UCAR/COMET: Final Outreach Project Report: August 31, 2004
(Partners Project/UCAR Award #S03-38670)

"Assimilation of MODIS Temperature and Water Vapor Profiles into a Mesoscale Analysis System"

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1. Project Objectives and Accomplishments

1.1 Academic and Forecast Partners

*The PI (Dr. Lazarus) hired a graduate student, in support of the proposed work, July 2003. The student was be paid (in part) under this grant until the granted "No-Cost" extension date of 31 May 2004. Note that the proposed hire date was about a half year later than proposed, due in part to the academic calendar and availability of a qualified student.

*As per the proposal we began archiving the MODIS Aqua data stream from the University of Wisconsin-Madison's (SSEC) direct broadcast. The data stream uses the MOD07_L2 algorithm for retrieving vertical profiles of temperature and water vapor (20 vertical levels at 5 km horizontal resolution). The algorithms are based on statistical regression methodology and are adapted from the International TOVS Processing Package (ITPP). The data are ftp'd daily from the University of Wisconsin's Space Science and Engineering Center (SSEC). The files are archived, at Florida Tech, on a Sun Solaris workstation and backed up on 5 Gb tapes. Our local archive begins May 2003.

*Florida Tech is archiving 20 km Rapid Update Cycle (RUC) model data from NCEP (note that, due to bandwidth issues, the NWS Melbourne office initializes ADAS with the 40 km RUC). RUC data were used, in part, to test (evaluate) the quality and compatibility of the MODIS temperature and water vapor profiles data and the background field.

* The NWS Melbourne office continued to work toward an optimal configuration of ADAS suitable for operations and the post-event analysis research for this project. Configuration adjustments have been shared with the PI. The analysis domain was expanded to include the entire Florida peninsula (except for the southern Keys). The larger domain now includes the entire peninsular Florida coastline for the Atlantic and Gulf of Mexico, thus increasing the spatial area over water. The resolution is now 4 km, but the analysis cycle remains 15 minutes.

* An identically configured ADAS was set-up on the new NWS Melbourne linux cluster to support the local model. However, this version runs only to support the latest local model run (4 times daily). Subsequently, the office has begun operational runs of the Advanced Regional and Prediction System (ARPS) and ADAS [in an intermittent data assimilation (IDA) cycle] on this cluster. Currently, forecasts are initiated with a 'warm start', i.e. initialized with the ARPS Data Analysis System (ADAS). The IDA cycle incorporates observational data into the ARPS model by alternating between ADAS analyses that initialize very short-range ARPS forecasts over a specified

time interval. The IDA is typically run over a one hour pre-forecast period, but can be adjusted to any length. Of course, an ultimate goal is to get the MODIS data into this analysis/forecast cycle. Much of this project reflects an effort towards accomplishing this objective (e.g., data thinning, evaluating the retrieved profiles for bias, etc.)

*In direct support of the project, NWS Melbourne is posting (on the Southern Region server) daily files containing surface observations from the various Florida networks and Kennedy Space Center mesonet and tower network. These are the ingested data sets used to create the operational ADAS analyses.

*Because of limited bandwidth, we have set-up a ‘parallel’ version of the NWS operational ADAS (instead of archiving the NWS ADAS analyses here at Florida Tech as first proposed) This will facilitate testing and evaluation as we will be able to develop the support software within the same framework as that used for operations.

*We purchased IDL software and are using it to read/analyze the MOD07_L2 data as first proposed.

The following were obtained from Mr. Brad Zavodsky’s Master’s Thesis, which was written under the auspices of this COMET grant. <u>A copy of the thesis will be provided upon completion</u>.

Bias Evaluation

*We have conducted a thorough evaluation of the MODIS data stream. Because we proposed to assimilate the profile data into ADAS, it is important that we understand its variability and (spatial) representativeness. In order to accomplish this, we have examined approximately one year of the MODIS retrieved temperature and vapor profiles. In particular, we compared the MODIS profiles with both the RUC and upper air stations within the NWS ADAS/ARPS domain (Key West/EYW, Tampa Bay/TBW, Jacksonville/JAX, Miami/MFL, and Cape Canaveral/XMR). Because the satellite overpass through the ADAS domain does not generally coincide with sonde times, we perform a time interpolation, using consecutive radiosondes (12 h apart), to match the satellite

Table of Average Distance between 10 Proximity Soundings and Radiosonde Location

Month	EYW (24.55°N, 81.75°W)	TBW (27.70°N, 82.40°W)	JAX (30.50°N, 81.68°W)	MFL (25.75°N, 80.37°W)	XMR (28.47°N, 80.55°W)	Combined
May 2003	59.14 ± 10.73	33.95 ± 5.07	62.55 ± 7.83	55.64 ± 4.94	59.86 ± 6.64	54.20 ± 7.09
June 2003	104.96 ± 12.78	55.10 ± 8.54	66.66 ± 10.13	80.80 ± 9.65	56.23 ± 9.73	73.71 ± 10.24
July 2003	59.79±10.48	38.31 ± 6.05	70.08 ± 8.77	50.70 ± 7.23	51.44 ± 6.01	53.86 ± 7.71
August 2003	83.15 ± 10.00	51.28 ± 6.28	46.21 ± 7.43	76.64 ± 7.39	54.97 ± 7.23	62.58 ± 7.65
September 2003	119.33 ± 14.23	72.21 ± 7.28	56.87 ± 6.68	98.29 ± 10.45	72.90 ± 8.33	84.22 ± 9.44
October 2003	57.29 ± 9.03	86.23 ± 9.49	61.61 ± 12.00	45.55 ± 7.32	84.63 ± 8.03	66.07 ± 9.24
November 2003	66.07 ± 6.21	29.76 ± 4.28	38.65 ± 4.62	85.77 ± 3.47	67.94 ± 5.08	56.04 ± 4.78
December 2003	82.63 ± 7.72	42.76 ± 4.41	51.21 ± 4.59	70.63 ± 5.47	66.23 ± 5.59	62.37 ± 5.56
January 2004	66.97 ± 7.92	45.81 ± 5.38	58.35 ± 9.28	56.58 ± 4.46	66.23 ± 5.01	57.84 ± 6.60
February 2004	59.59 ± 9.76	55.95 ± 8.24	127.73 ± 15.48	62.15 ± 5.25	86.25 ± 6.25	77.98 ± 9.26
March 2004	84.04 ± 7.06	41.68 ± 6.98	50.94 ± 4.18	83.54 ± 5.31	63.96 ± 4.03	62.43 ± 5.57
April 2004	56.66 ± 8.50	42.28 ± 4.53	62.60 ± 6.56	55.97 ± 6.14	77.99 ± 6.80	57.75 ± 6.49

swath time. Ten proximity MODIS soundings (i.e. retrieved temperature and vapor profiles) are first averaged and then compared to soundings from each of the upper air sites. The table above indicates the average distance (km) between the MODIS profiles and the corresponding upper air data. An example of the monthly-average difference between the RUC, MODIS and upper air temperature/water vapor profiles is given for the month of December 2003 in Figures 1 and 2. Despite the fact that the satellite overpass (for the Florida ADAS domain) occurs around 06 and 18 UTC (i.e. non-sonde hours) the RUC remains highly coupled to the upper air data - especially temperature with only small discrepancies through much of the troposphere (note that the tropopause placement is an issue however). For this month, the MODIS water vapor shows relatively good agreement with the upper air data (on the order of 1 g kg^{-1} or less) - especially in the mid-troposphere where the MODIS/sonde differences are less than the RUC/sonde.

