the imperfect correction of the light leak from band 31 into band 36. The post-launch correction coefficients effectively remove the contamination.

Terra MODIS Response Versus Scan (RVS) characterization was not measured at system level in pre-launch tests. Shortly after launch, UW reported unexpectedly large asymmetry in the MODIS LWIR bands. In response, MCST made adjustments to the L1B operational software and subsequent characterization of RVS using on-orbit views of the closed nadir aperture door (NAD) in Year 2000 were applied. The mirror side dependence in the MODIS LWIR band observations was reduced but not eliminated; some asymmetry remains in the MODIS cross track profiles. Analysis of global data sets revealed the ongoing asymmetry in several MODIS LWIR bands, particularly band 36 (Figure CCM2). This reinforced the need for a Terra deep space maneuver (DSM) that was performed in spring 2003; the resulting high quality RVS characterization was applied to the operational L1B processing algorithm and effectively removed the cross track asymmetry in the LWIR bands.

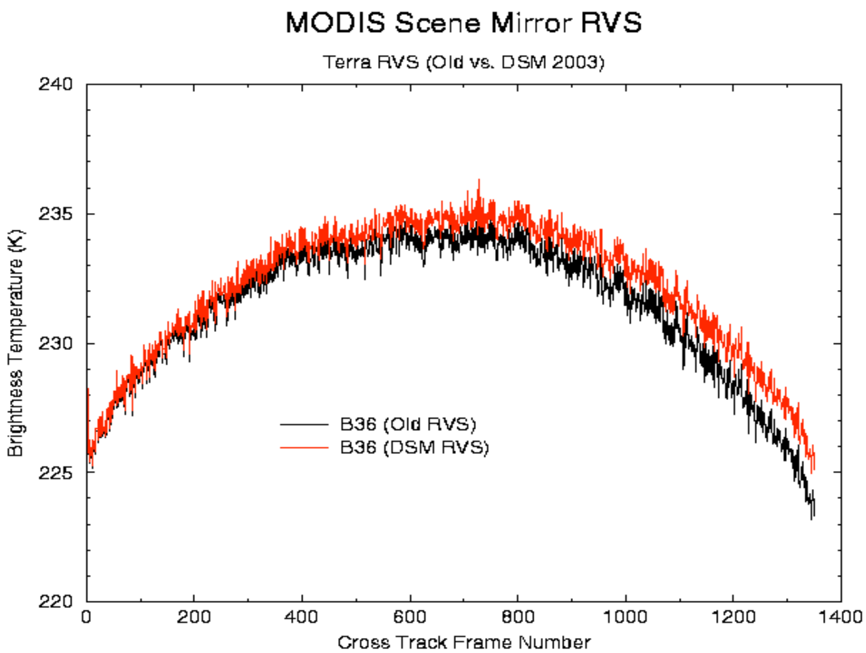


Figure CCM2. Sample Terra MODIS cross track profile for band 36 (14.3 μm) using Year 2000 RVS characterization (black) and deep space maneuver (DSM) based RVS characterization (red) from Year 2003. The Year 2000 RVS caused asymmetry in the profile with the end-of-scan region (right side) colder than the begin-of-scan region (left side). Using the Year 2003 RVS, the expected symmetry was restored.

Terra and Aqua MODIS in-orbit observations showed prominent detector striping and unexpected surface reflectance in band 26 (1.38 μm) that hindered thin cirrus detection in the MODIS cloud mask. Terra MODIS pre-launch near field response (NFR) data revealed a possible light leak into band 26. A correction model and coefficients were developed at UW using on-orbit data for both Terra and Aqua MODIS. The correction was adopted into operational L1B production at the GSFC DAAC and the radiometric integrity of the 1.38 um measurements was largely restored. An example of corrected band 26 imagery is given in Figure CCM3.

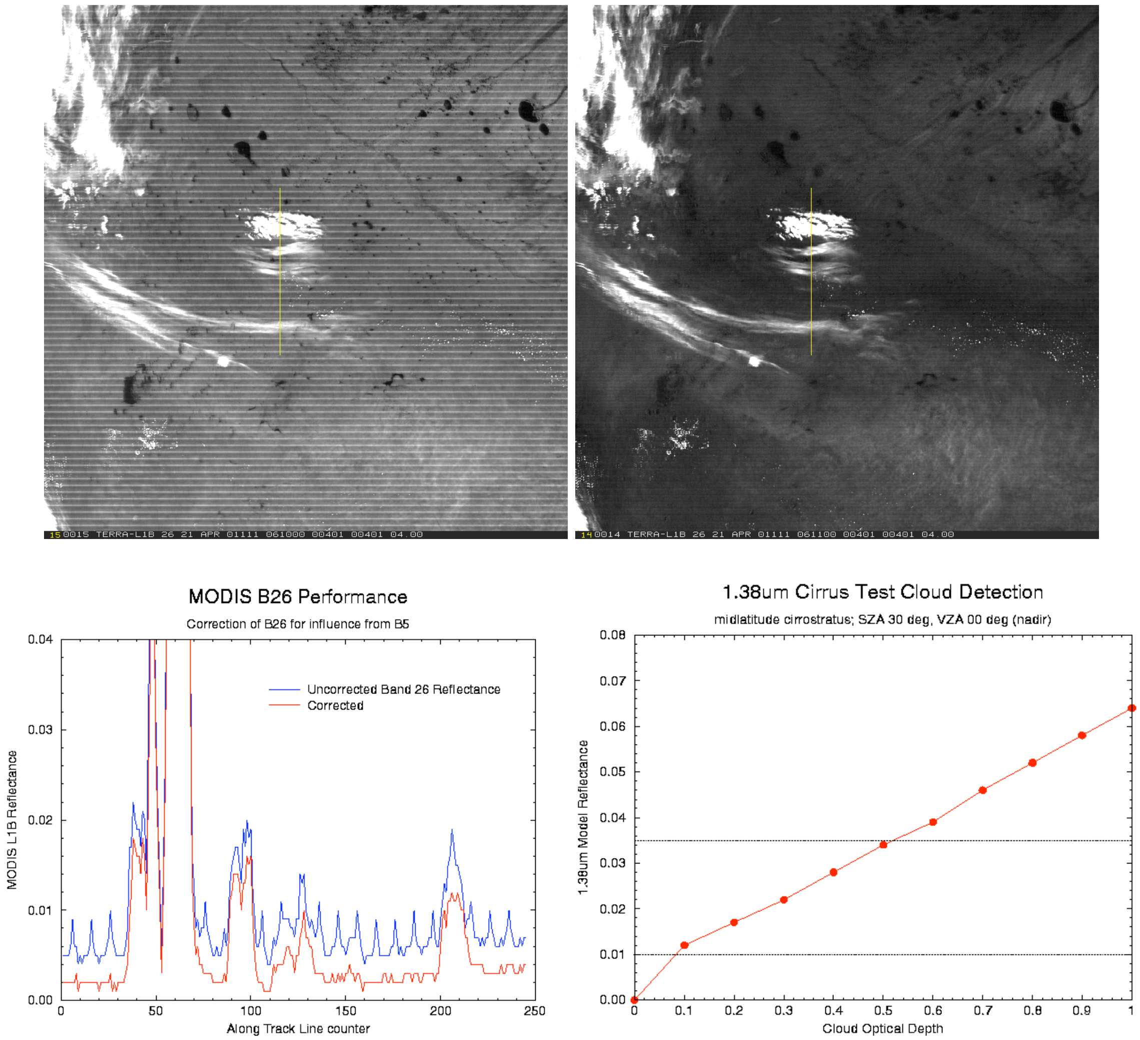


Figure CCM3: MODIS Band 26 L1B image on 21 April 2001 (top left) and after correction (top right) for striping and influence from a spectral leak near 1.25 um. Striping and surface reflection are much reduced in the corrected image. An along track profile (bottom left) shows striping is diminished (regular blue spikes are muted in the red trace) and the surface reflectance is reduced (elevated average signal of blue trace versus red trace) in the corrected data, effectively increasing the contrast between cirrus cloud features and the background. Correcting the imagery allows the cirrus cloud threshold to be reduced to near 0.01 reflectance (lower right).

As part of the assessment of the MODIS thermal band radiometric accuracy and the validation of the MODIS cloud products validation, NASA ER-2 aircraft have been used to underfly the Terra and Aqua satellites. The ER-2 payload has included the MODIS Airborne Simulator (MAS), the Scanning High resolution Interferometer Sounder (SHIS), and the Cloud Physics Lidar (CPL). Dedicated field campaigns included the WISC-T2000 (March 2000), TX-2001 (March 2001), and TX-2002 (November 2002). Through these efforts, most MODIS bands have been shown to be meeting the pre-launch radiometric specifications (Moeller, et al. 2003a, Moeller, et al. 2003b). Figure CCM4 shows an example for Terra MODIS from the TX-2001 experiment. A few bands in the LWIR CO2 region appear to be outside of specification; however, imperfect characterization of the upper atmosphere (above ER-2 flight level of 20 km) leaves uncertainty in the results of bands 35 and 36. Similar results were found for Aqua MODIS (Figure CCM5) using data collected during the TX-2002 experiment.

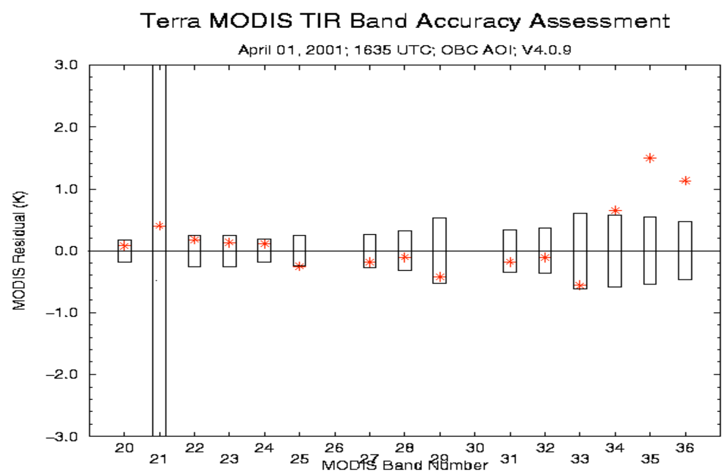


Figure CCM4. Terra MODIS L1B calibration residuals (stars) inferred from comparisons to MAS and SHIS instruments on the ER-2 platform from 01 April 2001 over the Gulf of Mexico. MODIS L1B radiometric accuracy specification (open bars) is achieved in most bands (stars within the open bars). Positive residuals indicate MODIS L1B calibrated temperature is warmer than expected.

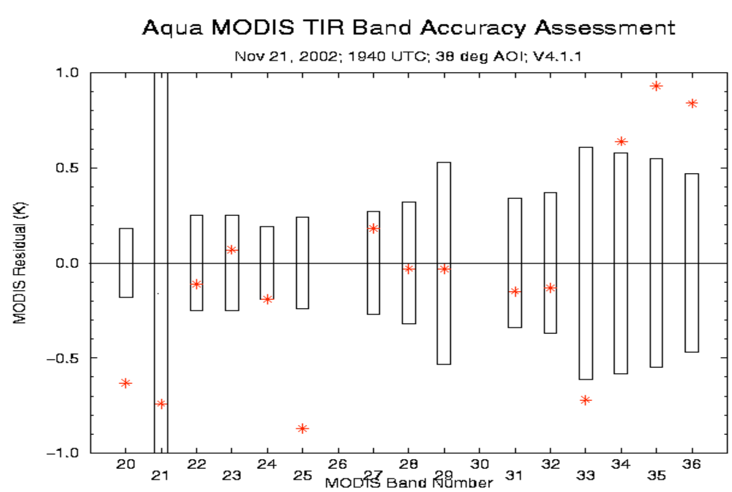


Figure CCM5. Same as Figure CCM4, except for Aqua MODIS on 21 November 2002 over the Gulf of Mexico. The residuals for most spectral bands fall within the radiometric accuracy specification envelope. Band 20 results are not considered meaningful because of sunglint in the data scene.

