Model Evaluation of the Impact of Thermally Induced Valley Circulations in the Lake Powell Area on Long-Range Pollutant Transport

M. Segal, C.-H. Yu and R. A. Pielke

Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado

A numerical mesoscale model was used to simulate meteorological fields in the Lake Powell area during the summer, providing an input to a Lagrangian-type transport/dispersion model evaluation. The main objective of the study was to use these modeling tools in order to evaluate the local effect of thermally-induced circulations on large-scale transport of polluted air masses into that area. Results indicated a substantial modification of the transport characteristics due to the local terrain-forced circulations. Most noticeable are: (i) trapping of pollutants within the Lake Powell valley, (ii) upward and downward venting of pollutants in convergence/divergence zones associated with these circulations, and (iii) slowing of cross-valley transport as compared to equivalent situations involved with flat terrain.

study is designed specifically to provide an evaluation of modifications to long-range transport by mesoscale effects in that area during the summer using the modeling tools outlined in the next section. Generally, the impact of mesoscale thermally-induced circulations on long-range transport of a polluted air mass is unaddressed in the literature. Therefore, although the present study provides a specific evaluation for the Lake Powell area, it also provides some insight as to the related impact of valley circulations in the general case.

Modeling Aspects

A numerical mesoscale meteorological model was applied in a two-dimensional domain along a northwest-southeast cross section in the Lake Powell area (crossing through Page, Arizona; see Figure 1 for an illustration of the cross section location) as adopted in Yu and Pielke.² In this region, the terrain acquires a general two-dimensional symmetry (i.e., uniform terrain along the lake direction), thereby justifying using a two-dimensional model version for the preliminary study reported in this paper. The model computed meteorological fields are used as input for a Lagrangian particles scheme to predict their transport/dispersion.

Numerical Mesoscale Meteorological Modeling

The formulation of the numerical mesoscale model used in the present study is given in detail in Pielke,⁹ Mahrer and Pielke,¹⁰ and McNider and Pielke,¹¹ and also is summarized in Pielke.¹² The model was validated successfully in studies of mountain/valley thermally-induced flows similar to the situation considered in the present study (e.g., Segal *et al.*,¹³ McNider and Pielke,¹⁴ Abbs,¹⁵ among others).

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Observations in the Lake Powell area have indicated that a significant visibility impairment often exists in this area located in southern Utah and northern Arizona (a schematic illustration of the area is provided in Figure 1). Since several National Park areas within this region are mandated by federal legislation as Class I areas under the Prevention of Significant Deterioration (PSD) of the federal air quality program, considerable research effort has been devoted in recent years to understand the atmospheric processes affecting visibility in that area. Studies evaluating the potential contribution of local sources in the area to the visibility impairment is reported, for example, in Bluemental *et al.*,¹ and Yu and Pielke.² Most of the focus in recent years, however, has been directed to visibility oriented studies including evaluations of the impact of long-range transport of polluted air masses into the area during the summer. During the summer, a shallow thermal low dominates the lower atmosphere of the southwest United States (e.g., Tang and Rieter³). Studies reported, for example, by Pitchford,⁴ Macias,⁵ Fluchini *et al.*,⁶ Ashbaugh *et al.*⁷ suggest that southwest synoptic flow associated with that meteorological system may lead to the long-range transport of polluted air masses from southern California and southern Arizona into the

Lake Powell area. Also, these studies suggested situations involved with southeast synoptic flow advecting polluted air into the Lake Powell area from New Mexico and Texas. This second common transport situation is associated with flow around the west side of a subtropical ridge which is situated to the east of the thermal heat low.

All of the transport studies in this region, however, have been based on observed synoptic wind data. The temporal and spatial resolution of such data is typically insufficient to evaluate the impact of mesoscale generated circulations (i.e., mountain/valley flows with typical horizontal scales of less than several hundred kilometers) on the large-scale transport. Therefore, in those studies, the transport modification of a pollutant mass by mesoscale circulations were not considered. Also in those studies, turbulence processes were not considered. Hence, while these synoptic transport evaluations provide bulk information concerning air movement over mesoscale domains, additional evaluations are required when thermally-induced circulations exist along the path of the pollution (see, for example, Pielke *et al.*,⁸ for a detailed evaluation and discussion of this aspect).

The Lake Powell area, which is located in the Colorado River basin, is affected by valley-induced circulations. Our

Figure 1. Illustration of the Lake Powell area. The simulated cross-section is indicated by the line *ab*.

The terrain cross section used for the simulations, which consists of elevation variations larger than 1000 m, is illustrated in Figure 2. The meteorological conditions simulated reflect July conditions in that area. Table I provides the general information related to the meteorological model simulations. Two background flow situations were simulated: 1) southeast synoptic flow of 2.5 ms^{-1} (i.e., crossing the valley perpendicularly) as a background flow; and 2) southwest synoptic flow of 2.5 ms^{-1} (i.e., along-valley direction).

Transport/Dispersion Modeling

Using the wind and turbulence fields computed by the meteorological model, a Lagrangian approach is applied to evaluate the transport and dispersion of pollutants. This dispersion and transport considers both the synoptic and mesoscale (i.e., valley circulation) flows. The detailed formulation is given in McNider¹⁶ and described also in Pielke *et al.*,¹⁷ and McNider *et al.*¹⁸; thus, it is outlined in this paper only briefly. The model consists of tracking a release of a large number of particles representing a pollutant air mass advected and diffused, in the general case of a three-dimensional domain, using the formulation:

$$x_i(t + \delta t) = x_i(t) + [u_i(t) + u'_i(t)] \delta t$$

$$i = 1, 2, 3 \quad (1)$$

where $x_i(t)$ is the old x , y , and z position of a particle and $x_i(t + \delta t)$ is its position following time interval δt (in the present study $\delta t = 20 \text{ sec}$); u_i are the u , v , and w velocities computed by the

meteorological model and u'_i are turbulence velocity fluctuations parameterized statistically based on the meteorological model boundary layer predictions.

