Appendix G-5: The Low Level Jet in Maryland: Profiler Observations and Preliminary Climatology

The Low Level Jet in Maryland: Profiler Observations and Preliminary Climatology

Report Prepared for the Maryland Department of the Environment,
Air and Radiation Administration

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Executive Summary

1. 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.
2. 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.
3. 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".
4. Because they primarily occur at night, 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.
5. Data from the Fort Meade radar profiler from August, 1998 to November, 2002 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 the sounding data that form the standard climatological database.
6. The long duration (≥ 5 h) LLJ is observed on ~ 15% 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 43% of all days.
7. 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 re-inforced by inertial effects as surface friction dissipates after sunset.
8. The mid-Atlantic coastal LLJ typically occurs between 1900-0600 EST. Peak winds are ~ 19 ms^{-1} with mean peak winds for all hours during a jet of 14 ms^{-1}. This implies an average transport distance of 200-300 km. The jet maximum occurs ~ 470 m above ground level with a top at ~ 1.1 km.
9. O_3 concentrations are enhanced when southwest LLJs occur with an average peak of 82.5 ppbv. 44% of these days exceed the 8-hour Code Orange threshold (85 ppbv) and 22% 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.

10. 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.
11. 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, on the order of 60-80 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.
12. 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.
13. 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

Transported O_3 and precursors are critical components of local air quality. While the Baltimore-Washington region has large emissions of O_3 precursors, research studies during high O_3 episodes show that a significant fraction of total observed O_3 is transported into the region from other locations. Transport of pollutants on the regional scale during high O_3 events are typically from the west to northwest above the surface – at altitudes of approximately 500-2000 m above ground level. Significant sources of O_3 precursors are found west of the mid-Atlantic and can be transported into the mid-Atlantic.

Recent intensive observational programs in the mid-Atlantic (NARSTO-NE 1995, NEOPS-Philadelphia 1999, 2002) have routinely observed synoptic scale transport from the west and northwest during high O_3 events. In addition to this sustained large scale flow, the presence of an intermittent low-level transport regime, oriented southwest to northeast, has been observed. This transport regime, commonly called the coastal low level jet (LLJ), was most frequently observed during the nighttime hours, often in association with severe O_3 episodes. While the existence of a coastal LLJ has been known for some years, it has not been routinely observed. The coastal LLJ is primarily a nighttime phenomenon so that National Weather Service weather balloons, launched at 1200 and 0000 UTC daily (0800 and 2000 EDT), do not usually observe its occurrence. As a result, little is known about its frequency and climatology.

Radar wind profilers, giving continuous wind observations from the surface to near 4 km, allow full resolution of intermittent phenomena like the LLJ. The radar profiler installed at Fort Meade (FME) in Maryland, with several years of quality assured data now available, can be used to provide a preliminary climatology of the LLJ in Maryland. In this report, the LLJ will be described theoretically (Section 1), the feasibility of observing the jet using profiler data determined (Section 2), a definition of the LLJ appropriate to air quality concerns provided (Section 3), the frequency of the LLJ in all seasons calculated (Section 4) and the association of the LLJ with poor air quality episodes investigated (Section 5 and Section 6).

Section 1: Science of the LLJ

The low level jet (LLJ) is a transient maximum in wind speed observed in the lowest 0-2 km of the troposphere. 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 LLJ can form in response to a variety of influences, often called forcings. A common forcing that can lead to the development of a LLJ is a region of strong baroclinicity (horizontal temperature gradient) often associated with an approaching frontal boundary. Baroclinicity can also be induced by terrain height differences (*Holton, 1967*). Mountain barriers that split wind fields can induce LLJs as well as land-sea breezes and mountain-valley winds. Inertial oscillations developing as the nocturnal boundary layer develops can also induce, or strengthen, LLJs. To complicate matters further, more than one type of forcing can be involved in the development of the LLJ.

For the analysis presented here, the focus will be on the mid-Atlantic nocturnal coastal plain jet. This LLJ is driven primarily by terrain-induced baroclinicity enhanced by the inertial oscillation. Terrain effects are discussed in greater detail in ***Appendix A***. How terrain differences induce temperature gradients, and, hence, wind fields, can be summarized as follows: For a given slice of the atmosphere above and parallel to sea level over the mid-Atlantic, the western side, near the mountains, will be close to ground level, while the eastern side, where ground level is approximately equal to sea level, will be much above ground level. After sunset, the ground gives off its heat rapidly. As air is a poor conductor of heat, the air nearest the surface will cool much faster than air slightly higher. As a result, for a given height above sea level, the western side of the mid-Atlantic will cool rapidly while the eastern side will cool little, if at all. A horizontal temperature gradient is thus induced with its strongest magnitude just above the top of the nocturnal inversion. This horizontal temperature gradient induces a southerly wind in the lower portion of the troposphere.

In addition to terrain-induced effects noted above, winds can accelerate in the residual layer, located just above the nocturnal inversion, as friction, which retards wind speed in the well mixed planetary boundary layer during the day, disappears after sunset (*Figure 1*). The sudden loss of friction, which is strong in a well mixed mid-day environment, causes an acceleration, termed the "inertial oscillation" (*Blackadar, 1957*). The magnitude of the acceleration can vary from case to case but is typically on the order of 2-5 ms^{-1}. This acceleration persists through the nighttime hours until the winds slowly return to geostropic balance. The observed veering of the winds in the jet from southwest in the late evening to a more westerly by early morning is a function of the Coriolis force returning the winds to geostrophic balance.

For air quality concerns, the most important aspect of the LLJ is that it forms in the residual layer (*Figure 1*). The residual layer contains the remnants of the well mixed boundary layer from the previous afternoon. The well-mixed residual layer is homogenous, retaining the structure and air mass characteristics of the previous day. The impetus for the intensive study of the LLJ in the Great Plains was its role in the development of severe weather outbreaks (see, e.g., *Maddox, 1983*). In that situation, the

LLJ transported, in bulk, warm, moist Gulf of Mexico air rapidly northward into an environment primed for convection. In the mid-Atlantic, our concern is the chemical constituents transported within the LLJ. Aircraft observations during high O_3 episodes in the mid-Atlantic have shown that the residual layer in non-urban areas can contain O_3 concentrations of 80-110 ppbv with significantly higher concentrations downwind of the major urban areas (*Ryan et al., 1998*). Transport of O_3 and its precursors by the LLJ can therefore be a major factor in the magnitude of local O_3 concentrations.

Section 2: Feasibility of Profiler Data for Observing the LLJ

The radar profiler at Fort Meade is a pulse Doppler radar that determines wind velocity by transmitting a pulse of electromagnetic energy and receiving back-scattered energy from any "target" that it encounters. The back-scatttered "returns" are sampled at specific time intervals after each pulse to create a profile of winds at specific heights. These intervals are typically referred to as "range gates". The "targets" are aerosols, particulate matter or any of a number of refractive irregularities. Refractive irregularities are anything that occur in the path of the transmitted wave and alter its path or change its course. Wind velocity is determined is by tracking the irregularities within the overall, or larger scale, wind flow. For example, turbulent eddies are carried along by larger scale winds. Wind speed and wind direction can be determined by measuring the Doppler shift in the wavelength of the return signal as the eddy moves along in the mean flow.

The profiler, under operating conditions such as at Fort Meade, can observe winds with a vertical wind resolution of ~ 60 m (in low mode) over a range of 120-2000 m with wind speed accurate to ~ 1 ms^{-1} and wind direction to ± 10°. Given these parameters, the radar profiler is theoretically capable of accurately observing the mid-Atlantic nocturnal LLJ. As noted above, previous observations have shown that the coastal nocturnal LLJ persists for several hours, with peak winds in excess of 10 ms^{-1}, and over a depth of several hundreds of meters within the first 2 km above ground level. The configuration of the FME profiler suggests that it can easily resolve an individual LLJ (***Appendix B***).

The next pertinent question is whether the data available from the FME profiler is sufficient to provide a local climatology of the LLJ. At the time this study was undertaken, quality assured data were available for the period July 1998 through November 2002. While a complete climatology requires a much longer period of study, this is a useful preliminary dataset as it brackets two warm, and more polluted summer seasons (1999 and 2002) and a cool and quite clean summer season (2000). The FME profiler began routine operations in late July 1998 with consistent data collection beginning in August. Although there are some periods of missing data early in the operation at FME, there is an approximately 92% data capture rate over the period. A more detailed discussion of data completeness is given in ***Appendix C***. While the occurrence of missing profiles is quite low during the study period, individual data points within a profile were more likely to be missing. Overall, 30-40% of possible data points within a profile are not determined. This does not mean that 30-40% of the profiles are missing but simply that the returns from any specific range gate (altitude) were not sufficiently robust to provide a high quality consensus wind measurement. Typically, this means that there were insufficient targets available to provide a strong return signal. Lack of targets most frequently occurs in clean (few aerosols), or less turbulent air masses. This is most likely to occur during the winter season (*Figure 2*) and at higher altitudes where turbulence is often less (*Figure 3*). In the summer months, which are of most interest to this study, data capture is much improved with a missing data point rate of only 13-20%. It is worth noting that, even at a 40% loss rate, at least 10 data points are available in the first 1.5 km. This is similar to, and often greater than, the number of significant and mandatory levels provided by radiosondes in the current climatological record.

