NOTES TO ACCOMPANY A VIDEOCASSETTE OF COMPUTER-GENERATED MOVIES OF MESOSCALE ATMOSPHERIC FLOWS OVER COMPLEX TERRAIN

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1. OVERVIEW

The accompanying VHS videocassette contains copies of five short, computer-generated, 16-mm movies made by members of Professor Roger Pielke's mesoscale modeling group over the past decade. Two of the movies deal with mesoscale meteorological influences on the long-range transport and dispersion of air pollutants, two deal with air pollutant dispersion for sources located near elevated terrain, and one is concerned with wind power potential along sections of the U.S. East and Gulf Coasts. Total viewing time is approximately 24 minutes.

All five movies are based on numerical simulations made with a mesoscale meteorological model (MMM) originally developed for sea-breeze modeling (Pielke, 1974). This prognostic numerical model solves the hydrostatic primitive equations and includes a terrain-following vertical coordinate, short-wave and long-wave radiation parameterizations, a first-order turbulence closure scheme, and a multi-layer soil model (Mahrer and Pielke, 1977; McNider and Pielke, 1981; McCumber and Pielke, 1981). In the first four movies, atmospheric dispersion is modeled by using wind and temperature fields predicted by the meteorological model as input to a Lagrangian particle dispersion model (LPDM). This second model simulates atmospheric dispersion by releasing a large number of independent passive tracer particles either simultaneously or sequentially from one or more sources to represent an ensemble-average instantaneous (puff-type) or continuous (plume-type) release. A variety of source geometries – point, line, area, or volume – can be modeled. Individual tracer particles are advected using a combination of the resolved wind from the MMM and a stochastic subgrid-scale wind generated using a turbulence parameterization and MMM model-predicted fields (see McNider, 1981; McNider et al., 1980, 1982, 1988; Pielke, 1984; Moran, 1991). Brief summaries of each of the five films on this videocassette follow.

All of the movies were produced at the National Center for Atmospheric Research in Boulder, Colorado using NCAR's DICOMED Computer Output Microform system. The DICOMED film camera shoots individual film frames directly from plots drawn onto a graphics CRT screen. Since 16-mm film transport speed is 24 frames per second, 7200 plots are required for a five-minute movie. More information on NCAR's film-making facility may be found in Henderson (1982), Grotjohn and Chervin (1984), and Hansen (1985, 1988).

2. MOVIE SUMMARIES

2.1 Influence of Mesoscale Circulations on Pollutant Dispersion

Producers:	R.W. Arritt and M.D. Moran
Date:	February, 1986
Length:	4 minutes, 30 seconds
References:	Moran et al. (1986), Arritt (1988)
Sponsor:	Electric Power Research Institute

This first film shows the influence of two types of terrain-forced mesoscale atmospheric circulations on long-range pollutant transport and dispersion. In the first segment, mountain-valley winds modify the transport and dispersion of pollutant being carried from Ohio across the Appalachian Mountains to Virginia by northwesterly synoptic-scale flow. In the second segment, lake breezes and land breezes modify the synoptic-scale southward transport of pollutant from Ontario across Lake Ontario to New York and Pennsylvania.

Atmospheric transport and dispersion may also be described as the sum of *mean advection, differential advection*, and *turbulent diffusion*. Terrain-forced mesoscale circulations can deform pollutant clouds due to both vertical and horizontal wind shear (i.e., differential advection) and modify turbulent diffusion through shear and buoyancy effects (e.g., Moran et al., 1986; McNider et al., 1988; Moran, 1991).

Daytime upslope flows and nighttime downslope flows may act either to retard or enhance the transport wind depending upon height above the ground, slope orientation, and slope position relative to the pollutant mass. Similarly, the onshore low-level flow and offshore upper-level return flow associated with a sea breeze (reversed for a land breeze) can also modify the larger-scale transport wind. Formation of nighttime cold pools can prevent the pollutant from mixing down to the ground, as can the stable atmospheric layer just above a cold water surface. Daytime convergence over mountain ridges may result in enhanced vertical velocities and increased vertical dispersion. Similar venting can occur in a sea-breeze convergence zone.

In the first segment, a 2-D version of the MMM was run for a 700-km-wide, 7.5-km-high, NW-SE-oriented vertical cross section with 63 grid points in the horizontal and 23 vertical levels. Horizontal mesh size was 20 km in the NW two-thirds of the domain and 5 km in the SE one-third so as to better resolve the terrain features of the Shenandoah Valley region. Synoptic-scale flow was northwesterly at 2.5 m s^{-1} for this springtime case.

