6A.1 ESTIMATION OF CONVECTIVE PLANETARY BOUNDARY LAYER EVOLUTION AND LAND-ATMOSPHERE INTERACTIONS FROM MODIS AND AIRS

Joseph A. Santanello, Jr.*[1,2], and Mark A. Friedl[3]
[1]ESSIC-UMCP, [2]NASA-GSFC Hydrological Sciences Branch, [3]Dept. of Geography & Environment, Boston Univ.

1. INTRODUCTION

Land-atmosphere (L-A) interactions and coupling remain weak links in current observational and modeling approaches to understanding and predicting the Earth-Atmosphere system. The degree to which the land impacts the atmosphere (and vice-versa) is difficult to quantify given the disparate resolutions and complexity of land surface and atmospheric models. However, the convective planetary boundary layer (PBL) serves as a short-term memory of land surface processes (through the integration of regional surface fluxes on diurnal scales), and therefore is diagnostic of the surface energy balance. Further, the PBL and land surface equilibrium reached each day describes the degree of coupling and the impact of feedbacks within the L-A system. As such, knowledge of the diurnal evolution of the PBL can be instrumental in estimating surface fluxes and properties across regional scales as well as quantifying and improving L-A representations in coupled models.

Sensors aboard two new polar-orbiting satellites offer the ability to monitor diurnal temperature and moisture conditions in the convective planetary boundary layer (0-4 km) at regional scales. The Moderate Resolution Imaging Spectroradiometer (MODIS) aboard Terra and Aqua and the Atmospheric Infrared Sounder (AIRS) aboard Aqua are designed to measure radiances emitted from the lower troposphere and the land surface at unprecedented spatial and spectral resolution (Menzel and Gumley 1998). Therefore, atmospheric profiles retrieved from these sensors should be able to resolve daily temperature and moisture profiles in the PBL that previously could only be diagnosed using synoptic radiosonde networks.

The spatial resolution of MODIS and AIRS matches the typical integrating scale of the PBL (10-100 km) and therefore offers the opportunity to monitor such properties in a spatially continuous fashion. Previous attempts to exploit the relationship between the PBL and the land surface have been hampered by insufficient measurements (in time and space) and incomplete understanding of the defining relationships among PBL and land surface properties (Diak and Whipple 1993, 1994). However, through the combination of new remote sensing data and improved methodologies that are optimized for such data, the ability of the PBL to be used as an accurate proxy for land surface processes and conditions can now be reassessed.

*Corresponding author address: Joseph A. Santanello, Jr., Room 8, Bldg. 22, NASA-GSFC Code 614.3, Greenbelt, MD 20771; sntnello@hsb.gsfc.nasa.gov

With these issues in mind, this paper examines atmospheric temperature profile retrievals from MODIS and AIRS, focusing on the potential utility of these sensors to infer PBL structure and evolution and, by extension, land surface properties and energy balance. The results highlight the current utility and limitations of satellite remote sensing in the PBL and the potential for improving estimates and coupled modeling of the relevant processes.

2. BACKGROUND AND METHODOLOGY

2.1 Sensor Development and Profile Retrieval

Instruments aboard geostationary and polar-orbiting satellites have been used to observe and retrieve information on the condition of the atmosphere and land surface for over 25 years (Menzel and Gumley 1998). Radiometers and sounders measure infrared radiances in multiple spectral bands, each of which is designed to measure radiation received from a different level of the atmosphere. Radiances are then combined with a first-guess profile of atmospheric temperature and moisture using a set of simulated regression relationships to obtain the final retrieval product (Seemann et al. 2003; Chahine et al. 2001; Schmit et al. 2002; Menzel et al. 2002). Prior to MODIS and AIRS, the ability of remote sensing instruments to obtain profiles at resolutions required by current atmospheric and climate models has been limited by insufficient bandwidth and retrieval algorithms.

The MODIS instrument was launched aboard EOS-Terra (MOD-T) on 18 December 1999 and EOS-Aqua (MOD-A) on 4 May 2002. MODIS was designed with fine horizontal spatial resolution (5 km) that improves on prior capabilities to monitor land surface temperature and surface conditions, as well as the horizontal gradients in these properties. MODIS also provides better identification of cloud contamination, which is important for the profile retrieval process (Seemann et al. 2003). Although it is not technically a sounding instrument, the 36 spectral bands of MODIS are able to retrieve vertical distribution of temperature in 20 integrated layers, and the weighting functions near the surface are improved compared to GOES. However, the MODIS retrieval algorithm still assumes that surface air and brightness temperatures are identical, which limits the accuracy and vertical resolution near the surface, particularly in the PBL.