Profiler data are collected in both “low” and “high” modes. The low mode covers from 0.11 to 1.5 km and the high mode from 0.32 to 4 km. The distance between range gates is ~ 60 m in the low mode and ~ 200 m in the high range. Previous work on the Great Plains LLJ by *Whiteman et al., 1997* showed better agreement with radiosonde observations in the low mode. The poorer performance in the high mode is due, in part, to smoothing effects over the 200 m distance between range gates. In addition, the first gate of the high mode, at ~ 320 m, compared to 110 m in the low mode, may interfere with observing the lower branch of the LLJ. Results from the analysis of missing range gate data above suggest that, in operational use, profiler resolution is less than the theoretical maximum. This further limits the use of the high mode data. For the purposes of this study, therefore, the low mode is 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., *Weaver, 2004*). 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: Frequency of the LLJ

For all LLJs, forced by a variety of the processes detailed above, long duration (≥ 5 hours) events occur on ~ 15% of all days. The LLJ occurs preferentially during the warm season with 72% of the cases occurring during the period April-September (or ~20% of all warm season days). Overall statistics are given in *Table 2*. In general, the LLJ is a nocturnal phenomenon in Maryland and has a peak in the summer season although it can be observed in all seasons (*Figure 4*). The initiation time of the jet is, on average, from mid-afternoon to early evening. Mean maximum wind speed is 14.6 ms^{-1} although the criteria for identifying the LLJ limit the distribution to cases with maximum wind ≥ 8 ms^{-1}. The mean height of the jet maximum is 0.52 km with a top at 1.13 km. The base of the jet is difficult to determine with accuracy due to the lower limit of the profiler data but the height of the nocturnal inversion is typically on the order of 100-200 m above ground level making for a total depth of the jet of ~ 700-900 m. Wind direction, as might be expected from a variety of forcing mechanisms, varies considerably, with a median of 217°. Other studies of the mid-Atlantic LLJ (e.g., *Weaver, 2004*) have shown a much higher frequency of occurrence. This difference is primarily due to the duration requirement discussed above. If the duration requirement is relaxed, the frequency of the LLJ increases (*Table 3* and *Figure 5*).

This analysis is most concerned with the classic terrain induced summer season southerly LLJ that is frequently observed in association with high O_3 events (*Table 2*). Here, we analyze only those cases with wind direction in the jet core between 180-270°. The average frequency of these cases is ~ 25 per year. The start hour averages 1725 EST, about three hours later than the overall mean, but the median start time is 1900 EST (*Figure 6*). The end hour varies from 0200-1000 EST with a median value of 0600 EST

(*Figure 7*). The southwest jets are thus a nocturnal event and occur overwhelmingly during the summer season (80 of 96 cases).

Peak winds in the southwest LLJ average 18.6 ms^{-1} with an average event peak (mean of each peak wind from all profiles between the beginning and end of the jet) of 14.1 ms^{-1} (*Figure 8*). The mean level of maximum wind is 0.47 km with a top at 1.14 km (*Figure 9 and Figure 10*). The level of maximum wind is consistent with the Great Plains jet where the median height ranged from 426-456 m through the nighttime hours (*Whiteman et al., 1997*). Wind direction groups closely around the southwest, as expected, with little difference between mean and median wind direction (220°). This limited variance is consistent with terrain-induced jet development (*Figure 11*). An example of a profiler observation of a coastal LLJ is given in *Figure Appendix 5*.

Section 5: Association of the LLJ with O_3 Episodes

A number of studies have shown that the transport of O_3 and precursors by the LLJ can affect O_3 concentrations at locations well downwind from emissions. In several cases, a secondary maximum in surface O_3 was observed during the nighttime hours. The mechanism for this rise in O_3 was thought to be mechanically forced downward mixing from the high vertical shear zone at the base of the jet. *Corsmeier et al., 1997* observed a secondary maxima in O_3 in rural Germany that was, on average, 10 % of the following day maximum. *Salmond and McKendry, 2002* also observed a secondary O_3 maxima in the Lower Fraser Valley of British Columbia associated with low level jets that occasionally exceeded half the previous day's maximum ozone concentration. Similar results were found over a more urban area in Germany in *Reitebuch et al., 1999*. Most of these studies looked at short episodes occurring during intensive field campaigns and were not developed with a climatological database such as is presented here.

Days on which LLJs are observed in Maryland are enhanced with respect to O_3. For all southwest LLJ cases, mean peak 8-hour O_3 in the Baltimore metropolitan area was 82.5 ppbv compared to 68.2 ppbv for all summer season cases. 44% of the southwest LLJ cases exceed the Code Orange threshold and 22% exceed the Code Red threshold. Thus, LLJ cases are likely to be associated with high O_3.

The next pertinent question is whether high O_3 cases are likely to include LLJs. For the period from August, 1998 to November, 2002, the Baltimore metropolitan area experienced 150 cases of 8-hour O_3 maximum ≥ 85 ppbv (Code Orange AQI). Of this total, 57% (n = 86) observed a LLJ within 36 hours of the O_3 maximum. "Same day" LLJs, that is, a LLJ observed during the morning of an O_3 event was observed in 28% of the total high O_3 cases, with 13% on the preceding day and 15% on the following day. The southwest LLJ accounted for the vast majority of the high O_3 cases (78%).

Code Red cases (8-h $O_3 \geq 105$ ppbv) are less frequent, 48 over the same period. Of these, 62% observed LLJs within 36 hours of the exceedance and 42% on the same day. Southwest LLJs accounted for all but two of these cases. Of the 24 extended severe episodes, defined as Code Orange or Code Red O_3 persisting for 3 or more days, 17 contained instances of LLJs. For Code Red cases, however, there is a much closer connection between the LLJ and high O_3. Nearly half of the Code Red O_3 cases occurred on the same day of the LLJ. This implies, at the least, that the air mass within the LLJ, as it arrives from the southwest and west-southwest overnight, is polluted with respect to O_3 and 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 6. 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. Nor are there high elevation O_3 monitors along the coastal plain that remain in the residual layer overnight. 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 12 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 12*. 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 (*Figure 13*), 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 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 14*). 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 15*). 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 16*).

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. 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.

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.

Section 6: 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 17-19*. Note that the HYSPLIT back trajectories in *Figure 19* 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 20-21* 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 means 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 features non-standard LLJs *and* Code Red O_3. The outstanding 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 22*). 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 23*). A southwest LLJ was observed on the night of May 9-10 with convection and lower O_3 observed on May 10 (*Figure 24*). In other similar cases, the strong winds, and later convection associated with the front will decrease O_3 concentrations (*Figure 25*).

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 November, 2002 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 ~ 15% 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 43% 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 1900-0600 EST. Peak winds are ~ 19 ms^{-1} with mean peak winds for all hours during a jet of 14 ms^{-1}. This implies an average transport distance of 200-300 km. The jet maximum occurs ~ 470 m above ground level with a top at ~ 1.1 km.

O_3 concentrations are enhanced when southwest LLJs occur with an average peak of 82.5 ppbv. 44% of these days exceed the 8-hour Code Orange threshold (85 ppbv) and 22% 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 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.

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. Future work should be directed to improving forecasts of LLJ formation and making direct aircraft measurements within the jet core itself.

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)			
	All LLJ Cases	**Southwest LLJ Cases**	**Summer Season Southwest LLJ**
Number of Cases	213	96	80
Mean Start Time (EST)	1430	1725	1750
Median Start Time (EST)	1800	1900	1930
Mean End Time (EST)	0800	0625	0550
Median End Time (EST)	0700	0600	0600
Maximum Wind Speed (ms^{-1})	19.5 ± 8.0	18.6 ± 6.8	16.4 ± 5.2
Mean Maximum Wind Speed (ms^{-1})	14.6 ± 4.6	14.1 ± 3.6	13.2 ± 3.0
Mean Wind Direction (degrees)	199	220	221
Median Wind Direction (degrees)	219	220	223
Mean Height Maximum Wind (km)	0.52 ± 0.15	0.47 ± 0.15	0.48 ± 0.14
Median Height Maximum Wind (km)	0.52	0.46	0.46
Mean Height of Top of Jet (km)	1.13 ± 0.18	1.14 ± 0.19	1.20 ± 0.10
Median Height of Top of Jet (km)	1.18	1.20	1.22

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

Variation of Frequency of Low Level Jets With Respect to Duration Criteria				
	Duration Requirement			
	2 hours	**3 hours**	**4 hours**	**5 hours**
1998	56	32	23	13
1999	117	89	64	46
2000	165	106	66	48
2001	148	105	85	61
2002	138	86	60	46
Total	624	418	298	214
% All Days	42.6%	28.6%	20%	14.6%