Ia. MODIS Calibration Lessons Learned

- Strong involvement in pre-launch characterization of an instrument is essential for post-launch corrective efforts.
- In pre-launch characterization, merging in-band and out-of-band measurements was difficult because there was no common reference. This made it difficult to evaluate the influence of cross-talk found in pre-launch data sets. Out of band measurements must be tied to in-band measurements to be useful in assessing the influence of OOB features when uncovered.
- Excessively noisy detectors contribute to striping and detract from science products. In extreme cases, they compromise a spectral band entirely. If at all possible, noisy detectors should be replaced before going to orbit.
- Optical light leak influence can be mitigated with on-orbit observations of special sources such as the moon or the earth, in the case of opaque atmospheric bands. However, significant effort was expended to make these corrections and the 1% radiometric accuracy specification is in question in some of these bands. If at all possible, optical light leaks should be fixed with pre-launch hardware modifications.
- Electronic cross-talk is difficult to characterize using on-orbit data, including onboard sources. These should be fixed pre-launch.
- OBC warmup-cooldown does not enable determination of calibration coefficient changes for thermal bands with typical signal levels outside the OBC dynamic range.
- Nighttime on-orbit data is effective for developing correction coefficients for thermal band leaks into the reflectance bands.
- Validation of thermal window bands can be accomplished to within 0.25 K using the ER-2 platform with SHIS and MAS instruments. Upper tropospheric thermal band validation is challenging because atmospheric absorption above the aircraft level must be inferred.
- Detector and mirror side striping in thermal bands can be mitigated, but not eliminated, by empirical distribution function (EDF) analysis.
- High quality Relative Spectral Response (RSR) measurements during pre-launch were essential when evaluating L1B accuracy during post-launch.
- Pre-launch characterization of RVS was insufficient, however the deep space maneuver provided definitive data for effecting a correction algorithm
- MODIS experience reveals that there is a need for time dependent correction factors and careful attention to details.
- Utilization of characterization data takes time.

Ib. Calibration Conference Papers and Publications

Ackerman, S. A., C. C. Moeller, W. P. Menzel, J. D. Spinhirne, D. Hall, J. R. Wang, H. E. Revercomb, R. O. Knuteson, E. W. Eloranta, A. W. Nolin, and M. D. King, 1999: WINCE - A winter cloud experiment. Tenth Conf. On Atmos. Radiation, AMS, 28 June – 2 July 1999, Madison, WI, pp 467-470.

Gunshor, M. M., T. J. Schmit, and W. P. Menzel, 2000: Intercalibration of geostationary (GOES, Meteosat, GMS) and polar orbiting (HIRS, AVHRR, MODIS) Infrared window and Water Vapor Radiances. CGMS XXVIII held 16 – 20 October 2000 in Woods Hole, MA. EUMETSAT publication.

King, M. D., W. P. Menzel, P. S. Grant, J. S. Myers, G. T. Arnold, S. E. Platnick, L. E. Gumley, S-C. Tsay, C. C. Moeller, M. Fitzgerald, K. S. Brown, and F. G. Osterwisch, 1996: Airborne scanning spectrometer for remote sensing of cloud, aerosol, water vapor, and surface properties. *J. Atmos. and Oceanic Tech.*, 13(4), pp. 777-794.

King, M. D., S. Platnick, C. C. Moeller, H. E. Revercomb, and D. A. Chu, 2003: Remote sensing of smoke, land, and clouds from the NASA ER-2 during SAFARI 2000. *J. Geophys. Res.*, **108**, D13, 8502.

Ma, X.- L., Z. Wan, C. C. Moeller, W. P. Menzel, L. E. Gumley, and Y. Zhang, 2002: Simultaneous retrieval of atmospheric profiles and land-surface temperature/emissivity from Moderate Resolution Imaging Spectroradiometer thermal infrared data: extension of a two-step physical algorithm. *Applied Optics*, **41**, No. 5, 909-924.

Ma, X.- L., Z. Wan, C. C. Moeller, W. P. Menzel, L. E. Gumley, and Y. Zhang, 2000: Retrieval of geophysical parameters from Moderate Resolution Imaging Spectroradiometer thermal infrared data: evaluation of a two-step physical algorithm. *Applied Optics,* **39**, No. 20, pp 3537-3550.

Moeller, C. C., H. E. Revercomb, S. A. Ackerman, W. P. Menzel, and R. O. Knuteson, 2003: Evaluation of MODIS thermal IR band L1B radiances during SAFARI 2000. *J. Geophys. Res.*, **108**, D13, 8494.

Moeller, C. C., R. O. Knuteson, D. Tobin, H. E. Revercomb, and W. P. Menzel, 2003: Assessment of Aqua MODIS and AIRS TIR band L1B radiances using ER-2 based observations during TX-2002, Earth Observing Systems VIII, 3-6 August 2003, SPIE Vol. 5151, pp. 355-366.

Moeller, C. C., R. A. Frey, S. A. Ackerman, L. E. Gumley, and W. P. Menzel, 2002: Reducing striping and near field response influence in the MODIS 1.38 um cirrus detection band. Poster presentation at the AGU annual spring meeting, AGU, Washington D.C., 28-31 May 2002.

Moeller, C. C., D. D. LaPorte, H. E. Revercomb, and W. P. Menzel: “Radiometric evaluation of MODIS emissive bands through comparison to ER-2 based MAS data. Earth Observing Systems VI Conference, SPIE Annual Meeting, San Diego, CA, 1-3 Aug 2001, pp 211-221.

Moeller, C. C., M. M. Gunshor, W. P. Menzel, O. K. Huh, N. D. Walker, and L. J. Rouse, 2001: Recent monitoring of suspended sediment patterns along Louisiana's coastal zone using ER-2 based MAS data and Terra based MODIS data. 11th Conference on Satellite Meteorology and Oceanography, AMS, Madison, WI, 15-18 Oct 2001, pp 65-68.

Moeller, C. C., P. S. Grant, D. D. LaPorte, L. E. Gumley, P. Hajek, W. P. Menzel, J. S. Myers, and S. White, 1996: Blackbody emissivity considerations for radiometric calibration of the MODIS Airborne Simulator (MAS) thermal channels. EOS Observing System Proceedings, Vol. 2820, 5-6 Aug 1996, Denver, CO, SPIE, pp. 44-55.

II. MOD35 Cloud Mask and Clear Sky Radiance

IIa. Cloud Mask

The MODIS cloud mask algorithm is based on the long experience in cloud detection at UW using data from such operational satellites as AVHRR, HIRS, and GOES. In addition, use of the MODIS Airborne Simulator before Terra data became available was extremely valuable.

The cloud mask algorithm (MOD35) has undergone modifications with each update opportunity; however, they were generally made following a plan whereby issues affecting basic conceptual domains (e.g. daytime ocean) were addressed first, then problems in more specific ecosystems or conditions (e.g. daytime desert, snow-covered areas), and then in very localized situations (e.g. rivers, shallow lakes at night, etc.). The following major improvements and enhancements have been made:

- Use of ancillary snow/ice maps and additional spectral tests during daytime to complement the NDSI for snow/ice detection
- Use of thermal and near-IR clear-sky restoral tests to reduce false cloudiness over arid and semi-arid regions
- Use of additional solar and near-IR reflectance data in sun-glint areas to improve clear/cloudy sky discrimination
- Use of 1-km cloud mask results as ancillary input to the 250-m algorithm
- Changes necessary to process Aqua data, including the use of 2.1 μm rather than 1.6 μm reflectances for snow detection
- Use of NDVI test in coastal/shallow water situations
- Adjusted 1.38 μm thin cirrus test thresholds after de-striping/cross-talk correction of L1B reflectance data
- Significant changes to non-cloud obstruction tests which greatly reduce false smoke detection
- Modifications to existing tests and new cloud and clear tests for the polar regions at night have been added

The final changes made under the current contract were a further refinement of the sun-glint algorithm and implementation of a stricter 0.86 μm cloud test threshold for daytime ocean surfaces. A 3.7-11 μm clear-sky restoral threshold test in sun-glint conditions was lowered from 15K to 13K. This change results in significant reduction in oval-shaped false cloud signals near the outside edges of sun-glint patterns. Also, the 0.86 μm cloud test threshold and clear-sky confidence limits were modified in order to detect additional very small cumulus clouds and very thin cirrus clouds that are sometimes characterized by very small reflectance values. Figure RAF1 shows the improvement in an example Aqua scene from 14 June 2003.

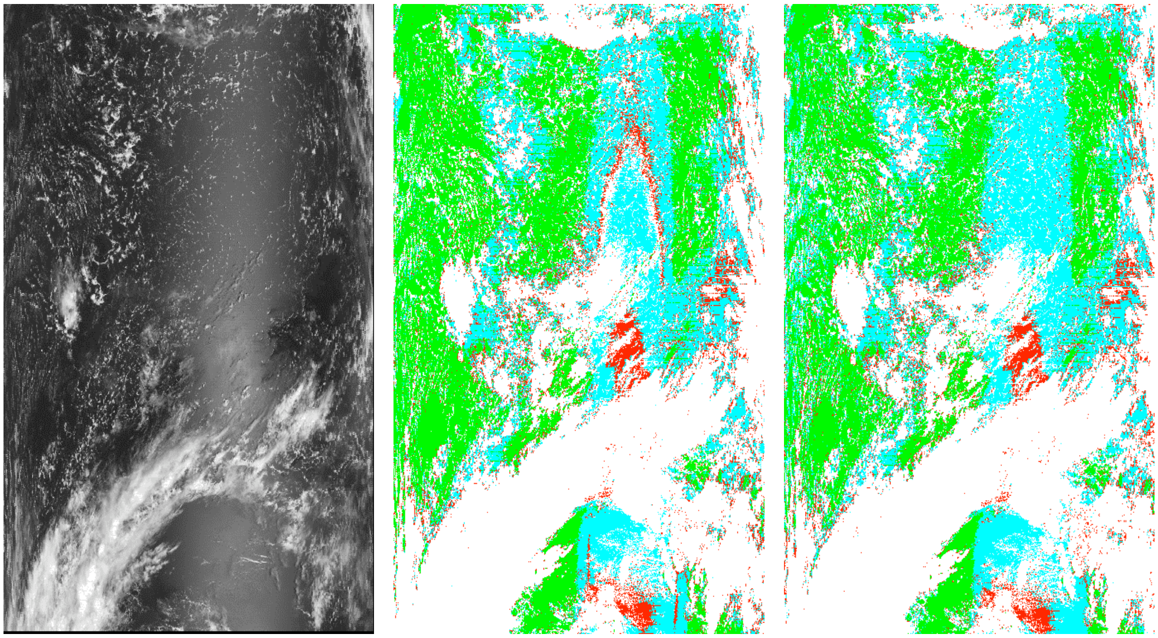


Figure RAF1. Example of final improvements made under current contract. MODIS band 2 imagery from ocean with sun-glint is shown at left, cloud mask results from previous version (middle) and from updated version (right). Green is confident clear, cyan is probably clear, red is uncertain, and white is confident cloud.

IIb. Clear sky radiances

Clear sky radiances for 27 MODIS bands are being routinely generated from UW direct broadcast MODIS data as a test for automated DAAC production. Samples of the real-time direct broadcast clear sky products are at http://cimss.ssec.wisc.edu/db_clrrad/. The files are being used for a number of purposes:

- Detection of cloud shadows. Comparison between current and recent observations of clear sky radiances in bands 2, 6 and 7.
- MOD35 temporal consistency checks. Comparison of the 8-day clear sky radiance files to current observations in bands 2 and 31.
- MOD06CT bias correction. A correction between the observed clear and calculated clear based upon a forward calculation. The input biases will be computed in a rolling eight-day window of daily clear radiance file composites for bands 31, 33-36.
- MOD07 bias correction. A correction to the input channels using a clear minus calculated clear value determined from forward model calculations. The biases will be used as input and updated monthly or seasonally for bands 24, 25, 27-36.

Several different executables are being delivered to the DAAC as part of the clear sky radiance file generation. Included in the software package are modules that (1) run a forward model to generate the calculated clear sky radiances for 27 different channels, (2) generate a granule based clear sky radiance file based upon the users input criteria, and (3) composite daily and eight day clear sky radiance files. It is hoped that the clear sky radiance software suite will be included as part of Terra collection 5. An example of a global daily clear sky brightness temperature composite is depicted in Figure KIS1.

