Appendix G-4: Radar Wind Profiler Observations in Maryland: A Preliminary Climatology of the Low Level Jet

Radar Wind Profiler Observations in Maryland:
A Preliminary Climatology of the Low Level Jet

Report Prepared for:

The Maryland Department of the Environment

Air and Radiation Administration

Report Prepared by:

Charles A. Piety

Department of Atmospheric & Oceanic Science

The University of Maryland

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Executive Summary

1. The low level jet (LLJ) is an ephemeral increase in wind speed found in the lower portion of the planetary boundary layer (0-2000 m). Low level jets have been observed over many locations around the world but the most well known and widely studied LLJ occurs over the Great Plains of the United States. A weaker, less studied LLJ occurs along the Mid Atlantic coastal plain area of the United States.
2. The LLJ can form in response to a variety of atmospheric processes which typically involve a sloping terrain and are closely linked to sunrise and sunset. One important cause of the LLJ is the rapid decrease (with height) in surface frictional effects which decouples the layer of air near the earth's surface from the air just above it (in the residual layer). Like the Great Plains LLJ the Coastal Plains LLJ is primarily the result of terrain-induced temperatures differences and accelerations which develop after sunset when vertical mixing decreases abruptly.
3. Given that the LLJ is a night time feature with a comparatively short temporal scale (hours versus days for larger scale weather features) measuring the LLJ has historically been difficult. In part this is so because the standard launch time for weather balloons by the National Weather Service radiosonde network does not coincide with LLJ processes. Radar profilers, which provide fine-scale, continuous observations, offer a chance to more accurately and completely observe the LLJ.
1. Owing to the complex nature of the LLJ and the local effect which are important to individual LLJ's, there are no universal criteria for identifying the presence of a LLJ. A wind speed criteria, developed for the study of the Great Plains LLJ, is used in this study with two important modifications. First, the wind speed threshold is reduced to 8 ms^{-1} to reflect the weaker terrain forcing in this region, and, second, a duration requirement of 5 hours is applied. The second criterion is applied so that the LLJs studied here are "transport relevant".
2. Data from the Fort Meade radar profiler from August, 1998 to December, 2003 are analyzed in this study. Data capture during this period was quite good with missing profiles accounting for only 8% of all data. Individual data points (wind observations) within a profile are more often not captured and missing data points within a profile are more frequent than entire profiles being missing. Summertime data capture rates within a given profile are much better than in winter. Increased vertical resolution provided by radar wind profilers mark a significant improvement from the standard climatological database derived from radiosonde data alone.
3. The long duration ($\geq$ 5 h) LLJ is observed on ~ 13% of all days and ~ 20% of summer days during the study period. Shorter duration LLJs are much more frequent with jets of $\geq$ 2 hours occurring on ~36 % of all days.
4. While LLJs can be induced by a variety of factors, the southwest, or coastal plain, LLJ is primarily forced, in stable weather conditions (also conducive to O_3 formation), by terrain-induced temperature gradients and re-inforced by inertial effects as surface friction dissipates after sunset.

5. The mid-Atlantic coastal LLJ typically occurs between 22:30 - 06:00 EST. Peak winds are ~ 33 ms^{-1} with mean peak winds for all hours during a jet of 14.4 ms^{-1}. This implies an average transport distance of 200-300 km. The jet maximum occurs ~ 550 m above ground level with a top at ~ 1 km.
6. O_3 concentrations are enhanced when southwest LLJs occur with an average peak of 82.5 ppbv. On these days 44% of the time O_3 exceeds the 8-hour Code Orange threshold (85 ppbv) and 22% of the time the Code Red threshold (105 ppbv) is exceeded. When southwest LLJs are not associated with high O_3, it is typically due to thunderstorm formation or cloud cover in advance of frontal boundaries.
7. The LLJ is a common characteristic of high O_3 episodes in Maryland. For 24 multi-day (≥ 3 consecutive days above Code Orange) episodes during the period, LLJs were observed for part or all of 17 episodes (70%). Overall, 42% of Code Red days also have an occurrence of the LLJ.
8. Without aircraft observations within the core of the LLJ, it is difficult to directly assess the magnitude of O_3 and other pollutants transported into Maryland by the LLJ. A time series of surface based observations can be used to indirectly measure the air mass characteristics of the jet within the residual layer. Air from the residual layer, during LLJ activity, is believed to be mixed down to the surface. While a precise measurement within the residual layer of the LLJ has been elusive, it appears that O_3 concentrations within the jet are on the order of 70-100 ppbv with $PM_{2.5}$ levels in the 30-40 μgm^{-3} range. The upper range in O_3 is obtained from recent ozonesondes measurements over Beltsville, MD. on August 4-5th and August 12-13th, 2005.
9. Thus the jet transports polluted air into the region at levels consistent with the regional load and occasionally higher.
10. Weather patterns conducive to the development of the LLJ are similar to the standard mid-Atlantic high O_3 cases with diffuse high pressure overhead. LLJs are also found in advance of frontal boundaries and can contribute to thunderstorm development.
11. Future work should be directed to improving forecasts of LLJ formation and using good forecasts to direct aircraft measurements within the jet core itself.

Introduction

Air quality over the Baltimore – Washington (B-W) region is a function of precursor emissions from local and regional source regions. Field studies during periods of high ozone over the B-W have shown that a significant portion of the total observed O_3 is transported into the region. Aircraft studies have shown that regionally, the common direction of transport is from the west to northwest at 500-2000 m aloft. These results are generally accepted by the scientific community given the prevailing winds over the mid Atlantic and the significant sources of O_3 precursors located west of the mid-Atlantic region.

Comprehensive field studies (*NARSTO-1995, NEOPS-Philadelphia 1999, 2002*) have regularly observed synoptic scale transport from the west to northwest during periods of poor air quality over the mid Atlantic. Another transport mechanism associated with high O_3 over the mid Atlantic, one that is the diurnal in nature, is the nocturnal low level jet (LLJ). Over the Eastern US the LLJ, also referred to as the coastal low level jet, has been identified as a channeled flow process with a horizon scale believed to be on the order of hundreds of kilometers. While the theory of the LLJ has been known for several decades until recently it was not routinely measured. The dearth of detailed LLJ studies is related to the fact that the LLJ is mostly a nighttime, boundary layer, process and thus, the National Weather Service radiosondes, which are launched at 12:00 and 00:00 UTC daily (08:00, 20:00 EDT), do not typically record its occurrence.

Boundary layer radar wind profilers, which provide continuous wind observations from the surface to ~4 km, can be an important tool used to measure intermittent phenomena such as the LLJ. The radar profiler located in Fort Meade, MD (from 1998-2004) provided several years of quality assured boundary layer wind data. In this study data from the Fort Meade wind profiler was used to develop a climatology of the LLJ over Maryland. The following topics will be addressed in this report: the theory of the LLJ (Section 1), the details of the radar wind profiler and it's effectiveness as an instrument to measure the LLJ (section 2), a definition of the LLJ that is relevant to air quality issues (Section 3), the frequency of the LLJ in all seasons (Section 4), the association of the LLJ with poor air quality over the Baltimore Non Attainment Area (Section 5), the nocturnal LLJ evolution and related transport issues (6) and lastly, synoptic scale weather conditions associated with LLJs and high O_3 (Section 7).

Section 1: Theory of the LLJ

This section focuses on an atmospheric phenomenon known as the nocturnal, low-level jet (LLJ) and the connection between the LLJ and O_3 concentrations at the surface and within the planetary boundary layer (PBL). A better understanding of the low level jet process may prove crucial in determining the location and timing of maximum ozone surface observations and successfully modeling of ozone transport during severe pollution events over parts of the United States.

The LLJ is found in many locations around the world including Europe (*Kraus et al., 1985*), Africa (*Anderson, 1976*) and Australia (*Malcher and Krause, 1983*). The most famous, and widely studied, LLJ is found in the Great Plains of the United States and a weaker version is common along the eastern US seaboard (*Bonner, 1968*). Maximum wind speeds within the jet are on the order of 10-20 ms^{-1}. The base of the jet is typically 100-300 m above the surface but it has been observed up to 900 m (*Stull, 1999*). The areal extent of the LLJ can be on the order of 100's of km wide and ~ 1000 km in length. While the upper atmosphere jet stream has been likened to a ribbon of fast moving air, the LLJ is more in the nature of a sheet of intermittent high winds.

The PBL is the lowest part of the atmosphere, thus its directly influenced by the earth's surface. Boundary layer winds often exhibit complex behaviors particularly at night with the nocturnal LLJ a prime example (*Stull, 1999*). ***Figure 1***. shows PBL evolution over land during periods when high-pressure weather patterns prevail (*Stull, 1999*). During synoptic weather patterns with stronger zonal flow a schematic of the boundary layer could look significantly different with generally more uniform mixing present. For the former case, the height and structure of the PBL diurnally changes at different rates. One can divide this already shallow layer in to three sub-layers: a very turbulent mixed layer (typically present during daylight hours), a less turbulent residual layer which occupies space that was formerly the mixed layer, and below that a nocturnal, stable boundary layer that has periods of sporadic turbulence (Stull, 1999). The LLJ forms and resides in the residual layer. It is important to note, that during the nighttime, the PBL is often comprised of thin, stratified layers with different physical and chemical properties (*Stull, 1999*). In general, vertical and horizontal transport by the LLJ is not only of keen interest to the air pollution community, the meteorological community also endeavor to understand LLJ processes because other types of transport (i.e. temperature, moisture, energy) associated with the LLJ are important to weather (*Djuric, 1980, Benjamin, 1986*).

At night, when synoptic conditions are calm a stable temperature "inversion" (a decrease in temperature with height) forms as cooler more dense air from aloft subsides to the ground and the earth radiates energy stored during the day. On cloud-free evenings the LLJ begins to form shortly after the sun sets and the atmosphere cools down. The wedge cool air in the stable nocturnal boundary layer decouples the surface layer from the residual layer and acts like a smooth object which allows the air just above it (in the residual layer) to flow rapidly past the inversion mostly unencumbered by surface friction (*Stull, 1999*). As the sun rises, its energy returns to heat the land and the lower atmosphere begins to mix as the warm air rises. The jet diminishes as the temperature inversion which set up the night before erodes and surface friction slows winds speeds. If stable synoptic conditions persist the same conditions the next night could allow the low-level jet to reform with equal strength and similar consequences. Low-level jet formation results in an altitudinal gradient in wind speed and direction that induces mixing between the otherwise stratified layers. This result is important to the air quality community because any full description of pollution transport, and transformation, must include an accurate assessment of all physical processes (*Rao el at, 1994*).

Low-level jet stream flow is often associated with, and enhanced by, the presence of a mountain range. Mountains and pressure gradients on either side of a developing LLJ help to concentrate the flow of air into a corridor or horizontal stream (*Hobbs, 1996*). East of the Rocky Mountains and east of the Appalachian Mountain range are two common locations for LLJ formed over the United States (***Figure 2***, *Bonner, 1968*). There may be other locations in the US where LLJs occur that have not been measured. The width of the stream can vary from location to location (and weather pattern) but is typically less than several hundred km wide and not greater than 1000 km long. In extreme cases, winds in a LLJ can flow at speeds of 60 ms^{-1} or more but average speeds are in the range of 10-20 ms^{-1}.

Even though nighttime low-level wind speed maxima have been observed for a long time (*Goualt, 1938*) much is still unknown about them because of their transient nature and diminutive vertical scale. The theory of low-level jet formation received attention from Alfred Blackadar and others in the 1950's (*Means, 1952, Blackadar, A. 1955*). In the late 1960's William Bonner proposed a climatology of LLJs over the United States based on analysis of PBL observations from a two-year study of low-level wind maxima using weather balloons (*Bonner, 1968*). From that work (with limited data compared to modern day standards) it was shown that the majority of the low level jets, and the most intense jets, occurred over the Great Plains region. This is plausible because one of the important factors for LLJ development is a difference in rates of heating and cooling between a sloped terrain and flat surface. Another common location for LLJ formation over the US is the eastern side of the Appalachian Mountains. Low-level jets transport more than just O_3. Over the Central Plains of the U.S. transport of moisture into the base of developing thunderstorms by low level jets leads to the formation of nocturnal thunderstorm clusters called Mesoscale Convective Complexes. These large thunderstorms can cover areas as large as a state and produce torrential downpours, damaging winds and even tornadoes.

Section 2: Wind Profiler Theory and the Efficacy of Wind Profiler Data to Observe the LLJ

The general principles of the wind profiler are detailed by, among others, *Balsley and Gage* (*1981*) and *Rotter* (*1990*). Radar (Radio Detection And Ranging) technology had undergone continuous refinement since its introduction over 50 years ago. Theoretical studies in the 1950s revealed that radio waves are scattered by turbulence in the atmosphere in a predictable way that might allow monitoring of atmospheric parameters. Conventional weather radars detect reflections from objects in the air (e.g. hydrometers) rather than the air itself. Wind profiler radars, on the other hand, rely on the scattering of electromagnetic energy by minor irregularities (sometimes called spectral moments) in the index of refraction. The index of refraction, which itself is a function of the amount of aerosols in the atmosphere, is related to the speed at which the electromagnetic energy propagates through the atmosphere. When an electromagnetic wave encounters a refractive index irregularity, a small amount of energy is scattered in all directions. Energy scattered toward its point of origin in known backscattering. The essence of radar wind profiling involves measuring the backscattered energy to the profiler resulting from these spectral moments.

Radar wind profilers like the one at Fort Meade emit pulsed electromagnetic energy (at ultra high frequency, 404 MHz) and then receive backscattered energy from any target that it encounters (***Figure 3***). The returned energy is sampled at specific time and height intervals to produce a wind profile at known heights. By tracking turbulent eddies within the overall, or larger scale wind flow wind velocity is determined. Measuring the Doppler shift of the return signal associated with the turbulent eddies is how the measure of wind direction and speed is performed (*Gage 1981*).

The science related to examining wind data not withstanding, the measurement method must be of a sufficient temporal and spatial resolution to determine the local climatology of the LLJ. As mentioned previously, the coastal nocturnal LLJ occurs within the lowest 2 km of the atmosphere, persists for several hours and has peak winds in excess of 10 ms^{-1} with a depth several hundred meters. The profiler operating at Fort Meade has a vertical resolution of 60 m beginning from 110 m extending up to 1500 m (low mode). Wind speed measurements are accurate to within 1 ms^{-1} and wind direction to ± 10º. Therefore, the radar profiler is theoretically capable of accurately observing the Mid-Atlantic nocturnal LLJ. The data set used in this study covers August 1998 – December of 2003. A much longer time period would be desirable to present a more complete climatology. However, this data set does afford sufficient information for a preliminary climatology as it encompasses the warm, more polluted summer seasons (1999 and 2002) and the relatively cool and clean summers (2000, 2001 and 2003). While there are some periods of missing data early in the operation at FME, there is approximately a 90% data capture rate over the period. ***Figure 4*** shows a maximum of missing data during winter months (when the cleanest most stable air masses occur) and a minimum during the summer months (the period of most interest for this study). The occurrence of missing profiles is quite infrequent while bad individual data points, within a profile, are more common. Overall, 30-40% of possible data points with a specific profile are not resolved. While this may appear to be a large number it should be noted that this does not imply that 30-40% of the profiles are missing. Rather, that the returns from any specific range gate (height) were not adequately robust to give a high quality consensus wind measurement. Often the reason for poor consensus was too few "targets" to provide a strong backscatter return signal. One common reason for insufficient data points is clear skies which contain relatively few aerosols. Another explanation is a very stable atmosphere which can inhibit eddy turbulence occurrence (particularly in the upper portion of the boundary layer). ***Figure 5*** shows that data points at higher altitudes, serendipitously above the height of the LLJ, are preferentially missing over lower altitude data.

Wind profilers can be operated in a course (high) or fine (low) mode; in this study only the fine mode data was evaluated. In the fine mode data points occur at 60 m intervals (110 m -1500 m) while in the course mode data is spaced 200 m apart (320 m – 4000 m). Other studies involving the Great Plains jet LLJ (*Whiteman et al., 1997*) have found radiosonde data compares better to low mode than does high mode data. One reason for the poorer correlation with radiosonde data is the averaging effects over the wider range gate. Another limitation of the high mode data is that the altitude of the lowest gate (~320 m) may hinder the observation of the lower portion of the LLJ. Therefore for this study only the low mode data was used.

Section 3: Definition of the LLJ

There are no universal rules for identifying a feature of variable magnitude like the LLJ. As noted above, an inertial acceleration, driven by the loss of friction in the residual layer after sunset, is present on nearly every occasion that a nocturnal boundary layer develops – that is, in all but high wind and precipitation cases. At what point this increase in wind speed aloft becomes a "jet" is not patently obvious and no clear LLJ threshold exists. The most commonly used criteria for identifying the LLJ follows the ground breaking work of *Bonner, 1968*. In that study, two basic criteria are set. First, a threshold value for maximum wind, 12 ms^{-1}, and, second, a "fall off" value from the wind speed maxima upward to the next wind speed minimum or to a selected top layer. These criteria were further refined in *Whiteman et al., 1997* to include slightly weaker (10 ms^{-1}) jets. The speed criteria applied in this case follows *Whiteman et al., (1997)* with the addition of still weaker speed criteria (8 ms^{-1}) due to the expected weaker terrain-induced forcing for the coastal LLJ as compared to the Great Plains LLJ. The criteria to identify the coastal LLJ are given in ***Table 1***.

In addition to the wind speed criteria, two additional criteria are added that are specific to this dataset and application. First, ≥ 25% of all range gates within a given profile must report good data to quality for inclusion in the dataset. This translates to 5 data points within the first 1.5 km and is not a stringent constraint. Second, and more important, the LLJ must persist for 5 hours or more to be classified as a jet. The reason for the duration requirement relates to the particular application to air quality studies. For LLJs to affect air quality transport on greater than a local scale, the jet must be active for a relatively long length of time. Assuming a conservative measure of 10 ms^{-1} wind speed for a 5 hour period, an air parcel within the jet would travel approximately 180 km or roughly the distance from Richmond to Baltimore. Transport at this distance has regional and intra-regional transport implications. The duration requirement is unique to this application so that the frequency statistics determined here will likely be significantly lower than that reported in other studies (e.g., *Zhang, 2005*). However, to determine the frequency of transport of O_3 and precursors at policy relevant scales, a duration requirement is necessary. Details of the data processing to create the final data files are given in ***Appendix D***.

Section 4: Statistics of the Low Level Jet

Using a more relaxed criteria for LLJ detection, other studies (*Zhang et al., 2005*) have observed a significantly higher frequency of LLJ occurrence than reported in this analysis. In that study shorter duration LLJs were included and the results of this study better match those findings when LLJs of any duration are included (see ***Figure 6, Table 2***). For all LLJ events of 5hr duration or greater, associated with any of the processes discussed in the previous section, occurred on 13 % of all days (n = 251). ***Figure 7*** shows the majority (69%, n = 173) of these events took place during the warm season (April-September). Summary statistics are presented in ***Table 2***. Given that the LLJ is mostly a nocturnal phenomena the average start and end times may provide information about the results. The LLJ was found to typically occur after sunset with the median start time and end time of 23:00 (***Figure 8***) and 06:00 (***Figure 9***) respectively. For all wind profiles with maximum wind speeds greater than ≥ 8 ms^{-1} the maximum mean wind speeds is 14.4 ms^{-1} (± 4.2 ms^{-1}) (***Figure 10***). The mean height of the wind speed maximum (the core of the jet) is 0.546 km (± 0.160 km) (***Figure 11***) with the top of the jet 0.900 km (± 0.161 km) (***Figure 12***). Because of limited data points, the height of the base of the jet it is difficult to determine directly. During synoptic conditions when the LLJ is often observed the height of the nocturnal inversion is typically 100-200 m above the surface layer. Assuming the LLJ forms just above the nocturnal inversion, and the profile is symmetric the depth of the LLJ is on the order of 500-700 m. The median direction of maximum winds was 215 ° (***Figure 13***). The wind direction was more varied than height and speed of the LLJ. This result is not unexpected given the variety of the forcing mechanisms associated with the LLJs.

A separate analysis of summertime "southwest LLJs" (180° ≤ maximum winds in the jet ≥ 270°) was performed. An example of a southwest LLJ is given in ***Figure 14***. These LLJs are of interest as they are believed to be a classic, terrain induced, phenomena which occur frequently during high ozone episodes. The average frequency of these cases was 29 per year. The mean starttime was of 22:00 EST comparable to the mean and median starttime of LLJs from all seasons. The mean endtime of 06:30 EST for southwest LLJs falls in between the overall mean (06:00 EST) and median (07:30) endtime. These results confirm that the southwest LLJ is a nocturnal event that occurs mostly in the summer season (109 of 158 cases). Peak winds in the core of the southwest low level jet average 14.2 ms^{-1}. The average height of the base of the LLJ of 0.500 km is consistent with height of the Great Plains jet (*Corsimeir, 1997, Bonner, 1969*). A relatively tightly grouped average direction of 225° (± 56°) for the southwest LLJ is common in a terrain-induced environment. It should be noted that the determination of what constituted a southwest LLJ was somewhat relaxed. A LLJ was classified a southwest LLJ if any of the individual profiles (within the 5hr period) were in between 180° - 270°. This may have introduced LLJs with a mean wind direction at the maximum wind speed that was not from the southwest. Inspection of ***Figure 13*** shows a clear southwesterly signal in the LLJs with some spurious LLJs from other directions.