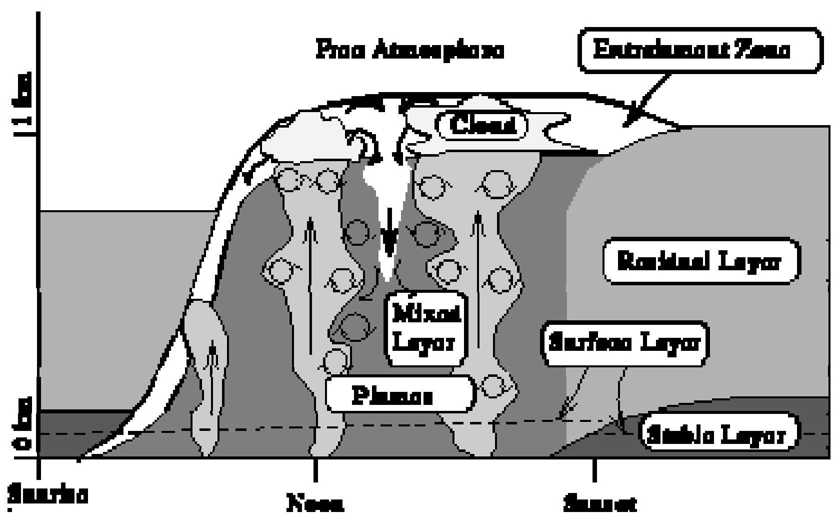


Figure 1. Time series depiction of the development of the planetary boundary layer, from Piironen A. K., 1994: Analysis of Volume Imaging Lidar Signals, M.S. Thesis, University of Wisconsin, Madison, WI, text can be found at: http://lidar.ssec.wisc.edu/papers/akp_thes/node6.htm

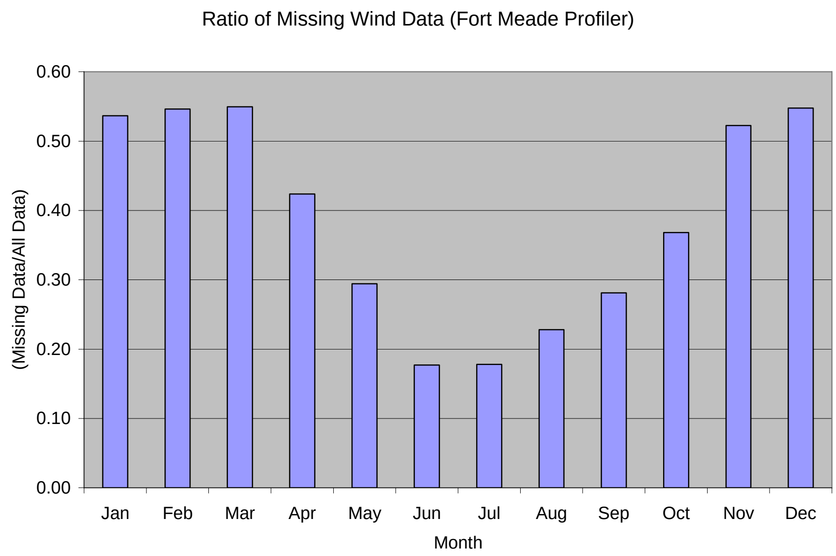


Figure 2. Monthly variations in the rate (percentage) of missing range gate data from the Fort Meade profiler (August, 1998 to November, 2002).

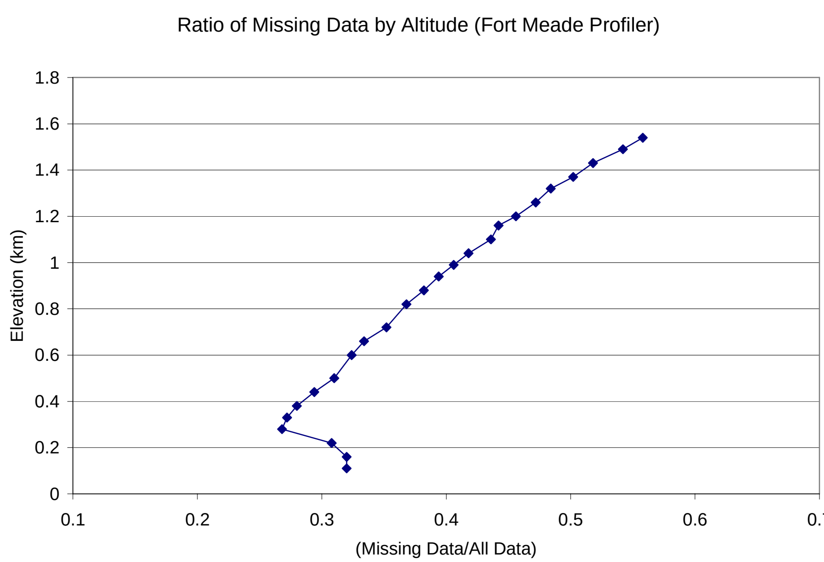


Figure 3. Missing range gate data at the FME profiler as a function of altitude (km).

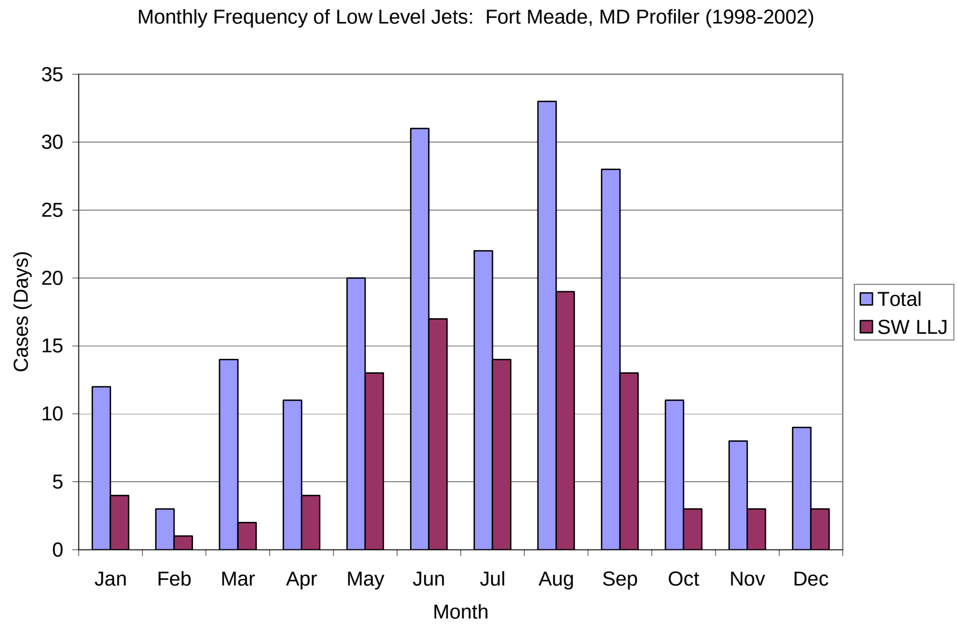


Figure 4. Frequency of the long duration (≥ 5 h) LLJ observed at FME by month.

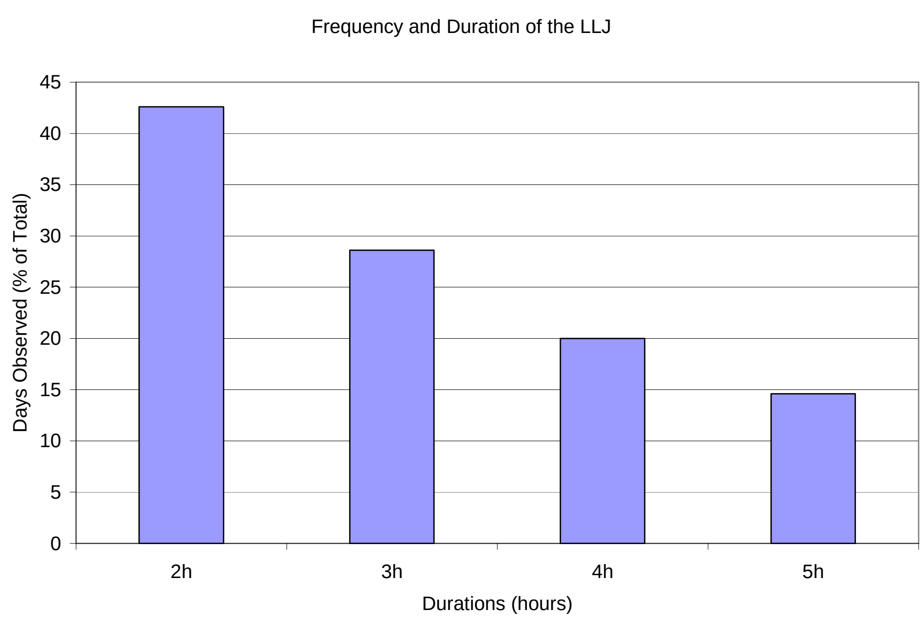


Figure 5. Frequency of the LLJ at FME as a function of its duration (in hours).

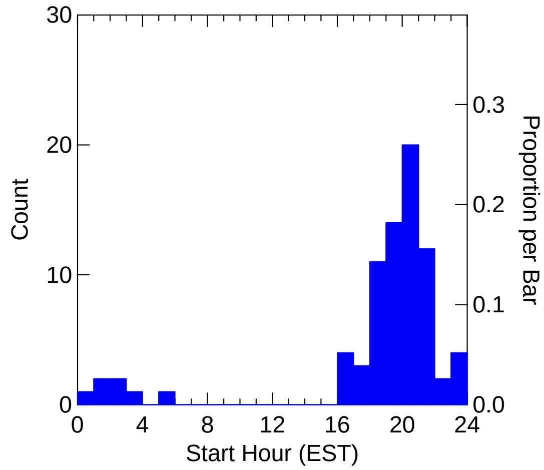


Figure 6. Frequency of the initial, or start, time of the southwest LLJ. The start hour is defined as the time at which the jet first exceeds the threshold wind speed criteria given in Table 1.