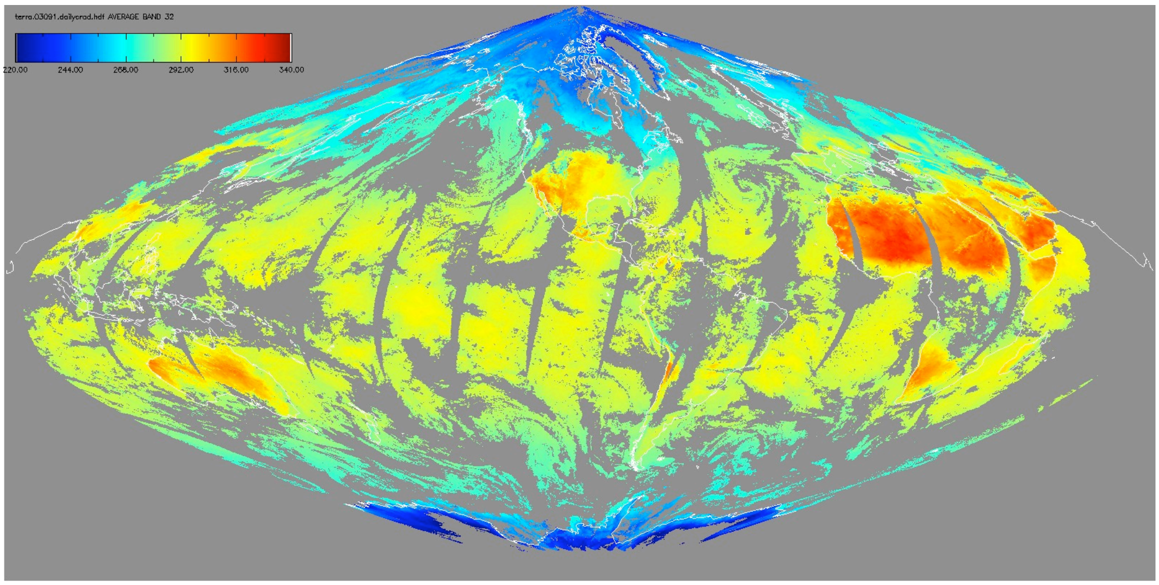


Figure KIS1. Clear sky brightness temperatures from MODIS band 32 (12 μm) on 1 April 2003. The image was created from the clear sky radiance daily composite file.

IIc. MODIS Cloud Mask and Clear Sky Composite Lessons Learned

- The global cloud mask evolved from showing good skill in typical atmospheres to addressing challenging ecosystems (desert, high terrain, frozen tundra) and situations (polar night). Regional enhancement to a global cloud mask requires continual vigilance.
- Various applications of satellite radiance data may require multiple cloud masking algorithms.
- Synthetic data was valuable in testing end-to-end performance of the MODIS processing chain; however, it is not very useful for testing individual algorithm science.
- Strong leadership is necessary when developing a data processing system as large and ambitious as that of MODIS. While there may be more than one path to success, leaders must evaluate options and make decisions in a timely manner.
- Continuity is invaluable. The atmosphere team could not have met software delivery deadlines or have code run as smoothly as it does without Rich Hucek, who has been with the team from the beginning.
- Software standards, though sometimes painful to implement, are necessary for smooth integration of code into a system.

- It is still an open question whether scientists should write algorithm software. Trade-offs exist between less elegant codes that scientists are intimately familiar with versus more elegant software rewritten by professional programmers that scientists find difficult to debug.

IId. Cloud Mask Related Publications

Ackerman, S.A., K. I. Strabala, W. P. Menzel, R. A. Frey, C. C. Moeller, and L. I. Gumley, 1998: Discriminating clear-sky from clouds with MODIS. *J. Geophys. Res.,* **103**, D24, 32141-32158.

Ackerman, S. A., K. I. Strabala, W. P. Menzel, R. A. Frey, C. C. Moeller, and L. I. Gumley, B. A. Baum, S. W. Seemann, and H. Zhang, 2002: Discriminating clear-sky from clouds with MODIS – Algorithm Theoretical Basis Document (MOD35). NASA MODIs Web site http://modis-atmos.gsfc.nasa.gov/reference_atbd.html..

Li, J., Z. Yang, H.-L. Huang, W. P. Menzel, R. A. Frey, and S. A. Ackerman, 2001: High spatial resolution surface and cloud type classification from MODIS multi-spectral band measurements. AMS 11th Conference on Satellite Meteorology and Oceanography, 15-18 October 2001, Madison, Wisconsin. AMS publication.

Li, J., W. P. Menzel, Z. Yang, R. A. Frey, and S. A Ackerman, 2003: High spatial resolution surface and cloud type classification from MODIS multi-spectral band measurements. *Jour. Appl. Meteor.*, **42**, 204-226.

Liu, Y., J. Key, R. Frey, S. Ackerman, and W.P. Menzel, 2004, Nighttime polar cloud detection with MODIS, *Jour. Appl. Meteor.*, submitted (January 2004).

III. MOD06 Cloud Top Properties

IIIa. CO_2-slicing Cloud Top Pressures

The University of Wisconsin-Madison has extensive experience in deriving cloud top pressures and effective cloud amounts from polar orbiting HIRS and geo-stationary GOES sensors using the CO_2-slicing method. CO_2 slicing determinations of semi-transparent cloud top pressures have been found to be within 50 hPa against airborne lidar measurements (Frey et al., 1999). A long time series of global monthly means has been constructed using HIRS and it is hoped that this may be continued with use of MODIS data. During the current contract, there has been an effort to continue utilizing the CO_2-slicing algorithm (MOD06CT) in much the same way as with HIRS, and to also take advantage of the finer spatial resolution and enhanced cloud detection capabilities of MODIS. In addition, while the method is best suited to retrievals of middle and high clouds, it is recognized that other investigators need cloud top pressures at many locations and times, including those where lower clouds predominate.

To this end, the following enhancements have been made since the launch of Terra:

- Quality control was adjusted so more numerical weather prediction (NWP) model moisture profiles could be used and more cloud top pressures retrieved
- Adjustments were made to Terra algorithms including cloud versus clear radiance thresholds, spectral response functions, and atmospheric transmittance functions in order to process Aqua data
- The number of atmospheric levels was increased from 40 to 101 for better vertical resolution in the calculation of cloud top properties
- Solutions of radiative transfer calculations of cloud top pressure based on NWP model profiles matching CO2 radiance observations were required to occur in troposphere away from the tropopause and earth surface
- The "window channel" radiances were corrected for atmospheric moisture absorption effects producing more accurate low cloud pressure retrievals, especially in humid regions where clouds had been placed too high.

An issue that has been only partially addressed is that of inconsistent radiometric response and quality between detectors in the long wave CO_2 absorption bands (33-36). Sensitivity to thin clouds is reduced, especially in Terra data, where band 34 is severely compromised. The problem has been ameliorated somewhat by a judicious choice of clear versus cloudy radiance thresholds, but a more robust correction is needed.

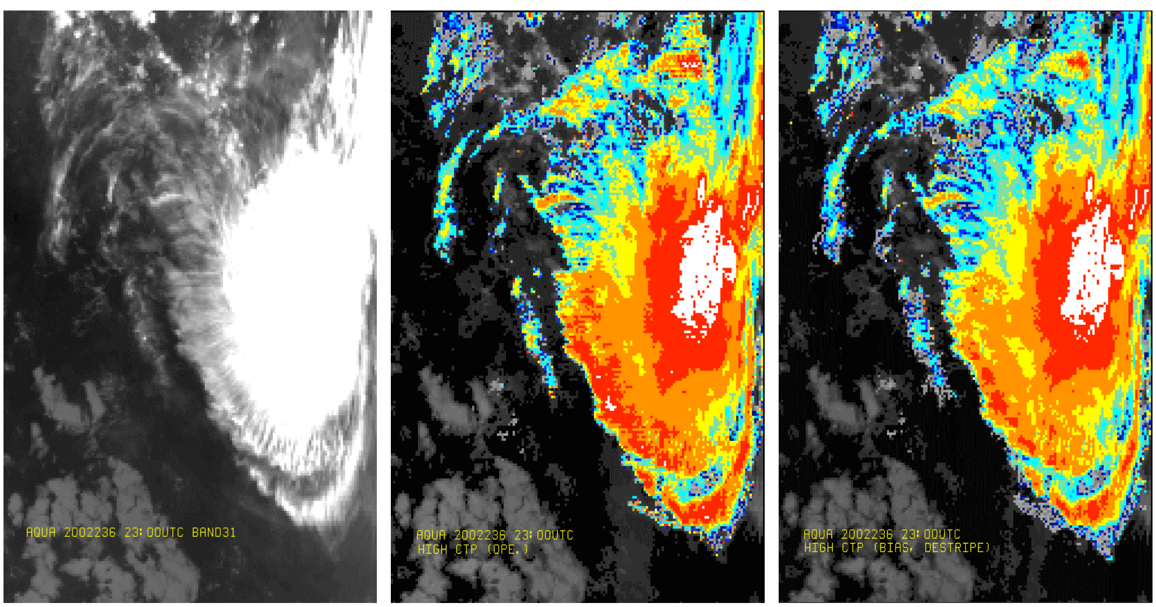


Figure RAF2. Aqua MODIS over tropical oceans on 14 Aug 2002 at 23 UTC. (Left) 11 μm brightness temperatures (white is cold, dark is warm). (Middle) Cloud top pressures from current operational algorithm. (Right) Latest update using de-striped input radiances and clear-sky bias adjustments. Colors show cloud top pressures higher than 390 hPa with white being the highest (about 100 hPa) and navy 360-390 hPa.

Figure RAF2 shows a tropical ocean scene observed by Aqua MODIS on August 24, 2002 beginning at 23:00 UTC. The three images show 11 μm brightness temperatures (left) and cloud top pressures from the current operational algorithm (center) and the last updated version (right) developed under the current contract. Colors show clouds with tops higher than 390 hPa where white represents the highest (□100 hPa) and navy somewhat lower (360-390 hPa) cloud tops. MOD06CT cloud pressures are calculated and reported at 5-km resolution (5x5 boxes). The latest update takes advantage of de-striping in the CO_2 absorption bands and clear-sky radiance bias adjustments based on results from the cloud mask (MOD35). The benefits of de-striping may be seen in the top center of the image where more spatially consistent values are reported. The bias adjustment results in the retrieval of more optically thin mid-level and high clouds positioned near the edges of thicker and more opaque clouds. It also adjusts cloud top pressures of low clouds to more reasonable values (not shown in this scene).

IIIb. Trends in High Cloud Properties

Twenty five years of HIRS data (since 1978) have been processed to infer cloud trends (Figure WPM1); MODIS data are now adding to this climatology. Comparisons of MODIS and HIRS cloud property determinations reveal some differences in part due to the increased MODIS spatial resolution (MODIS averaged 5 km versus HIRS single pixel 20 km) but also in part due to remaining difficulties in implementing the best MODIS CO_2 algorithm. Most significant of these are (a) detector to detector response differences that manifest themselves in striping and (b) measured versus calculated clear sky radiances differences. Terra and Aqua MODIS cloud properties have been found to be in good agreement for one example day in Table WPM1.