Section 5: Nocturnal LLJ Evolution and Related O_3 Transport Issues

The horizontal and vertical distribution of O_3, and its precursors, is a function of different scales of motion in the atmosphere that can generally be separated into three groups: large-scale, meso-scale (channeled flow), and micro-scale (local winds) (*Vukovich et al., 1977, Milianchus, et al. 1998, Berman, et al., Rao el at, 1994*). Perhaps more categories could be devised but for the purposes of transport over the North America this classification scheme is convenient. Large-scale weather patterns (>1000 km) characterize what is often referred to as regional scale transport during high ozone periods. Regional transport has been well documented (*Vukovich et al., 1977, Ryan 1998, Roa 1994, Seinfeld, 1989*). Operational numerical weather models often simulate the large-scale transport accurately (*Ryan et al., 1998*) because of their relatively long temporal, and big spatial scale. Channeled flow such as the low-level jet, on the other hand, is a more challenging transport mechanism to replicate in numerical models because it is smaller and occurs on more rapid times scales. Micro-scale winds are the smallest scales of motion; they can be very challenging to model because of their sometimes “sub-grid”, chaotic nature.

One major limitation to a good understanding between the relationship of the LLJ to ground level ozone is a dearth of comprehensive meso-scale air quality and meteorological measurements (*Zhang et al., 2001*). Difficulty in accurately modeling PBL pollution transport is also the result of an incomplete understanding of the complicated atmospheric wind patterns occurring within the lowest 2000 meters of the atmosphere. The LLJ is often described as a mesoscale feature because of its range of horizontal dimensions (> 1000 km long x 200 km wide) but viewed vertically it is very thin (~500 m) and may best be assayed with a micro-scale approach.

In 1994, in response to a recommendation from the U.S. National Research Council the North American Research Strategy for Tropospheric Ozone (NARSTO) was established to fill the gap in scientific understanding of the tropospheric O_3 (NARSTO, 2000). The mission of NARSTO is to design and coordinate a coherent, long term science focused, policy-relevant research program emphasizing the atmospheric processes involved in tropospheric O_3 and O_3-precursor formation, transformation and transport (NARSTO, 2000). From NARSTO directed studies to measure regional and local-scale circulation patterns, as well as boundary layer evolution processes, data were gathered during a severe high ozone episode over the Northeastern United States during July of 1995 (*Zhang et al., 1998, Berman, 1999*). On a related front recent studies have attempted to understand better the connection between ozone vertical profiles and boundary layer atmospheric processes (*Corsmeier, 1997, Reitebuch et al. 1999, Zhang et al., 1998, Zhang et al., 1999, Salmon and McKendry, 2002*). Simultaneously, modern efforts have been made to improve numerical modeling of boundary layer processes by using finer scale models with different boundary layer schemes (equations to represent the transfer of momentum and energy) to describe evolution of the nocturnal boundary layer and the corresponding low level jet (*Zhang et al., 2000, Seaman, 2000, Ku et al. 2001, Shafran, 2000*).

Horizontal transport is perhaps the easier of the two mechanisms to visualize - pollution is moved away from an area on a horizontal plane in the direction of wind flow. ***Figures 15*** and ***16*** depict a theoretical case of vertical O_3 transport associated with a LLJ. Vertical transport can be tougher to conceptualize because for one, ozone gradients are created from different rates of ozone removal at different levels. Another reason is that when downward vertical transport is occurring, ozone concentrations are enhanced aloft relative surface values. This is so because a main loss mechanism for ozone (dry deposition to the surface) is not a factor in the residual layer (*Seinfeld, 1989*).

The next several paragraphs will provide some background information on the current understanding of low-level jet formation and highlight some of the recent findings from the studies mentioned above.

Transport and modeling scientific studies concerning low level jets have strived to make better estimates of horizontal (advection) and vertical (turbulent mixing) transport processes related to the LLJ and the consequences of such actions on surface ozone concentrations. At a rural site in Germany, *Corsmeier et al.* (1997) observed secondary maxima in surface ozone at nighttime that supported the notion that downward transport from the residual layer was occurring. The secondary maxima was, on average, 10 % of the next days ozone maximum but at times could be as much as 80 % of the maximum (*Corsmeier, et al. 1997*). The secondary ozone maxima were well correlated with an increase in wind speed and wind sheer. The strong vertical sheer over the very thin layer can result in mechanical mixing that leads to a downward flux of ozone from the residual to the near surface layer (***see figures 15 and 16***). Analysis of wind profiles from aerological stations in northeastern Germany revealed the spatial extent of that particular LLJ was up to 600 km in length and 200 km in width. The study concluded the importance of ozone transport by low level jets was twofold: ozone could be transported hundreds of kilometers at the jet core level during the night. Additionally, pollutants can be mixed to the ground far from their source region. *Salmond and McKendry* (*2002*) also observed a secondary ozone maxima (in the Lower Fraser Valley, British Columbia) associated with low level jets that occasionally exceeded half the previous day's maximum O_3 concentration. The largest increases in surface ozone concentration occurred when boundary layer turbulence coincided with ozone levels greater than 80 parts per billion were observed aloft. In addition the study suggests horizontal transport efficiency during a low level jet event could be as much as six times more efficient than transport with light winds without a low level jet. Over a more urban area in Germany *Reitebuch* (*1999*) observed a secondary ozone maxima associated with low-level jet evolution. The theory of ozone transport down from the residual layer to the surface was supported by observed decreases in concentrations of NO, NO_2 and CO in the residual layer during secondary O_3 maxima. Unlike O_3 in the residual layer, NO, NO_2 and CO concentrations should be low relative to surface concentrations (*Reitebuch, 1999, Seinfeld, 1998*). As in other studies, speed and directional sheer was detected during the transport events. Calculations of the average wind speed and duration of the LLJ during these events suggested that horizontal transport of pollution on the order of several hundred kilometers. Investigations into boundary layer and vertical structure of ozone observed at a costal site in Nova Scotia described how temperature and differences surface roughness associated with a marine environment can induce LLJ formation and pollution transport (*Gong, 2000*). This interesting case study looked at a LLJ associated not with mountain topography, but rather from strong horizontal sea surface gradients causing the necessary forcing.

Recent attempts to numerically investigate boundary layer evolution and LLJ formation have focused on evaluating different boundary layer schemes (*Zhang, 1999, Shafran, 2000, Zhang, 2005*). These studies assessed a "state of the science" meteorological model's ability to reproduce boundary layer dynamical processes. In doing so inputs for corresponding air quality models were generated and determinations were made as to the affect uncertainties in meteorological models has on predicted pollution concentrations. The basic findings were that certain boundary layer mechanisms better capture boundary layer processes and that while several schemes predict derived parameters such as temperature, relative humidity well, horizontal winds are not represented as well.

The studies cited above mark important step towards assaying the vertical turbulent fluxes of pollutants (and energy) that establish a link between the surface layer and the residual layer above which determine the pollution budgets in the very shallow nocturnal boundary layer. The efforts also serve to underscore that the complexity of nocturnal winds in the boundary layer and identify key research paths. Potential solutions to these challenges revolve around continuous, high-resolution measurements within the boundary layer. A dense network of boundary layer radar wind profilers and radio acoustic sounding systems (RASS) are promising techniques because they offer the ability to evaluate, on a useful temporal spatial scale, wind, temperature and moisture in the boundary layer over a wide area. Aircraft operations are another sampling approach, and with these studies the horizontal morphology of the PBL in real time and space.

Section 6: The LLJ, high O_3 Episodes and Related Transport

Days on which LLJs are observed in Maryland are enhanced with respect to O_3. For days on which 5 hr LLJs occurred (n =109) the average 8hr maximum ozone concentration was 80 ppbv compared to 68% for all ozone season cases. Code orange levels occurred 42% of the time 5 hr southwest LLJ's were observed while 20 % of the time the mean peak 8hr ozone reached the code red threshold. Therefore, LLJs appear to be a common part of high O_3 over Maryland.

Also of interest is also how often high ozone cases involve LLJs. From 1999-2003 (May–September) the Baltimore metropolitan area experienced 119 cases when the mean peak 8 hr concentration was ≥ 85 ppbv (Code Orange AQI). Thirty eight times (32% of the time) a LLJ was observed within 24 hrs of the peak O_3. The majority of these cases the LLJ began the evening prior to the maximum O_3 occurrence. This is reasonable given the average start time of ~ 22:00 EST (***see Figure 8***) and duration ≥ 5 hours. Concerning all of the LLJs, the southwest LLJ was the dominant type of LLJ during these high O_3 events (63%). Code red cases (8hr O_3 ≥ 105 ppbv) occurred 51 times over the same period; 42 % of the time a LLJ was observed within 24 hrs. Nearly all of these LLJs were from the southwest.

Examining extreme ozone episodes (code red or code orange for 3 consecutive days) shows a stronger connection between LLJs and high ozone. Greater than 80% of the time a LLJ was associated a "severe" ozone episode. Nearly half the code red cases occurred on the same day of th LLJ. These results suggest the air mass within the LLJ, particularly LLJs from the southwest, is enhanced with respect to O_3 and O_3 precursors.

What are the characteristics of the air mass within the LLJ? As noted earlier, LLJs can be forced by a variety of effects. Some of these effects are associated with weather conditions that are conducive to O_3 formation and some not. Examples of both types are provided in more detail in Section 7. For many reasons, including air traffic and air space controls and limited forecast skill, it has not yet been possible to penetrate the mid-Atlantic LLJ with instrumented aircraft. Thus, there are no direct measurements of air quality within the core of the LLJ. While we do not have measurements within the LLJ itself, we can indirectly determine the approximate magnitude of O_3 transported within the jet by measuring O_3 concentration changes as air aloft, in the residual layer, mixes downward in the morning hours. We know, see ***Figure 1***, that as the nocturnal boundary layer breaks down by buoyant mixing in the late morning and early afternoon, the residual layer will be mixed downward first. By analyzing a time series of O_3 for high O_3-LLJ cases, the air mass characteristics of the LLJ can be estimated.

Figure 17 shows hourly O_3 concentrations from four representative O_3 monitors in the Baltimore metropolitan area for the subset of high O_3-LLJ cases (n = 61). These monitors are located at Fort Meade, co-located with the profiler, Essex, an urban site northeast of the Baltimore city center, Padonia, a suburban site north of Baltimore, and South Carroll, and ex-urban site well west of Baltimore. Three facts are worthy of note in ***Figure 17***. First, the high O_3-LLJ cases are characterized by a strong regional O_3

signal. Averaged over all cases, O_3 concentrations are essentially equal at the four widely scattered sites. While there is a good deal of day-to-day variation driven by local emissions and winds the consistency in O_3 concentrations, across a wide variety of local conditions (urban to rural), indicates that the regional scale O_3 concentrations are a key factor in local O_3 concentrations. Second, the hourly time series in ***figure 17*** shows a rapid late morning increase in O_3 concentrations. This increase is primarily a response to downward mixing from the residual layer (*Zhang and Rao, 1999*). The magnitude of this increase suggests that the residual layer, in this set of cases, contains on average, O_3 concentrations at least on the order of 60-80 ppbv. In individual cases, the impact of mixing downward from the residual layer can be much higher (***Figure 19***). Finally, unlike the case studies reported above showing secondary O_3 maxima during the overnight hours, there is no evidence, on the climatological scale, of this effect being widespread. Several reasons can be advanced for the lack of an early morning O_3 signal. The pre-existing relatively polluted nature of the air mass beneath the nocturnal inversion in Maryland during these cases may mask the impact of this mixing and brief, turbulence induced, incursions may not be sufficiently long in duration to be resolved by hourly averaged O_3 observations.

Because O_3 has a distinct diurnal cycle, with late afternoon maxima driven by photochemistry, it is difficult to precisely assess the contribution of downward mixing from the residual layer, as compared to local photo-chemical production, in causing late morning O_3 increases (*Zhang and Rao, 1999*). An alternative approach to corroborate the O_3 results shown above is to look at a time series of $PM_{2.5}$ concentrations. As a general rule, $PM_{2.5}$ concentrations, after a brief morning rush hour peak, tend to decrease as mixing continues during the late morning and early afternoon hours (***Figure 20***). However, for the LLJ cases, $PM_{2.5}$ concentrations increase further during the late morning and early afternoon hours suggesting that the air mass is polluted with respect to $PM_{2.5}$ concentrations as well (***Figure 21***).

The conclusions that can be reached from the analysis of high O_3-LLJ cases is that, if a LLJ develops over Maryland, we are likely to observe higher than average O_3 concentrations with mean peak O_3 just below the Code Orange threshold. Approximately one-half of all southerly LLJ cases reach the Code Orange threshold and approximately one-fourth reach the Code Red threshold. For all observed Code Orange cases in Baltimore, approximately 60% observed a LLJ within 36 hours of the occurrence and 42% of all Code Red cases observe a LLJ on the morning of the event. Therefore, the LLJ is a key characteristic of high O_3 in the Baltimore area.

While the characteristics of the air mass transported within the LLJ have not yet been directly observed in Maryland. We can make estimates of these characteristics by indirect means. Measurements of late morning O_3 concentrations, which are primarily a function of downward mixing from the residual layer, show concentrations on the order of 60-80 ppbv overall with higher concentrations also occurring. A similar analysis of $PM_{2.5}$ concentrations shows a secondary increase, after the morning rush hour, in the range of 30-40 μgm^{-3}. The conclusion that can be reached from indirect measurements is that the air mass in the residual layer, in which the LLJ resides, is polluted and can contribute to peak concentrations locally.

As mentioned above, detailed, direct measurements of trace gases with the coastal LLJ have yet to be obtained. This is in large part because of the restricted air-traffic patterns and the timing of the LLJ. Given the dearth of direct measurements within the LLJ inspection of ground level O_3 from an elevated site in near proximity of the LLJ may provide some insight into the chemistry within the LLJ. Hourly O_3 plots for selected MD monitors and Methodist Hill present LLJ case studies during periods of high ozone over the Mid Atlantic region (***Figures 22-24).*** Methodist Hill is an elevated site located ~100 km west-northwest from the Fort Mead profiler. The height of Methodist Hill monitor (630 m) is situated just above the height of the core of the LLJ determined in this study (546 m). Each case studies periods when southwest LLJs were observed at Fort Meade and code red (1hr $O_3 \geq 125$ ppbv) conditions were observed either on the same day or the following day. The figures show that O_3 at Methodist Hill, during the time of LLJ activity, is ranging from ~85 of ~110 ppbv. Secondary O_3 maximums (a maximum in O_3 occurring well after sunset) 10-15 % of the next day peak O_3 were observed during these periods. The plots help support the belief that O_3 levels at the height of the LLJ are enhanced with respect to surface O_3 levels. The secondary O_3 maximums further suggest that some of the O_3 from aloft is being vertically mixed down to the surface.

While we do not have complete measurements of trace gases within the LLJ, recently two short field campaigns (*Taubman et al., 2005, in press*) conducted over Beltsville MD (where the Fort Meade profiler now resides) provide a snapshot of O_3 concentrations within the LLJ ***(Figures 25-26)***. Two LLJs were detected by profiler data at Fort Meade on the early morning hours of the 5^{th} and 14^{th} of August, 2005. Maximum O_3 concentrations within the LLJ were on the order of 80-100 ppbv. Maximum wind speeds in the core of the LLJ were very near the average value determined in this study (~14 ms^{-1}). The mean wind direction was from the southwest (~240°). Surface O_3 values from the Beltsville CASTNET site (10 min. averages) indicted the presence of a secondary O_3 maximum on August 5^{th} coincident with LLJ formation (***Figures 27-28***). The O_3 profile on the morning of the 15^{th} showed a weaker, but broader, secondary ozone maximum than the 5^{th}. While these two samples represent a small data set they provide an excellent benchmark for future studies.

Section 7: Synoptic Scale Weather Conditions Associated with LLJs and High O_3

Weather patterns associated with rapid increases in O_3 accompanied by the presence of LLJs are similar in most respects to the "classic" mid-Atlantic high O_3 episodes (*Ryan et al., 1998*; *Michelson and Seaman, 2000*). Standard features include an upper air ridge with its axis over or west of the region; diffuse surface high pressure straddling the region with the center of high pressure typically over the Appalachians; and synoptic scale transport aloft from the west and northwest. Examples from a high O_3–LLJ case in June of 1999 are shown in ***Figures 29-31***. Note that the HYSPLIT back trajectories in ***Figure 30*** do not resolve transport by the LLJ at low levels (500 m). This is due to the relatively coarse resolution of the archived Eta fields used by HYSPLIT (80 km grids) to determine the back trajectories. This resolution is not sufficient to resolve transport on the spatial scale of the LLJ. Upstream O_3, determined from an analysis of AIRNOW peak O_3 images, are not overwhelming but do tend to be in the moderate to upper moderate range (70-100 ppbv) which is consistent with aircraft observations aloft during high O_3 episodes in the mid-Atlantic. Examples of regional O_3 concentrations are given in ***Figures 32-33*** for two rapid onset O_3 cases where LLJs were observed.

LLJs tend to occur as part of the standard high O_3 weather pattern because diffuse high pressure near the surface dictates that synoptic scale winds will be light, often variable, so that weaker effects, such as terrain-induced temperature gradients, can determine local wind speed and direction. For forecasting these events, the development of the standard high O_3 weather pattern is also a good indicator of the expected presence of a LLJ.

As noted above, the vast majority of high O_3-LLJ cases feature a southwest jet. There are a handful of cases, however, that feature non-standard LLJs *and* Code Red O_3. One good example of this type of case was the termination day of the NARSTO-NE event of July 12-15, 1995. Although the standard LLJ was observed for the majority of days during this multi-day episode (see, *Ryan et al., 1998*), a northwest jet was observed on the night before the final day of the event (July 15). The small subset of Code Red non-standard LLJ cases observed during the period studied here also contained a northwest wind maximum. Although the synoptic scale weather patterns in these cases are not particularly different from the standard cases, the presence of a lee trough offshore, with northwest winds in its wake, hint at a difference ***Figure 34***. This jet may be induced by mountain barrier effects as the larger scale flow is perpendicular to the spine of the Appalachians.

The LLJ is not always associated with high local O_3 concentrations. Historically, the LLJ was first studied because of its coincidence with periods of strong and dangerous convection – not a situation conducive to high O_3. In those cases, the LLJ acted as a conveyor, moving very moist, unstable air northward into a developing storm. Our analysis has focused on the LLJ as a possible conveyor of O_3 and precursors into the region. However, the coastal LLJ can also act as a contributor to convective activity. In a number of cases analyzed here, the LLJ was associated with the development of strong convection as a high O_3 episode came to an end.

Thunderstorms and convection lead to lower O_3 concentrations as deep vertical mixing, cloud cover, and rain combine to reduce the potential for O_3 to accumulate. In addition, the southwest LLJ can, given the proper synoptic scale weather pattern, transport relatively clean Gulf of Mexico air into the region, lowering background O_3 concentrations. High O_3 episodes often terminate as a cold front approaches from the west. LLJs in these cases are forced, in part, by synoptic scale effects. Winds increase from the southwest ahead of the frontal boundary and a jet can develop in the nighttime hours as friction is reduced. The larger scale dynamics can add to or replace the standard terrain and inertial effects. An example of this effect is shown for the May 9-10, 2000 O_3 event. On May 9, high O_3 was observed in the mid-Atlantic (***Figure 35***). A southwest LLJ was observed on the night of May 9-10 with convection and lower O_3 observed on May 10 (***Figure 35-36***). In other similar cases, the strong winds, and later convection associated with the front will decrease O_3 concentrations (***Figure 38-39***)

In summary, the weather patterns historically associated with high O_3 in the mid-Atlantic are also conducive to the development of the southwest LLJ. Of particular interest is a weak and diffuse high pressure field over the region that leads to light near surface winds and allows terrain effects to become dominant. LLJs can also act to reduce O_3 concentrations locally, primarily by enhancing the potential for thunderstorm development and by transporting Gulf of Mexico air masses, typically unmodified maritime tropical air and thus quite clean, into the region. The O_3 reducing LLJ is often associated with the westward advance of a cold front and can be found often on the termination day of a multi-day event.