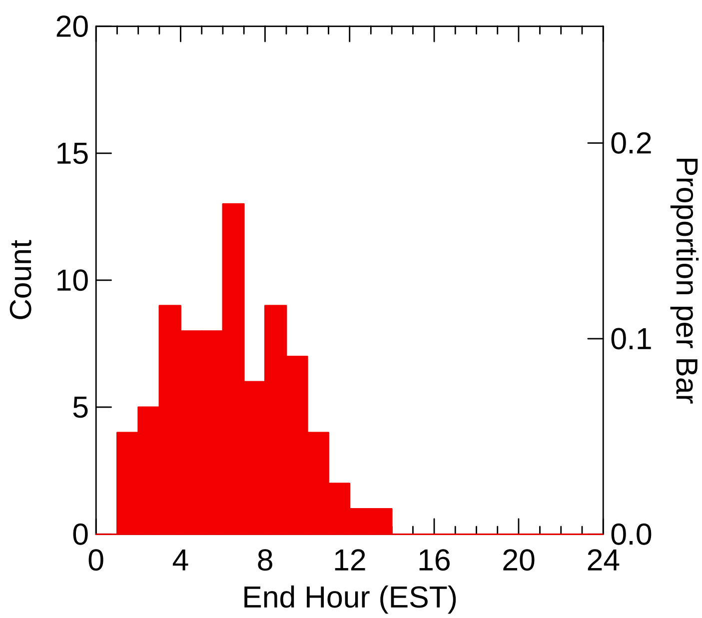


Figure 7. Frequency of the termination, or end, time of the southwest LLJ. The end hour is defined as the time at which the jet no longer exceeds the threshold wind speed criteria given in Table 1.

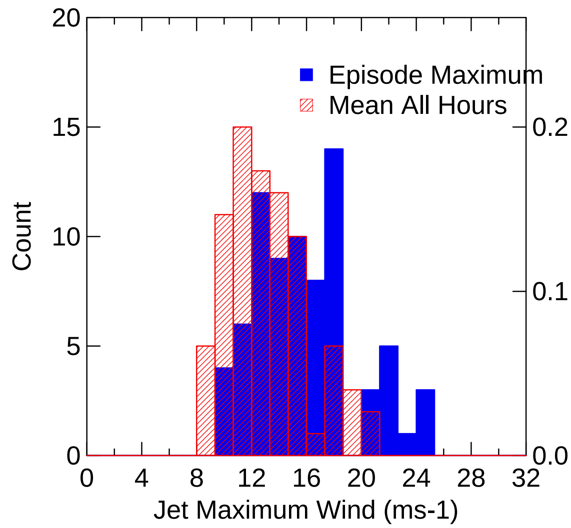


Figure 8. Frequency of peak wind speed (filled blue bars) and event averaged peak wind (striped red bars) for the southwest LLJ cases.

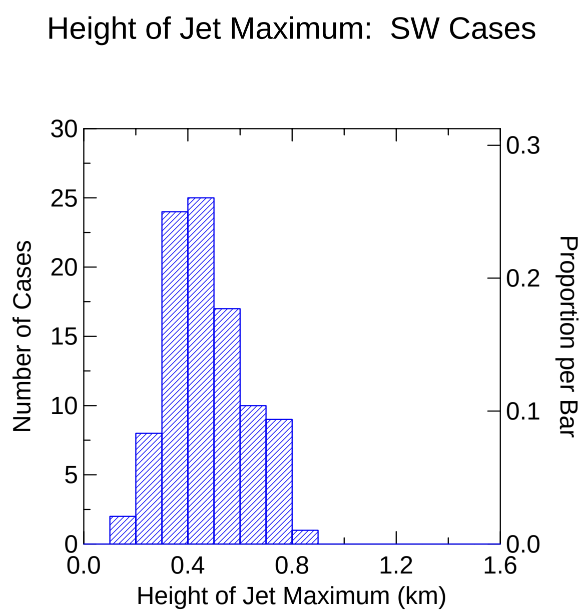


Figure 9. Frequency of the height (in km) of the level of peak wind within the southwest LLJ.

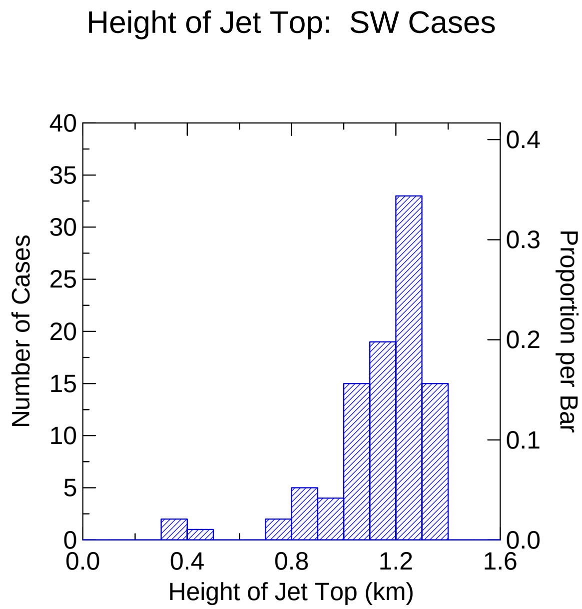


Figure 10. Frequency of the height (in km) of the top of the southwest LLJ.

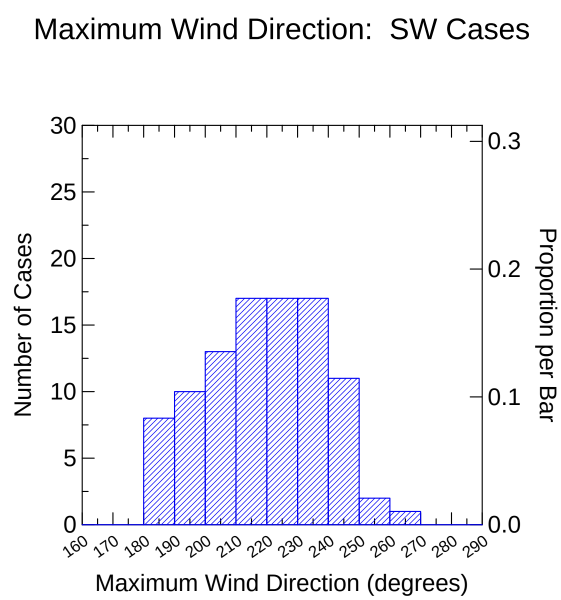


Figure 11. Mean wind direction at the level of maximum wind for the southwest LLJ.

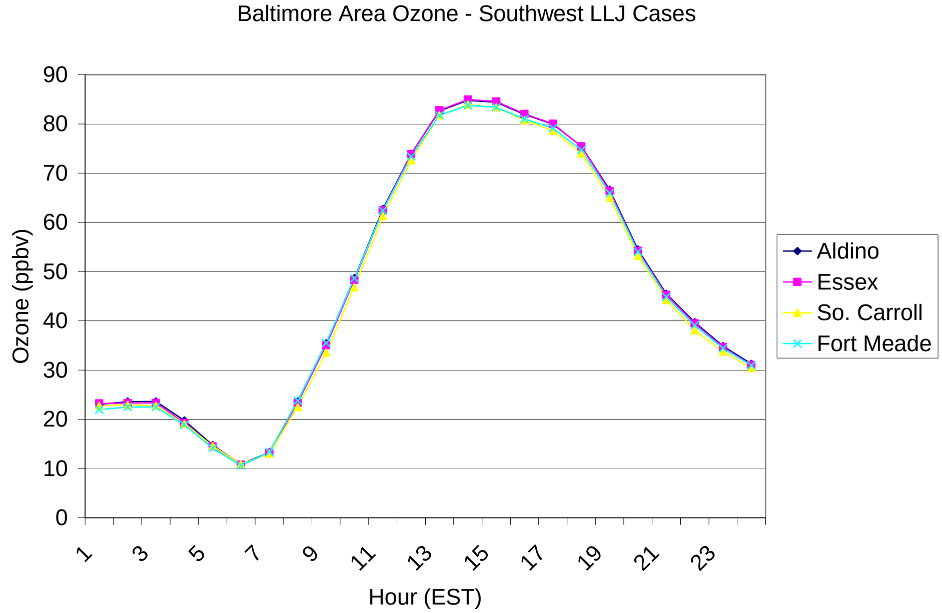


Figure 12. Time series of O_3 concentrations at four selected Baltimore area O_3 monitors for the subset of high O_3-LLJ cases (n = 61).