AIRS and the Advanced Microwave Sounding Unit (AMSU) and the Microwave Humidity Sounder of Brazil (HSB) were launched aboard EOS-Aqua on 4 May 2002 (Chahine et al. 2001). AIRS employs 2378 spectral channels (0.20 K SE) at 50 km horizontal resolution, and was designed based on the results of previous experiments using aircraft and instruments with high spectral resolution (e.g. HIS; Diak et al. 1994). AIRS vertical temperature profiles are specified to have an accuracy of 1 K in 1-km thick layers, and are produced for 28 vertical levels. The retrieval method assigns trapezoidal weighting functions at low levels of the troposphere to resolve fine-scale variation in temperature and moisture. These functions are used to fine-tune an initial guess from synthetic regressions applied in a fashion similar to MODIS retrievals (Fetzer et al. 2003; Susskind et al 2003), and are critical to profile accuracy and biases in the lower troposphere.

2.2 Methods for Diagnosing L-A Interactions

Santanello et al. (2006, 2005) present a detailed examination of the relationships among PBL and land surface properties from an empirical and modeling perspective. Traditional methods based on heat conservation in the PBL were shown to be unsuccessful in diagnosing regional fluxes on diurnal scales due to incomplete parameterization of entrainment and advection processes. As a result, alternative methods were developed based on relationships between observable properties of the PBL and the land-surface. In turn, a methodology was established that enables limited observations of PBL structure to be converted into estimates of land surface energy balance and surface conditions.

Namely, the results presented in Santanello et al. (2005) show that PBL height (h) can be estimated with reasonable accuracy using observations of initial atmospheric stability in the PBL (γ), diurnal change in 2 meter or mixed-layer temperatures ($\Delta\theta$), and near-surface soil moisture (w). More importantly, these relationships are only weakly dependent on soil and vegetation conditions since the PBL integrates these properties for a given location, an important consideration for the application of remote sensing data. This methodology was inverted to estimate soil moisture from PBL structure, which was then linked directly to sensible heat flux. Although the precise nature of the relationships is site-specific, this strategy only requires estimates of large-scale features of the PBL, most of which may be detectable from profiles of temperature retrieved by MODIS and AIRS.

To expand the applicability of this methodology, Santanello et al. (2006) used a coupled PBL-land surface model to examine the sensitivity of L-A coupling to changes in surface properties. They found that the PBL and land surface equilibrium for a given location and conditions is principally governed by feedbacks of PBL growth and entrainment on surface flux evolution. These L-A feedbacks are critical to understanding and quantifying the coupling of the PBL and land surface and the processes involved.

3. INSTRUMENT AND SITE SPECIFICATION

3.1 MODIS

Atmospheric temperature and moisture profiles from MOD-T and MOD-A were obtained and processed for 44 clear-sky days in June and July 2003 at the ARM-SGP central facility in Lamont, OK. Overpass times for MOD-T and MOD-A ranged from 1630 to 1855 UTC and from 1930 to 1955 UTC, respectively, depending on the exact orbital path of the satellite. MODIS standard temperature profiles are produced at 20 vertical levels, 7 of which are below 600 mb (620, 700, 780, 850, 920, 950, and 1000 mb). Support products (from which the standard products are generated) are available from MODIS at much finer vertical resolution (101 levels), but because MODIS is not a sounder there is little additional information in the support data (S. Seemann; pers. communication).

3.2 AIRS

AIRS Level-2 temperature profiles were obtained and processed for the same dates as MODIS at Lamont, OK. AIRS daytime overpasses (AIRS-d) are identical to MOD-A, with 6 levels below 600 mb available from the standard product (600, 700, 850, 925, 1000, 1100). The AIRS support product provides 17 levels below 600 mb (617, 639, 661, 683, 706, 729, 753, 777, 802, 827, 852, 878, 904, 931, 958, 986, 1013 mb), but again there is little information in these additional levels compared to the standard product.

AIRS nighttime overpasses (AIRS-n) occur between 0730 and 0930 UTC, which is close to the timing of morning radiosonde ascents (1130 UTC) at Lamont, OK. Therefore, AIRS-n retrievals should more closely reflect the bulk state of the early-morning lower troposphere, which is highlighted by a morning surface inversion and, on occasion, a residual mixed-layer. Most importantly, stability in the mixed layer is estimated from morning profiles of potential temperature, and is a significant predictor of PBL growth.

For both MODIS and AIRS data, estimated dry bulb temperatures were first converted to potential temperature and plotted against the pressure levels of each product. In theory, the staggered overpass times of Terra (~1630 Z) and Aqua (~1930 Z) allow diurnal variability in atmospheric structure and properties to be assessed during a critical period of convective PBL growth that would be highly reflective of surface fluxes and conditions.