Conclusions

The low level jet (LLJ) is a transient maximum in wind speed observed in the lowest 0-2 km of the troposphere. While LLJs are found in many locations around the world, the most famous and widely studied jet is found in the Great Plains of the United States with a weaker version common along the eastern seaboard. The LLJ can form in response to a variety of influences including terrain effects, land-sea breezes, abrupt changes in near-surface friction, and flow around mountain barriers. The coastal LLJ in the mid-Atlantic is primarily formed due to terrain-induced temperatures differences and accelerations that develop after sunset as mixing, and surface-based frictional effects, decrease abruptly.

There are no universal criteria for identifying the presence of a LLJ. A wind speed criteria, developed for the study of the Great Plains LLJ, is used here with two important modifications. First, the wind speed threshold is reduced to 8 ms^{-1} to reflect the weaker terrain forcing in this region, and, second, a duration requirement of 5 hours is applied. The second criterion is applied so that the LLJs studied here are “transport relevant”.

Because they primarily occur at night, outside standard weather balloon launch times, LLJs in the mid-Atlantic have only been observed in special field programs and are not routinely observed by the National Weather Service radiosonde network. Radar profilers, with continuous observations, offer a chance to accurately and completely observe the LLJ.

Data from the Fort Meade radar profiler from August, 1998 to December, 2003 are analyzed in this study. Data capture during this period was quite good. Missing profiles account for only 8% of all data. Capture of individual data points (wind observations) within a profile is more difficult and missing data points within a profile are more common. Data capture rates within a given profile is much better in summer than winter and, over all, more vertical resolution is provided by the profiler than sounding data contained in the standard climatological database.

The long duration (≥ 5 h) LLJ is observed on ~ 13% of all days and ~ 20% of summer days during the study period. Shorter duration LLJs are much more frequent with jets of ≥ 2 hours occurring on 36% of all days. While LLJs can be induced by a variety of factors, the southwest or coastal plain, LLJ is primarily forced, in quiescent summer weather conducive to O_3 formation, by terrain-induced temperature gradients and reinforced by inertial effects as surface friction dissipates after sunset. The mid-Atlantic coastal LLJ typically occurs between 2200-0600 EST. Peak winds are ~ 33 ms^{-1} with mean peak winds for all hours during a jet of 14.4 ms^{-1}. The peak wind of 33 ms^{-1} is likely wind associated with a synoptic scale wind flow that mimicked the profile of a LLJ. This wind speed and duration statistics implies an average transport distance of 200-300 km. The jet maximum occurs ~ 550 m above ground level with a top at ~ 1 km.

O_3 concentrations are enhanced when southwest LLJs occur with an average peak of ~80 ppbv. On 44% of these days exceed the 8-hour Code Orange threshold (85 ppbv) and ~20% exceed the Code Red threshold (105 ppbv). When southwest LLJs are not associated with high O_3, it is typically due to thunderstorm formation or cloud cover in advance of frontal boundaries. The LLJ is a common characteristic of high O_3 episodes in Maryland. For 24 multi-day (≥ 3 days above Code Orange) episodes during the period, LLJs were observed for part or all of 17 episodes (70%). Overall, 42% of Code Red days have an occurrence of the LLJ.

Without aircraft observations within the core of the LLJ, it is difficult to directly assess the magnitude of O_3 and other pollutants transported into Maryland by the jet. A time series of surface based observations can be used to indirectly measure the air mass characteristics of the jet as the residual layer, which includes the LLJ, is mixed downward. While no precise measurement is possible, it appears that O_3 concentrations within the jet are, on average, at least on the order of 60-80 ppbv (recent measurements detecting ~100 ppbv) with 30-40 μgm^{-3} of $PM_{2.5}$. Thus the jet transports polluted air into the region at levels consistent with the regional load and occasionally higher. LLJs are also found in advance of frontal boundaries and can contribute to thunderstorm development as they can also transport warm, moist air into region.

Weather patterns conducive to the development of the LLJ are similar to the standard mid-Atlantic high O_3 cases with diffuse high pressure overhead. The fact that LLJs are coincident with synoptic weather patterns that produce high O_3 episodes implies that, until this process is accurately accounted for, modeling efforts related to severe O_3 events will be hampered. Future work should be directed to improving forecasts of LLJ formation and making direct aircraft measurements within the jet core itself. Correlating radar profiler data from several different locations will also provide a more complete picture of the costal plain LLJ morphology.

Table 1. Criteria for Identifying Low Level Jets

Criteria for Identifying Long Duration Low Level Jets		
1. Wind Speed Maxima/Minima (Surface to 1.5 km)		
Code	Maximum Speed Threshold (ms^{-1})	Minimum Speed Above (ms^{-1})
LLJ-2	8	4
LLJ-3	10	5
LLJ-4	12	6
LLJ-5	16	8
LLJ-6	20	10
2. Duration Requirement		
Wind velocity maxima above thresholds given above must be sustained for 5 hours or more. Not every consecutive profile must show a LLJ but one within each hour must (profile frequency was ~ 2 per hour for most of period).		

Note: Wind velocity threshold adapted from *Whiteman et al., 1997* and *Bonner, 1968* with addition of weaker threshold for LLJ-2 and duration requirement.

Table 2. Low Level Jet statistics.

Statistics for Long Duration Low Level Jets (Fort Meade, MD. 1998-2003)			
	All Seasons All Directions Cases	**All Season Southwest Cases**	**Warm Season Southwest Cases**
Number of Cases	251	158	109
Mean Start Time (EST)	22:30	23:30	23:00
Median Start Time (EST)	23:00	22:30	20:30
Mean End Time (EST)	07:30	06:30	05:00
Median End Time (EST)	06:00	07:00	06:00
Mean Duration (HR)	8 ± 2	8 ± 3	8 ± 3
Median Duration (HR)	7	7	7
Maximum Wind Speed (ms^{-1})	33.7		
Mean Maximum Wind Speed (ms^{-1})	14.4 ± 4.2	14.2 ± 4.1	13.4 ± 3.3
Mean Wind Direction (degrees)	248 ± 103	225 ± 93	225 ± 56
Median Wind Direction (degrees)	215	217	224
Mean Height of Maximum Wind (km)	0.546 ± 0.160	0.533 ± 0.161	0.494 ± 0.137
Median Height of Maximum Wind (km)	0.533	0.500	0.466
Mean Height of Top of Jet (km)	0.907 ± 0.161	0.900 ± 0.161	0.894 ± 0.137
Median Height of Top of Jet (km)	0.906	0.899	0.893

Data shown is for all LLJs, southwest LLJs and southwest LLJs during the warm season (Apr-Sep). Time period covered was August 1998-December 2003.

Variation of Frequency of Low Level Jets With Respect to Duration Criteria				
	Duration Requirement			
	2 hours	**3 hours**	**4 hours**	**5 hours**
1998	64	39	18	12
1999	134	81	49	34
2000	179	101	58	38
2001	167	100	67	50
2002	160	107	75	59
2003	149	107	74	58
Total				
% All Days	35.6%	27.5%	17.5%	12.9%

Table 3. Low Level Jet Frequency as Related to Duration Requirements

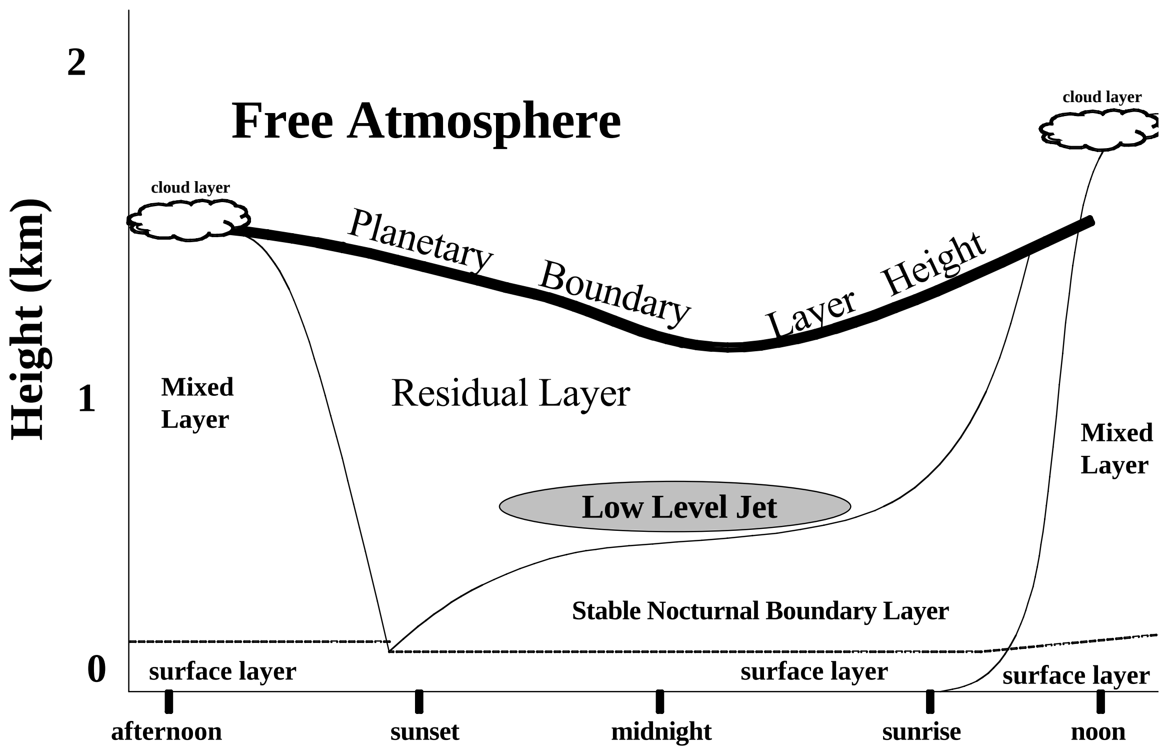


Figure 1. Planetary boundary layer in a high pressure region over land. Three major layers exist (not including the surface layer): A turbulent mixed layer; a less turbulent residual layer which contains former mixed layer air; and a nocturnal, stable boundary layer which is characterized by periods of sporadic turbulence. This figure was adapted from figure 1.7 and figure 1.12 of "*An introduction to Boundary Layer Meteorology*" (*Stull, 1999*).

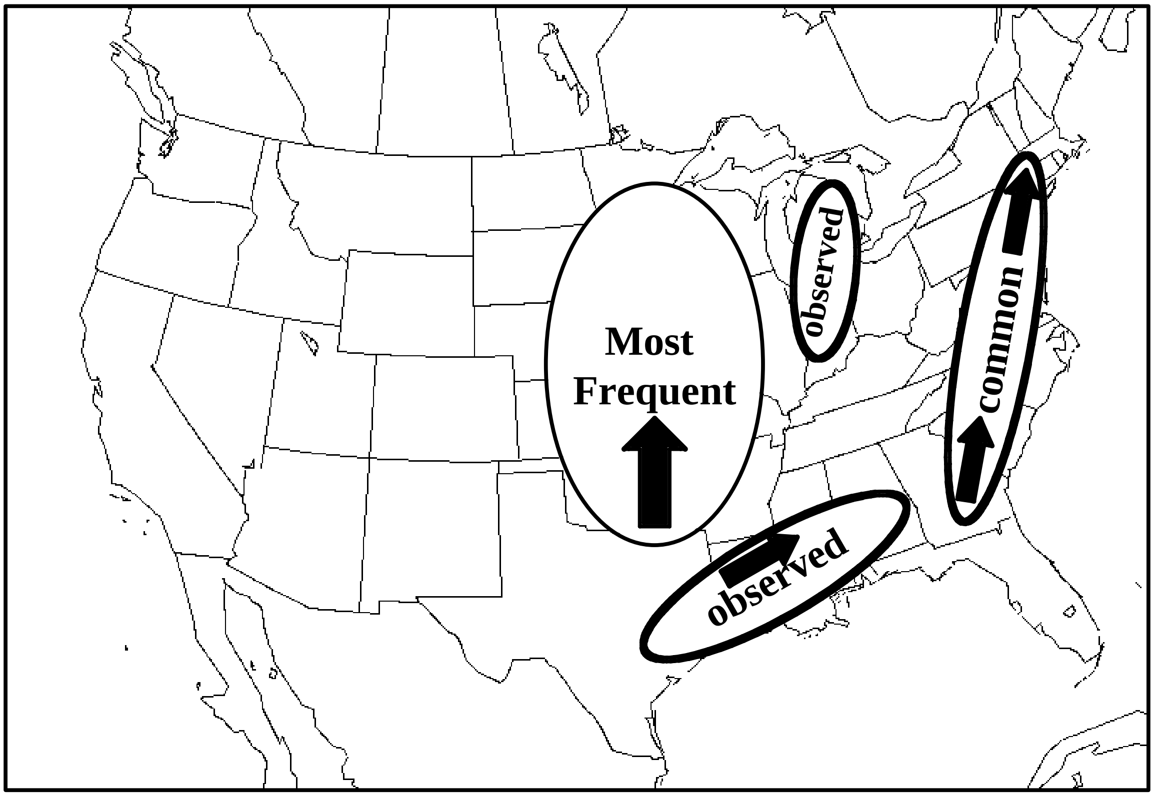


Figure 2. A figure of the climatology of LLJ observations based on a study from *Bonner* (*1968*). These data represent two years worth of radiosonde data over a limited (by modern standards) area. It is very possible that other low level jets will be observed elsewhere is the United States with better data coverage.

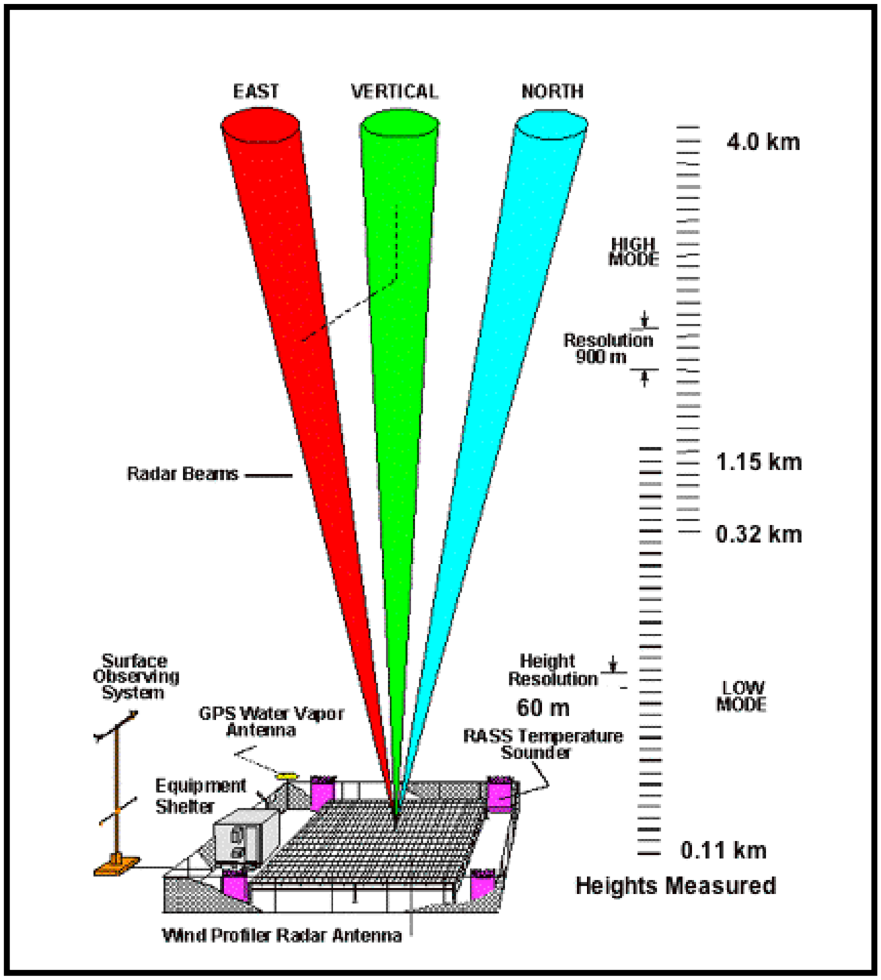


Figure 4. An image of a Boundary Layer Wind Profiler from the NOAA Profiler Network. The wind profilers in the NOAA Profiler Network (NPN) operate continuously, alternating sampling modes every 1 minute between a low or high mode, and switch beam positions (eastward, northward, or vertical) every 2 minutes. The low mode contains range gates (sampling heights), spaced every 60 m in the vertical. The low mode samples the lower atmosphere, beginning at 110 m above ground level (AGL) and continues to 1.5 km AGL. The high mode slightly overlaps the top of the low mode, beginning at 320 m AGL and extends to a maximum height of 4 km AGL.

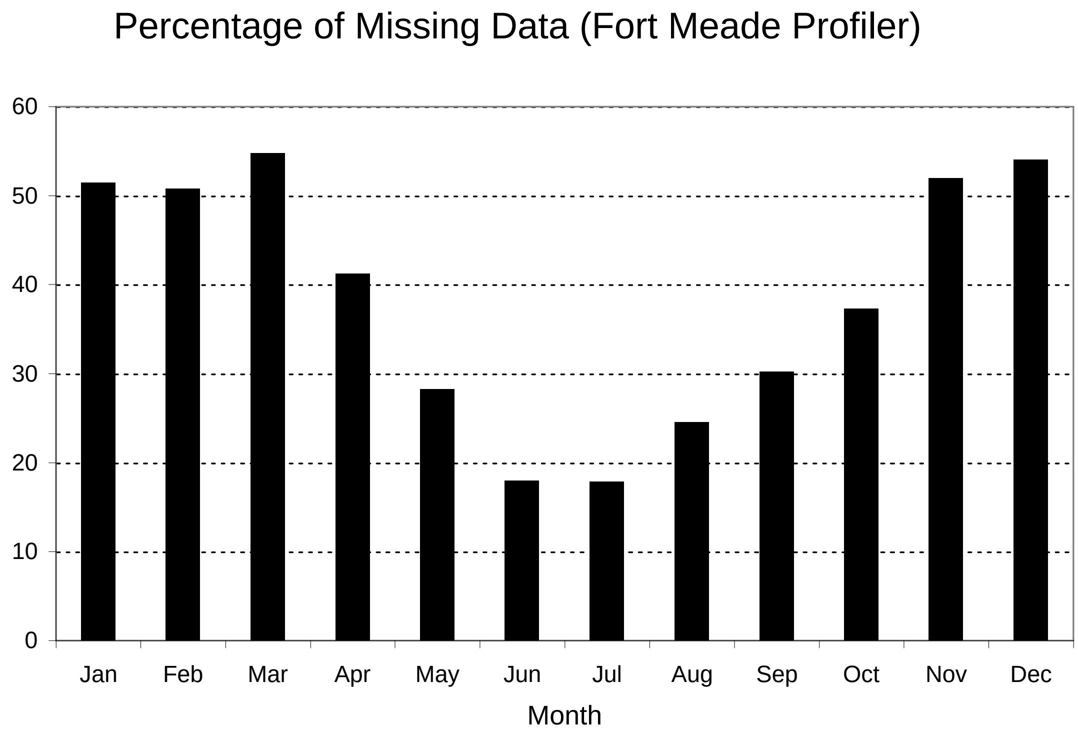


Figure 4. Monthly rates of missing range gate data at the Fort Meade profiler (August 1998-December 2003).

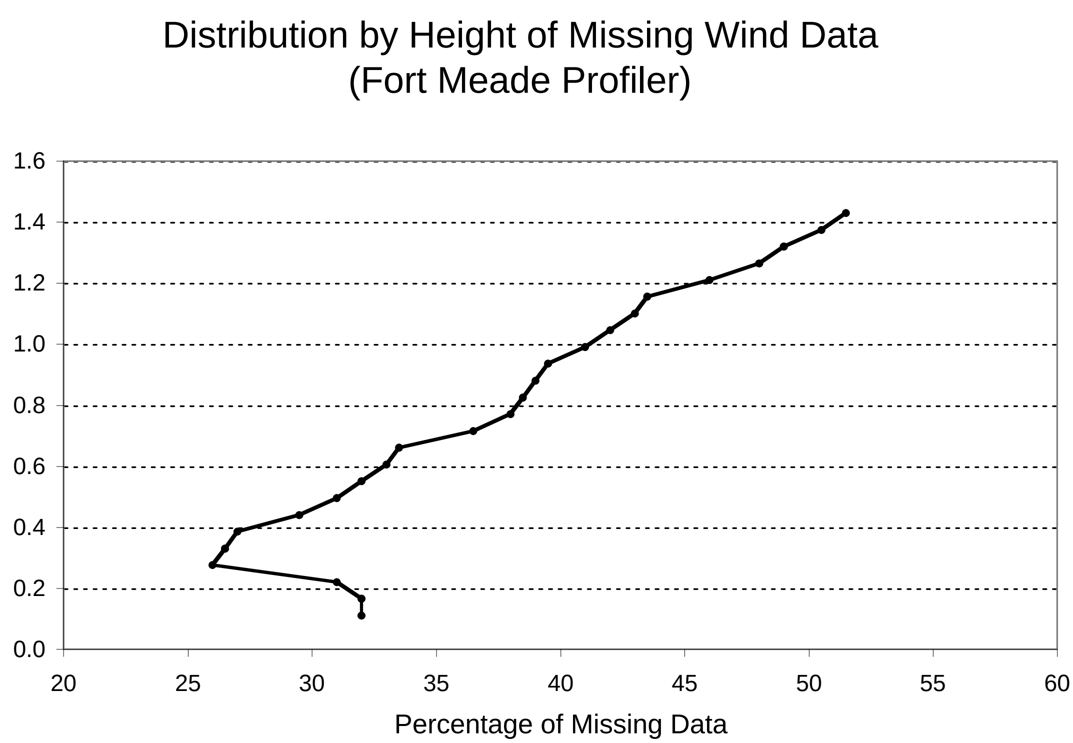


Figure 5. Missing Range gate data at the Fort Meade Profiler as a function of altitude.

