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Assessing Seasonal Transport and Deposition of Agricultural Emissions in Eastern North Carolina, U.S.A.

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Abstract — There is an increasing interest regarding the fate of nitrogenous compounds emitted from agricultural activities in the southeastern United States. Varying climate, topography and proximity to the Atlantic Ocean particularly complicates the problem. An increased understanding of the interaction of synoptic scale flow with mesoscale circulations would constitute a significant improvement in the assessment of regional scale transport and deposition potential. This knowledge is necessary to facilitate current and future modeling attempts in the region as well as for planning future monitoring sites to develop a cohesive regional policy for the abatement strategies. The eastern portion of North Carolina is used as a case example due to its high, localized emission of nitrogen compounds from agricultural waste. Three periods: July 2–7, 1998, October 5–11, 1998, and December 12–19, 1998, corresponding to three different seasons were studied. Surface wind and thermodynamic patterns were analyzed using surface observing stations and archived-model analysis results centered over eastern North Carolina. Diurnal and seasonal patterns were identified for dispersion and concentration values obtained using an air pollution transport and dispersion model. This mesoscale information was used to draw qualitative conclusions regarding the possible trends and deviations in the dynamic trajectories as well as the resulting near-surface concentrations and deposition potential in eastern North Carolina. Results show that highly variable seasonal and diurnal atmospheric circulations characterize the study domain. These variations can significantly impact the transport and fate of pollutants released in this region. Generally, summer provides the highest potential for localized deposition, while fall can provide opportunity for long-range transport. The results also suggest that mean climatological or seasonally averaged flow patterns may not be sufficient for analyzing the fate of the agricultural releases in this region. At the very least, mean and variance based analysis is required to capture the climatology of the dispersion and deposition patterns. These patterns in eastern North Carolina appear to be sensitive to the strength and location of air mass boundaries along the coastal plain, indicating diverse scale interactions affecting the variability and uncertainty in the regional pollutant transport.

Key words: Air pollution, atmospheric deposition, North Carolina, trajectory analysis, nitrogen compounds.

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Introduction and Background

Processes associated with many environmental problems such as air quality, acid rain, hydrology, and water quality are strongly influenced by different aspects of the circulation of the atmosphere (YARNAL, 1993). Field monitoring studies have long suggested the potential importance of regional and long-range atmospheric transport to the distribution of agricultural chemicals in the environment (KURTZ, 1990; MAJEWSKI and CHAPEL, 1995). However, application research is severely hampered by uncertainties in the mesoscale and diurnal patterns of near-surface winds and thermodynamic structure. Therefore, local scale transport and deposition of surface chemical or agricultural waste emissions are not well understood.

North Carolina exhibits a large variation in its temporal and spatial climate due to complex topography and proximity to the Atlantic Ocean. Recent research has also shown that a significant teleconnection exists between climate in North Carolina and global patterns such as El Niño-Southern Oscillation (ROSWINTIARTI *et al.*, 1998; RHOME *et al.*, 2000). In addition, the presence of sea-breeze circulation along southeastern North Carolina further complicates the regional wind patterns (GILLIAM *et al.*, 1999). This circulation consists of a shallow low-level onshore flow and an opposing return flow aloft. Often associated with this phenomenon is a mesoscale front with a narrow convergence zone and upward motion along the leading edge. Surface convergence zones and the associated vertical motions have been shown to have a significant impact on the parcel trajectory and wet deposition (COOTER *et al.*, 1997). These interactions among atmospheric motions at different spatial scales in eastern North Carolina and the implications on meteorology and pollutant transport and deposition are discussed in this paper. To date little emphasis has been placed on the impacts of mesoscale variability on climatic or mean wind fields and the transport and deposition patterns in coastal North Carolina.

One pollutant that is gaining considerable attention in North Carolina is the large-scale emissions of nitrogen compounds such as ammonia from agricultural swine-based farm activity (ANEJA *et al.*, 1997). In a study reported by WALKER *et al.* (2000) there has been a substantial increase in the swine population and related nitrogenous emissions and deposition in southeastern North Carolina in recent years. Figure 1 shows the observed annual precipitation — weighted ammonium concentration (mg/L) obtained from the National Atmospheric Deposition Program/National Trends Network (NADP/NTN) site in eastern North Carolina (Site NC35). Overall, there is a significant increase in the amount of airborne nitrogen collected from rainfall in the form of ammonium (formed as a result of ammonia linking with sulfates, nitrates, and chlorides). ANEJA *et al.* (1997) suggest, these emissions have a diurnal maximum during the afternoon as well as a seasonal maximum during the summer primarily due to maximum lagoon water temperatures. For instance, in 1998, the NC35 site in eastern North Carolina, showed a seasonal mean ammonium deposition of 0.54 kg.ha^{-1} in fall as against 2.06 kg.ha^{-1} in summer. It is hence

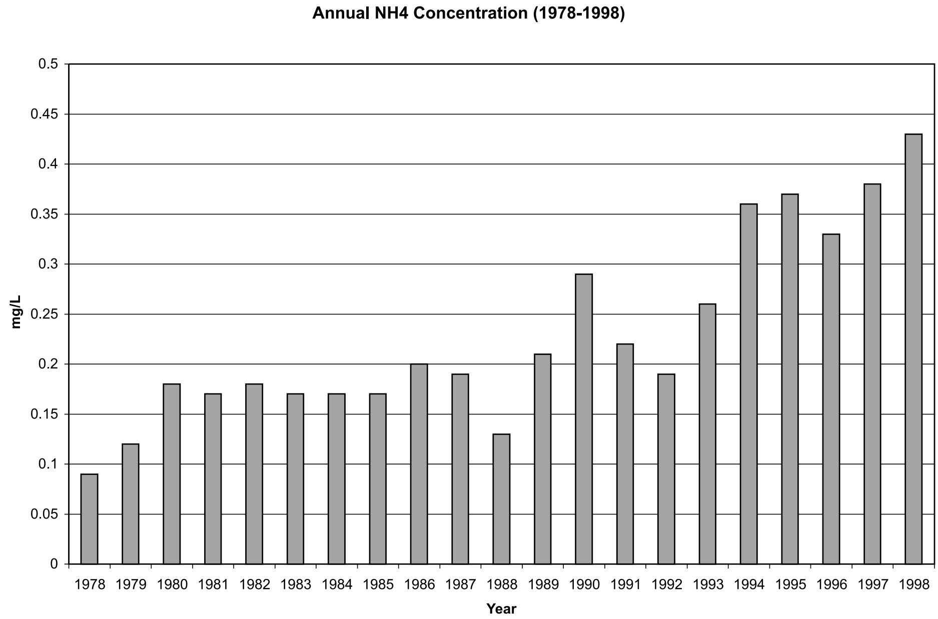

Figure 1
Annual ammonium concentration at the NADP/NTN site NC35 in Clinton, North Carolina. The increasing ammonium and related reduced nitrogen concentrations and deposition are considered to be significantly related to the increase in the agricultural emissions from animal waste lagoons in eastern North Carolina.

important to study the seasonal variations in the thermodynamic and wind patterns to assess the potential for transport and deposition in eastern North Carolina. Identification of critical meteorological regimes that can create deviations in transport and deposition patterns will constitute a significant improvement in the understanding of atmospheric loading of nitrogen to sensitive areas along the mid-Atlantic region.