Findings:

1. The MODIS retrievals generally underestimate the lower tropospheric moisture (i.e., below 800 hPa), except for December 2003 and January 2004. The dry bias may, in part, be due to a combination of moist low levels and overlying dry air that might result in a lower moisture estimate in the smooth (i.e. coarse vertical resolution) MODIS profiles. Seemann et al. (2003) indicate that dry biases are common when the Total Precipitable Water (TPW) is greater than 17 mm and moist biases are commonly found when TPW is less than 17 mm. Monthly averaged TPW statistics from May 2003 through April 2004 obtained from the Suominet GPS receiver on the FIT campus are shown in Figure 3. Clearly, December and January were low TPW months. Conversely, when compared to sonde data, the March and April (2004) mid-tropospheric MODIS profiles are too moist. These two months appear to be somewhat anomalous in terms of their low TPW (compare the March 2003/2004 TPW - 27.6 mm vs. 18.6 mm and that for April 2003/2004 - 25.0 mm vs. 21.8 mm). A skew-T (EYW) for 12 UTC 3 March 2004 indicates that dry air was generally present above approximately 850 hPa, which is consistent with the relatively large moist bias between 850 and 500 hPa in the difference between the radiosonde and MODIS for March 2004 (Fig. 5). The dry layer extends upward to around the 400 hPa level which correlates nicely with the top of the moist bias layer in shown in Fig. 4.

2. The MODIS retrievals are typically degraded under conditions in which large temperature gradients exist in the vertical. The largest discrepancies between the (MODIS) retrieved temperature profiles and the upper air data occur near the tropopause level. These shortcomings are well-known as the number of channels (5) that are used to estimate the synthetic coefficients are too few to adequately resolve vertical gradients in temperature and moisture.

3. Lower tropospheric MODIS temperature biases transition from cool during the summer to warm during the winter.

The Variogram

1. Variograms (Sen 1997), i.e. plots of the spatial variance of the temperature and vapor profiles (with the background subtracted out) as a function of ‘station’ separation, were produced for every MODIS overpass of the ADAS/ARPS domain from May 2003 through April 2004. The basic premise behind these diagrams is to better estimate the error covariance length scale(s). The model error covariances are typically assumed to be Gaussian in most analysis methods (OI, Variational Assimilation, Bratseth). An example of a ‘cumulative’ variogram for temperature is

shown in Figure 6 for a 17 November 2003 1931 UTC MODIS swath. The cumulative variogram is computed via a summation over the squared difference between all the observation-minus-background pairs [there are *n(n-1)/2* pairs, where n is the number of observations]. The background field is removed, in part, to prevent ‘recorrelation’ at some distance. Note also that the observation-minus-background is what is referred to as the “innovation” (or correction) which, when multiplied by the analysis weight is the analysis increment (e.g., Kalnay 2003). Prior to the summation, the differences are sorted according to the distance between observation pairs. Note also that the variogram shown in Fig. 6 is normalized. A valid question is whether there is useful information in these diagrams. Obviously, at zero lag (distance), the variance is zero. The slope of the variogram provides an estimate of the rate of decorrelation (w.r.t. distance). Assuming the number of observation pairs are uniformly distributed for all distances (they are not), a steep (gradual) slope indicates rapid (slow) decorrelation. Following the work of Sen (1997), the variograms are ‘flipped’ [i.e. we take 1 - $\gamma(d)$, where $\gamma(d)$ is the cumulative variogram and d is the distance lag] so that the variogram resembles an analysis weighting function (i.e. a correlation of one for zero distance lag approaching zero correlation at large distance separations). These inverted variograms were then ‘fit’ using a nonlinear curve fitting algorithm in IDL. Figure 7 illustrates various curve fits for the inverted variograms. The Guassian fit (Fig. 7c) is the best of the 4 fits shown (the others are: linear, log, and exponential). Note that the shape of these curves however are somewhat dependent on the data distribution, for example the ‘plateau’ of the variance at large distances (e.g. Fig. 6) is an artifact of the diminishing number of observation pairs. The same reasoning applies, in part, to the relatively flat variance at small observation separation as well. Furthermore it is not necessarily intuitive that the cumulative variograms should behave in such a manner given that the background field has been subtracted from the observations. One might expect that the cumulative variance would increase linearly as a function of distance provided that the observation pair distances were evenly distributed across all lags.

2. The Bratseth (ADAS) method assumes that the background error covariances are Gaussian, $\rho(d) \sim e^{-d^2/R^2}$, where R is a ‘free’ parameter referred to as the decorrelation length scale. With the exception of Kalman filters, background error covariance models are generally assumed to be fixed (i.e. do not vary in time). Obviously, model errors can be dependent on the “climate” and hence there is no reason to assume, a priori, that the error covariances are static. From the Gaussian fit to the variograms, we obtain estimates of vertical profiles of R stratified by month. An example of these for temperature (for March/April 2004 and May 2003), is shown in Figure 8. Note that, for these months, the decorrelation length scale generally increases with height indicating that the greatest variability in the MODIS retrieved temperatures occurs in the lower troposphere as one might expect.

3. Additionally, because we are interested in potentially ‘thinning’ the data for <u>operational</u> use (a MODIS swath through the Florida NWS Melbourne ADAS/ARPS domain may have upwards of 15,000 profiles), one can use the slope of the curve (near zero distance lag) to determine an appropriate scale at which to subsample the profiles. The ‘red arrow’ on Figure 6 indicates that there is little variance in the temperature up until a normalized distance of 0.05. An example of a thinned satellite swath is shown in Figure 8. Note that the data may be subsampled, or “super observations” can be created whereby satellite profiles are combined.