3.3 ARM-SGP Data

To evaluate temperature profiles from MODIS and AIRS, radiosonde data from the ARM-SGP central facility were obtained for the dates selected. Radiosondes were launched at 1130, 1730, 2030 and 2330 UTC at Lamont, OK, which includes but extends beyond the diurnal window sampled by Terra and Aqua. Studies of PBL diurnal evolution confirm that because PBL growth is largest from 1300-1900 UTC, and therefore the small mismatch in afternoon observation times between Aqua and the radiosondes should not significantly affect comparisons between observed and retrieved PBL properties (Gryning and Batchvarova

1998; Yi et al. 2001; Dolman et al. 1997; Kustas and Brutsaert 1987; Peters-Lidard and Davis 2000).

Temperature and humidity data were processed from radiosonde data to obtain profiles of potential temperature (θ) and specific humidity (q) at ~10 meter vertical resolution for each ascent. From these profiles, the height of the capping inversion (h), initial stability in the layer of PBL growth (γ), and 2m-potential temperature change ($\Delta\theta_{2m}$) were estimated using techniques described in Santanello et al. (2005).

Surface meteorological and flux data were acquired for each day of the study. Energy Balance Bowen Ratio (EBBR) measurements were chosen to represent fluxes of sensible, latent, and soil heat along with net radiation at 30 minute intervals. Extended facilities (EF-12 and EF-5) were also used to compute a spatial average of fluxes over a ~100 km area surrounding Lamont, OK, which makes the data less dependent on a single site condition and better represents the fetch of surface heat and moisture into the PBL. Average hourly 0-5 cm volumetric soil water content (w) was quantified using a five-sensor average of measurements spaced across and surrounding the EBBR instruments.

3.4 Methodology

To date, there has not been an thorough analysis of MODIS and AIRS temperature profile retrievals in the lower troposphere. Therefore, the first section of results is an evaluation of profile retrievals using radiosonde measurements at ARM-SGP. Following this, PBL properties estimated from MODIS and AIRS profiles are tested in the methodology described in Santanello et al. (2006, 2005). Finally, the results present a statistical analysis of cloud-cleared radiances measured by MODIS and AIRS to determine correlations between radiances and PBL and land surface properties.

4. RESULTS

4.1 Evaluation of MODIS Temperature Retrievals

Profiles of θ retrieved from MOD-T at on 5 July 2003 at 1755 UTC and 10 July 2003 at 1635 UTC are shown in Figure 1a. When compared with observations, MOD-T profiles match the nearly constant lapse rate of the free atmosphere θ relatively well when compared with those below 4 km. The MOD-T profiles should lie somewhere in between the morning (1130 UTC) and afternoon (2330 UTC) observations, yet the near-surface θ are closer to the morning observations. This is most likely a function of the fact that MODIS does not distinguish between surface and near-surface temperatures. An inflection point near 4 km exists in both plots, where MOD-T seems to be responding to heating in the PBL, but the details of mixed-layer structure and PBL height cannot be discerned.

The overpass time of MOD-A is 2-3 hours after MOD-T and near maximum h. Profiles of θ from MOD-A at 1930 UTC on 5 July 2003 and at 1945 UTC on 10 July 2003 are compared with radiosonde observations in Figure 1b. There is a greater response to heating in the mixed-layer seen in MOD-A profiles as a result of its later overpass time relative to MOD-T, but PBL height and structure of the mixed-layer are still not accurately represented. Overall, the bands and weighting functions of MODIS in the lower troposphere are too broad and specific information of relationships between radiances and PBL structure cannot be discerned.

4.2 Evaluation of AIRS Temperature Retrievals

AIRS-d retrievals of θ are plotted in Figure 2a for 15 June and 28 July 2003 along with radiosonde observations from Lamont, OK. On 28 July, observed h (600 mb; 3700 meters) is nearly twice that of 15 June (800 mb; 1905 meters). Overall, AIRS-d profiles show greater vertical resolution and accuracy than MODIS and are sensitive to the development of the mixed-layer and inversion at the top of the PBL. However, pinpointing the exact h is still difficult, and perhaps more importantly, the retrieved θ in the PBL is not constant with height as is typically observed in the mixed-layer.

The reason for these inaccuracies is that a bias exists in the θ profiles in the PBL that is inherent in the AIRS retrieval algorithm. The negative (cold) bias creates an inflection point in the mixed-layer and a curved θ profile shape with minimum temperatures near the 800 mb level. Weighting functions that help to shape the profile retrievals have inflection points at 857 mb, which contribute to the negative bias near this height. Also, the bias is not uniform and depends on conditions in and above the PBL, which excludes the possibility of a uniform post-retrieval correction. On days with low h, the profiles actually have a positive slope throughout, with no obvious inflection point. Profiles on days with the largest PBL growth, on the other hand, exhibit strong inflection points that are at higher heights. In fact, the gradient of θ from the surface to the inflection point is highly correlated with h (R^2 = 0.90) for the entire dataset.

