Landsat Atmospheric Correction: The Good, the Bad, and the Ugly

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ABSTRACT

Atmospheric correction of satellite images is a critical image processing step where the influence of the atmosphere is removed or greatly reduced. The top of the atmosphere radiant temperature is usually lower than the surface temperature, but it may be reversed when the atmosphere is warmer than the surface. For many applications, this is not acceptable and requires an atmospheric correction model to account for the atmospheric absorption and emission (primarily from water vapor). Surface water temperatures for four Landsat images are calculated. ERDAS IMAGINE image processing software has an add-on module called ATCOR (ATmospheric CORrection) where atmospheric correction is applied to Landsat images to ensure thermal contrasts within images are due to actual differences in water temperature and not caused by atmospheric effects. The results are compared with in-situ buoy temperatures and differences range from <1 to 5 degrees celsius. The methodology and results of atmospheric correction are discussed.

INTRODUCTION

In the thermal window from 10 to 12 μm, the difference between the surface and top of the atmosphere typically ranges from 1 to 5 K (Prata et al. 1995). For many applications, this is not acceptable and requires an atmospheric correction model to account for the atmospheric absorption and emission (primarily from water vapor). Atmospheric correction of satellite images is an image processing step where the influence of the atmosphere is removed or greatly reduced. In this study, atmospheric correction is applied to each image to ensure thermal contrasts within images are due to actual differences in water temperature and not due to atmospheric effects. ERDAS IMAGINE image processing software has an add-on module for atmospheric correction called ATCOR. ATCOR was developed by Geosystems GmbH for ERDAS and contains two modules: ATCOR2 (atmospheric correction for flat terrain) which is used in this study and ATCOR3 (atmospheric correction for mountainous regions).

IMAGE PROCESSING STEPS

The first step in performing the atmospheric correction is to create a single file of the Landsat 7 ETM+ bands for input to ATCOR2. Band 6 records in the thermal infrared region with two separate sensors (low gain and high gain). Only one thermal band may be included, so the low gain was selected. Sensor input information required by ATCOR2 are image acquisition date, layer band assignment, scale factors, sensor type, pixel size, and calibration file. Atmospheric input includes solar zenith angle, model for solar and thermal region, visibility, and ground elevation. The image acquisition date and layer band assignment input are both straightforward. The output scale factors are used to scale the data for efficient processing and outputting, and the temperature scale factor was set to four with an offset of zero. Therefore, if the output image has a digital number value of 100, the ground temperature equals 25°C. Landsat 7 ETM+ is selected as the sensor type, and the gain-setting specifications for each band are required. These settings are included in each Landsat image metadata file and are dependent on the gain setting strategy for the Landsat 7 Long Term Acquisition Plan. This includes a fixed categorization of surface cover types of the Earth, and gain setting rules that are surface cover and sun angle dependent (Irish 2000). The input setting for bands with low gain setting is 1.0 and high gain is 1.5 with exception of band 6 with high gain of 2.0 (Richter 2002). Each sensor is set according to the region being imaged and the time of year. In the winter images (January and February), the sensor is set to high gain for bands 1-5 and 7 for the study area region. During the summer image dates (September and August), the sensor is set to high gain for bands 1-3, 5 and 7, but low gain for band 4. Pixel size is read from the uncorrected image file, and indicates the spatial resolution (30 meters) of each band. Band 6 is resampled from 60 to 30 meters when the bands are stacked in ERDAS IMAGINE. A calibration file is necessary for converting DN to at-sensor radiance (using equation 1) and includes bias (c_0) and gain (c_1) for the specific image (using Table 1).

