Improving the Characterization of Pollution Transported into Texas Using OMI and TES Satellte and *In Situ* data and HYSPLIT Back Trajectory Analyses

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Abstract

Utilizing Tropospheric Emission Spectrometer (TES) and Ozone Monitoring Instrument (OMI) and *in situ* data for ozone (O_3) and nitrogen dioxide (NO_2) and Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT), we assess whether air parcels exhibiting enhanced ozone in the lower troposphere above Texas have moved locally (*i.e.*, within Texas) or remotely (*i.e.*, outside of Texas). We focus on TES dates that provide observations of high O_3, over Texas's lower troposphere – specifically: August 5th-7th, 2006, July 22nd, 2006, July 6th-8th, 2006, August 23rd, 2006, August 23rd, 2006, July 31st-August 2nd, 4th, 6th, 2005, and June 21st, 2009. Four day back trajectory analyses of all dates show that upper-, mid-, and lower-tropospheric air over Texas (*i.e.*, air at 12, 10, 9, 7, 5, 3, 1, 0.5, and 0.1 km), containing high O_3, as shown by TES, is transported from the Gulf of Mexico, Southeast USA, Midwest USA, Northeast USA, the Atlantic Ocean, Pacific Ocean, Mexico, etc., in almost all cases. The only exception is air at 1 km on July 22nd, 2006, which shows that air at this altitude originated within Texas. Often the back trajectories started in the lower troposphere over East Texas originate over the Southeastern USA. TES shows O_3 enhancements in the lower troposphere and OMI show O_3 and NO_2 enhancements via tropospheric column profiles (O_3 between 45 and 50 ppbv; $NO_2 \geq 5.5$ molecules cm^{-2}). These enhancements complement the HYSPLIT four day trajectory analyses, which gives further indication that they are governed by transport from remote sources. Dates with co-located satellite and *in situ* data (*e.g.*, August 2nd, 2005) further suggest that there could be utility in combining satellite and *in situ* data and modeling tools in doing work for developing State Implementation Plans (SIPs) for compliance with Environmental Protection Agency (EPA) and the Texas Commission on Environmental Quality (TCEQ) air quality (AQ) standards.

Introduction and Motivation

Numerous studies have revealed that air quality (AQ), like climate change, is not just a local, but also a regional and global issue that recognizes no political boundaries (Wotawa and Trainer, 2000; Colarco et al., 2004), a fact that presents challenges for international relations and for state agencies trying to develop effective State Implementation Plans (SIPs) to come into compliance with Environmental Protection Agency (EPA) and the Texas Commission on Environmental Quality (TCEQ) air quality (AQ) standards. Insights into the regional and global nature of AQ are greatly assisted by the current generation of satellite instruments; for example, Fishman et al. (2008)s stress the importance of AQ issues in design of future space-based observation platforms. Furthermore, chronic exposure to poor air quality is associated with elevated health risks (McConnell et al., 2002; Bell et al., 2004) and negative impacts on crop yields (Chameides et al., 1999).

Over the past several decades, there has been significant urban growth in various areas of Texas, such as Houston. Analogous to other cities in Texas, Houston now supports a population base that results in significant auto emissions and regularly suffers from some of the highest ozone (O_3) concentrations in the United States (Morris et al., 2009). A variety of factors contribute to Houston's O_3 pollution. It is the 4th largest urban population in the U.S., much of wich commutes from remote suburbs, resulting in broad NO_x ($NO + NO_2$) throughout the Hostoun-Galveston-Brazoria Region (HGBR). Houston contains of the largest petrochemical production sectors in the world, frequently producing co-located, concentrated hydrocarbon (HC) and NO_x emissions; this is also compounded by the fact that HC reactivities in the Houston ship channel area are 2-5 times higher than those over other U.S. urban locations (Kleinman et al., 2002; Daum et al., 2003). In addition, the Parish power plant in Thompsons, TX is one of the top 5 emitters of CO_2 in the U.S. (http://www.cgdev.org/) and produces more than 5300 tons/year of NO_x (http://www.tceq.state.tx.us/cgi-bin/compliance/monops/site_photo.pl). Widespread forests in East Texas are a source of biogenic volatile organic compounds (VOCs). Also, persistent high pressure and fair weather during summer and a location near Galveston Bay and the Gulf of Mexico frequently lead to stagnant air over the HGBR and/or recirculation of pollution via a land-sea breeze circulation (Banta et al., 2005) Lastly, long-range transport of O_3 and precursors from remote locations can exacerbate local pollution levels (Pierce et al., 2009).

The transport of pollution from remote sources into the state of Texas has been shown in several studies, including two using satellite data (Pierce et al. 2009, McMillan et al., 2010). The McMillan et al. (2010) study illustrated the transport of carbon monoxide (CO) from fires in the Pacific Northwest into the Houston area using data from the Atmospheric Infrared Sounder (AIRS) and results from the Realtime Air Modeling System (RAQMS) chemical transport model. The Pierce et al. (2009) study also used RAQMS and data from instruments on the Aura satellite to illustrate effects on ozone production in Dallas and Houston of pollution generated in the upper Midwest. This report presents a complementary study by using both Tropospheric Emission Spectrometer (TES) and Ozone Monitoring Instrument (OMI) satellite and *in situ* data for ozone (O_3) and nitrogen dioxide (NO_2) and Hybrid Single Particle Lagrangian Integrated

Trajectory Model (HYSPLIT) analyses to estimate the source of enhanced tropospheric ozone events in Texas from 2005 through 2009.

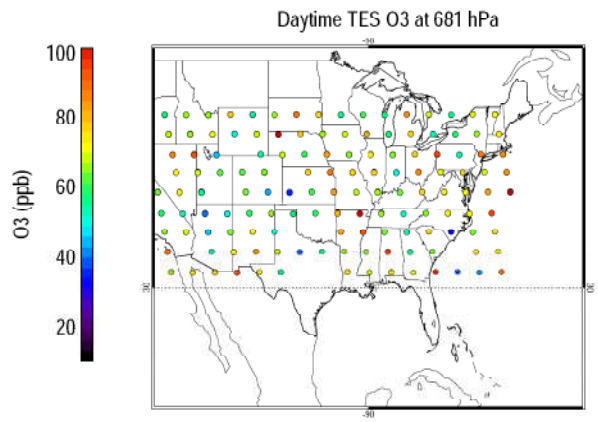

Figure 1: TES daytime observations of ozone over North America during a 16 day repeat cycle in August 2006. Nighttime O_3 coverage is similar for the TES global **survey.**

TES Measurements

TES is a Fourier Transform Spectrometer that was launched on the Earth Observing System Aura satellite on July 15, 2004 [Beer et al., 2001]. TES provides global profiles of O_3, CO, as well as $H_2O_{(v)}$, HDO, and temperature among others. **Figure 1** shows an example of the spatial pattern of TES 'Global Survey' (GS) measurements for a 16 day repeat cycle in August 2006. TES GS measurements are made every other day, providing profile measurements for over 3000 locations over the globe in about 27 hours. The latitudinal coverage of TES has been modified over the course of the mission; currently global survey data are collected from 50N to 30S to preserve lifetime. Since September 2004, the continental United States has been regularly sampled by TES GS observations. Individual profiles from TES GS observations are spaced approximately 180 km apart, but they provide both daytime and nighttime observations with coverage across North America and coastal oceans. During science and validation campaign periods, TES is capable of taking observations with better spatial resolution made over smaller geographic regions. These special observations (SO) provide profiles spaced about 45 km apart, primarily during the daytime. In the Spring/Summer 2006 and the summers of 2007 and 2008, extensive TES SO campaigns were carried out over North America. During February-March 2006, nighttime special observations were taken as well.

TES can typically distinguish two vertical layers in the troposphere for ozone, and CO measurements are sensitive to one layer in the troposphere, centered at about 600mb. Typical averaging kernels for both daytime and nighttime ozone observations from TES are shown in **Figure 2**. The TES averaging kernel provides a means of quantifying the sensitivity of the TES measurement to ozone in the atmosphere. Detailed discussion of TES averaging kernels can be found in Worden et al, [2007] or in the TES Data User's Guide [Osterman et al, 2009]. The averaging kernels in **Figure 2** show TES sensitivity in the lower troposphere for both observations, with some sensitivity in the free troposphere during the day. If enough ozone is present or if thermal contrast is good, TES can resolve upper and lower tropospheric ozone. The TES ozone observations have been validated against numerous data sources [Boxe et al, 2010; Nassar et al, 2008; Richards et al, 2008; Osterman et al, 2009]. The ozone profiles show a positive bias of 3-10 ppbv for the TES v002 data [Nassar et al, 2008]. Ozone retrievals from more recent TES data versions has been shown to be largely consistent with v002. Over the Northern hemisphere, the region of focus for this study, the bias is usually at a maximum near 200mb. This bias is

persistent over time, and should not impact the spatial analysis. We will have to account for the bias when making comparisons to model runs and other remote sensing measurements. An example of TES ozone as a function of latitude from a TES special observation is shown in **Figure 3**. This "curtain" plot shows a broad area of enhanced ozone in the middle/upper troposphere over Texas and the Gulf of Mexico and a smaller area over east Texas in the lower troposphere. TES data can provide information on these broad (in latitude) ozone features such as that seen in **Figure 3**. As mentioned above, the vertical sensitivity of TES is good enough to often resolve broad "layers" in the troposphere like the upper and lower tropospheric features seen in **Figure 3**.

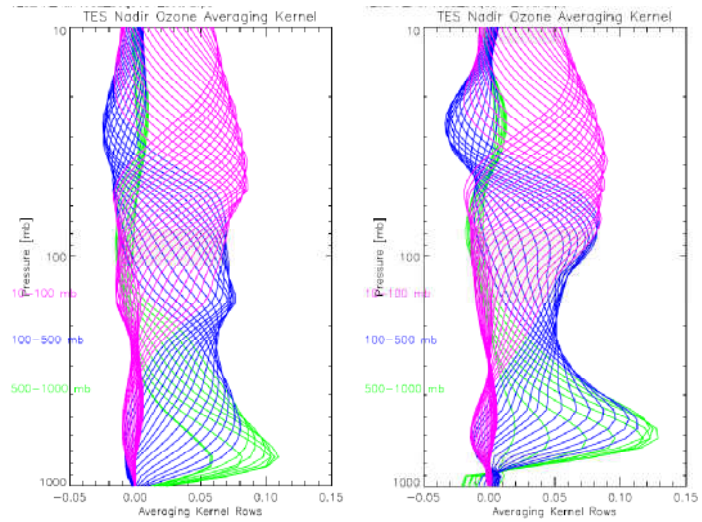

Figure 2: A plot of TES averaging kernels for daytime (left) and nighttime (right) observations showing instrument sensitivity to ozone over the United States.

All versions of the TES O_3 data (*i.e.*, V001, V002, V003, V004) have been validated in recent studies (Worden et al., 2007; Nassar et al., 2008; Boxe et al., 2010). **Figure 4** shows the TES-sonde ozone percent and absolute differences relative to sondes (for TES V004) from 2005-2008 for the entire state of Texas. **Figure 4 (a)** and **(b)** shows that the mean difference or bias is between 5 and 10% in the troposphere and stratosphere, and the absolute differences are zero from the surface to the upper troposphere and less than 0.25 ppbv in the upper troposphere-to-lower stratosphere. Hence, the TES data are valid to use within the context of this report.

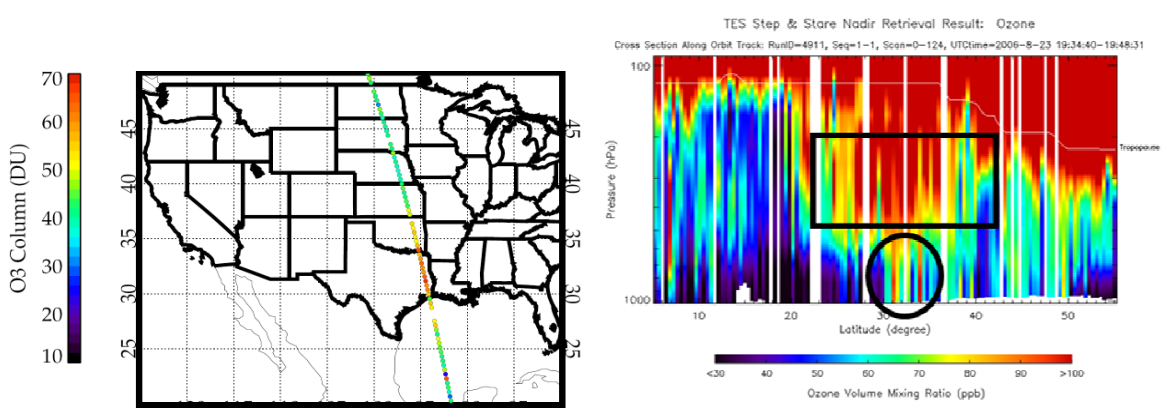

Figure 3: TES curtain plot showing high ozone in the middle/upper troposphere and in the lower troposphere over East Texas in August 2006. Map shows location of TES observations and the tropospheric ozone column measured by TES.

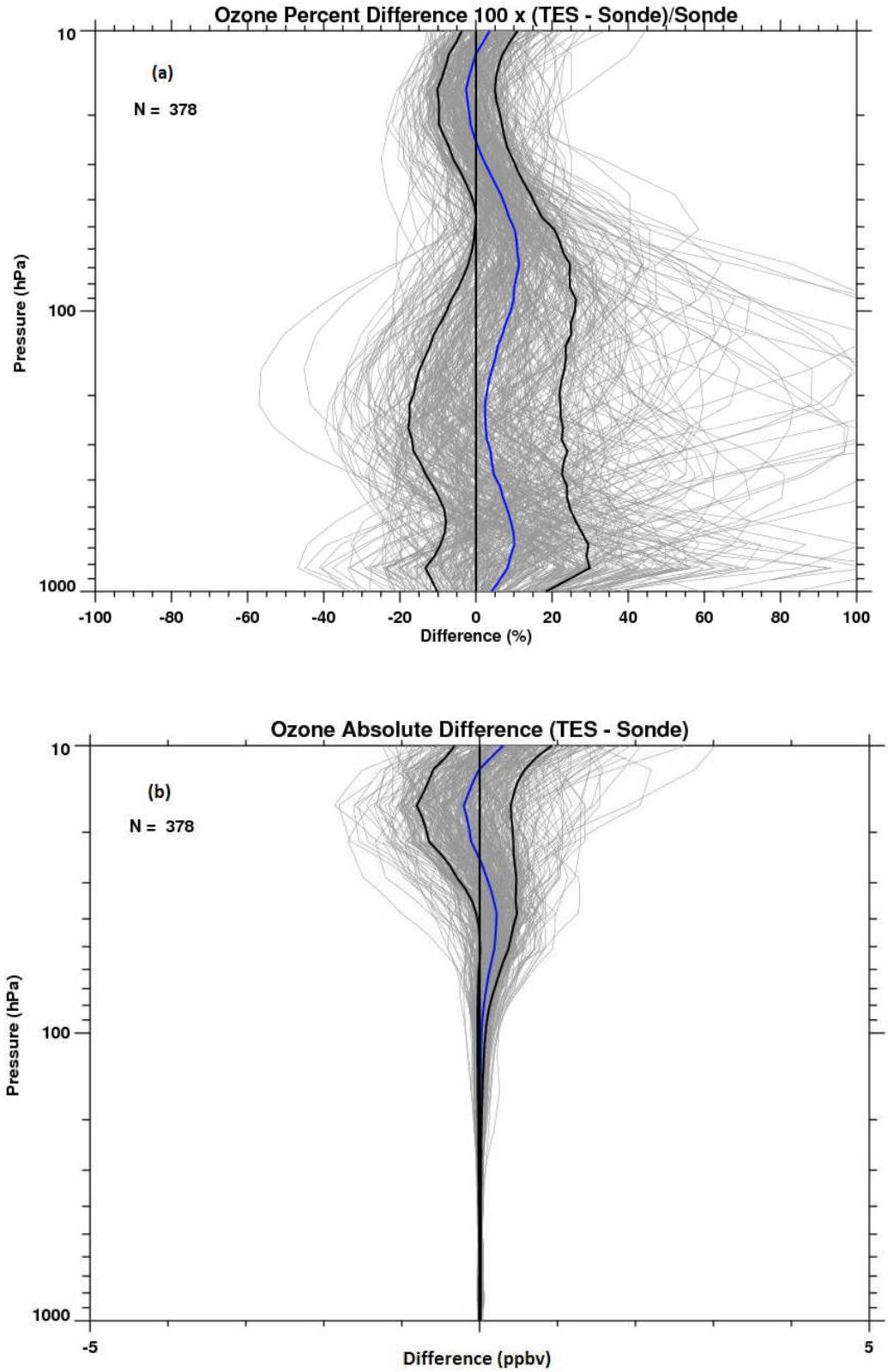

Figure 4. TES-sonde ozone percent differences **(a)** and absolute differences **(b)** (for TES version 4) for the four seasons (months abbreviated in parentheses) in the northern

midlatitudes (35 to 56° N). Individual profiles are shown in gray, mean are overlaid in dark blue.. Mean minus one standard deviation and mean plus one standard deviation ranges are overlaid in black. The number of coincident comparisons is "n." This Figure illustrates comparisons using TES version 4.

Similar to TES, OMI is one of out a total of four instruments onboard the Aura spacecraft, which is flown in sun-synchronous polar orbit at 705 km altitude with a 98.2^o inclination. Aura has an equatorial crossing time of 01:45 p.m. (ascending node) with around 98.8 min per orbit (14.6 orbits per day on average). OMI has a footprint of 13 × 24 km at nadir, while TES has a footprint of 5 × 8 km at nadir. OMI is a nadir-scanning instrument that at visible (350-500 nm) and UV wavelength channels (UV-1: 270-314 nm; UV-2: 306-308 nm) detects backscattered solar radiance to measure column ozone with near global coverage (aside from polar night latitudes) over the Earth. Aside from ozone, OMI can also determine cloud-top pressure, aerosols and aerosol parameters, NO_2, SO_2, and other trace constituents in the troposphere and stratosphere (Levelt et al., 2006). Total ozone from OMI is derived from the TOMS version 8 algorithm. OMI tropospheric NO_2 columns (Bucsela et al., 2006) are obtained from the NASA Goddard Earth Sciences Distributed Active Archive Center.

Methodology

Our goal with this project was to examine the TES data record for evidence of high ozone and carbon monoxide in the middle and/or lower troposphere over Texas and Southeastern United States. We looked at the TES data during time periods suggested by TCEQ, though we also looked at TES data from other dates. The test dates were as follows: study were: August 5th-7th, 2006, July 22nd, 2006, July 6th-8th, 2006, August 23rd, 2006, August 23rd, 2006, July 31st-August 2nd, 4th, 6th, 2005, and June 21st, 2009. We look in depth at July 6, 2006, July 22, 2006 and August 4, 2005. We provide a more general discussion of the 2005. TES O_3 data and trajectory analyses of other dates are included in the appendix.

Using the TES data for ozone as a starting point, we then examined the back trajectories of the air observed by TES. We used the Hysplit online model to perform these trajectories (http://ready.arl.noaa.gov/HYSPLIT_traj.php). The Hysplit model can give an idea of the history of the air parcel observed by TES. We focused primarily on cases where TES suggested enhanced ozone in the lower troposphere, but also examined cases with high mid-tropospheric ozone.

TES satellite data has limited by spatial coverage and it has poor sensitivity to trace gases at low altitudes (*e.g.*, boundary layer) or during cloudy conditions (*i.e.*, high optical depth scenarios). We cannot provide observations illustrating the high free tropospheric ozone observed by TES being entrained into the boundary layer. We attempt to show that there are many times where reservoirs of enhanced lower/middle tropospheric ozone sitting over or to the east of Texas. While this analysis is fairly unsophisticated in its approach, we hope that it provides an idea of the nature and frequency of transport of ozone into the free troposphere above Texas and leads to further work in this area. Assimilation of TES data into chemical transport models such as GEOS-Chem would be a possible tool to use satellite data and models together to further study these types of events.

Many locations, throughout the year, frequently exceeded EPA's eight-hour ozone concentration of 75 ppbv. For example, in 2005, 2006, 2007, 2008, and 2009, Texas had 1450, 1300, 530, 350, and 370, respectively, locations that experienced ozone concentrations ranging from 76 to 126 ppbv. During this timeframe, Texas experienced 80 to 120 days/year where O_3 exceeded the EPA limit for exposure (http://www.tceq.state.tx.us/cgi-bin/compliance/monops/site_photo.pl). Follow up work on this project could involve trying to work on regional project taking satellite data and working with ground based measurements of boundary layer characteristics and ground based air quality measurements (perhaps from the 2006 Texas Air Quality Study II).

Results and Discussion

July 6, 2006

On July 6, TES had just begun taking a series of special observations in support of the Texas Air Quality Study II. This particular "Step & Stare" (SS) observation obtained measurements over the Gulf of Mexico, just to the east of Beaumont, through East Texas (including over Longview) and up into Oklahoma and Kansas (**Figure 5 (a) and (b)**). The measurements were made in the afternoon (19:40 UTC). The TES data for that date shows enhanced levels of ozone and carbon monoxide in the lower troposphere for the observations over the Texas and the Central US (Figure 5). It also shows a broad swath of high ozone in the middle/upper troposphere between 20-55 N latitude.

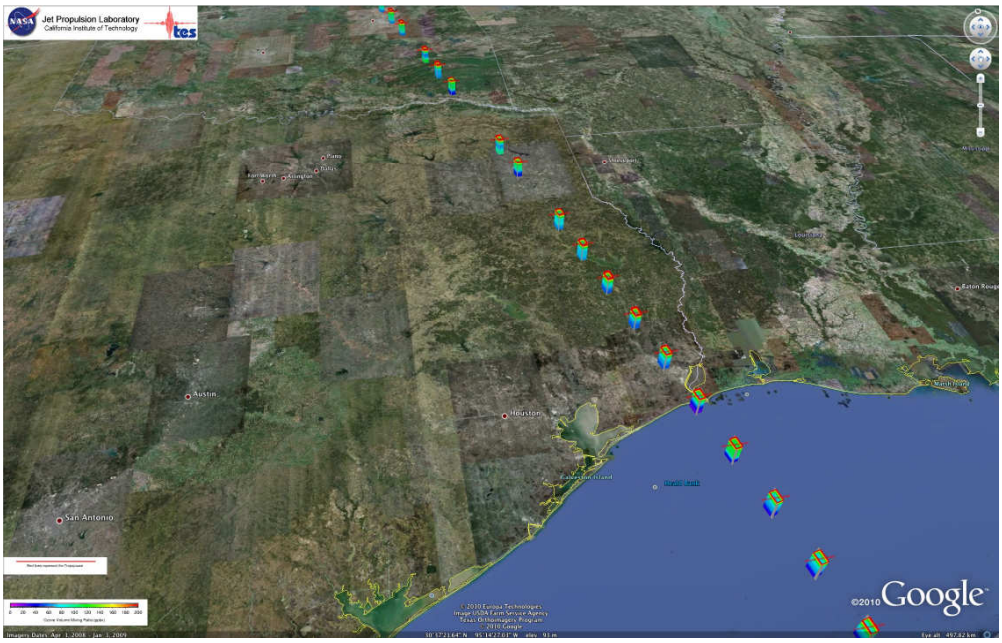

Figure 5: (a) Google Earth image of TES ozone measured on July 6, 2006. The columns show the location of the TES measurements.

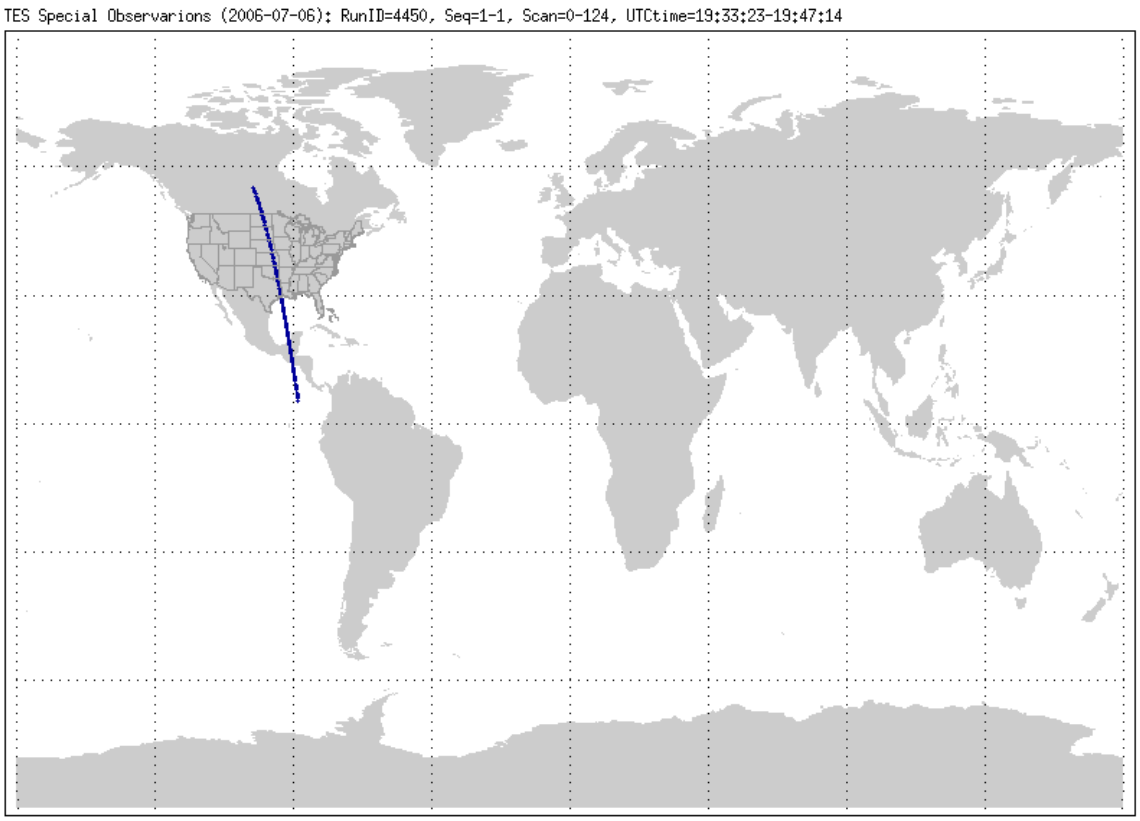

Figure 5 (b). TES geolocation track for July 6th, 2006.

As mentioned earlier, the TES data often has enough vertical resolution to resolve lower troposphere ozone from that in the upper troposphere. The averaging kernels from these TES retrievals suggest sensitivity peaks in the lower troposphere (near 700 hPa) with another peak in the middle troposphere. Images from the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on the Aqua satellite suggests broken

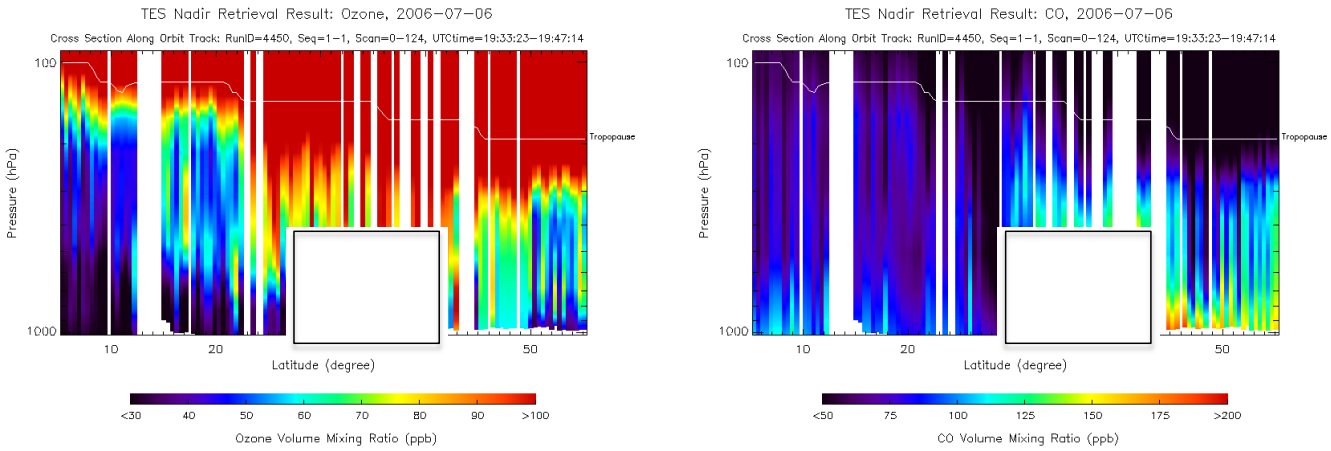

Figure 6: Curtain plot of ozone and carbon monoxide measured by TES on July 6, 2006. It shows a broad swath of enhanced middle/upper tropospheric ozone (between 20-55 N latitude). It also shows enhanced ozone and carbon monoxide in the lower troposphere over Texas and the Central US.

clouds in the observing locations though all internal TES quality flags suggest most of the profiles are of good quality. The clouds are heavier over the Gulf of Mexico and some of the lack of ozone seen in **Figure 6** over the Gulf could be due to the influence of clouds (TES would only measure to the top of the cloud if it is thick and fills the field of view).

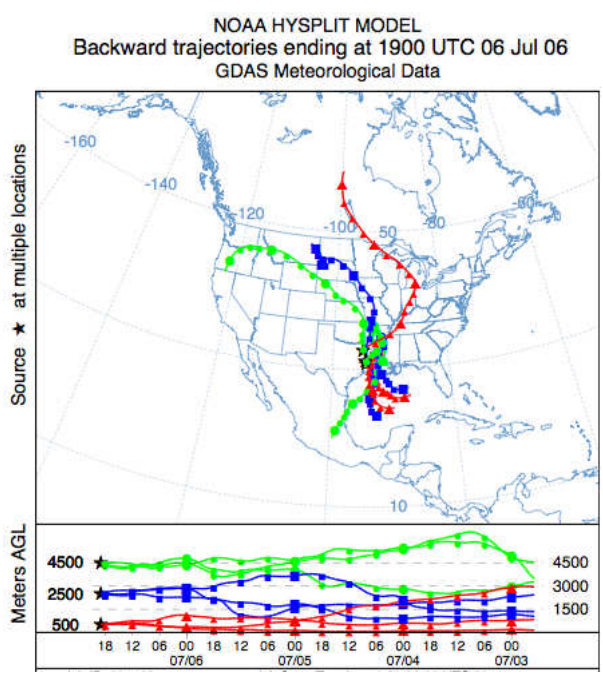

Figure 6 (a): Hysplit back trajectories for July 6, 2006 intitiated at three locations in East Texas.

We ran a series of back trajectories for July 6 to examine the history of the air parcels observed. Hysplit trajectories calculated from Houston show back trajectories taking the air over the Gulf and toward the SE US (not shown). The back trajectories initiated from the location of three TES footprints are shown in **Figure 6 (a) and (b)**. The four-day back trajectories started at three altitudes (0.5, 2.5 and 4.5 km) seem to show that the observations over SE Texas are measuring air that had been over the Gulf 2-4 days earlier. They do not suggest much vertical movement of the parcels. The trajectory started over Longview suggests that the highest values of lower tropospheric ozone (NE Texas) are seen in air parcels that originated over the central US at for the higher altitudes and tracing back to the Midwest/Great Lakes area for the near surface trajectory. **Figure (b)** shows a four day back trajectory analysis, starting at 0.1, 0.5, and 1 km. Again, it is clearly shown that high ozone measured over NE Texas is from remote sources.

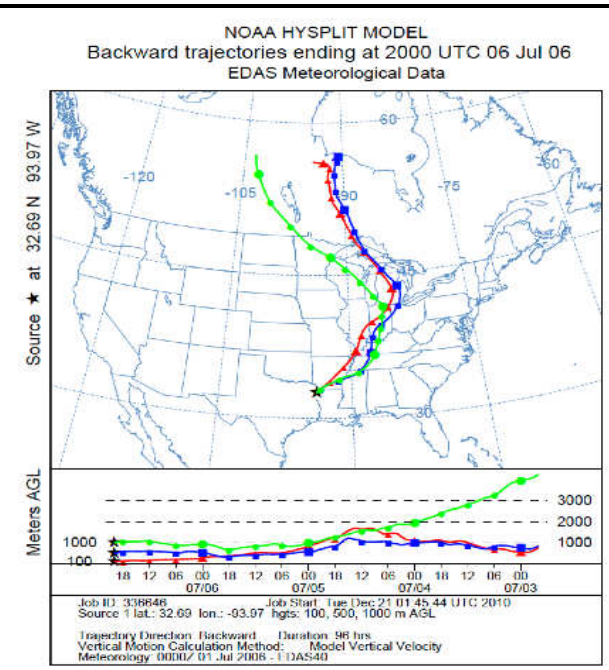

Figure 6 (b). Four day back trajectory, starting at 1, 0.5, and 0.1 km on July 6th, 2006, over NE Texas, at 33 °N latitude (at ~ -93.97 °Longitude).

TES data from global surveys on July 3-4 and July 5-6 (not shown) suggest there are high levels of middle tropospheric ozone over the Midwestern US and to a lesser

degree over the Southeastern US. The ozone measured over the Gulf of Mexico is on the order of 50-60 ppbv.

All other sites on July 6th, 2006 in Texas measured NO_2 at concentrations less than 46 ppbv (http://www.tceq.state.tx.us/cgi-bin/compliance/monops/site_photo.pl). The **Figure 7** displays tropospheric column measurement of NO_2 on July 22nd, 2006 from the Ozone Monitoring Instrument (OMI), which shows enhancements of NO_2 (*i.e.*, $\geq 5.5 \times 10^{15}$ molecules cm^{-2}) for the mid-to-eastern part of Texas. These enhancements encompass the latitude and longitude coordinates that also measured high O_3 greater than ~ 80 ppbv. On this day, no site in Texas made measurements exceeding the EPA standard limit for ozone exposure. Still, no *in situ* measurement site exist in the region, where TES measures high O_3 over Texas. Given the fact that TES O_3 and OMI NO_2 show enhancements in the lower troposphere, the satellite data complements the HYSPLIT four day back trajectory analyses, showing that such enhancements are governed by transport from remote sources.

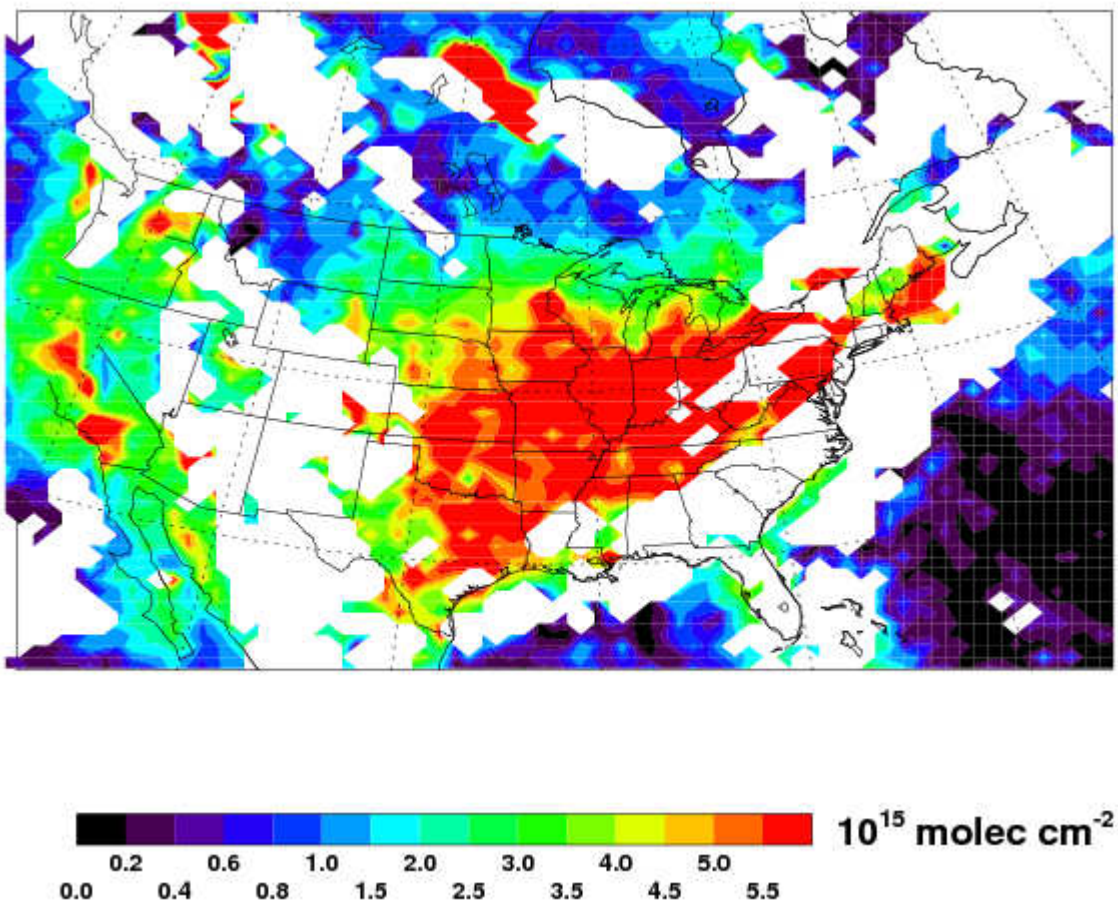

Figure 7. OMI NO_2 column measurement for July 6th, 2006.

July 22, 2006

The results for the July 22, 2006, the same TES SS track provide a very similar picture to that of July 6 (**Figures 8, 9, 10, and 11 (a)-(d)**). The area of high middle tropospheric ozone is not as broad in latitude as it on the 6th, but the trajectories suggest similar air parcels observed by TES originate from outside the state.