Figure 2b shows AIRS-n θ profiles plotted with 1130 UTC radiosonde data at Lamont, OK on 24 June and 27 July 2003. On days without a residual mixed layer and strong radiative cooling (e.g., 24 June), AIRS-n approximates the initial θ profile well throughout the PBL. When a residual layer is in place (e.g., 27 July), however, the AIRS-n profiles are sensitive to the elevated mixed-layer and show a more unstable profile (which causes the surface temperature to be overestimated). Because of the importance of early morning atmospheric stability in controlling PBL height, AIRS-n profiles were used to initialize the Oregon State 1-D PBL (OSU; Troen and Mahrt 1986) model. The OSU model predicted mixed-layer θ and h accurately throughout the day to within 1.0 K and 100 meters, respectively, suggesting that AIRS-n profiles contain significant information on the initial stability of the lower troposphere.

4.3 Analysis of AIRS Radiances

The radiances measured by AIRS in 2085 channels vary as a function of the atmospheric and surface

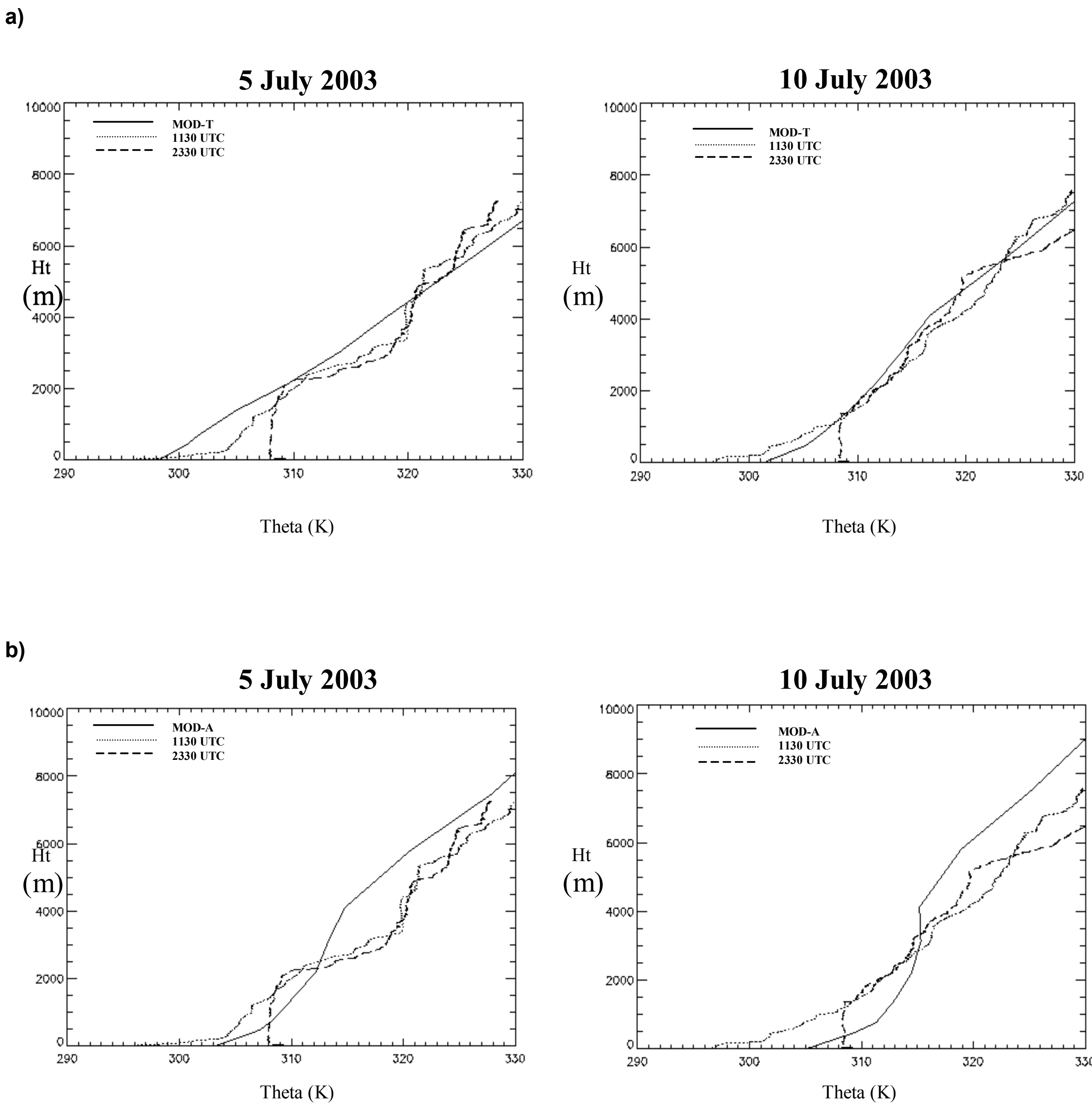
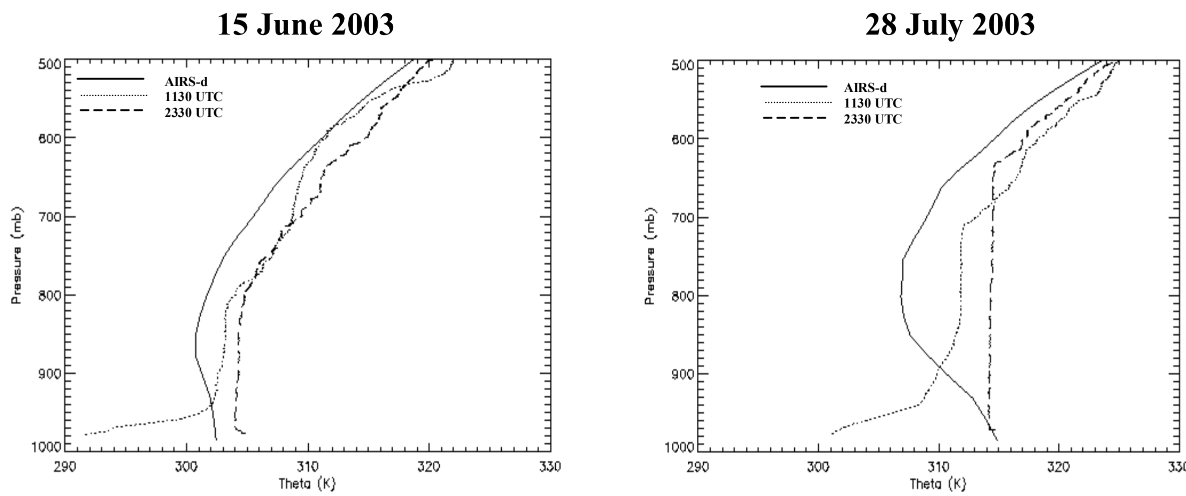