The radiance equation in the thermal spectral region can be written as (Kahle et al. 1980; Richter 1994; Gillespie et al. 1998):

$$L_s = L_p + \tau_v \, \varepsilon \, L_{surf} + \tau_v \, (1 - \varepsilon) E_{th} / \pi \qquad (1)$$

where L_s is at-sensor radiance, L_p is thermal path radiance, τ_v is ground-to-sensor atmospheric transmittance, ε is surface emissivity, L_{surf} is blackbody spectral radiance at the ground surface, and E_{th} is thermal downwelling flux on the ground. The surface temperature and radiance relationship is approximated by a second order polynomial fit:

$$T = k_0 + k_1 L_{surf} + k_2 L_{surf}^2 \qquad (2)$$

The polynomial coefficients for the Landsat 7 ETM+ sensor are k_0=210.6 and k_1=0.01 for a temperature range of 270 to 330 K. Three calibration files are created using gain and bias information from the Landsat 7 Science Data User's Handbook (Table 1). The first calibration file is for the winter image date prior to July 2000 (LMINs and LMAXs in Table 1 before sensor bias correction), the second is for image dates after July 2000 during the winter (high gain for bands 1-5 and 7, low gain for band 6), and the third is for image dates after July 2000 during the summer (high gain for bands 1-3, 5 and 7, low gain for bands 4 and 6). Landsat data are in units of $Wm^{-2}\ sr^{-1}\ \mu m^{-1}$and are converted to ATCOR2 data units of $mW\ cm^{-2}\ sr^{-1}\ \mu m^{-1}$.

Table 1 Landsat ETM+ spectral radiance for each band at digital numbers 0 or 1 and 255 ($W\ m^{-2}\ sr^{-1}\ \mu m^{-1}$).

Band Number	Before July 1, 2000				After July 1, 2000			
	Low Gain		High Gain		Low Gain		High Gain	
	LMIN	LMAX	LMIN	LMAX	LMIN	LMAX	LMIN	LMAX
1	-6.2	297.5	-6.2	194.3	-6.2	293.7	-6.2	191.6
2	-6.0	303.4	-6.0	202.4	-6.4	300.9	-6.4	196.5
3	-4.5	235.5	-4.5	158.6	-5.0	234.4	-5.0	152.9
4	-4.5	235.0	-4.5	157.5	-5.1	241.1	-5.1	157.4
5	-1.0	47.70	-1.0	31.76	-1.0	47.57	-1.0	31.06
6	0.0	17.04	3.2	12.65	0.0	17.04	3.2	12.65
7	-0.35	16.60	-0.35	10.932	-0.35	16.54	-0.35	10.80
8	-5.0	244.00	-5.0	158.40	-4.7	243.1	-4.7	158.3

Source: Landsat 7 Science Data Users Handbook (Irish 2000).

Solar zenith angle is calculated in ATCOR2, but this information is also provided in the Landsat image metadata. The model for solar region was set to U.S. standard maritime, and ATCOR2 provides six atmospheric models defined in Appendix A. An atmospheric model that is most similar to rawinsonde conditions during the image acquisition time is selected for each image (mid-latitude winter for January and February and mid-latitude summer/tropical for September and August). Visibility is set to fifteen kilometers since meteorological data indicate very clear conditions in the study area during all image dates (University of Delaware 2005, NOAA 2005a).

The SPECTRA module component of ATCOR2 allows the user to determine an appropriate atmosphere and visibility and to verify the calibration file without having to process the entire image. The atmospheric correction is run for selected pixels that in this case represent in-situ buoy locations (NOAA 2005b) to verify ATCOR2's resultant temperature estimates. Buoy locations (Figure 1) are plotted on the Landsat image, and the locations are selected as target areas.