Analyses
It is instructive to examine the impact of the MODIS profiles on the background field (RUC). This was done en masse as discussed above and for particular cases in March and April 2004 - the latter of which is shown here for a 1812 UTC MODIS swath on14 April 2004. Figure 10a shows the 1000 hPa temperature “innovations” (RUC minus MODIS) for the Florida ADAS domain. For this swath, differences are generally negative (MODIS is warmer) with most differences on the order of 2-3 ^{o}C. A ‘thinned’ difference field is shown in Figure 10b. Note that the thinned differences preserve the nature of the original differences in their respective regions. The RUC background (18 UTC 14 April 2004) at 1000 hPa is shown in Fig. 11a while a one-pass analysis with a decorrelation length scale of 60 km (with all MODIS data) is shown in Fig. 11b. Assuming that the observation errors are small, the innovations provide a good indication of the adjustment to the first-guess field. For example, one can see warming over southeast Florida, with little change in the background field to the southwest of Lake Okeechobee. Similarly, the warmer MODIS observations over the NE Gulf of Mexico produce a positive increment (i.e. warming) in this region. Figure 11c shows the ADAS analysis corresponding to the thinned profiles (i.e. for the case shown in Fig. 10b). Note that the analysis using the thinned profiles (with the same length scale as the analysis that uses all the data) more closely resembles the background. One motivation for thinning (i.e. creating super observations) is to combine observations that are ‘subgrid’ i.e. below the scale of the analysis, however in the presence of a large number of observations thinning may also be driven by computational issues. As discussed previously, the thinning scale was selected based on the variogram - with the idea that the thinned analysis resemble the full analysis (i.e. the removal of redundant information only). However that is not the case for these figures - suggesting that the low variance (for small distance separation) shown in Fig. 6 may, in part, be an artifact of the lack of observation pairs at these distances rather than a true lack of variance.

2. Related Accomplishments

2.1 Academic Partner

*This COMET proposal constitutes a student’s (Brad Zavodsky) Masters thesis here at Florida Institute of Technology (see Section 1 above). **A copy of the Master’s thesis will be forthcoming in October 2004.**

*The PI submitted an NSF proposal to study coastal showers. The NSF proposal, a significant motivation (i.e., to better resolve the thermodynamic structure upstream) for the work presented herein, was well-received but did not receive funding this year.

*The PI has a senior (undergraduate) meteorology student beginning to look at coastal shower events.

2.2 Forecast Partner

* The NWS Melbourne office has configured a version of Unidata's Local Data Manager (LDM) to share real-time ADAS analyses with the other Florida NWS offices for display on their respec-

tive AWIPS workstations. This was done through cooperation with the NWS Southern Region. If desired, other Florida offices now have the ability to utilize the analyses, and would be of further benefit if indeed MODIS data were eventually incorporated into the ingestion stream.

* The NWS Melbourne office has initiated pursuit for obtaining real-time MODIS data in experimental mode.

3. Summary of Benefits

3.1 Academic Partner

The collaboration with the National Weather Service office here in Melbourne is providing key operational experience to the PI's graduate student. The benefits include:

a.) c-shell scripting and linux/unix box experience (including learning about the crontab)
b.) HDF, NetCDF programming experience
c.) insight into the pitfalls and challenges of manipulating large data streams
d.) fostering interaction/communication between said graduate student and NWS office personnel, e.g., student has participated in several joint meetings and has also contacted/interacted directly with NWS employees without the direct supervision of the PI.
e.) learning to apply Gempak, GARP, and IDL graphics packages
f.) improving the student's understanding of data analysis/assimilation and how it applies to nowcasting and forecasting (e.g., time constraint issues, platform issues, data/background mismatch issues, data quality, etc.)Because satellite data will continue to play a growing role in operational meteorology, this project offers many practical opportunities/benefits for a student starting out in the field. Because of its size and high horizontal resolution, the MODIS data stream is somewhat intimidating - yet represents an important component of future local-to-regional scale operational data assimilation (this includes issues like bandwidth, real-time access, etc.). As we grapple with these issues, the project (and others like it) provide valuable tools and the training/experience that can be used throughout one's career.

*We have been in contact with several SSEC scientists and have received a copy of the forward radiative transfer model (called PFAAST) and related support software used to produce the temperature and vapor profiles from the Tera and Aqua radiances. SSEC contacts include Chris Moeller, Hal Woolf, and Suzanne Seeman. The PFAAST code was not used in this work as it was beyond the scope of what was proposed. The interaction with the aforementioned SSEC folks was positive and constructive and certainly beneficial to the PI and FIT.

3.2 Forecast Partner

* Florida Tech now serves as the ADAS archive library as configured and run over Florida by NWS Melbourne. It was essential for them to have ready access to the data, but it has also freed-up considerable resources for the NWS Melbourne office. This was indeed a mutual benefit.

*One of the best benefits from a local modeling perspective is the smart use of "thinned obs" and "superobs". For local modeling, managing resources is critical. There seems to a growing list of available data, but at what point does the "kitchen sink" begin to have a negative effect on the analysis (i.e. the cost/benefit of more and more data). The work done in conjunction with this proposal addresses these issues and should be of benefit to the Melbourne office as the data become available in near-real time.

* By having Florida Tech assimilate the MODIS temperature and water vapor profiles into ADAS in research mode, NWS Melbourne will have a better feel for the computational requirements for potential real-time employment.

*Improving analyses will reap dividends in the coming years for a variety of NWS products & services. Most importantly, to improve marine weather services for the day-1 period will be high-profile. Incorporating high-resolution satellite data into our analyses offers us that opportunity for improvement.

* The benefits of this project are broad, but are already being realized. For the NWS Melbourne office, it is consistent with and directly supports the Southern Region Local Modeling Initiative. It also is consistent with Applied Meteorology Unit activities for NWS Melbourne, as the relative value and impact of MODIS profile data is considered for ingestion into the assimilation system. The Space Flight Meteorology Group has a direct interest in the results of this project since they, too, run a data assimilation system over east central Florida for operational space shuttle support. Finally, the project has helped establish a professional rapport between Florida Tech and the various Florida NWS offices which, in turn, has fostered a sister COMET Project with NWS Miami and NWS Melbourne to investigate GOES SST data to retrieve over-ocean air temperatures.

4. Presentations and Publications

Zavodsky, B., S. M. Lazarus, P. Blottman, and D. Sharp, 2004: Assimilation of MODIS temperature and water vapor profiles into a mesoscale analysis system. *20th Conference on Weather Analysis and Forecasting/16th Conference on Numerical Weather Prediction*, Seattle WA, pp.