Figure 1. Vertical profiles of potential temperature retrieved from a) MOD-T and b) MOD-A on 5 July 2003 at 1755 UTC and 10 July 2003 at 1635 UTC along with radiosonde observations at the ARM-SGP central facility.

a)



b)

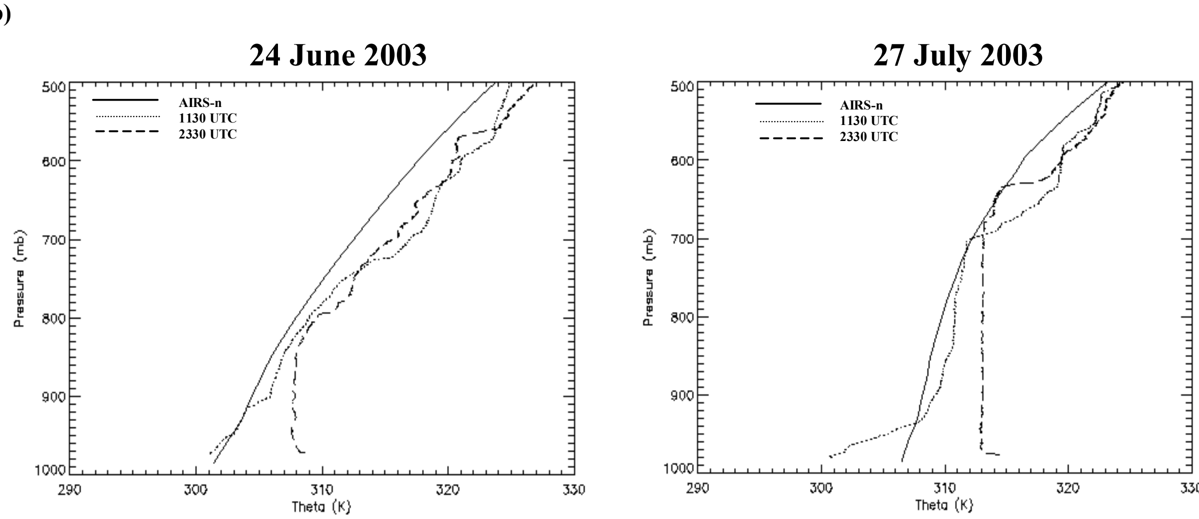


Figure 2. Vertical profiles of potential temperature retrieved from a) AIRS-d on 15 June 2003 and 28 July 2003 at 1930 UTC and b) AIRS-n on 24 June 2003 and 27 July 2003 at 1930 UTC, along with radiosonde observations at the ARM-SGP central facility.

temperatures throughout the day, and are therefore sensitive to the amount of heat input to the PBL. If the retrieved profiles were more accurate, the area between AIRS-n and AIRS-d would exactly indicate the total heat storage in the PBL. Instead, a closer look has to be taken at the radiance measurements used to generate the θ profiles.