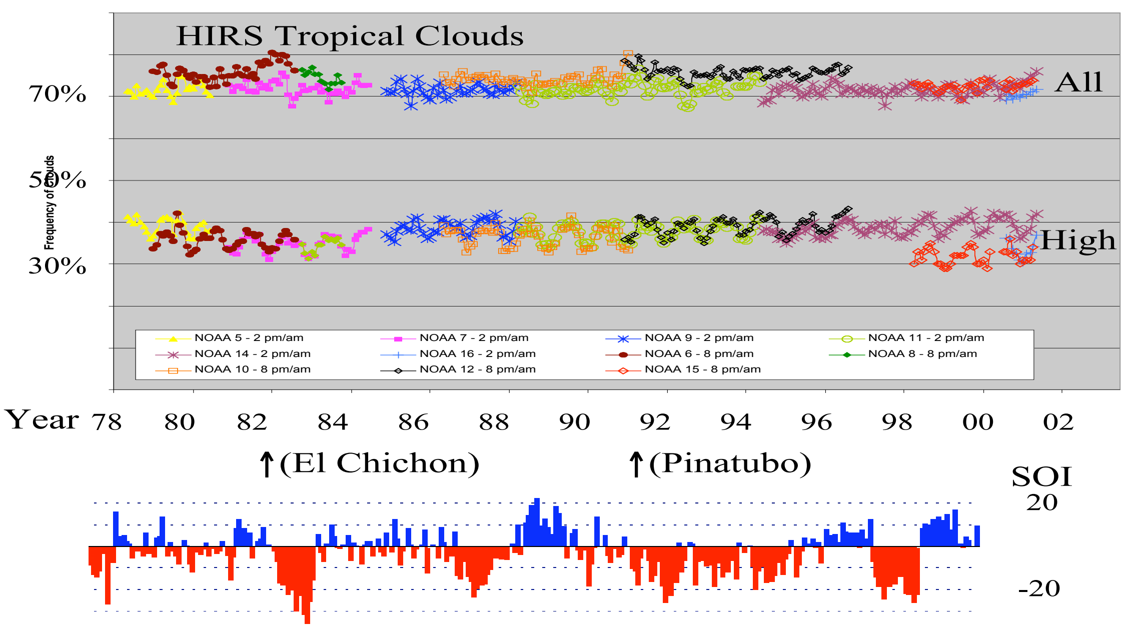
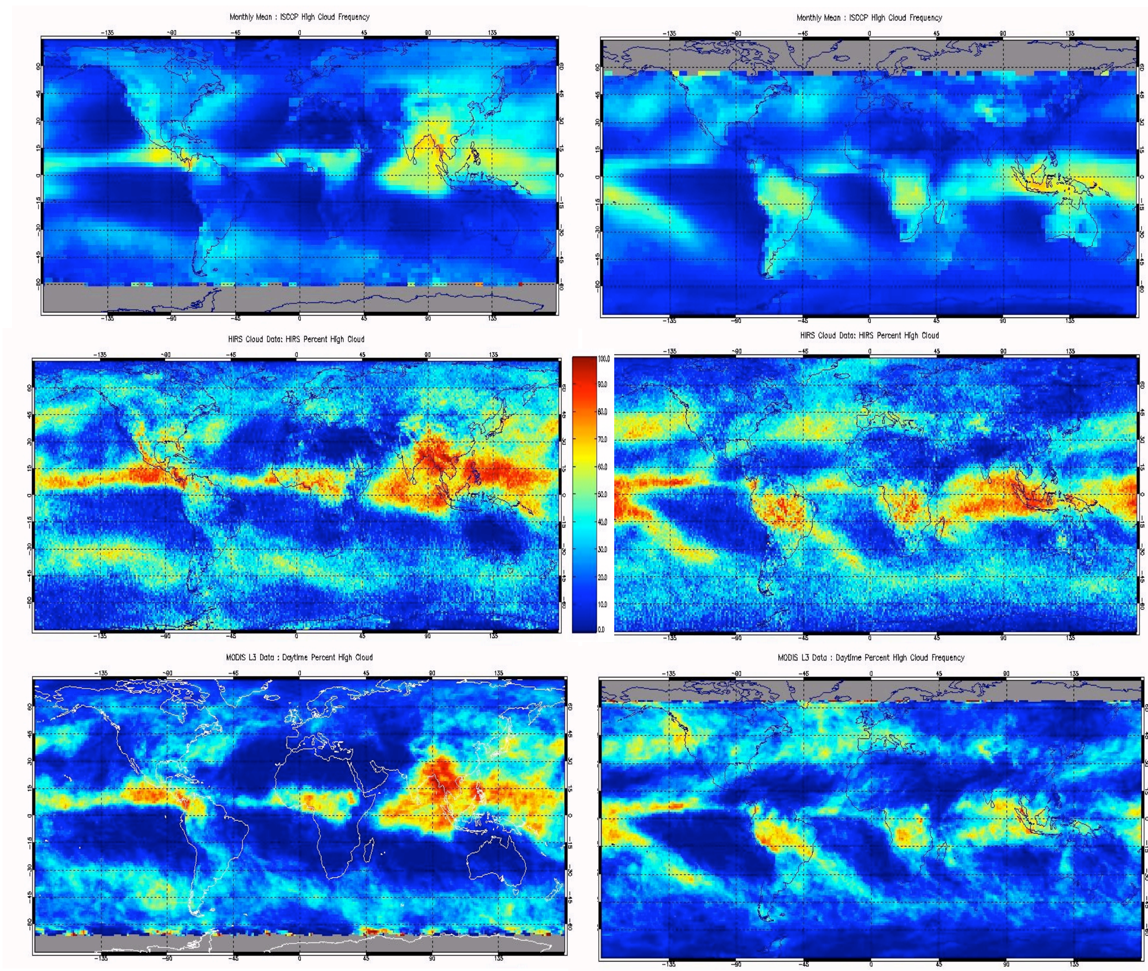


Figure WPM1: The UW HIRS detection frequency of all and high tropical (25N to 25S) clouds by individual satellites along with the Southern Oscillation Index (SOI) and significant volcanic eruptions from 1978 to 2001.

Table WPM1: Aqua Global Cloud Statistics for 24 August 2002 with Aqua minus Terra Global Cloud Statistical Differences (in parentheses). Differences are less than 2% in all categories. Thin clouds have effective cloud amounts $N\varepsilon < 0.5$ and IR optical depths <0.7. Thick clouds have $0.5 < N\varepsilon < 0.95$ and IR optical depths from 0.7 to 3.0. Opaque clouds are opaque to the IR window with $N\varepsilon > 0.95$ and IR optical depths > 3.0. Cloud top pressure is indicated by pc.

	All Clouds (%)	Thin (%)	Thick (%)	Opaque (%)
High (pc<400 hPa)	20.1 (+0.3)	6.0 (-0.4)	9.4 (-0.2)	4.7 (+0.1)
Middle (pc<700 hPa)	22.8 (-0.1)	0.5 (+0.2)	5.8 (+1.6)	16.5 (-1.9)
Low (pc>700 hPa)	27.6 (-0.2)	0.0 (0.0)	0.0 (0.0)	27.6 (-0.2)
Clear	29.4 (-0.0)			



ISCCP (top), HIRS (mid), & MODIS (bot) for Jul (left) & Dec (right)

Figure WPM2: Monthly mean global distributions of ISCCP, HIRS, and MODIS detection of high cloud cover in July (left) and December (right) 2002. Color bar indicates the percentage of observations that found clouds.

Figure WPM2 shows monthly, daytime frequencies of high clouds from ISCCP (top), HIRS from NOAA-14, 16, and 17 (middle), and MODIS (bottom). The MODIS (MOD06CT) and HIRS (Wylie and Menzel, 1999) are for the months of July 2002 (left) and December 2002 (right). The ISCCP (International Satellite Cloud Climatology Project) is from the same two months but also averaged over the years 1983-2001. High clouds are those with cloud top pressures < 440 hPa. Latitudes are 75S to 75N. The patterns are remarkably similar between the data sets, especially MODIS and HIRS. The MODIS displays sharper contrast between regional climates (for example, between subtropics and the Inter Tropical Convergence Zone). The "blockiness" seen in the HIRS data is due to a relatively coarse sampling frequency.

IIIc. Estimation of Cloud Phase and Detection of Cloud Overlap

Automated detection of multi-layered clouds in daytime MODIS data is now being demonstrated with both Terra and Aqua data collected in near real-time with the direct broadcast system at CIMSS. After software efficiency improvements, a full granule is processed in approximately 30 seconds on a desktop linux workstation. A set of web pages describing this effort is now available at http://cimss.ssec.wisc.edu/multilayer.

The daytime approach (Baum and Spinhirne, 2000; Nasiri and Baum, 2004) is based on analysis of data from a near-infrared (NIR) MODIS band, such as band 6 (1.64 μm) or band 7 (2.15 μm), and an infrared band (band 31 at 11 μm). The method incorporates results from the cloud mask and cloud thermodynamic phase product. The detection of multi-layered clouds in night-time data is also progressing; results with a method relying on 3.9 μm have recently been published (Baum et al. 2003). This paper explores the biases inherent in nighttime retrieval of various cloud properties and suggests a method to identify when thin cirrus may be overlying a lower-level cloud. While the daytime approach to multi-layered cloud detection has been developed to the point of being operational with the direct broadcast data collected at UW, the night-time approach needs further work before attempting to develop and implement an operational algorithm.

The IR-based cloud thermodynamic phase product uses 8.6 and 11 μm measurements and is generated at 5-km resolution in the operational environment. However, as part of the multi-layered cloud detection process, the cloud phase is being generated at 1-km resolution. The destriping process makes feasible the generation of cloud phase at 1-km resolution. An example is provided in Figure BB1. This Terra scene, recorded 1 July 2003 at 1458 UTC, contains a high-level ice cloud deck that overlies a low-level water deck in numerous places. One important item to note is that the IR cloud phase product has no evidence of striping at 1-km resolution; the destriping algorithm has had a very beneficial effect here.

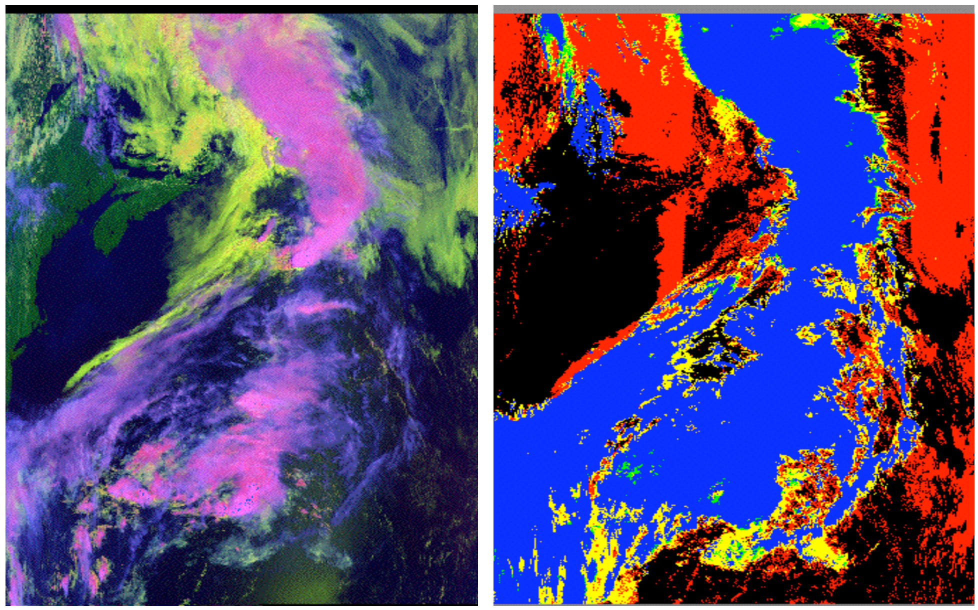


Figure BB1: (Left) False color image (R: band 1, G: band 6, and B: band 31, flipped). High ice clouds are pink or blue, low water-phase clouds are yellow, land is green, and water is dark blue. (Right) IR cloud phase with ice clouds (blue), water clouds (red), mixed phase clouds (green), and uncertain phase (yellow).

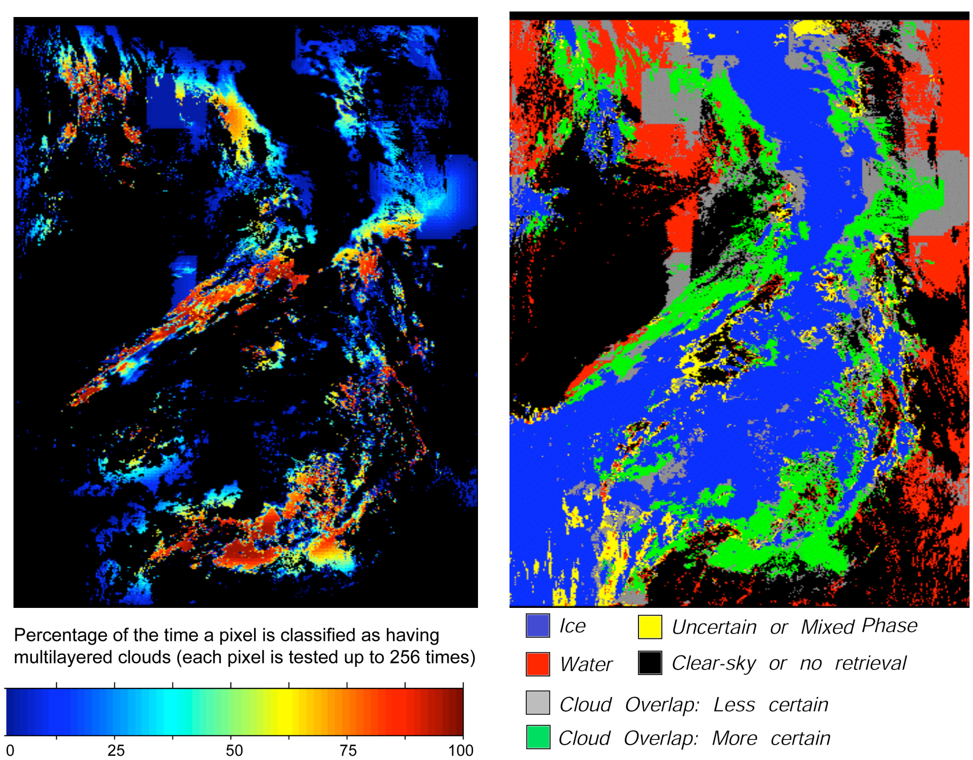


Figure BB2: (Left panel denotes the results from the multilayered cloud detection effort, with the red color denoting the pixels having the highest potential for being multilayered. The right panel merges the cloud phase and multilayered cloud results into a single product (as suggested by Dr. Catherine Naud from London University College).