Zavodsky, B., S. M. Lazarus, P. Blottman, and D. Sharp, 2004: *Assimilation of MODIS temperature and water vapor profiles into a mesoscale analysis system*. Presentation at the Florida Academy of Sciences, March 2004.

Lazarus, S. M., D. Sharp, P. Blottman and S. Spratt (NWS Melbourne), and Pablo Santos (NWS Miami). *Using satellite data to produce near real-time high resolution analyses and forecasts*. Invited talk at the University of Miami, 31 October 2003.

5. Problems Encountered/General Issues

5.1 Academic Partner

*Because of bandwidth issues associated with the Southern Region server, it was not practical to set-up an 'auto' download of the gridded binary ADAS output files. However because FIT has a parallel version of the ADAS, we were able to fully test the data assimilation cycle 'off-line'. Provided that the MODIS data are available in near-real time, the assimilation of the MODIS temperatures and moisture profiles is operationally feasible.

*The vertical resolution of the MODIS profiles is coarse (20 levels), horizontal variations in temperature and water vapor across the ADAS domain (e.g., compare with the 20 km RUC). Our comparisons and analyses indicate that the adjustments in the background temperature and moisture profiles might be better achieved by using horizontal gradient information rather than the retrieved moisture and temperature. Figure 12 shows a GARP generated satellite image that coincides with the previously discussed 14 April 1812 UTC MODIS overpass. 1000 hPa upper air data [temperature (top) and dew point (bottom), ^{o}C] for 12 UTC 14 April 2004 and 00 UTC 15 April 2004 are shown (right and left columns respectively). Also shown, in the middle column, is the RUC 1000 hPa temperature and MODIS 1000 hpa temperature (both ^{o}C). Clearly, although MODIS appears to be 'warm' relative to the RUC analysis, the temperature gradient is comparable (e.g., on the order of 4-5 ^{o}C from JAX to EYW).

*High vertical resolution AIRS retrieved temperature and moisture profiles are now available and may represent a better assimilation option than the MODIS profiles. However, this does not circumvent many of the issues discussed with respect to the MODIS profiles (i.e. timeliness, data quality, etc.).

*Quality control remains an issue concerning the MOD07_L2 data - as it does for all assimilated data. Herein we present a simple standard deviation check, which at times will allow erroneous data to make its way into the analysis. Note however that ADAS has its own QC which, for upper air data, compares the observations against the background field.

*As pointed out in the proposal, a challenge to a real-time assimilation/forecast cycle is the significant size of some of the data streams (e.g., WSR-88D). Albeit available just four times daily, the MODIS data poses similar computational obstacles (introducing thousands of observations within the ADAS domain, e.g. see Fig. 1). There are a number of different ways in which one can 'blend' or assimilate satellite data into ADAS - the simplest (but not necessarily the best) and the one opted for here, assimilates the temperature and vapor profiles (essentially an 'indirect' method because it converts the radiances). A 2D-VAR method that uses gradient information - either in the retrieved profiles or radiances may be a better candidate - in particular because it mitigates the impact of retrieval biases.

5.2 Forecast Partner

* The NWS Melbourne has attempted to routinely acquire the RUC 20 to improve the resolution of the analysis background field. However, due to insufficient bandwidth this effort continues to

fall short. It is believed that having the RUC 20 (instead of the RUC 40) will have a significant positive impact and continues to be pursued.

*The current state of satellite data availability remains an issue (due to processing and shear volume). The SSEC direct broadcast data is not real-time in the context of making it into the Melbourne analysis/forecast cycle - the former of which is run every 15 minutes. Clearly, using the raw radiances may expedite the data end of things - as it does not require additional computations necessary for the retrievals. Obviously, bandwidth issues are a significant limiting factor in getting large volume satellite data into a high resolution analysis system.

6. References

Kalnay, E, 2003: Atmospheric Modeling, Data Assimilation and Predictability. Cambridge University Press, 341 pp.

Sen, Zekai, 1997: Objective Analysis by Cumulative Semivariogram Technique and its application in Turkey. *J. Appl. Meteor.*, 36, 1712-1724.

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

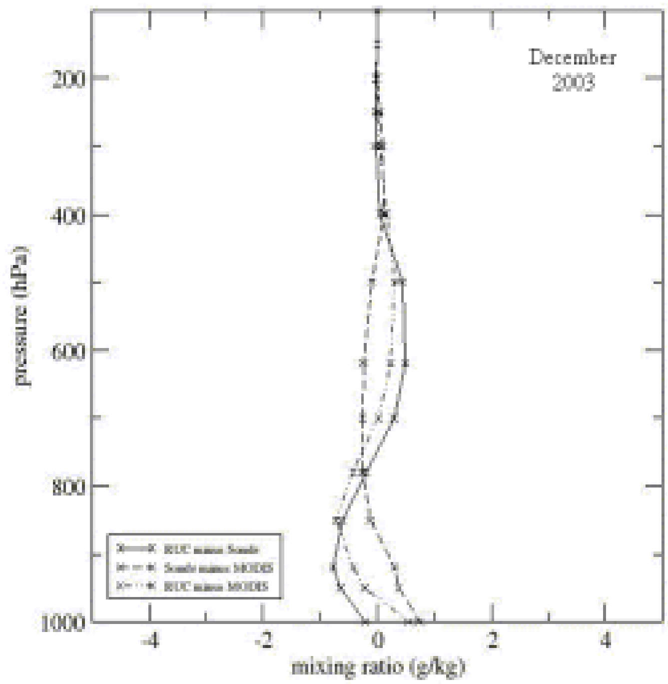

Figure 1: Mixing ratio (g kg^{-1}) bias statistics for December 2003. RUC minus upper air (solid line), upper air minus MODIS (long dash), and RUC minus MODIS (long dash/short dash).

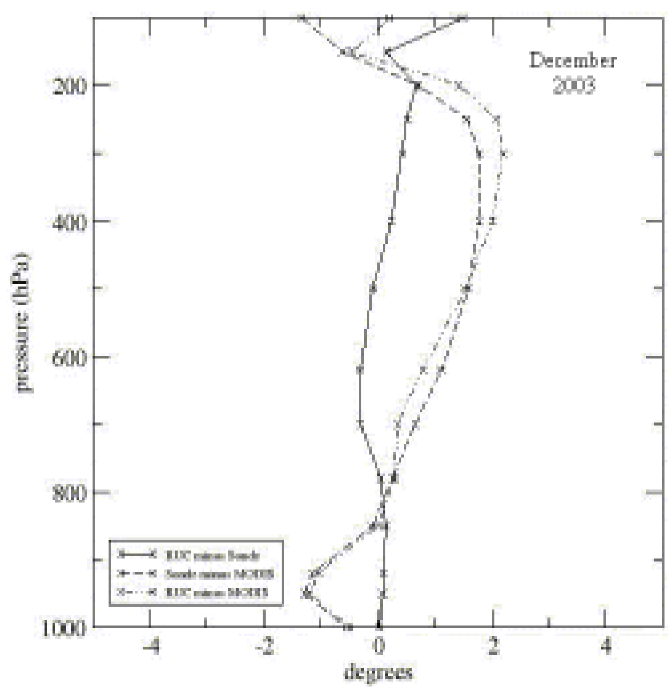

Figure 2: Same as in Fig.1 but for temperature (^{o}C).