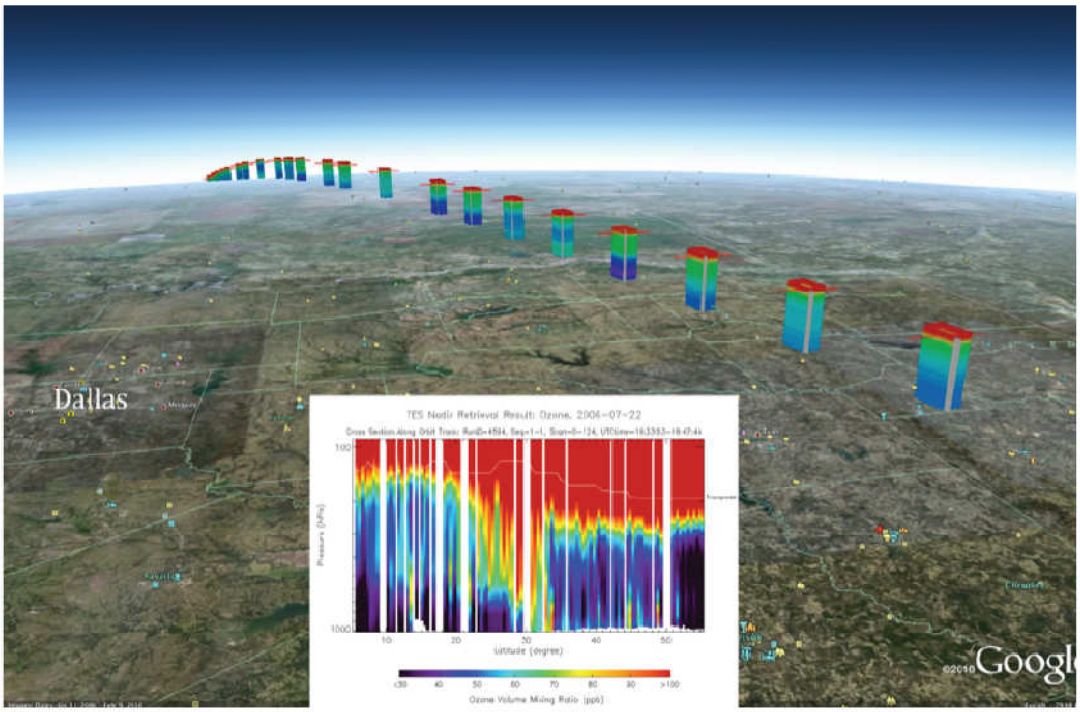

Figure 8. TES visualization of ozone at the border of Texas, Louisiana, Arkansas, and Oklahoma. Note, given TES's ~ 6 km vertical resolution, TES O_3 surface concentrations represent concentrations within a broad tropospheric layer.

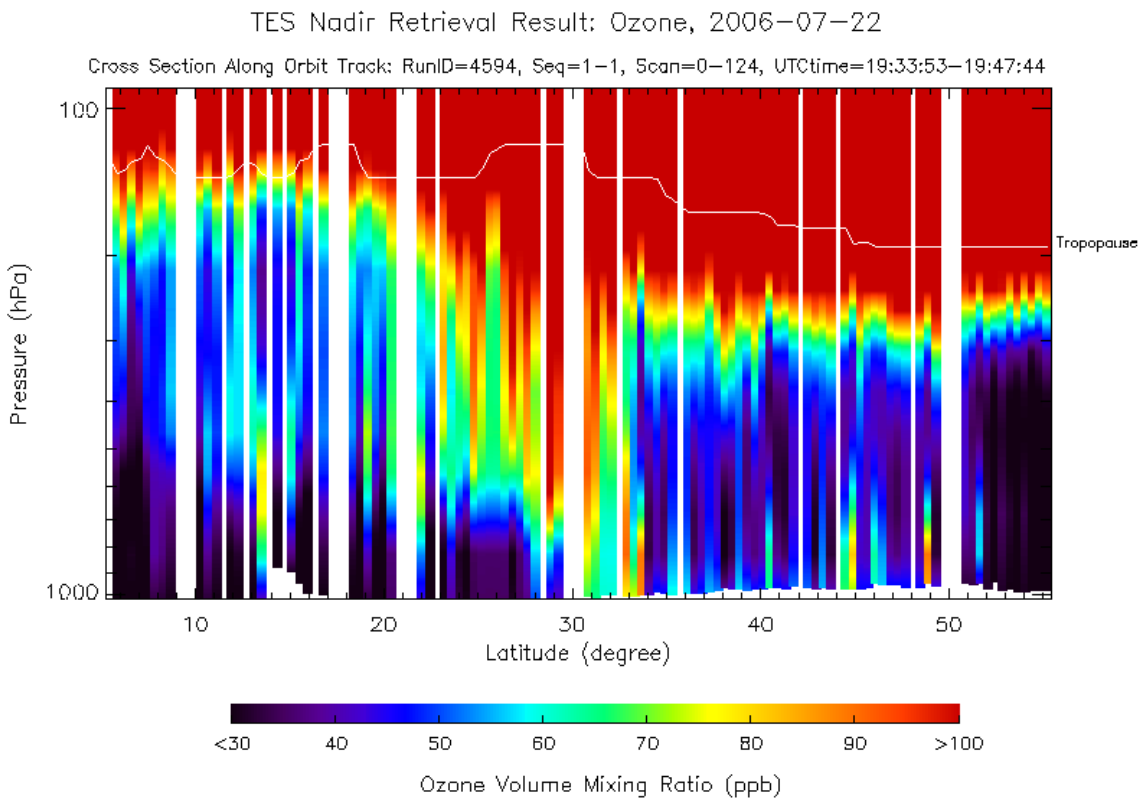

Figure 9: TES Nadir O_3 retrieval for July 22nd, 2006. Note, high lower tropospheric O_3 concentrations between 80-100 ppbv between 33 and 34 ^{o}N latitude (at ~ -93.97^{o} Longitude), which are located over NE Texas.

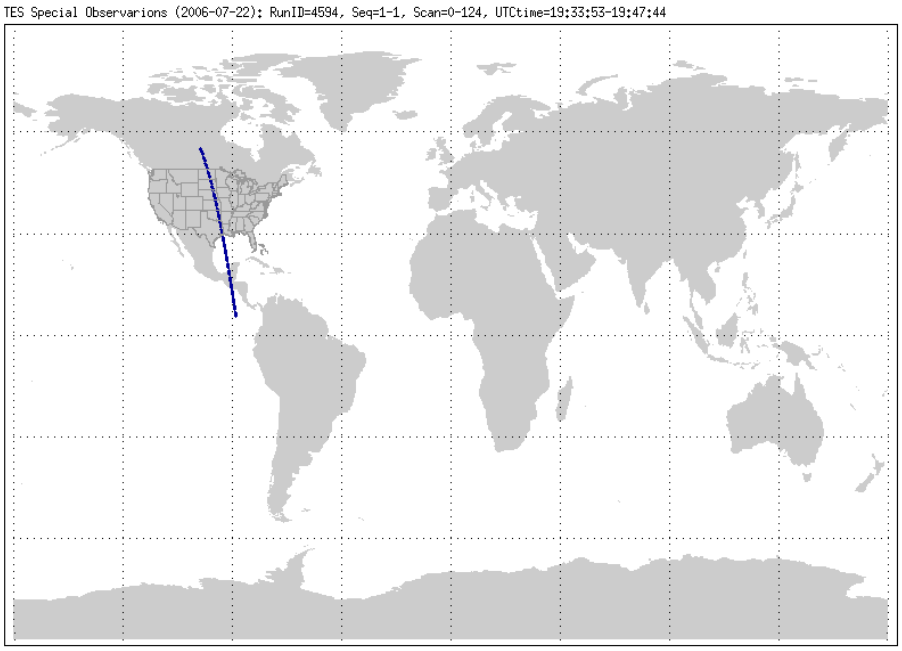

Figure 10: TES geolocation track for July 22nd, 2006.

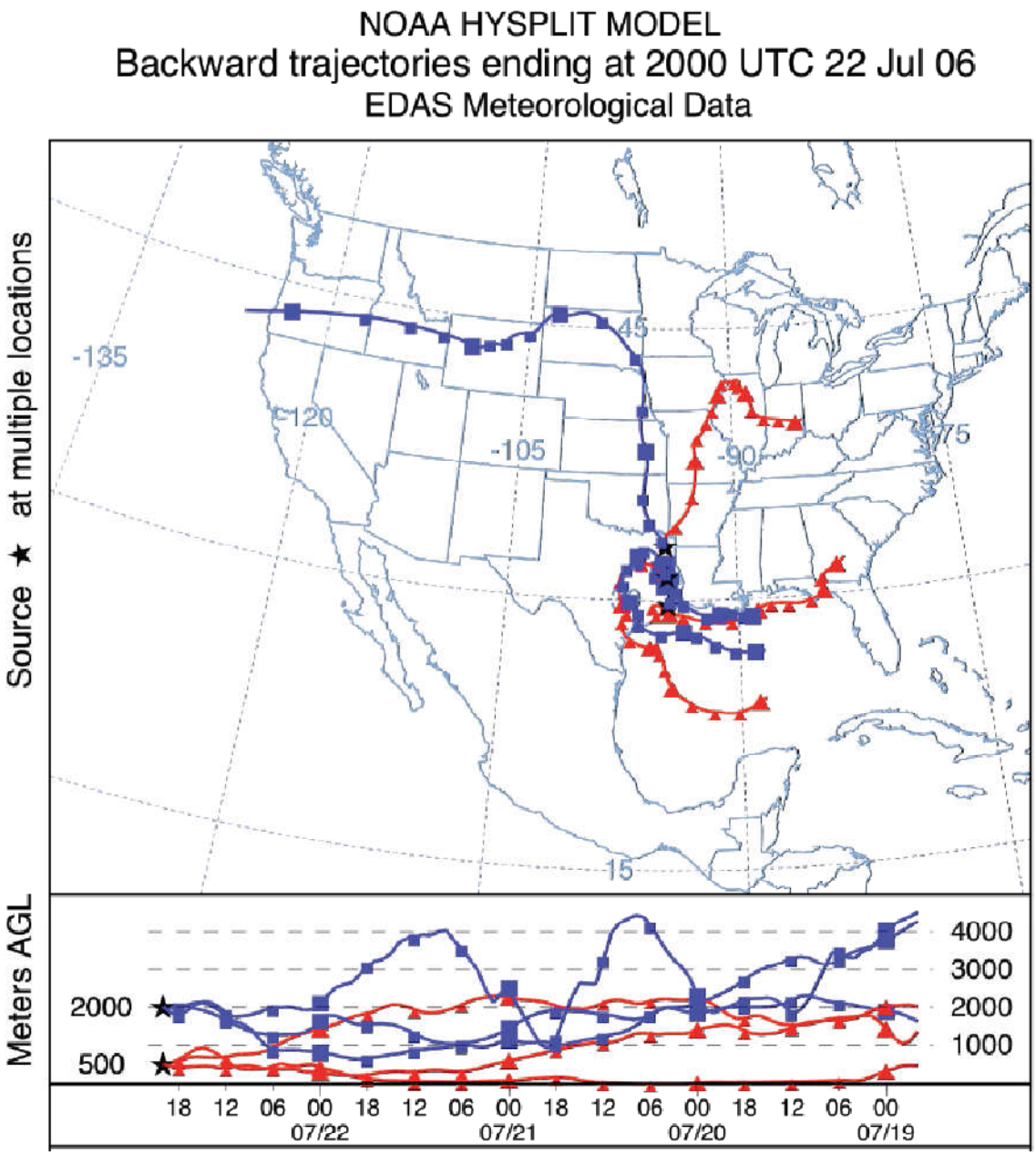

Figure 11 (a): Four day back trajectory, starting at 2 and 0.05 km on July 22nd, 2006, over NE Texas, between and 34 ^{o}N latitude (at ~ -93.97 ^{o}Longitude).

The four back trajectory analysis reported in the November 12th, 2010 progress report, starting at 2 and 0.5 km, show clearly that the high O_3 concentrations measured by TES in the lower troposphere (*i.e.*, close to the surface) is not sourced from Texas but are transported from the Gulf of Mexico, Southeastern US, Northwestern US, and Northwestern US. **Figure 11 (a)** also indicates that at 2 and 0.5 km, O_3 measured at these altitudes over NE Texas are transported remotely at higher altitudes.

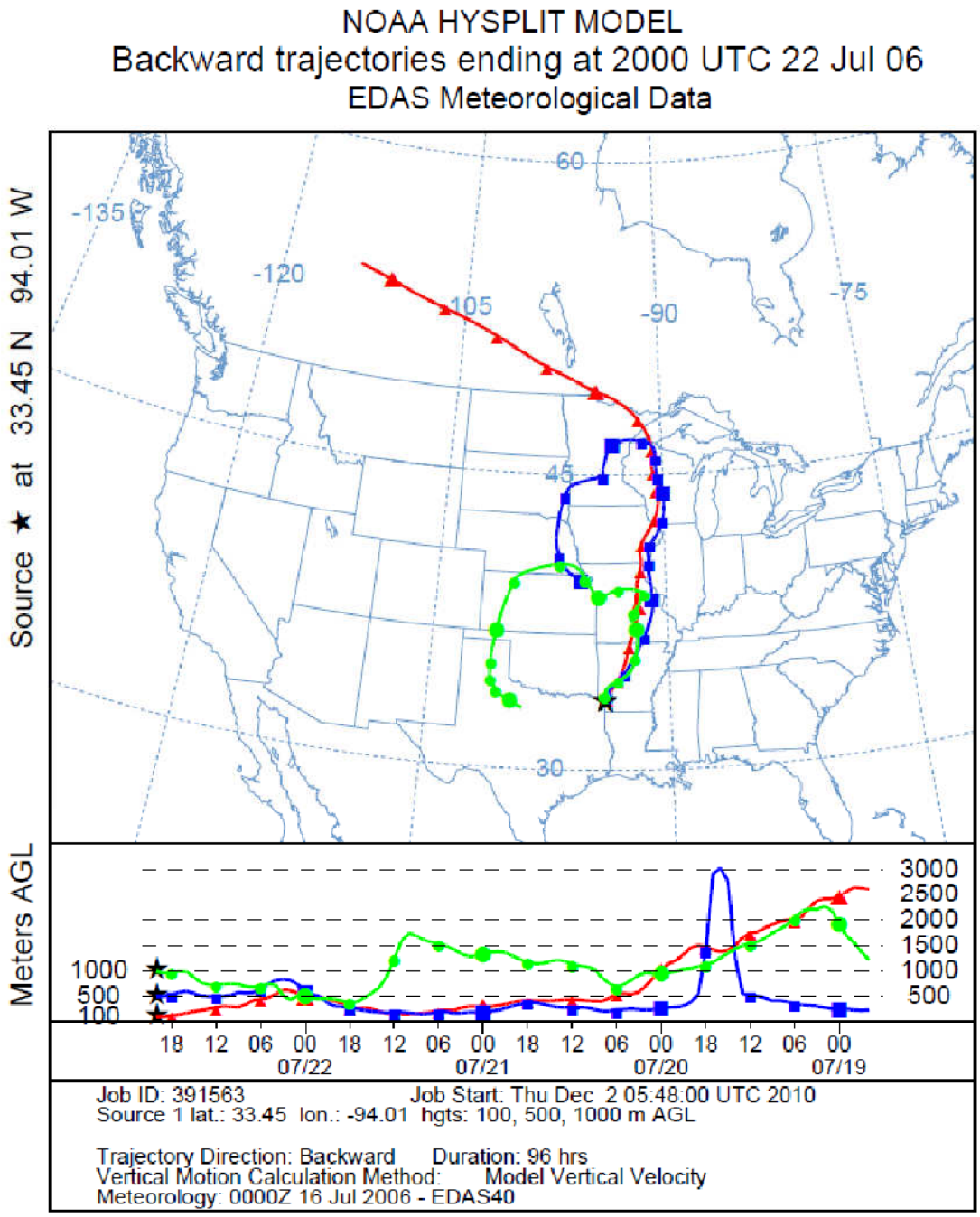

Figure 11 (b). Shows back trajectories for July 22nd, 2006 at heights of 1, 0.5, and 0.1 km. The 1 km back trajectory shows that O_3 values measured at 1 km are sourced just SW of Wichita Falls; although O_3 at 1 km is sourced from Texas, it likely represents only a small fraction of O_3 measured over NE Texas, especially considering that all other height trajectories show that ozone is sourced from remote sources – *i.e.*, outside of Texas.

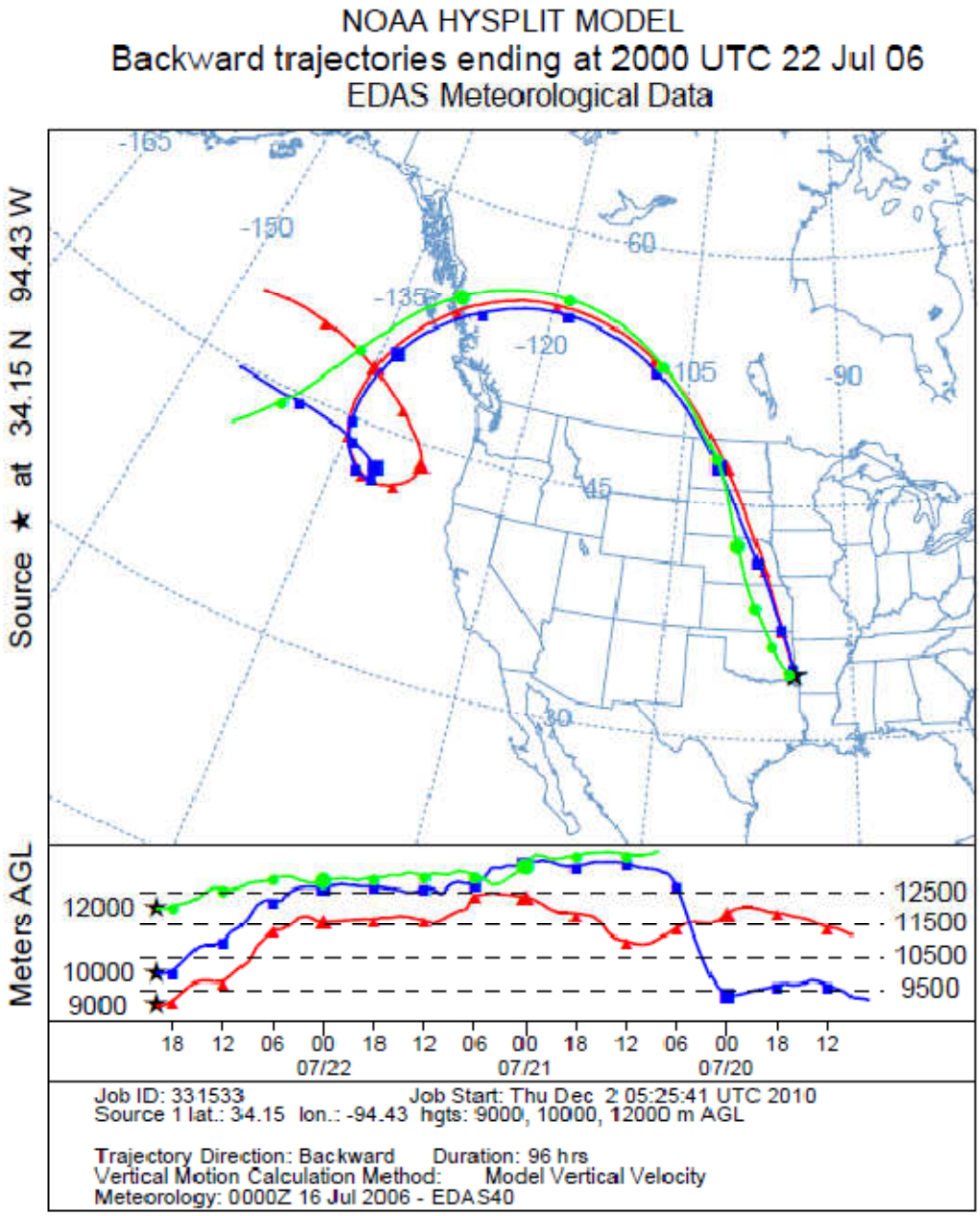

Figure 11 (c). shows back trajectories for July 22nd, 2006 at heights of 12, 10, and 9 km. Air parcels at these heights are sourced over the Atlantic Ocean.

Except for one Midlothian Tower in Midlothian, TX, which measured an NO_2 concentration of 54 ppbv at 8 p.m., all other sites on July, 22nd, 2006 in Texas measured NO_2 at concentrations less than 32 ppbv (http://www.tceq.state.tx.us/cgi-bin/compliance/monops/site_photo.pl). The **Figure 12** displays a tropospheric column measurement of NO_2 on July 22nd, 2006 from the Ozone Monitoring Instrument (OMI), which shows enhancements of NO_2 (*i.e.*, $\geq 5.5 \times 10^{15}$ molecules cm^{-2}) for the mid-to-eastern part of Texas. These enhancements encompass the latitude and longitude coordinates that also measured high O_3 greater than ~ 80 ppbv. The Italy High School site

was one site that measured O_3 concentrations (76 ppbv) above the EPA limit, which does not coincide with the location of the O_3 and NO_2 enhancements measured by TES and OMI. **Figure 13** shows a tropospheric column measurement of O_3 for July 22nd, 2006 from OMI, which also reveal ozone enhancements (*i.e.*, 45 to 50 DU) in the same region as those shown for NO_2 in **Figure 12**. Given the fact that TES O_3 and OMI NO_2 show enhancements in the lower troposphere, the satellite data complements the HYSPLIT trajectory analysis, showing that such enhancements have been transported from outside of Texas. The trajectories mostly point at the Midwestern USA as the previous location for the air mass observed by TES. The Longview area, which had shown enhanced surface O_3 (> 75 ppb) on several days in mid-July 2006, including on July 22. TES also showed high ozone above NE Texas on Aug 23, 2006 another day where the Longview area saw O_3 above the EPA limit (not shown).

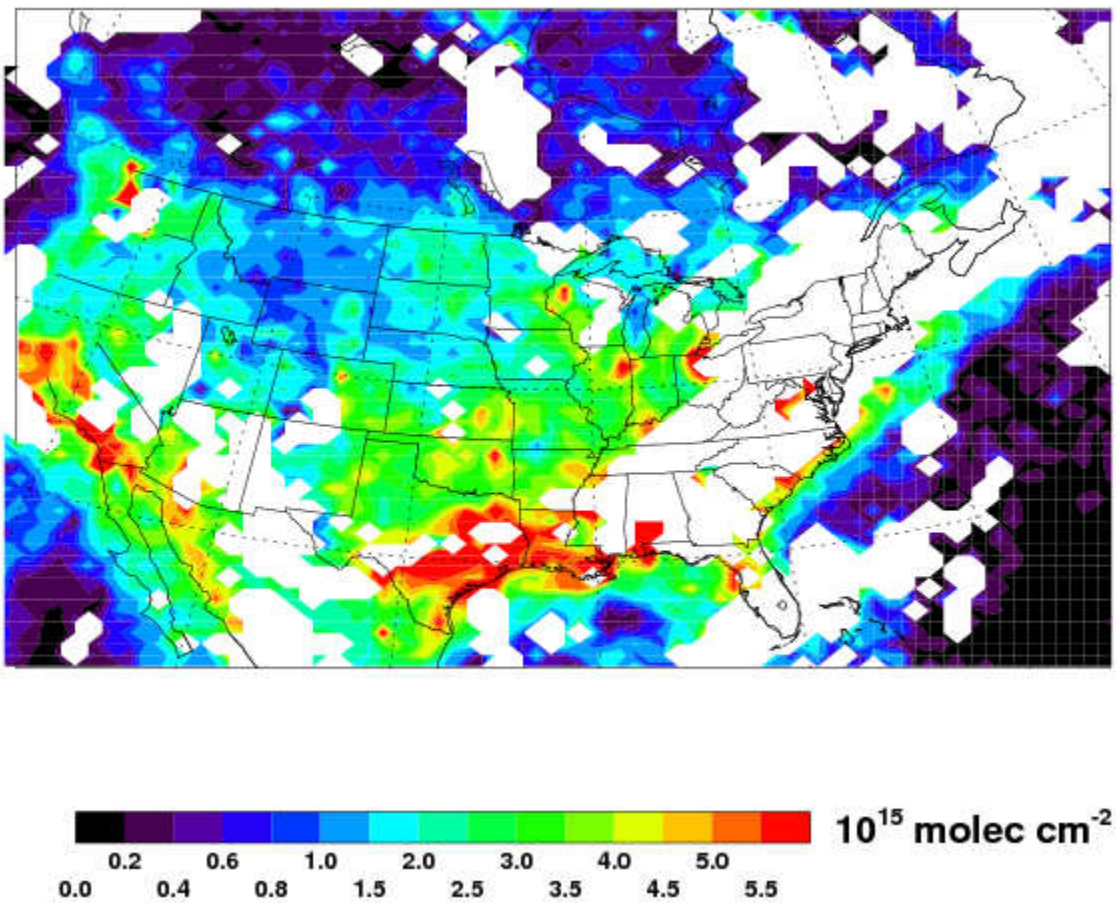

Figure 12. OMI NO_2 for July 22nd, 2006.

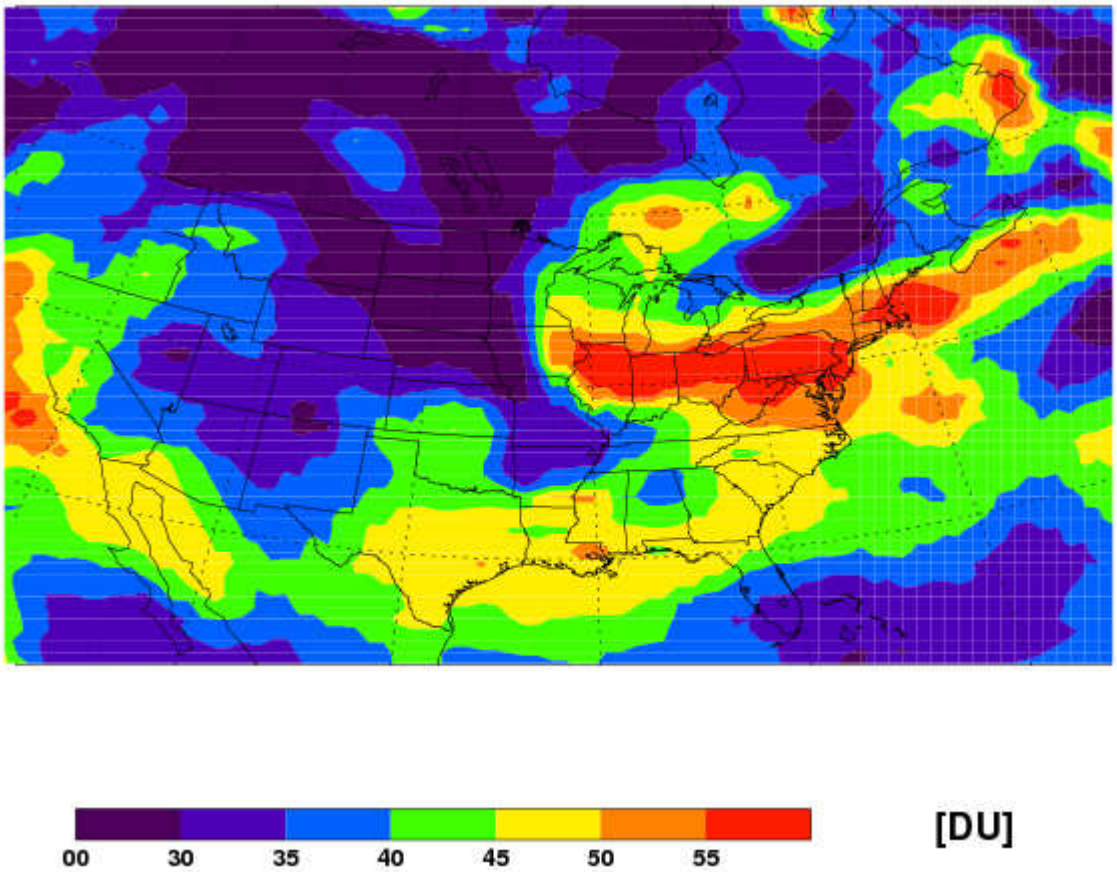

Figure 13. OMI O_3 for July 22nd, 2006.

August 2, 2005

Figures 14 and 15 represent TES ozone measurement track through the middle of Texas, where high O_3 concentrations are measured between 31 and 33 ^{o}N latitude (~ -97 ^{o}Longitude). This latitude-longitude bin is coincident with the locations of Forth Worth and Dallas, TX. All four day back trajectory analysis show that high ozone values measured over mid-Texas are sourced from the SE region of US and other remote locations (**Figures 16 (a)-(d)**).

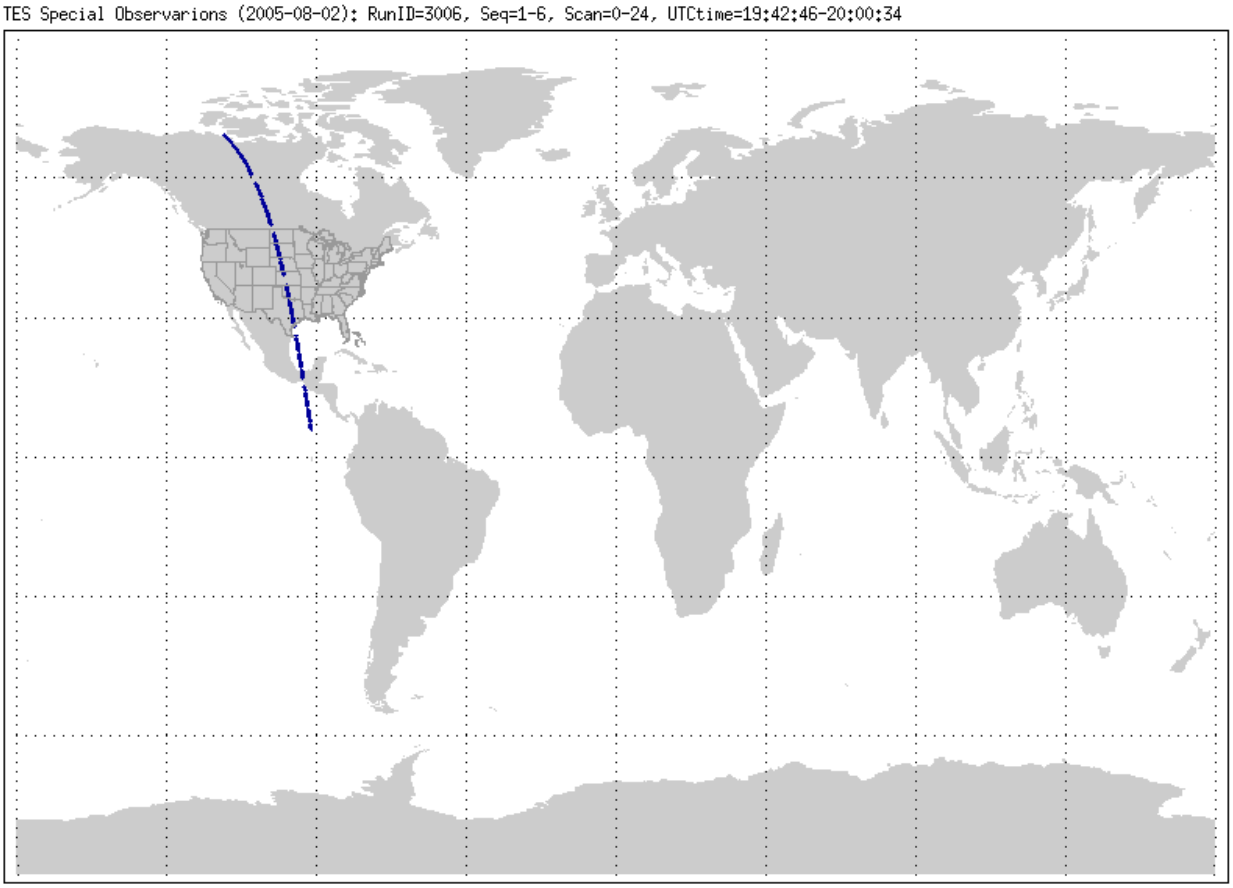

Figure 14. TES geolocation track for August 2nd, 2005.

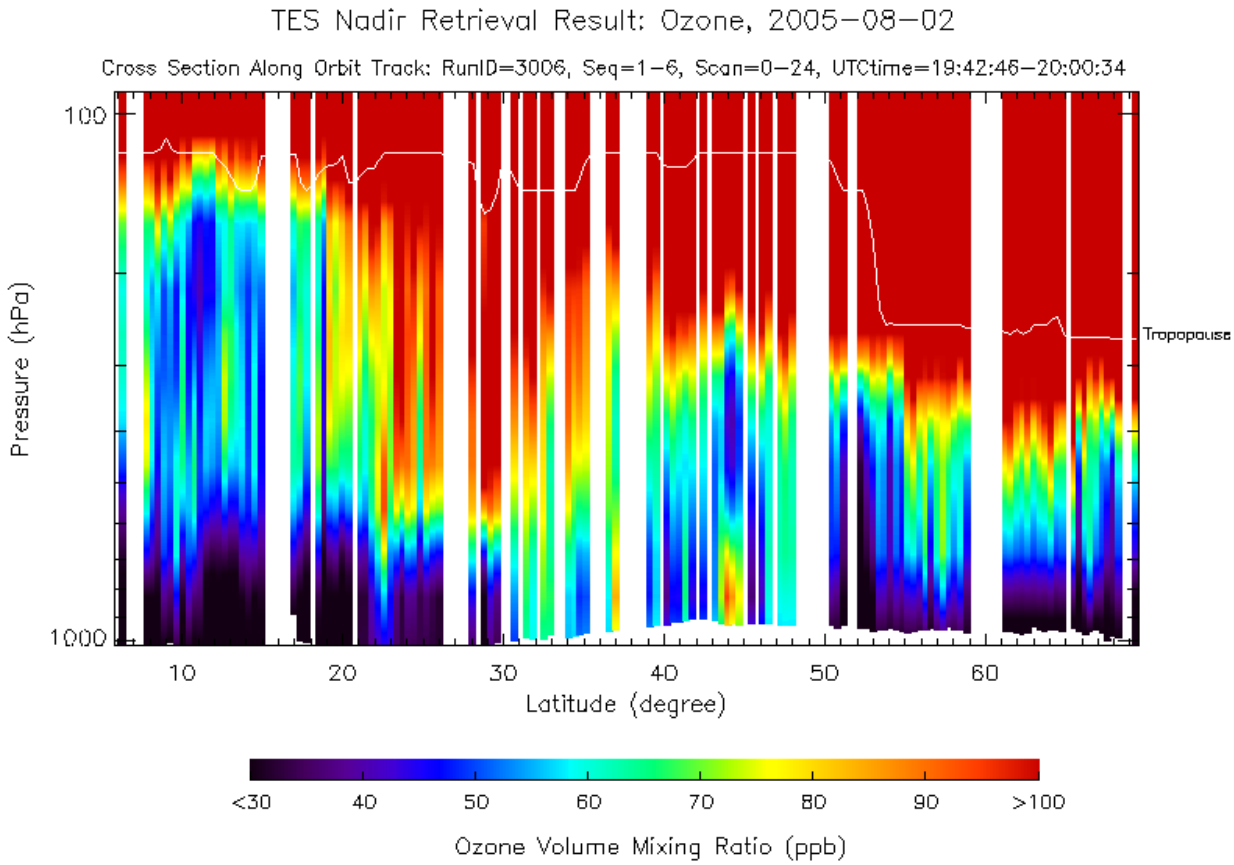

Figure 15. TES Nadir O_3 retrieval for August 2nd, 2005. Note, high lower tropospheric O_3 concentrations between 80-100 ppbv measured between 31 and 33 ^{o}N latitude (~ -97 ^{o}Longitude), located over mid-Texas.

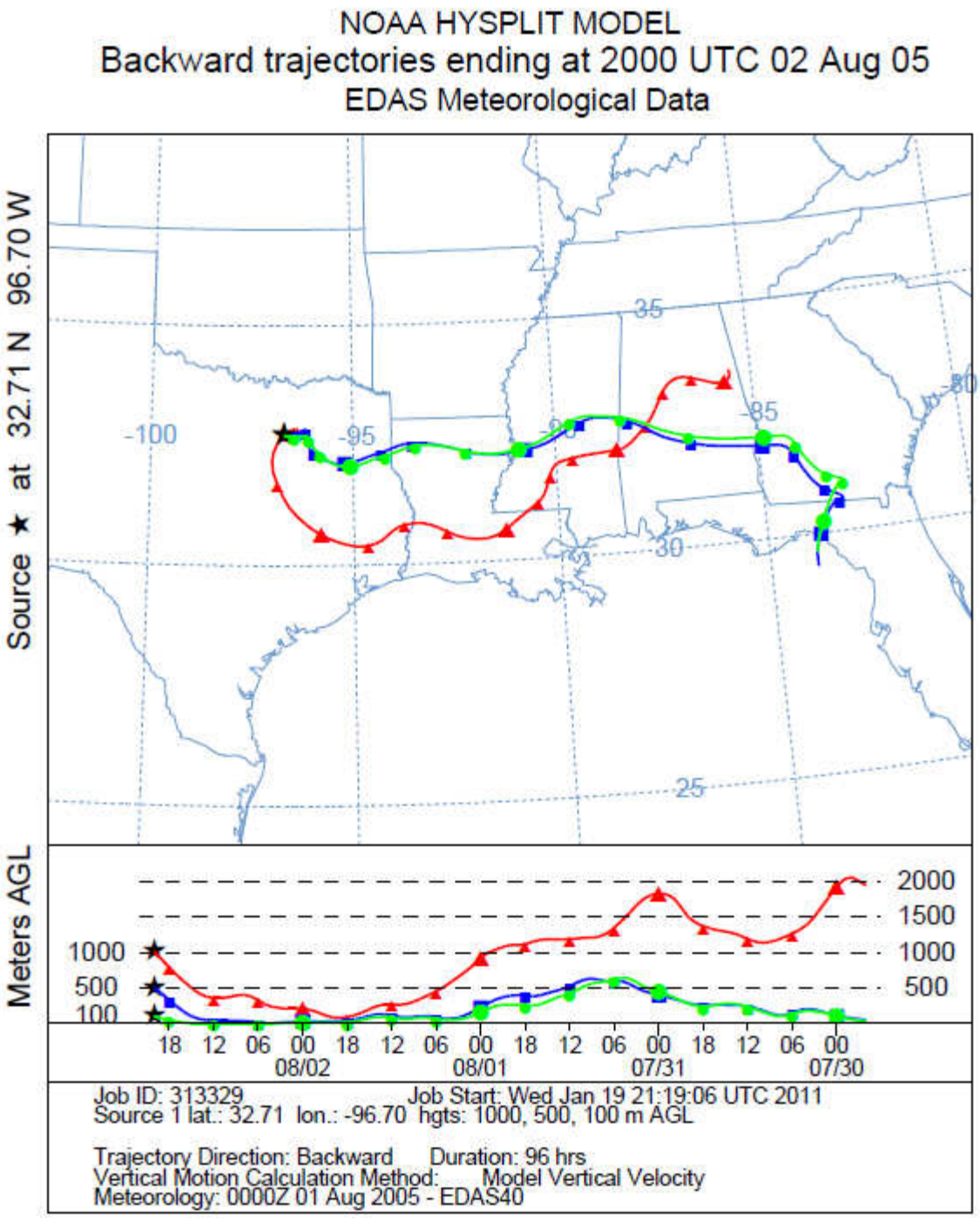

Figure 16 (a). Four day back trajectory, starting at 1, 0.5, and 0.1 km on August 2nd, 2005, over mid-Texas, starting from Dallas, TX.