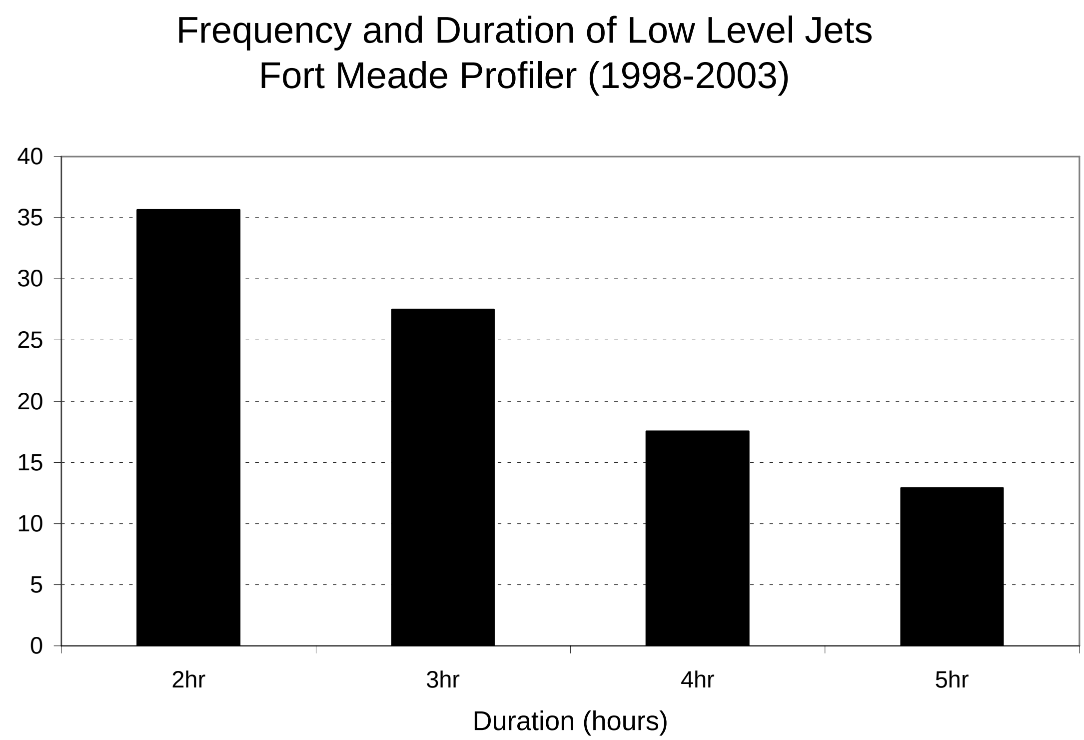


Figure 6. Frequency of the LLJ at FME as a function of LLJ duration (in hours).

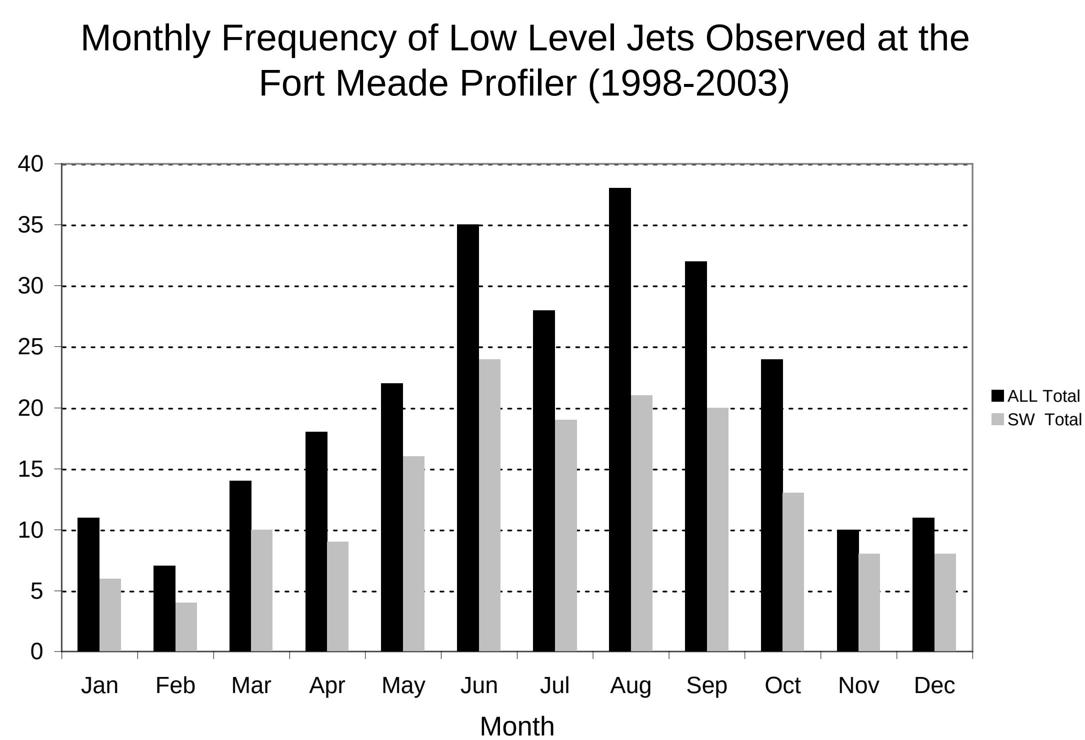


Figure 7. Monthly frequency of the long duration LLJ (≥ 5HR) observed at Fort Meade.

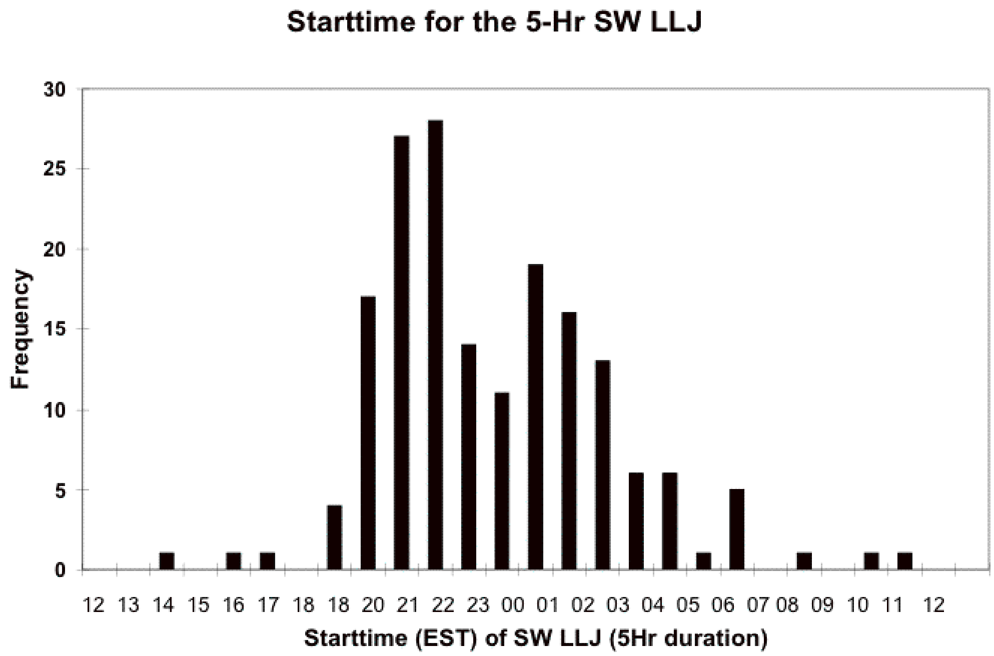


Figure 8. The frequency of initial, or start, time of the southwest LLJ. The start hour is defined as the time at which the LLJ first exceeds the threshold wind speed criteria given in Table 1. For ease of viewing the time period covers noon to noon EST.

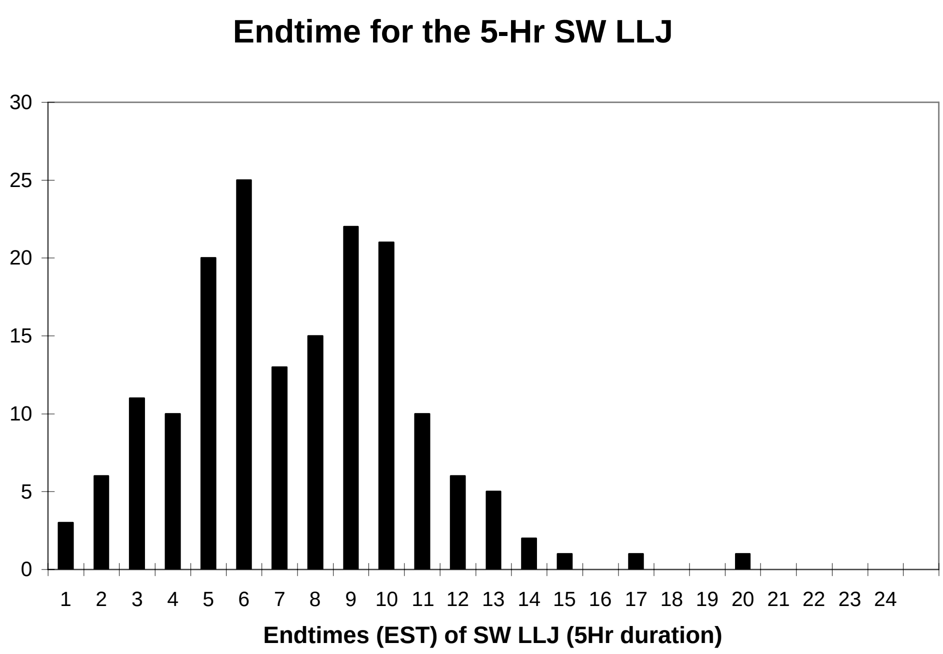


Figure 9. Frequency of termination, or end, time of the southwest LLJ. The end hour is defined as the time at which the LLJ no longer exceeds the threshold wind speed criteria given in Table 1.

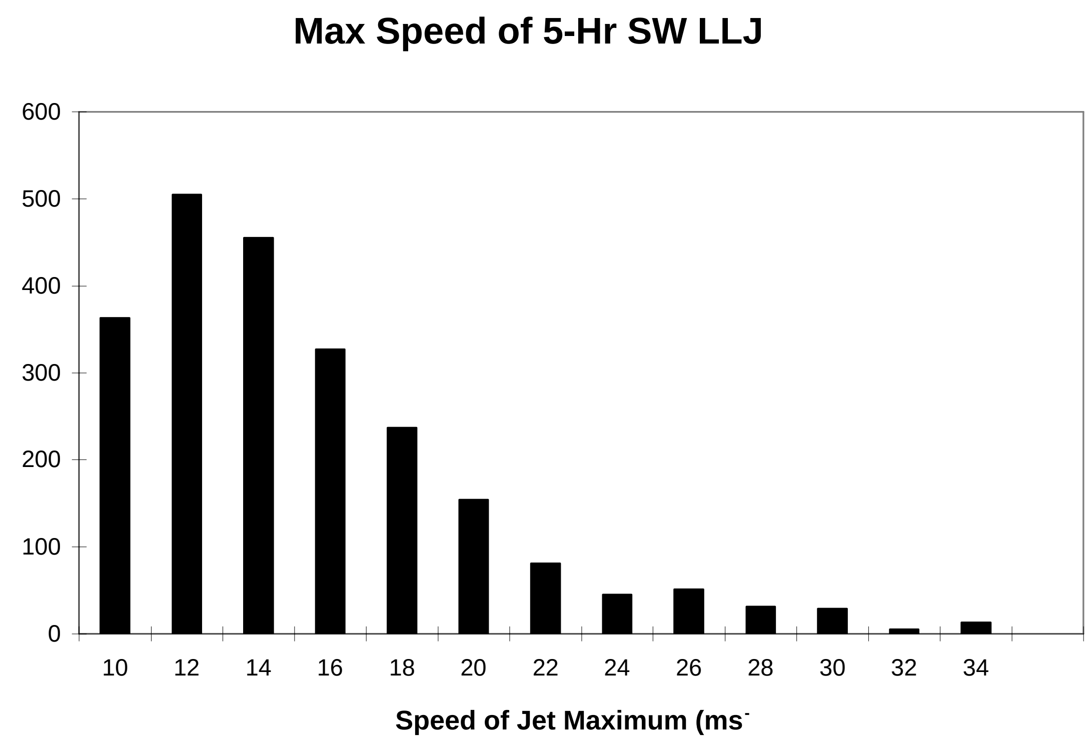


Figure 10. Frequency of the peak wind speed within the southwest LLJ.

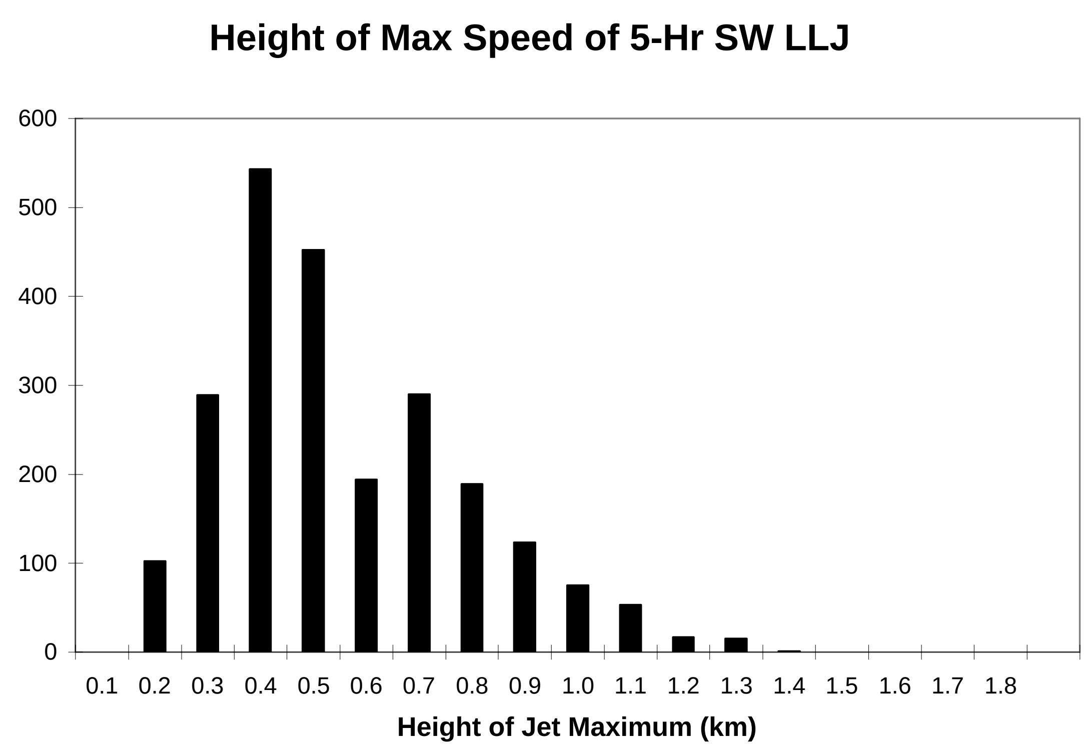


Figure 11. Frequency of the height of the maximum wind speed within the long duration southwest LLJ.

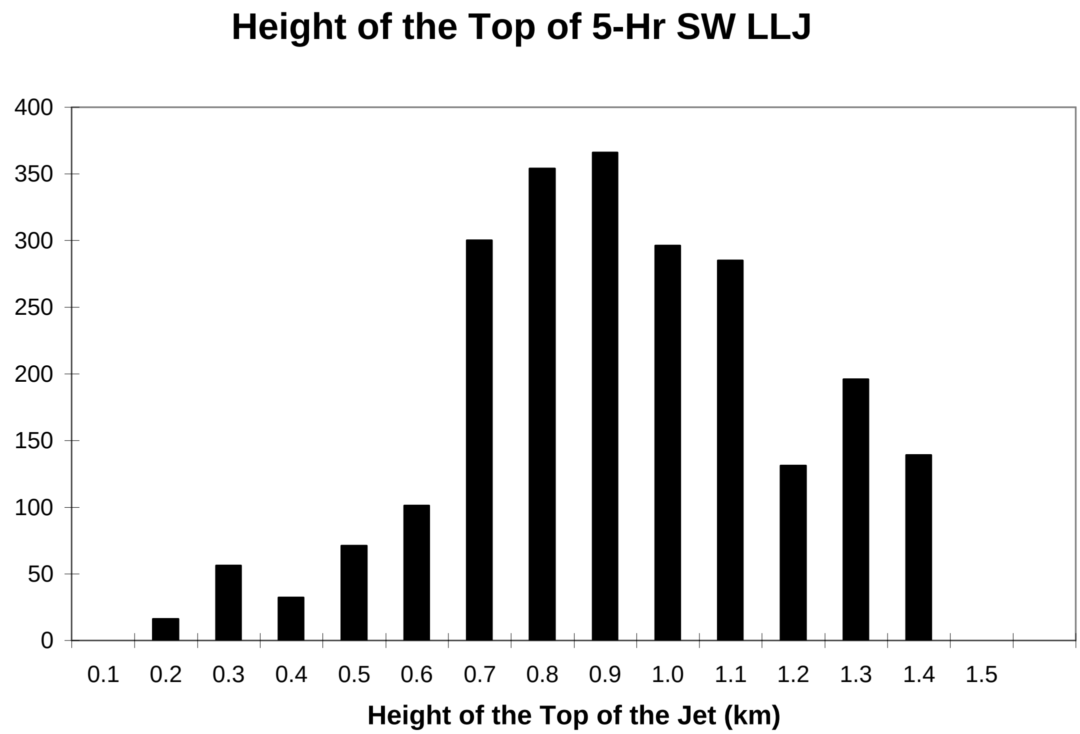


Figure 12. Frequency of the height of the top of the long duration southwest LLJ.

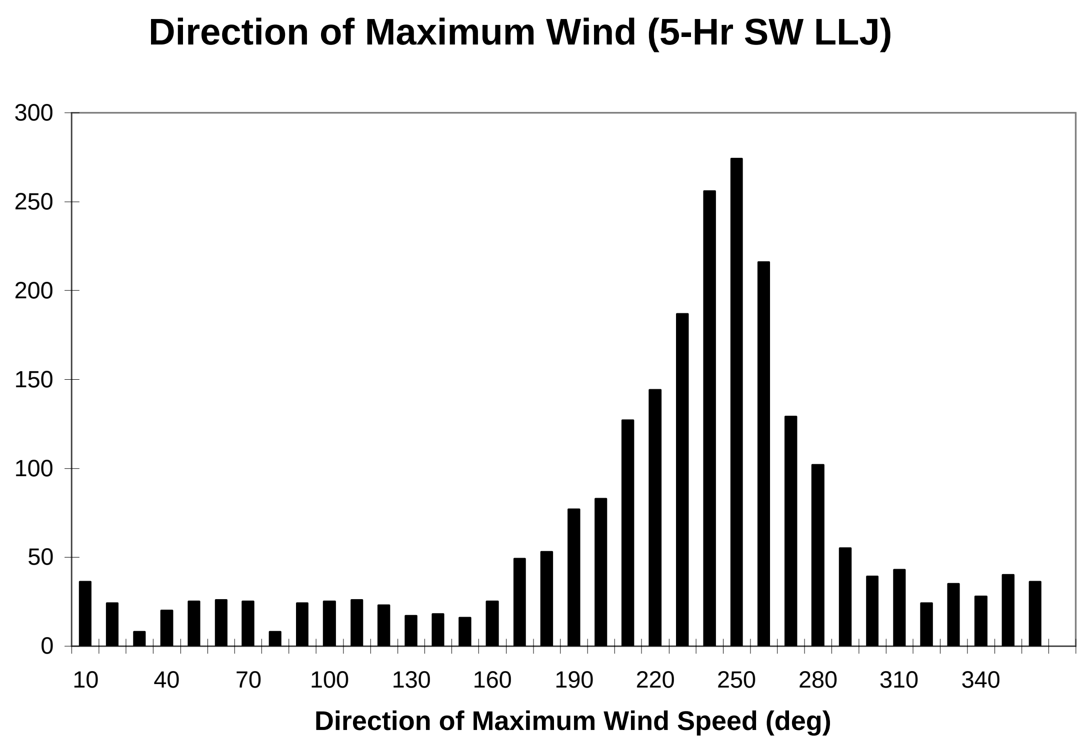


Figure 13. Frequency of the direction of the maximum winds for the long duration southwest LLJ.