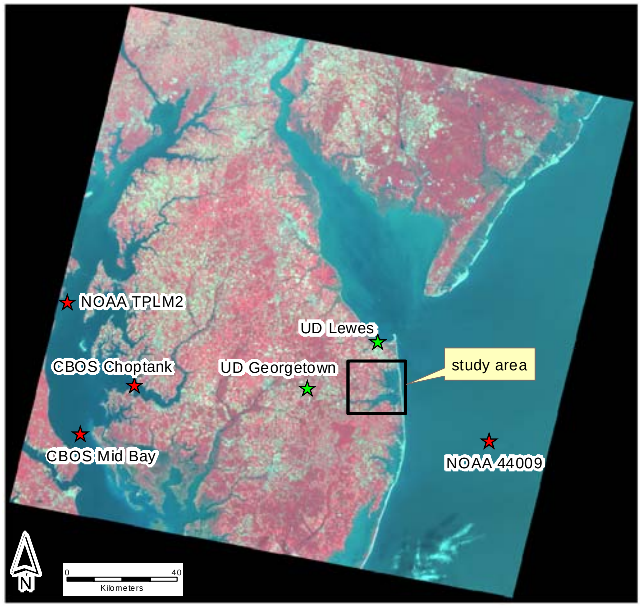

Figure 1 Location of buoys (red) and weather stations (green) maintained by the National Oceanic and Atmospheric Administration (NOAA), Chesapeake Bay Observing System (CBOS), and the University of Delaware (UD) on a Landsat winter image false color composite.

Selecting a target area in ERDAS IMAGINE will display temperature in °C when a thermal band is available. The initial image run in the SPECTRA module is the February winter image using the logical, physical-based choice of an atmospheric model given the rawinsonde temperature and humidity profiles. However, the temperatures are much further off from the corresponding in-situ temperatures than initial uncorrected temperatures previously calculated. As a result, the atmospheric conditions occurring during each image acquisition date are re-evaluated, and each thermal region model is run for all four Landsat images to determine the sensitivity of ATCOR2's various atmospheres to the resultant derived surface water temperature in each image (Table 2). ATCOR2's atmospheric models and results of this sensitivity test are then compared to actual atmospheric conditions estimated from rawinsonde stations.

Table 2 ATCOR2 thermal region model results (°C) for Landsat images.

1/29/2000				
region	**44009 (3.5)**	**TPLM2 (-0.7)**	**Mid Bay (0.4)**	**Choptank (*)**
dry desert	-1.3	-7.1	-6.1	-11.1
fall	8.1	4.0	4.7	1.2
midlat summer	2.3	-3.7	-2.7	-7.8
midlat winter	8.8	4.8	5.5	2.1
tropical	-7.4	-16.0	-14.5	-21.9
US standard	7.6	3.3	3.9	0.4

9/12/2001				
region	**44009 (24.0°C)**	**TPLM2 (*)**	**Mid Bay (25.4°C)**	**Choptank (25.9°C)**
dry desert	22.5	23.7	23.7	24.4
fall	25.1	26.0	26.0	26.5
midlat summer	26.5	27.7	27.7	28.4
midlat winter	25.2	26.1	26.1	26.6
tropical	26.4	28.2	28.2	29.1
US standard	25.3	26.3	26.2	26.8

2/19/2002				
region	**44009 (7.8°C)**	**TPLM2 (4.9°C)**	**Mid Bay (5.2°C)**	**Choptank (5.4°C)**
dry desert	0.4	*	-3.3	-3.6
fall	9.3	*	6.6	6.4
midlat summer	4.0	*	0.1	-0.1
midlat winter	9.9	*	7.3	7.2
tropical	-4.9	*	-10.4	-10.8
US standard	8.8	*	6.0	5.8

8/14/2002				
region	**44009 (24.6°C)**	**TPLM2 (26.8°C)**	**Mid Bay (27.1°C)**	**Choptank (29.8°C)**
dry desert	22.1	25.5	25.6	26.4
fall	24.8	27.6	27.4	28.0
midlat summer	26.1	29.5	29.6	30.5
midlat winter	25.0	27.4	27.5	28.1
tropical	26.0	30.6	30.7	31.9
US standard	25.0	27.6	27.7	28.3

* data not available

ATMOSPHERIC DATA

The three nearest rawinsonde stations (NOAA 2001a) are located at Aberdeen, MD, Sterling, VA, and Wallops Island, VA (Figure 2). Although two rawinsonde stations are located outside the Landsat image boundary, they represent the larger scale atmospheric conditions influencing the study area based on their spatial location to the northwest, west, and south of the study area. A radiosonde is a balloon-borne instrument platform with radio transmitting capabilities and contains sensors capable of measuring direct in-situ profiles of air temperature, humidity and pressure with height. A rawinsonde (or radio wind sonde) is a radiosonde package with radio-direction finding equipment to determine wind direction and wind speed at various altitudes.