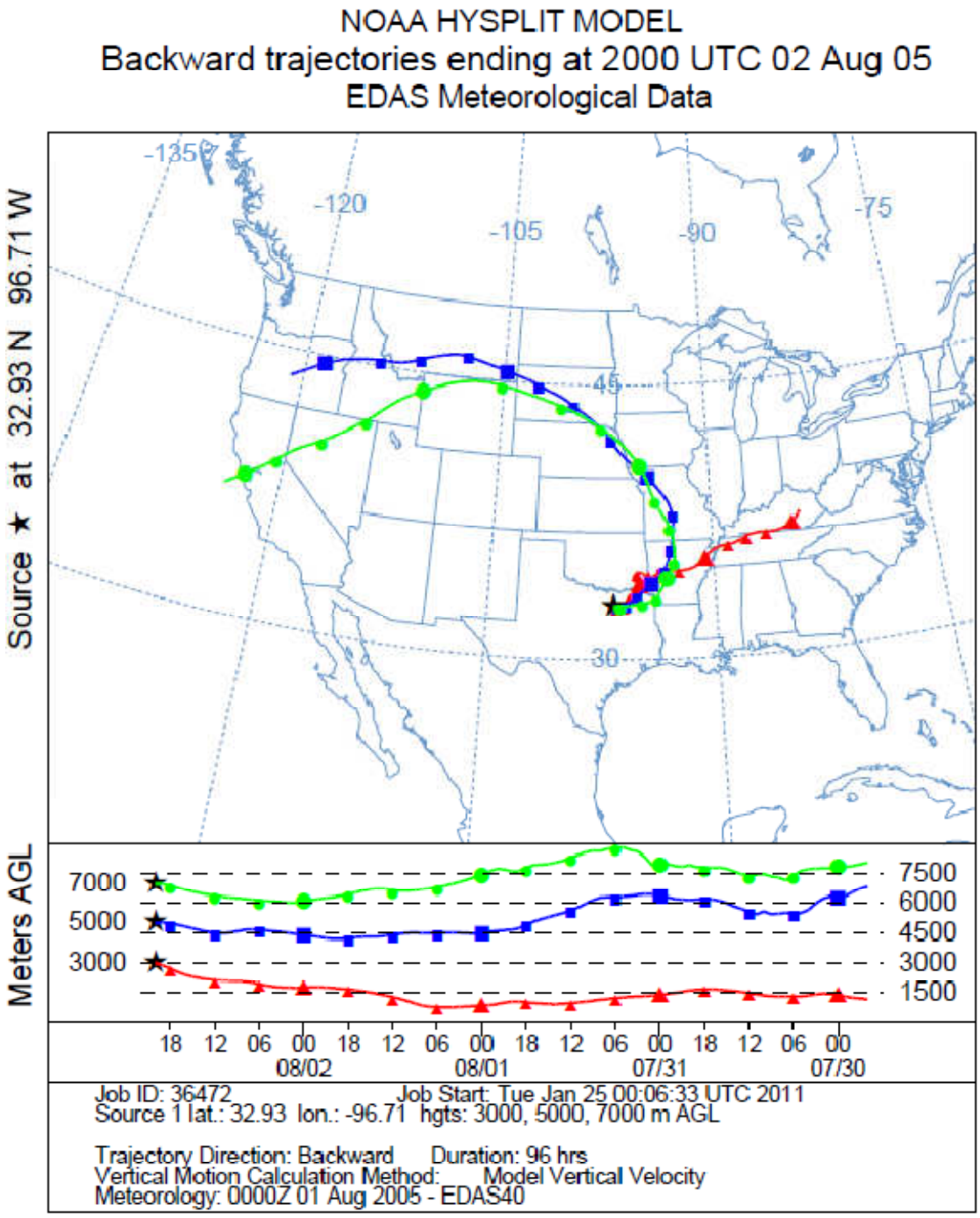

Figure 16 (b). Four day back trajectory, starting at 7, 5, and 3 km on August 2nd, 2005, over mid-Texas, starting from Dallas, TX.

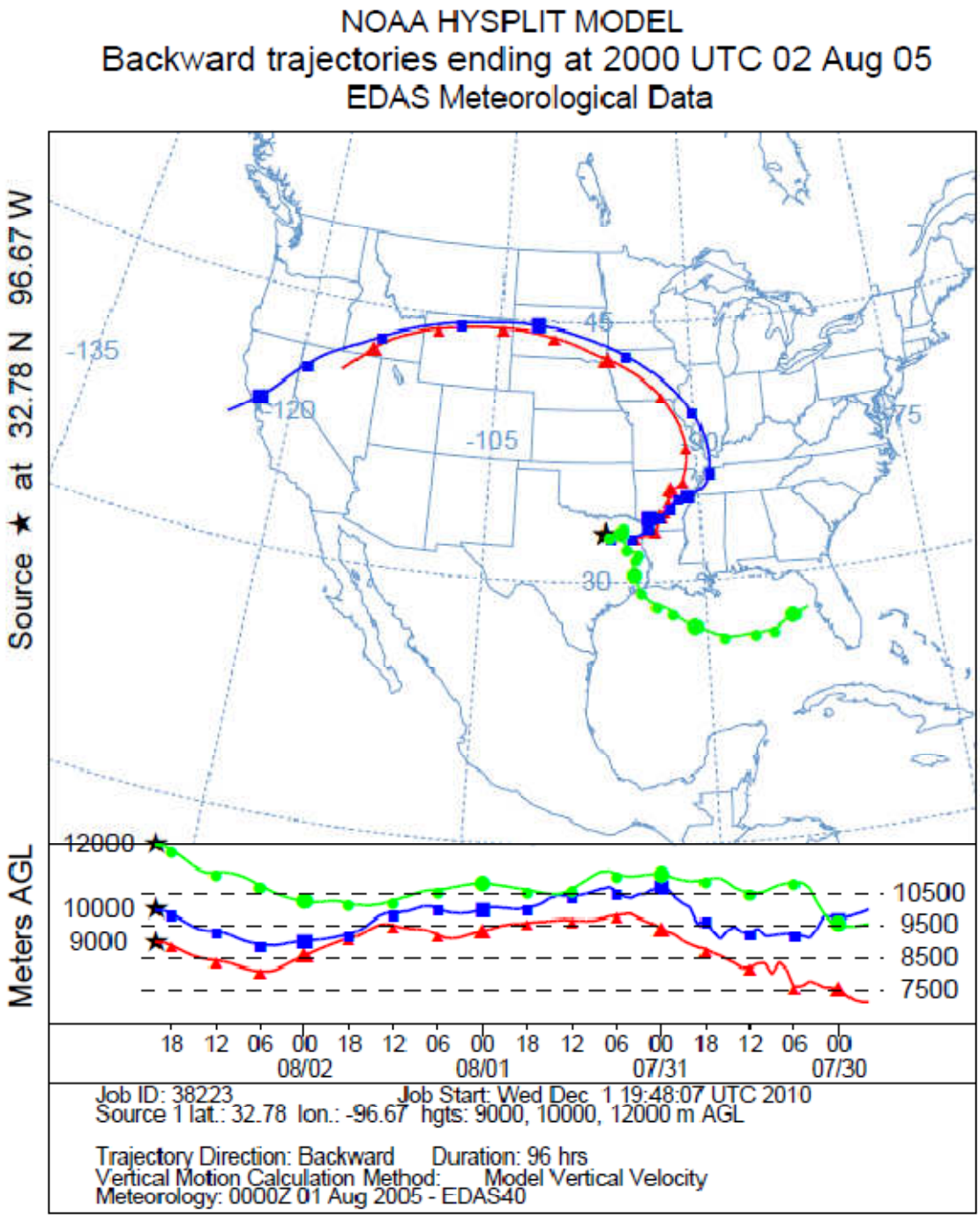

Figure 16 (c). Four day back trajectory, starting at 12, 10, and 9 km on August 2nd, 2005, over mid-Texas, starting from Dallas, TX.

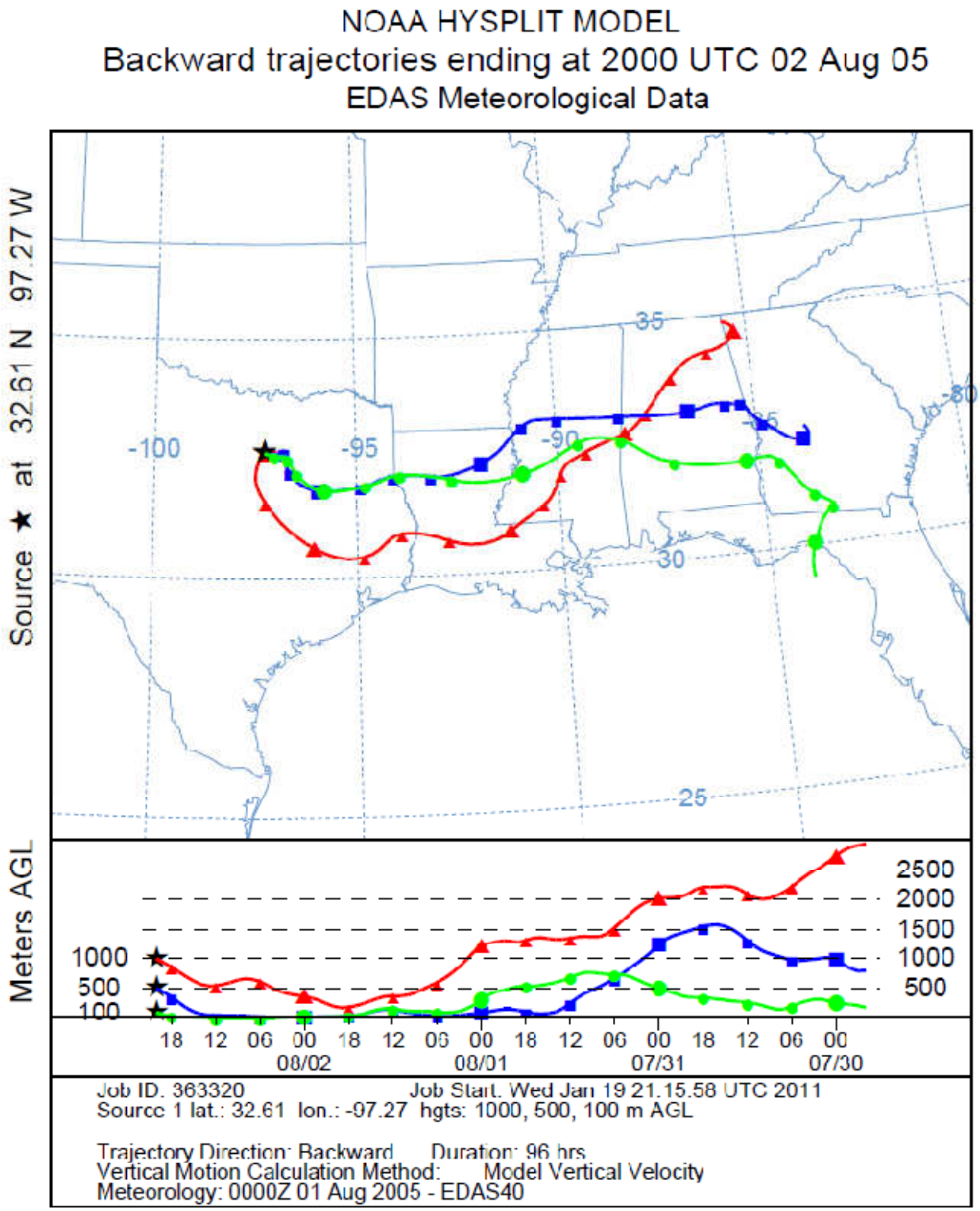

Figure 16 (d). Four day back trajectory, starting at 1, 0.5, and 0.1 km on August 2nd, 2005, over mid-Texas, starting from Forth Worth, TX.

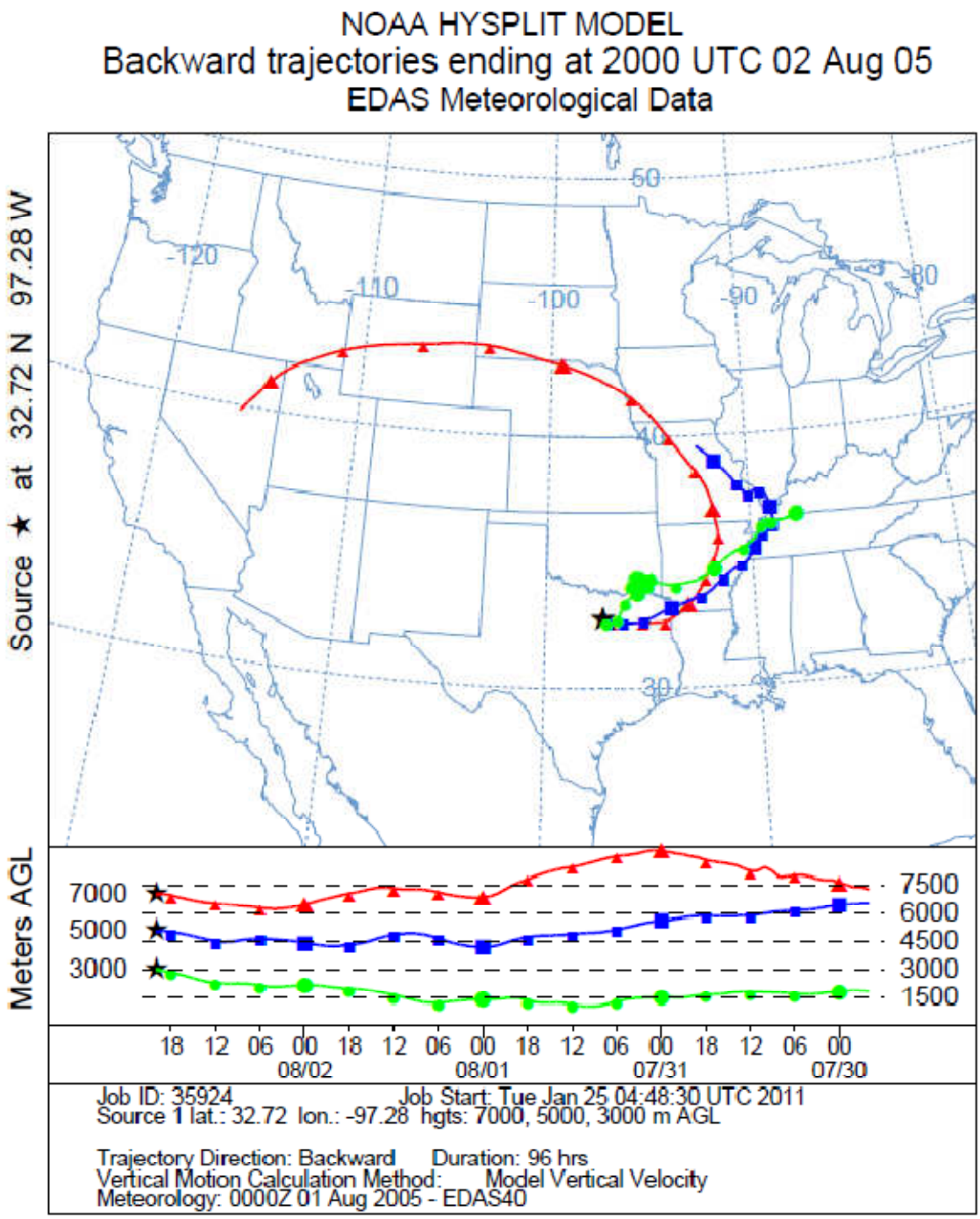

Figure 16 (e). Four day back trajectory, starting at 7, 5, and 3 km on August 2nd, 2005, over mid-Texas, starting from Forth Worth, TX.

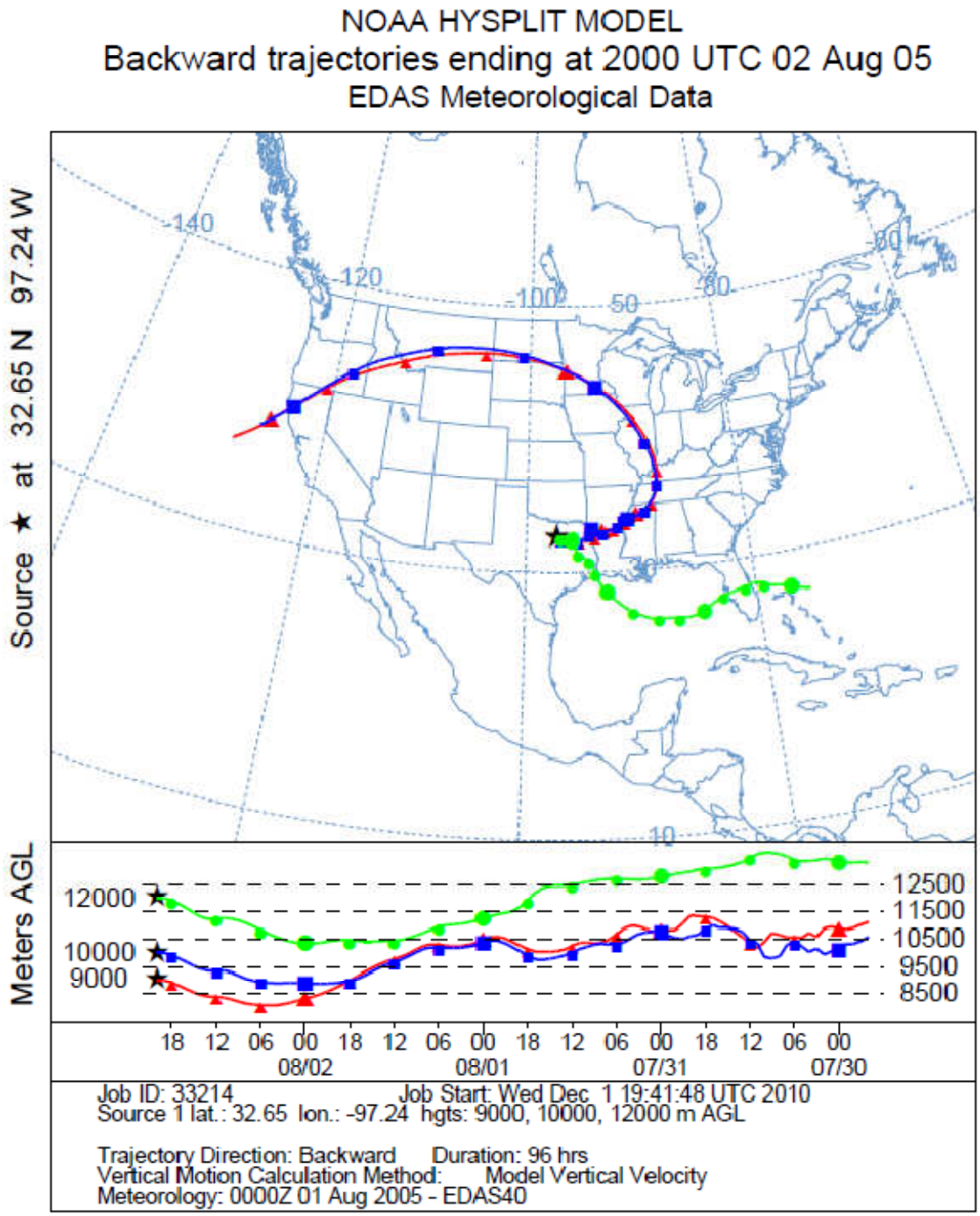

Figure 16 (f). Four day back trajectory, starting at 12, 10, and 9 km on August 2nd, 2005, over mid-Texas, starting from Forth Worth, TX.

All other sites on August 2nd, 2005 in Texas measured NO_2 at concentrations less than 29 ppbv (http://www.tceq.state.tx.us/cgi-bin/compliance/monops/site_photo.pl). The **Figure 17 and 18** displays a tropospheric column measurement of NO_2 and O_3 on July 22nd, 2006 from the Ozone Monitoring Instrument (OMI), which shows enhancements of NO_2

(*i.e.*, $\geq 5.5 \times 10^{15}$ molecules cm^{-2}) and O_3 (between 45 and 50 ppbv) for the mid-to-eastern part of Texas. These enhancements encompass the latitude and longitude coordinates for TES that also measured high O_3 greater than ~ 80 ppbv. On August 2nd, 2005, 29 sites measured O_3 concentrations (77 to 115 ppbv) above the EPA limit, which mostly coincide with the location of the O_3 and NO_2 enhancements measured by TES and OMI. Given the fact that TES, OMI, and *in situ* data show O_3 and NO_2, respectively, show enhancements in the boundary layer, all data sets complement the HYSPLIT four day back trajectory analyses, showing that such enhancements are governed by transport from remote sources. This study also show that combining satellite and *in situ* data and modeling tools can provide more quantifiable and accurate information for developing effective State Implementation Plans (SIPs) for compliance with Environmental Protection Agency (EPA) and the Texas Commission on Environmental Quality (TCEQ) air quality (AQ) standards.

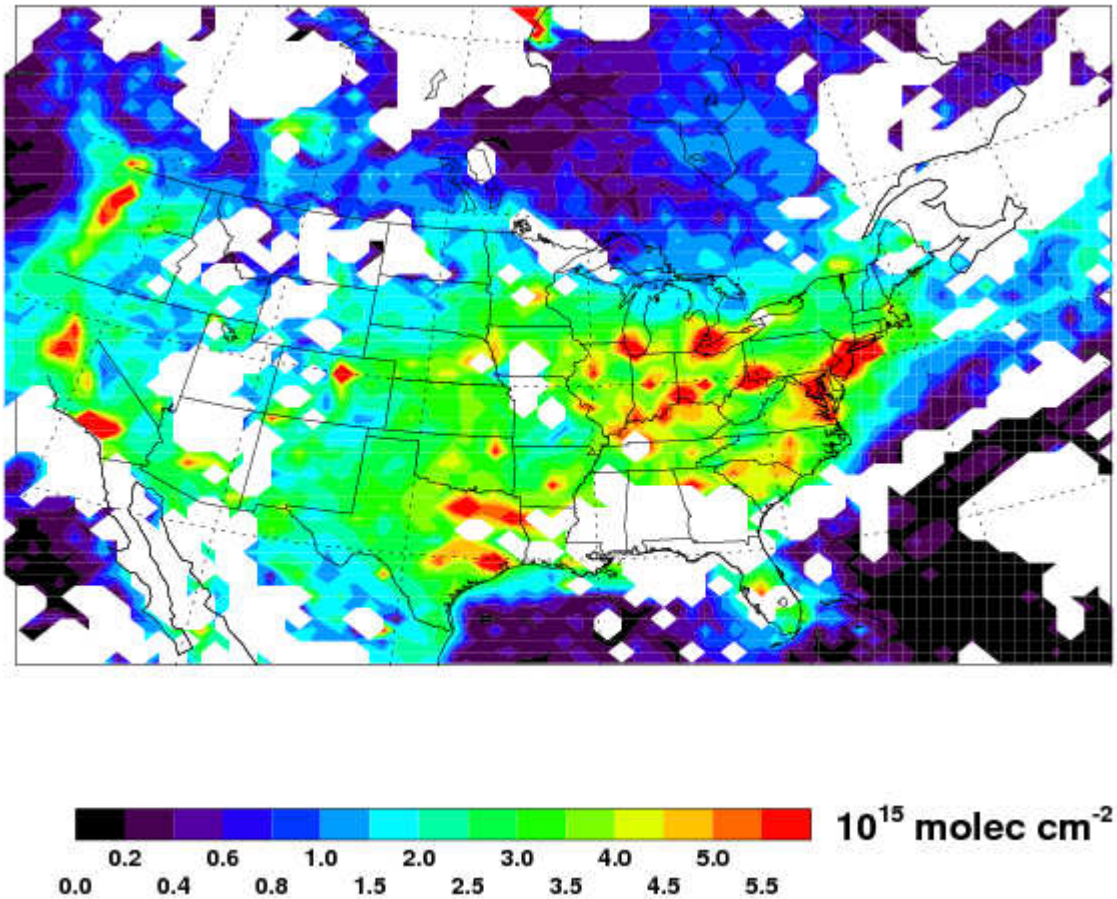

Figure 17. OMI tropospheric column measurement of NO_2 on August 2nd, 2005.

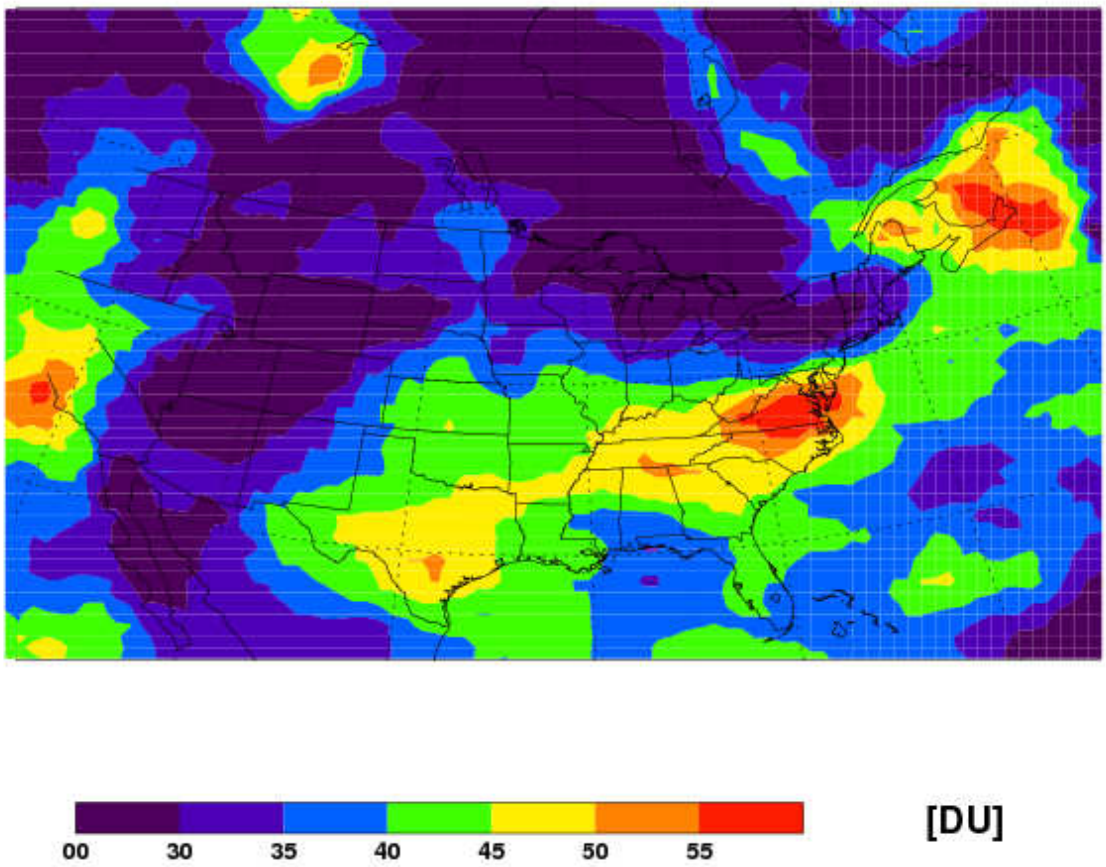

Figure 18. OMI O_3 tropospheric column for August 2nd, 2005.

Conclusions

We have examined over 20 days of TES data and run trajectories from the location of the TES and OMI measurements. Four day back trajectory analyses of all dates show that upper-, mid-, and lower-tropospheric air over Texas (*i.e.*, air at 12, 10, 9, 7, 5, 3, 1, 0.5, and 0.1 km), containing high O_3, as shown by TES, is transported from many locations across North America and the Gulf of Mexico. These include the Gulf of Mexico itself, the Southeastern USA, Midwestern USA, Northeastern USA, the Atlantic Ocean, Pacific Ocean, Mexico, etc., in all cases. The only case of a back trajectory (4 days) staying completely with the state of Texas is air over the lower troposphere, ~1 km, on July 22nd, 2006. TES O_3 and OMI NO_2 show enhancements in the boundary layer, complementing the HYSPLIT four day trajectory analyses, which gives further indication that such enhancements are governed by transport from remote sources. There was an indication on several dates that the lower tropospheric transport from the Southeastern US (see Appendix I). Dates with co-located satellite and *in situ* data (*e.g.*, August 2nd, 2005) further exemplify the need for combining satellite and *in situ* data and modeling tools as they can provide more quantifiable and accurate information for developing effective State Implementation Plans (SIPs) for compliance with Environmental Protection Agency

(EPA) and the Texas Commission on Environmental Quality (TCEQ) air quality (AQ) standards. In this work, we looked through much of the TES data corresponding to Texas and the SE USA during the dates specified by TCEQ. There are still more dates that could be examined. Linking the satellite data with studies of the boundary layer characteristics (and other ground based data) would further improve the ability to obtain a larger scale picture of the chemistry of the atmosphere for comparison to models and could be the basis of future work.

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Appendix

I. Summary of Transport Source Locations to Texas

Aug. 6th, 2005 – UT, mid-trop, LT – from Gulf, SE USA, Atlantic
Aug. 2nd, 2005 – UT, mid-trop, LT – from Gulf, SE USA, mid-West USA, NW USA, Atlantic Ocean
July 31st, 2005 – UT, mid-trop, LT —from Pacific Ocean, mid-West USA
Aug. 5th, 2006 – UT, mid-trop, LT – from SE USA, Atlantic Ocean, Gulf, NE USA
Aug. 4th, 2005 – UT, mid-trop, LT – from Gulf, mid-West USA, Western USA states (e.g., Nevada), Pacific Ocean, mid-West
Aug. 6th, 2006 – UT, mid-trop, LT – from Gulf
Aug. 7th, 2006, UT, mid-trop, LT – from Gulf, SE USA, Atlantic Ocean , Caribbean
Aug. 23rd, 2006 – UT, mid-trop, LT – from SE USA
July 6th, 2006 – UT, mid-trop, LT – from Gulf, Canada,
July 7th, 2006 – UT, mid-trop, LT – from Gulf, SE USA, and north-mid-west USA
July 8th, 2006 – UT, mid-trop, LT – from mid-west USA
July 22nd, 2006 – UT, mid-trop, LT – from Gulf and SE USA, Pacific Ocean, mid-West USA, Northern California, Nevada, Canada
June 21st, 2009 – UT, mid-trop, LT – from Caribbean, Mexico, SE USA, and mid-West USA, southern Florida

All of the start-heights throughout the troposphere and LS (i.e., 12, 10, 9, 7, 5, 3, 1, 0.5, and 0.1 km), starting from locations within Texas and the Texas, Louisiana, Arkansas, and Oklahoma border show high O_3 sourced outside of Texas, except for one case at 1 km on July 22nd, 2006. I think that this point should be really emphasized in the abstract of the report.

II. Additional Four Day Back Trajectory Analyses (arranged as a function of end-point location within Texas).

a) Austin, TX

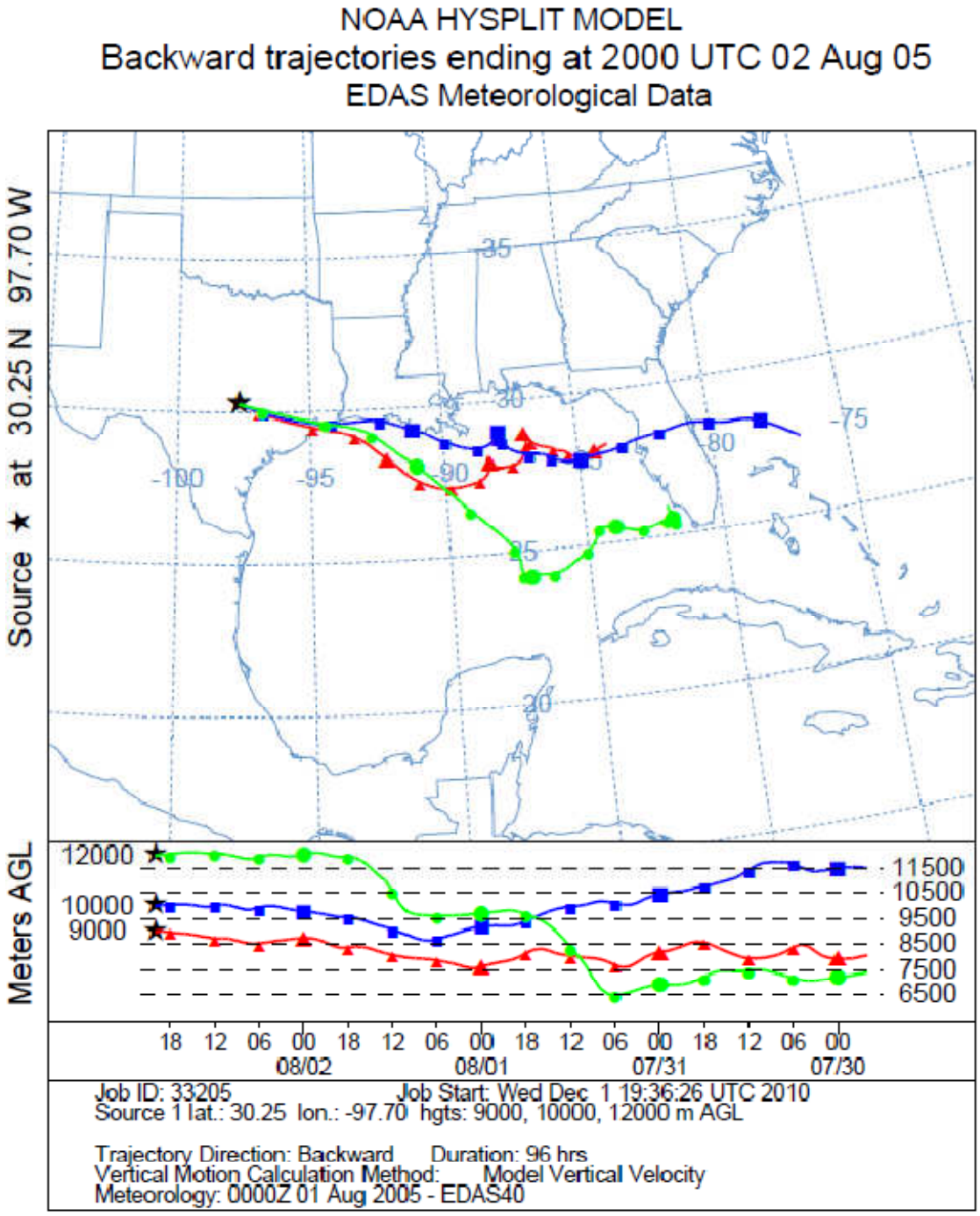

Figure A1. Four day back trajectory, starting at 12, 10, and 9 km on August 2nd, 2005, starting from Austin, TX.

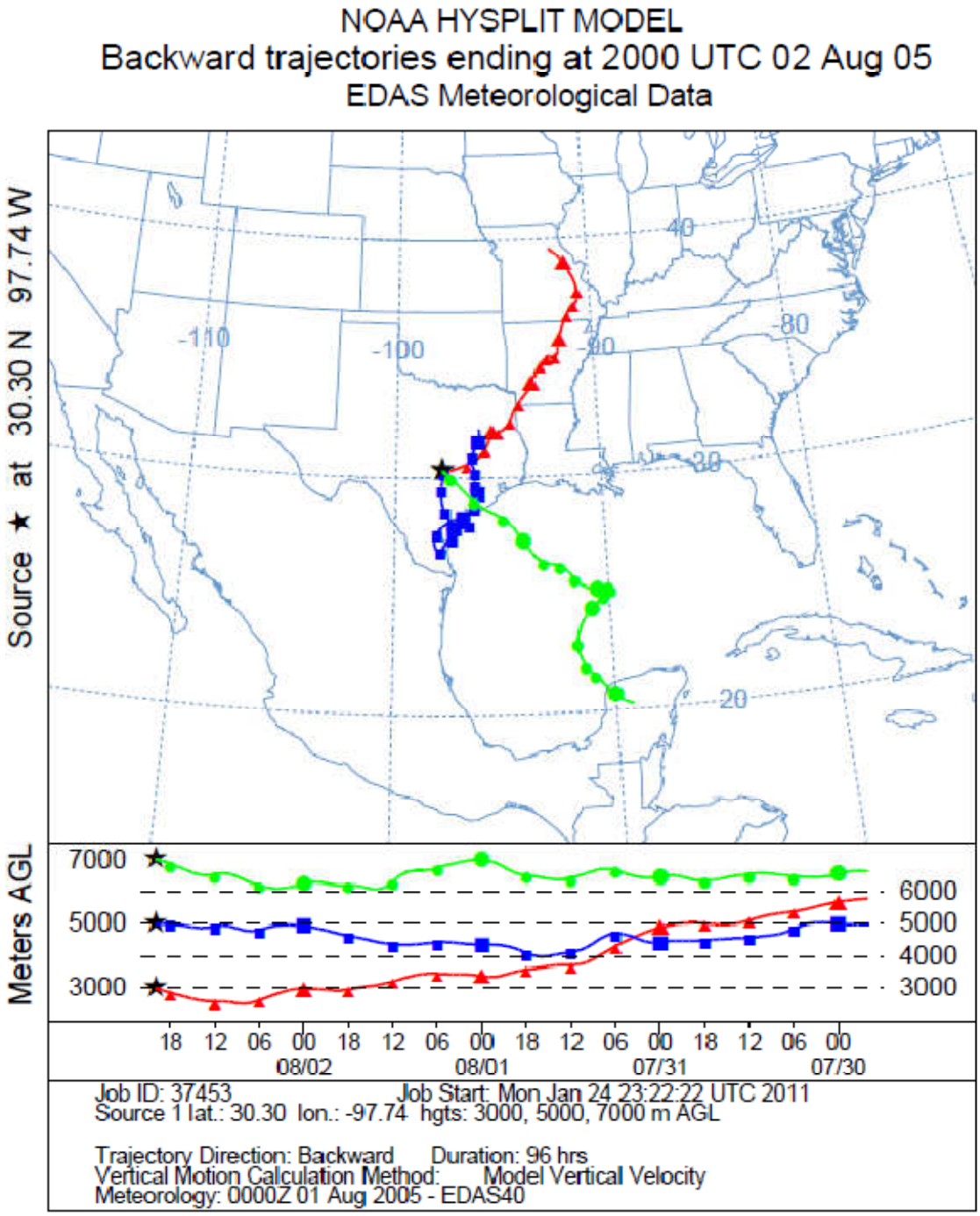

Figure A2. Four day back trajectory, starting at 7, 5, and 3 km on August 2nd, 2005, starting from Austin, TX.