The LPDM source consisted of an array or lattice of 500 particles uniformly spaced (in model grid coordinates) over an area 200 m deep and 60 km wide located on the lefthand side of the domain. The instantaneous "volume" release occurred at sunset (1800 LST) and the particles were tracked for 24 hours. Shortly after release, deformation of the pollutant mass due to differential advection is apparent. The pollutant crosses *above* the first valley (west of the Alleghenies) due to pooling of cold, stably-stratified air in the valley bottom. After sunrise, particles disperse uniformly in the growing convective boundary layer (CBL), moving up and down much more rapidly due to the increased turbulence intensity. Local circulations produced by strong daytime upslope flows act to trap and recirculate some of the pollutant. Toward the end of the simulation, the atmosphere again begins to cool and stabilize as the sun sets, and particle movement is sharply reduced. See Segal et al. (1988a) for a related study.

In the second segment, the 2-D MMM was run for a N-S vertical cross section, 560 km wide and 6 km high, with 37 grid points in the horizontal and 22 vertical levels. Horizontal mesh size was 10 km in the interior but stretched to 40 km near the lateral boundaries. Synoptic flow was from the north at 2.5 m s^{-1} for this summertime case.

An array of 500 particles uniformly spaced (in model grid coordinates) over an area 1 km deep and 40 km wide on the north shore of Lake Ontario was released at 0815 LST and followed for 24 hours with the LPDM. The development of the CBL is evident as the pollutant puff begins to grow upwards. Differential advection also begins to play a role. The southward transport of pollutant is retarded at low levels by the onshore lake-breeze flow but is enhanced above 500 m or so by the offshore return flow. Mesoscale "venting" due to enhanced vertical motions at the lake-breeze front is also evident. As the pollutant mass begins to move over the lake, mesoscale subsidence carries pollutant downward. A few tracer particles can be seen to move northward (to the left) in the low-level onshore flow. The stable stratification above the cold lake surface reduces downward turbulent transport and results in a low-level 'clean' zone. This last feature has important implications for dry deposition in stable flows. Near the end of this segment, two turbulent "bursts" are evident just before sunrise over the south (right) shore. Related studies include Segal et al. (1982), Pielke et al. (1983), and Segal et al. (1988b).

2.2 Plume Transport by Low-Froude-Number Flow Over a Triangular Hill

Producer:	R.W. Arritt
Date:	1985
Length:	1 minute, 30 seconds
References:	Arritt (1985), Arritt et al. (1987)
Sponsor:	U.S. National Park Service

This short movie examines rotational and diabatic influences on pollutant transport over mesoscale terrain. It consists of four segments.

The first two segments show the influence of release height on pollutant transport over an idealized 2-D triangular ridge under low-Froude-number conditions. In this simulation, the 2-D version of the MMM was altered to omit a number of physical processes: Coriolis force, diabatic heating, surface frictional stress, and atmospheric turbulent mixing. Although neglect of these processes is unrealistic, this "free-slip" simulation permitted isolation of the contribution of atmospheric stratification to upstream blocking. The ridge height H was 1200 m and ridge half-height width a was 4 km. Upstream wind speed U was specified to be 3 m s^{-1}. The ambient Brunt-Väisälä frequency N was constant everywhere and equal to 0.01 s^{-1}, giving an external Froude number value Fr of 0.25, where $Fr = U/NH$.

The 2-D MMM computational domain was 70 km wide and 6.5 km deep. The upper 2 km were specified to be a viscous damping layer of the form described by Durran and Klemp (1983) in order to inhibit the downward reflection of wave energy into the model interior. Horizontal grid size was 1 km. Thirty vertical levels were used: 5 m, 10 m, 17.5 m, 27.5 m, 40 m, 60 m, 100m, 150 m, 250 m, 400 m, 600 m, 900 m, 1200 m, ..., 5700 m, 6000 m, and 6500 m. Model time step was 7 s.

Particles were released in the LPDM at two-minute intervals 12 km upwind of the base of the ridge. Two release heights are shown, $0.25H$ (first segment) and $0.75H$ (second segment). For $Fr = 0.25$, significant upstream blocking occurs even with free-slip boundary conditions. Tracer particles released at height $0.25H$ remain in the stagnant zone upstream of the ridge. However, particles released at height $0.75H$ lie above the stagnant zone for this Froude number regime and are carried over the ridge by the ambient flow.