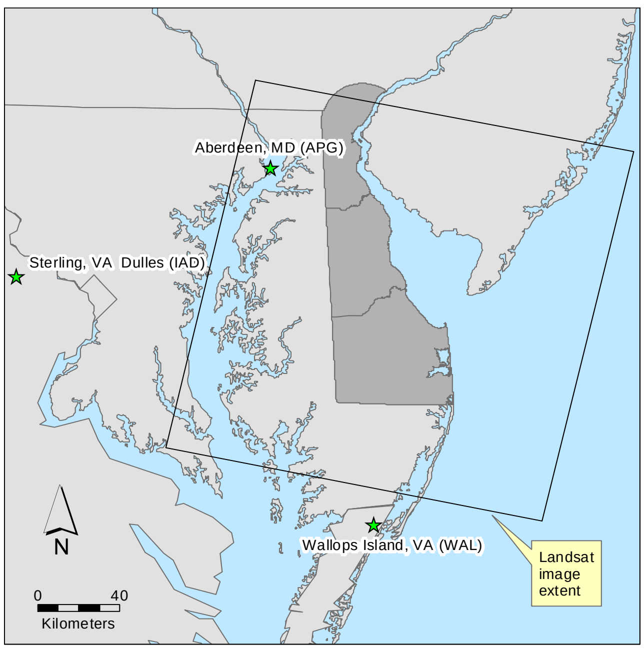

Figure 2 Location of rawindsonde stations maintained by the National Oceanic and Atmospheric Administration.

Rawinsonde data are downloaded (NOAA 2001a) for these three stations at 12:00 UTC (7:00 AM local time) on the morning of the Landsat image acquisition day (Appendix B). The atmospheric data are used to define the temperature and humidity profiles and to calculate total precipitable water vapor (PWV). PWV defines the total amount of water vapor in the atmospheric column above a point on the earth's surface or in a specific atmospheric layer (Robinson and Henderson-Sellers 1999) and given (in kilograms per unit area) by:

$$\mathrm{PWV} = 1/g \int_{surface}^{TOA} q\,dp \qquad (3)$$

where *g* is the acceleration due to gravity, *q* is the specific humidity and *dp* is the change in pressure levels.

Weather conditions on January 29, 2000 are very cold with clear skies. The surface winds are from the northwest with low humidity levels recorded throughout the entire atmosphere. Total precipitable water at Sterling is 0.34 g cm^{-2} and at Wallops Island is 0.35 g cm^{-2} with temperatures ranging from -8°C at the surface to -21 and -24°C at 500 mb at Sterling and Wallops Island, respectively. Surface observations in Georgetown, Delaware (University of Delaware 2005) at closer proximity (15 miles) to the study area are similar. Of the ATCOR2 atmospheric models, none resemble the actual atmospheric conditions on this day. The ATCOR2 mid-latitude winter model makes the most physical sense in terms of temperature profile on January 29, 2000, but the PWV in the actual atmosphere is two times drier than in the model. ATCOR2's mid-latitude winter atmosphere result in derived surface temperatures 5.5°C too warm in comparison to in-situ buoy temperatures. Surface water temperature values that are calculated without atmospheric correction are within 1.0°C of in-situ buoy temperatures. Water vapor is the main atmospheric absorber in the thermal infrared (10.4 to 12.5 μm) region of the electromagnetic spectrum and little to no atmospheric water vapor is present on this day, so atmospheric correction is deemed unnecessary.