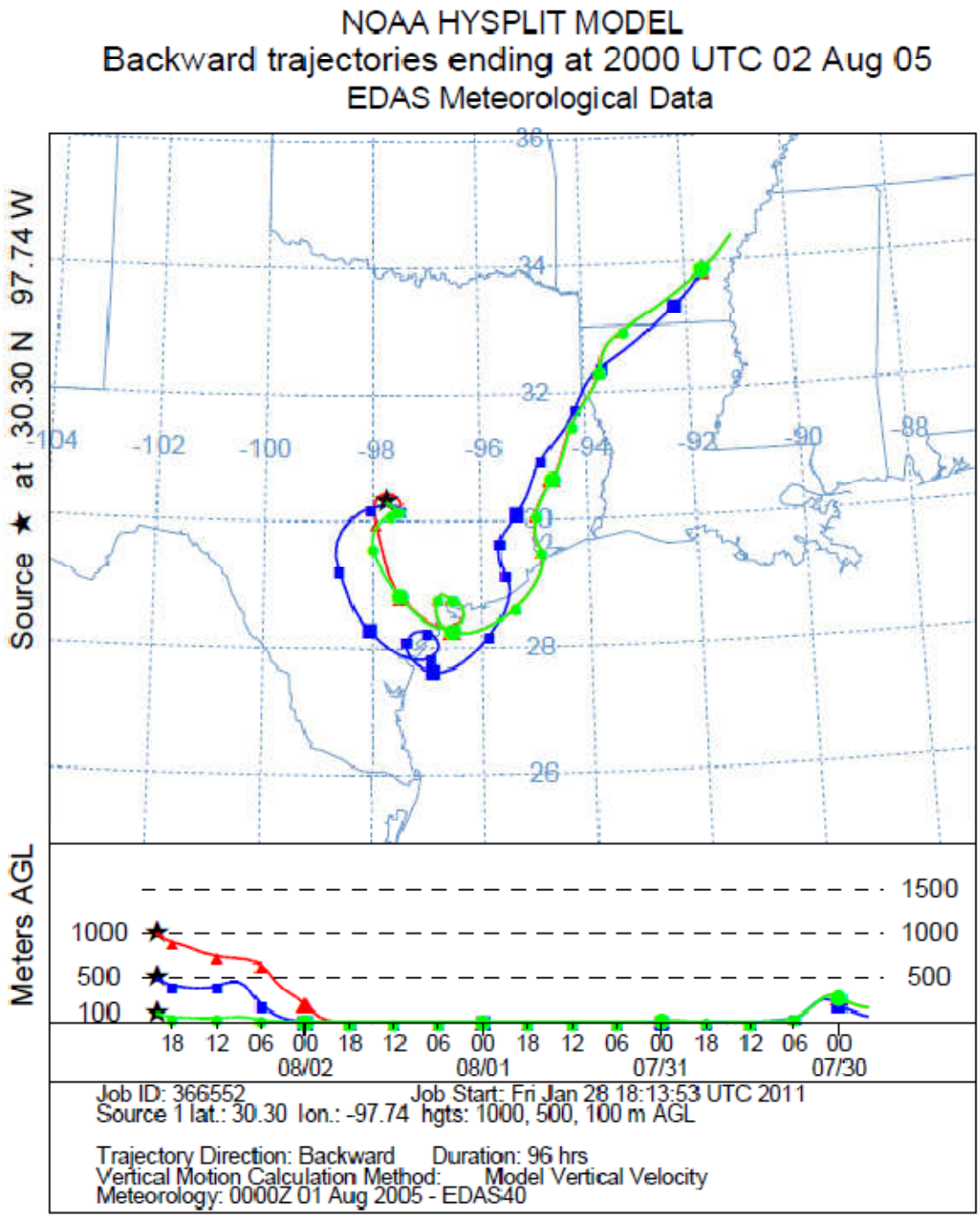

Figure A3. Four day back trajectory, starting at 1, 0.5, and 0.1 km on August 2nd, 2005, starting from Austin, TX.

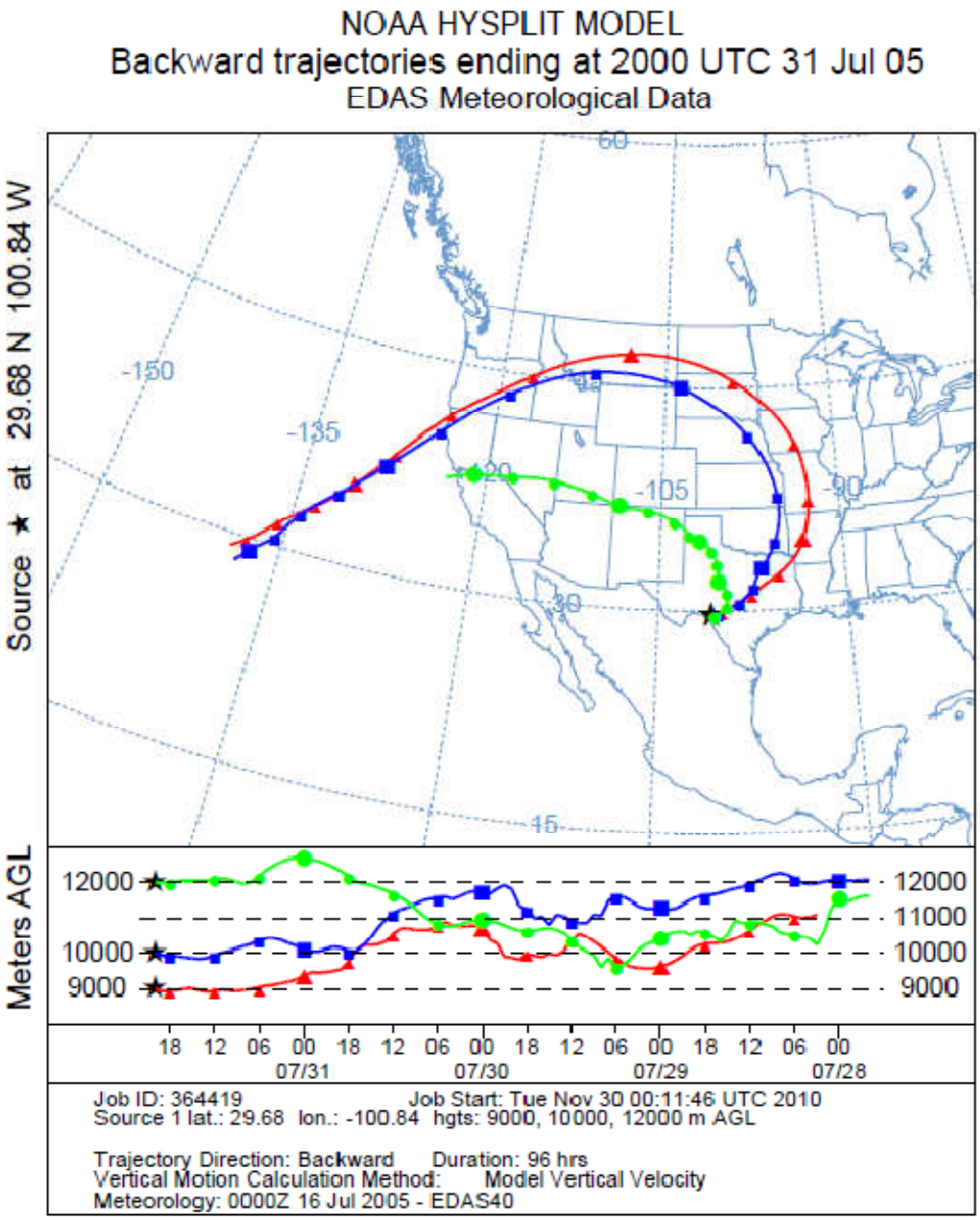

Figure A4. Four day back trajectory, starting at 12, 10, and 9 km on July 31st, 2005, starting from Cuidad Acuna, TX.

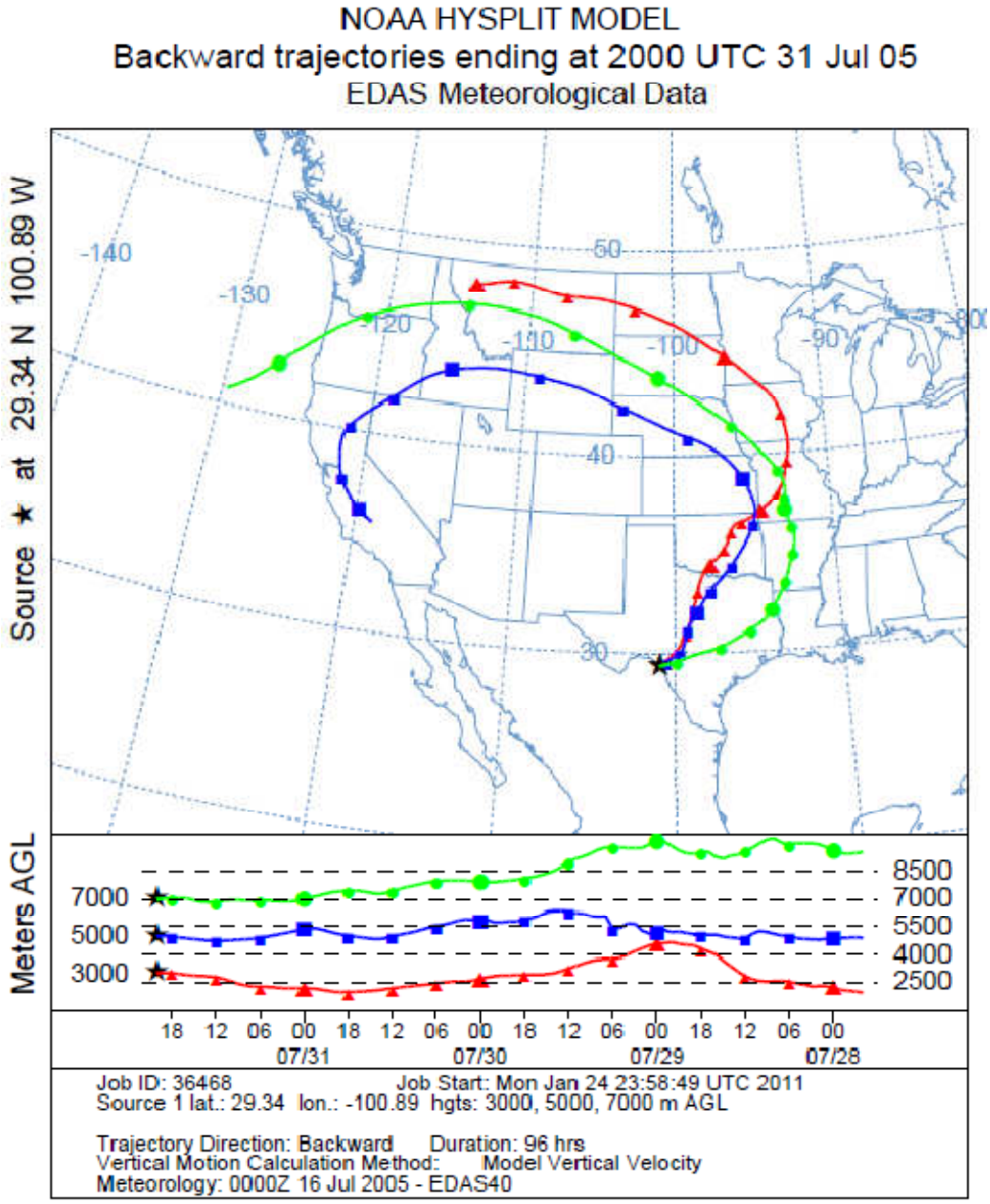

Figure A5. Four day back trajectory, starting at 7, 5, and 3 km on July 31st, 2005, starting from Cuidad Acuna, TX.

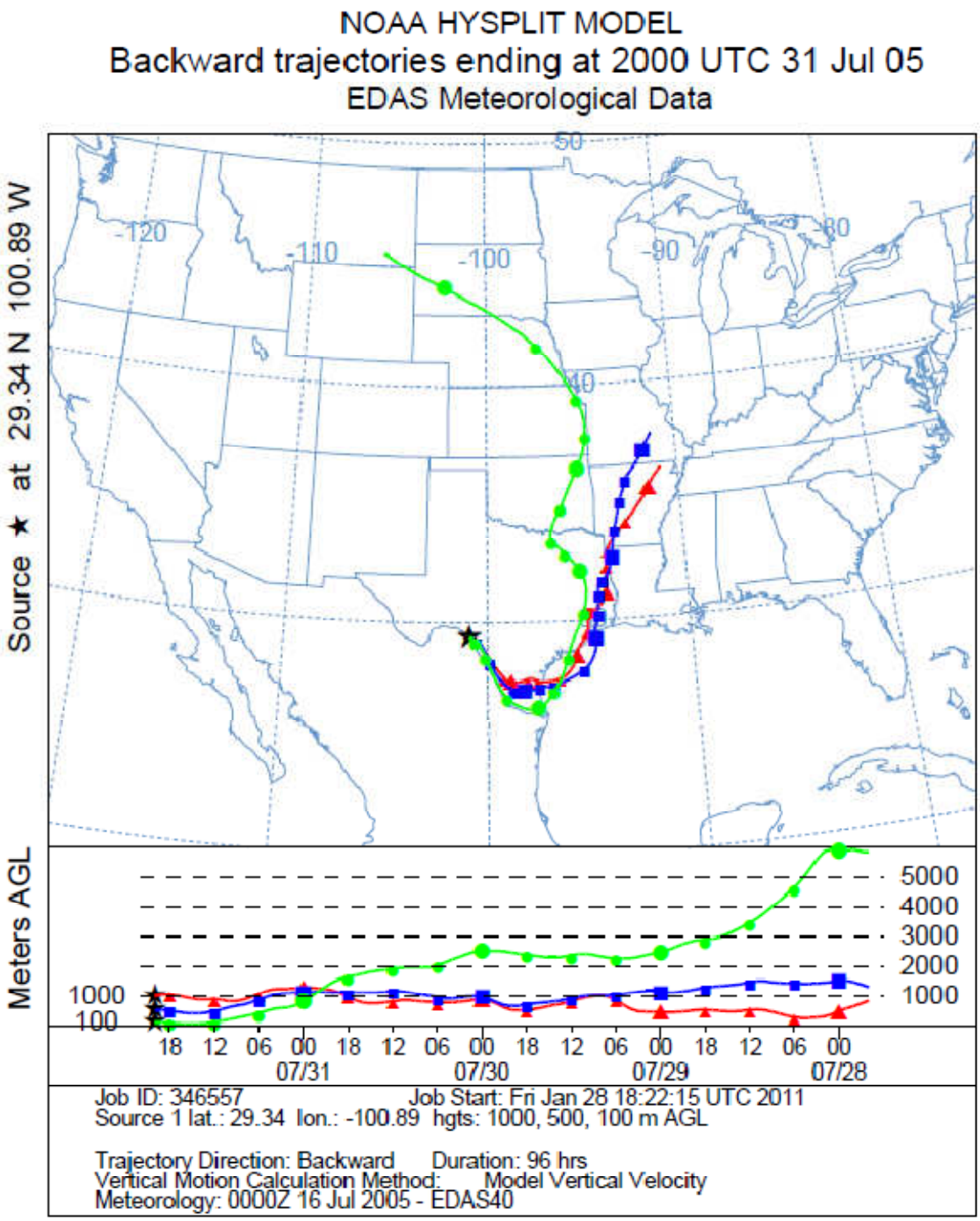

Figure A6. Four day back trajectory, starting at 1, 0.5, and 0.1 km on July 31st, 2005, starting from Cuidad Acuna, TX.

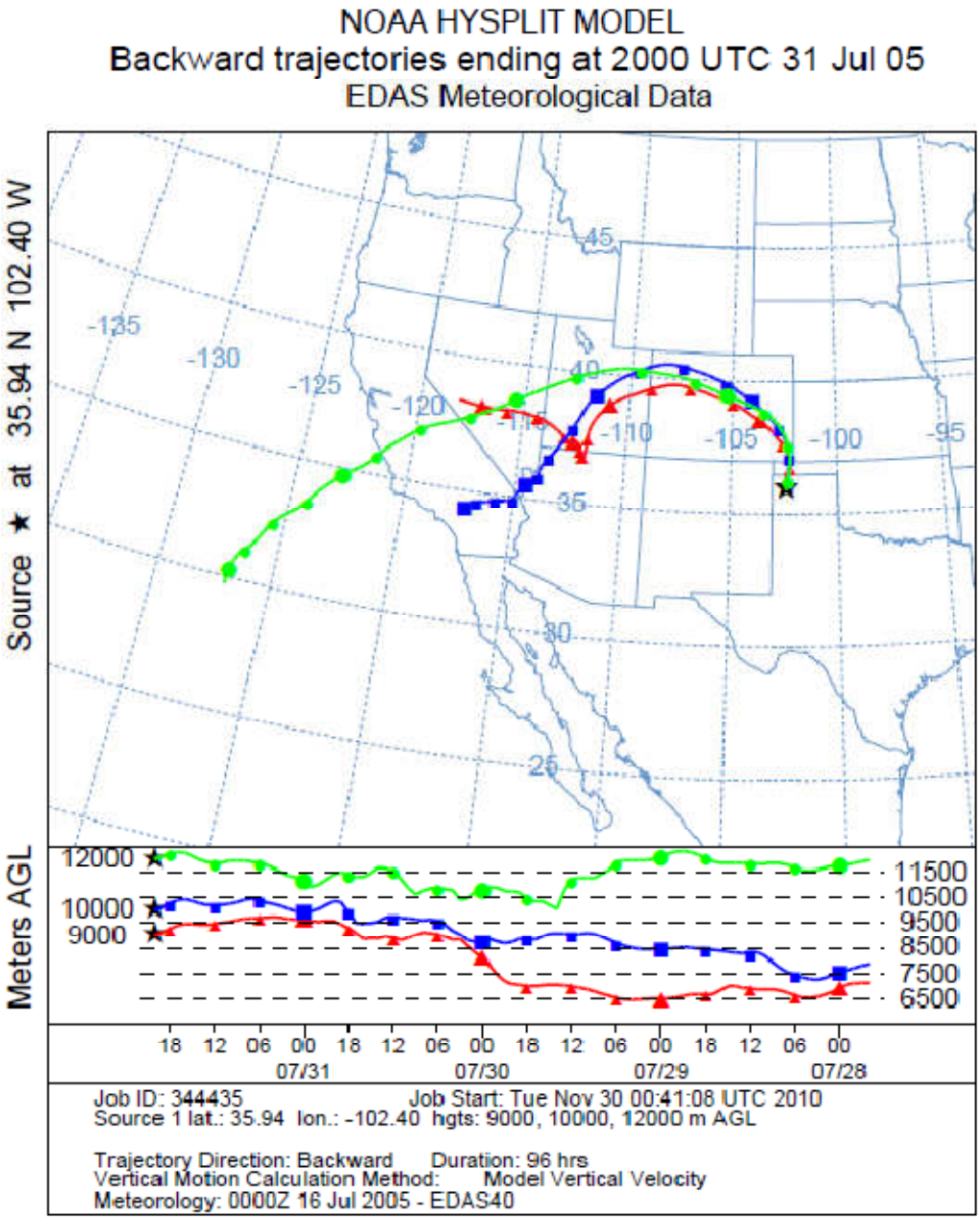

Figure A7. Four day back trajectory, starting at 12, 10, and 9 km on July 31st, 2005, starting from Dalhart, TX.

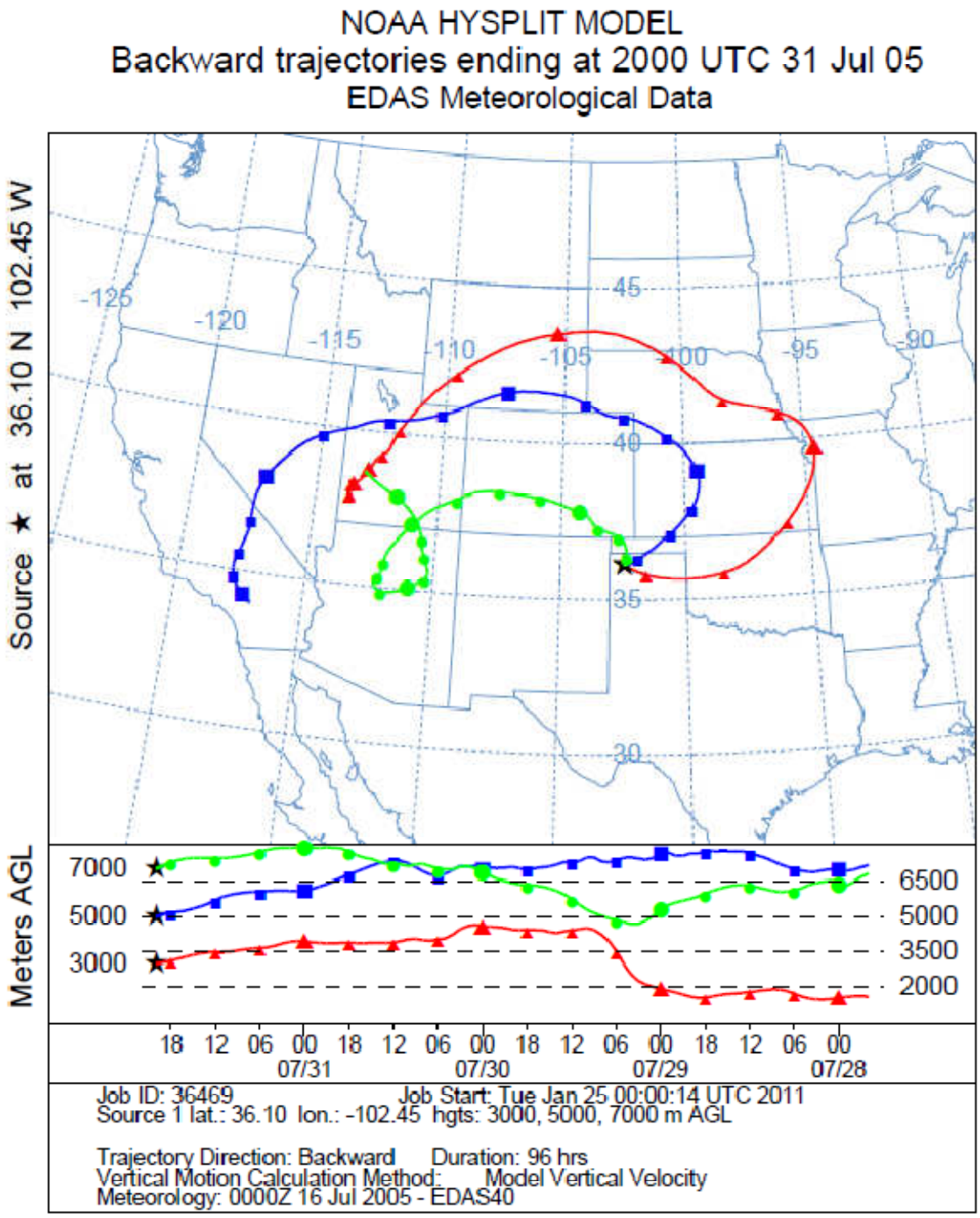

Figure A8. Four day back trajectory, starting at 7, 5, and 3 km on July 31st, 2005, starting from Dalhart, TX.

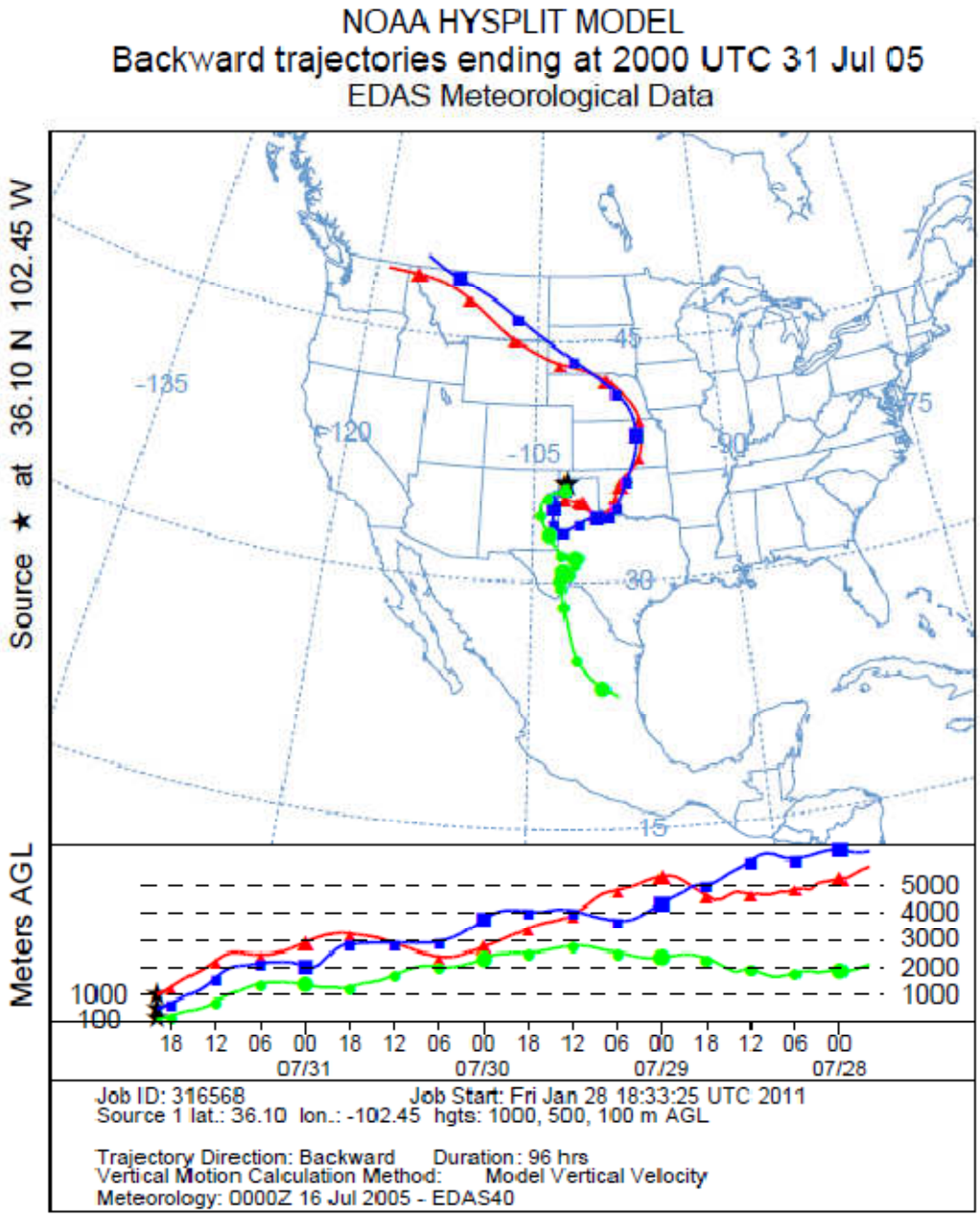

Figure A9. Four day back trajectory, starting at 1, 0.5, and 0.1 km on July 31st, 2005, starting from Dalhart, TX.

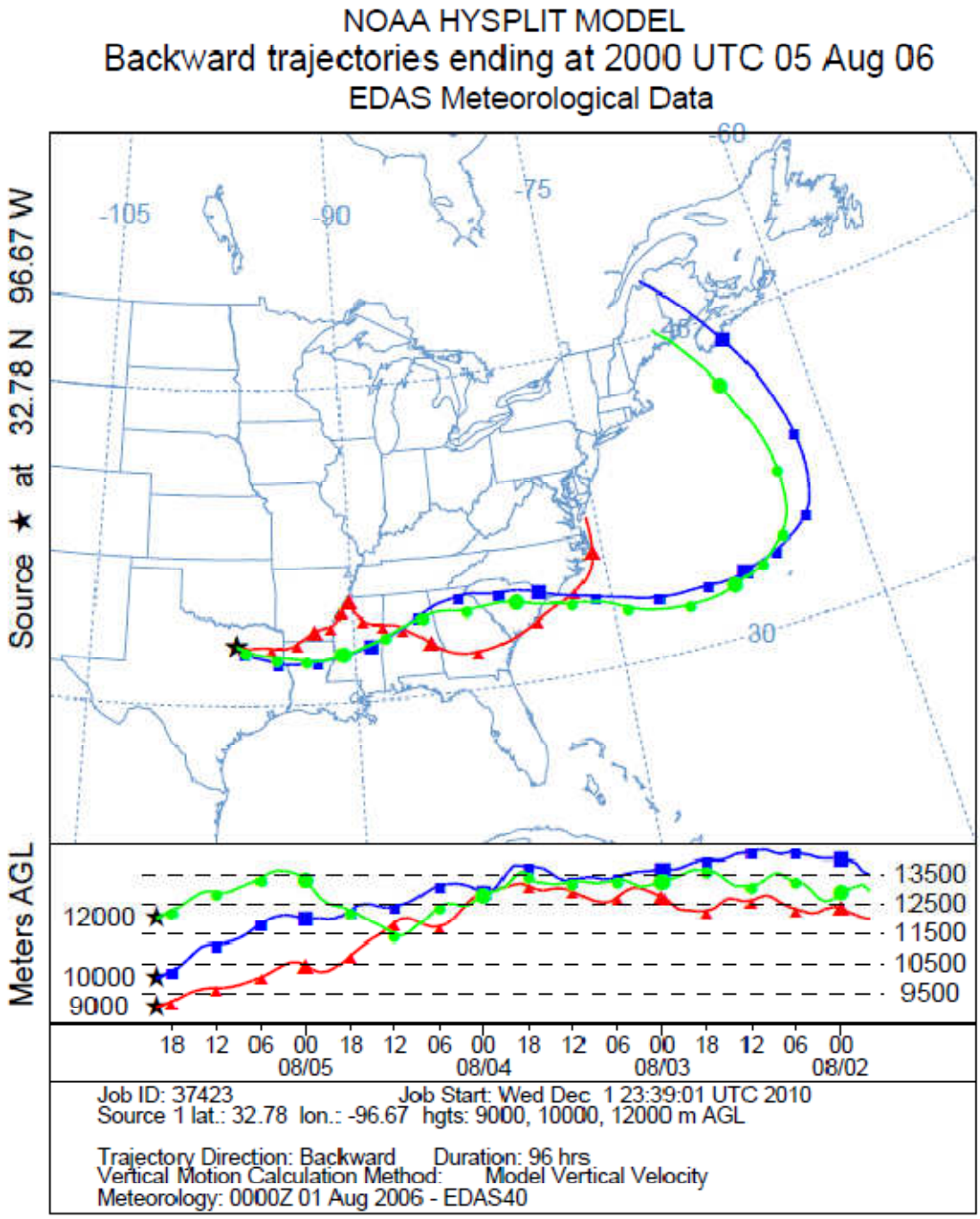

Figure A10. Four day back trajectory, starting at 12, 10, and 9 km on Aug 5th, 2005, starting from Dallas, TX.

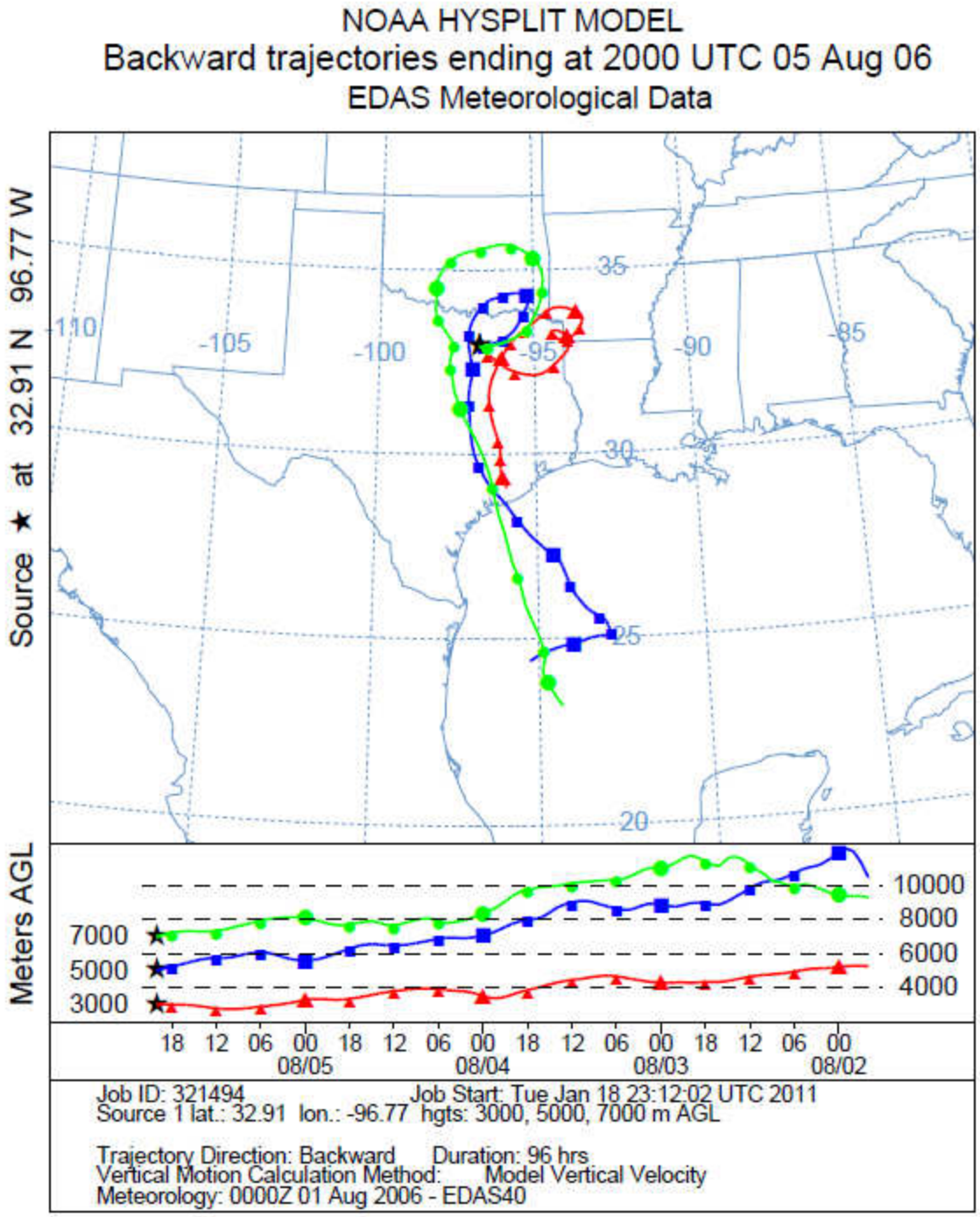

Figure A11. Four day back trajectory, starting at 7, 5, and 3 km on Aug 5th, 2005, starting from Dallas, TX.

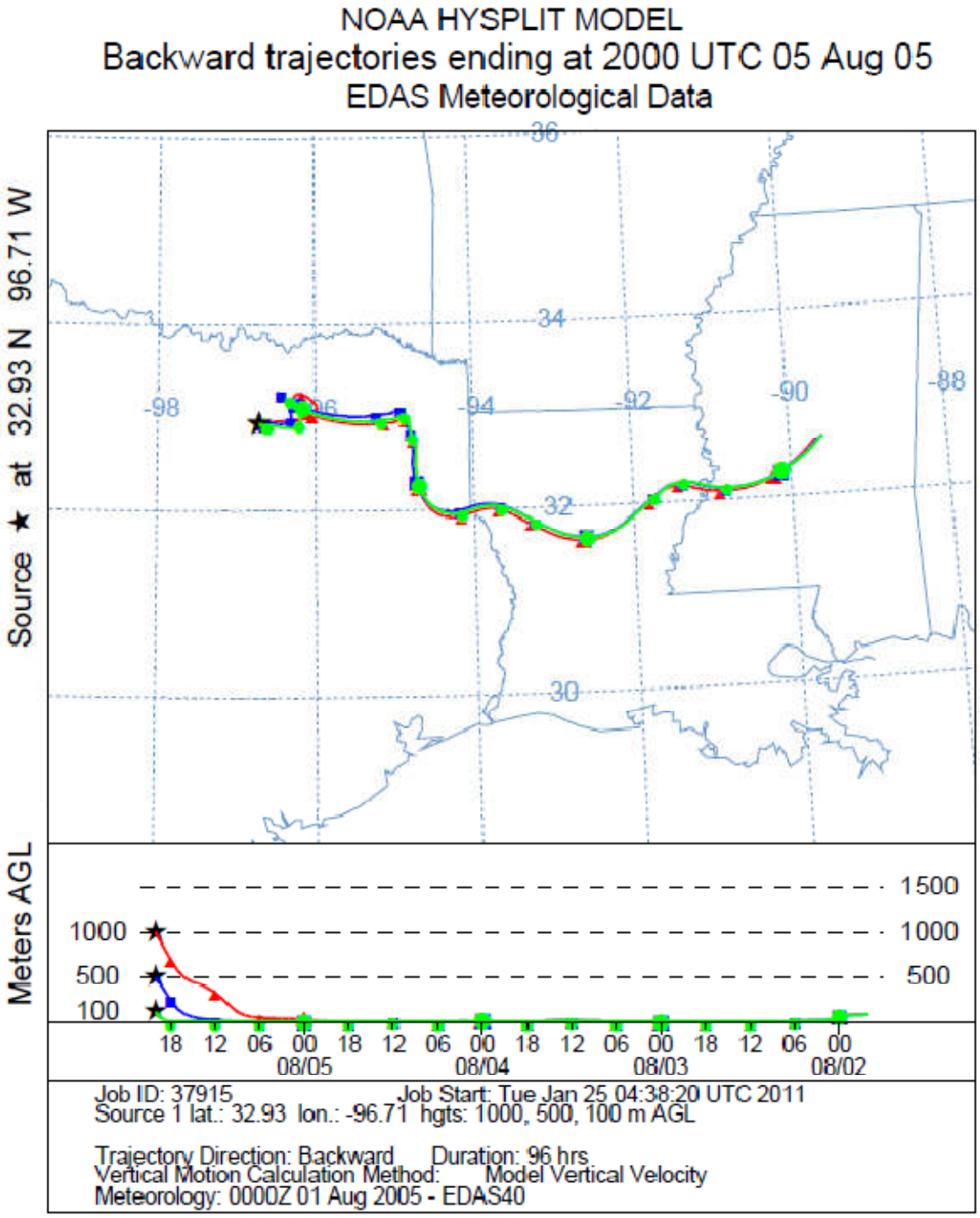

Figure A12. Four day back trajectory, starting at 1, 0.5, and 0.1 km on Aug 5th, 2005, starting from Dallas, TX.