Figure 3 shows the temporal change in cloud-cleared radiances from AIRS-n to AIRS-d overpasses on 3 days with widely varying PBL and surface conditions. The largest variability in 12-hour radiance changes occurs in the window region (~700-1250 cm^{-1}), which is most directly sensitive to the surface and near-surface heating. As Fig. 3 shows, there is a direct relationship between radiance changes in this region and observed w, H_s, and storage of heat in the PBL.

Given the large number of AIRS channels (2085) and their complex covariance with the variables of interest, statistical techniques were used to reduce the data to a more manageable level. Following Diak et al. (1994), a principal component analysis (PCA) was performed on night-day radiance changes from all AIRS channels for the 44 days of data. In each case, 3 principal components explained over 97 percent of the variance in the original bands, and the three components were used in a linear multiple regression on 11 PBL and land-surface variables of interest (soil moisture, sensible heat flux, latent heat flux, stability, Bowen ratio, net radiation, soil heat flux, PBL Height, 2m temperature change, and heat storage in the PBL).

Overall, the second principal component is correlated more highly with the surface signal while the first appears to be responding to heat input to the PBL. However, the R-squared values of the regression on H_s and h ($R^2 < 0.50$) were lower than those simulated by Diak et al. for ideal ($R^2 = 0.87$) and advective ($R^2 = 0.60$) conditions. From these results, it appears that the actual 12-hour radiance changes observed by AIRS are more weakly correlated with PBL variables than those simulated by Diak et al. (1994) for the HIS sounder.

PCA was also performed using the absolute values of AIRS-n and AIRS-d measured radiances. The resulting principal components computed from daytime radiances were more highly correlated with the 11 variables ($R^2 \sim 0.60$) than those from the 12-hour radiance changes discussed above. Specifically, the highest correlation of the first principal component computed from AIRS-d radiances is with w, H_s, and h. It is also important to note that these results are based on single overpasses rather than the two needed to compute radiance changes that, in effect, eliminates complications associated with large-scale diurnal processes such as advection.

The PCA revealed that there is significant information contained in AIRS-d radiances, but further investigation is required to discern which channels are most closely linked to PBL and land surface properties. Two random channels were chosen from the window region (933.0397 and 2530.886 cm^{-1}) and used in a linear multiple regression on the 11 variables of interest Surprisingly, these results ($R^2 = 0.64$ for w, and $R^2 = 0.53$ for H_s) indicate that surface conditions can be estimated more accurately from AIRS-d using only 2 channels, as opposed to the whole spectrum of 2085 channels used in the PCA.

5 channels were then found that showed the highest correlations with each of the 11 variables. Stepwise regression of these 5 channel radiances on each variable confirmed that each combination of channels was optimal and adding additional channels did not improve the results significantly. Results in Table 1 highlight that 92, 80, and 63 percent of the variance in w, H_s, and h, respectively, can be explained from radiances in five AIRS-d channels. Further, cross-validation tests holding out part of the data from the original 44 days only decreased the accuracy by 5 percent or less for each variable.

Overall, these results suggest that radiances from 5 AIRS-d channels can be used to estimate over 80 percent of the variance in surface soil moisture and sensible heat flux, and do not require specification of surface properties or atmospheric conditions. Soil wetness (and therefore H_s) is largely responsible for the heat transfer into the PBL, but other factors such as entrainment and advection also influence mixed-layer growth and likely explain the slightly lower skill for predicting PBL variables (h, γ, $\Delta\theta_{2m}$).

5. DISCUSSION AND CONCLUSIONS

In this paper, the ability of MODIS and AIRS to capture PBL structure and infer land surface properties and fluxes has been investigated. Temperature profile retrievals from MODIS show little skill in representing PBL structure, although alternative techniques can be used to maximize the information contained in MODIS brightness temperature measurements. AIRS, which is a far superior sounding instrument to MODIS, shows limited sensitivity to PBL evolution when compared with radiosonde data and contains a significant bias in its profile retrieval algorithm. The signal of L-A interactions is still present in AIRS temperature profiles, however, and may be useful in initializing atmospheric structure and constraining PBL growth models

An empirical analysis revealed that 5 or fewer individual AIRS channel radiances were more highly correlated with properties of the PBL and land-surface than the profile retrievals. Overall, the ability of so few AIRS-d channel radiances to estimate surface properties was a surprising result with a great deal of potential for future applications and investigation. Radiances from the land surface, near-surface, and upper troposphere respond to L-A interactions at multiple scales, and it would be particularly interesting to see if similar results are obtained for other regions and atmospheric conditions. If so, it may be possible to diagnose L-A coupling and evaluate models accordingly using a single AIRS overpass. Presumably, auxiliary data such as leaf area index and soil characteristics would improve results even further. Finally, the results from this paper are relevant to the future of remote sensing of the lower troposphere and convective PBL, which has been largely ignored to date. As this work has shown, a known bias still exists in common retrieval