Similar conditions occur on February 19, 2002, when surface temperature at 10:30 AM EST is 7°C in Georgetown, Delaware with winds from the south. Total precipitable water is quite variable at three rawinsonde locations (0.46 g cm^{-2} Aberdeen, 0.83 g cm^{-2} Sterling, 1.7 g cm^{-2} Wallops). An analysis of daily weather maps (NOAA 2002) reveals a high pressure system centered over the North and South Carolina coast with east winds at Wallops Island drawing in Atlantic moisture causing higher humidity levels versus Aberdeen and Sterling influenced by more continental air. The rawinsonde data indicate a temperature inversion from the surface to the 850-700 mb level. Winds are from the northwest at mid and upper levels in the atmosphere at both Aberdeen and Sterling rawinsonde locations, and winds are out of the northwest at Wallops Island. As with the January image, the ATCOR2 model atmospheres do not resemble actual atmospheric conditions indicated at the three rawinsonde locations. Atmospheric correction is therefore deemed unnecessary for the February image since there are clear skies, low humidity levels and temperature values derived from the image are within 0.5°C of in-situ temperature values.

On September 12, 2001, a strong high pressure system is located over the mid-Atlantic region with its center over southern Pennsylvania and northern West Virginia (NOAA 2001b). Surface winds are from the north to northeast at Georgetown, Delaware. The rawinsonde data from Aberdeen indicate winds at all levels from the northwest and north to northwest winds at Sterling. Total precipitable water is 1.75 g cm^{-2} at Aberdeen and 2.22 g cm^{-2} at Sterling, with no data available at Wallops Island. As with the winter images, the actual atmospheric conditions in the summer images do not match well with ATCOR2 model atmospheres. The rawinsonde data indicate warmer temperatures and higher humidity at lower levels with very dry and cold conditions at mid-levels. The fall and mid-latitude summer atmospheres are the closest to the actual atmospheric conditions and result in an overestimate of the derived surface water temperatures of 0.6 to 1.1°C and 2.3 to 2.5°C, respectively. The overestimated temperature values from ATCOR2 are closer to in-situ temperatures than the original underestimated temperatures without atmospheric correction. Given this and higher amounts of water vapor in the atmosphere, atmospheric correction is deemed necessary for the September 12, 2001 image.

The atmospheric conditions on August 14, 2002 indicate winds from the southwest at Aberdeen and Sterling with total precipitable water ranging from 3.8 to 4.4 g cm^{-2} at all three rawinsonde stations which closely matches the ATCOR2 tropical atmosphere (4.1 g cm^{-2}). However, moisture levels in the upper atmosphere are much drier than the ATCOR2 tropical atmosphere and closely resemble the ATCOR2 fall atmosphere. ATCOR2 fall atmosphere resulted in overestimated temperatures to within 1°C of in-situ temperature values, with the exception of the Choptank buoy (1.8°C underestimated temperature value compared to the buoy temperature). ATCOR2 tropical atmosphere resulted in temperatures ranging from 1.4 to 3.8°C higher than in-situ temperature values. As in the September image, the overestimated ATCOR2 temperatures in the August image are closer to actual buoy temperature measurements than the original uncorrected satellite derived temperature values.

VALIDATION OF ATMOSPHERIC CORRECTION

One of the basic assumptions in deriving surface water temperatures from satellite data is that the atmosphere does not vary significantly across the region of study. This is evaluated by examining the difference between image-derived surface water temperatures at each buoy pair location. For example, the difference in water temperature between Buoy 44009 and Mid Bay buoy locations without atmospheric correction and with two atmospheric correction models (fall and mid-latitude winter) result in the same range of temperatures at 2.6 to 2.7 ºC. Comparison of Buoy 44009 and Choptank buoy (difference of 2.4 to 2.9ºC) and Mid-Bay and Choptank buoy (0.1 to 0.2ºC) water temperatures show consistent values between no atmosphere and two atmospheric correction models. This supports the assumption that atmospheric conditions are fairly constant across the Landsat image.

A sensitivity test is also conducted to evaluate the effect of the atmospheric correction model on the derived surface water temperatures and to determine if identified thermal contrasts (signals) are above the level of uncertainty introduced by the choice of an atmospheric profile. No atmospheric correction, the fall ATCOR2 atmosphere and the mid-latitude winter ATCOR2 atmosphere were selected as end members of the possible range in atmospheric conditions on both winter image acquisition dates (with a colder and dry model atmosphere to a warmer and more moist model atmosphere). Both ATCOR2 atmospheres best match actual atmospheric conditions in terms of total precipitable water and temperature. Two small areas are selected in the study area that represent the warmest and coldest derived surface water temperatures and the difference (ΔT) is calculated for each atmospheric condition. The change in surface water temperature between these two areas is within 0.4°C for the no atmospheric correction and the two atmospheric models. This value is within the range of uncertainty in the derived surface water temperature (°C) and illustrates that the selection of a model atmosphere is not contributing enough noise to suppress the signal of spatial changes in surface water temperature.