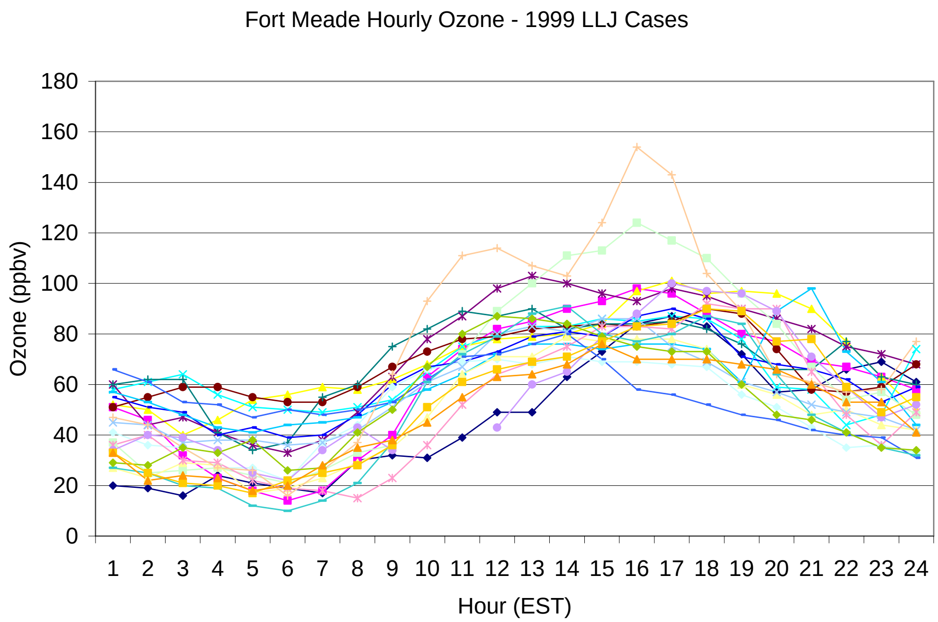


Figure 13. As in [Figure12] but for Fort Meade, MD and only for cases occurring during 1999.

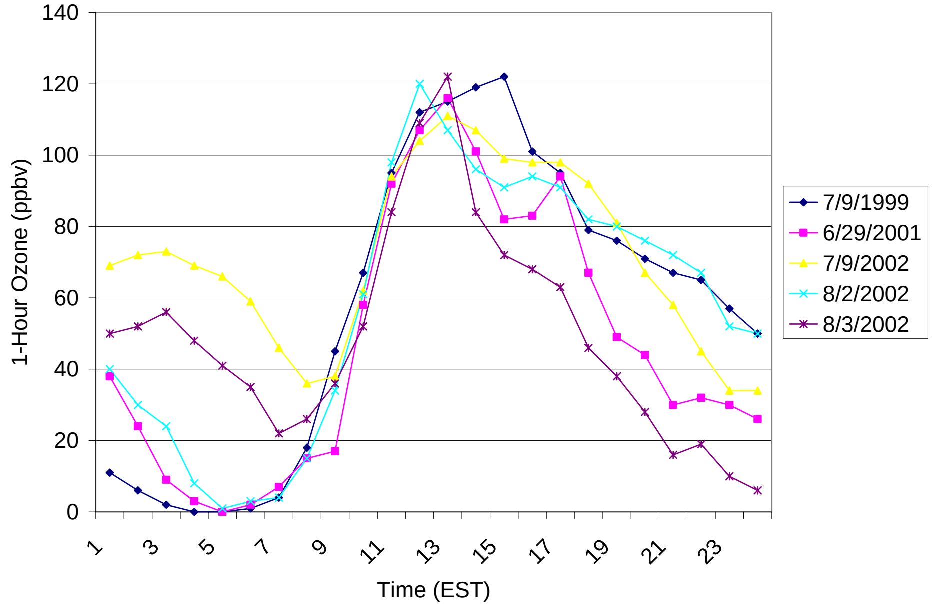


Figure 14. As in *Figure 13*, but for selected high O_3-LLJ cases in which late morning mixing effects were particularly strong.

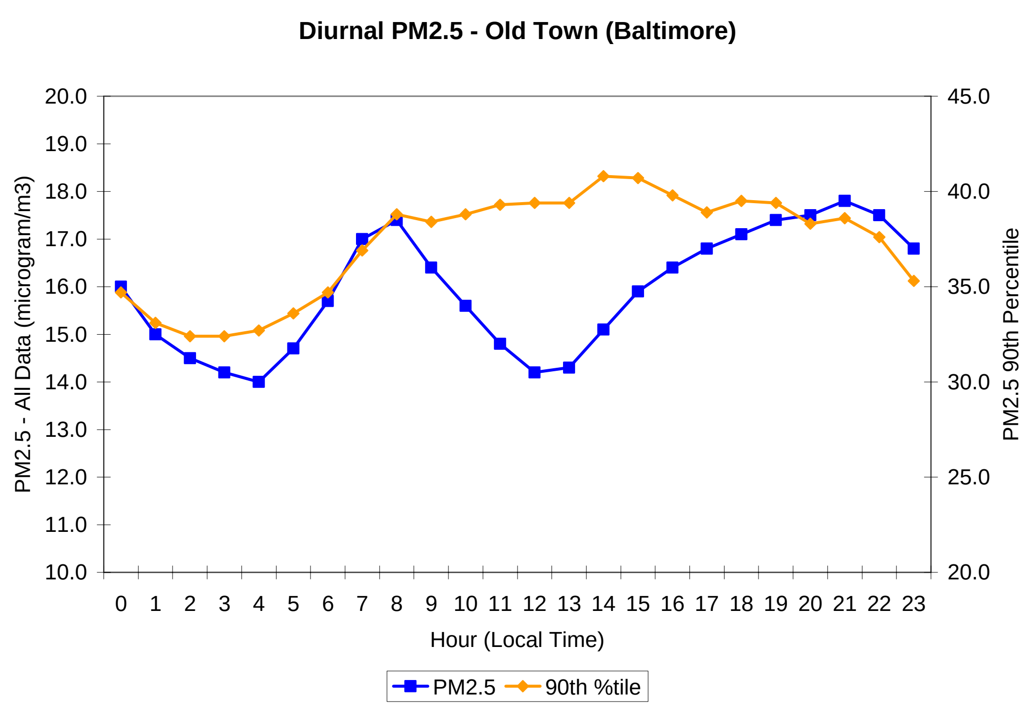


Figure 15. Hourly time series of $PM_{2.5}$ concentrations in Baltimore for the period 1999-2002. Blue line represents all data and the orange line only the highest 90^{th} percentile of cases (≥ 37 μgm-3).

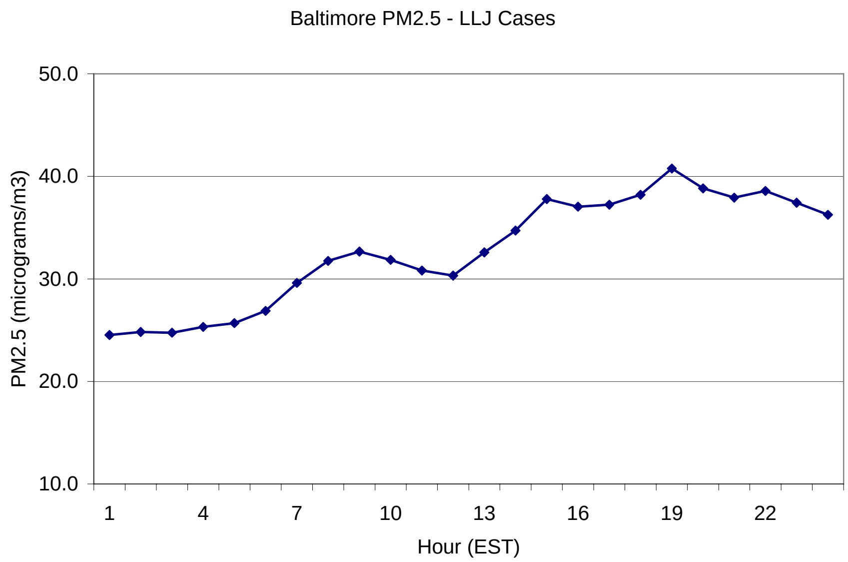


Figure 16. As in *Figure 15* but for only for the high O_3-LLJ cases analyzed in this study.

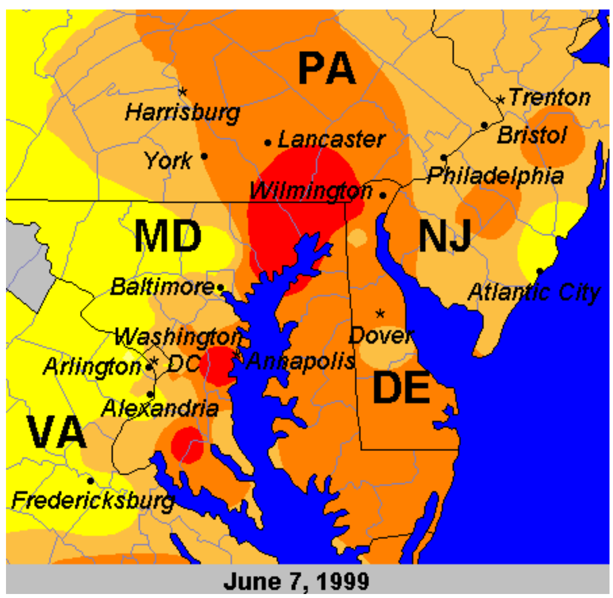


Figure 17. Peak 1-hour O_3 concentrations for June 7, 1999 as mapped by EPA AIRNOW. Concentrations contours are: Yellow (80-99 ppbv), light Orange (100-109 ppbv), dark Orange (110-124 ppbv) and Red ($\geq$ 125 ppbv).