Previous studies have investigated allied features for regions elsewhere in the United States. For instance, soil emissions and re-volatilization of chemical residue for agriculturally based chemicals have been modeled as responding to wind speed, humidity, temperature, solar radiation, cloud cover, precipitation and soil temperature (COOTER *et al.*, 1997). Chemical transport has been studied as a function of turbulent motions as well as horizontal and vertical advection by the regional scale wind field (CHANG, 1990). Wet and dry chemical depositions are known to be influenced by rain volume, temperature, wind speed, local and regional turbulence, radiation, and humidity (COOTER *et al.*, 1997). Hence, the effects of seasonal and different scale interactions on pollutant concentrations and deposition fields are of great relevance and interest for agricultural environmental analysis.

In the following section, we will describe a methodology for assessing the regional transport of agricultural emissions in eastern North Carolina. In the analysis, priority is given to readily available meteorological data sets. Based on the varying synoptic and mesoscale processes over eastern North Carolina, we will provide a qualitative assessment of the transport and dispersion potential for reduced nitrogen compounds. For this analysis, three different case scenarios are presented in section 3 corresponding to three different seasons (Winter, Fall, and Summer). In particular, the evolutions of the synoptic and mesoscale aspects of the seasonal case studies are presented in this section. In section 4, the spatial and temporal patterns for concentration and deposition in relation to varying (seasonal/diurnal) flow patterns for the three seasonal cases are discussed. Section 5 summarizes the results concerning the dependence of transport and deposition on synoptic and mesoscale wind fields, and how differing scales can interact in eastern North Carolina.

2. Methodology

Mesoscale wind and thermodynamic patterns for the summer, fall, and winter seasons over eastern North Carolina are investigated. Summer, fall, and winter periods were chosen for seasonal analysis as they represent varying complexity of the interactions of mesoscale and synoptic scale forcing. Spring patterns are somewhat similar to those during the fall, and so spring was not included in the seasonal analysis. These seasons were also chosen based on analysis of trends in precipitation–weighted concentration of ammonium obtained from National Atmospheric Deposition Program/National Trends Network site NC35 for 1998. The seasonal average values were 0.48 $mg.l^{-1}$ and 0.41 $mg.l^{-1}$ for spring and fall, as against 0.26 $mg.l^{-1}$ and 0.76 $mg.l^{-1}$ for winter and summer, respectively (cf., WALKER *et al.*, 2000). Thus, winter, fall, and summer were considered for analysis and one period was chosen to represent each of these seasons. The study periods were July 2–7, October 5–11, and December 12–19, 1998. These were chosen by factors such as data availability, presence of dominant synoptic and mesoscale features, as well as presence of both significant anomalies and dominant seasonal patterns that typically frequent the region.

The first part of this analysis was the interpretation of seasonal features in the wind and thermodynamic field over eastern North Carolina. Surface meteorological observations from over twenty weather stations across eastern North Carolina for the three periods were analyzed (NIYOGI *et al.*, 1997). The National Oceanic and Atmospheric Administration's (NOAA) Real-time Environmental Applications and DisplaY (READY) system was then used to analyze surface wind and moisture patterns over the study region. We chose 3-hourly archived analysis from the National Center for Environmental Prediction (NCEP) Eta Data Assimilation System (EDAS) for this study. EDAS is an intermittent assimilation system consisting of successive model forecasts and Optimum Interpolation (OI) analyses for a pre-forecast period (12-h for the early Eta) on a 38 level, 48 km grid.

The next step was the use of a tracer model to analyze transport and dispersion patterns. The HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory, Draxler and Hess 1997) model was used for computing air parcel trajectories for dispersion and deposition simulations. The dispersion of a pollutant is calculated by assuming either puff or particle dispersion. In the puff model, puffs expand until they exceed the size of the meteorological grid cell (either horizontally or vertically) and then split into new puffs, each with a share of the pollutant mass. In the particle model, a fixed number of initial particles are advected through the model domain by the mean and turbulent wind field components. The model's default configuration assumes a puff distribution in the horizontal and particle dispersion in the vertical direction. In this way, the greater accuracy of the vertical dispersion parameterization of the particle model is combined with the advantage of an ever-expanding number of puffs to represent the pollutant distribution. The Hysplit system also includes a detailed deposition module which explicitly accounts for dry and wet deposition along with resuspension following WESLEY (1989) and WALMSLEY and WESLEY (1996), similar to the approach adopted in RADM (Regional Acid Deposition Model, CHANG, 1990). Additional information pertaining to the Hysplit modeling system can be found in DRAXLER and HESS (1997).

To determine a potential source region for eastern North Carolina, the 1997 estimated inorganic nitrogen deposition from nitrate and ammonia data available from the NADP/NTN was analyzed. Figure 2 shows the annual mean for 1997, with a local maximum in deposition over southeastern North Carolina. Based on this, a source region was considered centered over 35.1 N and 77.9 W, in our analysis. A constant unit emission (mass units per hour) was used to facilitate a qualitative analysis of transport/dispersion based on wind and thermodynamic patterns. The units in this case are considered unimportant, as output air concentration units will be the same as input units. Further, since a non-reactive tracer is considered in the transport and dispersion model, the actual concentration will be a direct function of the source strength. A 10-m surface layer was used for the first source column in the Hysplit system, and the analysis was performed over 0.3-degree (about 33-km) horizontal grid resolution. The deposition option was active in all the transport and concentration runs in this study.

Assessment is then made regarding the seasonal variation in mesoscale climate and its impacts on transport/dispersion, and potential deposition of surface emitted pollutant species in eastern North Carolina. An interesting point for applications related to extension and policy planners is the access available to the analysis and plotting system over the internet. The model can be run interactively on the internet or installed on a local computer through the READY system (http://www.arl.noaa.gov/READY). Thus the applied methodology has the additional benefit of facilitating future studies by research/academic personnel as well as local governments interested in policy and regulation planning.

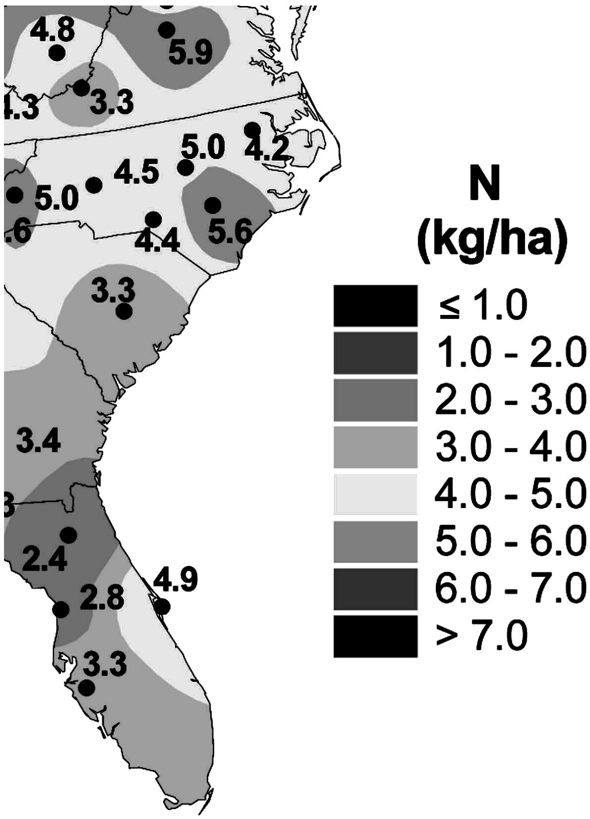

Figure 2
Observed inorganic nitrogen deposition for nitrate and ammonium for 1997 over North Carolina. Note the relatively high deposition values in southeast North Carolina.

3. Case Discussion

The meteorological setting for the three cases corresponding to the three seasons (winter, fall, and summer) are discussed in this section.

a) December 12–19

Winter in eastern North Carolina is characterized by land-sea gradients in temperature due primarily to the effects of the Gulf Stream on the coastal region. This area is a favored region for the formation of frontal boundaries that interact with synoptic scale patterns (RAMAN *et al.*, 1998). These boundaries can significantly affect the transport and deposition especially when superimposed with larger scale flow regimes. Winter flow patterns are unusual in comparison to the other seasons of interest and therefore concentrations and dispersion values may vary significantly.