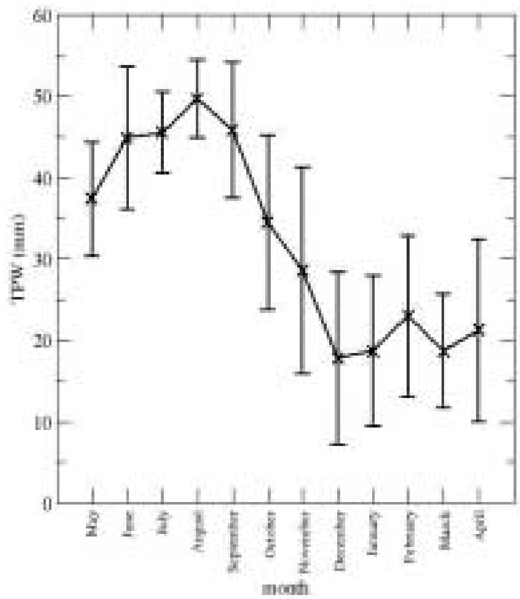

Figure 3: Monthly averaged values of total precipitable water for Melbourne, FL for May 2003 to April 2004) from Suomi-net GPS observations (available at http://www.gpsmet.noaa.gov/jsp/index.jsp).

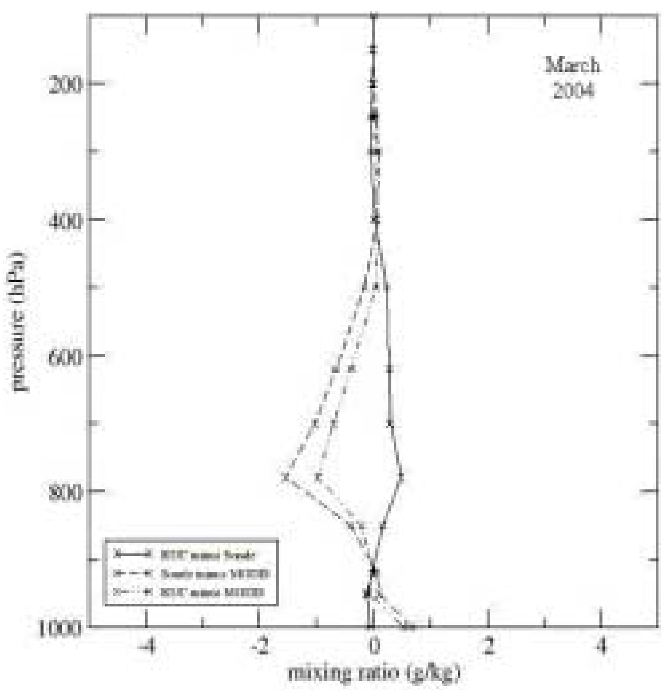

Figure 4: Same as in Fig. 1 but for March 2004.

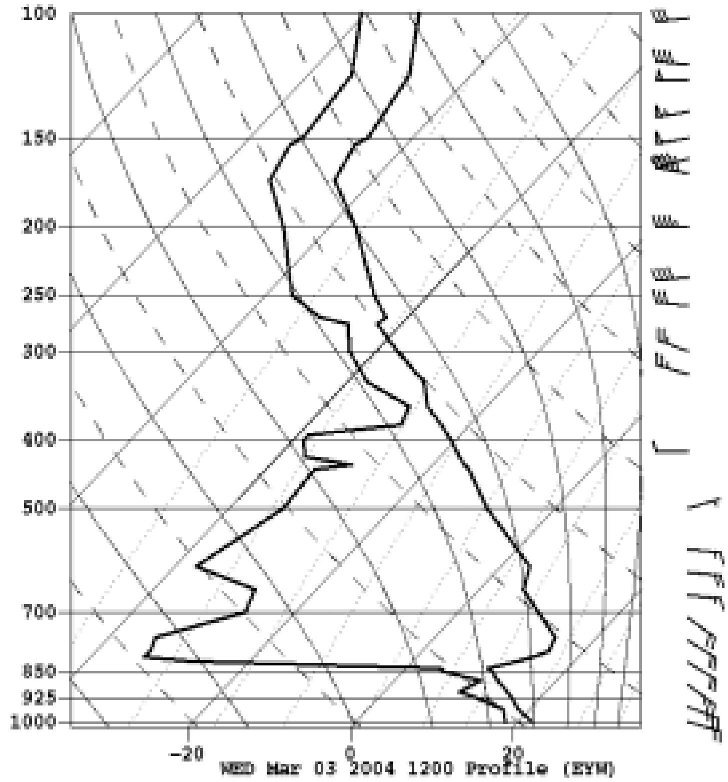

Figure 5: Key West RAOB 12 UTC 3 March 2004. Note significant temperature inversion near 850 hPa.

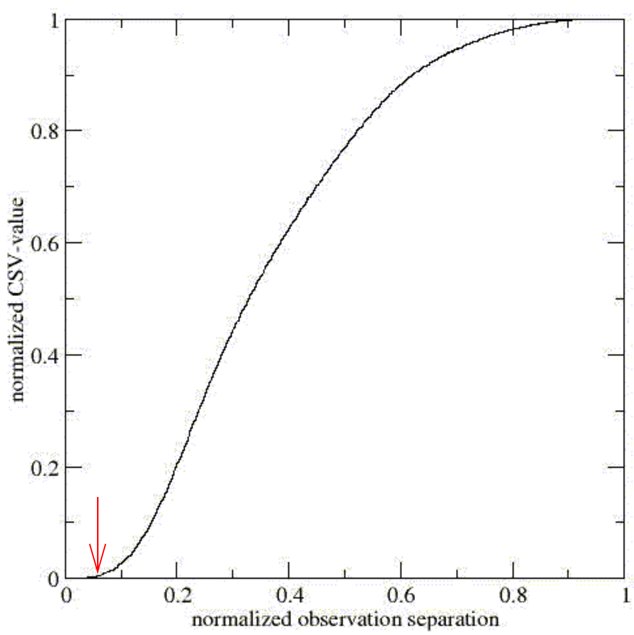

Figure 6: Cumulative variogram for 17 November 2003 1931 GMT MODIS swath. Red arrow indicates an approximate 'thinning' distance for redundant MODIS observations.