SUMMARY

Landsat Atmospheric Correction: The Good

On days with extremely low humidity, Landsat 7 thermal bands appear to provide very accurate estimates of surface water temperatures without atmospheric correction. For this particular set of Landsat images, atmospheric correction is not necessary for two winter images with cold, clear conditions and low humidity levels throughout the atmosphere.

Landsat Atmospheric Correction: The Bad

Atmospheric correction is necessary for two summer images with warm temperatures and humid conditions at lower levels of the atmosphere. Although atmospherically corrected temperatures are closer to in-situ buoy water temperatures, the amount of error is still considered unacceptable for this application. ATCOR2 is limited in use due to the constraint of having only six pre-defined atmospheres to perform atmospheric correction, particularly when atmospheric conditions are so variable.

Landsat Atmospheric Correction: The Ugly

An atmospheric correction algorithm that allows user input of local radiosonde data, such as MODTRAN, would be ideal, working within the framework of an image processing system. Access to this type of program was not available during the time of this research. Creating an atmospheric correction algorithm was not possible due to limited time, funding and programming knowledge.

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APPENDIX A

Table A.1 Profiles of standard atmospheres in ATCOR2.

Dry atmosphere

altitude (km)	pressure (mbar)	temperature (°C)	relative humidity (%)
0	1013	26.4	8
1	904	20.4	7
2	805	14.4	7
3	715	10.4	5
4	633	3.8	4
5	559	-3.0	4

Total water vapor content = 0.41 (g cm^{-2})

Mid-latitude winter atmosphere

altitude (km)	pressure (mbar)	temperature (°C)	relative humidity (%)
0	1017	-1.0	77
1	897	-4.5	70
2	789	-8.0	65
3	694	-11.5	57
4	608	-17.5	50
5	531	-23.5	47

Total water vapor content = 0.85 (g cm^{-2})

Fall (autumn) atmosphere

altitude (km)	pressure (mbar)	temperature (°C)	relative humidity (%)
0	1013	10.0	56
1	902	3.0	47
2	802	-1.0	41
3	710	-5.0	40
4	628	-9.0	40
5	554	-14.0	40

Total water vapor content = 1.14 (g cm^{-2})

1976 US Standard atmosphere

altitude (km)	pressure (mbar)	temperature (°C)	relative humidity (%)
0	1013	15.0	46
1	900	8.5	49
2	795	2.0	52
3	701	-4.5	51
4	616	-11.0	50
5	540	-17.5	48

Total water vapor content = 1.42 (g cm^{-2})

Mid-latitude summer atmosphere

altitude (km)	pressure (mbar)	temperature (°C)	relative humidity (%)
0	1013	21.0	76
1	902	16.5	66
2	802	12.0	55
3	710	6.0	45
4	628	0.0	39
5	554	-6.0	31

Total water vapor content = 2.92 (g cm^{-2})

Tropical atmosphere

altitude (km)	pressure (mbar)	temperature (°C)	relative humidity (%)
0	1013	26.4	75
1	904	20.4	73
2	805	14.4	74
3	715	10.4	48
4	633	3.8	35
5	559	-3.0	38

Total water vapor content = 4.11 (g cm^{-2})

Source: Richter 2002

APPENDIX B

Table B.1 Rawinsonde data on January 29, 2000 at 12 GMT.