Climatologically it is expected that the highest concentration values would be east of the source region since the mean winds are westerly over eastern North Carolina. However, eastern NC can be dominated by prolonged strong low-level northeasterly flows in the winter months due to a common pattern known as cold air damming (CAD). This pattern may typically occur 3–4 times per month during the winter season with a local peak during March (BELL and BOSART, 1988). Event duration may vary from hours to days. However, a local source of emission over southeastern NC would allow significant deviations in transport and deposition patterns in even the weakest and shortest CAD events. In addition, the strong static stability associated with this pattern and enhanced precipitation along coastal fronts can present near optimal conditions for enhanced local deposition fluxes.

The period December 12–19, 1998 was characterized by a CAD event. A cold dome of high pressure became entrenched over the mid-Atlantic on 12 December. Damming began during the day on the 12th as surface winds became increasingly northeast. Figure 3a shows the surface wind vectors overlaid with relative humidity (percentage) for this period. A convergence zone, typically associated with this pattern, is seen near the southeast Carolinas. A surface low formed over the northwestern Gulf of Mexico in response to an upper level trough over the

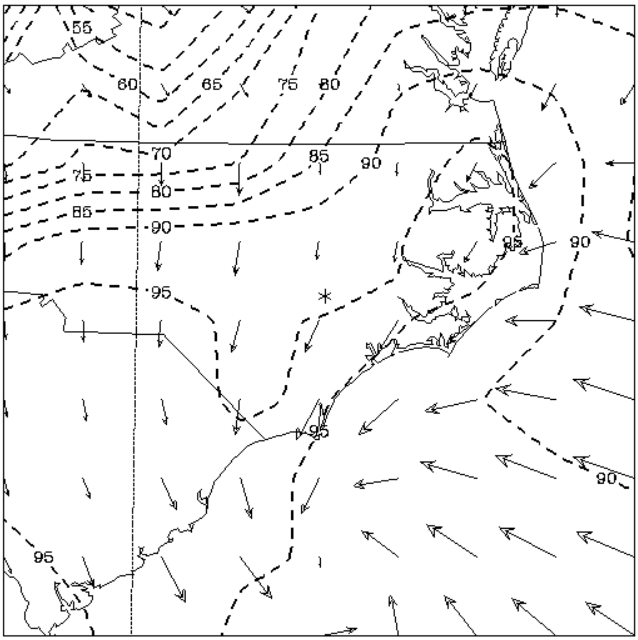

Figure 3a
00 UTC December 13, 1998 surface wind vectors (arrows) and relative humidity (dashed lines) for the study domain. A persistent northeasterly flow exists for this case. A convergence zone was also present which influenced local wind fields and transport.

central United States. The low strengthened as it interacted with strong baroclinicity along the mid-Atlantic coast. As shown in Figure 3b, rapid cyclogenesis occurred along the frontal boundary resulting in northwesterly flow over the domain and drainage of the cold dam near the end of the period. A strong anticyclone then moved over the region as the cyclone moved northeast and away from the domain. Resulting winds were light and variable. Thus the period from December 12–19, 1998 was characterized by the evolution of a common winter weather pattern in eastern North Carolina. The particular case demonstrated here was quite long and intense. A weaker and shorter case will be examined for the Fall in the following section.

b) October 5–11, 1998

Fall is characterized by an increasing southward invasion of Canadian air. Weak disturbances tend to move rapidly through the Carolinas. As a result, this season represents a somewhat dry period over eastern NC excepting landfalling tropical disturbances. Seasonally averaged winds are generally from the west, however flow patterns are highly variable depending on the frequency and strength of cold fronts passing through the region. Fall represents a period where high values of seasonally averaged wet deposition flux are less likely, but significant daily values are

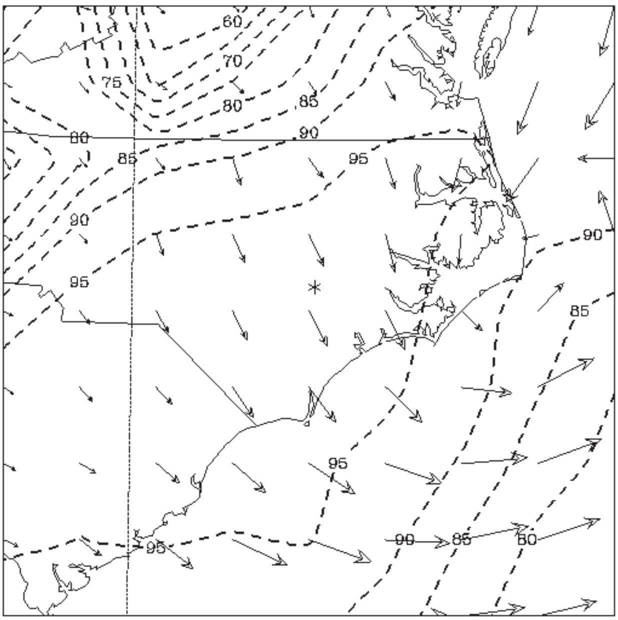

Figure 3b
Same as Figure 3a, except that the frontal boundary coincides with cyclogenesis that results in a northwesterly flow over the domain and drainage of the cold dam on December 13, 1998.

intermittently possible depending on local as well as diurnal scale interactions with larger scale forcing.

A strong anticyclone over New England dominated the first part of this period. The slow movement of this system allowed northeasterly flow to persist over eastern NC for several days. A strong disturbance and an associated cold front located in the central U.S. approached the region during the middle part of the case. Consequently, winds became increasingly southwesterly. Figure 4a shows the wind vectors and relative humidity variation over the domain for 8 October, 1998. Strong southerly flow dominates eastern North Carolina that changes to a more southwesterly flow ahead of the approaching cold front. Such low-level wind variations can cause significant changes in the pollutant transport and the resulting concentration patterns over the region. The cold front moved through the region and stalled off the coast. In addition, a series of weak surface lows formed and moved along the cold front. Figure 4b shows the frontal boundary slowly moving off the coast resulting north to northwest winds over the source region. This period, was thus characterized by highly variable flow patterns over eastern North Carolina as would be expected during Fall season. However, these daily variations are due primarily to rapidly evolving synoptic scale motions.

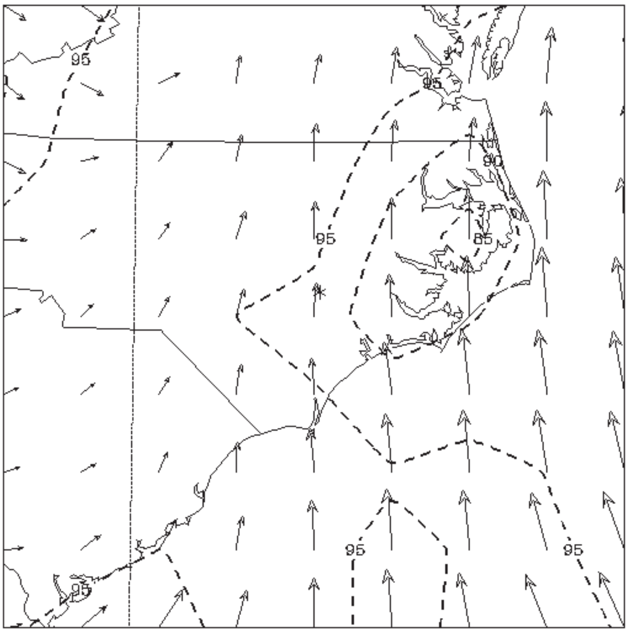

Figure 4a
Wind vectors and relative humidity variation (dashed lines) over the domain for 8 October, 1998. A strong southerly flow dominates the eastern North Carolina that changes to a southwesterly flow ahead of an approaching cold front.