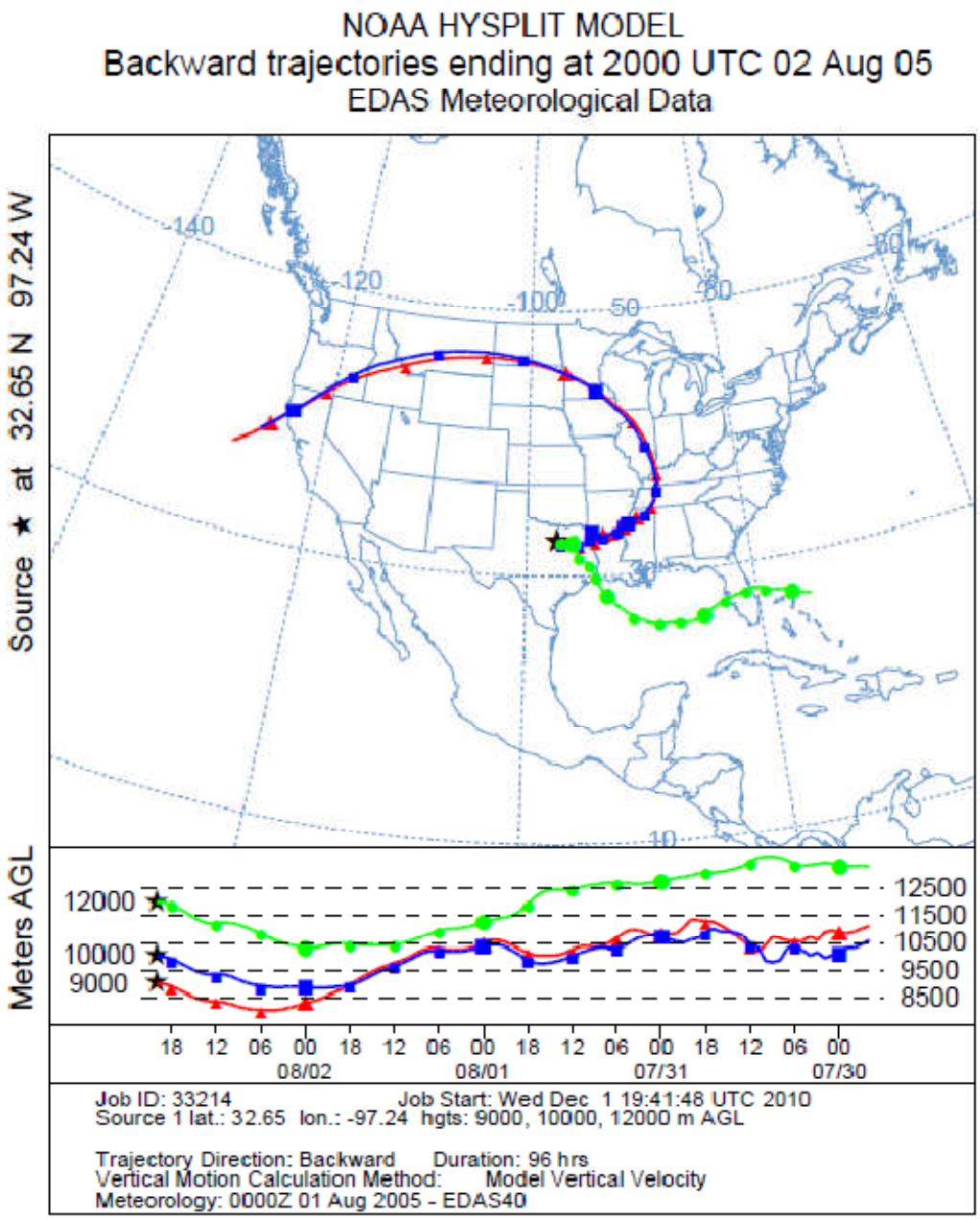

Figure A13. Four day back trajectory, starting at 12, 10, and 9 km on Aug 2nd, 2005, starting from Fort Worth, TX.

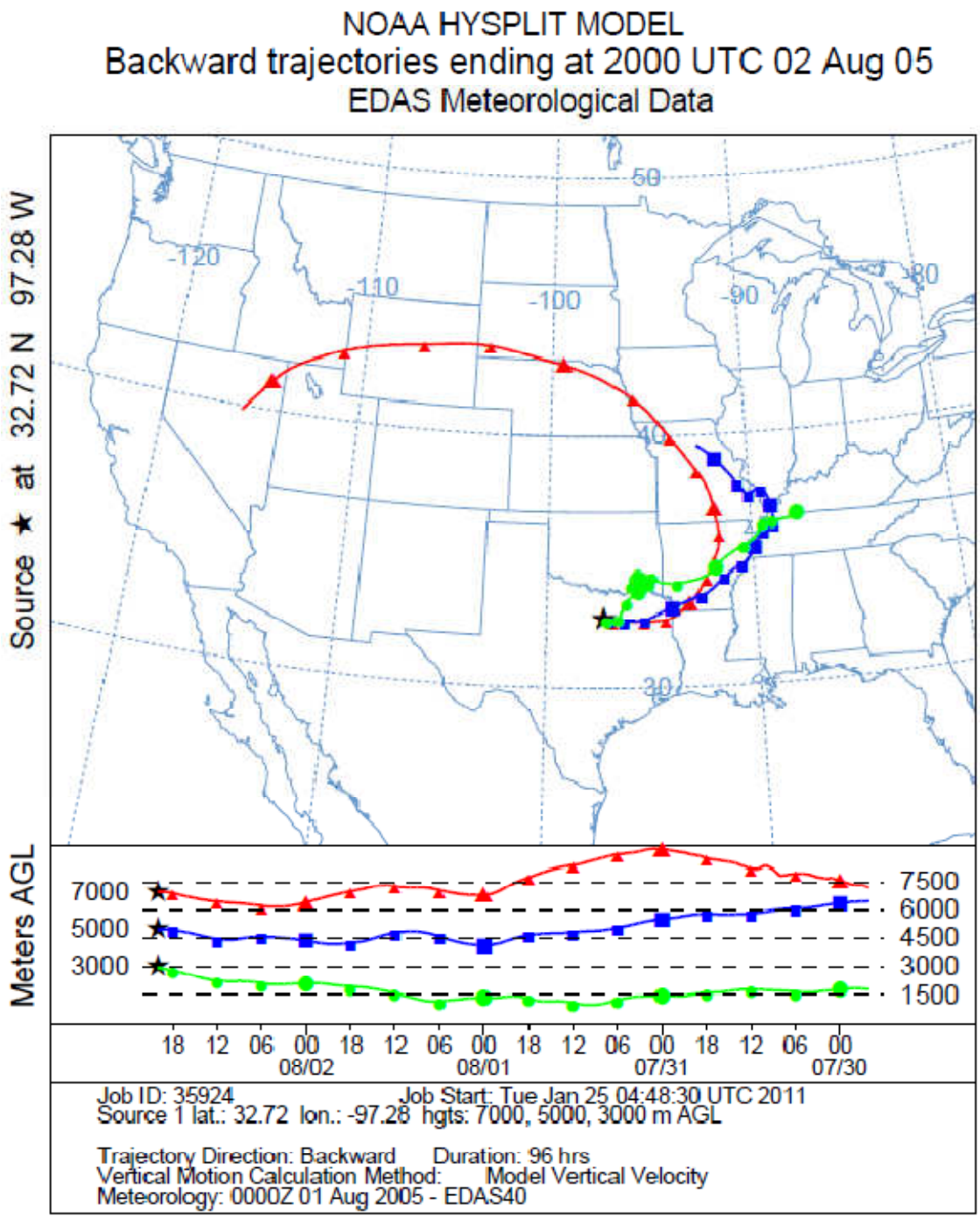

Figure A14. Four day back trajectory, starting at 7, 5, and 3 km on Aug 2nd, 2005, starting from Fort Worth, TX.

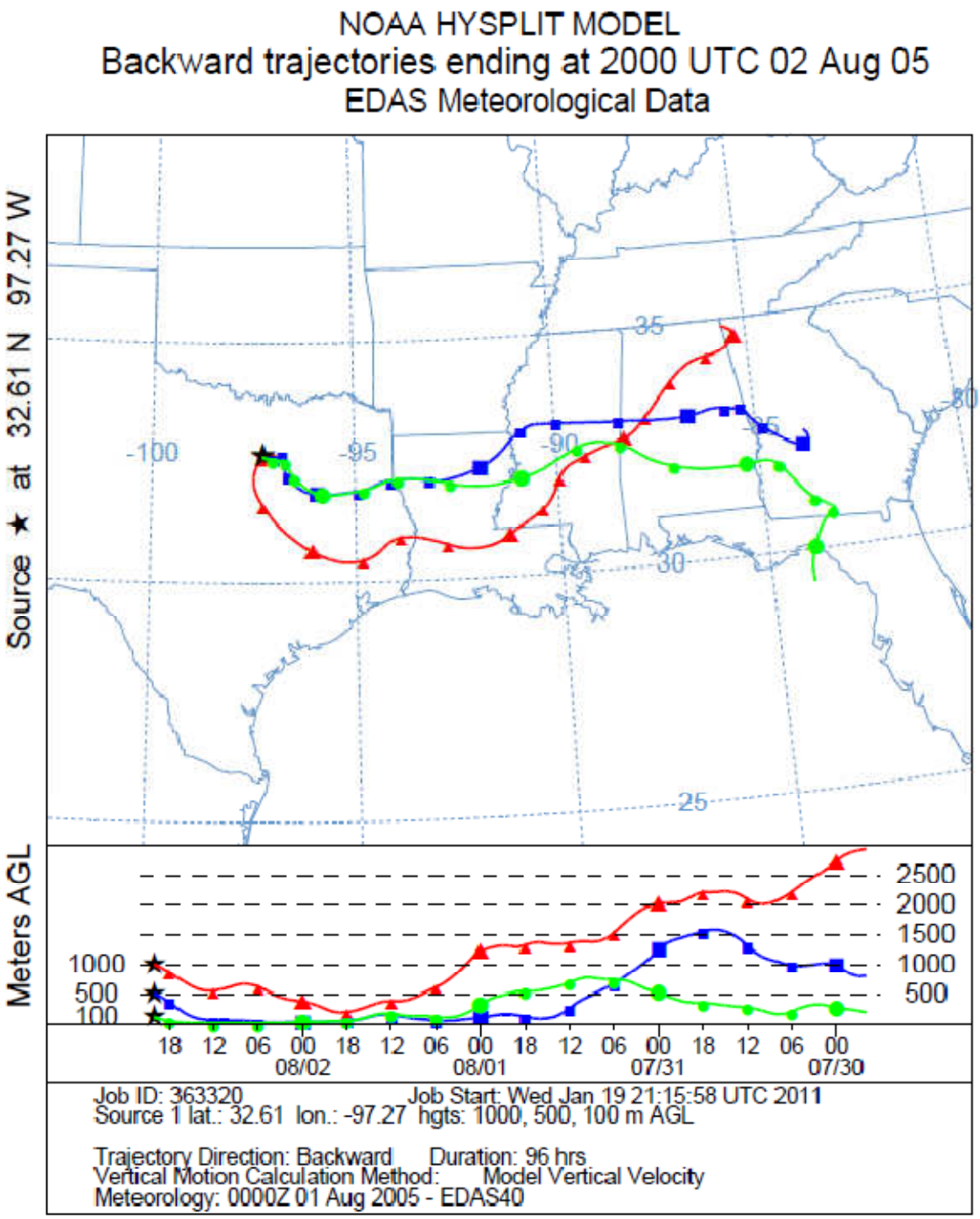

Figure A15. Four day back trajectory, starting at 1, 0.5, and 0.1 km on Aug 2nd, 2005, starting from Fort Worth, TX.

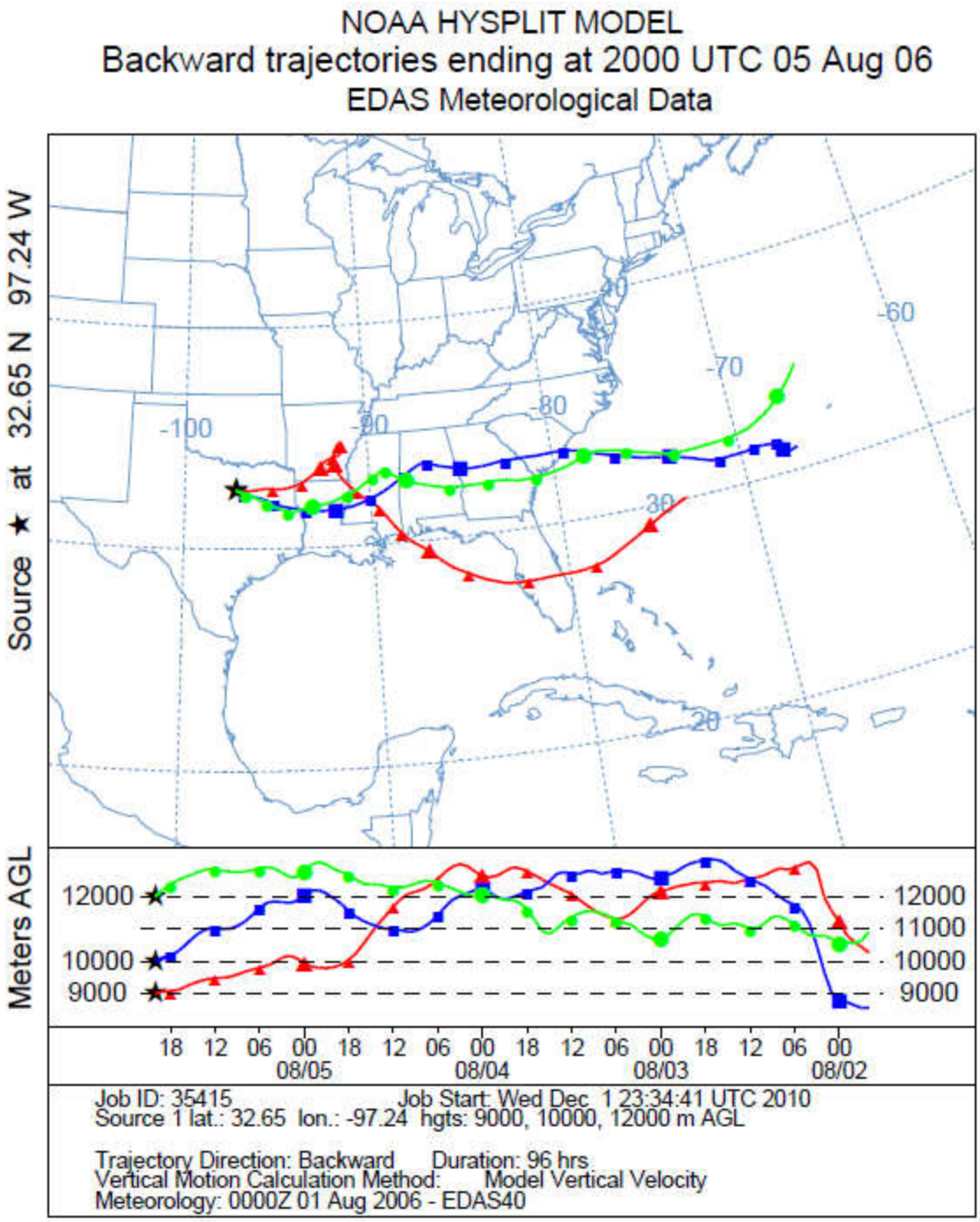

Figure A16. Four day back trajectory, starting at 12, 10, and 9 km on Aug 2nd, 2005, starting from Fort Worth, TX.

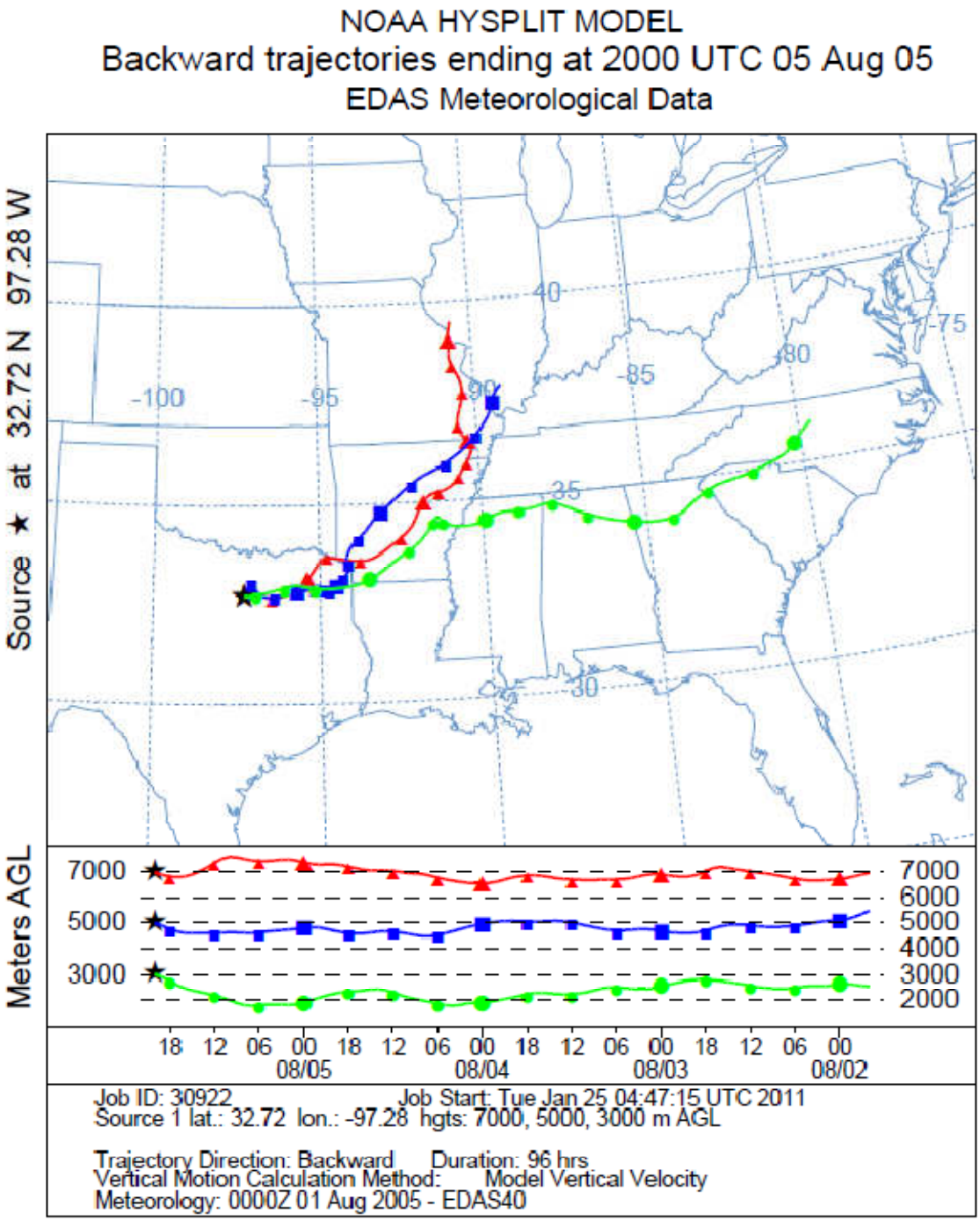

Figure A17. Four day back trajectory, starting at 7, 5, and 3 km on Aug 2nd, 2005, starting from Fort Worth, TX.

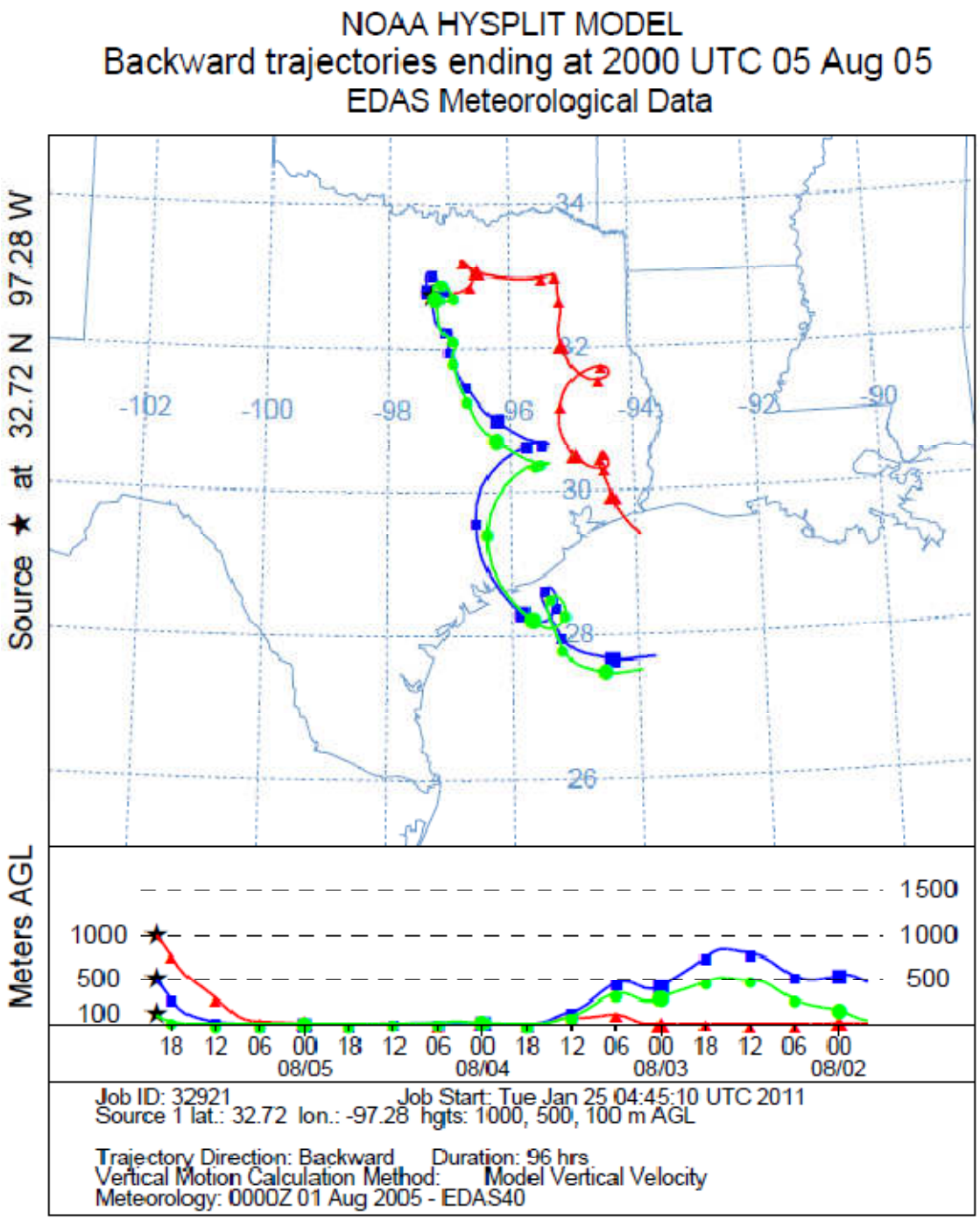

Figure A18. Four day back trajectory, starting at 1, 0.5, and 0.1 km on Aug 2nd, 2005, starting from Fort Worth, TX.

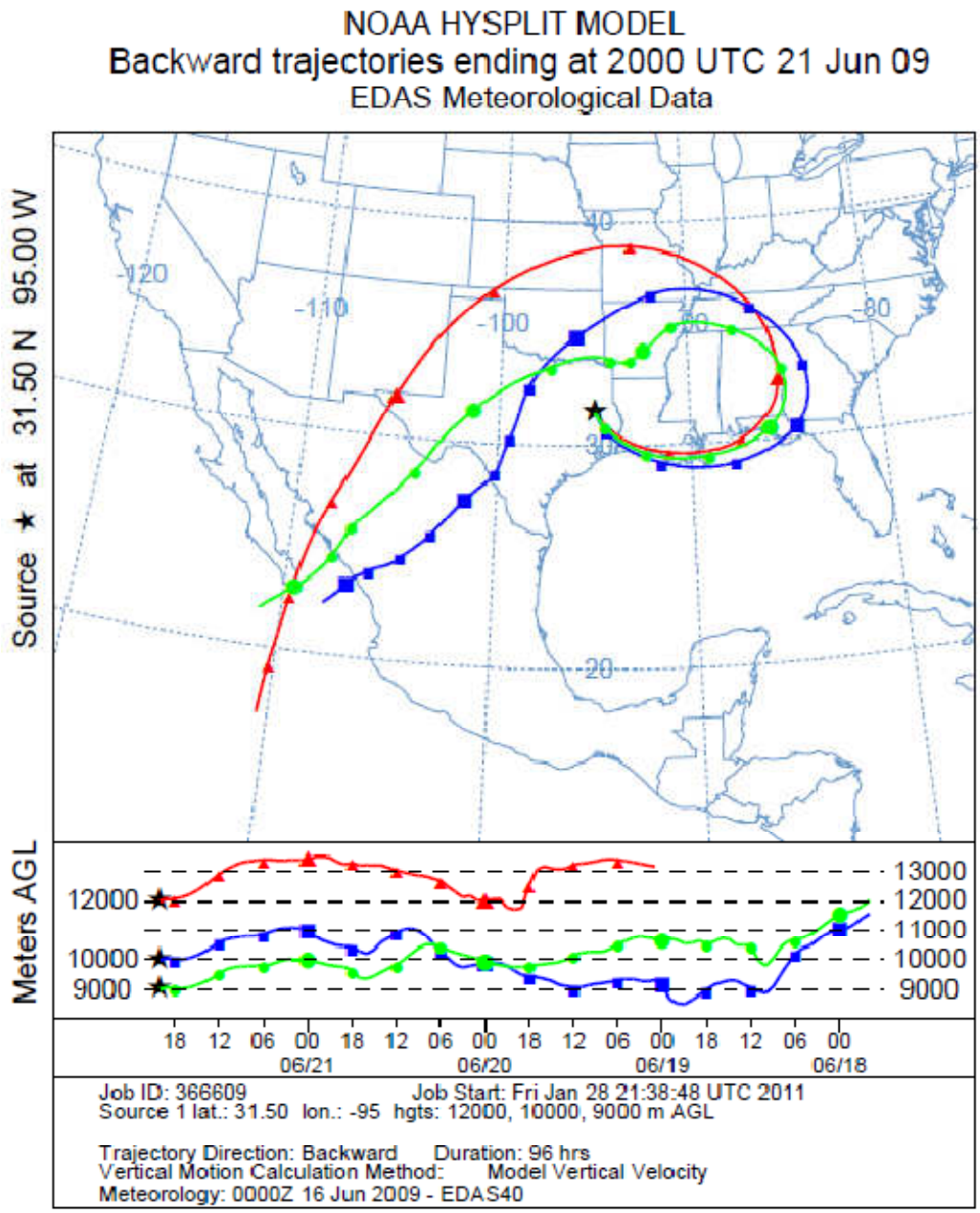

Figure A19. Four day back trajectory, starting at 12, 10, and 9 km on June 21st, 2009, starting from at 31.5 °N, 95 °W.

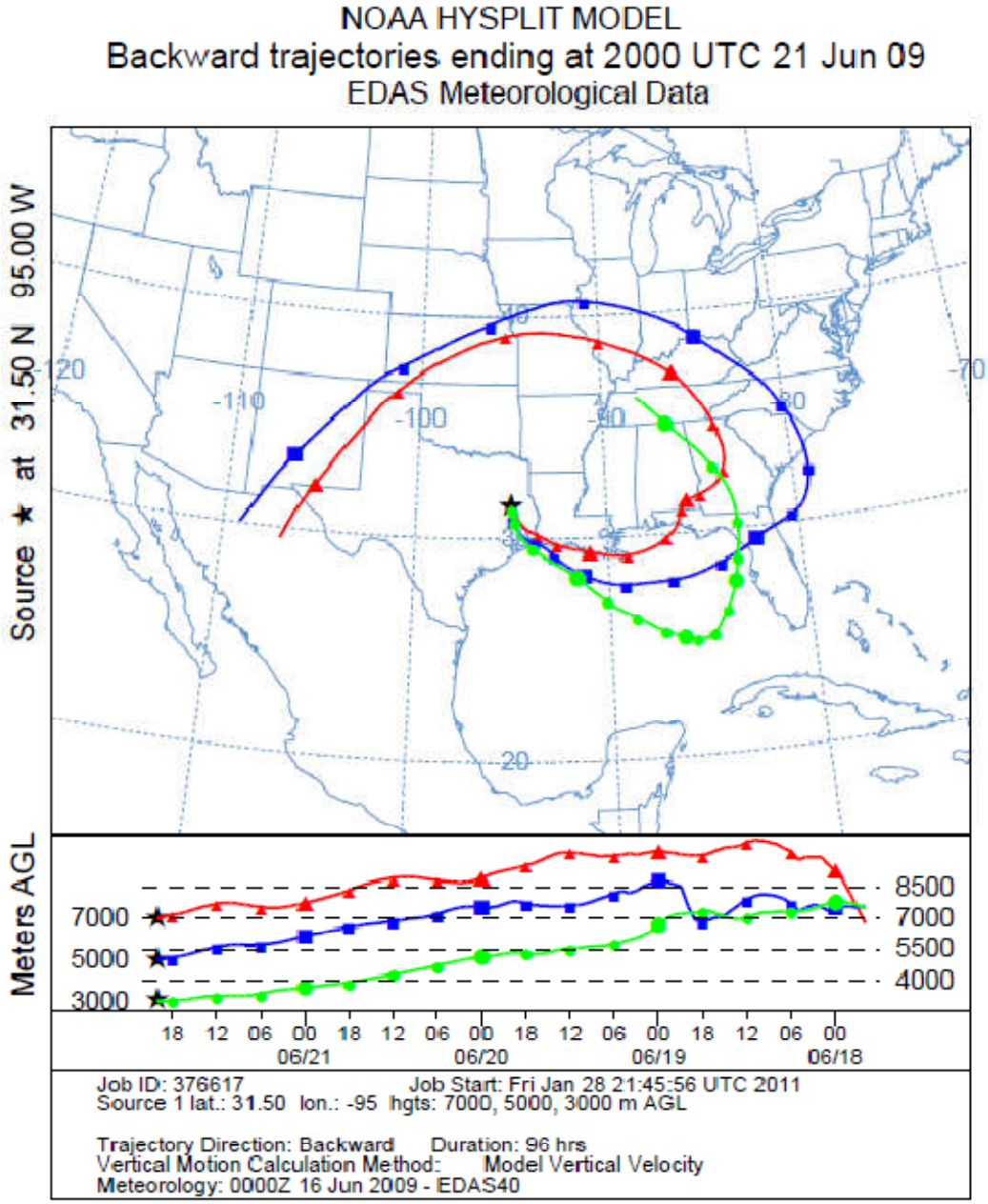

Figure A20. Four day back trajectory, starting at 7, 5, and 3 km on June 21st, 2009, starting from at 31.5 °N, 95 °W.

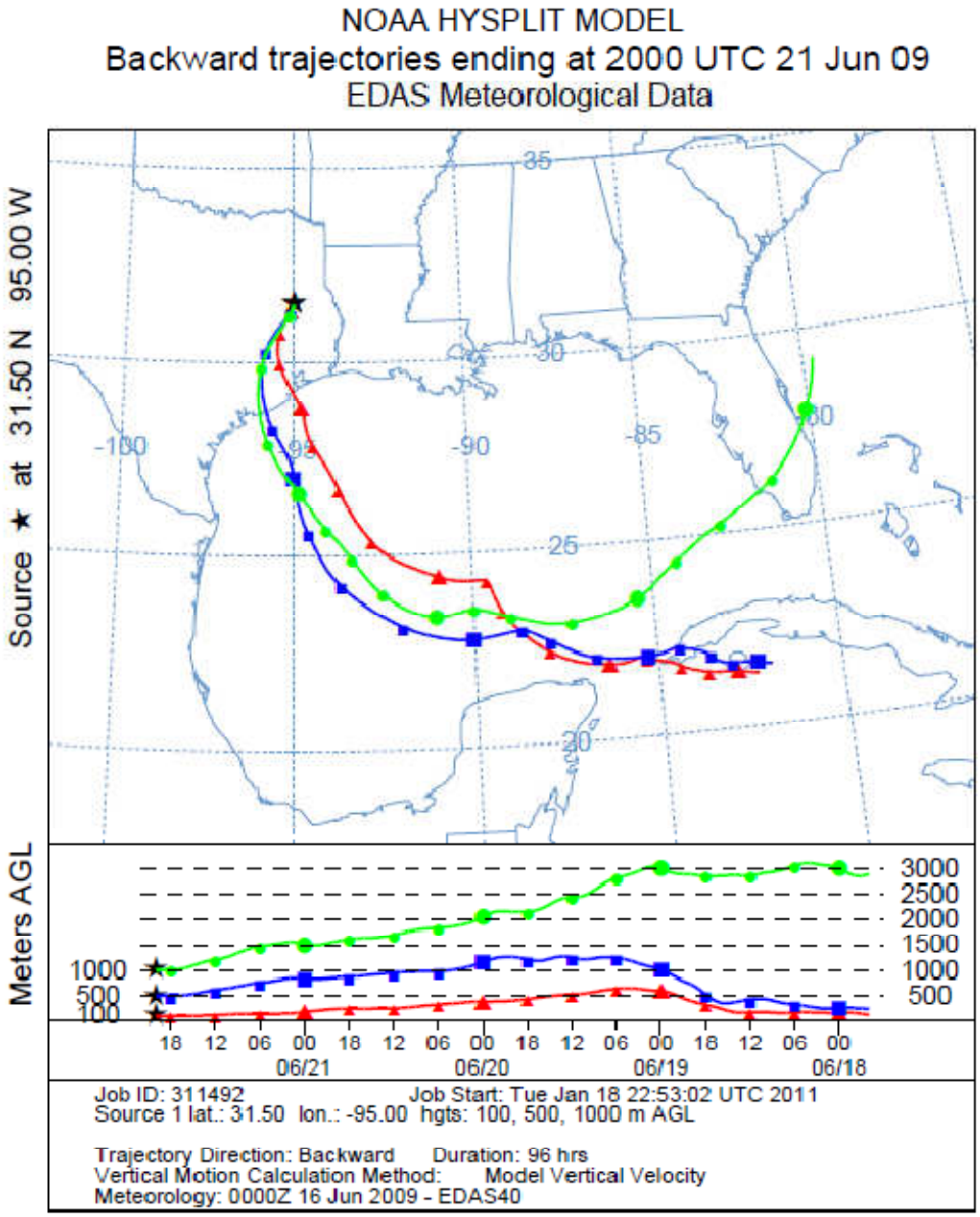

Figure A21. Four day back trajectory, starting at 1, 0.5, and 0.1 km on June 21st, 2009, starting from at 31.5 °N, 95 °W.

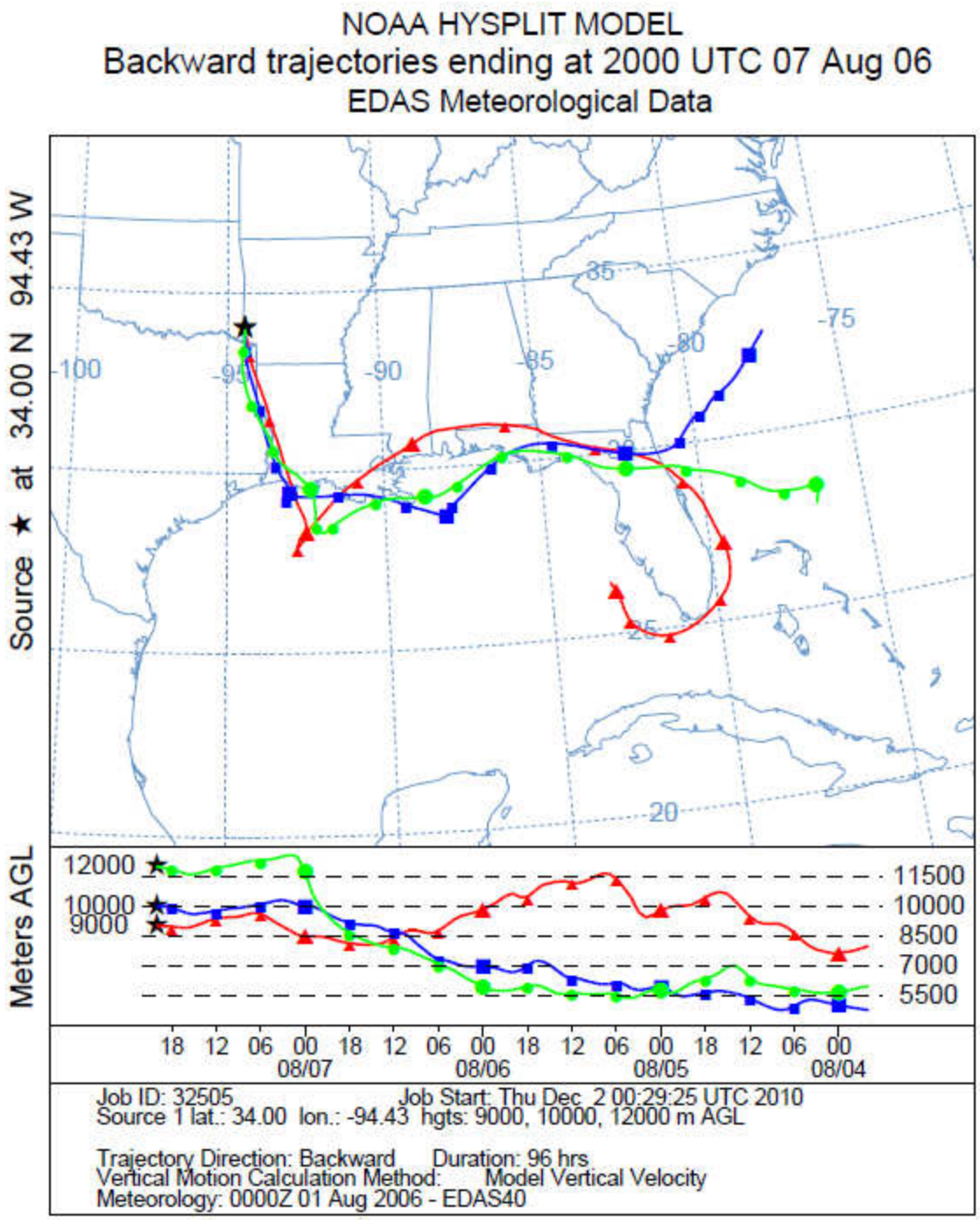

Figure A22. Four day back trajectory, starting at 12, 10, and 9 km on August 7th, 2006, starting from just south of Quachita National Forest, TX.