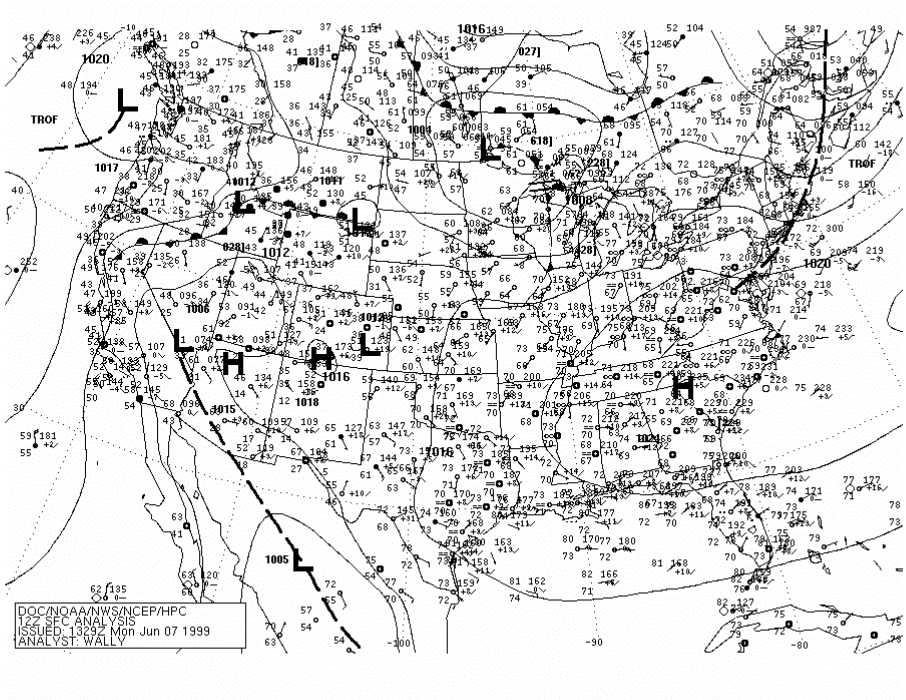


Figure 18. National Weather Service surface analysis for 1200 UTC, June 7, 1999.

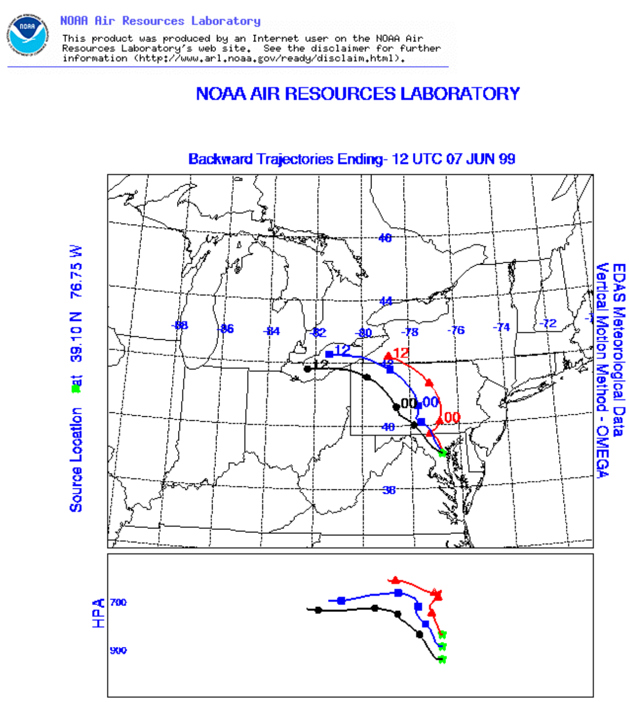


Figure 19. HYSPLIT back trajectories terminating at BWI on 1200 UTC, June 7, 1999. Back trajectories are for 24 hours at three levels (1500 m (red), 1000 m (blue) and 500 m (black). HYSPLIT uses Eta Data Assimilation System (EDAS) data on 80 km grids.

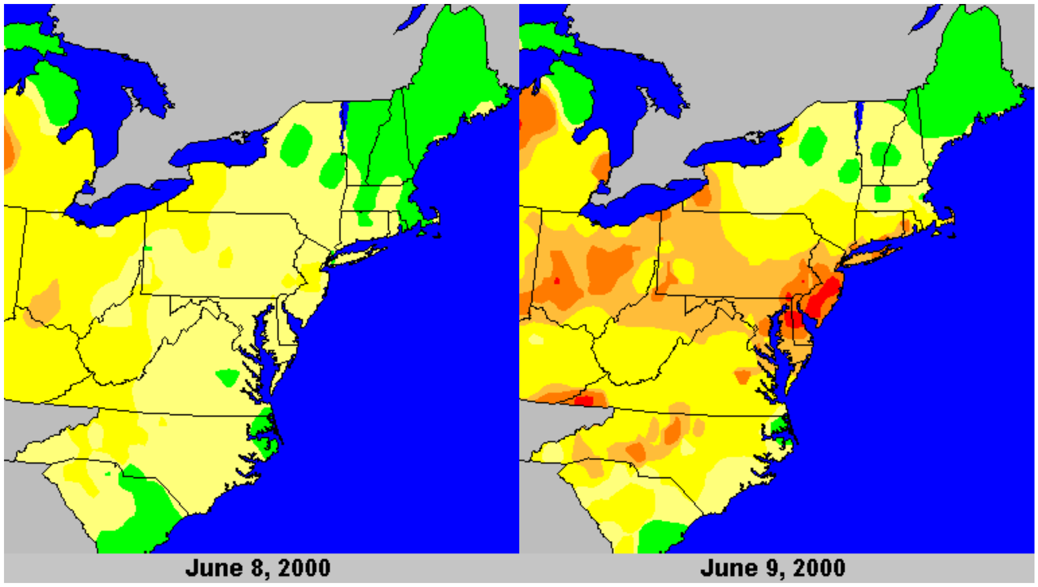


Figure 20. As in *Figure 17*, but for June 8-9, 2000.

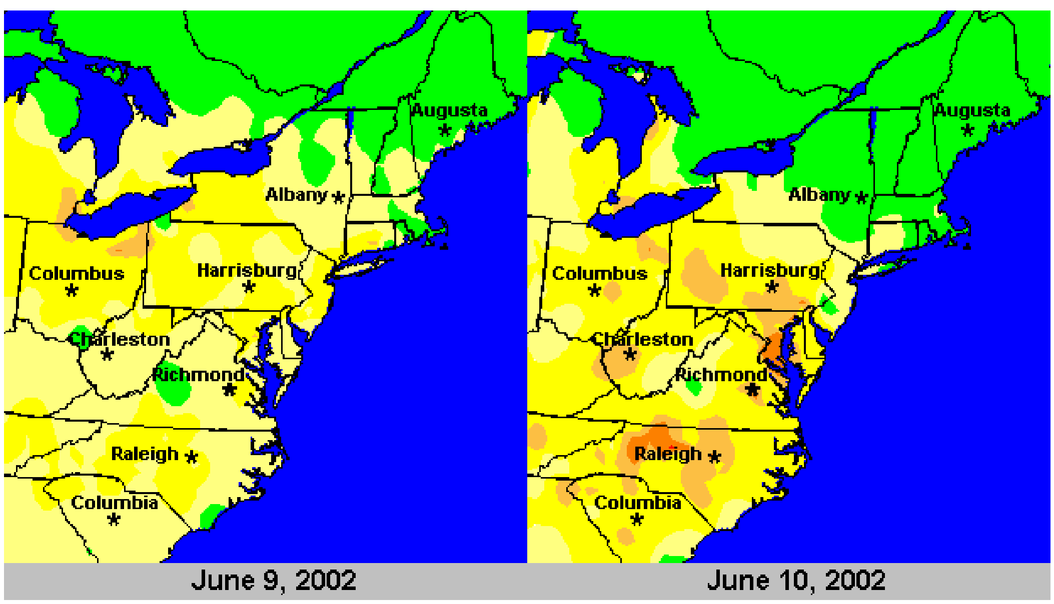


Figure 21. As in *Figure 17* but for June 9-10, 2002.

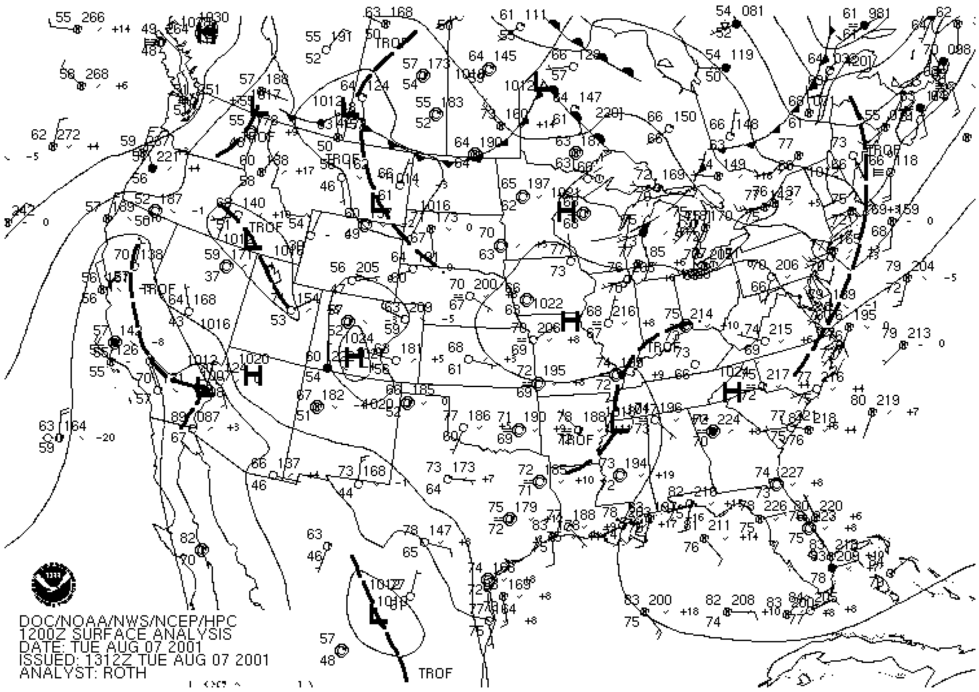


Figure 22. As in *Figure 18* but for 1200 UTC, August 7, 2001.