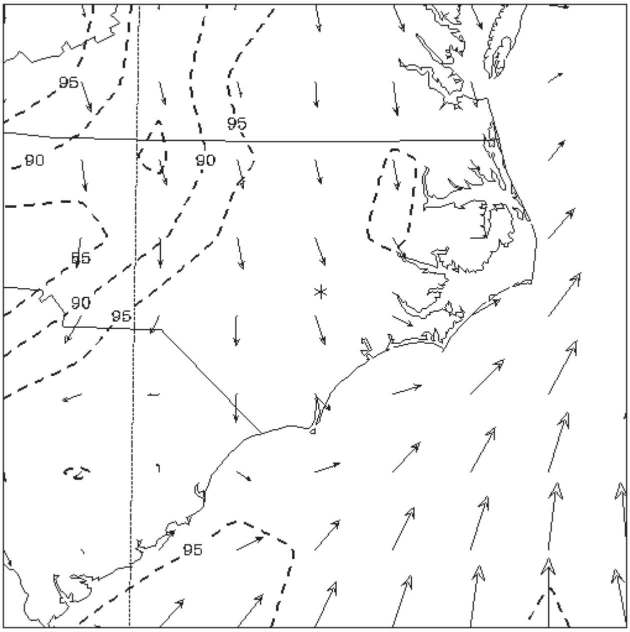

Figure 4b
Slow passage of the frontal boundary (shown in Fig. 4a) offshore resulting in northwest transport on October 8, 1998.

c) July 2–7, 1998

July is characterized by weak winds owing to decreased latitudinal temperature gradient. As a result, weather systems affecting the region are weak and slow moving. In addition, air masses originating from Canada usually make little southward progress and have limited effect on eastern North Carolina. The region becomes increasingly under the influence of a nearly permanent high-pressure system commonly known as the Bermuda High. South to southwesterly flow associated with this weather system can persist for several days. This flow regime favors the inland propagation of the diurnal sea breeze thus setting the stage for complex mesoscale circulations over eastern North Carolina. Blocking patterns are also more frequently observed during the summer months. Although summer is characterized by weak large-scale forcing, it represents the wettest time of the year (typically about 16 inches precipitation out of 48 inches annually, over the source region) due to the frequent occurrence of convection. In addition, mesoscale processes associated with land-sea interaction and physiological differences in soil characteristics can enhance convection over southeastern NC. Therefore, significant diurnal variation in transport and deposition of pollutants could exist. In addition, this season represents the best opportunity for potentially large daily deposition values due to a seasonal maximum in locally emitted nitrogen compounds and locally heavy rainfall associated with convection (cf., ANEJA *et al.*, 1997).

No significant synoptic scale weather events affected the region during the case period. A weak surface disturbance moved through the region and so significant daily variation in wind patterns existed. Figure 5 shows a case where northwesterly surface wind flow dominated the area, which would transport material over the ocean. Note also the large humidity gradient that parallels the coast in this flow regime. For the next day, as shown in Figure 6, there were southeasterly winds over the domain, which shift the moisture gradient inland. The pattern would favor transport over central portions of North Carolina with possible larger wet deposition values along the moisture gradient due to enhanced precipitation. The period July 2–7, 1998 was thus typical of summer conditions, characterized by highly variable flow conditions principally due to weak synoptic forcing leading to increasing importance of diurnal mesoscale circulations. Therefore, we will focus more on mesoscale processes and diurnal variations in the analysis for this period.

In summary, the three seasonal patterns examined here show distinct features and variability over the study domain (eastern North Carolina). In the following section, we will discuss how these patterns affect the distribution of model-simulated transport and deposition. Additionally, we also discuss the interaction between

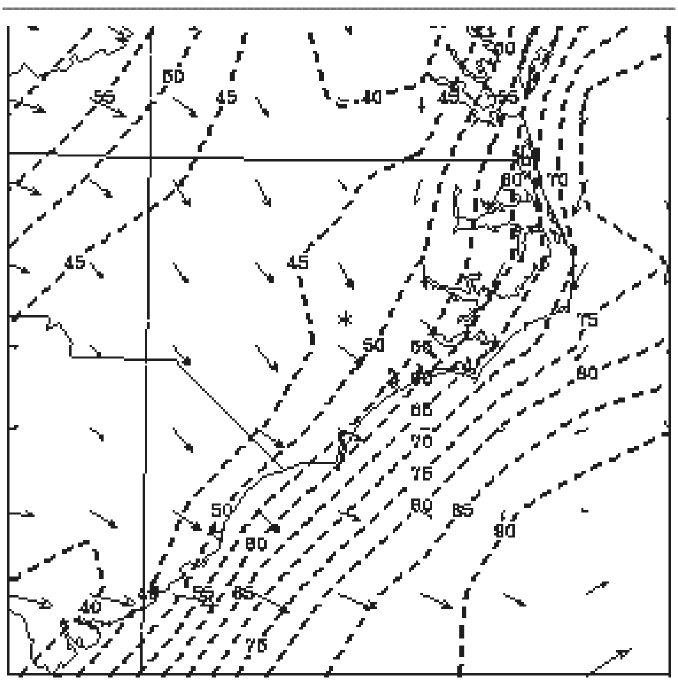

Figure 5
Strong offshore winds associated with a relative humidity gradient (dashed lines) parallel to the coast for 2–7 July 1998 case.

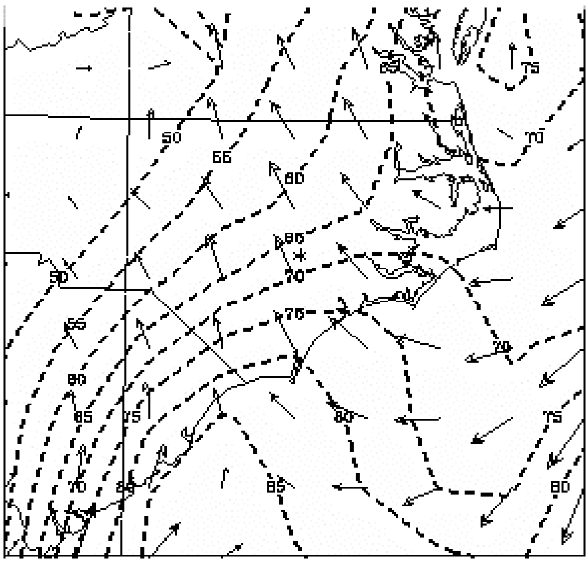

Figure 6
For the same case as in Figure 5, except that the surface winds show inland intrusion. The day-to-day shifting of the winds for the summertime scenario are significant source of uncertainty and variability for eastern North Carolina.

different scales of motions and the implications on transport/dispersion and deposition over eastern North Carolina.

4. Transport and Dispersion

The transport and dispersion patterns corresponding to the three cases discussed above are presented in this section.

a) December 12–19, 1998

This period encompasses the initiation, peak, and dissipation of a cold air damming pattern. In addition, cyclogenesis along the coastal front during this period allows analysis of the impacts of transport and deposition during rapid drainage of the dam as the winds back to the northwest. This period thus represents different potential patterns that could influence transport and deposition during the winter season. We will discuss implications on transport and deposition during the initiation, mature, and dissipation stages of the cold air-damming event.