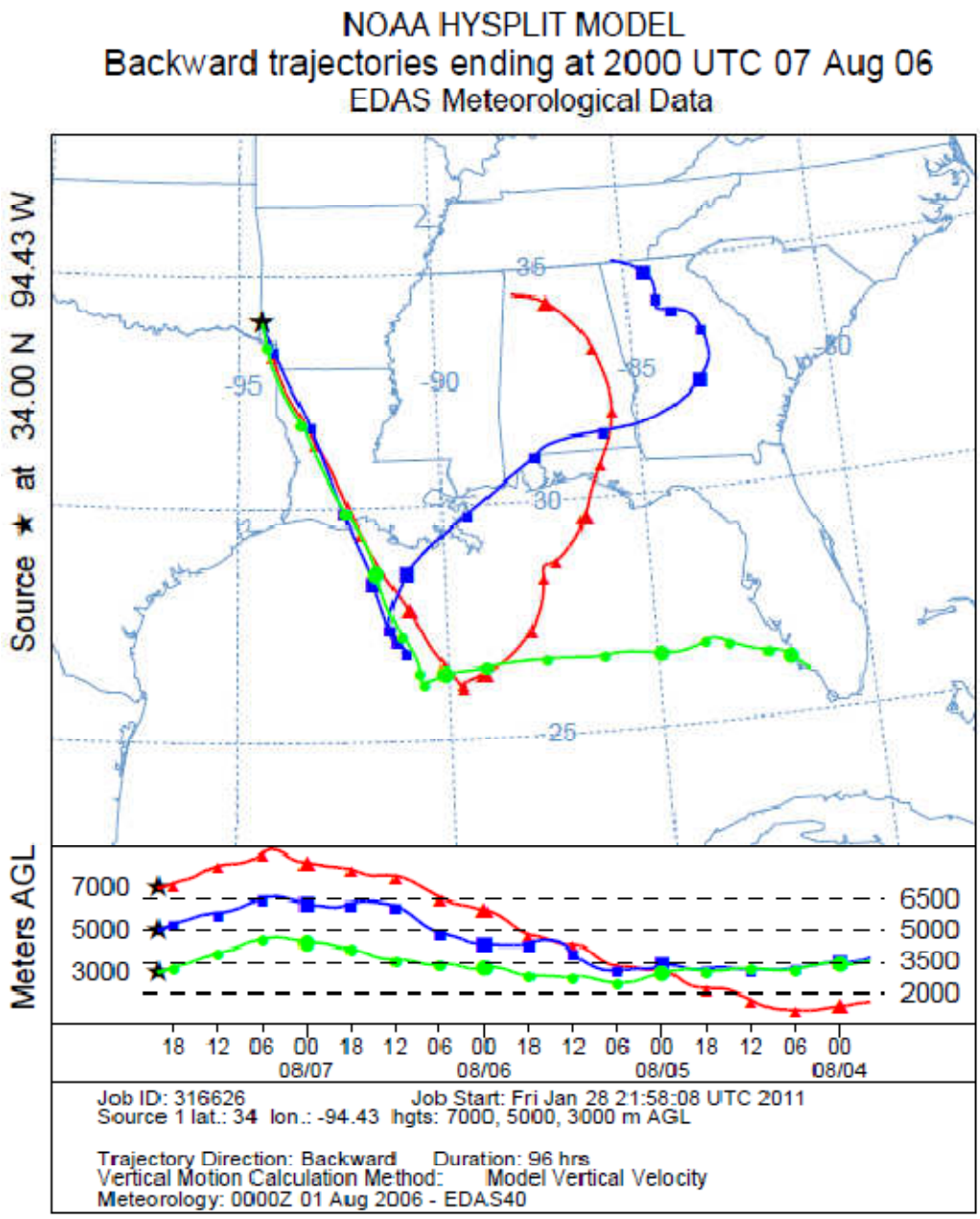

Figure A23. Four day back trajectory, starting at 7, 5, and 3 km on August 7th, 2006, starting from just south of Quachita National Forest, TX.

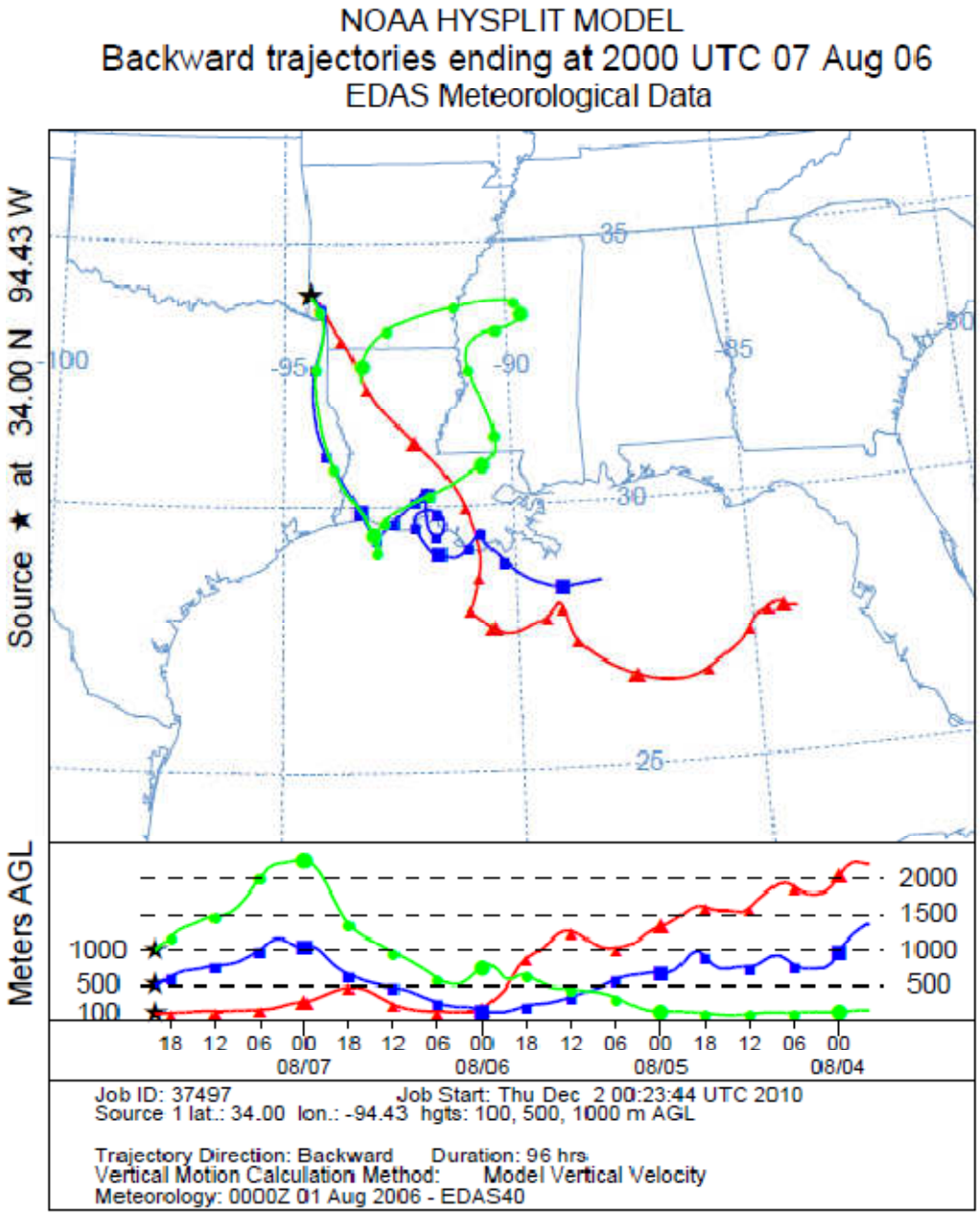

Figure A24. Four day back trajectory, starting at 1, 0.5, and 0.1 km on August 7th, 2006, starting from just south of Quachita National Forest, TX.

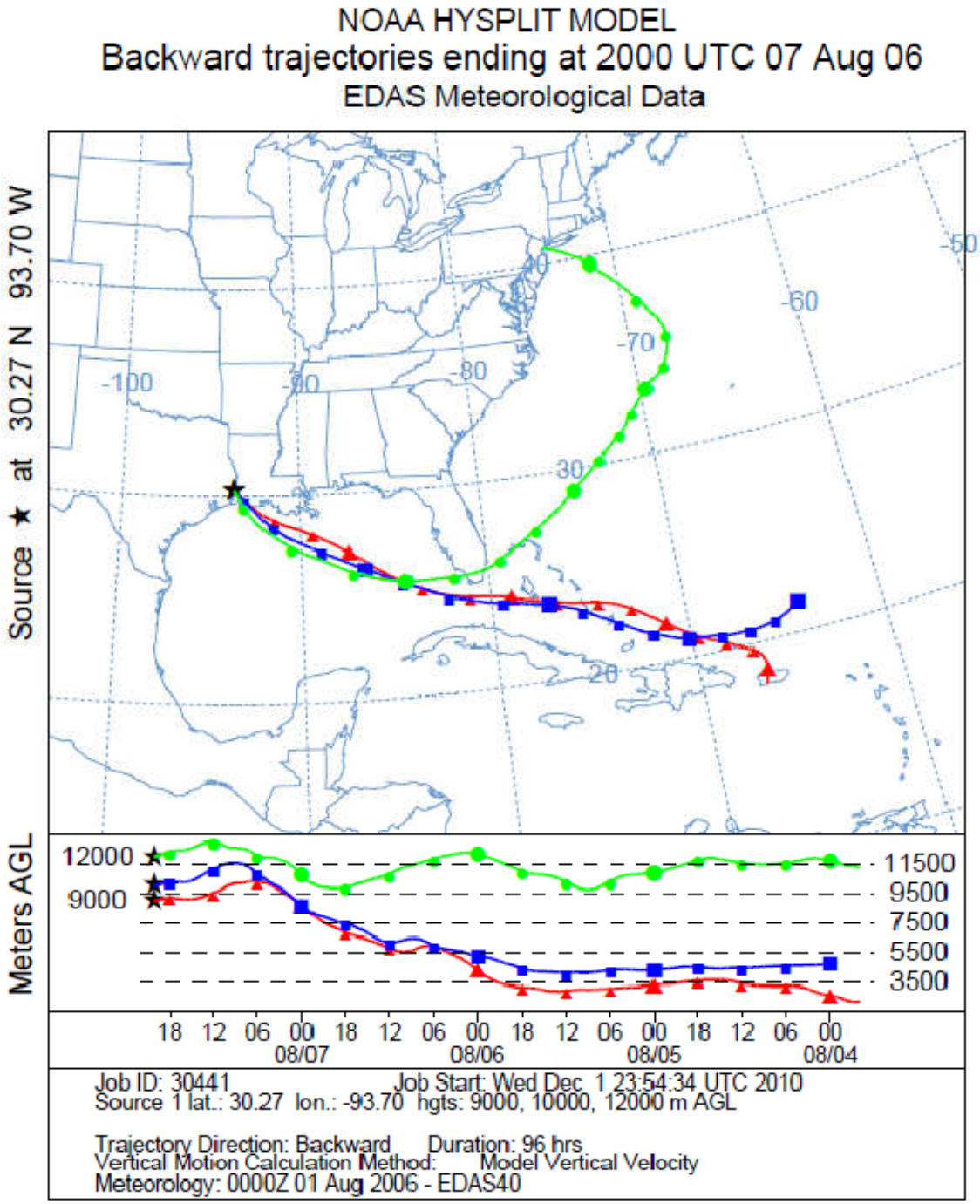

Figure A25. Four day back trajectory, starting at 12, 10, and 9 km on August 7th, 2006, starting from Lower-Texas-Louisiana border.

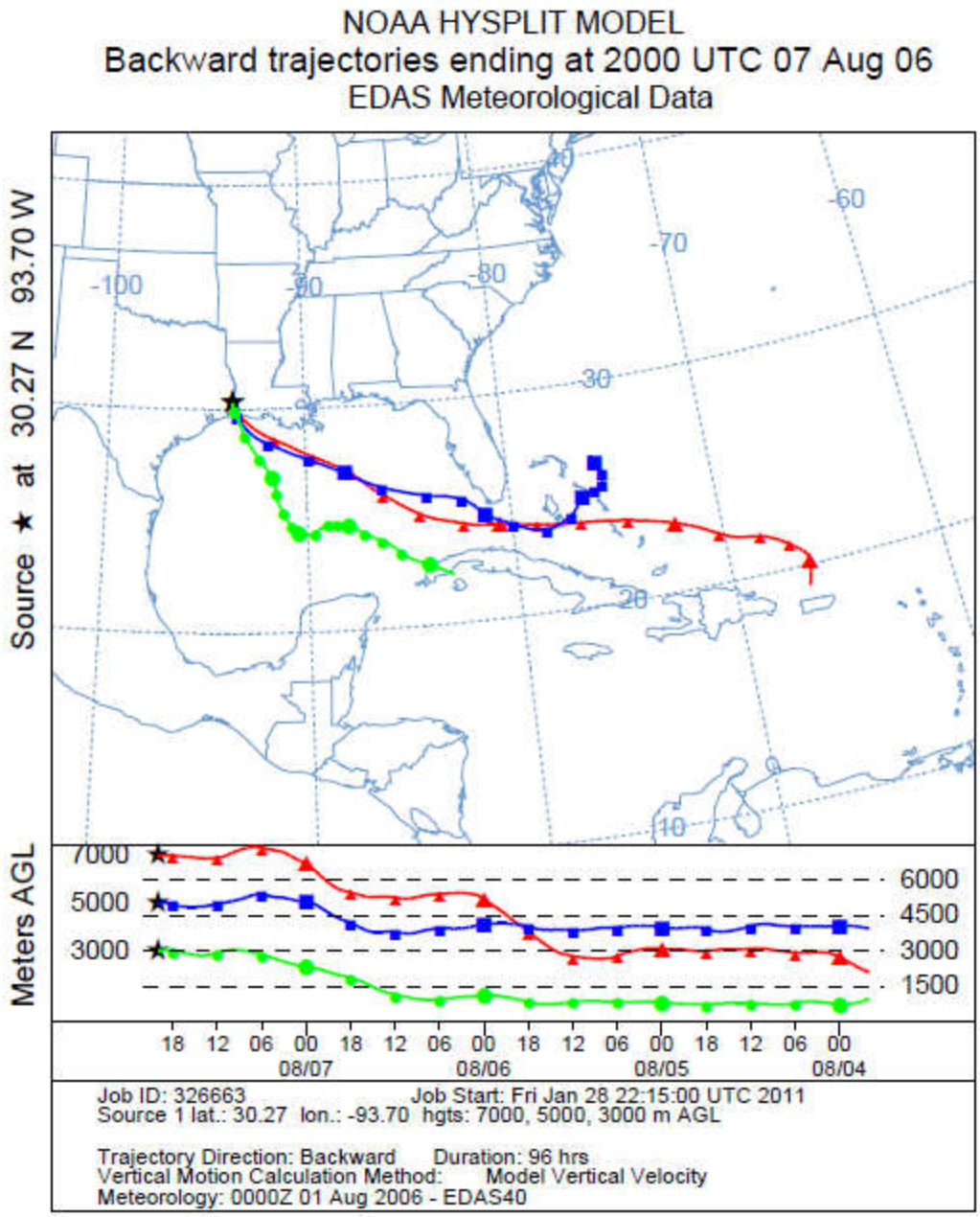

Figure A26. Four day back trajectory, starting at 7, 5, and 3 km on August 7th, 2006, starting from Lower-Texas-Louisiana border.

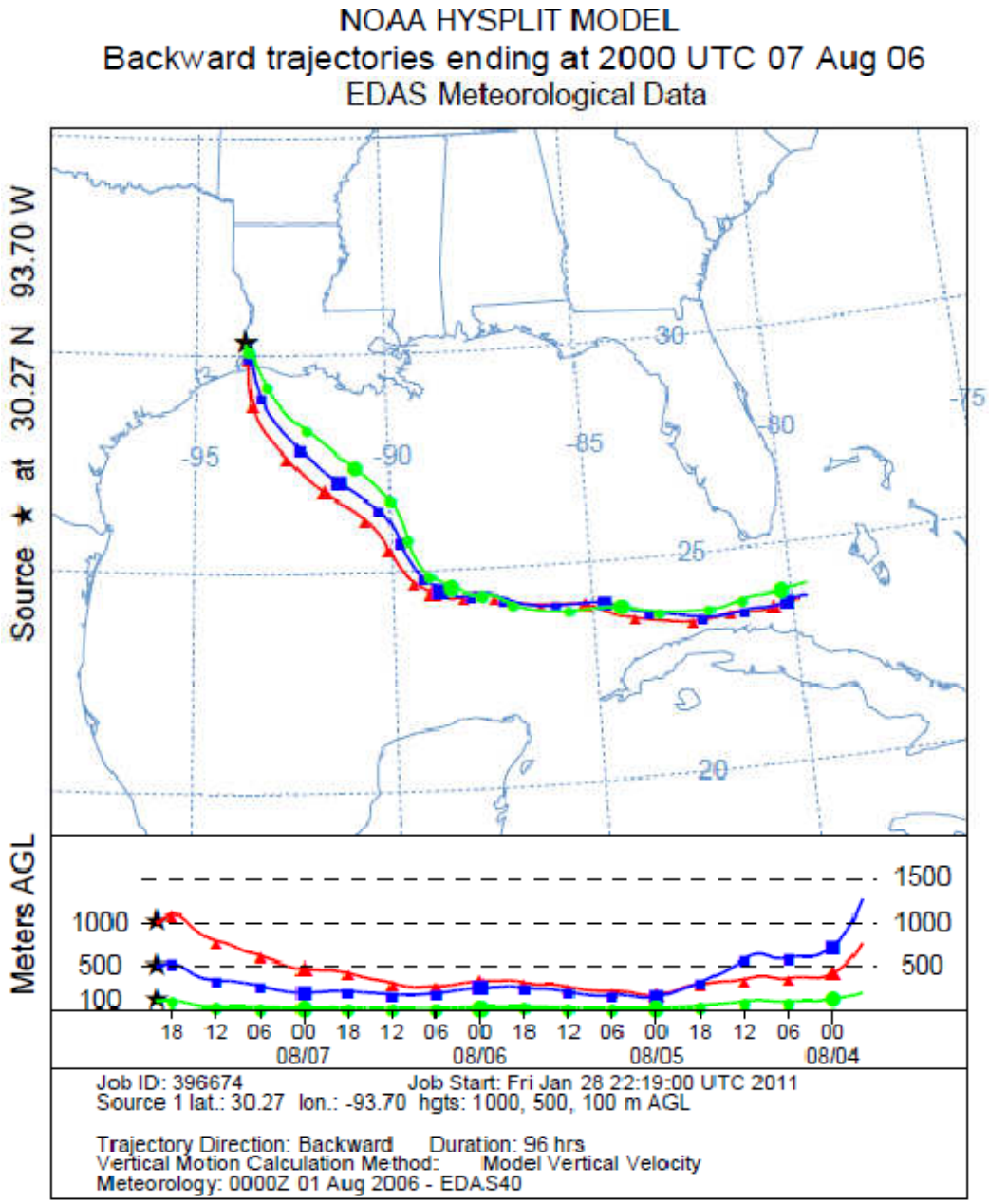

Figure A27. Four day back trajectory, starting at 1, 0.5, and 0.1 km on August 7th, 2006, starting from Lower-Texas-Louisiana border.

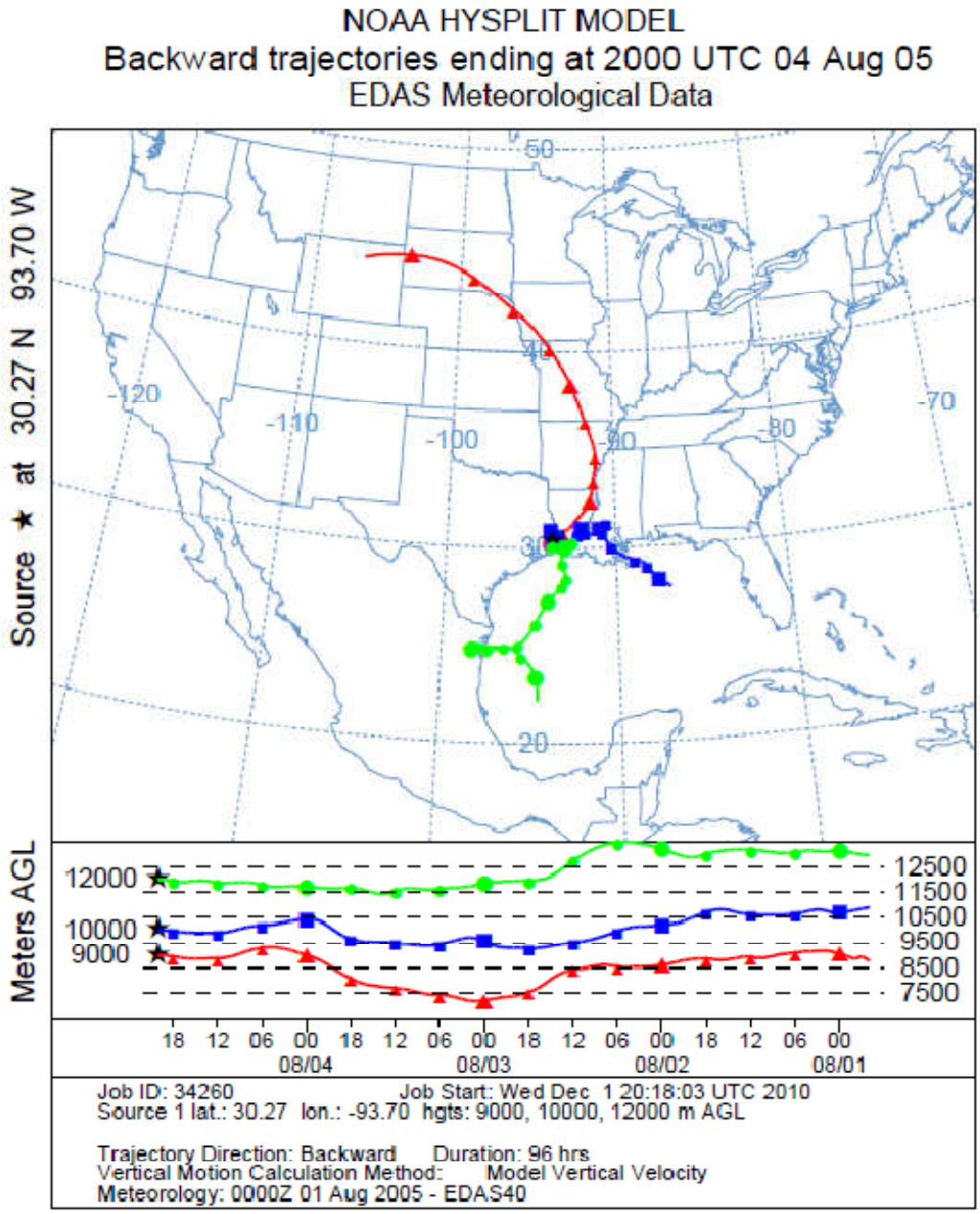

Figure A28. Four day back trajectory, starting at 12, 10, and 9 km on August 4th, 2005, starting from Lower-Texas-Louisiana border.

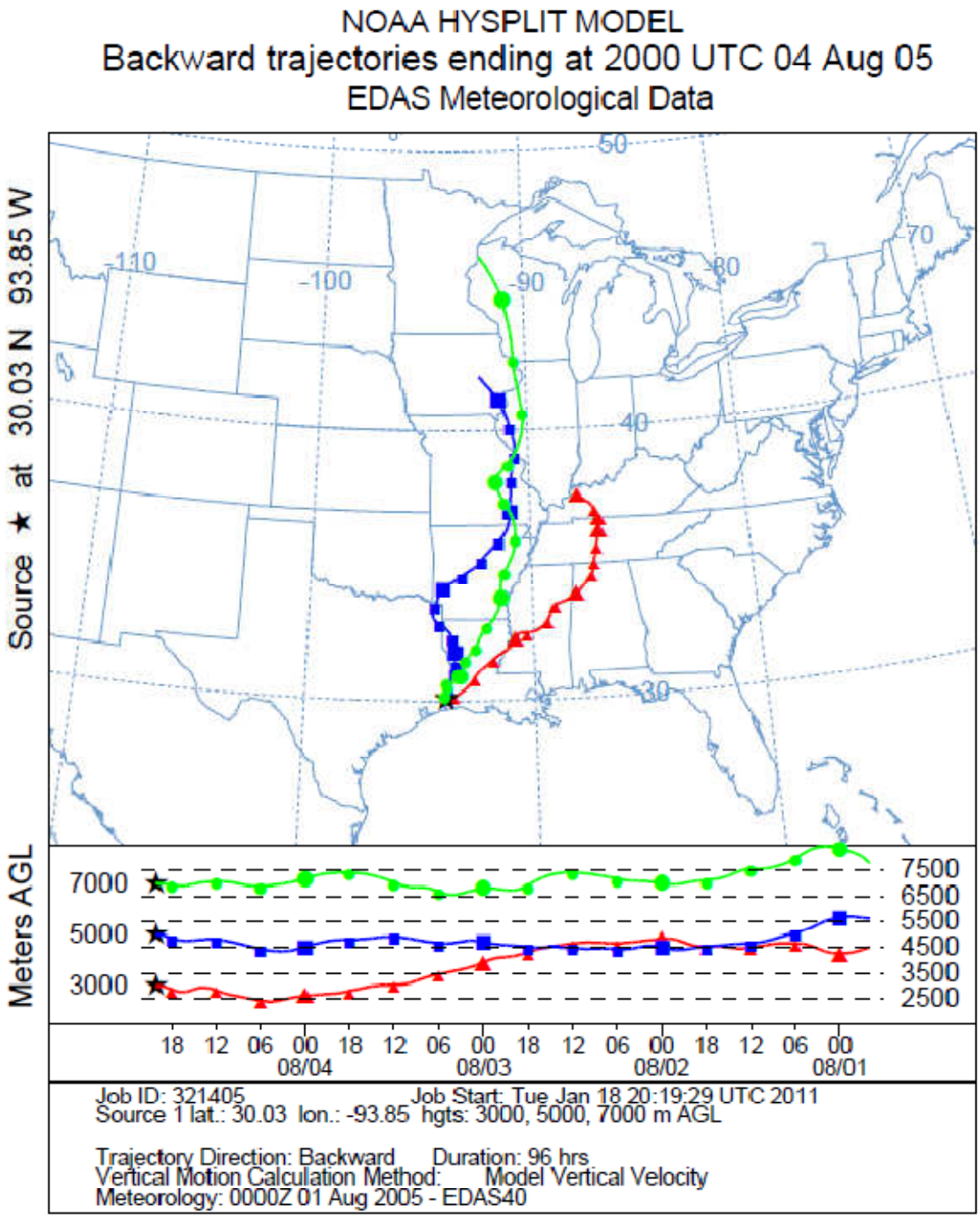

Figure A29. Four day back trajectory, starting at 7, 5, and 3 km on August 4th, 2005, starting from Lower-Texas-Louisiana border.

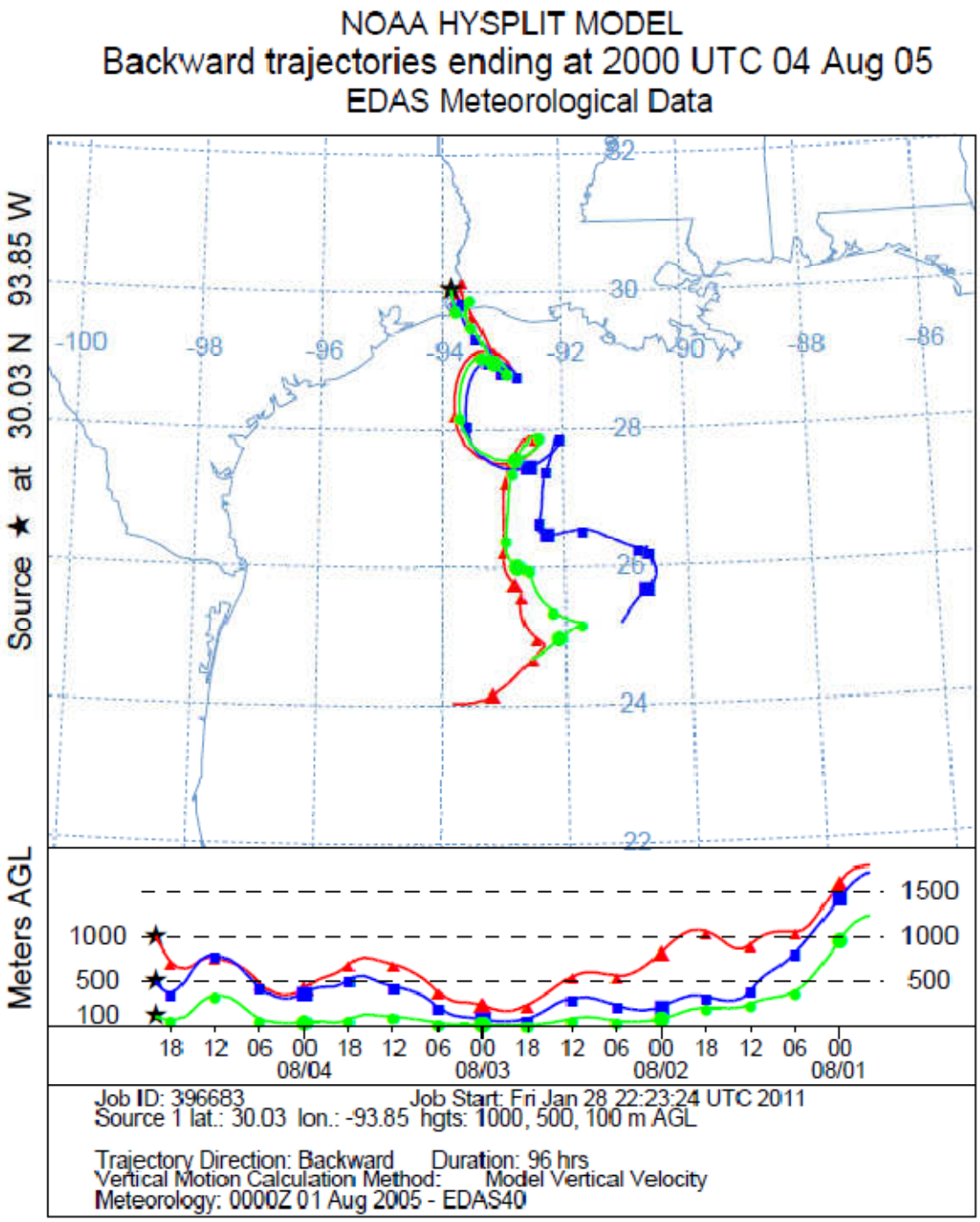

Figure A30. Four day back trajectory, starting at 1, 0.5, and 0.1 km on August 4th, 2005, starting from Lower-Texas-Louisiana border.

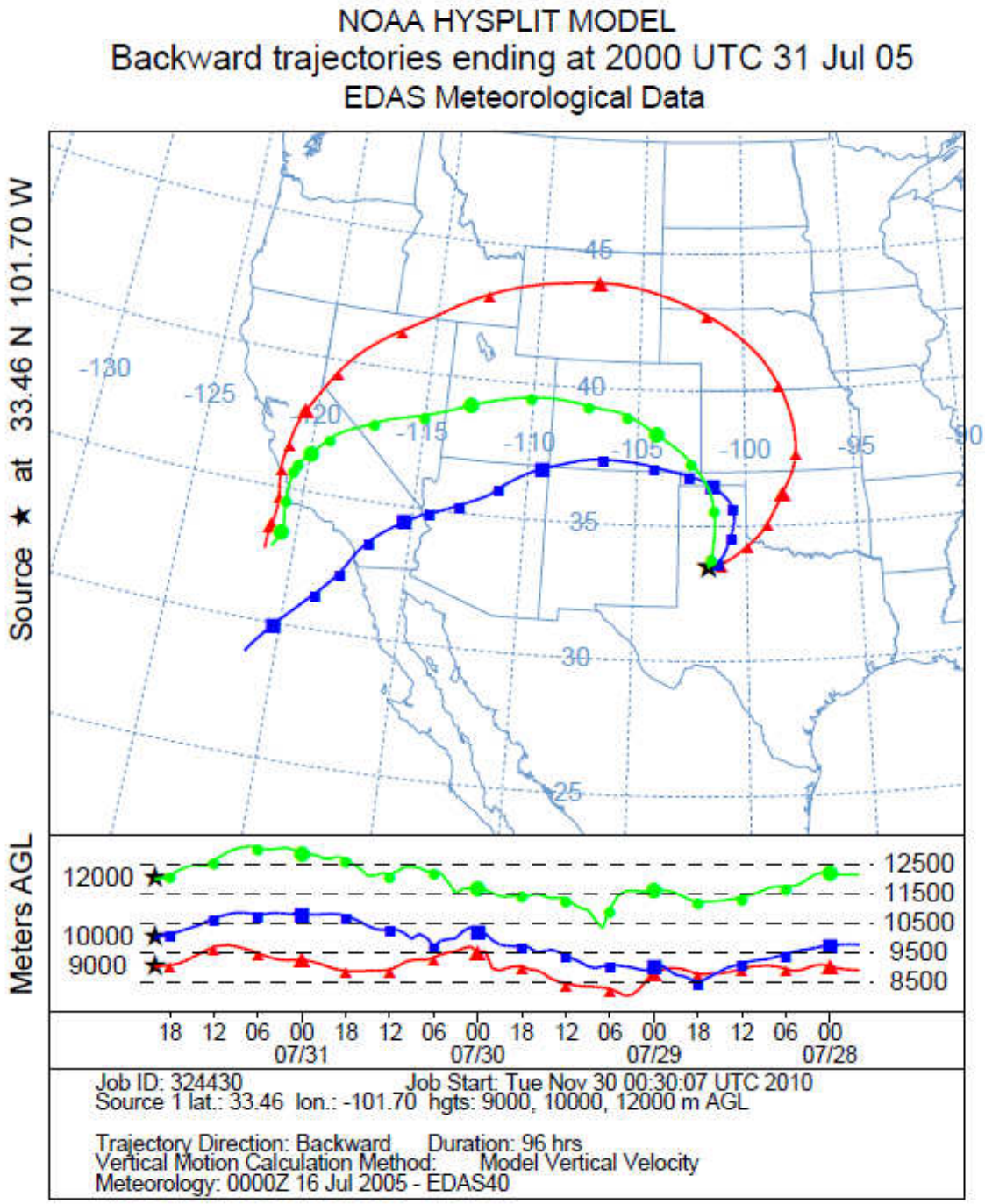

Figure A31. Four day back trajectory, starting at 12, 10, and 9 km on July 31st, 2005, starting from Lubbock, TX.

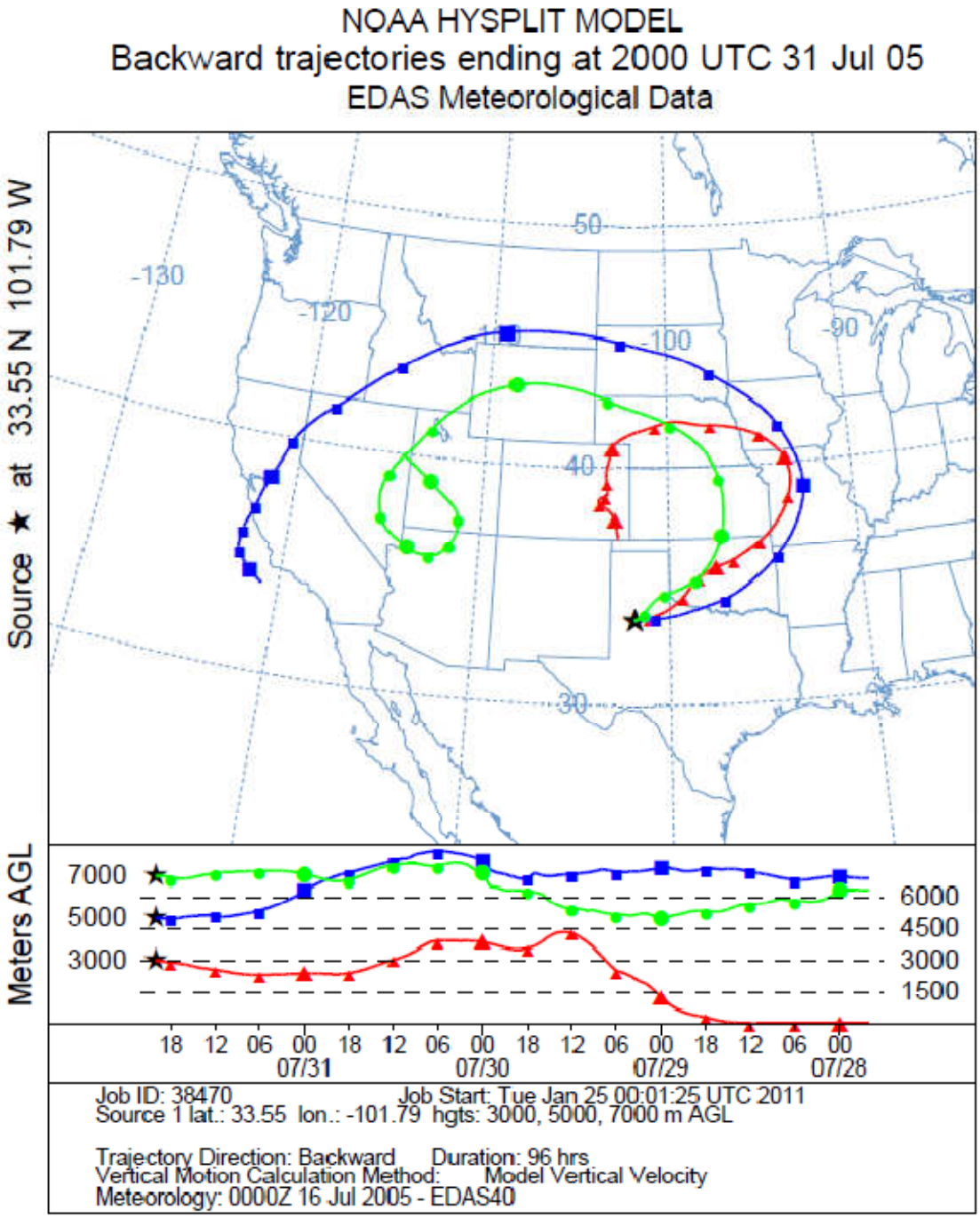

Figure A32. Four day back trajectory, starting at 7, 5, and 3 km on July 31st, 2005, starting from Lubbock, TX.