Given the cloud clearing and cloud phase products at 1-km resolution, the multilayered cloud detection method is applied to the granule, with results shown in Figure BB2. Visual comparison of the multilayered cloud product with the false color image shown above indicates that there is some facility for detecting optically thin ice clouds overlying a low-level water cloud. MODIS DB data has proven to be a useful testbed for continuous testing of the approach; these products are available for each daytime Terra and Aqua overpass for 8 days, with new overpass products replacing the earliest ones.

IIId. Combining MODIS and AIRS measurements

MODIS and Atmospheric Infrared Sounder (AIRS) were combined to investigate improved cloud property definition. MODIS is able to provide at high spatial resolution (1 ~ 5km) a cloud mask, surface and cloud types, cloud phase, cloud-top pressure (CTP), effective cloud amount (ECA), cloud particle size (CPS), and cloud optical thickness (COT). The AIRS is able to provide CTP, ECA, CPS, and COT at coarser spatial resolution (~ 13.5km at nadir) but with much better accuracy using its high spectral resolution measurements. The combined MODIS/AIRS system offers the opportunity for cloud products improved over those possible from either system alone. After colocation, MODIS cloud amount, type, and phase determination within the AIRS pixel enables identification of sub-pixel clouds and multi-layer cloud influences. Synergistic use of the MODIS/AIRS radiance measurements enables improved calculation of observed spectra (especially in the infrared window regions when cloud microphysical properties are included) and improved cloud property estimation. Figure JL1 provides an example for thin cirrus.

IIIe. Cloud Property Lessons Learned

- Noisy detectors contribute to striping and detract from science products. Destriping of the twenty optical system data (two mirror sides and ten detectors per spectral band) is imperative before product processing can begin. The empirical distribution function approach applied per granule is a viable option.
- With destriping of the IR data, it becomes feasible to produce the cloud top properties at 1-km resolution, which is useful for the cloud microphysical/optical property product and also for more detailed cloud trend studies.
- The cloud property algorithm must include consideration of radiance biases between measured and calculated clear sky radiances (especially over land surfaces) in the spectral bands employed. This requires a good understanding of the model (GDAS) surface skin temperature and emissivity.
- Understanding of the infrared window observations of ice clouds requires microphysical and optical cloud property considerations.
- Radiative transfer models used in the CO_2 slicing algorithm must take advantage of the improvements in the description and treatment of molecular absorption.
- Cloud top property retrieval adjustments benefited from access to MODIS direct broadcast data as a testbed with a variety of meteorological conditions.

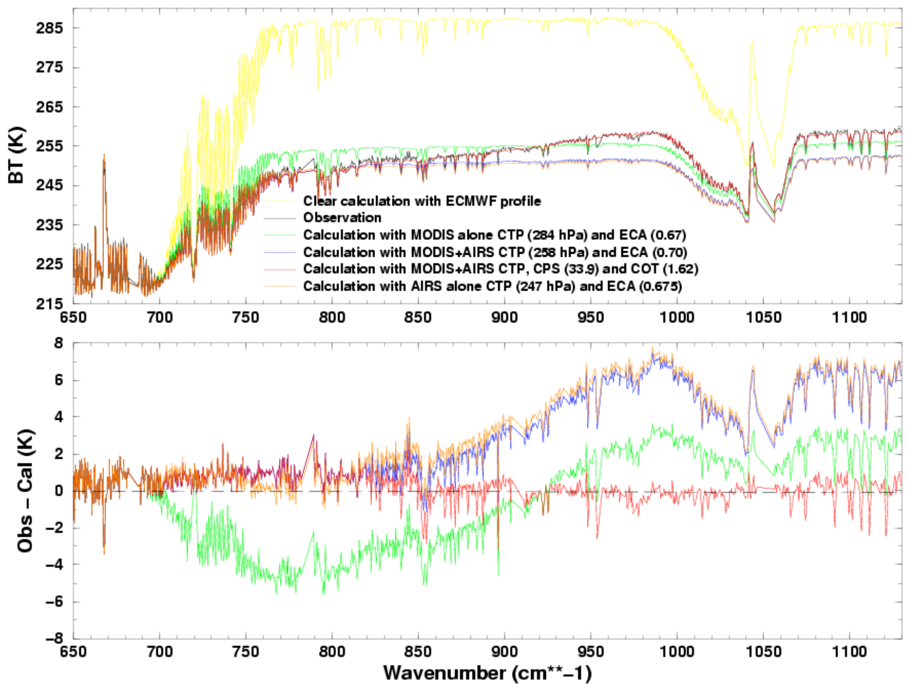


Figure JL1. The AIRS longwave clear brightness temperature (BT) calculation from the ECMWF forecast analysis (yellow line), the BT calculation from the MODIS cloud top pressure (CTP) and effective cloud amount (ECA) (green line), BT calculation from AIRS CTP and ECA (orange line), BT calculation from the MODIS/AIRS synergistically retrieved CTP and ECA (blue line), and the BT calculation from the MODIS/AIRS synergistically retrieved CTP plus the AIRS cloud particle size (CPS) and cloud optical depth (COT) (red line), as well as the BT observation (black line) spectra for an AIRS footprint viewing a thin ice cloud. The lower panel shows the corresponding BT difference between the observation and the calculation.

IIIf. Cloud Top Property Related Publications

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Baum, B. A. and J. D. Spinhirne, 2000: Remote sensing of cloud properties using MODIS Airborne Simulator imagery during SUCCESS. III. Cloud overlap. *J. Geophys. Res.*, **105**, 11,793-11,804.

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Zhang, H., 2001: Estimating thin cloud properties using an improved CO2 slicing approach. M.S. Thesis, Department of Atmospheric and Oceanic Science, University of Wisconsin-Madison, Madison, Wisconsin.

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IV. MOD07 Atmospheric Profiles

The MODIS atmosphere profile product MOD07 performs clear sky retrievals over land and ocean for both day and night using MODIS infrared measurements. Retrieved products include temperature and moisture profiles, integrated moisture (including total precipitable water, TPW), total ozone amount, lifted index, and surface skin temperature.

The MOD07 global product is well suited for observing seasonal changes in temperature, water vapor, and ozone. An example is presented in the sequence of 2002 monthly average TPW shown in Figure SWS1 for northern hemisphere winter (February), spring (May), summer (August), and fall (November). The northward shift of the moist air is evident as northern hemisphere spring turns to summer. During the southern hemisphere summer (February image), more moisture is seen over the Australian continent. In addition to providing information on global parameters, the high resolution of MODIS enables the delineation of small-scale gradients in temperature and moisture. Figure SWS2 shows an example of the gradients visible with the high spatial resolution of MODIS for three levels (850hPa, 500hPa, and 300hPa) of mixing ratio and temperature. The benefits of the high spatial resolution of MODIS are particularly apparent in the image of MOD07 TPW (Figure SWS3) retrieved during hurricane Lili on 2 October 2002. Because MOD07 only requires 5 pixels out of the 25 in a 5x5 FOV be clear, continuous retrievals can be made in the area of scattered clouds surrounding a hurricane.

Atmospheric retrievals from MODIS are routinely compared with products from other observing systems at three spatial scales: (a) a fixed point with ground-based measurements at the Southern Great Plains (SGP) Atmospheric Radiation Measurement-Cloud and Radiation Testbed (ARM-CART), (b) the continental scale with GOES sounder products, and (c) the global scale with retrievals from the Special Sensor Microwave/Imager (SSM/I), and Total Ozone Mapping Spectrometer (TOMS). Some recent comparisons are presented here.

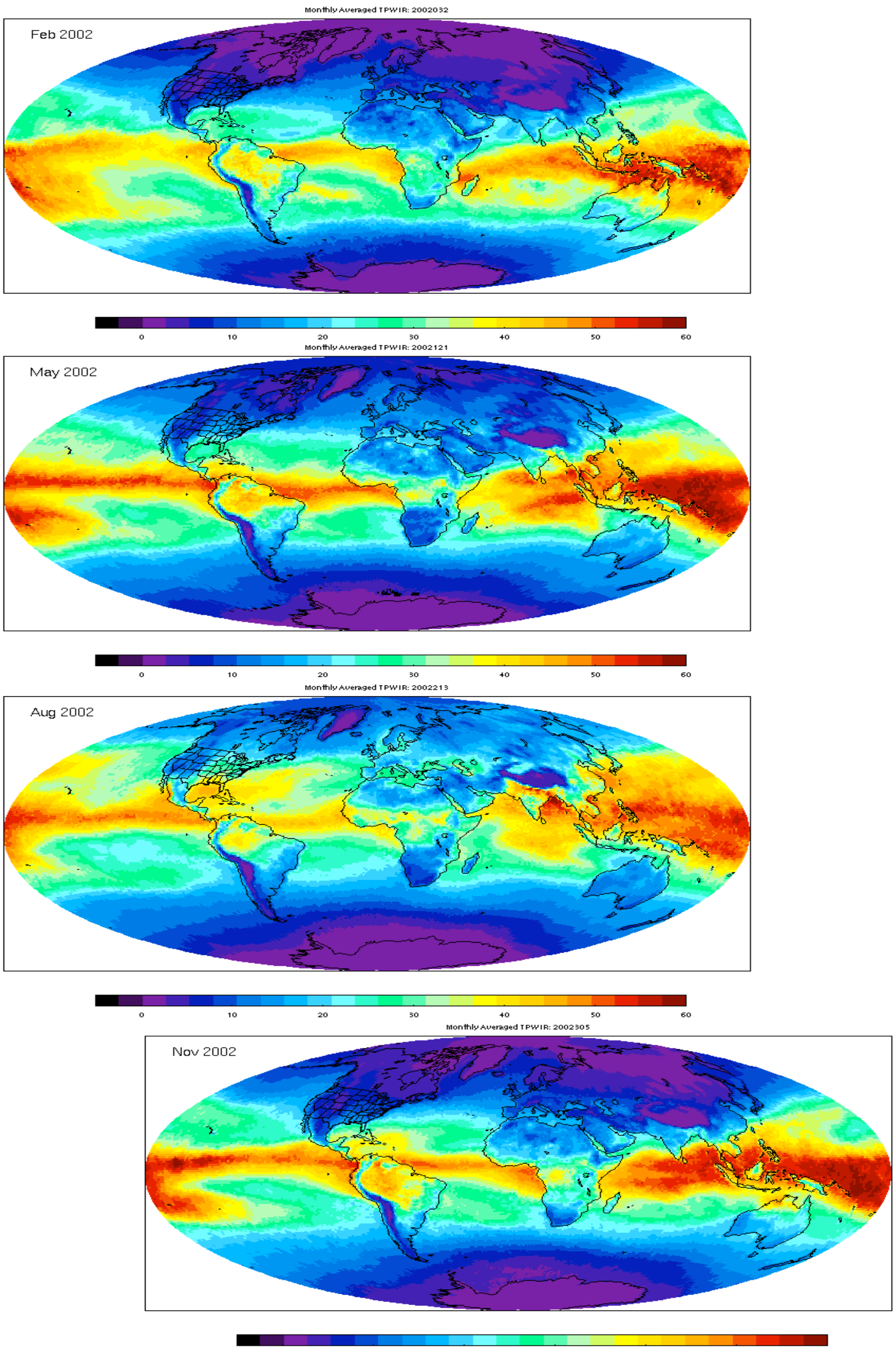

Figure SWS1: Monthly average TPW (mm) from the infrared product in MOD07 for February (top left), May (top right), August (bottom left), and November (bottom right) of 2002.