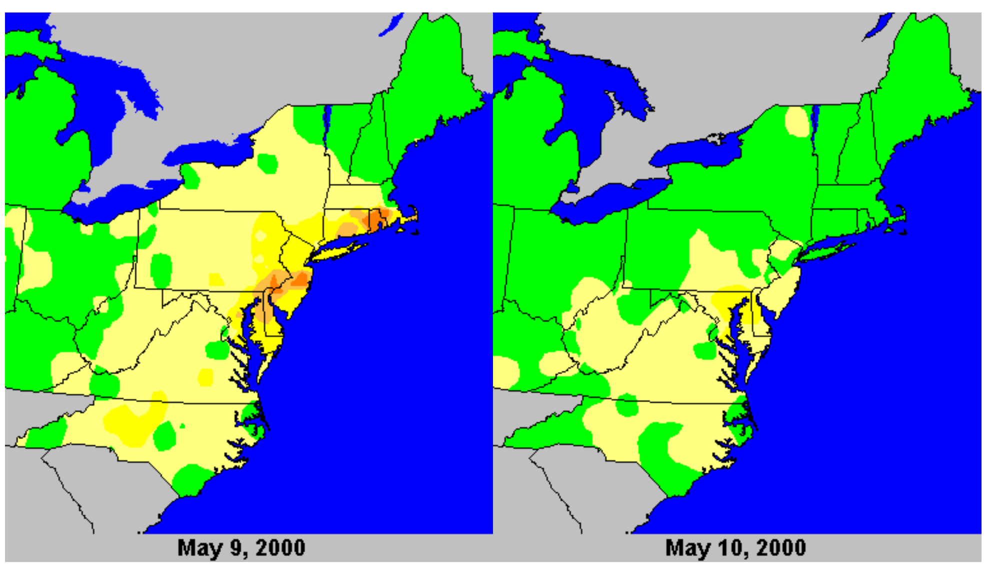


Figure 23. As in *Figure 17* but for May 9-10, 2000.

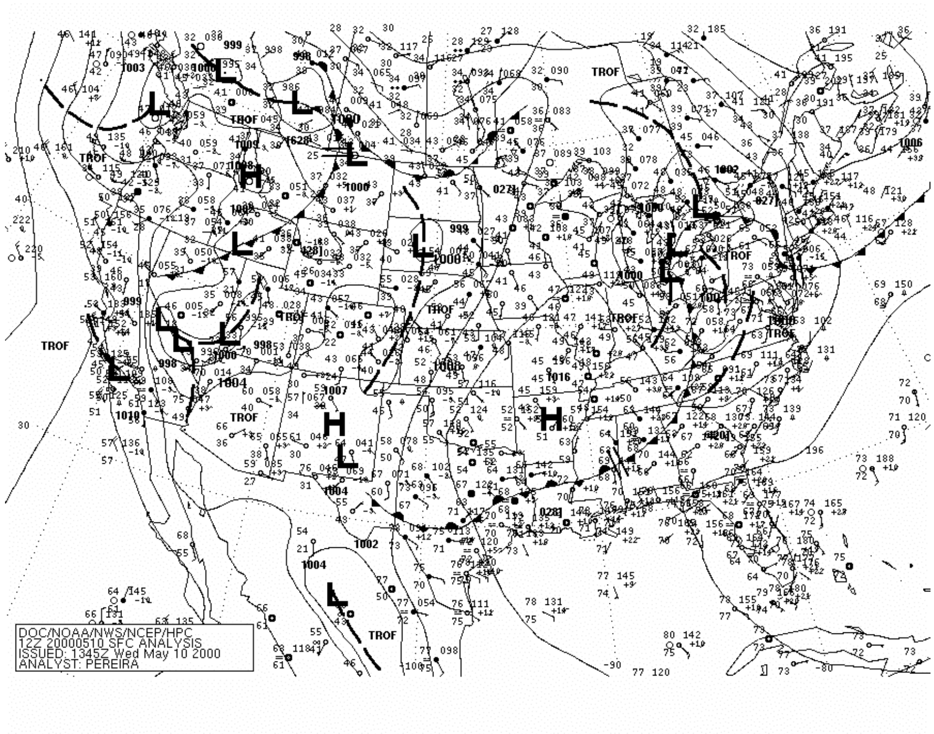


Figure 24. As in [*Figure 18*] but for1200 UTC, May 10, 2000.

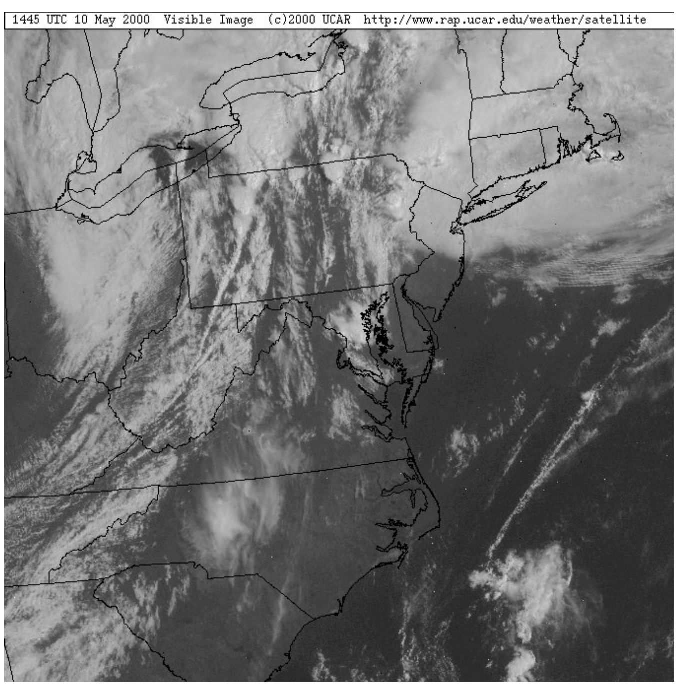


Figure 25. GOES East visible image for 1445 UTC, May 10, 2000. Convection is already developing by late morning ahead of a cold front approaching the Appalachians.

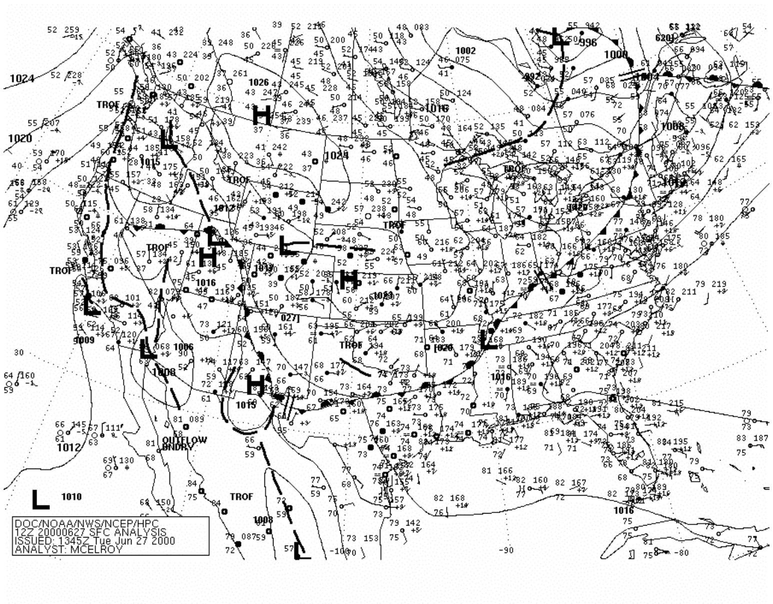


Figure 26. As in *Figure 18* but for1200 UTC, June 27, 2000.