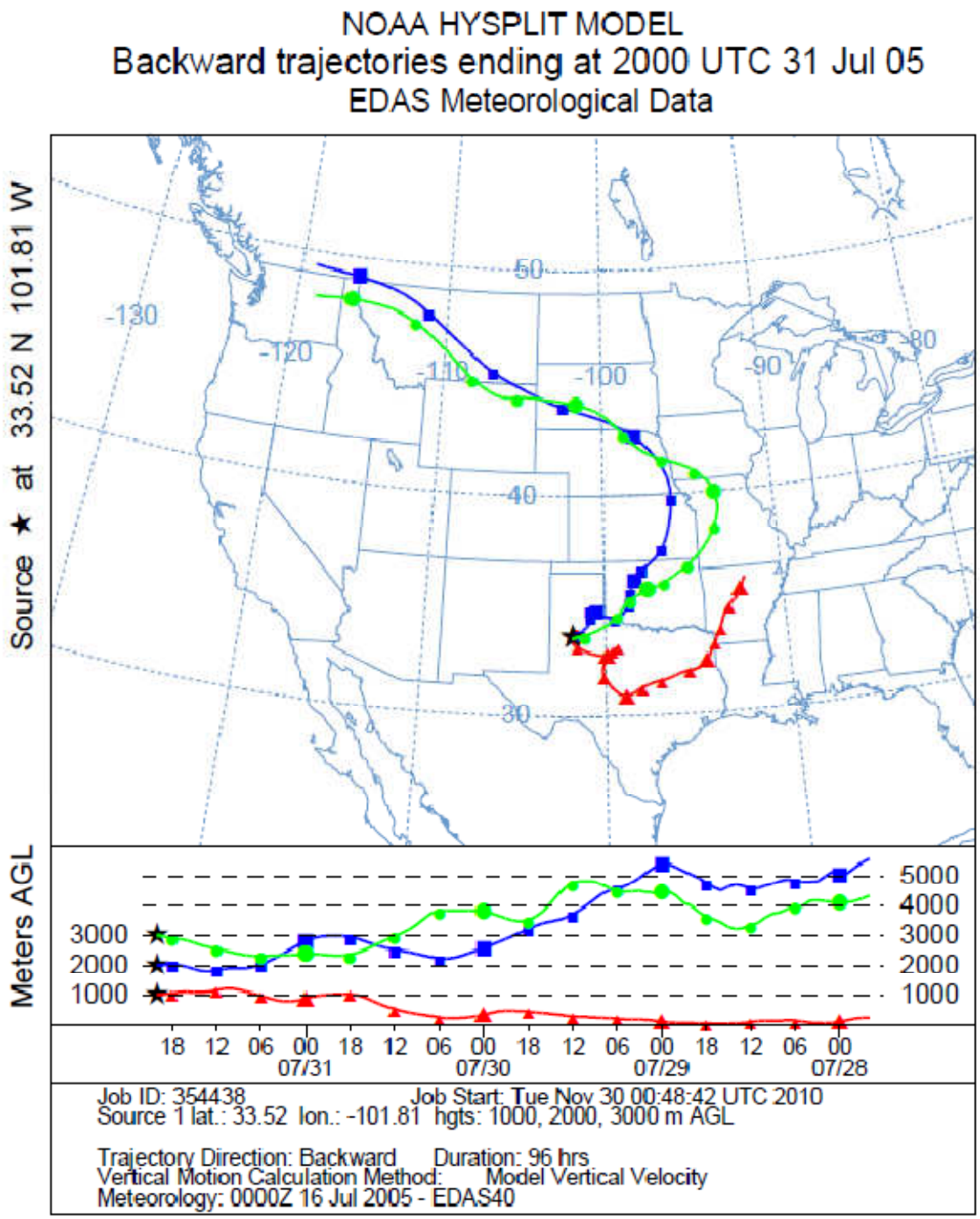

Figure A33. Four day back trajectory, starting at 3, 2, and 1 km on July 31st, 2005, starting from Lubbock, TX.

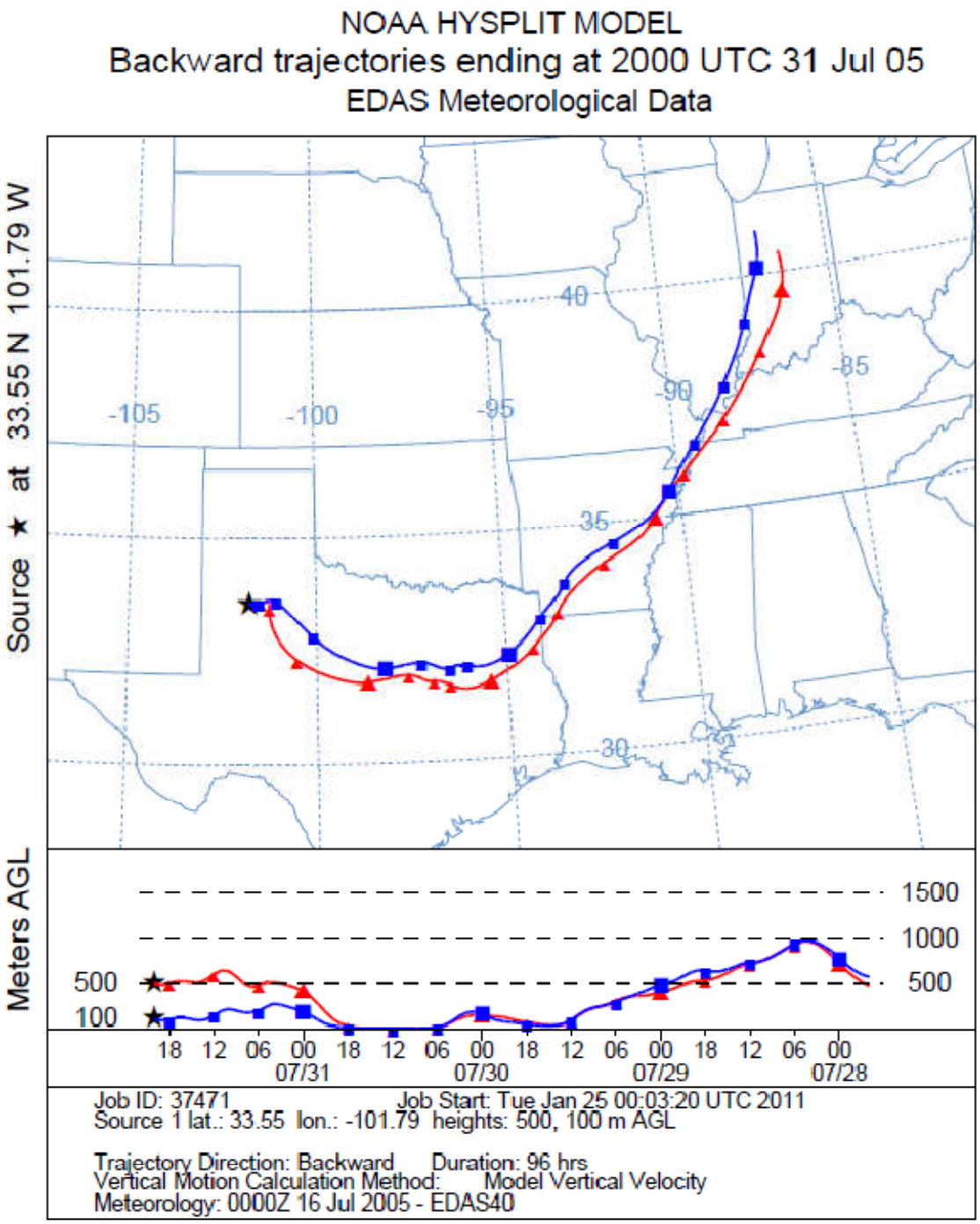

Figure A34. Four day back trajectory, starting at 0.5 and 0.1 km on July 31st, 2005, starting from Lubbock, TX.

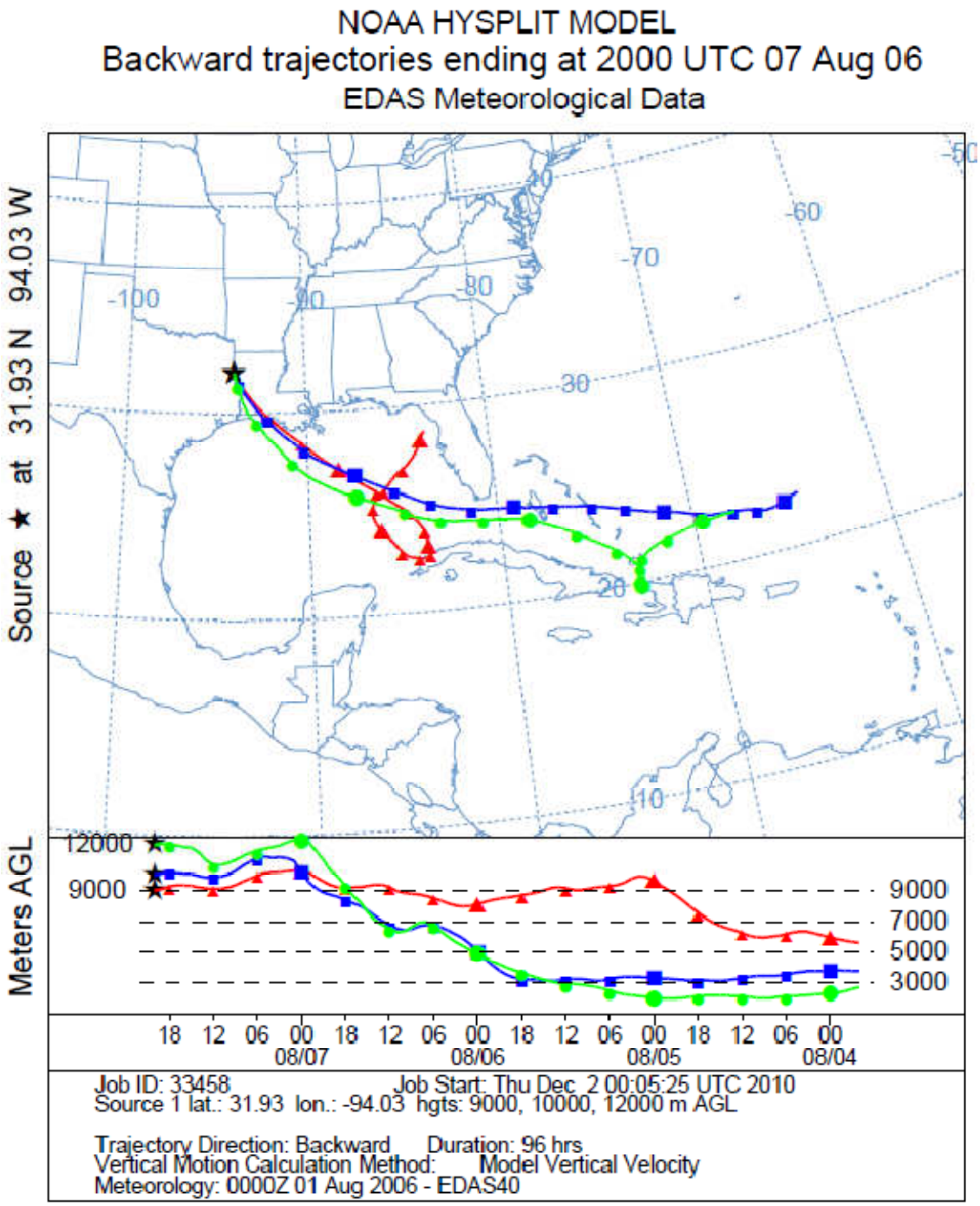

Figure A35. Four day back trajectory, starting at 12, 10, and 9 km on August 7th, 2006, starting from Middle-Texas-Louisiana border.

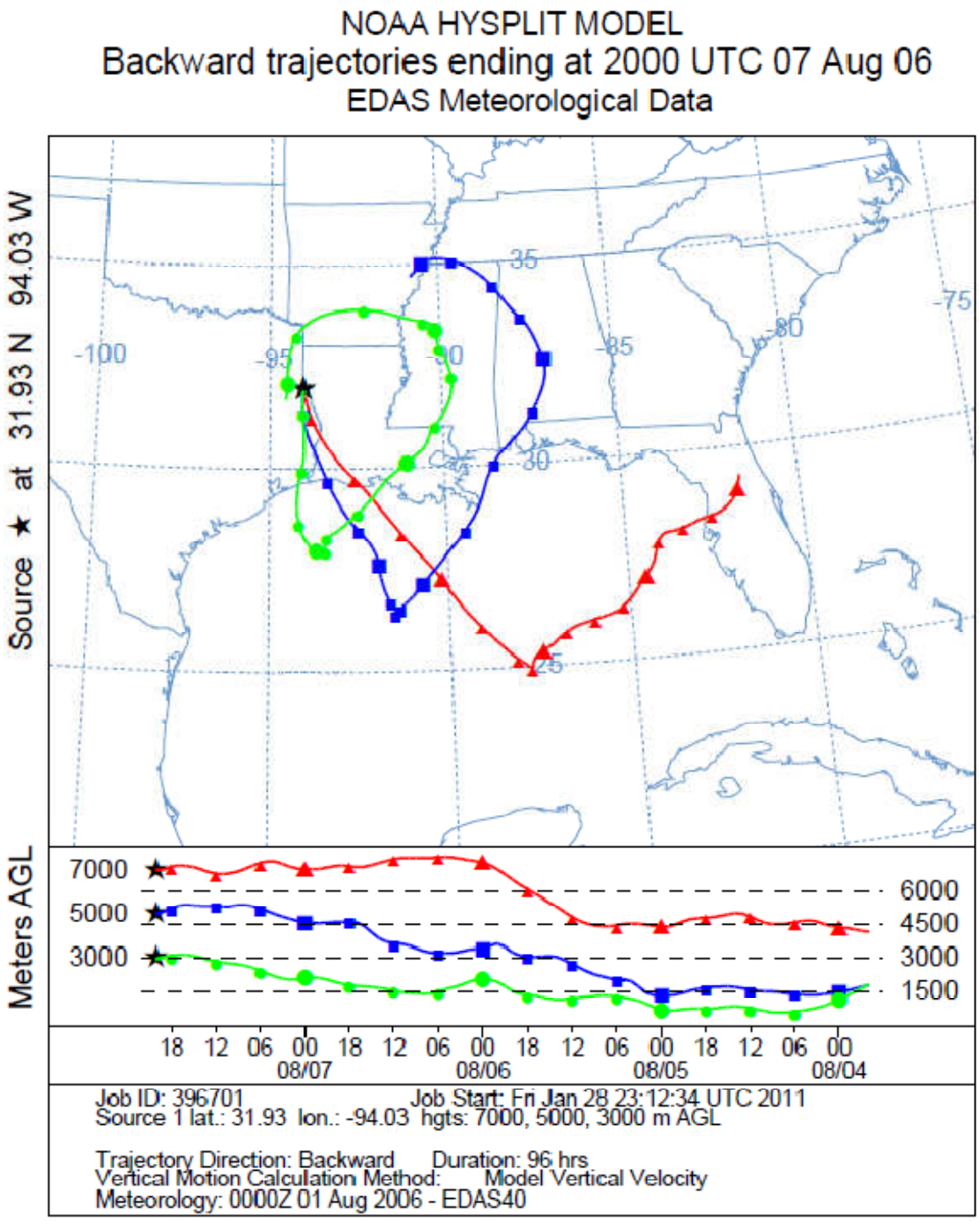

Figure A36. Four day back trajectory, starting at 7, 5, and 3 km on August 7th, 2006, starting from Middle-Texas-Louisiana border.

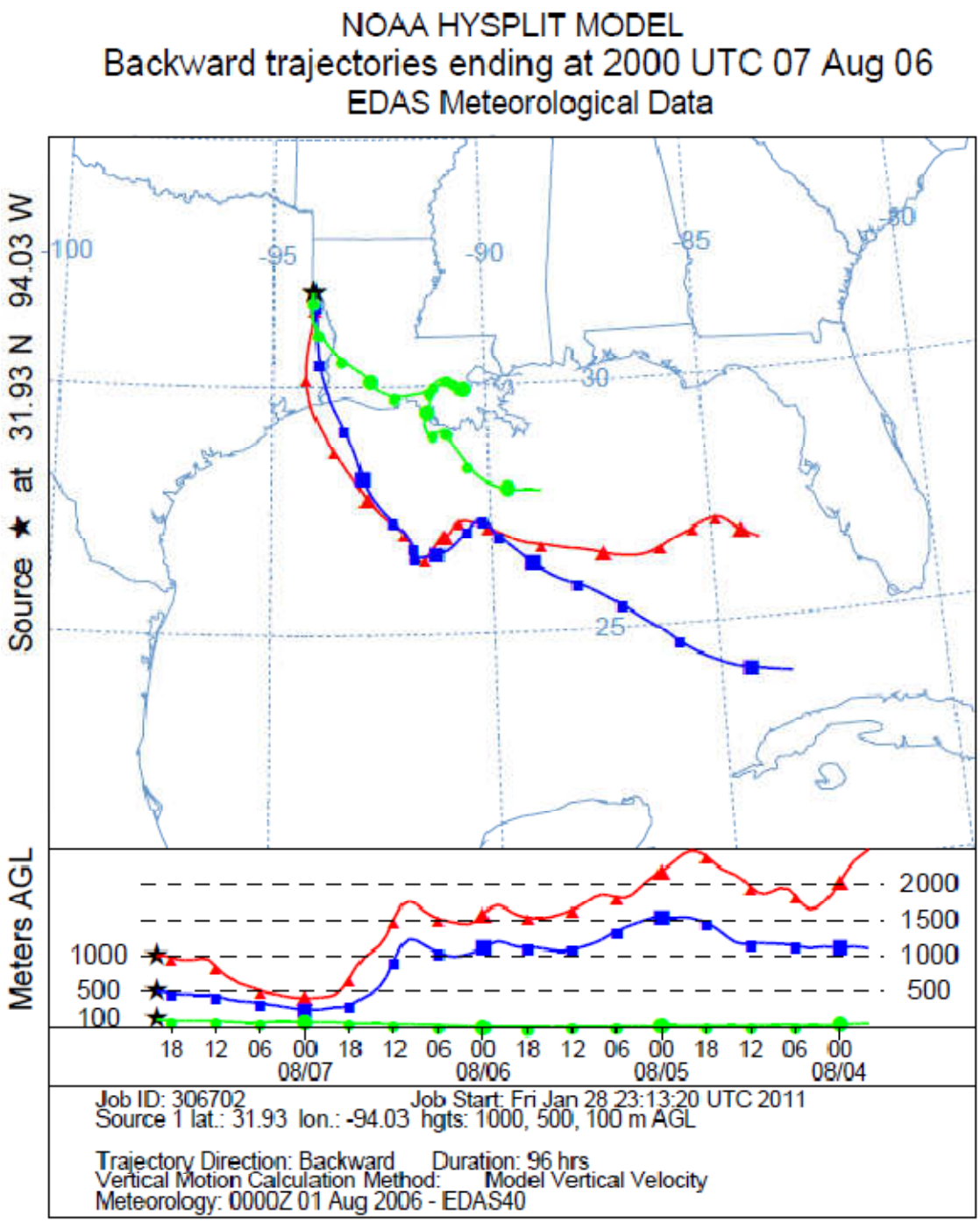

Figure A37. Four day back trajectory, starting at 1, 0.5, and 0.1 km on August 7th, 2006, starting from Middle-Texas-Louisiana border.

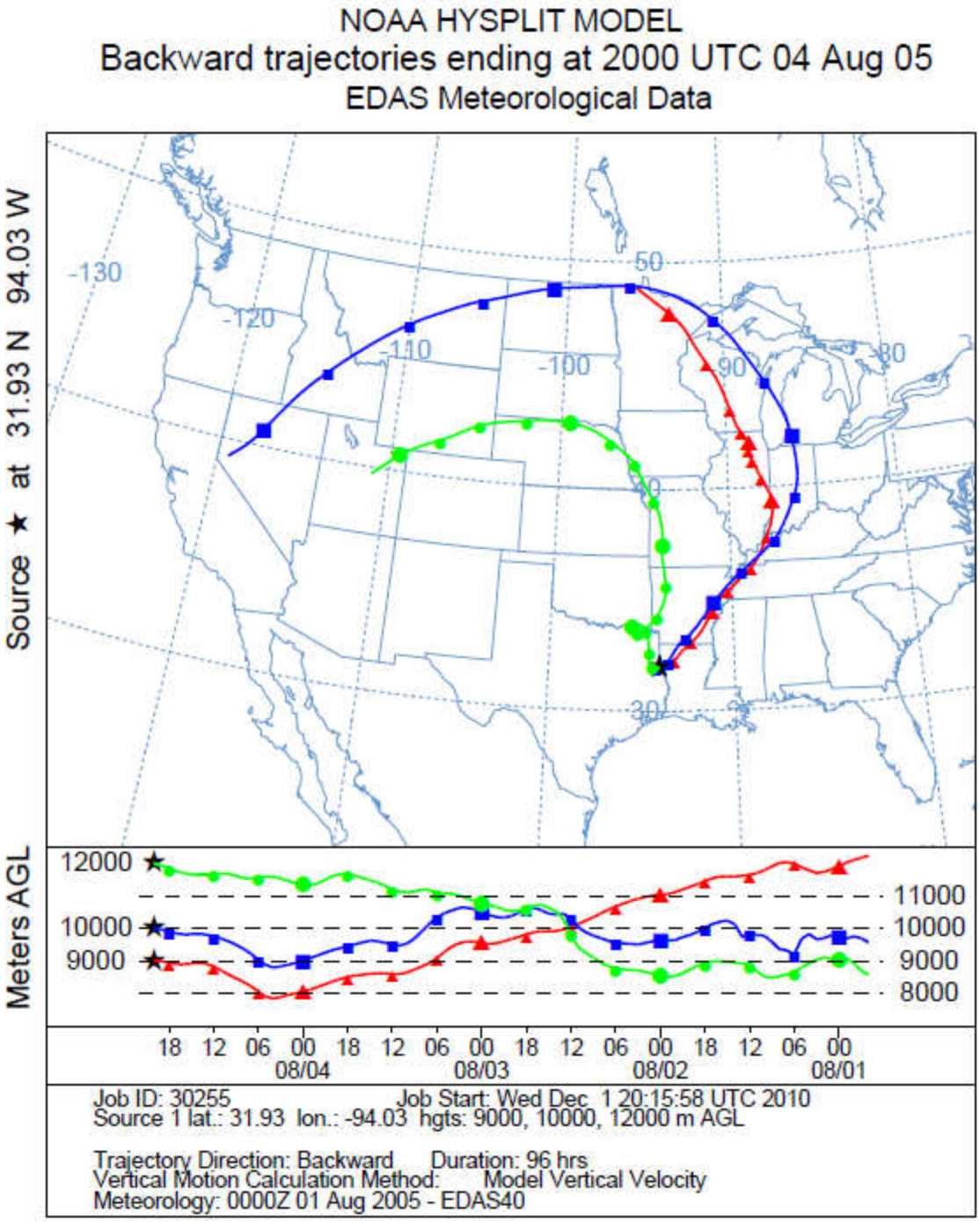

Figure A38. Four day back trajectory, starting at 12, 10, and 9 km on August 4th, 2005, starting from Middle-Texas-Louisiana border.

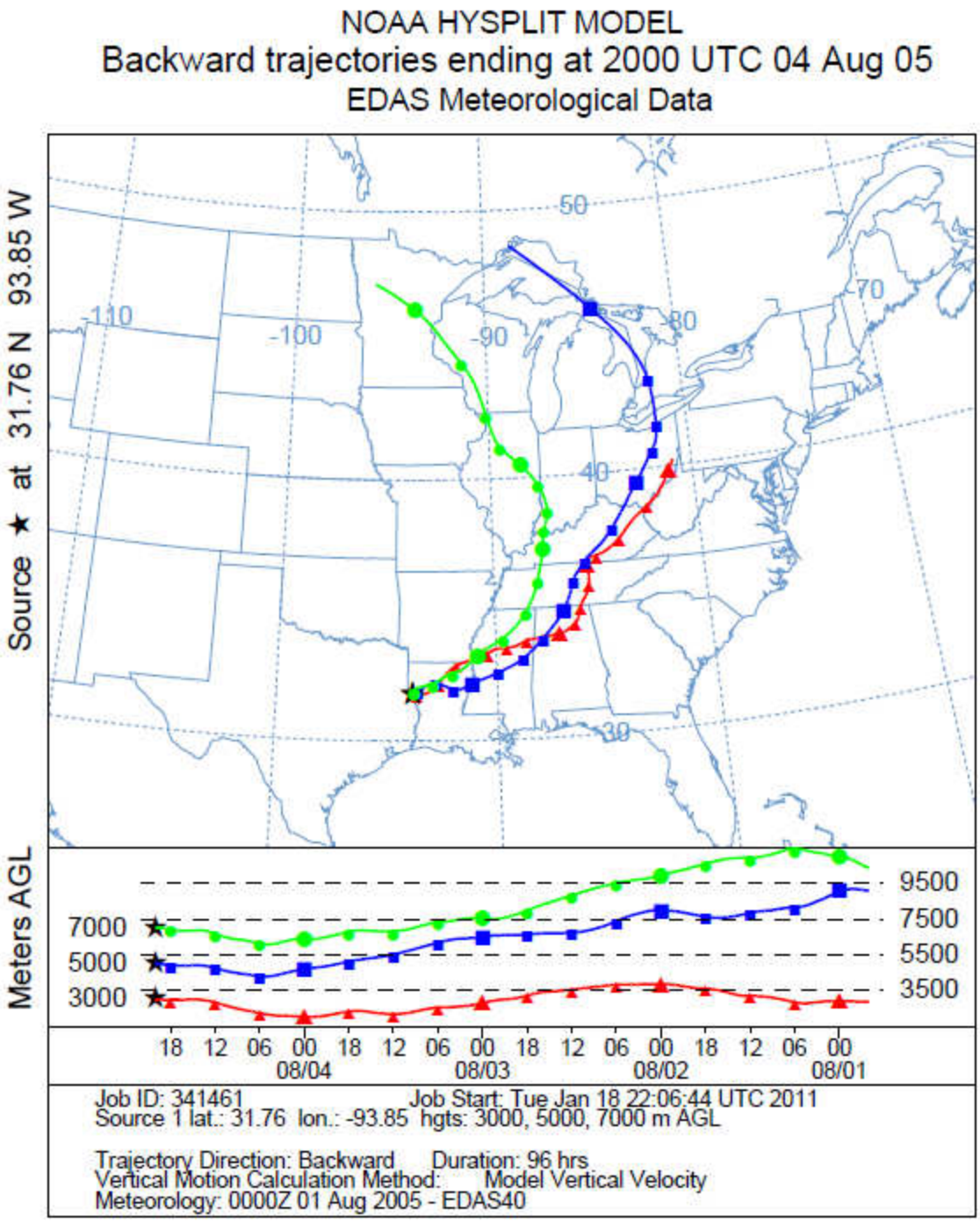

Figure A39. Four day back trajectory, starting at 7, 5, and 3 km on August 4th, 2005, starting from Middle-Texas-Louisiana border.

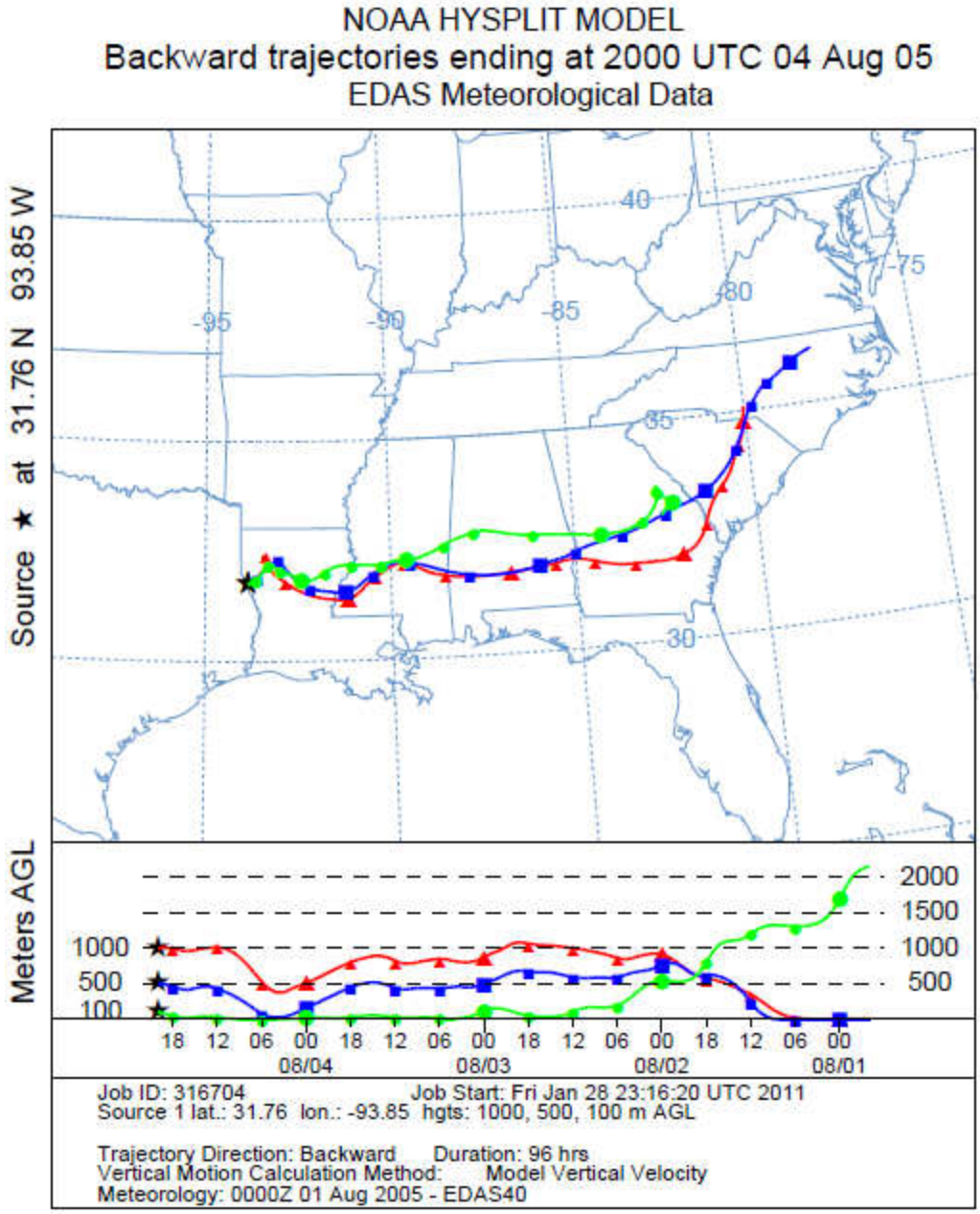

Figure A40. Four day back trajectory, starting at 1, 0.5, and 0.1 km on August 4th, 2005, starting from Middle-Texas-Louisiana border.

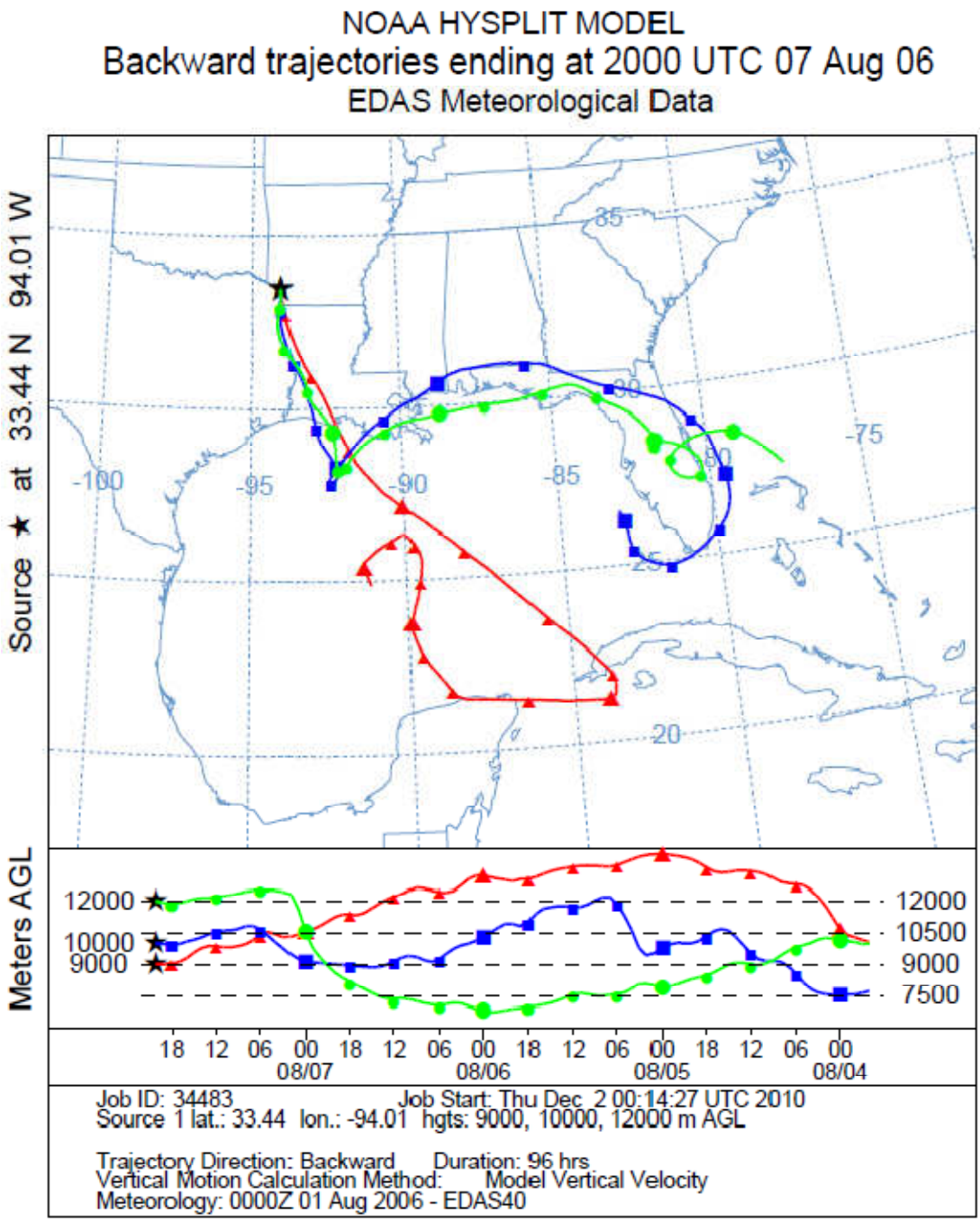

Figure A41. Four day back trajectory, starting at 12, 10, and 9 km on August 7th, 2006, starting from the Top-Texas-Louisiana border.

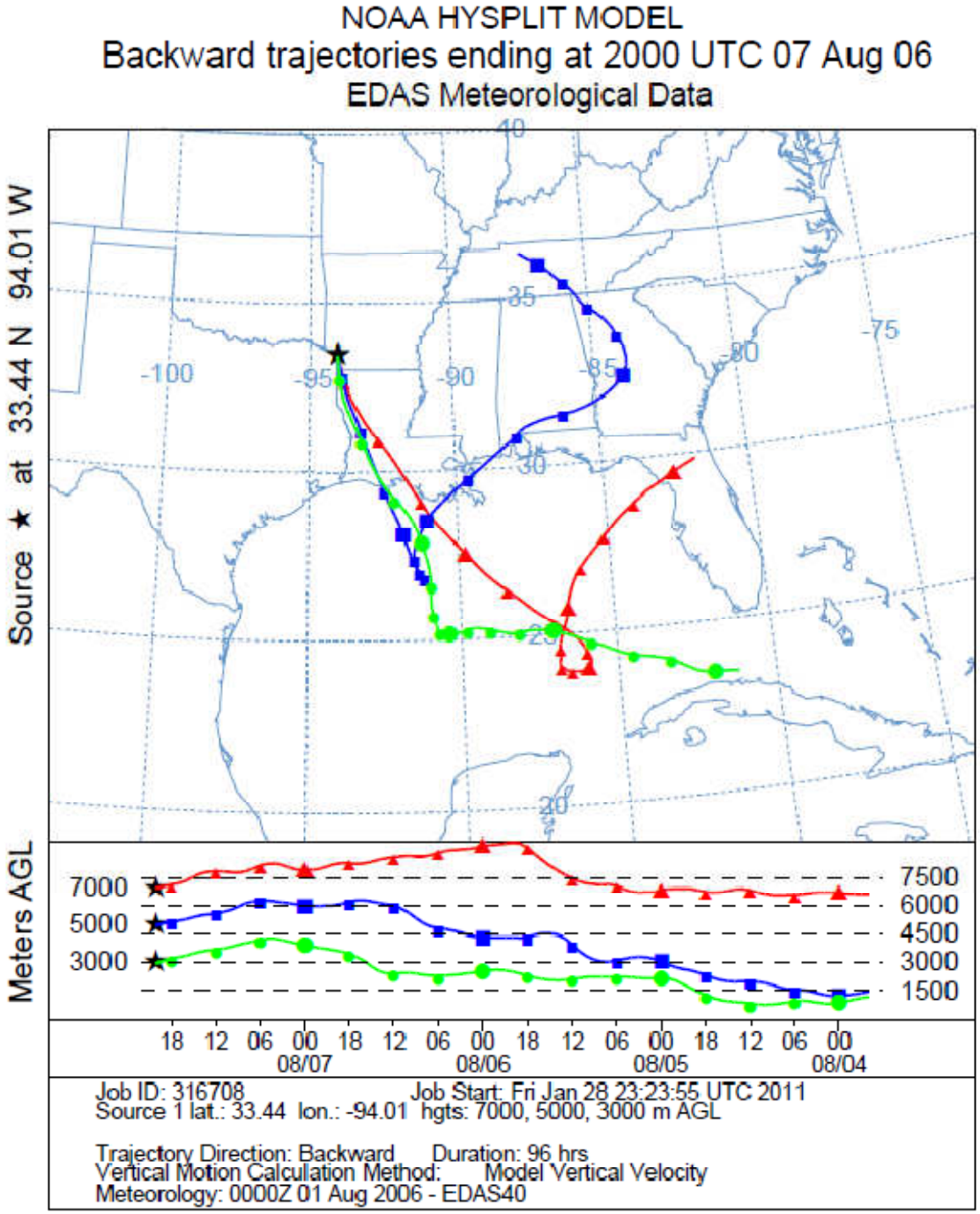

Figure A42. Four day back trajectory, starting at 7, 5, and 3 km on August 7th, 2006, starting from the Top-Texas-Louisiana border.