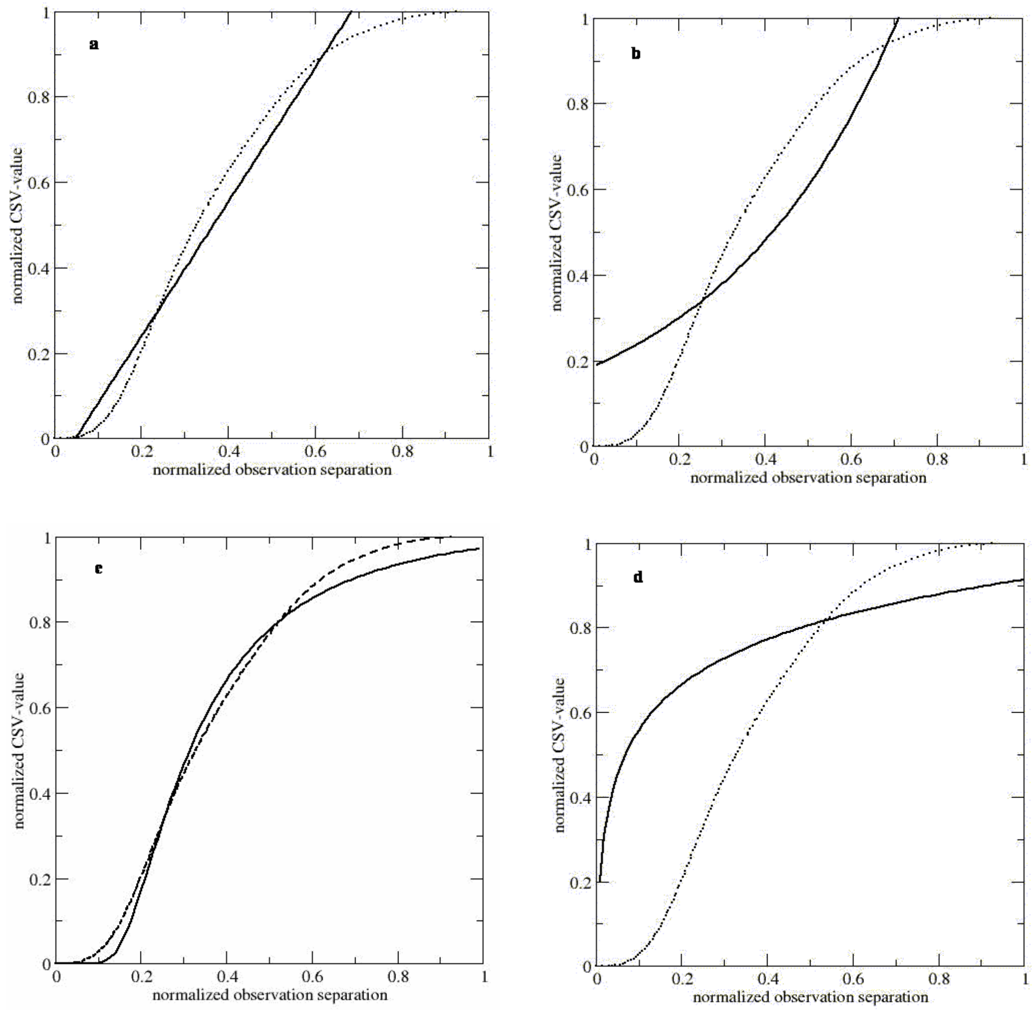

Figure 7: Various curve fits for the cumulative variogram in Fig. 6 including: a.) linear, b.) exponential, c.) Gaussian, and d.) logarithmic.

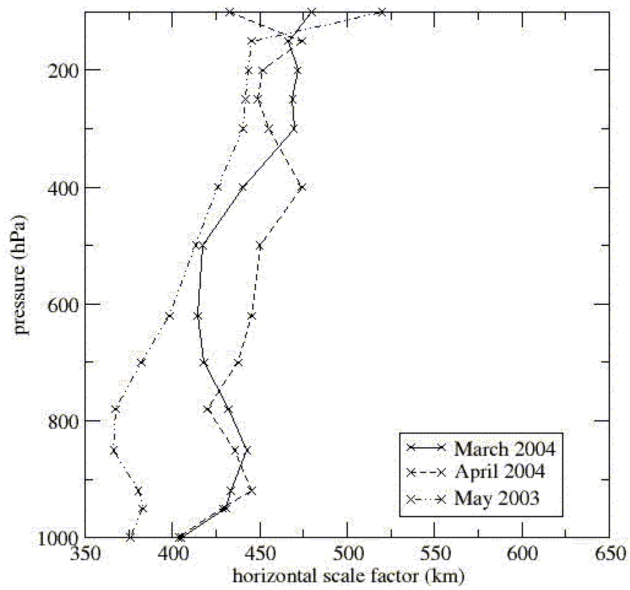

Figure 8: Horizontal temperature scale factor R(z), [from the Gaussian error covariance relation $\rho(d) \sim e^{-d^2/R^2}$] for May 2003, and March/ April 2004. Each of the 14 MODIS pressure levels are shown.

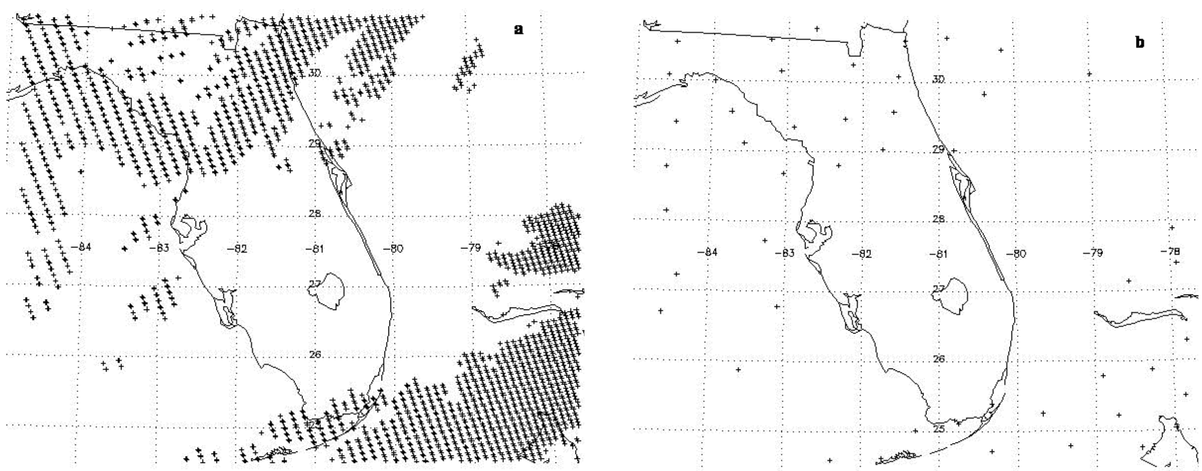

Figure 9: MODIS Observations for 18 January 2004 for the a) full swath and b) thinned swath.