Atmospheric profile from Aberdeen, MD
no data

Atmospheric profile from Sterling, VA

altitude (km)	pressure (mbar)	temperature (°C)	relative humidity (%)
0.1	1025	-7.9	67
1.1	902	-3.1	36
2.0	798	-4.9	2
3.1	700	-7.3	9
4.1	613	-12.9	4
5.1	539	-21.1	6

Total precipitable water vapor content = 0.34 (g cm^{-2})

Atmospheric profile from Wallops Island, VA

altitude (km)	pressure (mbar)	temperature (°C)	relative humidity (%)
0.0	1034	-7.1	45
0.9	921	-5.5	58
2.0	796	-4.9	2
3.1	700	-5.3	2
3.3	677	-6.7	2
5.6	500	-23.9	2

Total precipitable water vapor content = 0.35 (g cm^{-2})

Source: NOAA 2001a

Table B.2 Rawinsonde data on September 12, 2001 at 12 GMT.

Atmospheric profile from Aberdeen, MD

altitude (km)	pressure (mbar)	temperature (°C)	relative humidity (%)
0.01	1023	18.4	64
0.9	918	14.6	51
1.9	820	10.8	6
3.2	700	5.2	17
4.1	620	0.0	14
5.8	500	-11.7	13

Total precipitable water vapor content = 1.75 (g cm^{-2})

Atmospheric profile from Sterling, VA

altitude (km)	pressure (mbar)	temperature (°C)	relative humidity (%)
0.09	1014	10.2	97
0.9	925	14.6	67
2.0	807	11.4	35
3.0	715	5.0	24
4.3	609	0.0	15
5.9	500	-11.9	19

Total precipitable water vapor content = 2.22 (g cm^{-2})

Atmospheric profile from Wallops Island, VA
no data

Source: NOAA 2001a

Table B.3 Rawinsonde data on February 19, 2002 at 12 GMT.

Atmospheric profile from Aberdeen, MD

altitude (km)	pressure (mbar)	temperature (°C)	relative humidity (%)
0.01	1026	-6.1	96
1.0	903	1.8	18
2.1	789	0.0	13
3.1	700	-4.5	18
4.1	616	-10.1	21
5.0	543	-16.5	38

Total precipitable water vapor content = 0.46 (g cm^{-2})

Atmospheric profile from Sterling, VA

altitude (km)	pressure (mbar)	temperature (°C)	relative humidity (%)
0.09	1016	-8.9	89
1.0	912	5.6	7
2.4	759	-1.3	20
3.1	700	-3.5	3
3.9	627	-8.3	44
5.7	500	-20.1	40

Total precipitable water vapor content = 0.83 (g cm^{-2})

Atmospheric profile from Wallops Island, VA

altitude (km)	pressure (mbar)	temperature (°C)	relative humidity (%)
0.01	1026	-2.5	87
0.9	925	2.2	21
1.5	850	2.8	21
3.1	700	-4.3	21
3.9	633	-8.3	24
5.0	548	-16.1	50

Total precipitable water vapor content = 1.7 (g cm^{-2})

Source: NOAA 2001a

Table B.4 Rawinsonde data on August 14, 2002 at 12 GMT.

Atmospheric profile from Aberdeen, MD

altitude (km)	pressure (mbar)	temperature (°C)	relative humidity (%)
0.005	1017	24.0	87
0.8	925	26.6	34
1.9	816	16.0	59
3.0	718	8.0	57
3.9	643	1.4	64
4.4	597	0.0	7

Total precipitable water vapor content = 3.8 (g cm^{-2})

Atmospheric profile from Sterling, VA

altitude (km)	pressure (mbar)	temperature (°C)	relative humidity (%)
0.09	1008	21.6	77
0.8	925	26.6	39
1.6	850	19.8	56
3.1	711	7.4	77
3.9	641	4.0	8
4.6	593	0.0	6

Total precipitable water vapor content = 3.7 (g cm^{-2})

Atmospheric profile from Wallops Island, VA

altitude (km)	pressure (mbar)	temperature (°C)	relative humidity (%)
0.01	1019	23.2	83
1.0	906	23.2	57
2.2	789	13.6	90
3.2	700	7.4	61
3.9	642	4.8	33
4.8	576	1.2	7

Total precipitable water vapor content = 4.43 (g cm^{-2})

Source: NOAA 2001a