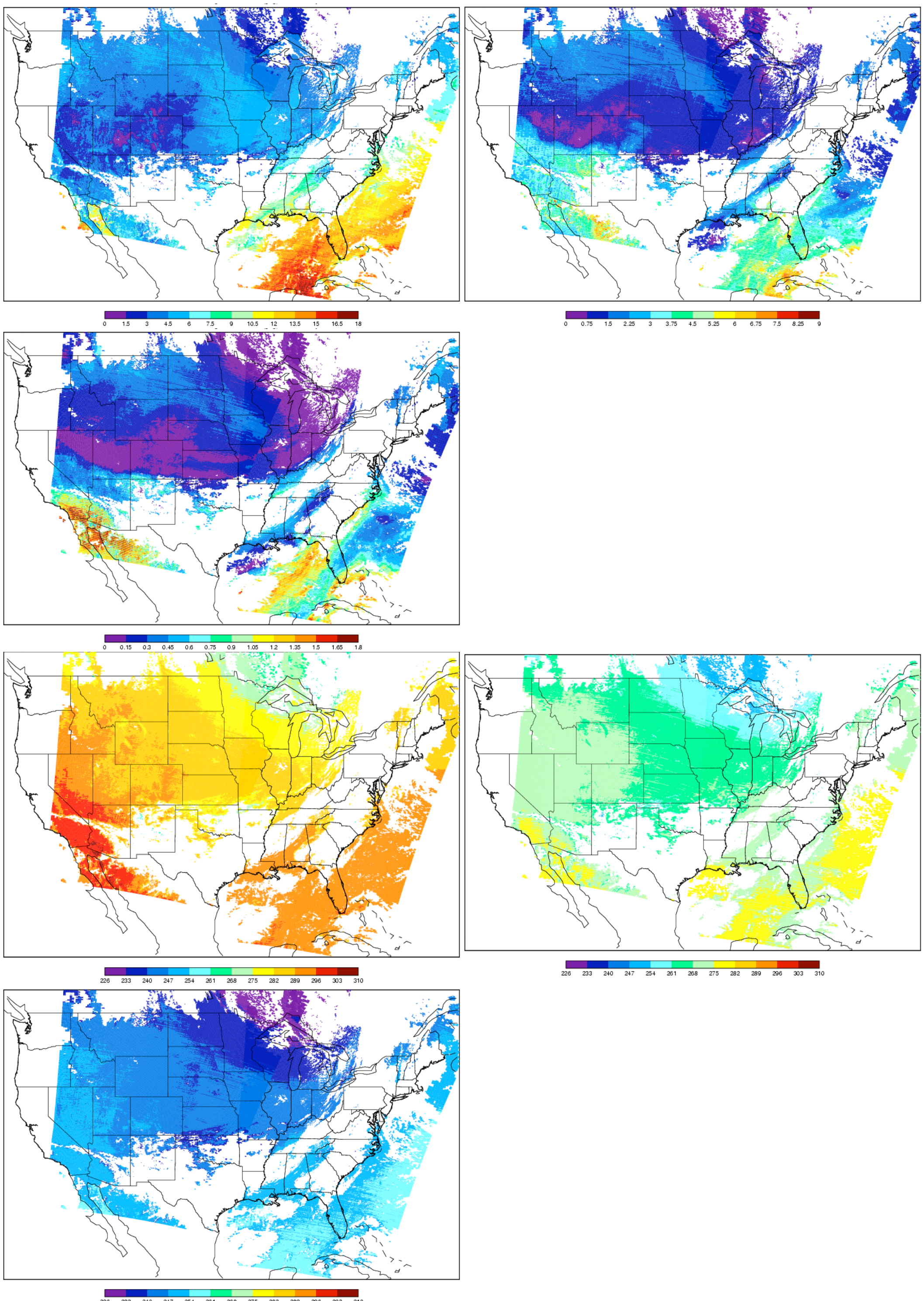

Figure SWS2: Mixing ratio (g/kg, top three) and temperature (K, bottom three) retrieved from Terra MODIS MOD07 for 12 October 2002 at 850hPa (left), 500hPa (right), and 300hPa (bottom).

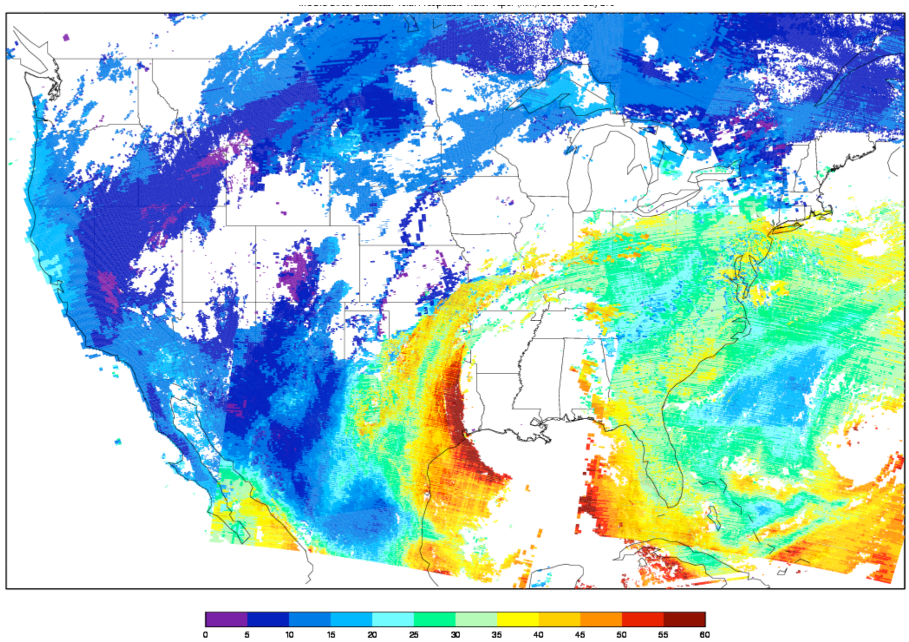

Figure SWS3: TPW (mm) retrieval from Terra MODIS as hurricane Lili came onshore over Louisiana (2 October 2002).

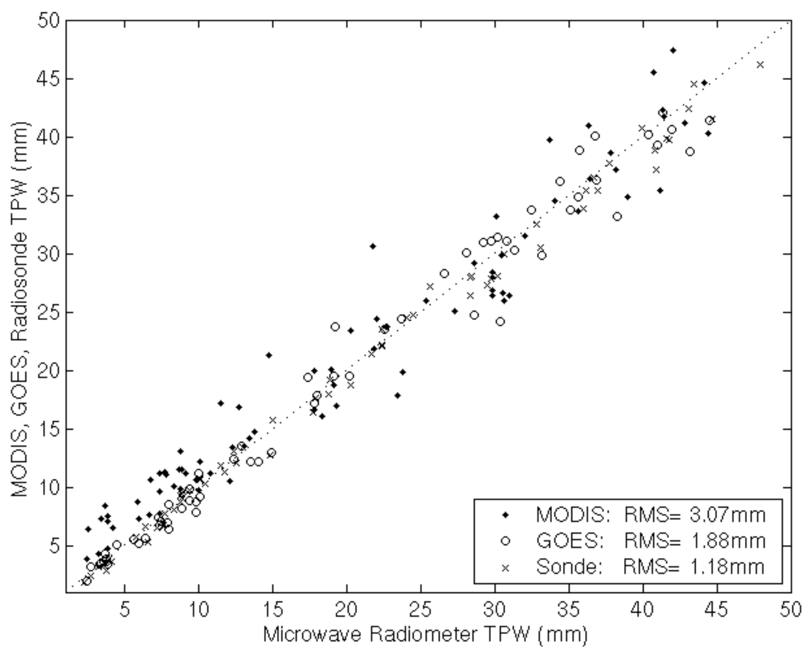

Figure SWS4. Comparison of microwave radiometer TPW at the SGP CART site with with Terra MODIS TPW, GOES TPW, and radiosonde TPW for 80 clear sky cases from April 2001 to August 2002.

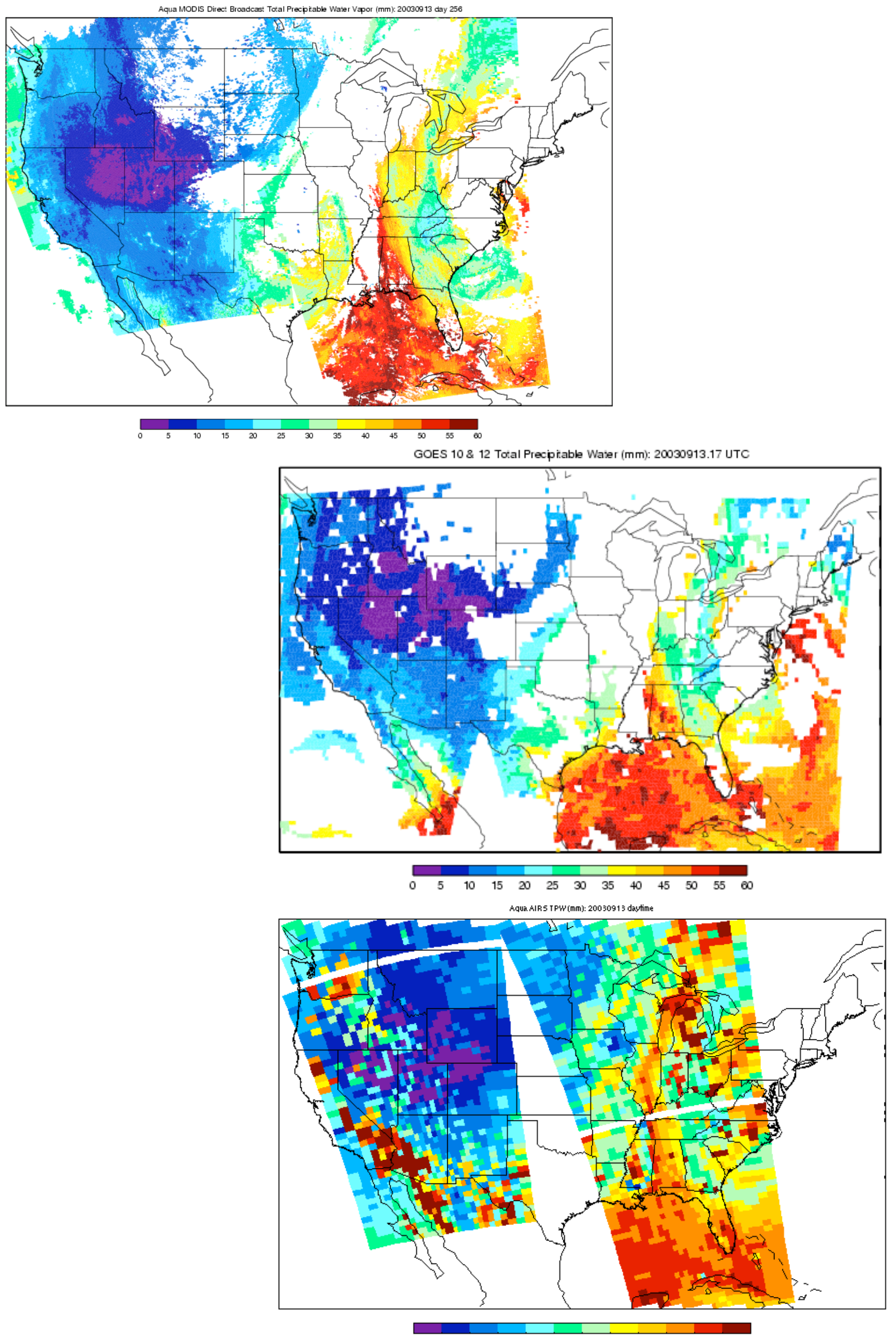

Figure SWS5: TPW comparison of MODIS on the Aqua satellite (top) with GOES 10 & 12 combined (middle) and AIRS on Aqua (bottom) for 13 September 2003. All Aqua daytime passes are combined onto the same image for MODIS and AIRS, while GOES retrievals are valid around 1700 UTC. MODIS data was received and processed by the UW-CIMSS direct broadcast system; AIRS operational products were retrieved from the NASA/Goddard DAAC.

MODIS TPW for 80 clear-sky cases from April 2001 to October 2002 are compared to retrievals from the GOES-8 sounder, measurements from the microwave radiometer (MWR), and radiosondes in Figure SWS4. The RMS difference between MODIS and MWR TPW collocated in time and space is 3.1 mm, MWR and GOES-8 is 1.9 mm, and MWR and radiosonde is 1.2 mm. For dry atmospheres (TPW<17mm), MODIS consistently overestimates the TPW, on average by 1.8 mm for 37 dry cases.

On the continental-scale, MODIS TPW is routinely compared to GOES-8 (now GOES-12) and GOES-10 sounder retrievals of TPW over the continental United States and Mexico. MODIS data received by direct broadcast at UW/CIMSS facilitates this comparison. Images of MOD07 temperature, mixing ratio, TPW, ozone, and lifted index are automatically generated twice daily and displayed online: http://cimss.ssec.wisc.edu/modis/mod07. Images of GOES TPW and lifted index are also displayed with the same color-map, geographic area, and projection for comparison. GOES TPW has been well validated (Schmit et al. 2002) and thus provides an excellent opportunity for routine evaluation of the MOD07 TPW. In Figure SWS5, MODIS TPW from the Aqua satellite compares quite well with that from GOES for 13 September 2003; MODIS highlights more detailed gradients due to its higher spatial resolution. The operational TPW retrievals from the Atmospheric Infrared Sounder (AIRS, 15km resolution) agree well on the larger scale features with MODIS and GOES, however there are some regions where AIRS retrievals show little agreement, particularly in the West.