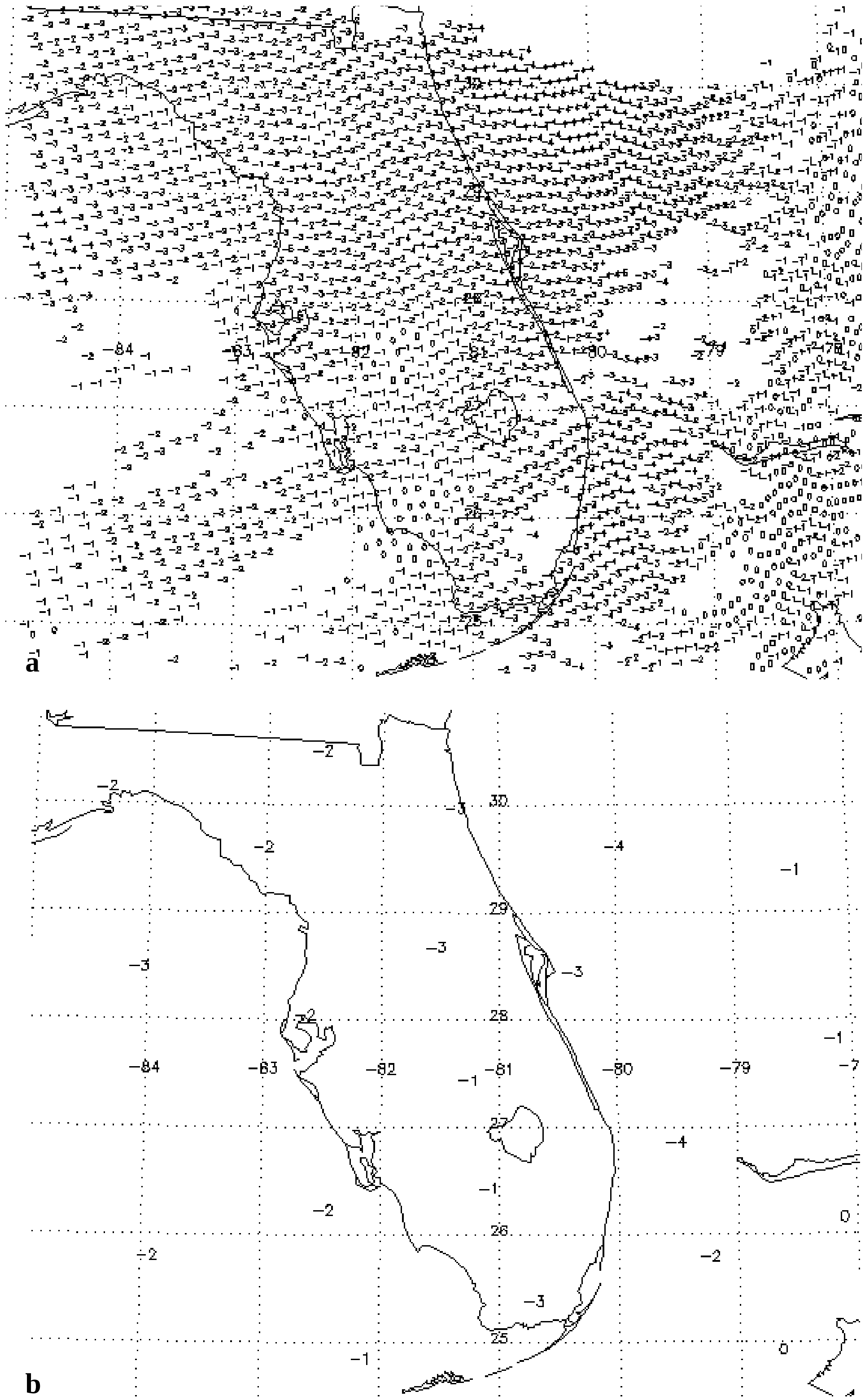

Figure 10: RUC minus MODIS temperature differences (^{o}C) for 1812 UTC 14 April 2004 MODIS swath for a.) all MODIS profiles, and b.) thinned MODIS profiles.