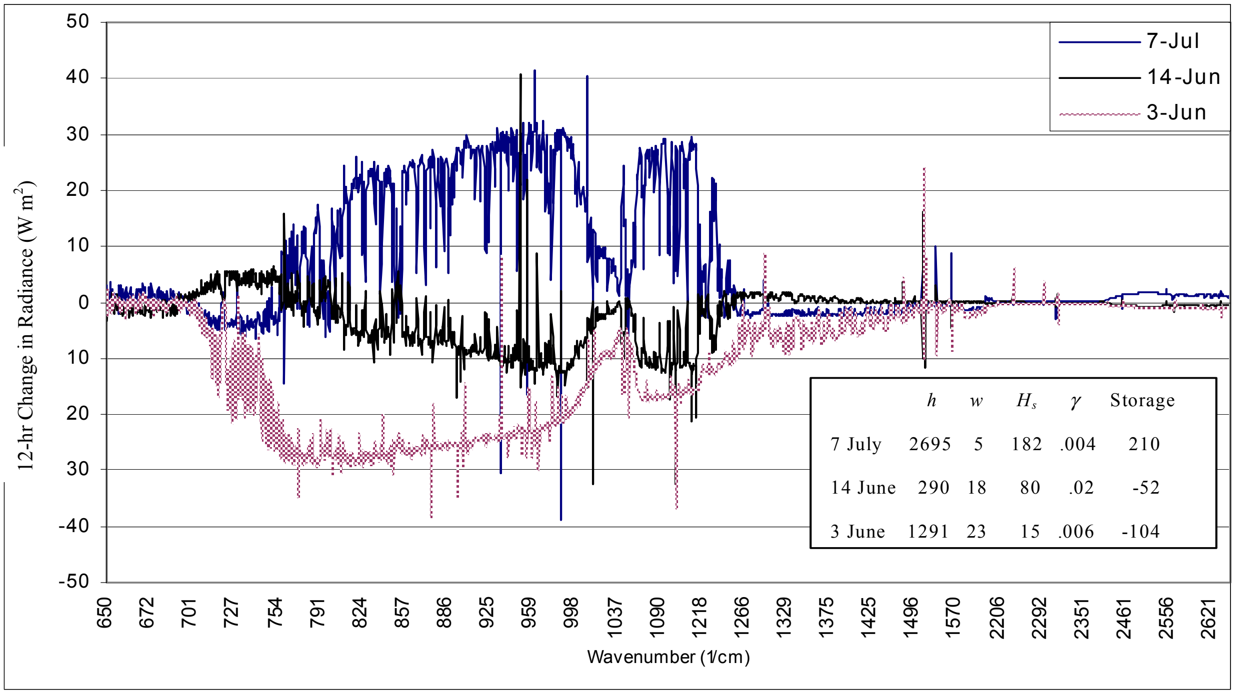


Figure 3. Changes in cloud-cleared radiance values from night to day (12-hours) measured by AIRS for three select days in June and July 2003 over the ARM-SGP central facility. Also listed are corresponding observations of PBL height (h, meters), soil moisture (w, $m^3\,m^{-3}$ *100), sensible heat flux (H_s, W m^{-2}), stability (γ, K m^{-1}), and heat storage in the PBL (W m^{-2}) for each day.

	2ch-window	5ch-γ	5ch-H_s	5ch-h	5c-w	5ch-$\Delta\theta_{2m}$
w	.63	.81	.92	.77	.82	.43
H_s	.53	.69	.80	.68	.75	.36
h	.24	.49	.44	.53	.63	.49
$\Delta\theta_{2m}$	.34	.43	.52	.50	.46	.52
γ	.09	.37	.20	.22	.25	.28
WN1	933.040	667.773	667.773	667.773	667.773	651.283
WN2	2530.89	696.603	903.775	896.183	693.028	694.948
WN3	--	701.617	992.448	922.731	903.775	937.907
WN4	--	796.038	2278.82	2273.90	2278.82	2285.74
WN5	--	2272.92	2519.99	2501.67	2519.99	2491.02

Table 1. R-squared values and wavenumbers of the channels (WN; cm^{-1}) used in the linear multiple regressions of AIRS individual channel radiances on soil water content (w), sensible heat flux (H_s), PBL height (h), 2m-potential temperature change ($\Delta\theta_{2m}$), and stability in the mixed-layer (γ).

algorithms that prohibit accurate estimation of near-surface profiles. Atmospheric sounding techniques should include more emphasis on PBL evolution in terms of band selection and retrieval algorithms. This will ensure that as technology and methods improve, identification of PBL height, stability, and mixed layer temperature will also improve.