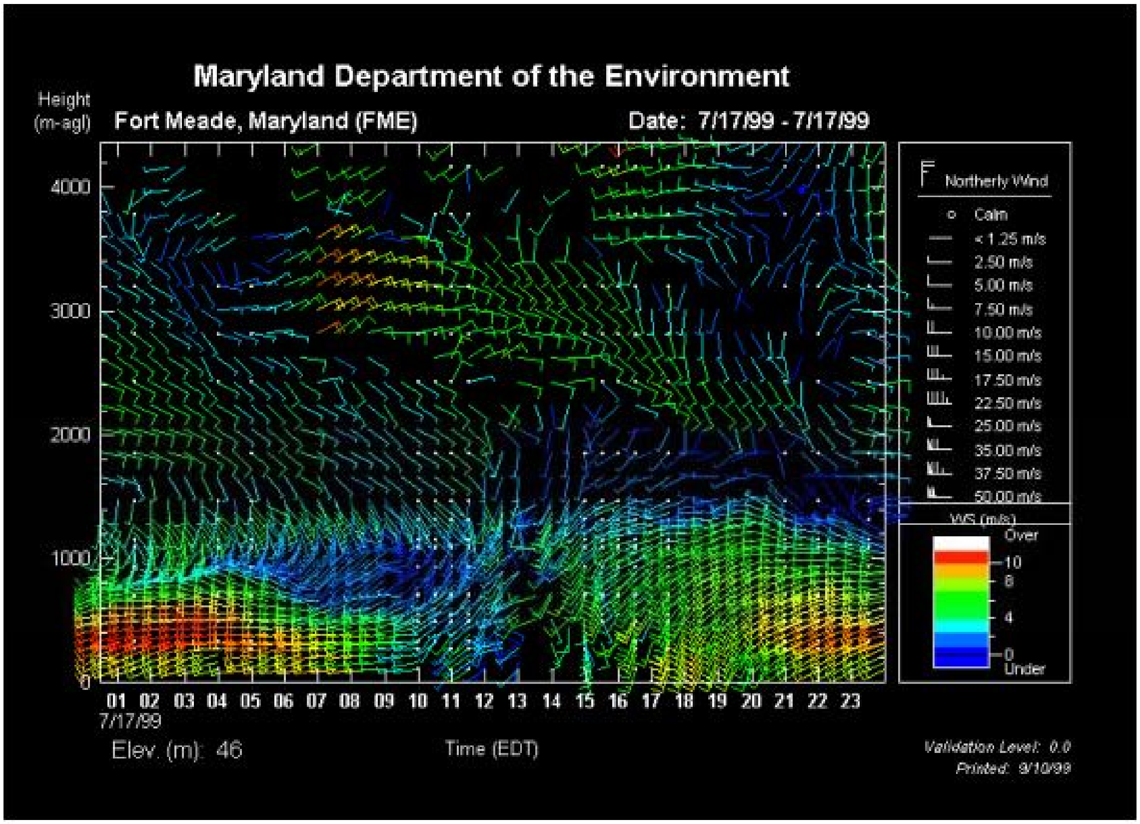


Figure14. An example of a long duration southwest LLJ.

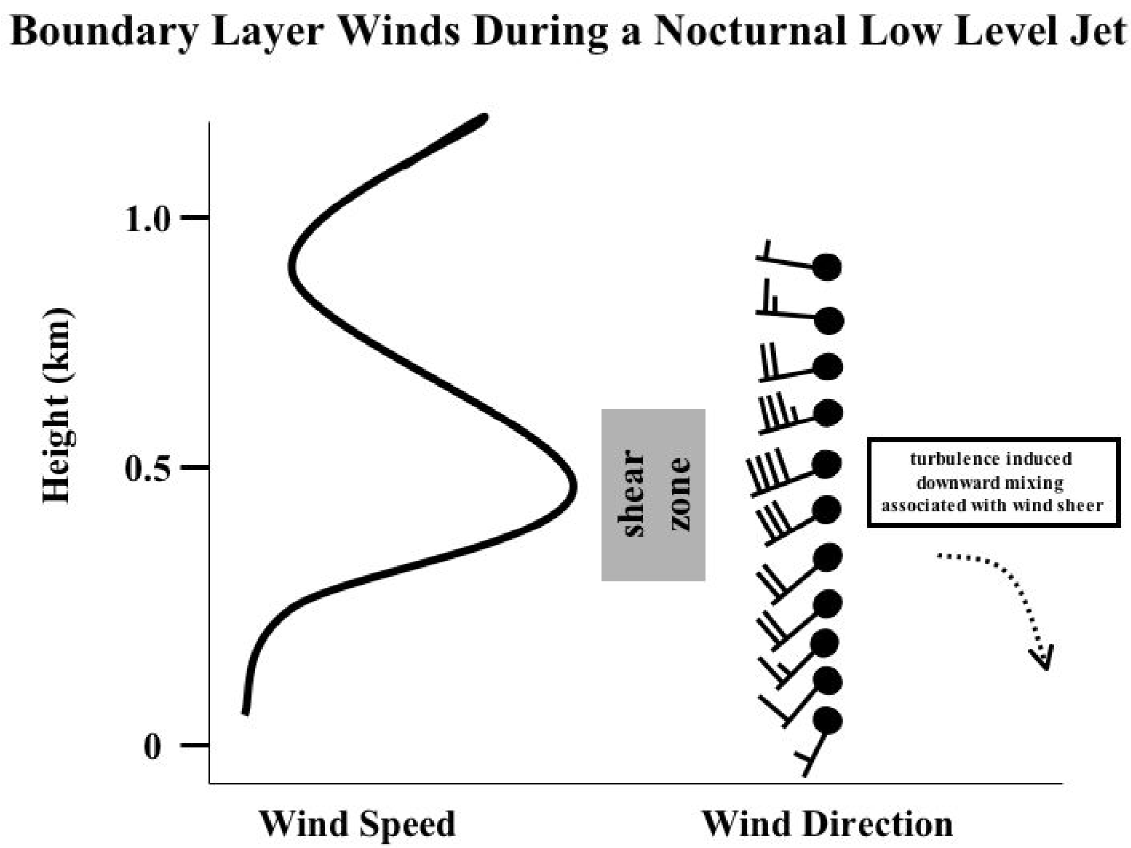


Figure 15. The nocturnal low level jet occupies a thin slice of the atmosphere near the Earth's surface. Abrupt changes in wind speed and wind direction with height associated with the low level jet create conditions favorable for downward transport of air to the surface layer (*Singh, et al. 1997; Corsmeier et a., 1997*).

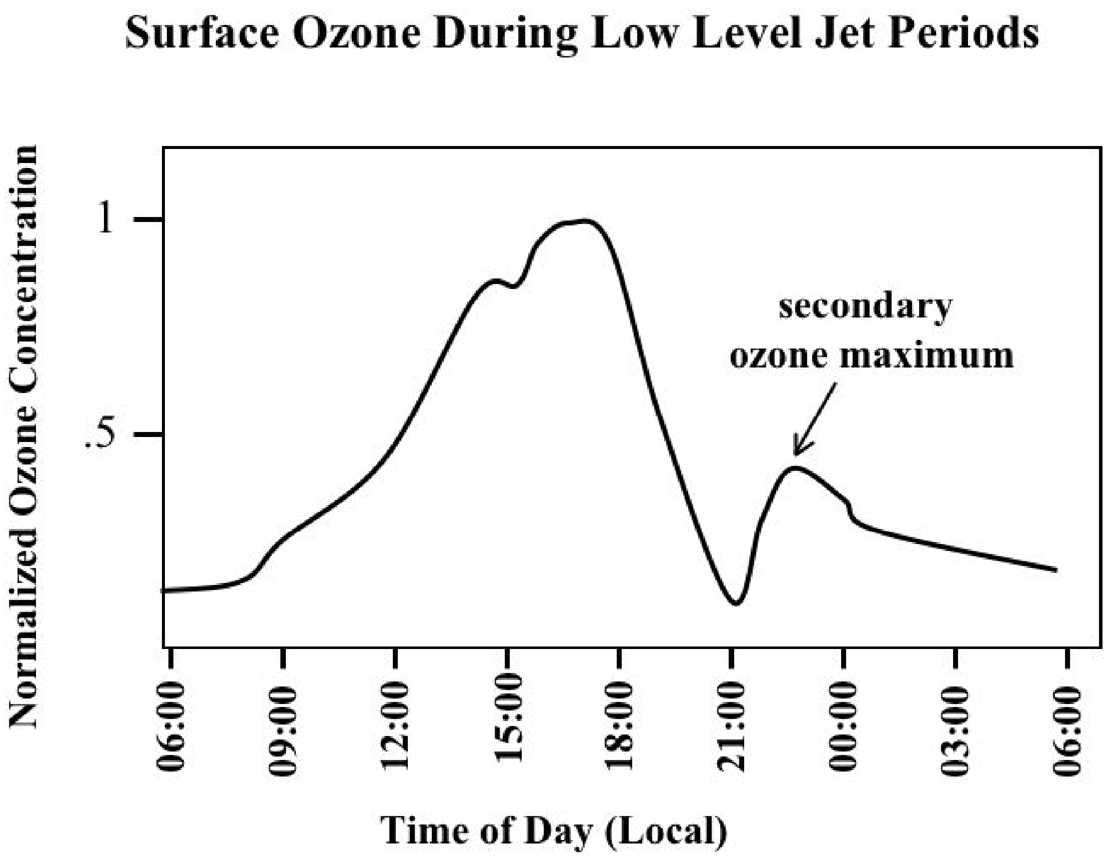


Figure 16. This curve was derived from a composite of several investigations (*Reitbuch et al., 2000; Corsmeier et al., 1997; and Salmond and McKendry, 2002*) of secondary surface ozone maximum (an increase in ozone over night not the result of photochemical production but instead from downward transport from the residual layer). The plot is not intended to represent any actual secondary maximum observed during these studies rather it is intended to illustrate the temporal profile of the secondary ozone maxima.

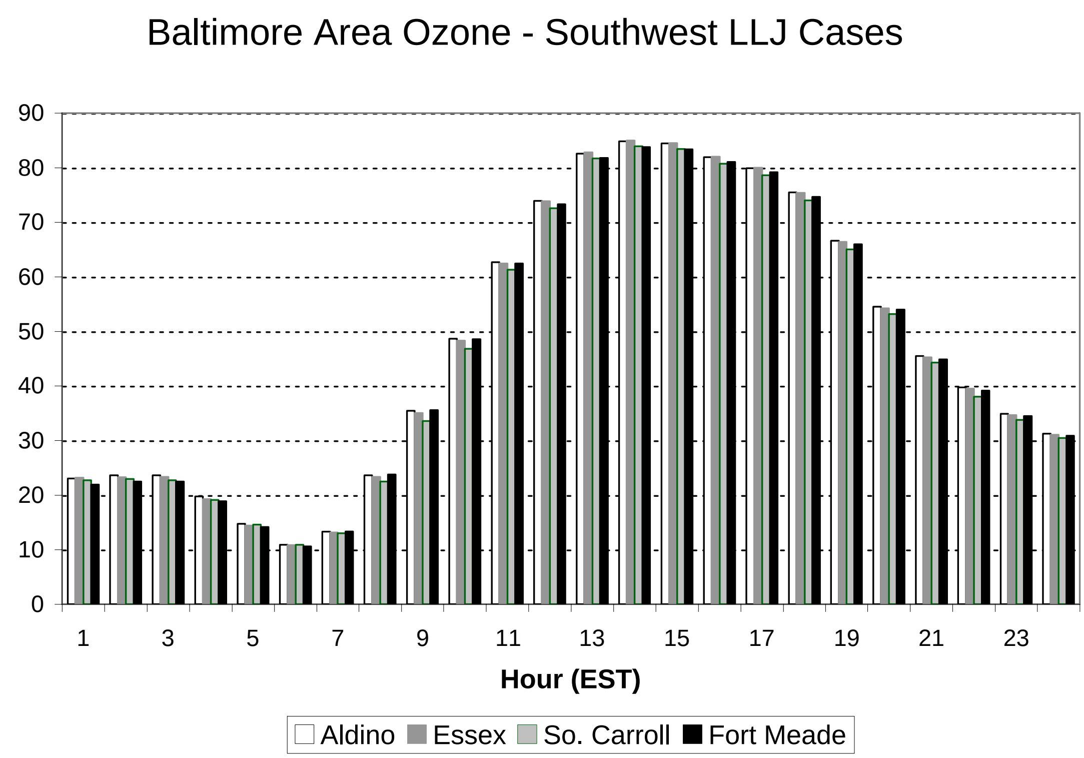


Figure 17. Time series of O_3 concentrations at four selected Baltimore O_3 monitors for the subset of cases of high O_3-LLJ cases (n=-61).

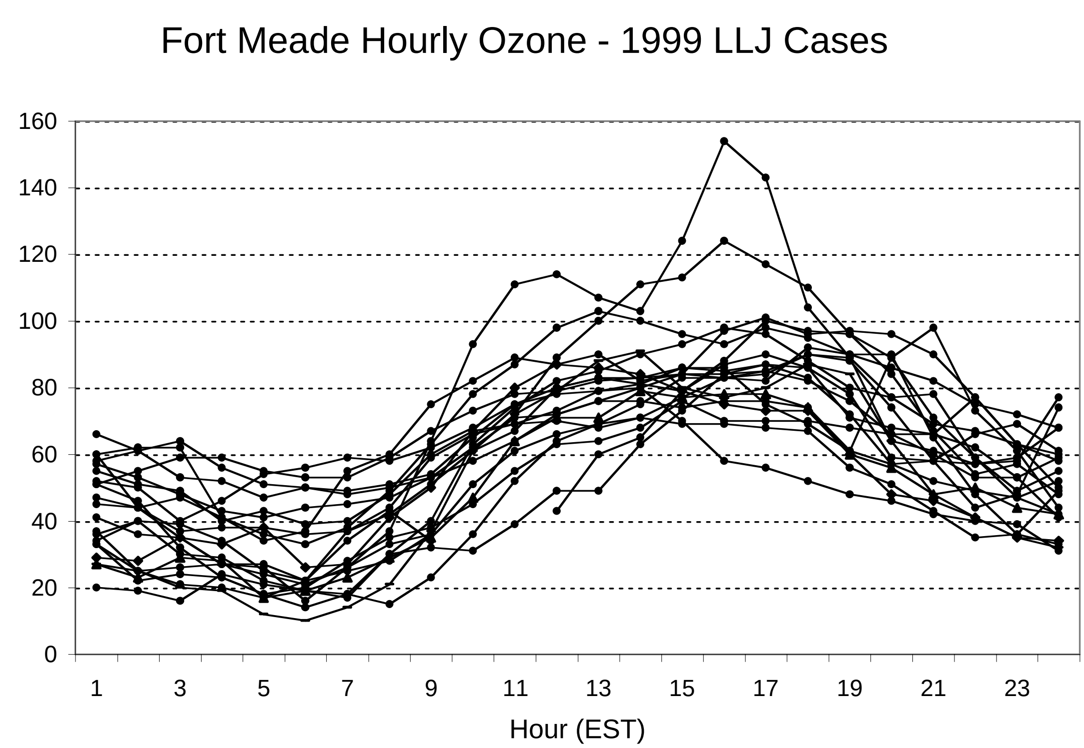


Figure 18. Time series of O_3 concentrations during high O_3-LLJ cases at Fort Meade during 1999.

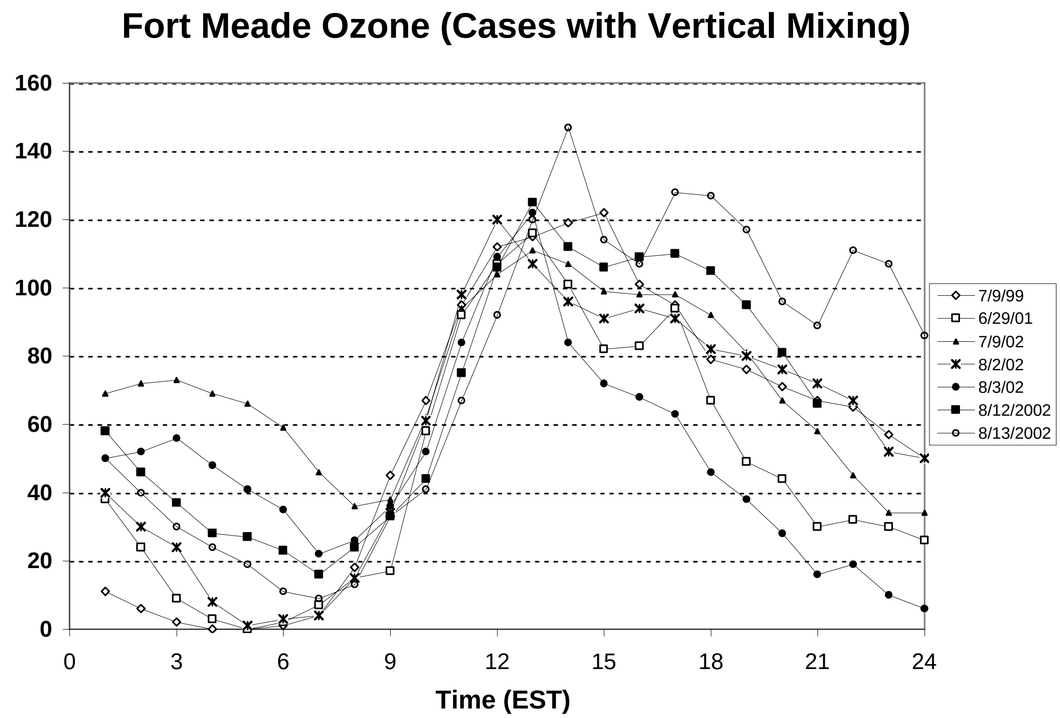


Figure 19. Time series of the O_3 concentrations during high O_3-LLJ cases at Fort Meade when late morning mixing effects were particularly strong.

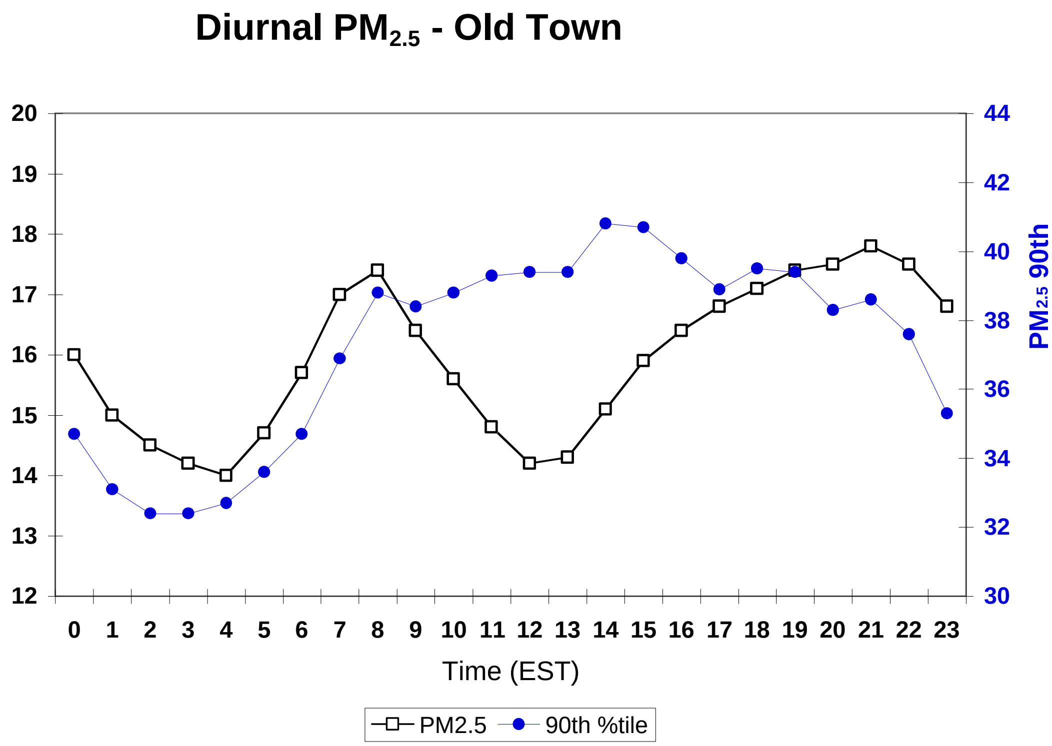


Figure 20. Hourly time series of $PM_{2.5}$ concentrations in Baltimore for the period 1999-2002. The blue line represents all data and the orange line only the highest 90^{th} percentile of cases (≥ 37 µg m^{-3}).