Transport during the initiation was highly variable due to rapidly veering surface winds. However, some transport to the southwest was noted, as winds are predominately northeasterly (not shown). Cold air damming initiation is not always associated with precipitation and so wet deposition values are expected to be variable depending upon the individual cases. However, due to prevailing northeasterly flow often associated with this pattern, higher concentration values are expected to the southwest of the source. Therefore, the potential for larger wet deposition values is also to the southwest of the source region. In absence of wet deposition, the increasing static stability and a thermal inversion associated with this pattern could increase the potential for dry deposition velocities with unstressed surface conditions (PLEIM *et al.*, 1999). Trajectory analysis during this period shows that the parcel had limited vertical movement. Model results initialized on 00 UTC 12 December show transport to southwest increasing with time, as winds become more northeasterly. Figure 7 shows that concentration distribution patterns become parallel to the coast (streak-like). That is, the surface convergence associated with the developing surface front increases low-level concentrations along the front. However, the highest concentrations remain stagnated in southeastern North Carolina during the initial stage as shown in Figure 7.

As the cold dam reaches maturity, the pollutants are oriented to the southwest. Figure 8 shows a sharp eastward gradient in the concentration patterns while the westward gradient is weak. This pattern is likely due to unstable air east of the coastal front causing vertical diffusion, and stable air (thermal inversion) west of the boundary inhibiting vertical diffusion. Surface emissions such as nitrogenous gases

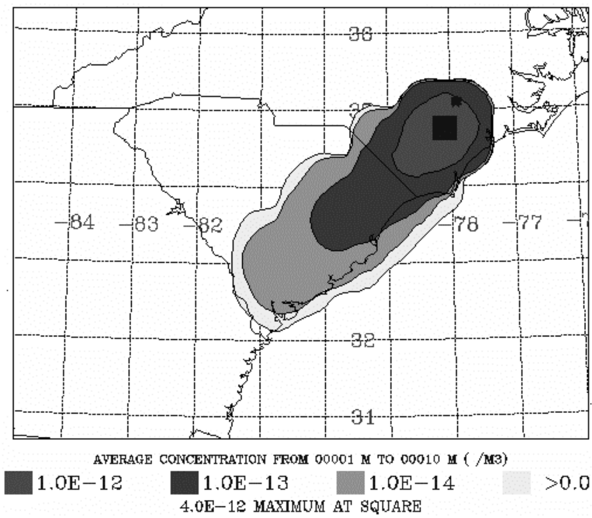

Figure 7
Concentration distribution for a ground-level source (closed square) in southeastern North Carolina from 24-hour model simulation for a wintertime scenario with a persistent northeastly flow beginning 00UTC December 12, 1998. Maximum concentration is shown at larger square just southwest of source region. Contour values are unit-less indicating mass units per cubic meter.

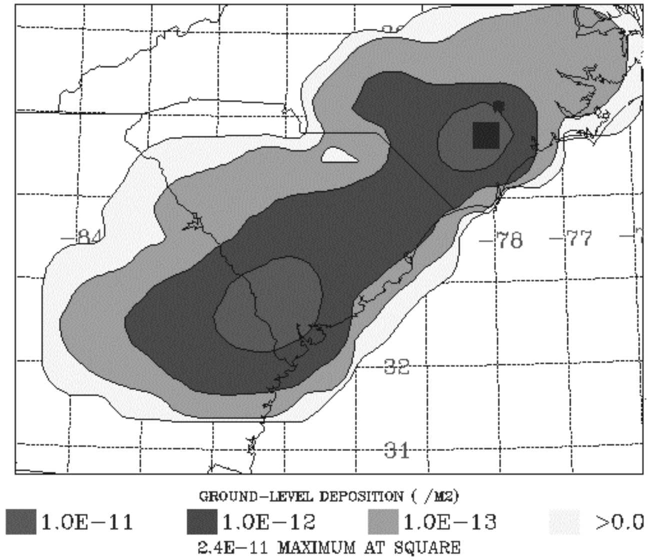

Figure 8
Same as in Figure 7 except the contours are for surface deposition. Note the local maxima in extreme southeastern North Carolina and along the South Carolina/Georgia border. Values are unit-less indicating mass units per cubic meter.

from the agricultural swine-lagoons in the eastern North Carolina can therefore be trapped in the low-level stable environment associated with the cold air dam. Such a winter case thus represents possible optimal conditions for long-range transport and deposition of chemical emitted in eastern North Carolina, to eastern South Carolina and Georgia as shown in Figure 8. Transport and deposition this far southwest of the source region is unlikely in other situations. Since upper-level winds are rarely oriented from the northeast during the winter, transport to the southwest must be governed by near-surface winds. Therefore surface winds need to be oriented from the northeast to facilitate pollutant transport to South Carolina and Georgia. The winter season appears to present the best opportunity for this type of near-surface wind pattern with a long duration.

As the pattern reached maturity, a weak surface low formed along the coastal front and moved rapidly out to sea. Pollutant concentration distribution patterns remained nearly uniform during this period. The only exception was the breakdown of the strong eastward gradient in concentration indicating that the low pressure associated with the front allowed some leakage through the front. However, the surface low was too weak and moved rapidly to initiate drainage of the dam and so the persistent flow regime and pollutant concentration distribution patterns remained similar for several additional days (not shown). However this pattern was eventually dissipated by a stronger cyclone along the coastal front which allowed the statically stable air to drain rapidly eastwards. In other such cold air damming cases, drainage may take several days as no significant synoptic forcing facilitates such dissipation. Thus pollutant concentrations can remain relatively high over eastern North Carolina even during winter. Additionally, such a meteorological setting can also be associated with light lingering precipitation, which can enhance regional wet deposition values. In this particular case, a low formed near the northern Florida coast and rapidly intensified as it encountered strong baroclinicity along the Carolina coast. However, initial northward movement of the surface low was slow and therefore initially enhanced the northeasterly flow over the area. The low deepened off the NC coast and drained the dam as it moved northeast. Resulting pollutant concentration patterns associated with this scenario are shown in Figure 9. Thus, during dissipation of the cold air dam, pollutant transport was primarily restricted to eastern and northeastern North Carolina. Pollutant transport towards the end of the event was also quite interesting as shown in Figure 10. As the low continued to move off the coast, the region began to be dominated by a strong migratory anticyclone. Higher concentration values remained almost entirely over eastern North Carolina due to weak steering currents as well as strong subsidence associated with the anticyclone. Precipitation is usually absent during such a pattern, thus reducing the wet deposition potential. However, since the period prior to this event is often

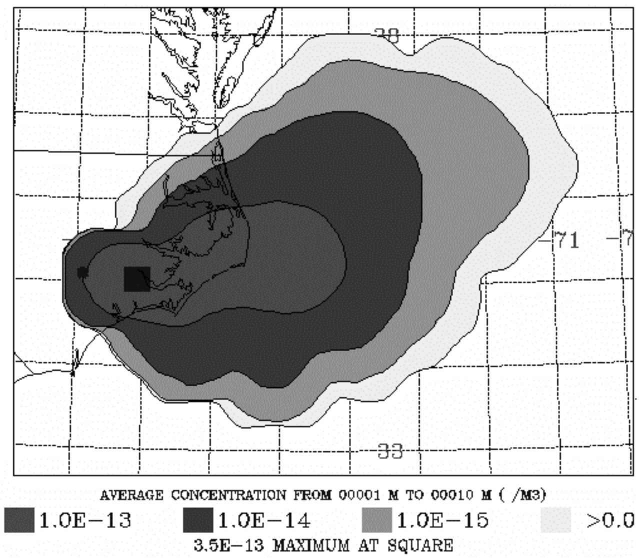

Figure 9
Concentration distribution for a ground-level source (small box) in southeastern North Carolina from 24-hour model simulation for a wintertime scenario beginning 00UTC December 17, 1998. Concentration pattern indicates rapid draining of the surface concentrations with the dissipation of the cold air damming pattern.