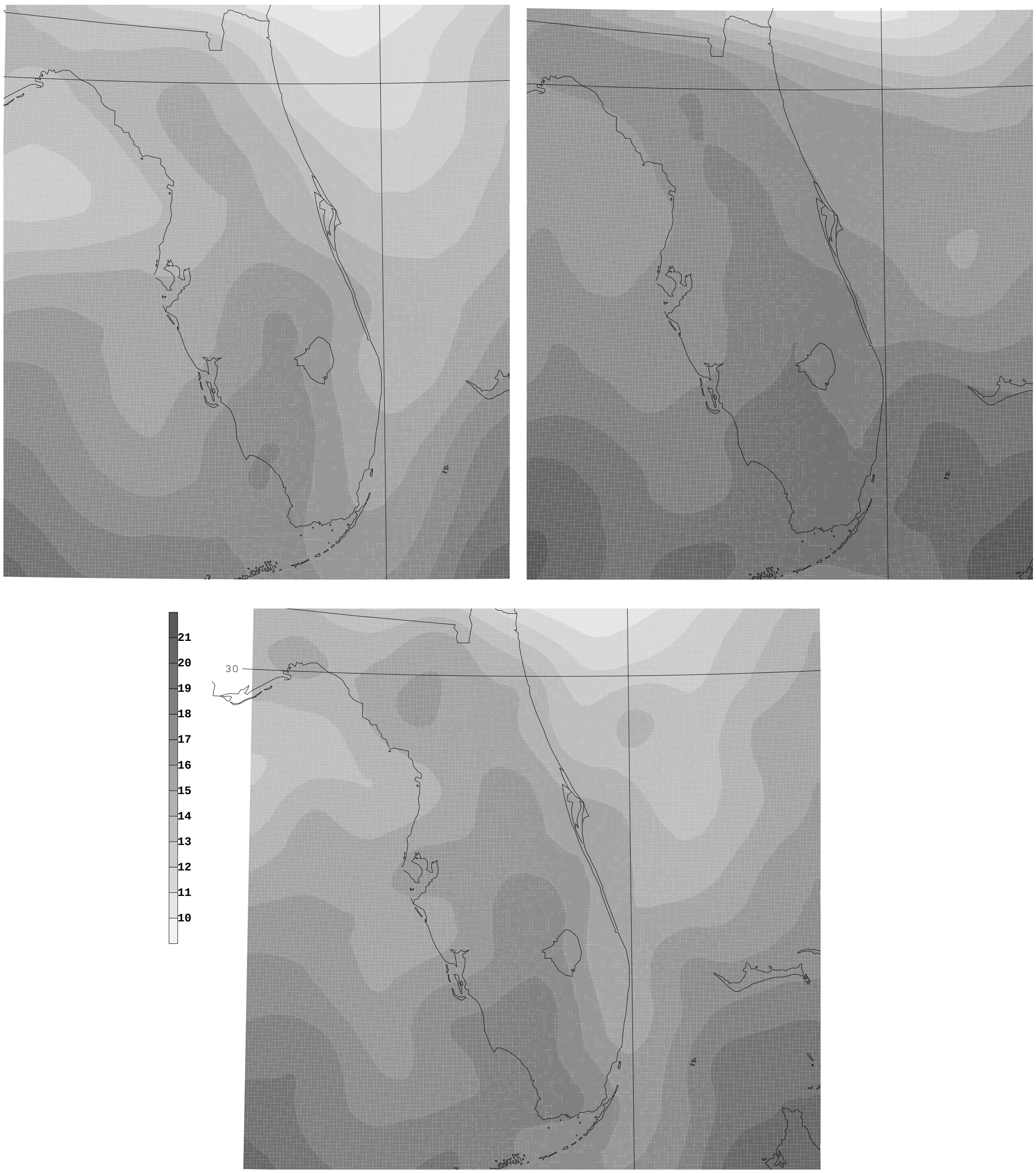

Figure 11: 1000 hPa temperature (^{O}C) for 18 UTC 14 April 2004 for a.) RUC 20, b.) one-pass ADAS analysis using all MODIS data, and c.) one-pass ADAS analysis using thinned MODIS data.

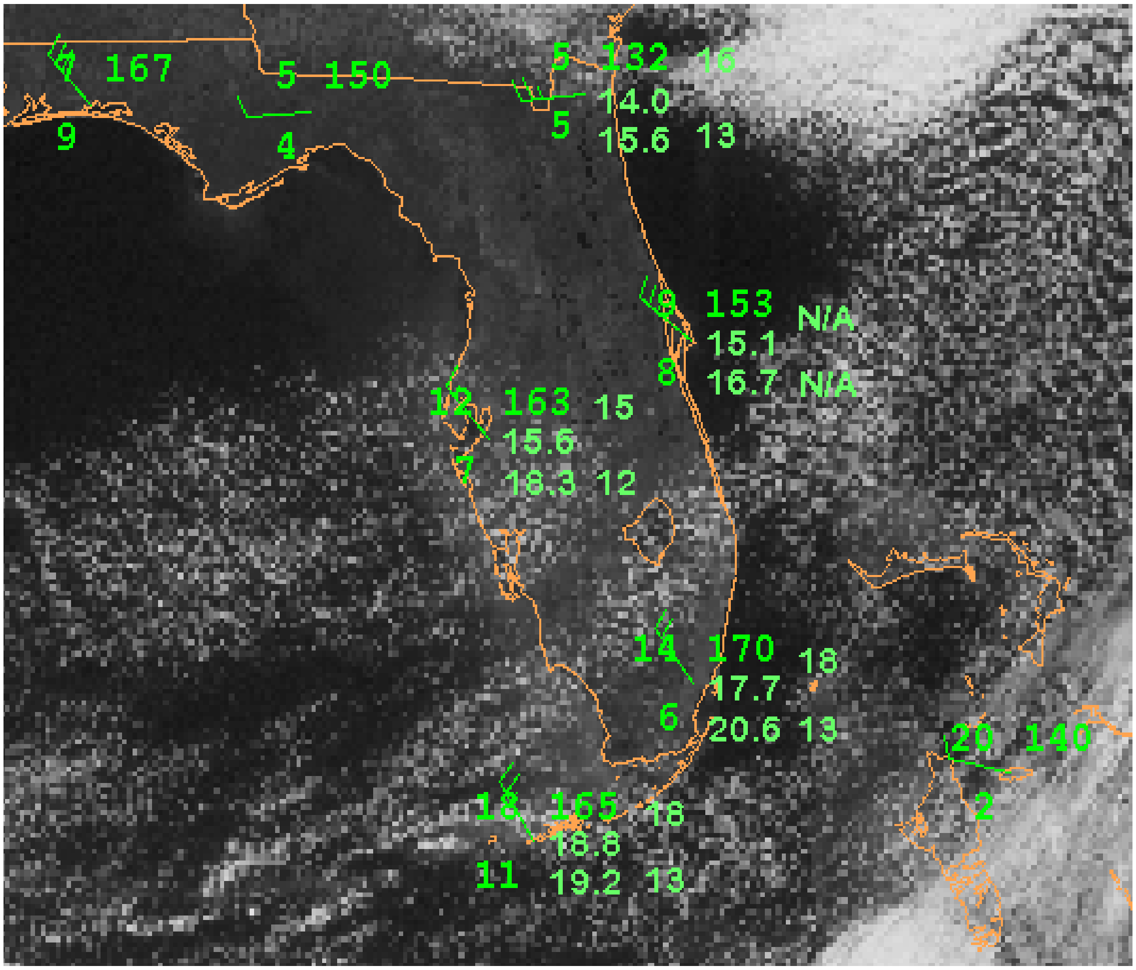

Figure 12: GOES-8 Visible satellite image (1815 GMT 14 April 2004) with radiosonde, MODIS and RUC20 data at 1000 hPa. Station location coincides with the wind barb. The 1000 hPa radiosonde data (for 14 April 2004 1200 GMT) is in the first column on the left (temperature ^{o}C-top, dew point temperature ^{o}C-bottom). The 1000 hPa radiosonde height (in meters) is at the top of the second column. The 1000 hPa RUC20 value is the middle value in the second column, and the 1000 hPa 10-proximity-sounding mean is the bottom value in the second column. The right column contains the 00 UTC radiosonde data at 1000 hPa for temperature ^{o}C (top) and dew point temperature ^{o}C (bottom).