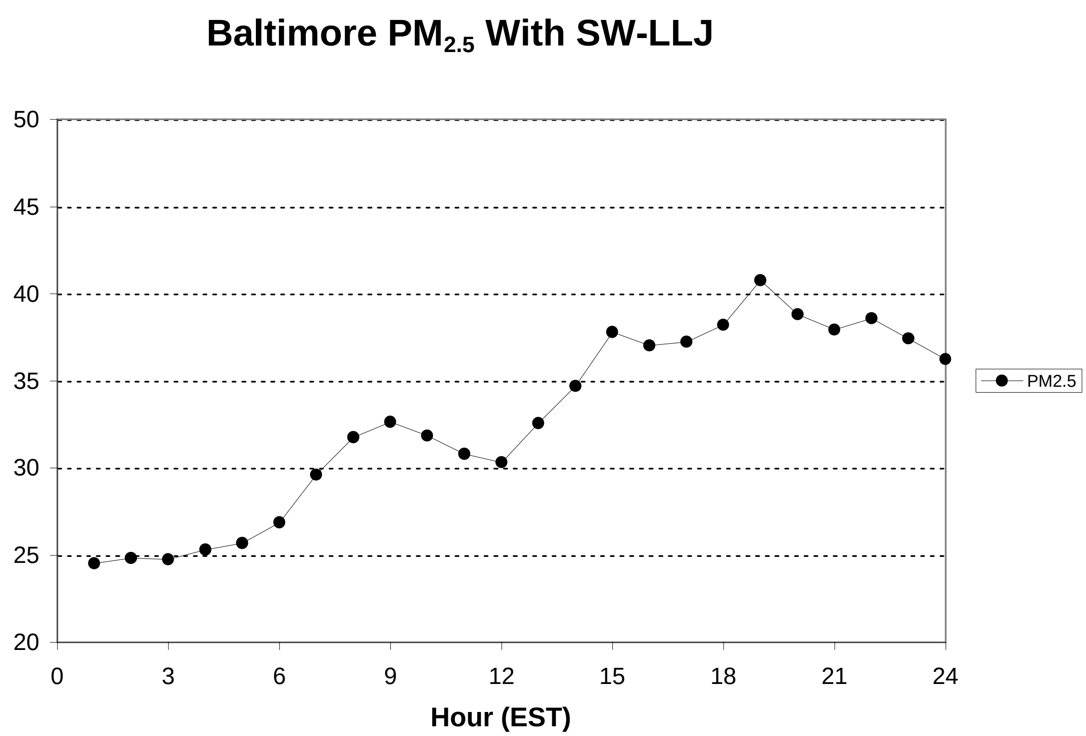


Figure 21. Hourly time series of $PM_{2.5}$ concentrations in Baltimore for the period 1999-2002. The blue line represents all data and the orange line only the highest 90^{th} percentile of cases (≥ 37 µg m^{-3})

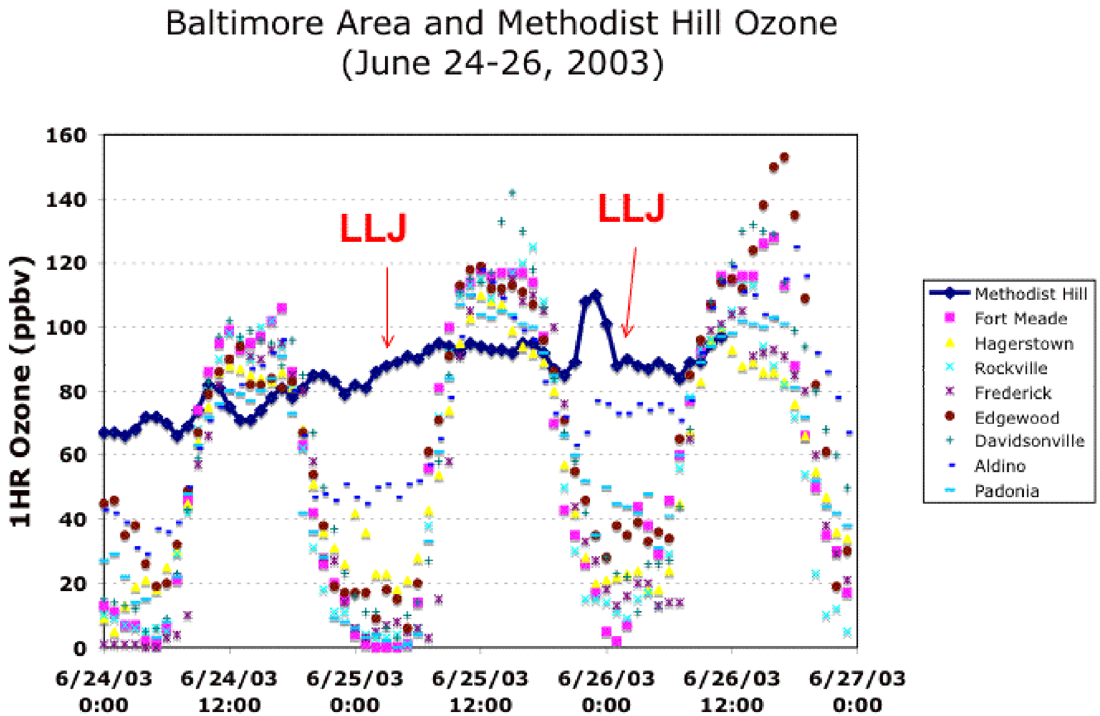


Figure 22. June 24-26, 2002 time series of O_3 concentrations at several Baltimore O_3 monitors and O_3 at the elevated monitor Methodist Hill during a high O_3-LLJ case.

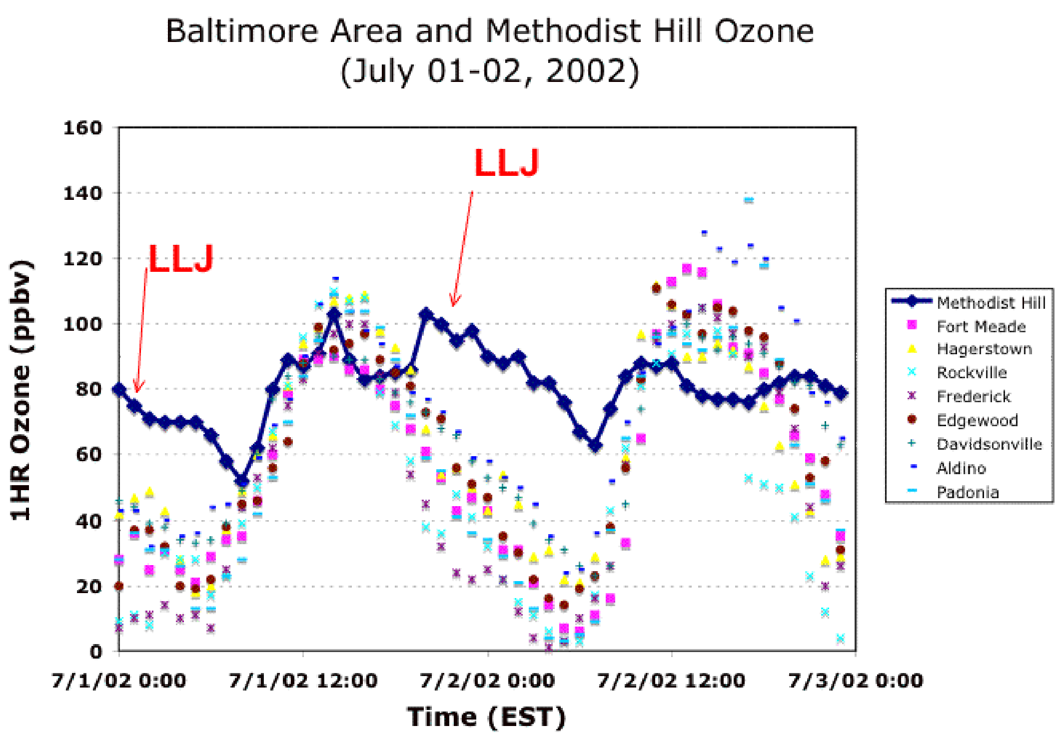


Figure 23. July 01-02, 2002 time series of O_3 concentrations at several Baltimore O_3 monitors and O_3 at the elevated monitor Methodist Hill during a high O_3-LLJ case.

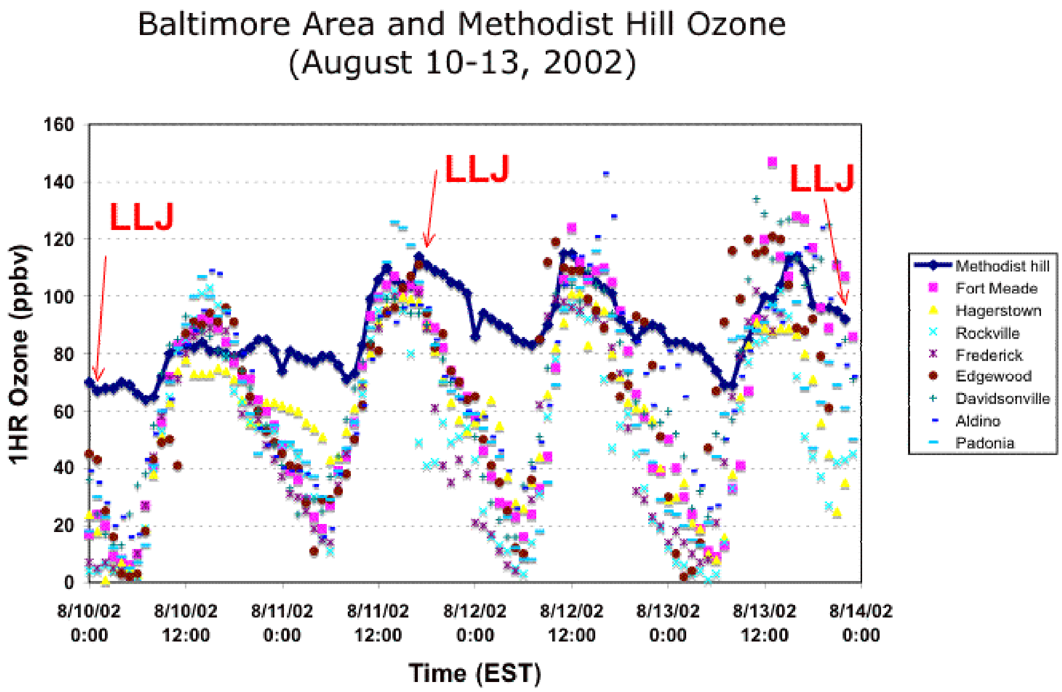


Figure 24. July 01-02, 2002 time series of O_3 concentrations at several Baltimore O_3 monitors and O_3 at the elevated monitor Methodist Hill during a high O_3-LLJ case.

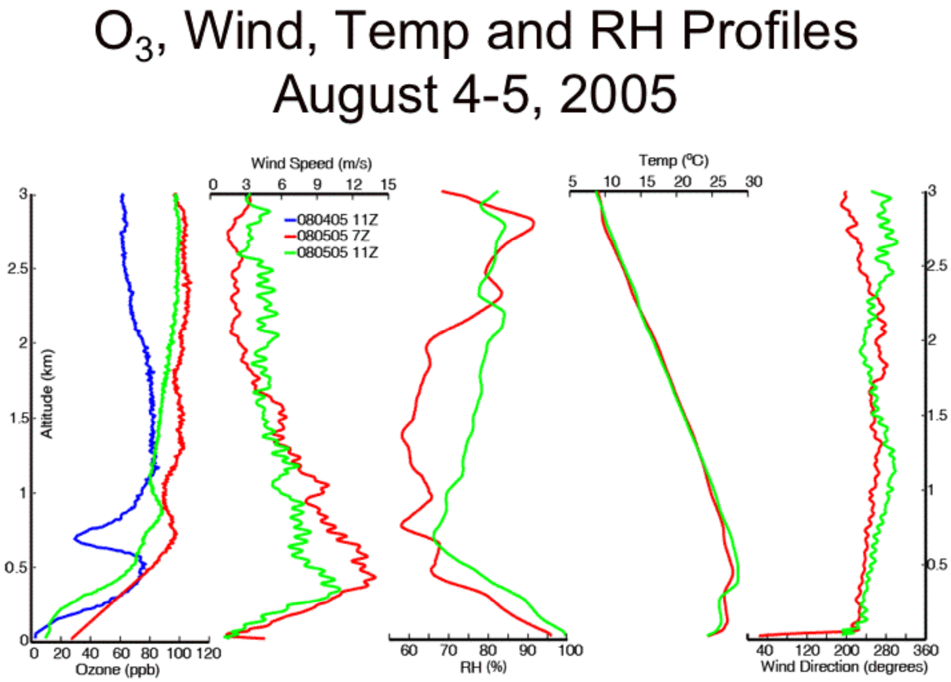


Figure 25. Data from ozonesondes launched at Beltsville, MD on August 4th 06:00 (blue line) and August 5th 02:00 (red line), 06:00 (green line). O_3, wind direction/speed, temperature and relative humidity presented. All times are EST.

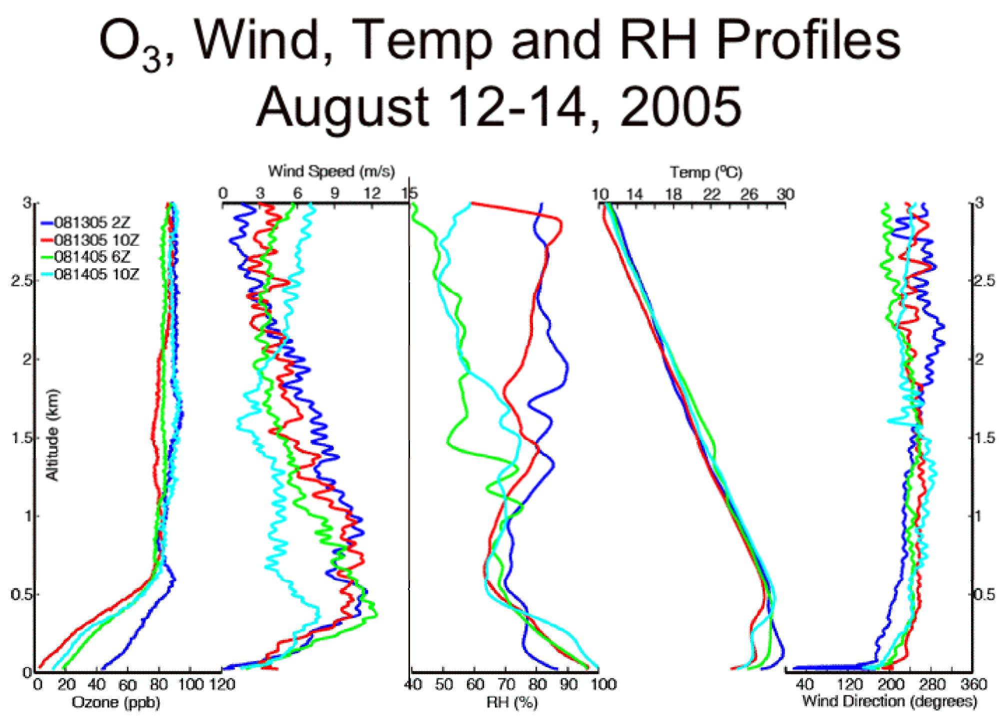


Figure 26. Data from ozonesondes launched at Beltsville, MD on August 12th 21:00 (blue line), August 13th 05:00 (red line) and August 14th 02:00 (green line), 05:00 (light blue line). O_3, wind direction/speed, temperature and relative humidity presented. All times are EST.

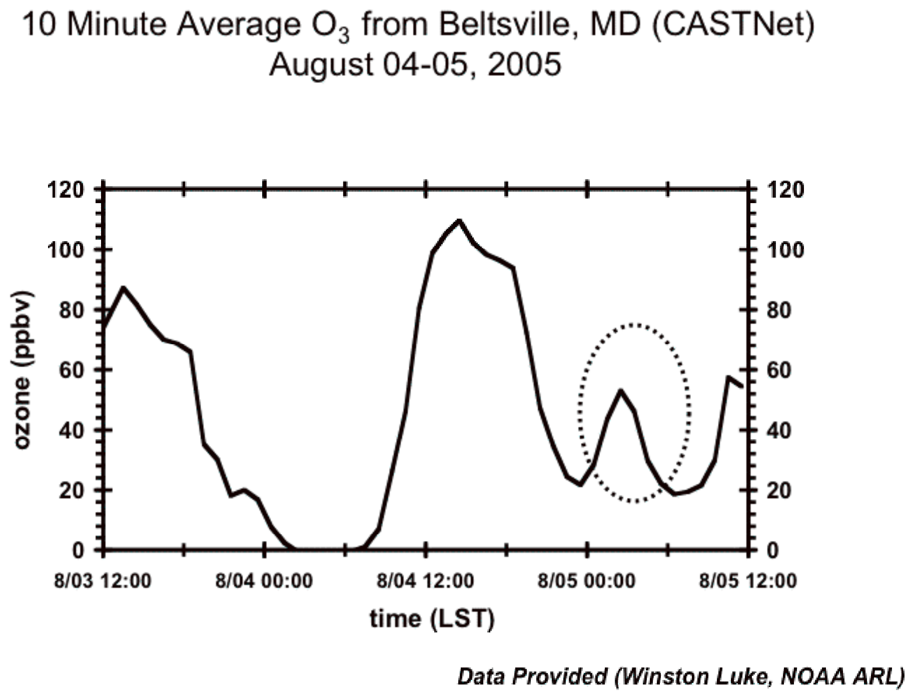


Figure 27. 10 minute average O_3 from the Beltsville, MD CASTNET site (August 3rd – 5th, 2005). Data provided by Winston Luke of the NOAA Air Air Resources Laboratory.

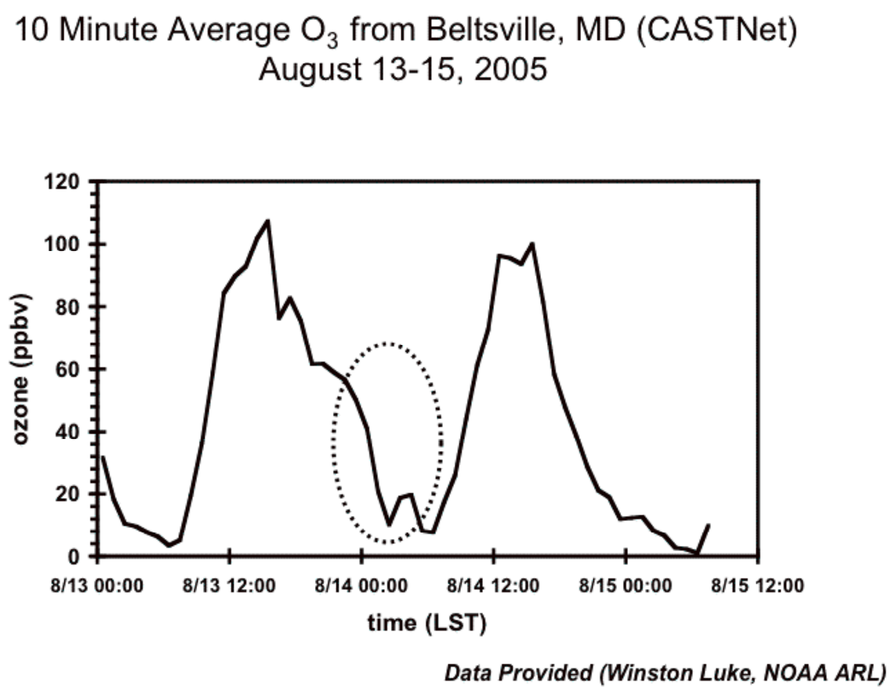


Figure 28. 10 minute average O_3 from the Beltsville, MD CASTNET site (August 12th – 14th, 2005). Data provided by Winston Luke of the NOAA Air Air Resources Laboratory.