The third and fourth segments of the movie show the impact of nocturnal slope flows on pollutant transport over a ridge. A full-physics version of the MMM was used for these simulations, including radiation, surface energy balance, Coriolis force, turbulent mixing, and surface friction. The ridge height was reduced to 200 m in order to raise the flow Froude number to 1.5. No upstream blocking (i.e., actual stagnation) occurs for Froude numbers greater than a critical value of unity but significant flow decelerations due to partial blocking can still occur in this Froude-number range. However, nocturnal drainage flows may occur on the windward slope even when no upstream blocking occurs. To show the impact of such flows, the MMM was first run with radiative cooling turned off, and then again with it turned on.

In the third segment, particles were released in the LPDM at regular intervals from 5 different heights upwind of the ridge after first running the MMM for 4 h as a form of dynamic initialization. No diabatic heating was present. As the flow fields were essentially in steady state by this time, particle trajectories can be equated to streamlines. All of the particles surmount the ridge, and the streamlines remain at nearly the same heights above the topography as those at which they were released. The effect of surface friction and partial blocking due to stable stratification is evident at low levels in the way particles released closest to the ground lag behind the others.

In the fourth segment, particles are again released at five heights but this time after four hours of simulated radiational cooling. A katabatic flow is well developed and nearly steady on the windward slope. The resulting streamlines obtained in the presence of thermal forcing are quite different from those produced by purely mechanical forcing. The low-level releases stagnate or pass close to the ridge surface due to the subsidence induced by the windward-slope drainage flow.

2.3 Numerical Simulation of Plume Behavior Near Terrain

Producer:	R.T. McNider
Date:	July, 1981
Length:	4 minutes, 30 seconds
References:	McNider (1981), McNider et al. (1982)
Sponsor:	U.S. Environmental Protection Agency

This early movie was made as part of a study of plume impingement in complex terrain. A 2-D version of the MMM was used in conjunction with the LPDM to explore the impact of nighttime drainage flows on plume behavior for an elevated pollutant source located close to the base of an idealized 2-D ridge. The model topography consisted of an 850-m-high N-S ridge with half width of 4.5 km. Model horizontal grid spacing was 0.5 km. The MMM run was started at sunset with a near adiabatic profile and a synoptic geostrophic wind of 2.5 m s^{-1} from the east (or right) blowing towards the ridge. A surface roughness value of 10 cm was used.

Westerly downslope flow developed soon after sunset on the east-facing (right) slope, opposing the larger-scale easterly flow. Near steady state was reached after one hour. The downslope flow extended up to a height of nearly 300 m AGL but the flow maximum occurred close to the surface at a height of 8 m.

"Puffs" of virtual tracer particles were released in the LPDM at a height of 300 m from a site 1 km to the east of the base of the ridge. Four releases were made in total, one at the start of the MMM simulation at sunset, one a half hour after sunset, one an hour after sunset, and one two hours after sunset. Each puff was followed for 1.2 hours. Two short movie segments are presented for each release. For the first release, the two segments are the same. For the second and third releases the first segment shows 10 km of the domain while the second segment is a "close-up" showing only 5 km of the domain. For the fourth release, the first segment shows a release at 300 m while the second segment shows a release at 600 m.

The behavior of the four releases is markedly different. In the first release, the pollutant puff is carried up and over the ridge by the ambient wind. The downslope flow was not a factor for this release as it had not had time to develop. In the case of the second release, however, only one half hour later, the presence of the drainage flow can be easily seen. Subsidence induced by the drainage flow carries particles down into the turbulent shear zone between the easterly ambient flow and the westerly drainage flow. The increased turbulence intensities arise from the destabilization of the vertical temperature profile by downslope advection and result in plume fumigation. Differential advection elongates the puff and most of the tracer particles are then carried back toward the source by the drainage flow. In the case of the third release, this mechanism is even more pronounced and very few particles reach the ridgetop. By the time of the fourth release, the drainage flow is so firmly established that it effectively counteracts the upslope ambient flow and reduces the horizontal transport to nearly zero. When the release height is increased to 600 m, however, much of the pollutant remains above the influence of the low-level drainage flow and is carried over the ridge by the background synoptic flow.

A major conclusion of this movie is that the dividing streamline hypothesis, which is based on values of ambient potential energy and kinetic energy, does not remain valid once other sources or sinks of energy such as thermal forcing come into play (see also Arritt et al., 1987).

2.4 Mesoscale Dispersion of the Chernobyl Radionuclide Plume

Producer:	M.D. Moran
Date:	February, 1987
Length:	8 minutes, 45 seconds
References:	Pielke et al. (1987a, 1988)
Sponsors:	Electric Power Research Institute, U.S. National Park Service, U.S. National Science Foundation.