Acknowledgments. This work was supported by NASA Headquarters under the Earth System Science Fellowship Grant NGT5-30405. Thanks also go to the AIRS Science Team who provided valuable and timely information on the profile retrieval process.

References

Chahine, M. T., H. Aumann, M. Goldberg, L. McMillin, P. Rosenkranz, D. Staelin, L. Strow, J. Susskind, and M. Gunson, 2001: AIRS-Team retrieval for core products and geophysical parameters. AIRS Algorithm Theoretical Basis Document, Level 2, JPL D-17006. Version 2.0, April 26, 2001.

Diak, G. R., and M. S. Whipple, 1993: Improvements to models and methods for evaluating the land-surface energy balance and 'effective' roughness using radiosonde reports and satellite-measured 'skin' temperature data. *Agric. For. Meteor.*, **63,** 189-218.

Diak, G. R., and M. S. Whipple, 1994: A note on the use of radiosonde data to estimate the daytime fluxes of sensible and latent heat: a comparison with surface flux measurements from the FIFE. *Agric. For. Meteor.*, **68,** 63-75.

Diak, G. R., C. J. Scheuer, M. S. Whipple, and W. L. Smith, 1994: Remote sensing of land-surface energy balance using data from the High-Resolution Interferometer Sounder (HIS): A simulation study. *Remote Sens. Environ.*, **48,** 106-118.

Dolman, A. J., A. D. Culf, and P. Bessemoulin, 1997: Observations of boundary layer development during the HAPEX-Sahel intensive observation period. *J. Hydrol.*, **188-189,** 998-1016.

Feltz, W. F., W. L. Smith, H. B. Howell, R. O. Knuteson, H. Woolf, and H. E. Revercomb, 2003: Near-continuous profiling of temperature, moisture, and atmospheric stability using the atmospheric emitted radiance interferometer (AERI). *J. Appl. Meteorol.,* **42,** 584-597.

Fetzer, E. J., J. Teixeira, E. T. Olsen, and E. F. Fishbein, 2004: Satellite remote sounding of atmospheric boundary layer temperature inversions over the subtropical eastern Pacific. *Geophys. Res. Lett.*, **31**.

Gryning, S. E., and E. Batchvarova, 1998: Regional heat flux over the NOPEX area estimated from the evolution of the mixed-layer. *Agric. Forest Meteorol.*, **98-9,** 159-167.

Kustas, W. P., and W. Brutsaert, 1987: Virtual heat entrainment in the mixed layer over very rough terrain. *Boundary Layer Meteorol.*, **38,** 141-157.

Menzel, W. P., and L. E. Gumley, 1998: MODIS Atmospheric Profile Retrieval Algorithm Theoretical Basis Document. Version 4.0, November 30, 1998. http://eospso.gsfc.nasa.gov/

Menzel, W. P., S. W. Seemann, J. Li, and L. E. Gumley, 2002: MODIS Atmospheric Retrieval Algorithm Theoretical Basis Document. Version 6.0, October 10, 2002. http://modis.gsfc.nasa.gov/data/algorithms.html

Peters-Lidard, C. D., and L. H. Davis, 2000: Regional flux estimation in a convective boundary layer using conservation approach. *J. Hydrometeor.*, **1,** 170-182.

Santanello, J. A., M. A. Friedl, and Michael B. Ek, 2006: Convective Planetary Boundary Layer Interactions with the Land Surface: Diagnostics and Feedbacks. *J. Hydrometeorol.*, under review.

Santanello, J. A., M. A. Friedl, and W. P. Kustas 2005: Empirical Investigation of Convective Planetary Boundary Layer Evolution and its Relationship With the Land Surface. *J. Appl. Meteorol.*, **44,** 917-932.

.
Schmit, T. J., W. F. Feltz, W. P. Menzel, J. Jung, A. P. Noel, J. N. Heil, J. P. Nelson III, and G. S. Wade, 2002: Validation and use of GOES sounder moisture information. *Wea. Forecasting*, **17,** 139-154.

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. *J. Appl. Meteor.*, **42,** 1072-1091.

Susskind, J., C. D. Barnet, and J. M. Blaisdell, 2003: Retrieval of atmospheric and surface parameters from AIRS/AMSU/HSB data in the presence of clouds. *IEEE Trans. Geosci. Rem. Sensing*, **41,** 390-409.

Troen, I. B., and L. Mahrt, 1986: A simple model of the atmospheric boundary layer; Sensitivity to surface evaporation. *Boundary Layer Meteorol.*, **37,** 129-148.

Yi, C., K. J. Davis, and B. W. Berger, 2001: Long-term observations of the dynamics of the continental planetary boundary layer. *J. Atmos. Sci.*, **58,** 1288-1299.