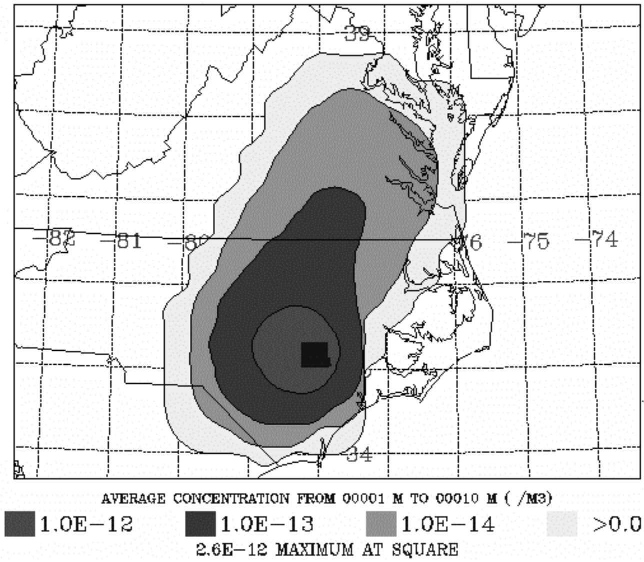

Figure 10
Same as in Figure 9 except 24-hour model simulation beginning 00UTC December 19, 1998 with the region being dominated by a anticyclone. Resulting winds are weak with highest concentration values remaining near the source region. Such a scenario can exhibit high-surface concentration and deposition possibilities for northern and central North Carolina.

marked by intermittent precipitation, the surface resistance for dry deposition is often the lowest (cf., Pleim *et al.*, 1999) and can lead to significantly high dry deposition values (cf., Finkelstein *et al.*, 2000; Niyogi *et al.*, 2000).

In summary, the persistent northeasterly flow associated with cold air damming over the mid-Atlantic appears to present optimal conditions for transport of surface emitted pollutants from sources in southeastern NC to portions of South Carolina and Georgia. This transport also appears to be sensitive to the duration of the event as strong static stability curtails vertical mixing and stronger upper-level winds are not generally oriented from the northeast. Therefore, it appears regions to the south and west of the source region (in southeastern North Carolina) can be vulnerable to higher concentration and deposition values during the winter season when cold air damming events are more frequent and strongest. Conversely, cyclogenesis along the southeastern United States coast appears to present the best opportunity for drainage of pollutants from eastern North Carolina, sweeping them off the coast. Alternatively, the presence of strong anticyclones over the southeastern United States will allow concentration to build in near the source regions.

A weaker and shorter case of the northeasterly flow regime described above is presented in next section for the Fall case.

b) October 5–11, 1998

For this case, as discussed earlier, an anticyclone situated over New England governs transport during the first part of the period. This establishes a prolonged northeasterly flow. This pattern is similar to the initialization stage of the cold air damming event mentioned above. However, a well-defined frontal boundary and associated surface convergence was not as evident as for the Winter case. The northeasterly flow does facilitate some transport south and west but, unlike the stronger cold air-damming event, long-range transport was not evident (not shown). The high pressure system slowly drifts offshore, and the winds veer to a more easterly southeasterly component. Figure 11 shows an inland surge of the plume that results as the high pressure system migrates offshore. For this scenario, high concentration buildup can be seen over northern South Carolina and the foothills of North Carolina as shown in Figure 11. However, this pattern of transport does not last long as the winds begin to veer to a southwesterly direction in response to an approaching cold front. The resulting concentration patterns show transport to north of the source region (not shown). The corresponding deposition pattern is shown in Figure 12. It will be generally dominated by wet deposition along and ahead of front because of precipitation. Note that significant deposition can be seen as far north as

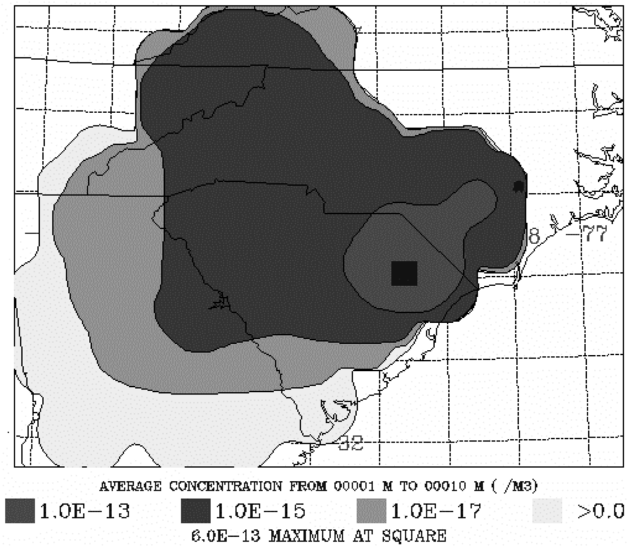

Figure 11
Concentration distribution for a ground-level source (small box) in southeastern North Carolina from 24-hour model simulation for a wintertime scenario beginning 00UTC October 6, 1998 indicating the transport resulting from a migratory high off the northeastern United States. Results delineate a scenario for which maximum concentration and deposition can be over extreme northern South Carolina and the foothills of North Carolina despite the source being in southeastern coastal NC.

the Chesapeake Bay area. With the approaching cold front, winds at the surface increase from the southwest thus enhancing the transport potential to the northeast of the source. In addition, enhanced static instability and vertical motions ahead of the front allow greater opportunity for the parcels to mix vertically and possibly escape the boundary layer. Such a scenario can lead to a greater potential for long-range transport. This is seen in the analyses of the deposition patterns shown in Figure 13. Significant ground-level deposition values are seen as far north as New England. As expected, the corresponding concentration values are much smaller as compared to the near-source values (not shown). Thus, the vertical mixing and stronger flow aloft represent near optimal conditions for long-range transport to the northeast. As the front passes through eastern North Carolina and stalls off the coast, winds over central and eastern North Carolina are primarily from the north and northeast while winds off the coast are much stronger and have a significant southerly component. The pollutant plume for this regime is now to the southeast of the source region representing a rapid change in transport (not shown). The enhanced surface convergence increases both surface pollutant concentrations as well as wet deposition potential along the front. Behind the front, winds are from the northwest and so transport is to the southeast. Concentration and deposition patterns contours become linearly oriented along the frontal boundary (not shown).

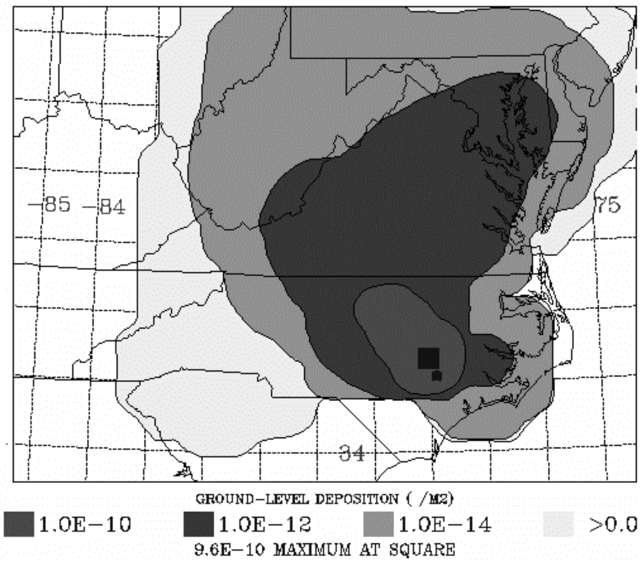

Figure 12
Ground-level deposition from 24-hour model simulation beginning 00UTC October 7, 1998. The highest deposition values have spread northward in association with veering winds ahead of an approaching cold front. Results suggests that higher concentration values and possible significant wet deposition values can affect almost entire North Carolina and points north for such a scenario.