This fourth movie shows an idealized 2-D simulation of the transport and diffusion of radionuclides emitted during the first 48 h of the 1986 Chernobyl accident. The intent of this simulation was to demonstrate the significant impact of terrain inhomogeneities and the diurnal cycle on the transport and dispersion of the radionuclide plume. Large-scale synoptic flow during this period was towards the northwest, carrying pollutants from the Ukraine across Byelorussia and the Baltic states to Sweden and Finland. Since the accident occurred in late April, Baltic sea surface temperatures were close to freezing. The presence of this large, cold body of water had two effects: air flowing over the Baltic was cooled so that downward turbulent mixing and dry deposition to the sea surface were reduced, and the strong thermal contrast between land and water drove a sea-breeze circulation on the southern Baltic coast.

The movie is divided into four segments. The first segment gives a brief introduction to and overview of the rest of the film. It should be pointed out that this simulation was made less than a year after the Chernobyl accident so that the values used for some simulation parameters such as pollutant release height were obtained by intelligent guesses rather than from onsite observations. This restriction combined with the assumption of steady, 2-D synoptic meteorology makes this an idealized simulation. However, the demonstration of mesoscale influences due to terrain inhomogeneities and the diurnal heating-cooling cycle is still valid. More recent information about the Chernobyl accident and real-data dispersion modeling may be found in articles by Albergel et al. (1988) and Wheeler (1988), among others.

The second segment shows 85 kPa and 50 kPa geopotential fields for Europe and western Asia at two times, the first about 90 minutes after the initial explosion and the second 48 h later. Geopotential contours (dm) are plotted as solid lines and cover the region from 30°N to 70°N and 0°E to 70°E. Gridded horizontal wind vectors for the same pressure levels are also plotted with 5° spacing. A background map of the area is plotted with light dotted lines. Finally, the diagonal SE-NW line from the Sea of Azov (46°N, 35.7°E) to SW Norway (62.3°N, 10°E) marks the 2-D meteorological model domain. In the MMM simulation, the background synoptic flow was assumed to be southeasterly, that is, parallel to this diagonal line, at all levels.

The third segment of the film shows the time evolution of four meteorological fields from the MMM simulation. The 2-D domain was 2280 km long with 40 km horizontal grid spacing. A telescoping grid with 22 levels extended to 6 km in the vertical. The background wind speed was 7.5 m s^{-1} from the southeast. The Baltic sea-surface temperature was assumed to be 5°C and uniform. The simulation started at 1000 LST on April 25, 1986, about 14.5 h before the initial explosion at Chernobyl, and continued for 64 h.

The first meteorological field shown is horizontal wind presented in vector form. The spacing of the terrain-following vertical levels is evident from this field. The location of the Baltic Sea is marked on the lower lefthand boundary by the zig-zag underline. The

Swedish coast lies on the lefthand side of the plot. The second field shown is the horizontal wind velocity component (m s^{-1}) parallel to the domain, that is, the southeasterly or northwesterly wind component. Dashed contours denote negative values, that is, flow from the right (southeast). The presence of a sea breeze on the southern Baltic coast during the daytime can be seen as this field evolves. The third meteorological field shown is the vertical velocity component (cm s^{-1}). Dashed contours denote negative or downward values. The sea-breeze circulation over the southern Baltic coast is evident in this field as well, (look for the side-by-side upward- and downward-moving columns near the southern Baltic coast). The fourth field in this segment is potential temperature (Kelvins). Several important features can be seen as the potential temperature field evolves. Daytime heating building the CBL over land is indicated by potential-temperature contours moving upwards. Nighttime stabilization near the ground due to long-wave radiational cooling is indicated by the multiplication of close-packed contours near the surface. The stable layer over the Baltic Sea shows little diurnal variation.

The fourth and final segment of the movie shows three 2-D projections of the Chernobyl radionuclide plume as it evolved during the first 48 h following the initial explosion in Reactor No. 4 at approximately 2230 GMT, April 25, 1986. Virtual tracer particles were released sequentially by the LPDM at a constant rate of 36 particles per hour starting at this time for 48 h. Particles were released from a fixed point 500 m above the ground. The choice of release height reflects the high temperatures (~2500°C) and positive exhaust gas buoyancy associated with the reactor graphite fire. The first projection, an XZ projection from the perspective of an observer in central Europe looking northeastward, gives a side view of the plume as it travels from the right side of the screen across the Baltic to Sweden. The release point is marked by an asterisk symbol. Initially, the elevated plume disperses little vertically due to the nighttime stable stratification. However, vertical mixing increases rapidly with the growth of the daytime CBL. The narrow elevated plume again appears 20 h or so after the start of the release followed again by daytime mixing.