Overall, it has been found that the primary value of the MODIS fields lies in the depiction of fine scale horizontal gradients. When combined with the increased atmospheric profiling capability of the AIRS, the MODIS offers improved sounding performance in cloudy conditions (by identifying sub AIRS field-of-view cloudiness) and delineates spatial gradients beyond the AIRS instrument resolution.

IVa. Major updates to the atmospheric profiles algorithm

Since Terra was launched in December 1999, a number of updates have been made to the MOD07 algorithm. Significant improvements were made over arid and semi-arid regions where the original at-launch algorithm considerably overestimated the moisture retrieved. Progress has also been made in moist areas with a very warm surface, where gradients of moisture were previously influenced by surface temperature. Magnitudes of retrieved quantities have been improved, particularly for moist cases. The current MODIS Atmospheric Temperature and Moisture Profile Retrieval Algorithm started operational processing on 1 October 2003. Some of the significant post-launch improvements to the algorithm and training data are summarized in this section.

In deserts and semi-arid areas

The original operational MOD07 retrieval algorithm produced unrealistically moist TPW and warm temperature retrievals over desert regions including northern Africa, Saudi Arabia, and the southwestern United States (See Figure SWS6). This resulted from emissivity values assigned to the training data profiles that did not properly represent actual emissivities, particularly in desert regions.

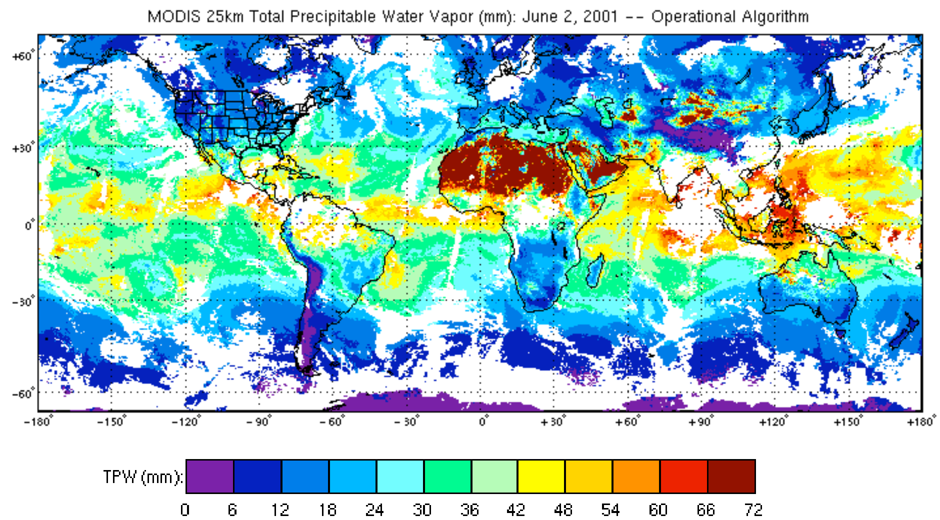

Figure SWS6. Global image of the operational version of MODIS TPW (mm) for 2 June 2001. This includes both ascending and descending orbits.

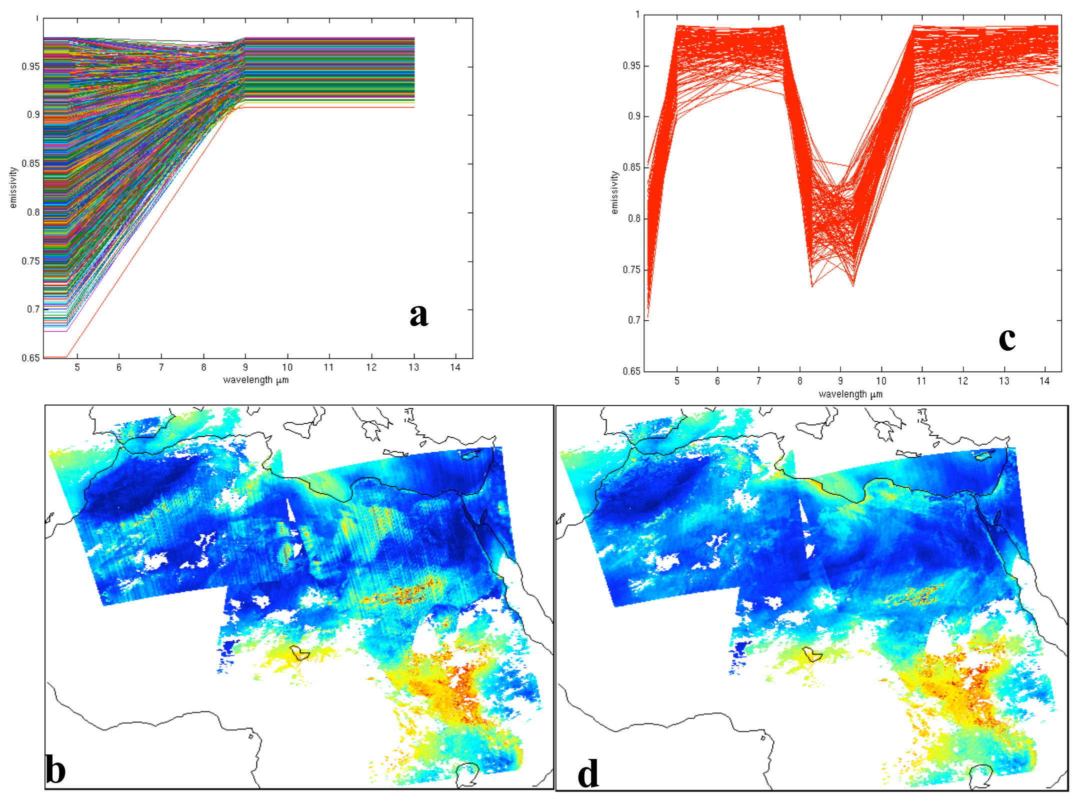

Figure SWS7. a) Emissivity spectra for all training data profiles used in the original algorithm. b) Aqua MODIS TPW (mm) for 24 August 2002 over the Sahara desert retrieved with coefficients derived using the emissivity spectra in (a). c) New emissivity spectra for desert profiles. d) As in (b) except retrieved with coefficients derived using different emissivity spectra for ocean, ice and snow, desert, and non-desert land such as those for desert shown in (c).

The emissivity originally assigned to the training data profiles had a mean of 0.85 at 4μm and 0.95 between 9μm and 14μm, with a linear interpolation in between (see Figure SWS7a). A standard deviation was applied to these values to simulate some variability among profiles. This approach did not properly represent actual emissivities. Removing most of the emissivity signal by differencing MODIS bands 24 and 25 made significant improvements in retrievals over the desert (see Fig SWS7b). However, during extremely hot conditions such as those found in the Sahara desert in August, some problems still remained. TPW from Aqua MODIS in Figure SWS7b shows along-track stripes of high moisture due to unstable retrievals on this hot day in August 2002. To address this problem, more representative emissivity values were assigned to each of the training profiles. Profiles were categorized as ocean, snow/ice, desert, and non-desert land, and appropriate emissivities were measured by the UCSB MODIS land group (http://www.icess.ucsb.edu/modis/EMIS/html/em.html). The new emissivities used for the desert profiles are shown in Figure SWS7c, and the improvement in the TPW retrievals using the training data set with the new emissivities is shown in Figure SWS7d.

Changes to training data

Radiosonde profiles of temperature, moisture, and ozone plus surface data from the NOAA-88b data set were used to compute the regression coefficients for the MODIS statistical retrieval. The NOAA-88b data was partitioned into seven zones based on the 11μm brightness temperatures (BT11) calculated from the profiles (BT11 < 245, 245-269, 269-285, 285-294, 294-300, 300-310, and > 310^{o}K) and each statistical retrieval uses only the subset of the training data corresponding to the appropriate BT11. It became evident that there was insufficient training data for very warm surfaces (the last two zones, BT11 > 300^{o}K). To improve the training for very warm surfaces, new radiosonde data from the north African desert regions for January – December 2001 were added to the training data set. After partitioning into seven BT11 zones and adding warm surface training data the MODIS TPW retrievals improved; one example is presented in Figure SWS8; the area in Kansas and Oklahoma that shows the most improvement has a warm BT11 that falls within the highest two classes (BT11 > 300^{o}K).

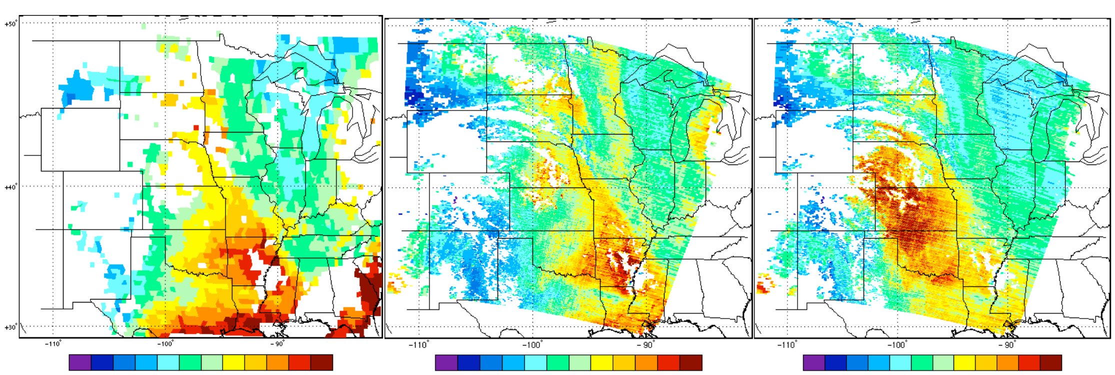

Figure SWS8. Total precipitable water (mm) from 20 August 2001 retrieved from GOES-8 (left), new operational MODIS (center), and MODIS without the 11mm brightness temperature zones (right). The MODIS granule began at 1735 UTC and GOES at 1800 UTC.

Radiance bias
Corrections for the difference between observed and forward model-calculated radiances (radiance biases) have been implemented in the MOD07 algorithm. Radiance bias corrections address instrument calibration errors, spectral response uncertainty, temperature and moisture profile inaccuracies, and forward model error. The bias corrections impact all retrievals, and help to bring the magnitude of the retrieved quantities more in line with other observations. Global radiance biases are computed regularly by comparing observed MODIS radiances with those computed from NCEP-GDAS surface pressure and profiles of temperature and moisture, regression-based skin temperature, and approximated ecosystem-based emissivity. Currently, these calculations are performed for ocean only to minimize errors due to inaccurate surface characterization. The bias corrections used in the algorithm are averaged globally and can be specified to be a linear function of either GDAS TPW or observed MODIS brightness temperature for each band. This is an improvement over averaging the biases by latitude, which caused sharp discontinuities along latitude lines in the product values.

Reduction of noise
In order to reduce noise in the MOD07 retrievals due to striping of the MODIS radiances, noisy or out of family detectors are omitted from the retrieval. Noise is further reduced by using the regression predictor BT25 instead of BT25 minus BT24 (which exacerbated the effects of striping). This is possible without affecting desert retrievals because of the improved emissivity characterization in desert areas.

Forward model updates
The forward model used to compute radiances from the training profiles was updated periodically. The latest version used in the operational MOD07 is based on the line-by-line radiative transfer model (LBLRTM) calculations obtained with LBLRTM-6.01 and the high-resolution transmission molecular absorption database HITRAN 2000. More recently, a new model based on a more sophisticated set of profiles (UMBC) and using a more updated LBLRTM (7.04) has become available and shows good improvement; this should be made operational when possible.

Skin temperature
Skin temperature is included as a retrieved variable in the same regression procedure used for atmospheric temperature and moisture. A Comparison of MODIS regression-based surface skin temperature with that measured by the infrared thermometer (IRT) at the SGP ARM-CART show that MODIS agrees well with the in-situ measurements, with an RMS difference of 1.8 K for 70 clear-sky cases from April 2001 to August 2002. The MODIS retrieved skin temperature was added to the MOD07 products, as the Surface_Temperature product SDS, replacing the NCEP-GDAS surface temperature.