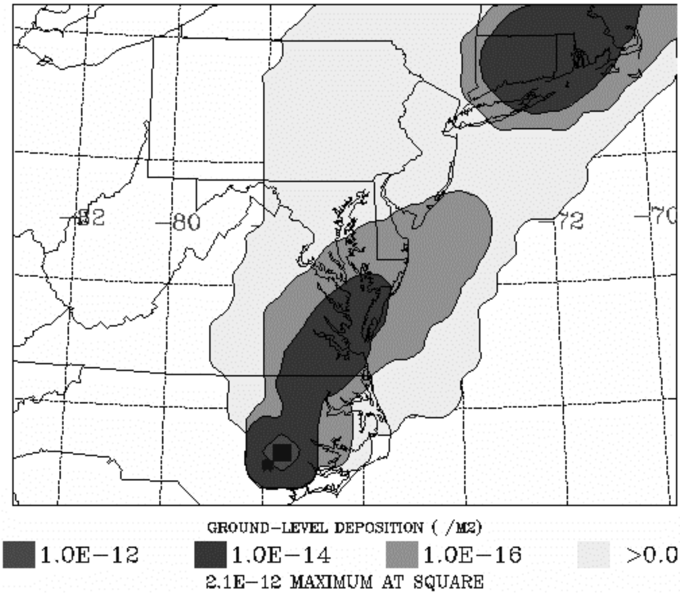

Figure 13
Same as in Figure 12 except from 24-hour model simulation beginning 00UTC. Scenario with a cold front to transport material even up to New England with the passage of cold front off NC coast.

This is primarily due to surface convergence and precipitation along the boundary. The front slowly moves offshore resulting in offshore transport.

Transport and deposition during the Fall season appears to be sensitive to the frequency and strength of cold frontal passage. In addition, precipitation ahead of and along the frontal boundary allows greater wet deposition potential. It also appears that the Fall season presents some potential for long-range transport and deposition of materials released in eastern North Carolina to points northeast of the source.

c) July 2–7, 1998

For the summer case, due to weak steering currents, significant long-range transport is unlikely and the pollutants are primarily confined to near source areas. During the first day of the period, transport is to the east with the strongest deposition values occurring along the coast as shown in Figure 14. In this regime significant wet deposition can occur in the event of convective precipitation. For day two, transport is more to the southeast as a weak low affects the surface wind pattern. Correspondingly, as shown in Figure 15, southeastern North Carolina and northeastern South Carolina show highest deposition potential. This pattern continues through day three. By day four of the period, as an effect of the Bermuda High, significant concentration values move due north of the source region. Such a

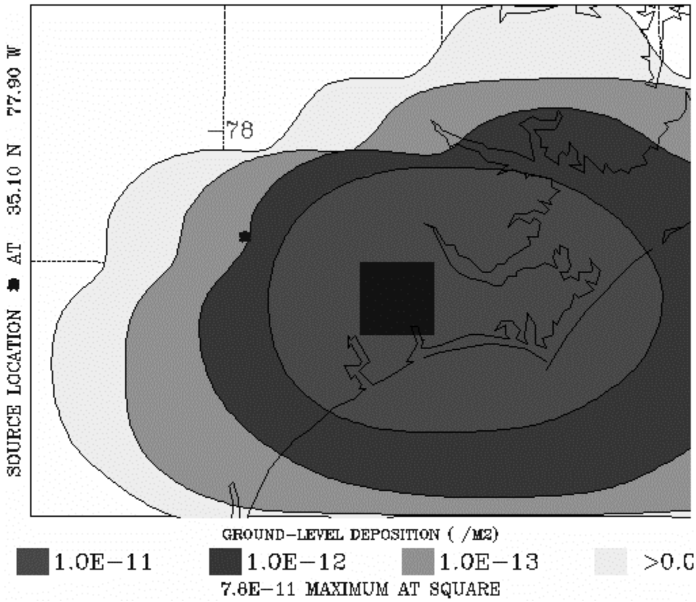

Figure 14
Ground-level deposition from 24-hour model simulation beginning 00UTC July 2, 1998. The source region is indicated by a small star with highest values indicated by a square. Transport under this regime is toward the southwest with high potential for significant wet deposition over extreme eastern North Carolina.

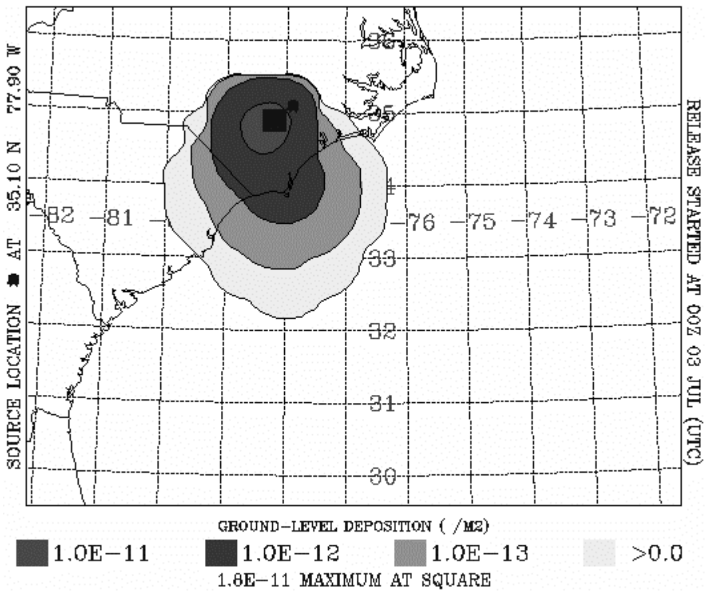

Figure 15
Same as in Figure 14 except from 24-hour model simulation beginning 00UTC July 3, 1998 for a summertime scenario providing peak concentrations in the southeast North Carolina region.

flow regime may persist for several days with uniform wind field leading to significant potential for concentration and deposition buildups over the region. However, the largest deposition values remain closer to the source region (Figure 16) as compared to the Fall case which can show similar southwesterly flow patterns (see Figure 13). This is due to several reasons. First, upper-level winds are typically weaker during the summer. Also, on a larger scale, strong subsidence associated with the Bermuda High may act to decrease the lifetime of the parcel above ground. This was evident in the trajectory analysis (not shown) as the parcels rapidly descended to the surface. The released material may be deposited and then re-emitted (see, for example, DRAXLER and HESS, 1997). This local deposition decreases the potential for long-range transport. As the pollutant moves further away from the source, concentrations are also significantly lowered due to dilution and mixing within the atmospheric boundary layer. Moreover, the summer boundary layer is typically deeper as compared to Fall. Another feature important for the summer condition is that the transport patterns often exhibit day-to-day variability in the concentration and deposition patterns. As seen in Figures 17a and 17b, there are distinct variations in the concentration values for 5 and 6 July. Figure 17a shows the pollutant deposition east and southeast of the source off the coast, while for the next day, the pollutant is