In the second projection, a downward-looking XY plan view, the overall plume is seen to develop "wiggles" as it travels. These are likely due to the inertial oscillation of the mean transport wind (McNider et al., 1988; Moran et al., 1990; Moran, 1991). In addition, some pollutant splits off from the main plume due to nighttime decoupling of the near-surface layer from the layers above and subsequent differential advection. This same phenomenon occurs as the plume is transported across the Baltic, increasing the effective lateral plume diffusion. The last projection is a YZ projection from the perspective of an observer at Chernobyl looking downwind towards Sweden. At first, the pollutant plume exhibits little dispersion but then rapidly mixes both upward and downward due to the development of the daytime CBL. Low-level backing (i.e., counter-clockwise rotation) of the wind beginning 18 h or so after the start of the release causes the bottom of the pollutant column to shift to the left (southwest). This results in enhanced lateral dispersion when this low-level pollutant is mixed vertically the next day, 30 h after the start of the release. The leading edge of the plume reaches the Baltic Sea at about the same time.

2.5 Coastal Zone Wind Energy Studies

Producers: M. Garstang, R.A. Pielke, and J.W. Snow
Date: October, 1979
Length: 3 minutes, 15 seconds
References: Garstang et al. (1980), Segal et al. (1982), Pielke et al. (1987b)
Sponsor: U.S. Department of Energy

This movie is the earliest of the five movies on the videocassette. It was prepared as part of a study on the wind power potential of the U.S. East and Gulf Coasts. The study consisted of two parts, a synoptic climatological component and a mesoscale modeling component. Synoptic weather charts were first analyzed for a number of representative coastal stations to determine the frequency of occurrence of a set of synoptic patterns. The MMM was then run for a number of archetypal synoptic scenarios to examine coastal flow patterns. Results from two summertime model runs are shown in this movie, one of Appalachee Bay along the Florida Panhandle and one of Chesapeake Bay on the Atlantic seaboard.

The first segment shows the time evolution of 4-m level horizontal wind vectors above Appalachee Bay for a 3-D MMM run. Grid dimensions were 35 × 26 × 11 and horizontal grid spacing was 10 km. The model vertical levels were located at 4, 10, 30, 50, 100, 500, 1000, 2000, 3000, 4000, and 6000 m. The intersections of the 83°W, 84°W, and 85°W lines of longitude with the 29°N and 30°N lines of latitude are marked on the background base map. The simulation began at sunrise (0600 LST) and ran for 24 h. A morning sounding (1200 GMT) made at Tampa, Florida on July 28, 1963 was used to initialize the model. The background synoptic wind was taken to be 5 $\mathrm{m\,s^{-1}}$ from the east. Initial PBL height was 900 m. Water temperature was 29°F. Time of day is indicated by the position of a stylized sun symbol ($\odot$) for daytime or star symbol ($\star$) for nighttime moving from right to left (i.e., east to west) at the top of the screen.

Sea breezes develop all along the Florida coast during the day but are strongest along the N-S-oriented coastline on the right side of the domain where the large-scale flow is offshore. This behavior is consistent with Estoque's (1962) findings. At night, the horizontal wind fields over the water, which were strongly perturbed by the daytime sea-breeze development, exhibit inertial oscillations.

The second segment of the movie shows the 4-m level horizontal wind vector field from the Chesapeake Bay simulation. Grid dimensions were 30 × 35 × 11 and horizontal grid spacing was 10 km. The model vertical levels were the same as in the Appalachee Bay case. The intersections of the 75°W, 76°W, and 77°W lines of longitude with the 37°N, 38° N, and 39° N lines of latitude are marked on the background base map. The simulation began at sunrise (0600 LST) and continued for 24 h. The atmospheric sounding used to initialize the model was taken at Dulles Airport on August 9, 1975. The background geostrophic wind was taken to be 6 m s^{-1} from the west-northwest. Initial PBL height was 1500 m. Water temperatures were assumed uniform and equal to 22° C. The same sun and star symbols as in the first segment are used to indicate time of day.

During the day, sea breezes develop along the west side of the Chesapeake Bay and the east coast of the Delmarva (Delaware-Maryland-Virginia) peninsula. At night, the offshore horizontal winds can be seen to undergo inertial oscillations once the daytime forcing is cut off. See Segal et al. (1982) for details.

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