IVb. Detection of Polar Low-Level Temperature Inversions With MODIS

The near-surface atmosphere of the polar regions is characterized by temperature inversions throughout most of the year. A method was developed for detecting and estimating the characteristics of clear sky, low-level temperature inversions using

MODIS. This procedure is independent of the atmospheric profile retrieval. It is based on an empirical relationship between the inversion strength, defined as the temperature difference across the inversion, or height, defined as the altitude difference, and the difference between brightness temperatures in the 7.2 _m water vapor and 11 _m infrared window bands.

It has been shown that inversion strength can be estimated by MODIS with an RMS difference of 2-3 ^{o}C with respect to radiosondes (showing no bias). Inversion height can be estimated with an RMS of 130-250 m. Examples are given in Figure JK1 for inversion strength and Figure JK2 for inversion height. With MODIS, temperature inversions can be observed at a spatial resolution as high as one square kilometer and a temporal sampling of up to fourteen times per day, providing an opportunity for detailed studies of the spatial distribution and temporal evolution of the high-latitude boundary layer. A journal paper has been submitted describing this work (Liu and Key, 2002).

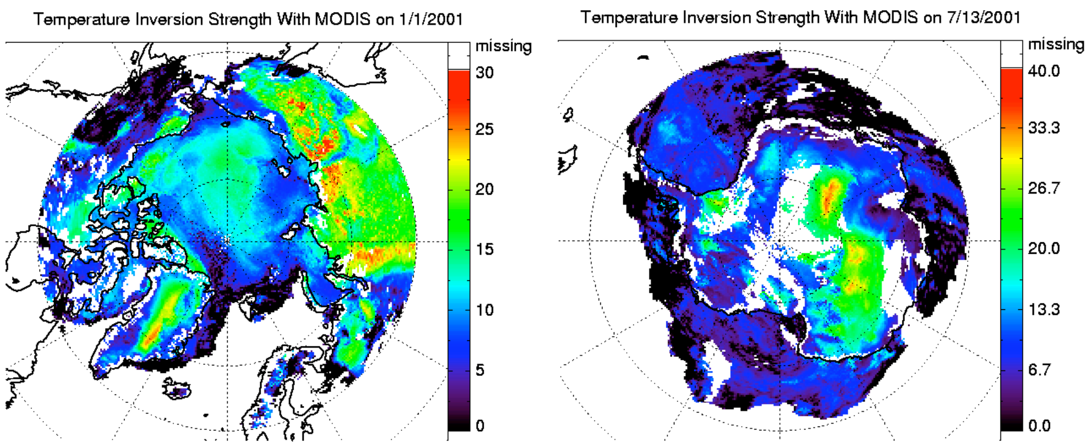

Figure JK1. Temperature inversion strength (deg ^{o}C) estimated from MODIS over the Arctic (left) and Antarctic (right) on a single winter day for each hemisphere.

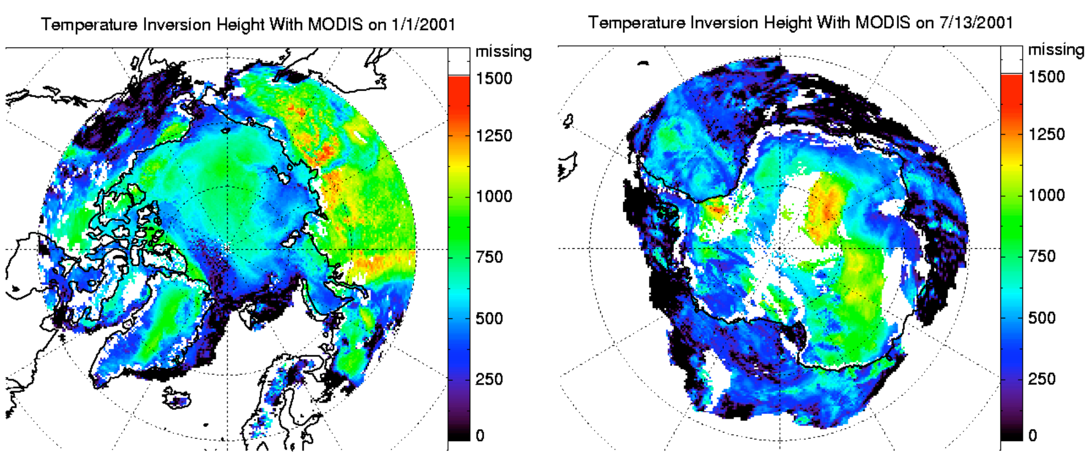

Figure JK2. Temperature inversion height (meters) estimated from MODIS over the Arctic (left) and Antarctic (right) on a single winter day for each hemisphere.

IVc. Atmospheric Profiles Lessons Learned

- Noisy detectors contribute to striping and detract from science products. Destriping of the twenty optical system data (two mirror sides and ten detectors per spectral band) is imperative before product processing can begin. The empirical distribution function approach applied per granule is a viable option.
- The atmospheric profiles regression algorithm based on radiosonde observations must include consideration of surface emissivity and radiance biases between measured and calculated clear sky radiances.
- A physical iterative algorithm can improve upon an initial regression retrieval, but it needs an accurate radiative transfer model and more computation resources for operational processing.
- Validation is essential to any algorithm development and refinement effort. Comparing product values with measurements from other well-validated ground- and satellite-based instruments identifies problems and quantifies their magnitude. Additionally, a good validation data set provides a test platform to evaluate the effects of algorithm changes and updates.

IVd. Atmospheric Profiles Publications

Liu, Y. and J. Key, 2003, Detection and analysis of clear sky, low-level atmospheric temperature inversions with MODIS, *J. Atmos. Ocean. Tech.*, **20**, 1727-1737.

Menzel, W. P., Seemann, S.W., Li, J., Gumley, L.E., 2002: "MODIS atmospheric profile retrieval algorithm theoretical basis document." Available through NASA MODIS Web site http://modis-atmos.gsfc.nasa.gov/reference_atbd.html.

Seemann, S.W., L. E. Gumley, J. Li, W. P. Menzel, and T. J. Schmit: "MODIS/TERRA Total Precipitable Water Product Evaluation". 11th Conference on Satellite Meteorology and Oceanography, Madison, WI, 15-18 October 2001. American Meteorological Society, 504-505.

Seemann, S.W., J. Li, L.E. Gumley, K.I. Strabala, W.P. Menzel, 2002: "Operational retrieval of atmospheric temperature, moisture, and ozone from MODIS infrared radiances." Proc. SPIE 3rd International Asia-Pacific Environmental Remote Sensing Symposium, Remote Sensing of the Atmosphere, Ocean, Environment, and Space: Applications with Weather Satellites, Hangzhou, China, October 23-27.

Seemann, S. W., J. Li, L. E. Gumley,, K. I. Strabala, and W. P. Menzel, 2002: One Year of Global Atmospheric Total Column Precipitable Water Vapor Retrievals from MODIS Infrared Radiances. Remote Sensing of the Earth's Environment from Terra – Lectures at the International Summer School on Atmospheric and Oceanic Sciences (ISSAOS 2002) from 25 – 30 August 2002 in L'Aquila, Italy. A Springer publication.

Seemann, S. W., J. Li, W. P. Menzel, and L. E. Gumley, 2003: Operational retrieval of atmospheric temperature, moisture, and ozone from MODIS infrared radiances. Jour. Appl. Meteor., **42**, 1072-1091.

V. Polar Winds

UW developed and completely automated the real-time processing of MODIS data for polar winds retrievals. MODIS level 1b granules for both north and south polar regions are obtained through the NOAA "bent pipe". Approximately 100 granules per day per satellite are transferred via FTP from a NOAA computer at Goddard Space Flight Center to UW. Wind retrieval procedures are then done at UW. Improvements have been made in the data acquisition procedure such that time lags have been reduced from 5-8 hours to 3-6 hours; i.e., MODIS polar winds are available within 3-6 hours after MODIS views any given area. Aqua MODIS data are now being processed in addition to Terra MODIS data.

The real-time winds are being used by the European Centre for Medium Range Weather Forecasting (ECMWF), the NASA Global Modeling and Assimilation Office (GMAO, formerly the Data Assimilation Office), the Candian Meteorological Centre, and the UK MetOffice in model impact studies and experimental forecasting systems. ECMWF put the winds into their operational system in January 2003. Real-time MODIS wind plots are available on the web at http://stratus.ssec.wisc.edu/products/rtpolarwinds.

Va. Polar Winds Lessons Learned

- Sequences of MODIS water vapor images from Terra and Aqua reveal tracers suitable for deriving atmospheric motion vectors.
- These motion vectors are providing positive impact in numerical weather prediction model forecasts.
- Future polar systems should include the capability for tracking water vapor features.

Vb. Polar Winds Related Publications

Key, J. R., D. Santek, C. S. Velden, and W. P. Menzel, 2001: Cloud Drift and Water Vapor Winds in the Polar Regions from MODIS. AMS 11th Conference on Satellite Meteorology and Oceanography, 15-18 October 2001, Madison, Wisconsin. AMS publication.

Key, J. R., D. Santek, C. S. Velden, N. Bormann, J.-N. Thépaut, L. P. Riishojgaard, Y. Zhu, and W. P. Menzel, 2003: Cloud-Drift and Water Vapor Winds in the Polar Regions from MODIS. . *IEEE Trans. Geosci. Remote Sens*., **41**, 482-492.

Key, J. R.**,** D. Santek, C. S. Velden, S. Levinson, N. Bormann, L. von Bremen, J.-N. Thépaut, L. P. Riishojgaard, Y. Zhu, and W. P.Menzel, 2003: Cloud-Drift and Water Vapor Winds in the Polar Regions from MODIS**.** CGMS XXXI held 10 – 13 November 2003 in Ascona, Switzerland. EUMETSAT publication.

Santek, D., J. R. Key, C. S. Velden, N. Bormann, J. Thépaut, L. P. Riishojgaard, Y. Zhu, and W. P. Menzel**,** 2002**:** Cloud-Drift and Water Vapor Winds in the Polar Regions from MODIS. CGMS XXX held 12 – 15 November 2002 in Bangalore, India. EUMETSAT publication.

VI. Acronyms List

AERI	Atmospheric Emitted Radiance Interferometer
AIRS	Atmospheric Infrared Sounder
ARM	Atmospheric Radiation Measurement (DOE)
ATBD	Algorithm Theoretical Basis Document
AVHRR	Advanced Very High Resolution Radiometer
CART	Cloud And Radiation Testbed
CIMSS	Cooperative Institute for Meteorological Satellite Studies
COT	cloud optical thickness
CPL	Cloud Physics Lidar
CPS	cloud particle size
CTP	cloud-top pressure
DAAC	Distributed Active Archive Center
DAO	Data Assimilation Office
DOE	Department of Energy
DSM	Deep Space Maneuver
ECA	effective cloud amount
ECMWF	European Centre for Medium Range Weather Forecasting
EOS	Earth Observing System
EOSDIS	Earth Observing System Data/Information Systems
FM	Flight Model
FTP	File Transfer Protocol
GMAO	Global Modelling and Assimilation Office
GOES	Geostationary Operational Environmental Satellite
HIRS	High resolution InfraRed Sounder
HIS	High-resolution Interferometer Sounder
IR	Infrared
ISCCP	International Satellite Cloud Climate Project
L1B	Level 1B
LWIR	Longwave Infrared
MAMS	Multispectral Atmospheric Mapping Sensor
MAS	MODIS Airborne Simulator
MCST	MODIS Characterization Support Team
MISR	Multi-angle Imaging Spectro-Radiometer
MODIS	MODerate resolution Imaging Spectrometer
MWIR	Midwave Infrared
MWR	Microwave Radiometer
NAD	Nadir Aperture Door
NDSI	Normalized Difference Snow Index

NEDT	Noise Equivalent Delta Temperature
NFR	near field response
OBC	Onboard Calibrator
OOB	Out-of-band
PFM	Proto Flight Model
PC	Photoconductive
PW	Precipitable Water
QC	Quality Control
RMS	Root Mean Square
RSR	Relative Spectral Response
RVS	Response Versus Scan
SHIS	Scanning High resolution Interferometer Sounder
SWIR	Shortwave Infrared
THORPEX	The Observing System Research and Predictability Experiment
TIR	Thermal Infrared
TIROS	Television InfraRed Operational Satellite
TOVS	TIROS Operational Vertical Sounder
TPW	Total Column Precipitable Water Vapor
TX-2001	Terra Experiment – 2001
TX-2002	Terra and Aqua Experiment - 2002
UW	University of Wisconsin – Madison
VIIRS	Visible Infrared Imager Radiometer Suite
WISC-T2000	Wisconsin Snow and Cloud Experiment – Terra 2000