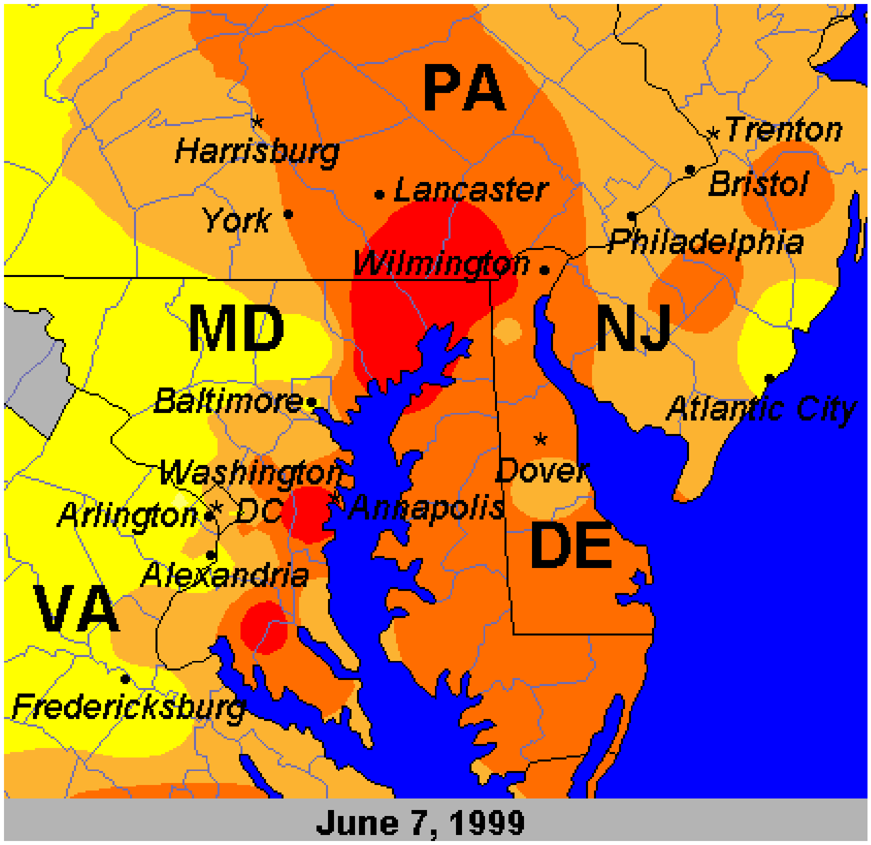


Figure 29. Peak 1-hour O_3 concentrations for June 7, 1999 as mapped by EPA AIRNOW. Concentrations contours are: Yellow (80-99 ppbv), light Orange (100-109 ppbv), dark Orange (110-124 ppbv) and Red (≥ 125 ppbv).

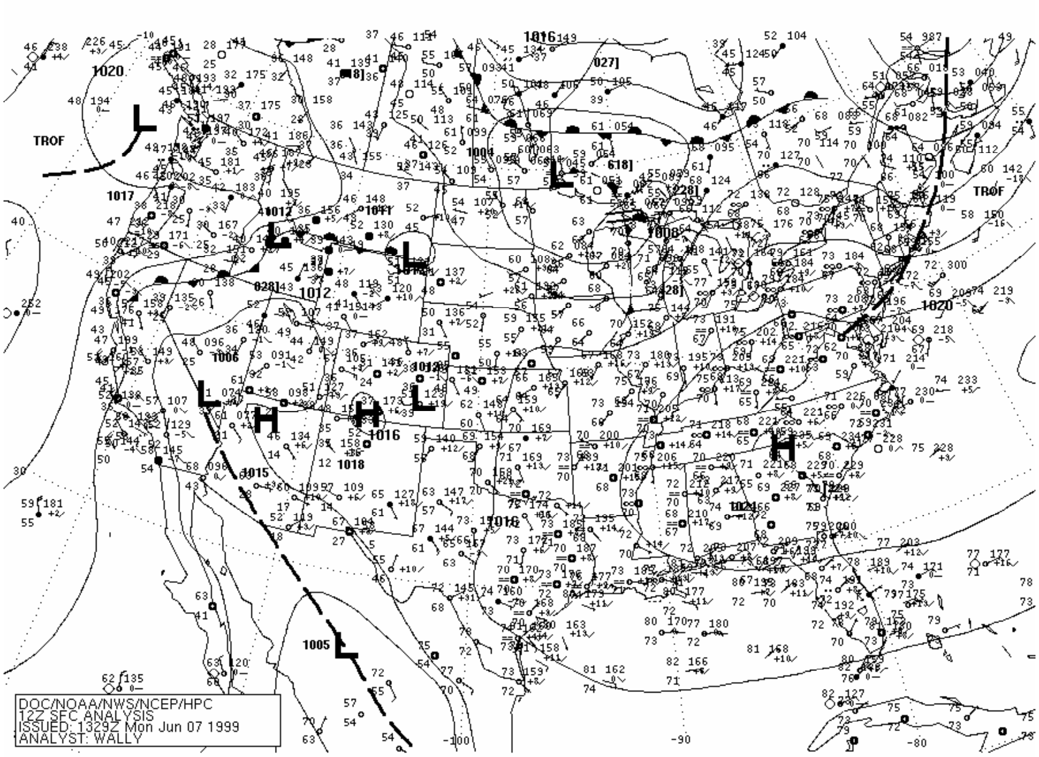


Figure 30. National Weather Service surface analysis for 1200 UTC, June 7, 1999.

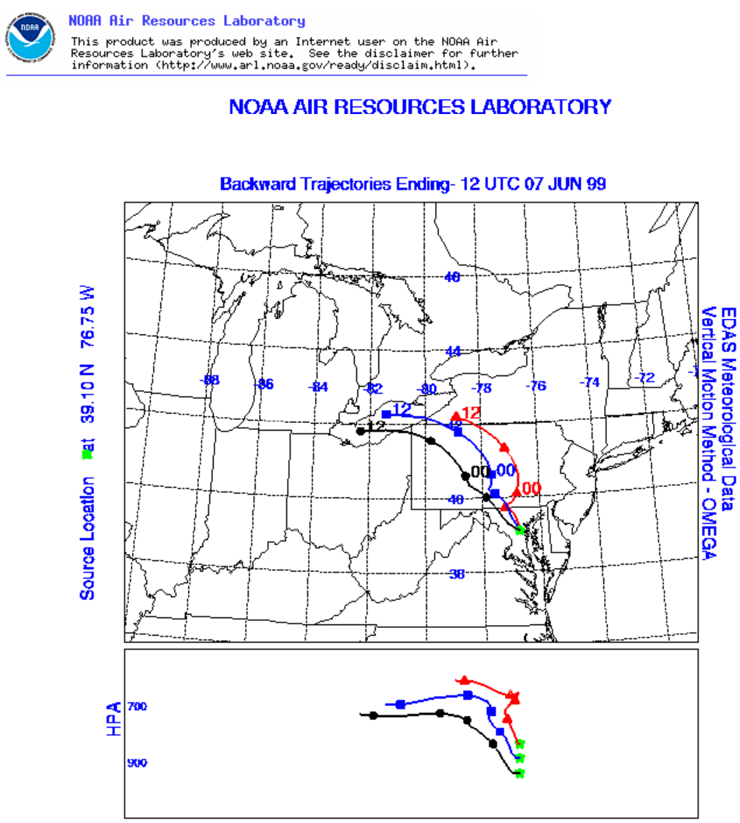


Figure 31. HYSPLIT back trajectories terminating at BWI on 1200 UTC, June 7, 1999. Back trajectories are for 24 hours at three levels (1500 m (red), 1000 m (blue) and 500 m (black). HYSPLIT uses Eta Data Assimilation System (EDAS) data on 80 km grids.

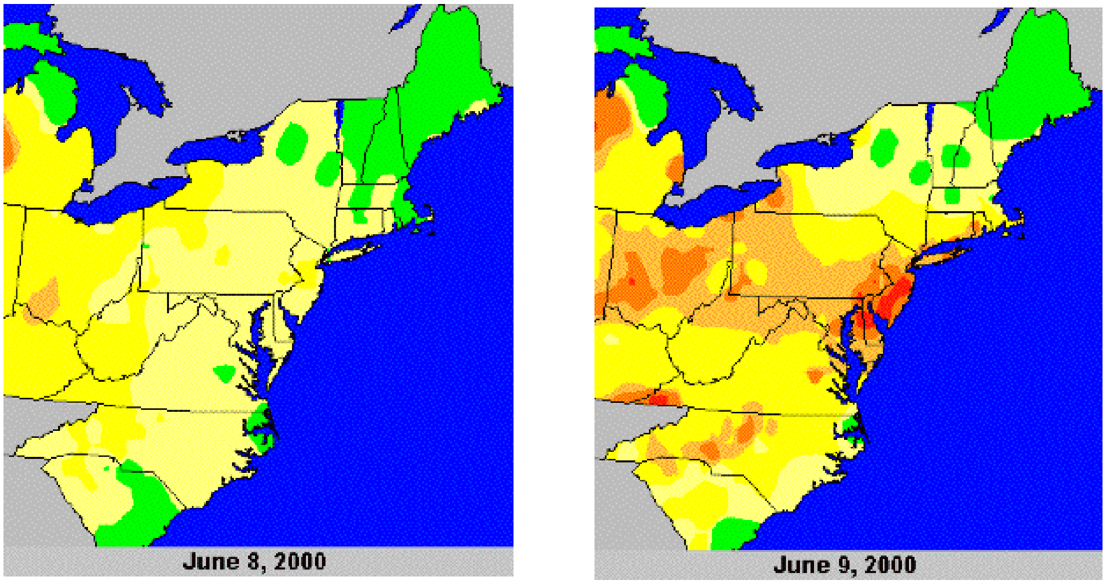


Figure 32. Peak 1-hour O_3 concentrations for June 7, 1999 as mapped by EPA AIRNOW. Concentrations contours are: Yellow (80-99 ppbv), light Orange (100-109 ppbv), dark Orange (110-124 ppbv) and Red (≥ 125 ppbv).

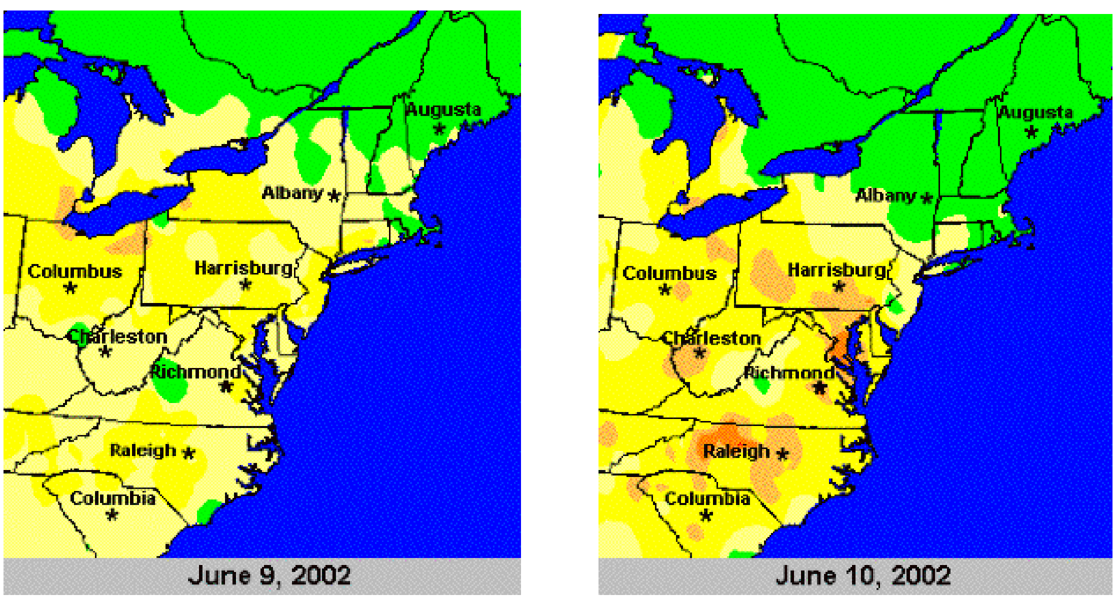


Figure 33. Concentrations contours are: Yellow (80-99 ppbv), light Orange (100-109 ppbv), dark Orange (110-124 ppbv) and Red (≥ 125 ppbv).

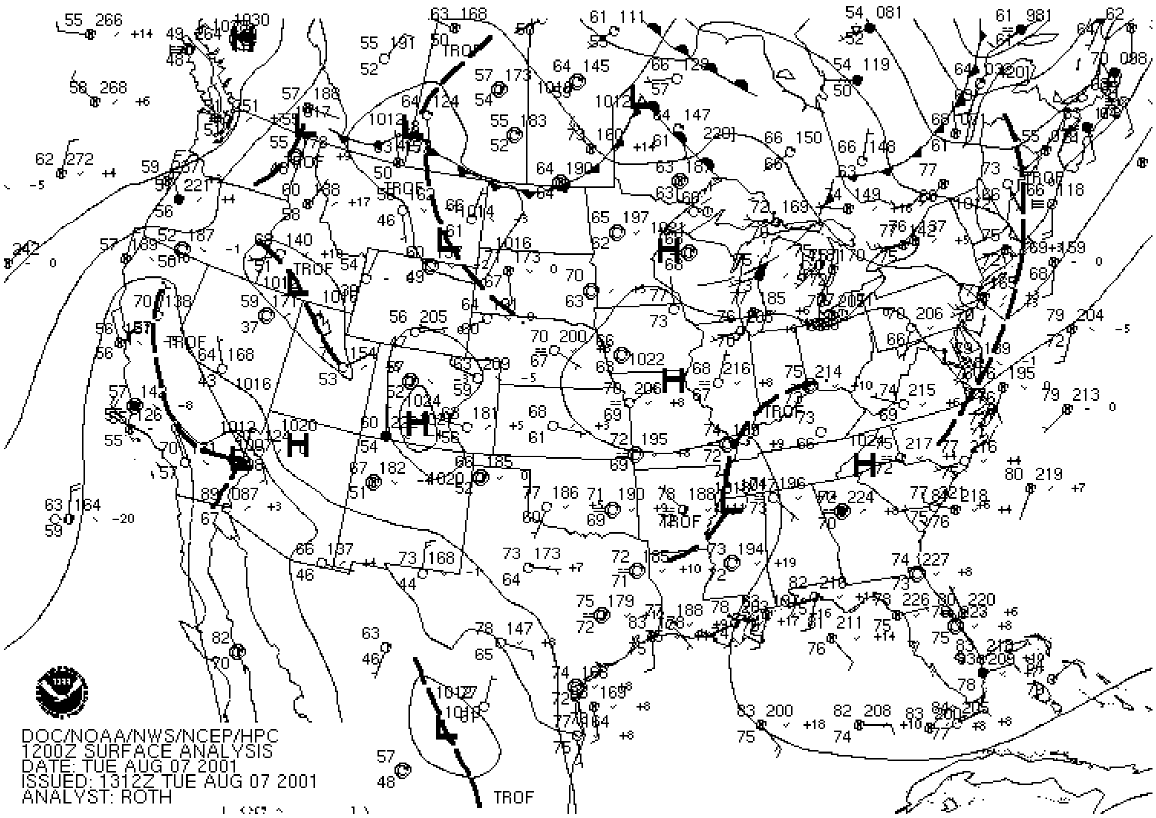


Figure 34 National Weather Service surface analysis for 1200 UTC, August 7, 2001.

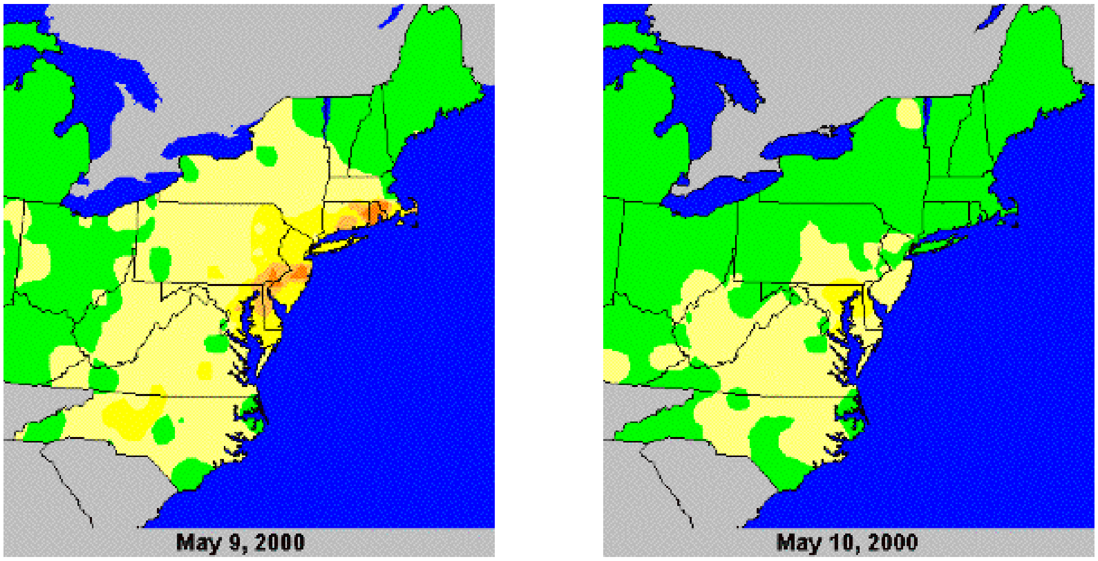


Figure 35. Peak 1-hour O_3 concentrations for May 9-10, 2000 as mapped by EPA AIRNOW. Concentrations contours are: Yellow (80-99 ppbv), light Orange (100-109 ppbv), dark Orange (110-124 ppbv) and Red (≥ 125 ppbv).

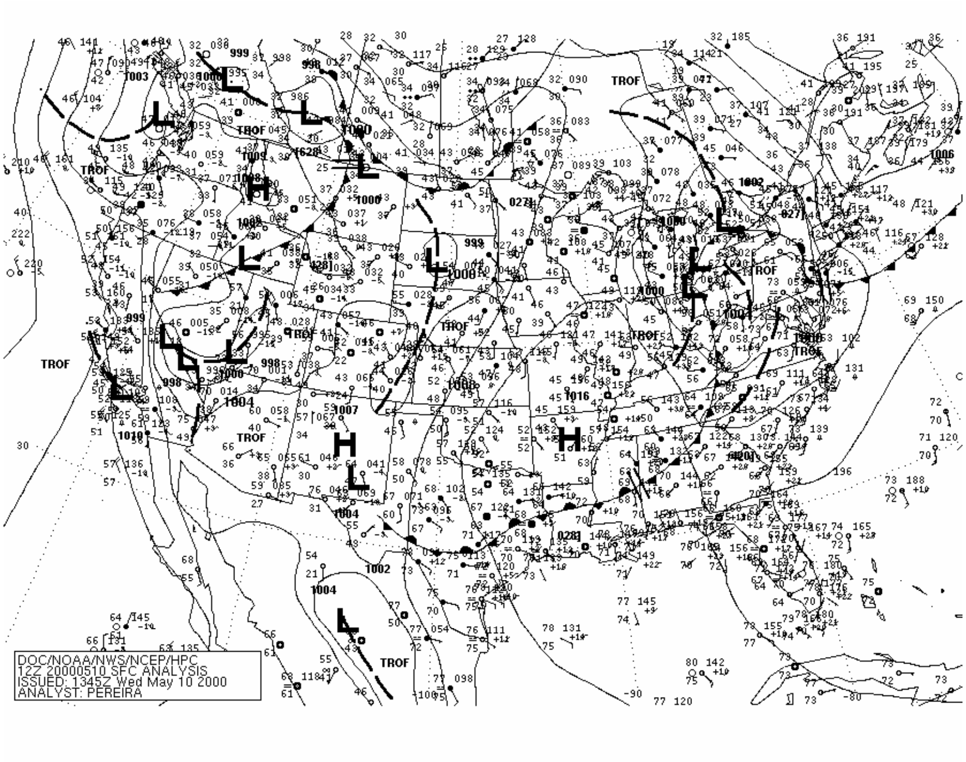


Figure 36. National Weather Service surface analysis for 1200 UTC, May 10, 2000.

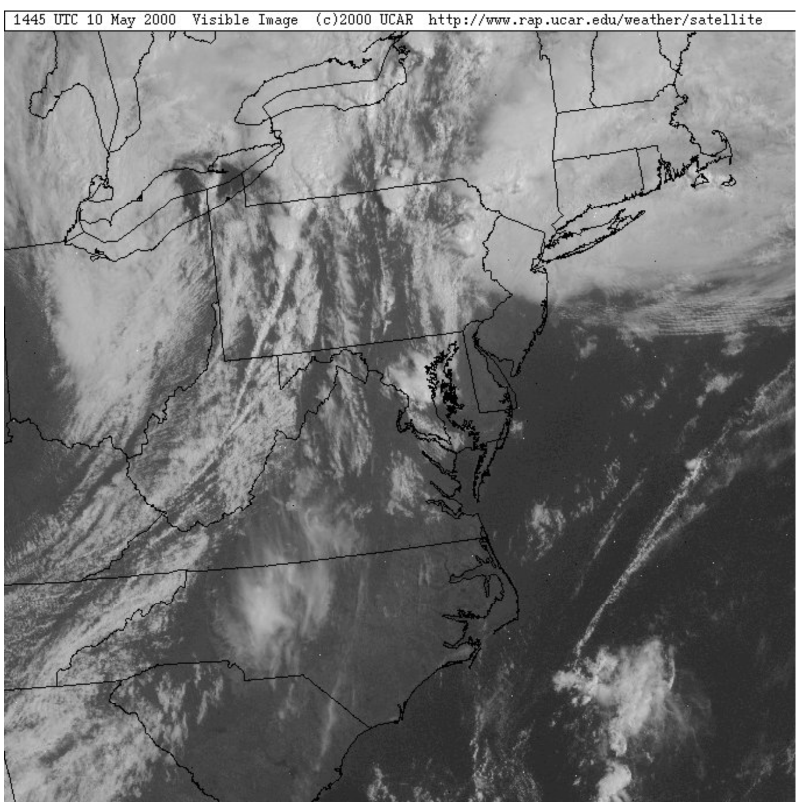


Figure 37. Goes East visible image for 1445 UTC, May 10 2000. Convection is already developing by the late morning ahead of a cold front approaching the Appalachians.