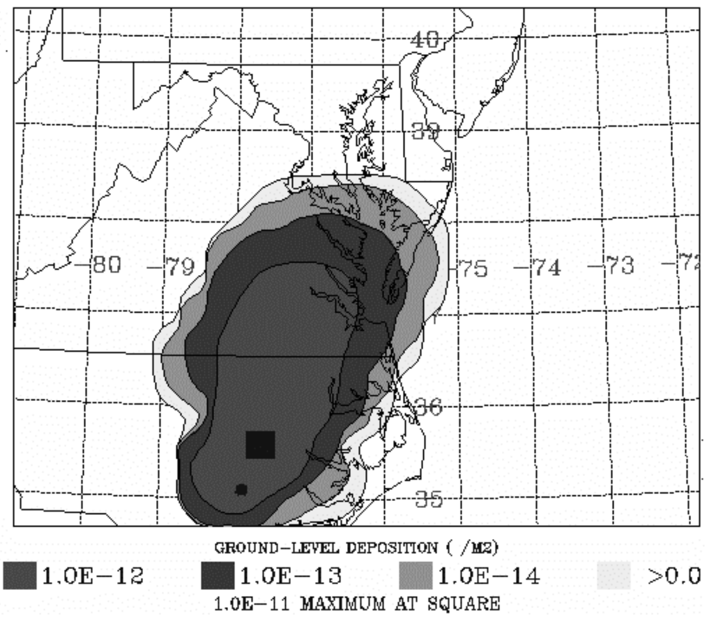

Figure 16
Same as in Figure 14 except from 24-hour model simulation beginning 00UTC July 4, 1998 representing transport and deposition dominated by the presence of the Bermuda High. The plume moves north of the source region possibly affecting southeastern Virginia.

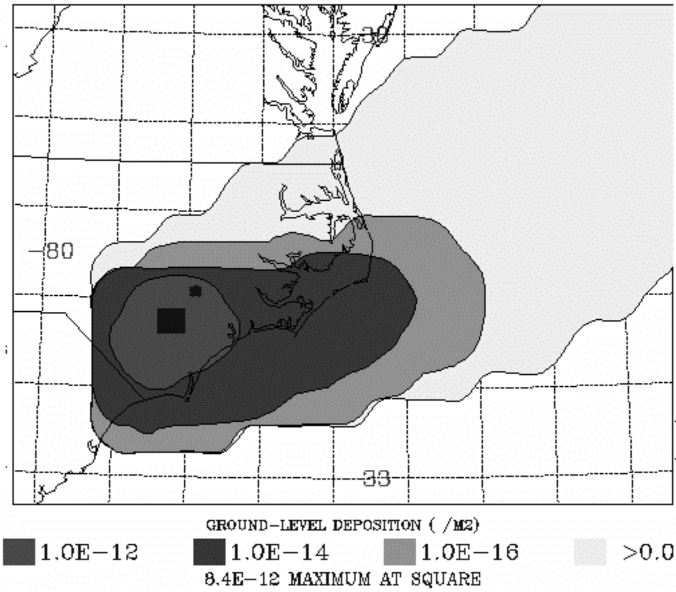

Figure 17a
Same as in Figure 14 except from 24-hour model simulation beginning 00UTC July 5, 1998. The plume is advected over portions of southeastern NC and southwest SC.

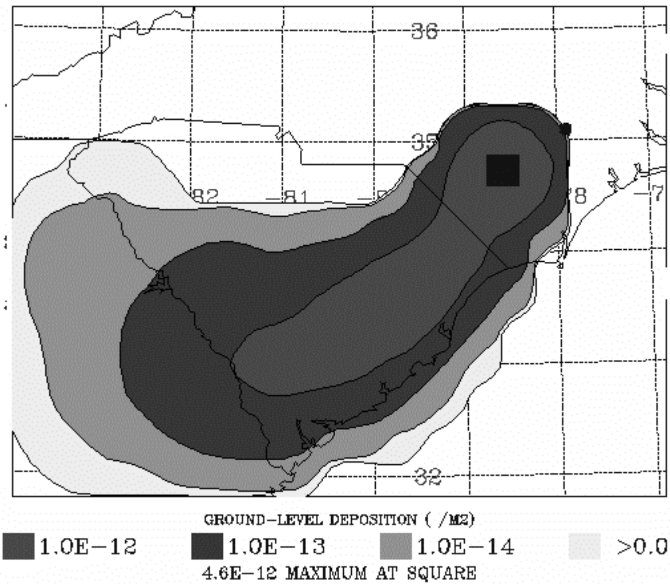

Figure 17b
Concentration distribution for a ground-level source (small box) in southeastern North Carolina from 24-hour model simulation beginning 00UTC July 6, 1998. Note the significant difference in patterns between Figure 17a despite only 24-hour difference in model initialization indicating that diurnal effects of the local forcings in the summertime scenario are dominant.

transported and deposited inland as shown in Figure 17b. Such a variation can be due to the interaction between large-scale winds and local land–sea breeze effects (and the return flow aloft) expected during the summer. This summer time land–sea breeze interaction along with the large-scale wind changes needs to be studied further. Thus the transport and dispersion associated with the summer scenario demonstrated significant day-to-day variability which can result in larger uncertainty for pollutant concentrations and deposition values over eastern North Carolina. These patterns, also appear to be sensitive to the track of weak surface disturbance that move through the region and to the location of the Bermuda High. Even though the wind field associated with the Bermuda High shows good temporal and spatial continuity, long-range transport is not likely due to weak upper-level winds and subsidence. Large concentration and deposition values are therefore typically restricted to near-source areas during the summer. Localized heavy rain associated with slow moving thunderstorms thus present the potential for significant localized nitrogen loading in eastern North Carolina.

5. Conclusions

This study assesses the potential for regional transport and deposition in eastern North Carolina for pollutant species such as reduced nitrogen typically emitted from agricultural sources. Using model analyses, mesoscale wind and thermodynamic patterns associated with three seasons are analyzed. Concentration and deposition patterns are then compared with respect to the wind and thermodynamic patterns during varying scenarios for the three periods.

Analysis shows there is a significant seasonal effect in the transport pattern over eastern North Carolina. There were distinct predominant or "climatological" wind patterns from different directions. However, in addition to the seasonal base flow, the study also identifies and highlights the role of local scale features such as coastal fronts and sea-breeze circulations interacting with large-scale events. Thus, a climatological analysis should consider the mean and the variance associated with the dispersion and deposition patterns, at the very least. Third, the analysis delineates significant day-to-day variability in the transport and deposition pattern especially during the summer case. All three case studies show these features to some extent in the outcome with summer (July case) demonstrating the largest variability. Additionally, it was shown that though seasons can be, in general, described by mean flow patterns, significant variations and dominant anomalous weather patterns inherently exist in this region, mandating a case by case analysis of the concentration and deposition patterns. With these interactions, there is also significant source of uncertainty and variability in the local scale concentration and deposition patterns. These uncertainties are compounded by the diurnal land-sea breeze cycle especially during the summer scenario when the background flow is weak.

In general, summer appears to present the best opportunity for significant local pollutant deposition. Weak winds, convection (often slow moving), and a seasonal peak in emissions may however, cause significant daily variability. Overall, Fall presented the best conditions for long-range transport and deposition. For all the three seasonal cases considered, in addition to the basal climatological flow pattern, day-to-day variations affect transport and deposition patterns in eastern North Carolina. Hence, analysis of seasonal means may not accurately depict this pattern, and more detailed weekly or daily analysis may be necessary to capture the regional pollutant loading.

One of the long-term goals of any pollution assessment study is to be able to develop a comprehensive budget of the atmospheric loading. In eastern North Carolina, for instance, such a budget would account for sources and sinks of nitrogen, and the associated uncertainty. To address this issue, the present study undertook the meteorological viewpoint pertinent to transport and regional deposition. Using routinely available observations and model results, an assessment is attempted. Although some general conclusions can be made regarding the vulnerability and uncertainty of the loading (source/sink) estimates, a budget was not possible. We believe interpretation of the local versus large-scale loading of nitrogen compounds over eastern North Carolina is still unresolved and needs to be addressed to help the task of assessing the regional budget.

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