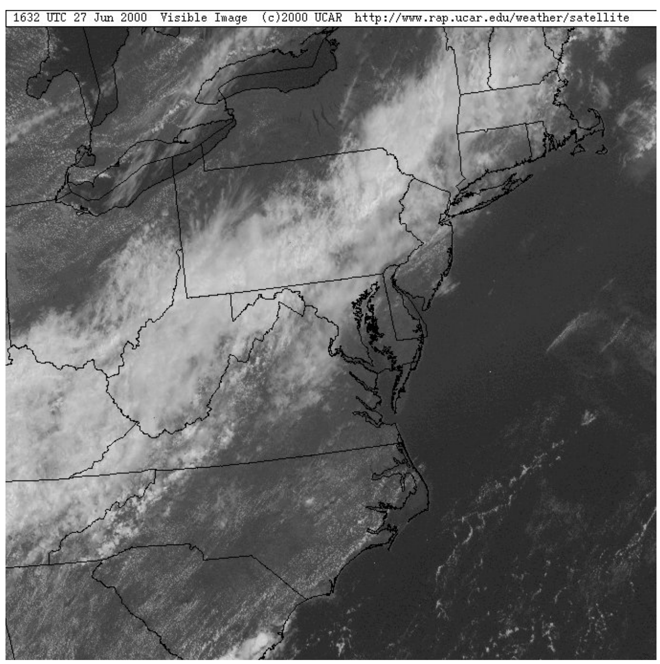


Figure 27. As in Figure 25 but for 1632 UTC, June 27, 2000. In this case the LLJ feeds moisture into an area of convection developing ahead of a cold front.

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*.

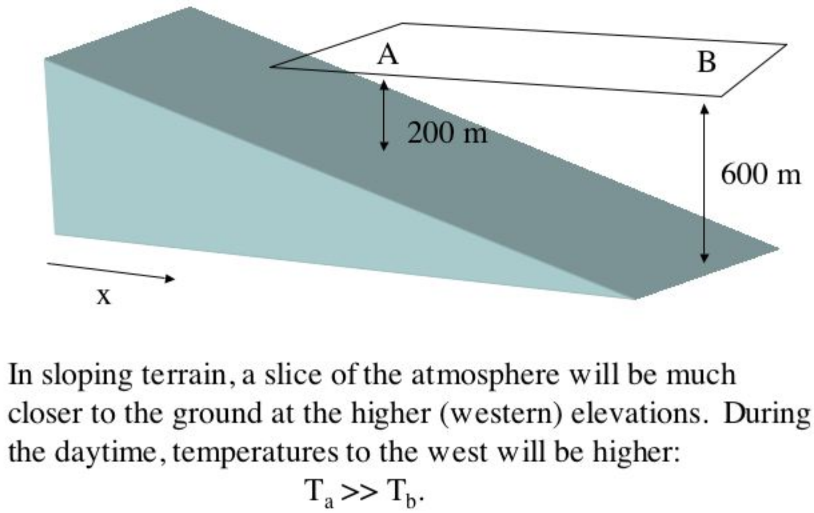
The thermal wind equation can help us to develop a simplified version of the coastal jet. In this simplified version we will look only at the north-to-south wind component (v_g) of the geostrophic wind:

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

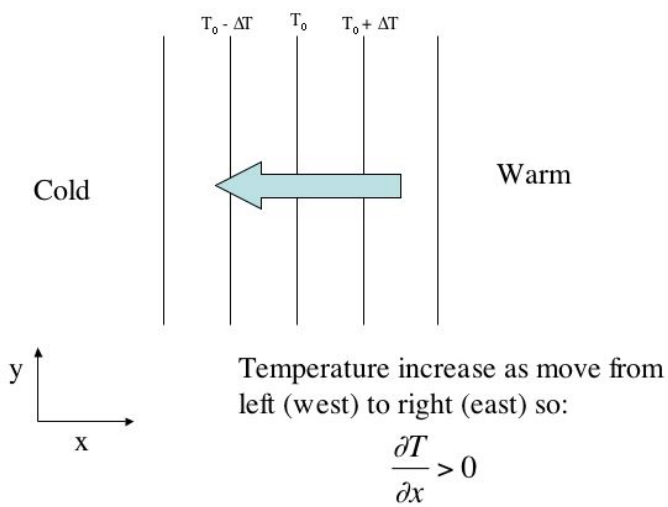
Using the standard convention that x increases as we move from west to east, Equation 2b tells us that if temperature decreases from west to east, then $\partial T/\partial x < 0$ and winds will decrease with height. Alternatively, if temperature increases from west to east, then $\partial T/\partial x > 0$ 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).

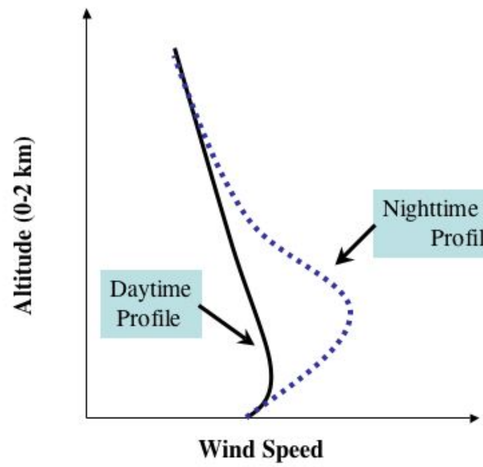
In the nighttime hours, however, the situation reverses. The ground cools rapidly and the layers near the surface cool quickly as well. At higher altitudes, however, the atmosphere cools little if at all. As a result, for a given slice of the atmosphere, the air in the higher elevations in the western 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).



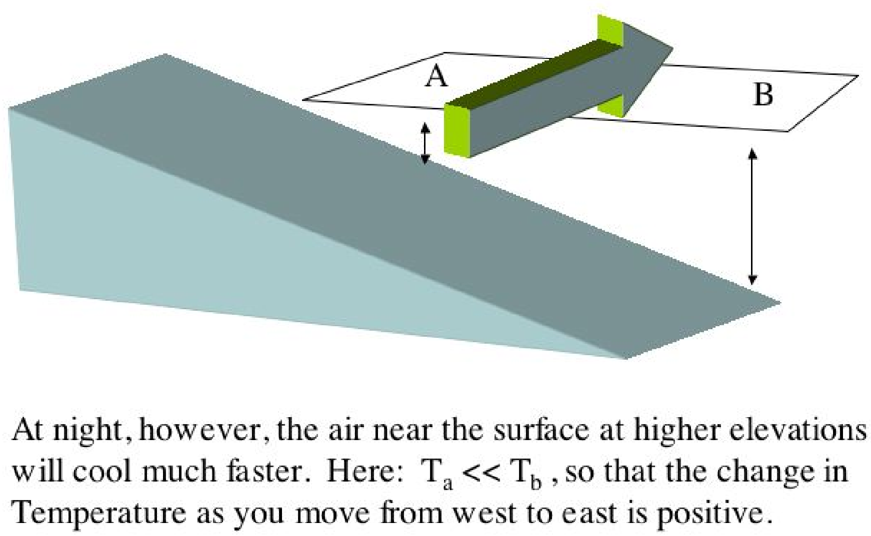
Appendix A-Figure 1.



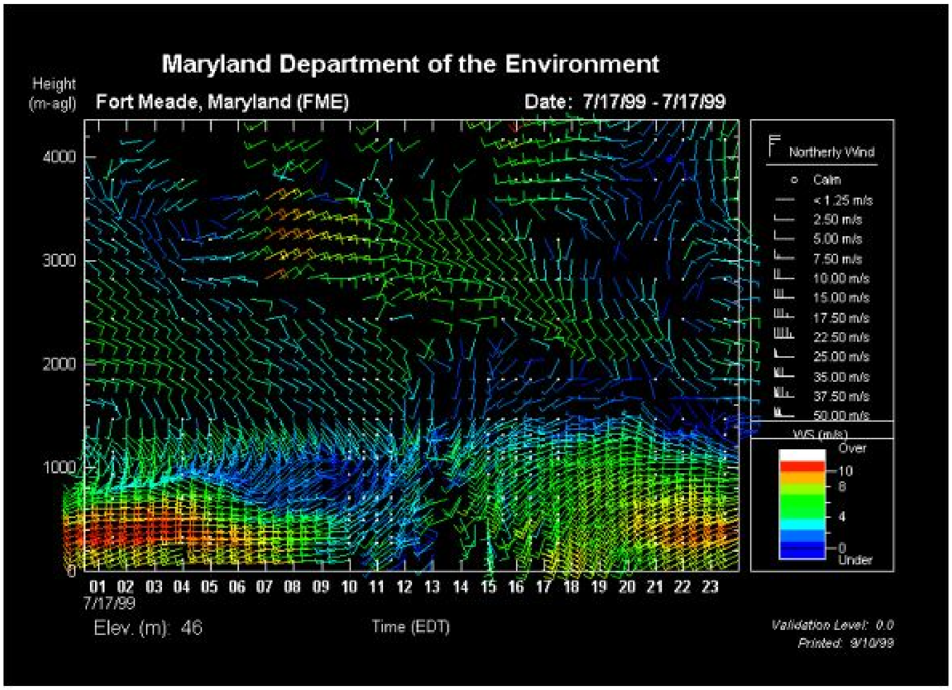
Appendix A-Figure 2.



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 standard FORTRAN 90 and are available upon request along with the data files themselves.

Program: llj-preprocess.f

Input: raw Consensus data files
Output: "infile"

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

↓

Program: llj-v1.1.f

Input: "infile"
Output: "statfile"
"outfile"

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

↓

Program: llj-post-v1.0.f

Input: "outfile"
Output: "scanfile"

Scans LLJ profiles and retains only those profiles sequential in time with provision for one missing profile allowed.

Program: llj-duration.f

Input: "scanfile"
Output: "duration"

Retains only those sequential LLJ profiles that reach a certain duration. Initially set to 5 hours, can be changed to fit other durations.

Program: llj-stats.f

Input: "duration"
Output: "episode"

Determines basic statistics of the LLJ for each long duration episode.

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