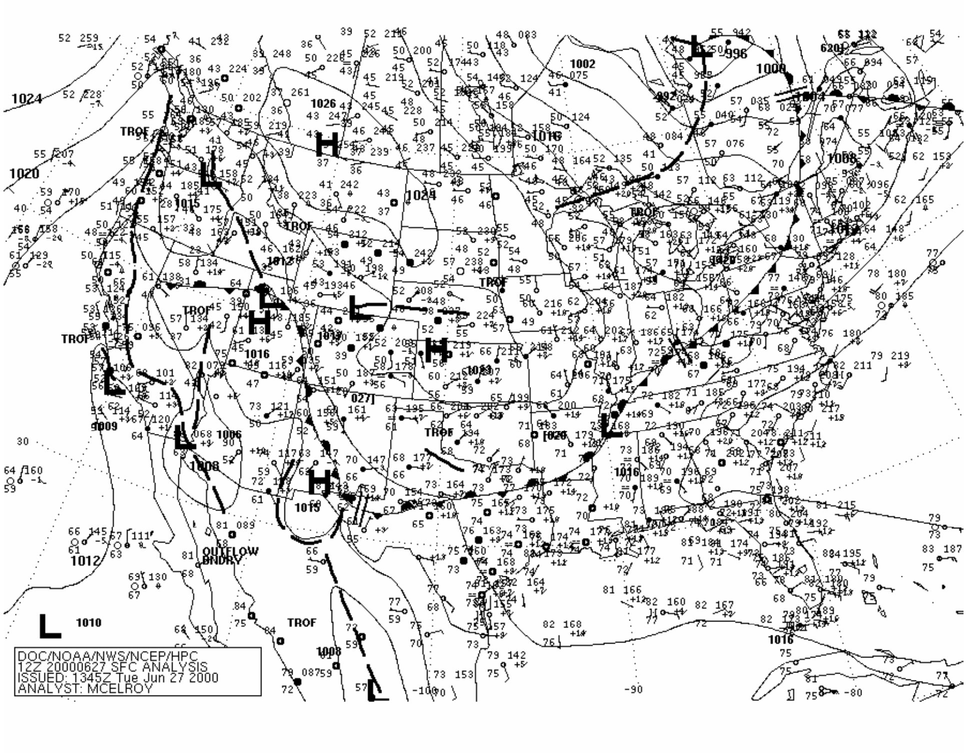


Figure 38 National Weather Service surface analysis for 1200 UTC, June 27, 2000.

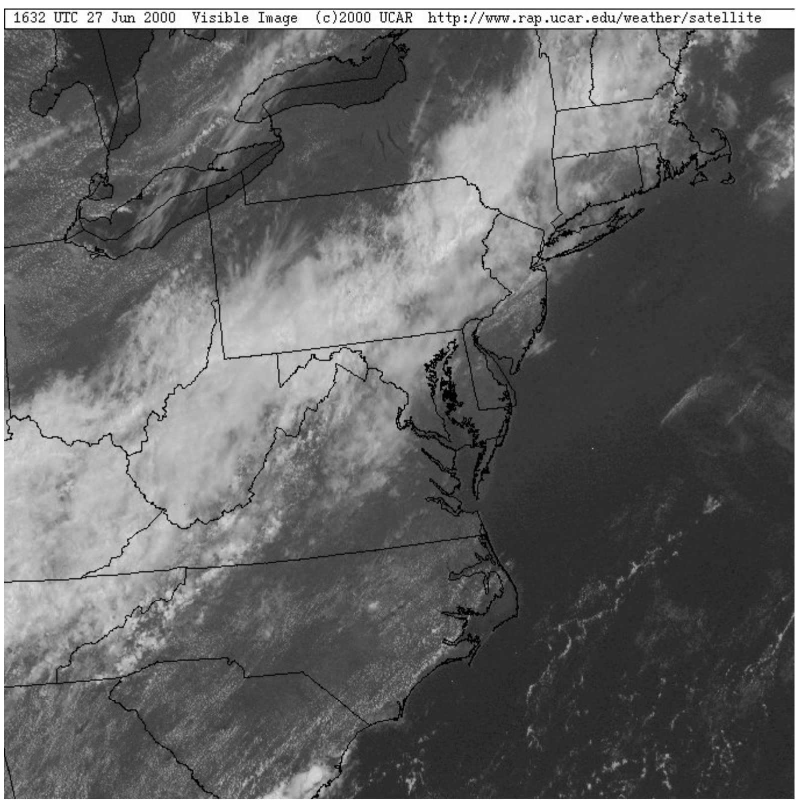


Figure 39. Goes East visible image for 1632 UTC, June 27 2000. Convection is already developing by the late morning ahead of a cold front approaching the Appalachians.

Appendix A: Theoretical Discussion of the Coastal Low Level Jet

Using Newton's Second Law and neglecting the effects of near-surface friction, we can determine the *geostrophic wind balance*:

$$fu_g = \frac{-1}{\rho}\frac{\partial p}{\partial x} \qquad \text{(1a)}$$

$$fv_g = \frac{1}{\rho}\frac{\partial p}{\partial x} \qquad \text{(1b)}$$

Where:

f = Coriolis force
u_g = geostrophic wind in the east-west direction,
positive u_g = westerly winds
v_g = geostrophic wind in the north-south direction,
positive v_g = southerly winds
ρ = density
p = pressure
x = distance, positive from left (west) to right (east).

Equations 1a and 1b (the geostrophic wind equations) tell us is that wind velocity, in the absence of friction, is proportional to pressure. To understand the LLJ, though, we know to know why there is a distinct layer (usually from 200-800 m) of strong winds. To determine the variation of wind with height (wind shear), we can substitute for pressure (p) from the ideal gas law (pV=nRT) and take the derivative with respect to height (z). These steps allow us to determine the change of wind with height and relate this change to an easily measured quantity: temperature. The derived equation is termed the "thermal wind equation":

$$\frac{\partial u_g}{\partial z} = \frac{-g}{fT}\frac{\partial T}{\partial y} \qquad \text{(2a)}$$

$$\frac{\partial v_g}{\partial z} = \frac{g}{fT}\frac{\partial T}{\partial x} \qquad \text{(2b)}$$

These equations tell us that the change in wind with height *vertically* (shear) is proportional to the change in temperature *horizontally*.

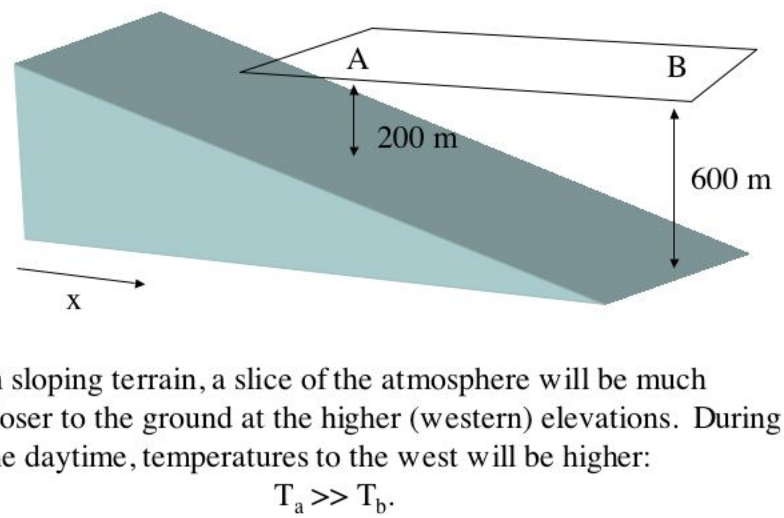
The thermal wind equation can help us to develop a simplified version of the coastal jet. In this simplified version we will look only at the north-to-south wind component (v_g) of the geostrophic wind:

$$\frac{\partial v_g}{\partial z} = \frac{g}{fT}\frac{\partial T}{\partial x} \qquad (2b)$$

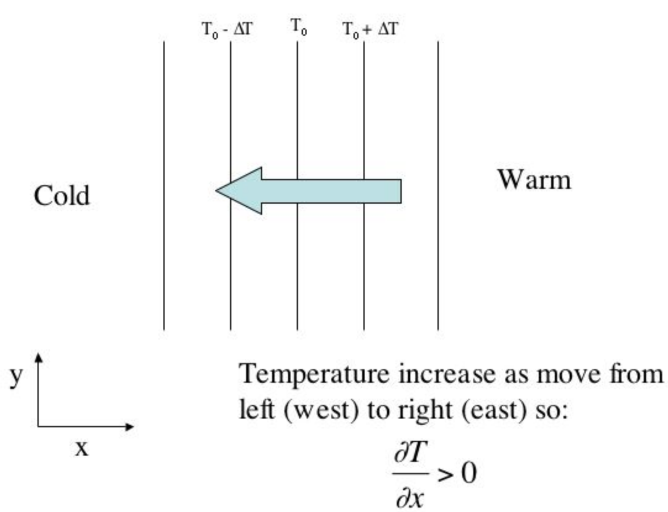
Using the standard convention that x increases as we move from west to east, Equation 2b tells us that if temperature decreases from west to east, then $\partial T/\partial x < 0$ and winds will decrease with height. Alternatively, if temperature increases from west to east, then $\partial T/\partial x > 0$ and winds will increase with height. As a result, for the coastal LLJ to form, a temperature gradient must exist with higher temperatures to the east.

Along the eastern seaboard, horizontal changes in temperature are, in the absence of large scale weather systems, driven by the interaction of the sloping terrain on the eastern slope of the Appalachian Mountains with diurnal variations in temperature in the lower atmosphere. The critical feature of the topography of the eastern coastal plain is that the land slopes downward as we move from the Appalachians to the seaside. If we take a slice of the atmosphere parallel to sea level (***Figure Appendix 1***), we see that the western end of the slice near the slopes of the Appalachians (A) is much closer to the ground than the eastern end of the slice over the ocean (B). During the daytime the ground surface warms and, because air is a poor conductor of the surface's heat, the lower atmosphere warms the most. As a result, temperature at A (T_a), near the surface, will be much higher than at B (T_b), further up in the atmosphere. In this situation, temperature decreases as we move from west to east, $\partial T/\partial x < 0$ and we expect, by equation 2b, that winds will gradually decrease with height (***Figure Appendix 2***).

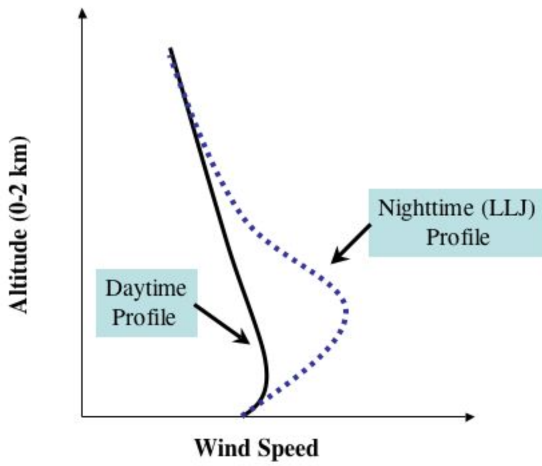
In the nighttime hours, however, the situation reverses. The ground cools rapidly and the layers near the surface cool quickly as well. At higher altitudes, however, the atmosphere cools little if at all. As a result, for a given slice of the atmosphere, the air in the higher elevations in the western mid-Atlantic cool rapidly while those along the coast do not. In this situation, temperature increases as we move from west to east so that $\partial T/\partial x > 0$ (***Figure Appendix 3***). In the layers in which there is a strong temperature contrast, winds therefore increase with height (***Figure Appendix 4***). In the mid-Atlantic, this is the layer in which we find the LLJ (e.g., ***Figure Appendix 5***).



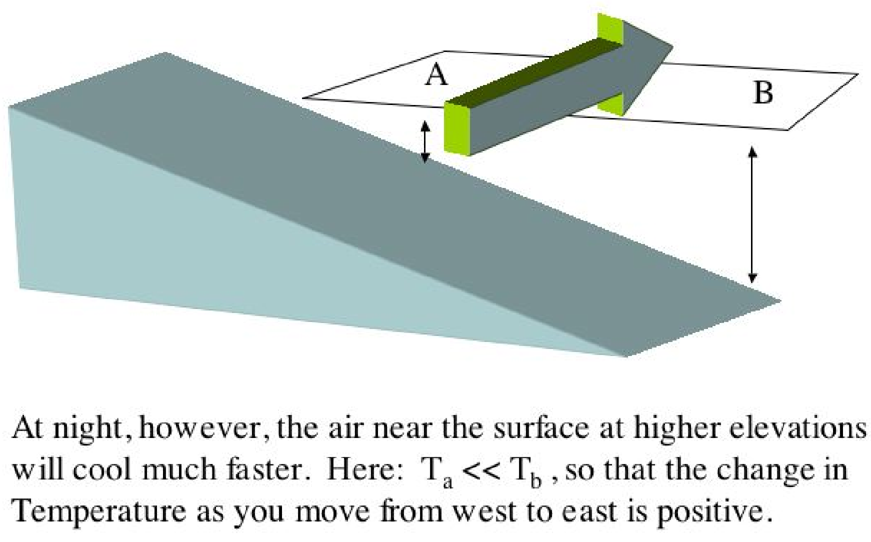
Appendix A-Figure 1.



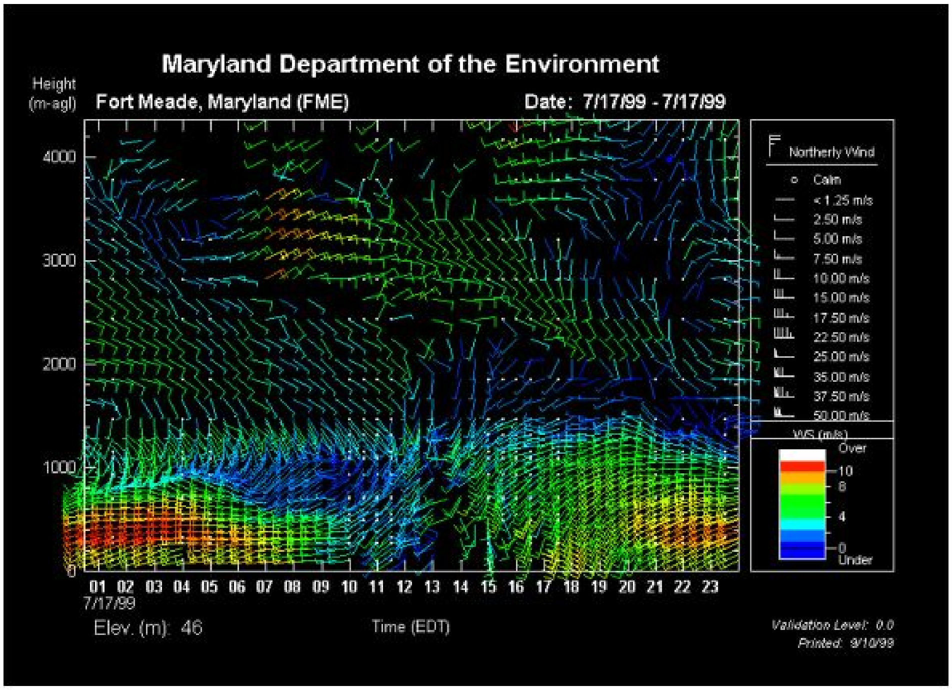
Appendix A-Figure 2.



Appendix A-Figure 3. Idealized vertical wind profiles for daytime (solid line) and nighttime (dashed line) when the LLJ is present.



Appendix A-Figure 4.



Appendix A-Figure 5. A characteristic LLJ as observed by the FME profiler. The red arrows (wind direction) in the lower left of the panel show the core of the LLJ during a high O_3 event on July 17, 1999.

Appendix B: Parameters of the Fort Meade Profiler

The profiler operational settings provided in this appendix are applicable for most of the analysis period. Beginning in June 14, 2002, changes were made to the operating parameters to make the FME profiler configuration consistent with profilers at other locations in the MANE-VU region. The key changes were: (1) Increase in maximum altitude for the low mode from 1.5 to 1.8 km; (2) Number of range gates increased from 25 to 36; and (3) consensus time increased from 25 to 55 minutes.

An example of a standard consensus data file is shown below (line numbers added for ease of reference). The operational settings are given in the first 10 lines with data following. A brief explanation of each line is given below.

```
1.      Ft Meade
2.     WINDS    rev 4.1
3.     39.11  -76.71     46
4.     01 07 29 00 05 12   300
5.     25  3  25
6.     03:05 (1.5) 03:04 (2.0) 03:04 (2.0)
7.     292 292 100 100 400 400 28 28
8.     10.0  10.0  1  1600 1600 25 25 400 400
9.     51 90.0   231 66.4   141 66.4
10.          HT   SPD DIR  Radials...
11.    0.110  8.7 154  -0.4   0.4   3.0  5  4  4   2   7   4
       0.165  8.1 153  -0.3   0.3   2.9  5  4  4   3  10   4
       0.220  8.6 155  -0.4   0.4   3.0  5  4  4   3   8   5
       0.275  8.5 159  -0.5   0.6   2.8  5  4  4   8  12   8
       0.330  9.4 167  -0.6   1.1   2.9  5  4  4   7  12   7
       0.385  9.6 171  -0.6   1.4   2.8  5  4  4   7  10   7
       0.440 10.1 174  -0.6   1.6   2.9  5  4  4   7  10   8
```

The first 10 lines give the operational configuration

Line 1: Location
Line 2: Software version
Line 3: Latitude, longitude
Line 4: Year, month, day, hour, minute, second, UTC offset (in minutes)
Line 5: Consensus averaging time
Beam directions (3 in this case)
Vertical range gates (25)
Line 6: Consensus details - for each beam (3 in this case)
Cycles required to reach consensus
Total cycles in each consensus period
Consensus window size (ms^{-1})

Line 7: Observation format details. Each detail is given separately. The two off-set (from the vertical) beams are given first and the overhead beam last.

Number of coded cells
Number of spectra
Pulse length (ns)
Interpulse period (ns)

Line 8: More observation format details. First values for each group corresponds to the off-vertical beams and the second to the vertical beam.

Maximum Doppler
Vertical correction applied (1 = yes)
Time delay to first gate (ns)
Number of range gates
Range gate interval (ns)

Line 9: Beam pointing direction.

Azimuth from north (= 0)
Elevation angle, horizon = 0

Line 10: Data Column headers

Line 11: Data

Altitude (km)
Horizontal wind (ms^{-1})
Direction (degrees)
Radial component for each beam
Number of cycles making consensus (for each beam)
Average signal to noise ration (SNR)

Appendix C: Missing Data

As noted in the text above, consensus averaging for any single range gate requires a number of distinct targets to accurately determine wind speed and poses a difficult constraint on data completeness. As a result, the data capture rate for any given range data was 60-70% overall. For low mode operation, this means 15-20 data points within the first 1.5 km. This rate of data capture is at or in excess of the significant and mandatory levels used in the standard climatological upper air database and is sufficient to resolve the LLJ.

The FME profiler did experience several extended periods in which profiler data was not available due to mechanical or software reasons, or to site conditions. These "hard down" periods were limited and overall only 8% of all days were included in this category. A list of the longer periods follows. There are also occasional single days with missing data during the period that are not specifically noted here.

September 27 – November 11, 1998
April 26- May 11, 1999
December 10-30, 1999
January 17-25, 2001
August 21-23, 2001
May 9-13, 2002
May 17-27, 2002

Appendix D: Data Processing

A series of processing programs were developed to transform the raw profiler consensus files to a format that could be used for analysis. All programs are in the JAVA program code and are available upon request along with the data files themselves.

Program: Data_Line_List.java

Input: raw Consensus data files
Output: "Data_Line_List.txt"

Scans raw data file; identifies badly formatted profiles (usually blank lines or corrupted lines).

Program: Condition_Found.java

Input: "Data_Line_List.txt"
Output: Many files:
"Event_Means"
"Profile_Means"

Analyzes missing data, determines occurrence of LLJ in each profile.

Program: Analyze_Data.java

Input: "Data_Line_list.txt"
Output: "LLJ_Statistics"

Scans LLJ profiles and retains only those profiles sequential in time with provision for one missing profile allowed. Returns statistics for LLJs of various duration, season and direction.

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