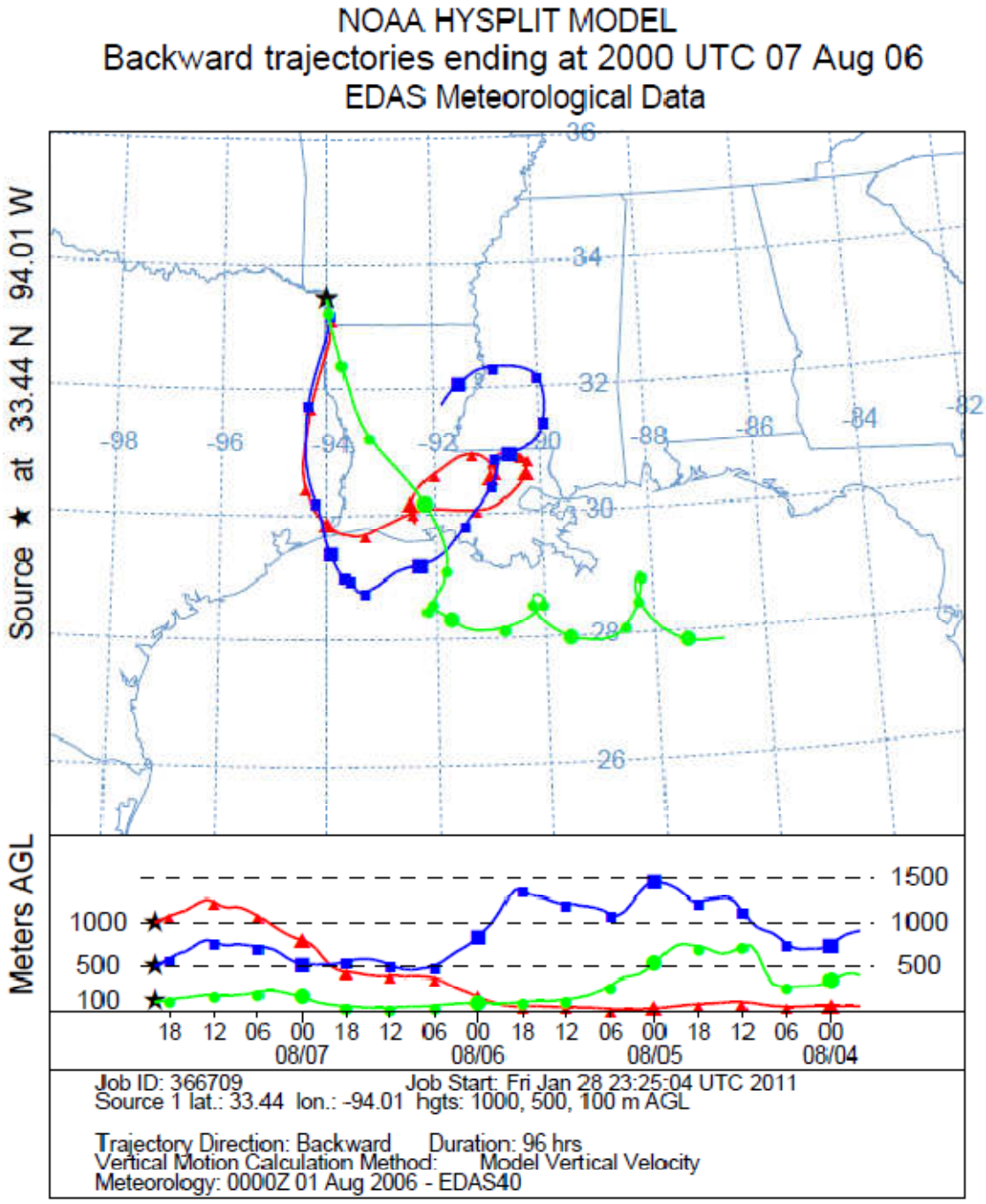

Figure A43. Four day back trajectory, starting at 1, 0.5, and 0.1 km on August 7th, 2006, starting from the Top-Texas-Louisiana border.

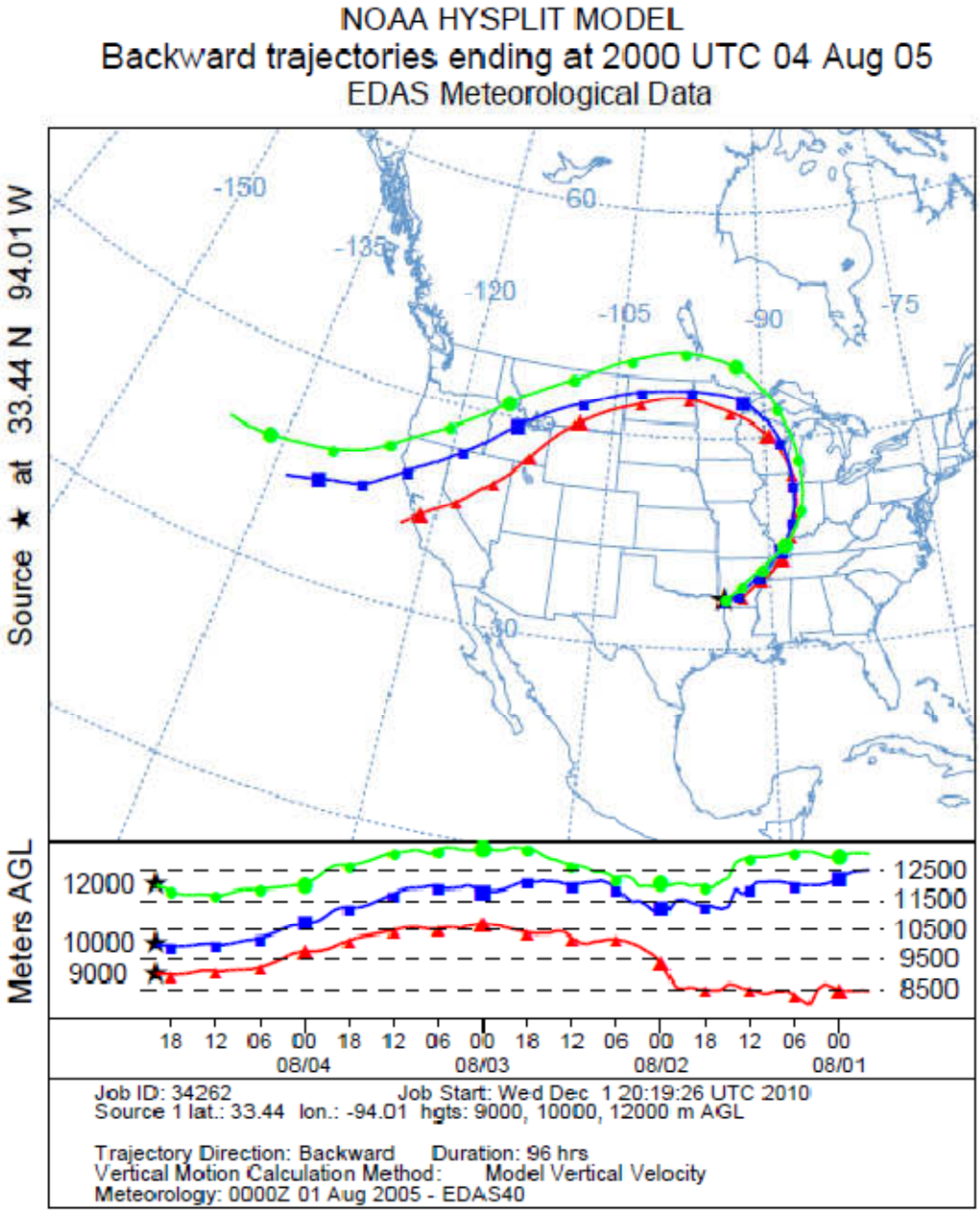

Figure A44. Four day back trajectory, starting at 12, 10, and 9 km on August 4th, 2005, starting from the Top-Texas-Louisiana border.

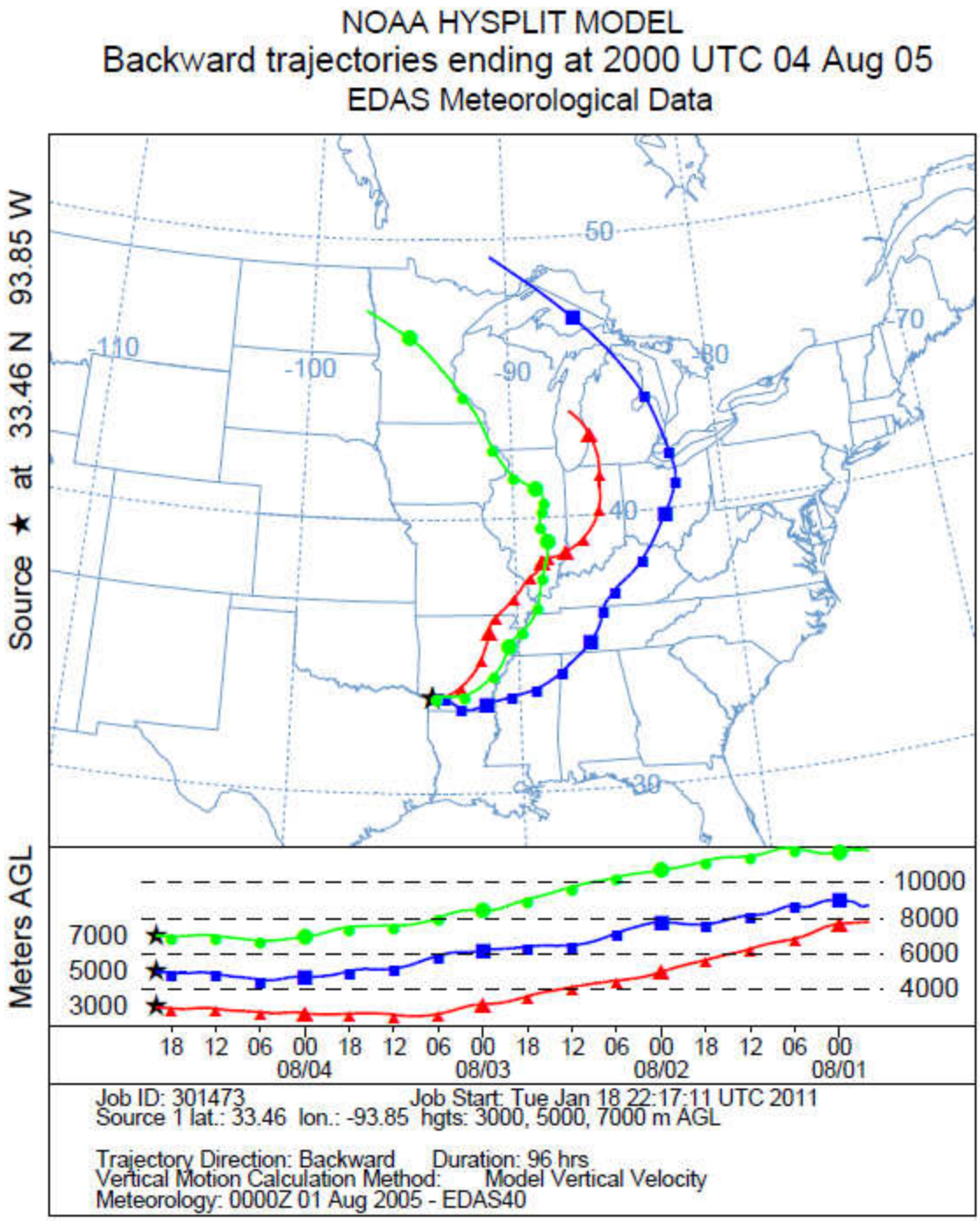

Figure A45. Four day back trajectory, starting at 7, 5, and 3 km on August 4th, 2005, starting from the Top-Texas-Louisiana border.

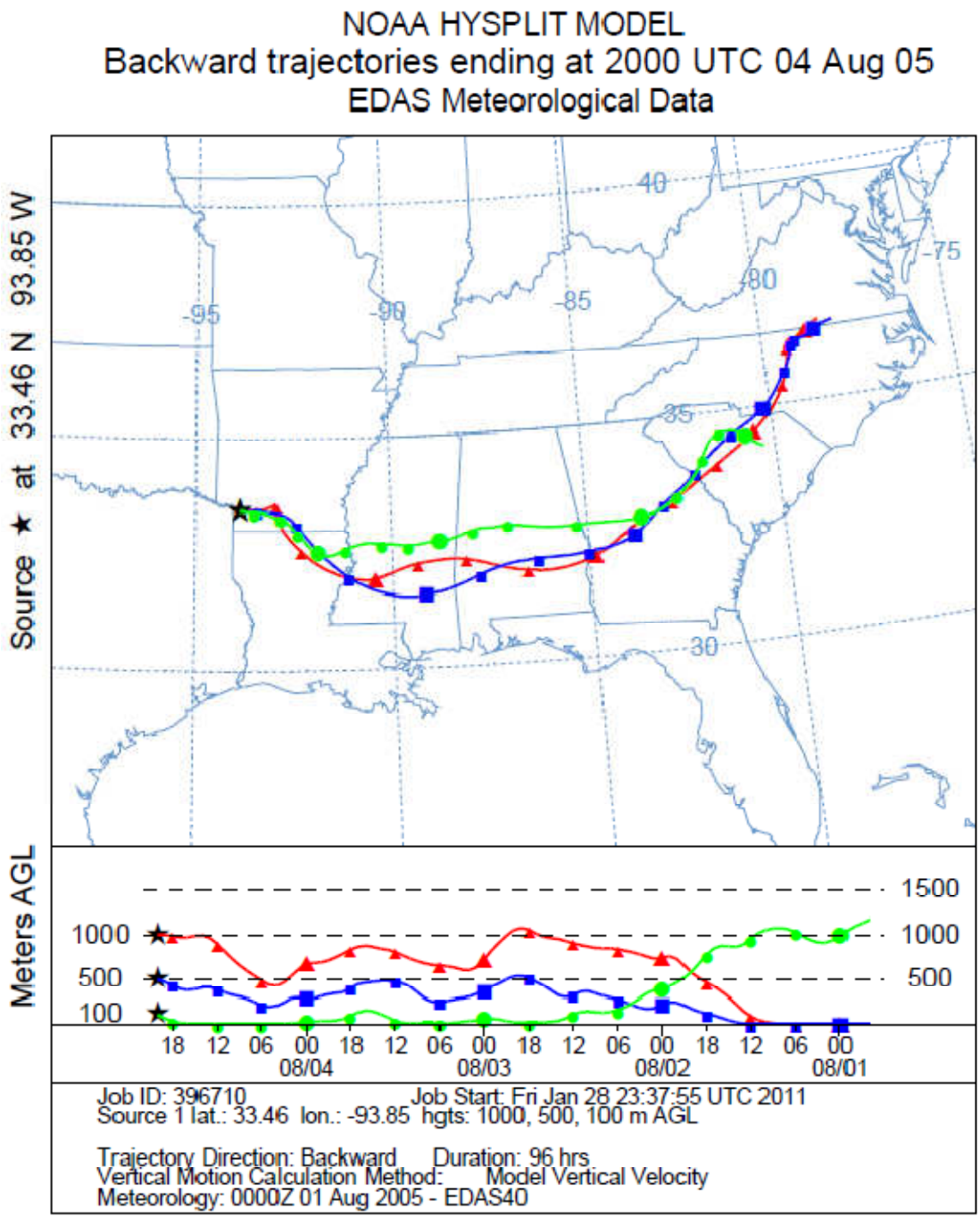

Figure A46. Four day back trajectory, starting at 7, 5, and 3 km on August 4th, 2005, starting from the Top-Texas-Louisiana border.

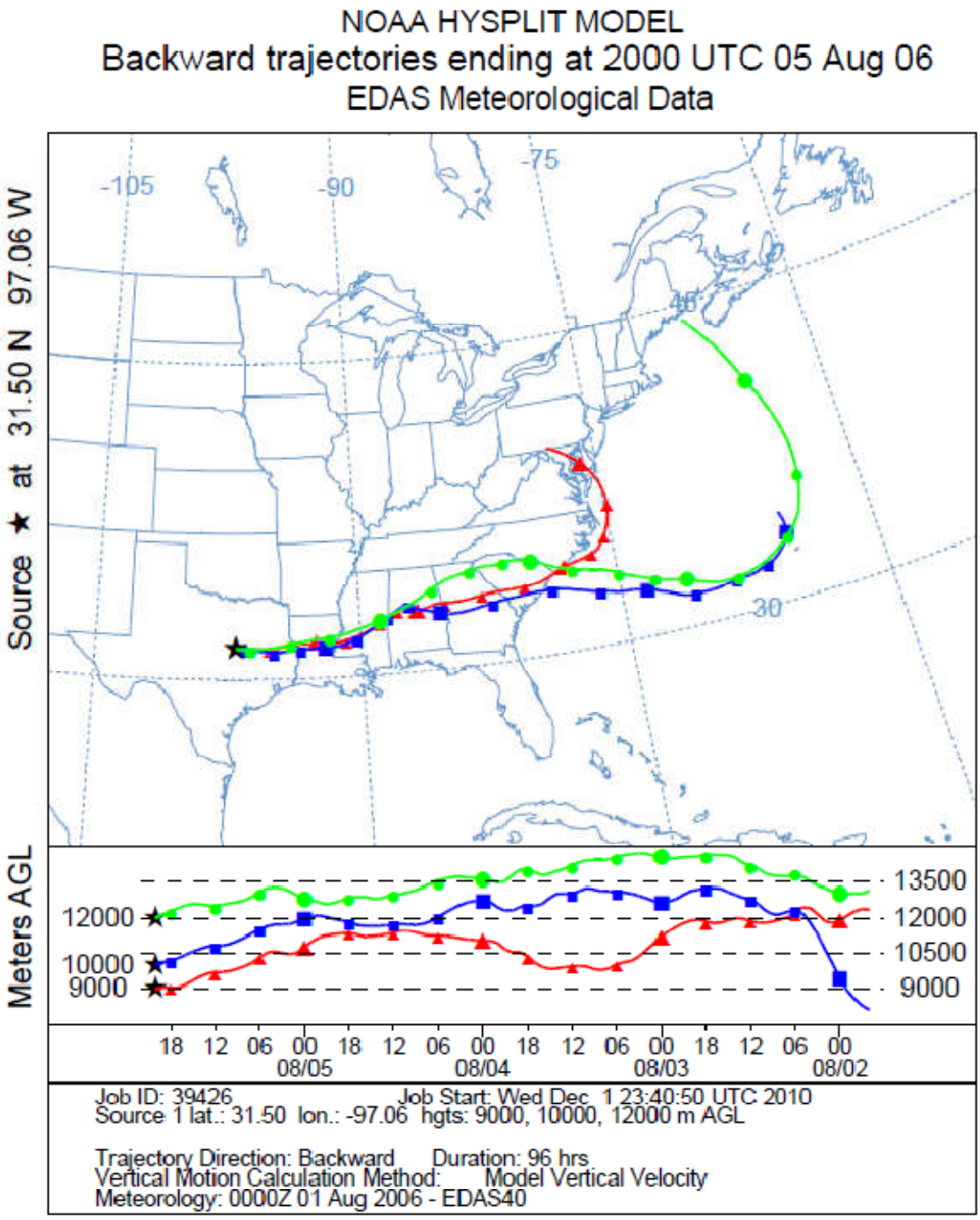

Figure A47. Four day back trajectory, starting at 12, 10, and 9 km on August 5th, 2006, starting from Waco, TX.

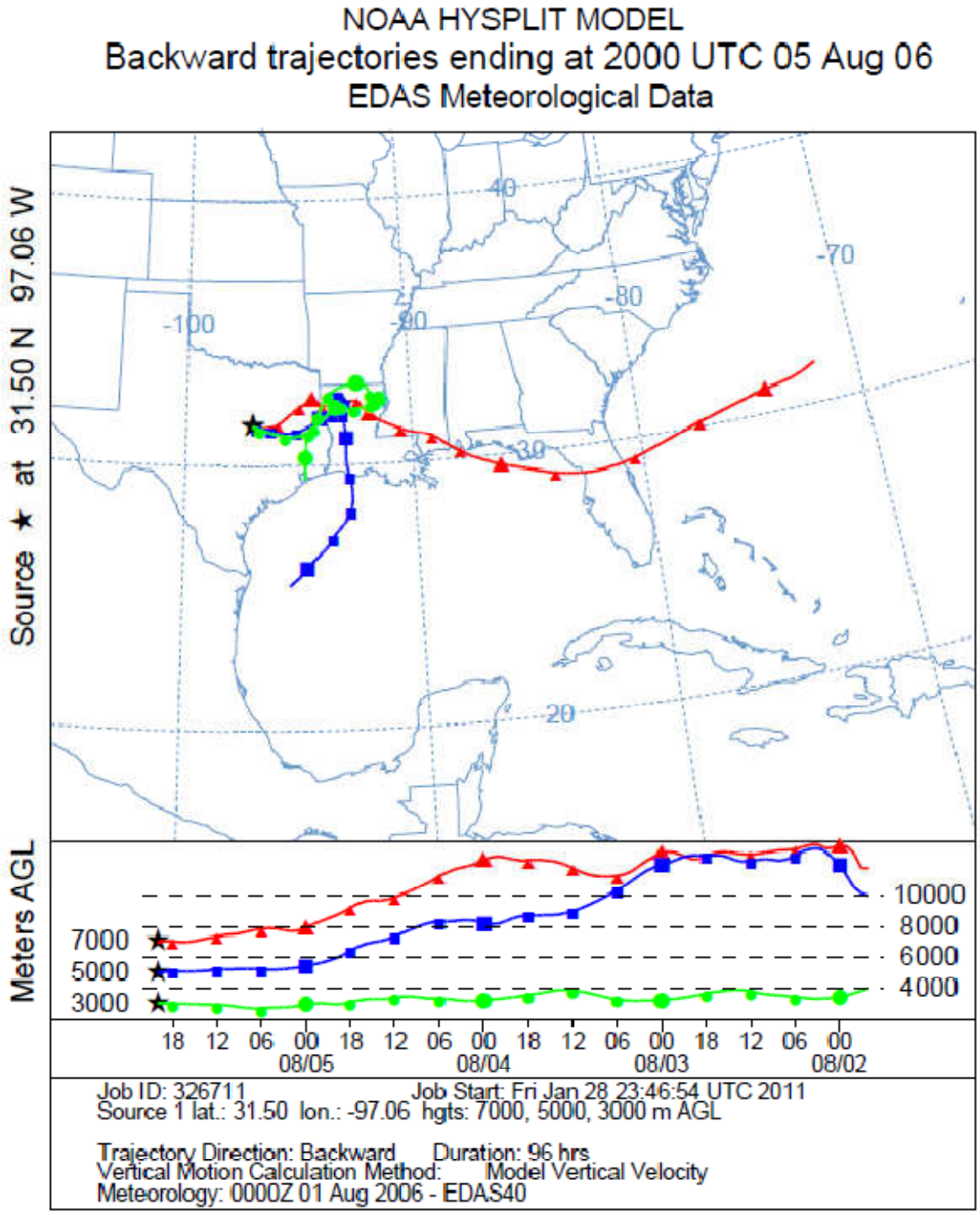

Figure A48. Four day back trajectory, starting at 7, 5, and 3 km on August 5th, 2006, starting from Waco, TX.

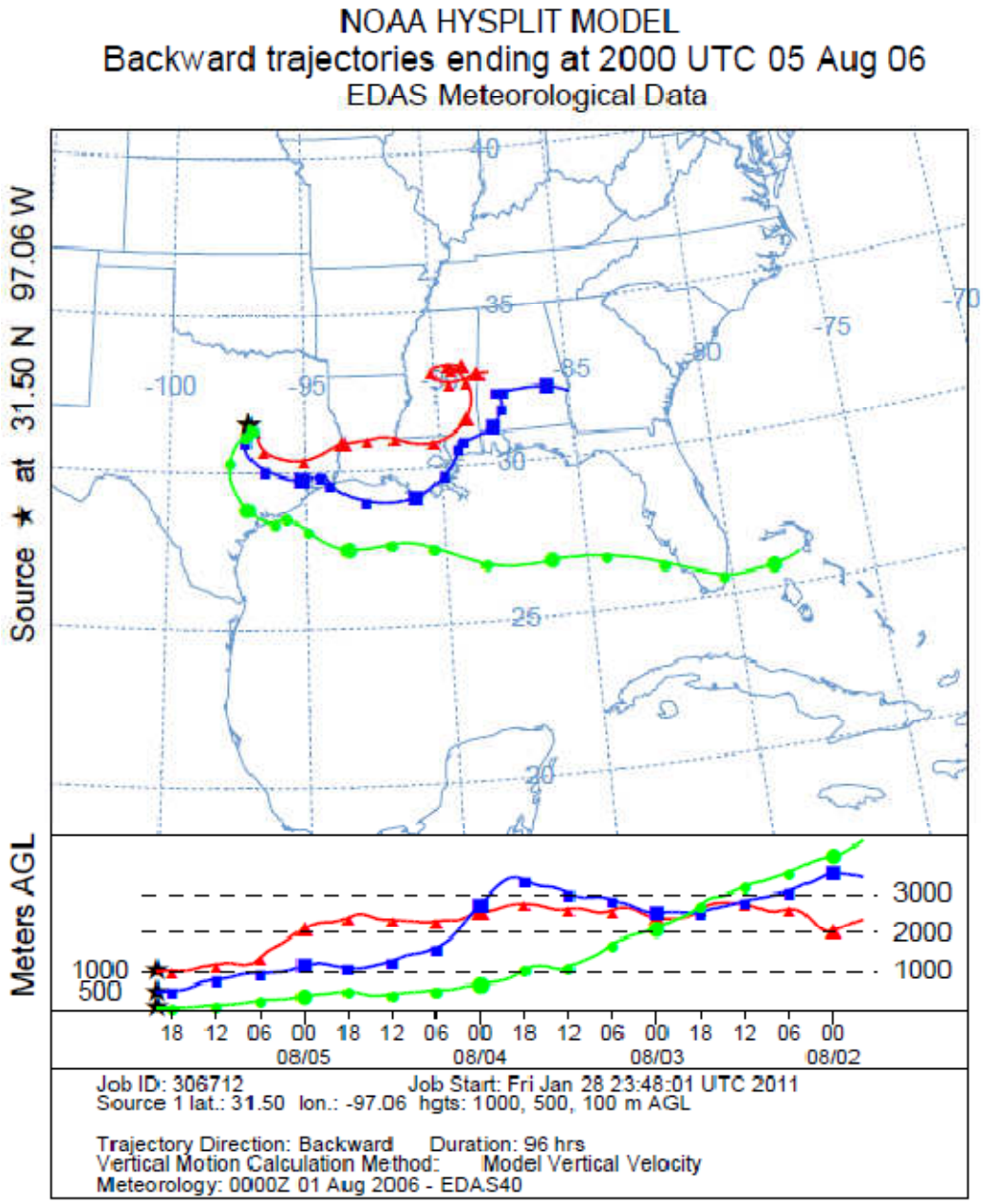

Figure A49. Four day back trajectory, starting at 1, 0.5, and 0.1 km on August 5th, 2006, starting from Waco, TX.

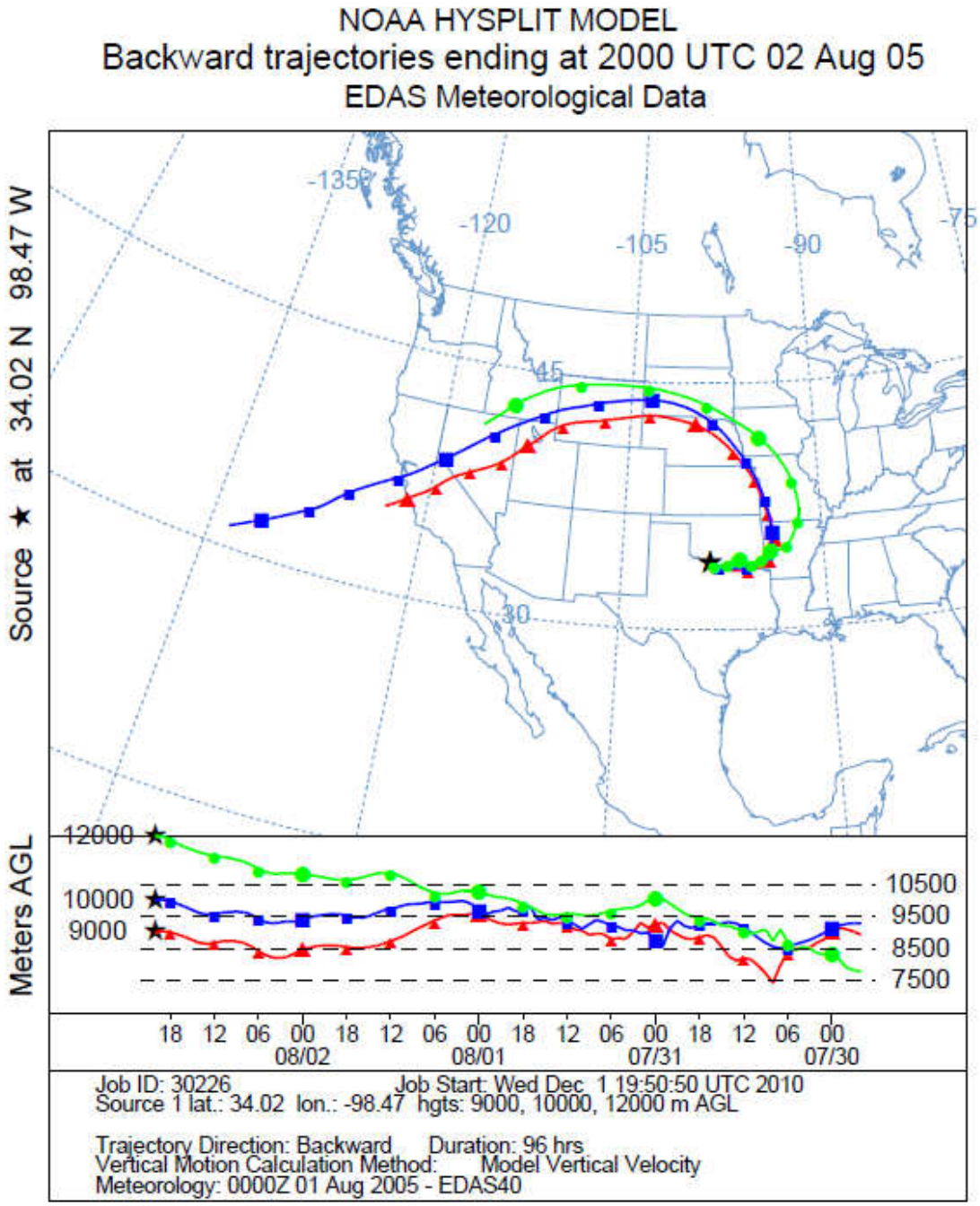

Figure A50. Four day back trajectory, starting at 12, 10, and 9 km on August 2nd, 2005, starting from Wichita Falls, TX.

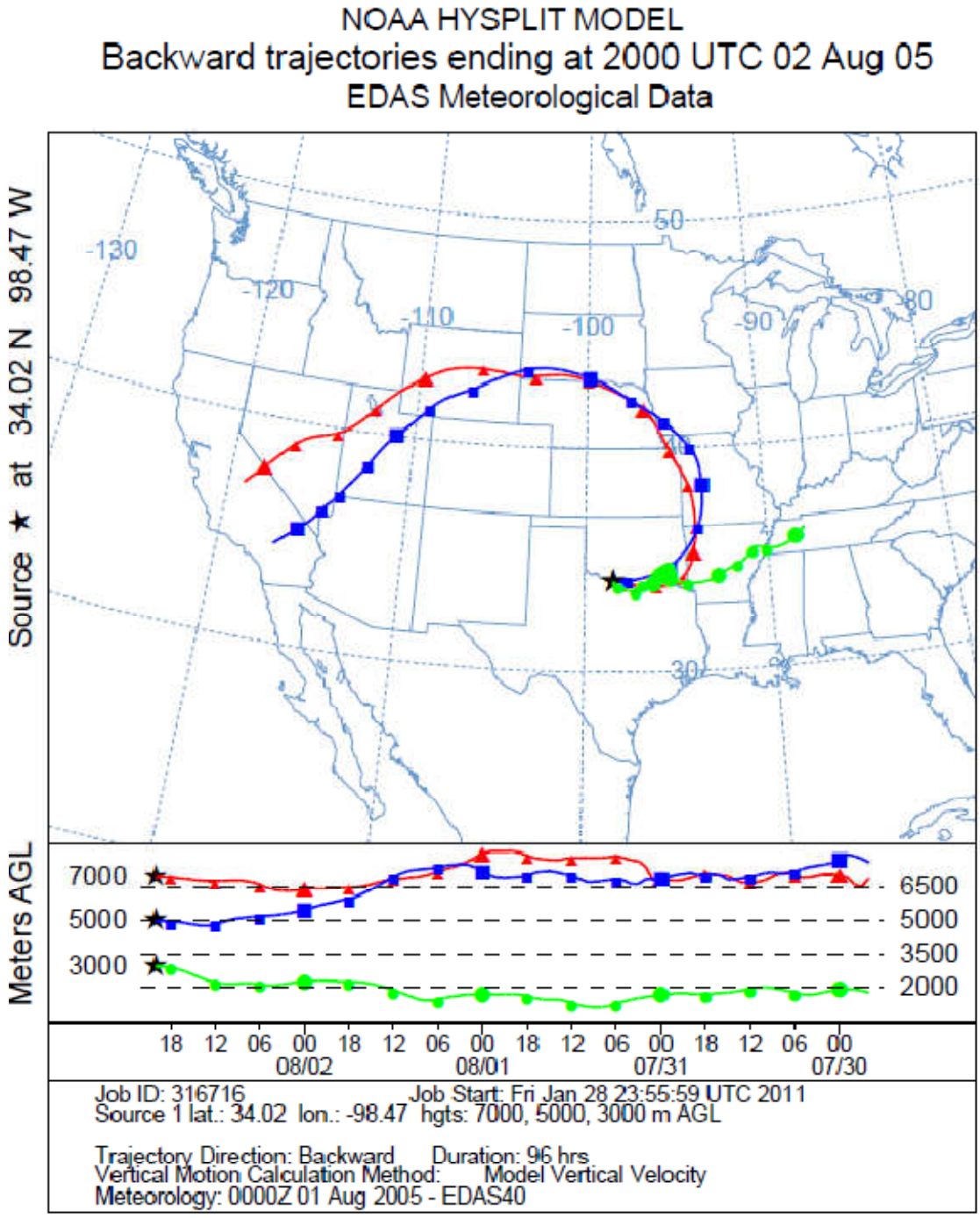

Figure A51. Four day back trajectory, starting at 7, 5, and 3 km on August 2nd, 2005, starting from Wichita Falls, TX.

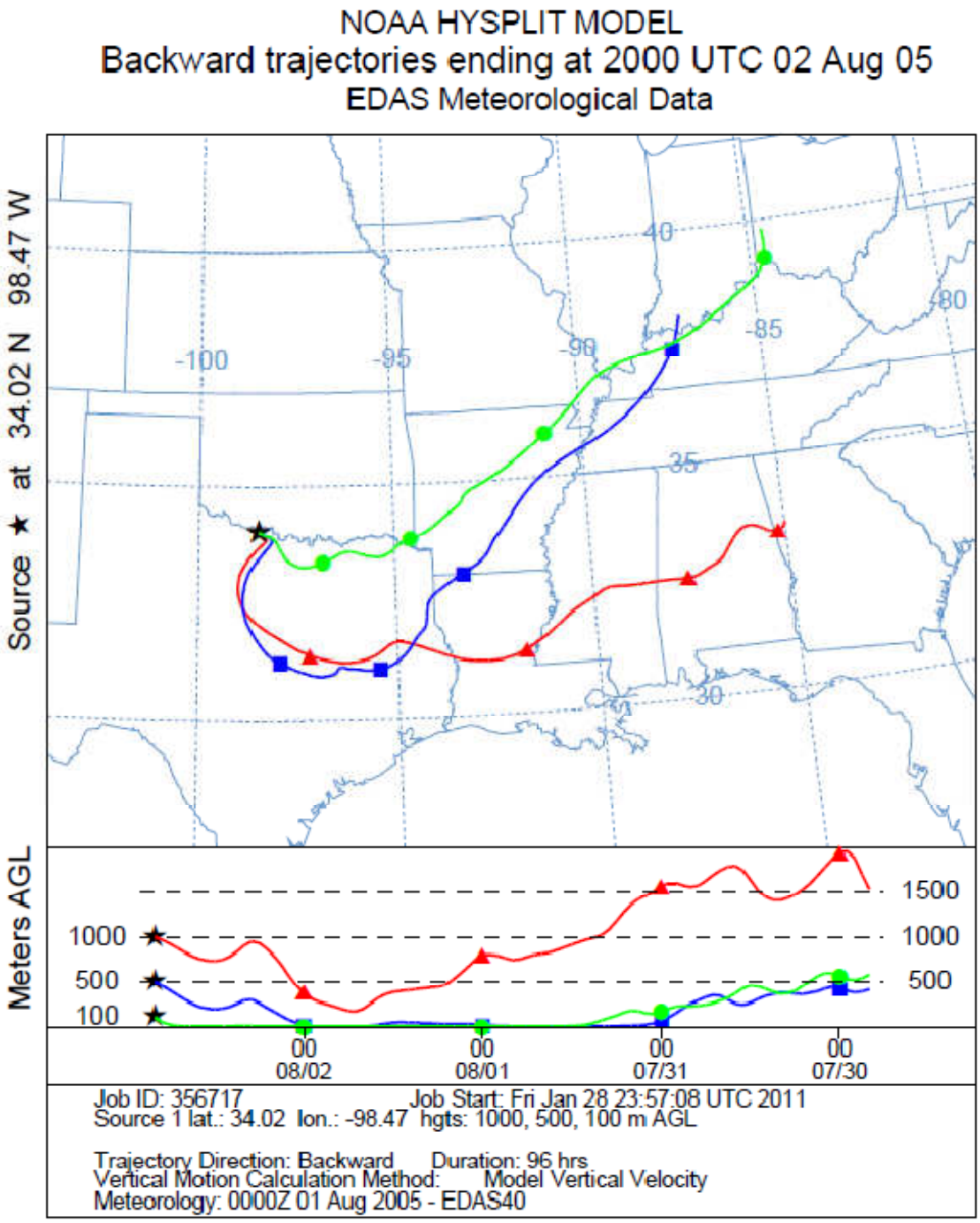

Figure A52. Four day back trajectory, starting at 1, 0.5, and 0.1 km on August 2nd, 2005, starting from Wichita Falls, TX.