The turbulence velocities are provided by the relation:

$$u'_i(t) = u'_i(t - \delta t)R(\delta t) + u''_i$$

$$i = 1, 2, 3 \quad (2)$$

where $R(\delta t)$ is the Lagrangian autocorrelation function at time lag δt and u''_i is a random component with a Gaussian distribution of zero mean and variance defined by the local turbulence variance. A validation of the scheme is reported in McNider¹⁶ and McNider *et al.*¹⁸

A set of transport simulations as outlined in Table II were carried out. In the cross-valley (i.e., southeast) synoptic flow situations, a volume of pollutant, represented by particles, was located initially at the southeastern boundary of the simulated domain. Its

initial height was 600 m and its horizontal extent 15 km. The volume was differentiated graphically into three layers indicated by α (bottom layer); β (the medium layer); and γ (the upper layer) as illustrated in Figure 4a. Transport simulations for this situation are listed in Table II (Cases 1–4). They consist of a release of the volume at various hours of the day with and without turbulent effects. This cross-valley simulation provides an illustration for situations involved with pollutant air transport to the Lake Powell area from New Mexico and Texas.

The second situation reflects a southwest synoptic flow of 2.5 ms^{-1} (i.e., along the valley direction). Particles were released in this case from the middle of the valley as illustrated in Figure 9a. The particles volume had an initial horizontal extent of 30 km and depth of 600 m. The simulated transport cases for this situation are listed as Cases 5–7 in Table II. These cases provide an illustration for situations involved with pollutant air transport into the Lake Powell area from the direction of southern California.

The pollutant mass as represented by the particles was assumed in both simulations to be initially horizontally uniform in order to represent long-range transport into the region without mesoscale or turbulent dispersion upstream. This was done so that the influence of the mesoscale and turbulent flows in the Lake Powell area could be best visualized. In reality in both simulated cases, it is expected that intervening complex terrain between the source and the Lake Powell area would substantially influence the dispersion and transport in a similar manner as occurs within the Lake Powell area itself.

Simulation Results

Cross-Valley Synoptic Flow— Meteorological Fields

Representative meteorological fields in the simulated cross section for the

Table I. Input parameters for the meteorological model.

Simulated domain top—9600 m
Lowest terrain height within the simulated domain—~1300 m ASL
Domain horizontal extent—150 km
Model horizontal grid interval—5 km
Integration time step—60 sec
Model vertical number of levels—28
Simulation start hour—2100 LST
Solar declination for the simulated day—July 10
Initial boundary layer depth—250 m
Initial potential temperature lapse rate $\partial\theta/\partial z$:
a) 0 K/1000 m for $z \leq 250 \text{ m}$
b) 2 K/1000 m for $250 < z \leq 2450 \text{ m}$
c) 4 K/1000 m for $2450 < z \leq 9600 \text{ m}$
Latitude—37°

Figure 2. Representative meteorological fields for the cross-valley transport cases (southeasterly synoptic flow) for the simulated vertical cross section, for nighttime (0500 LST) and daytime (1400 LST); (a) and (b): u component of the wind (cross-valley) is given in ms^{-1} ; dashed contours as well as shaded sections indicate negative values of u (southeasterly flow); (c) and (d): vertical velocities (cm s^{-1}); dashed contours as well as shaded sections indicate negative values of vertical velocities (subsidence); (e) and (f): potential temperature (K).

nighttime (0500 LST) and the daytime (at 1400 LST) are given in Figure 2. The geostrophic flow is southeasterly with a wind speed of 2.5 ms^{-1} , as indicated in Figure 2a.

At the end of the nocturnal period, drainage flow is indicated to be shallow with speeds of several ms^{-1} (Figure 2a). The synoptic flow is perturbed only slightly at the valley top due to terrain dynamic effects and interaction with the valley thermally-induced circulation. A shallow layer with downward vertical velocities is modeled along the slopes as shown in Figure 2c (note that dashed contours as well as shaded sections in all the presented figures reflect negative vertical velocity values). The potential temperature field (Figure 2e) consists of a shallow, relatively cool surface-based inversion layer along the

slopes which deepens toward the valley bottom where the turbulence is reduced.

The daytime meteorological features are presented for 1400 LST when the thermally-induced valley circulation is

around its peak. Upslope thermally-induced flows are somewhat less intense along the southeastern slope than those along the western slope (Figure 2b), which is attributed to a steeper western slope as well as the coupling of the upslope flows with an opposing synoptic flow along the southeastern slope. A significant feature in the flow field is the intensification of the flow aloft over the southeastern slope due to the return flow centered at about 3 km in Figure 2b which was caused in response to the low level upslope flows (the flow intensification aloft to a peak wind speed of around 7 ms^{-1} is caused by a superposition of the return circulation and the southeast synoptic flow at that altitude). The horizontal convergence due to the coupling between the synoptic and thermally-forced flows along the southeastern slope is noticeable in the vertical velocity features (Figure 2d). Sinking of air over the middle of the valley involved with the upslope circulations is also pronounced. The potential temperature contours (Figure 2f) indicate the daytime depth of the boundary layer (mixing depth). An upward orientation of the contours is associated with the near-neutral thermal stratification which is typical for that layer. The boundary layer depth, as indicated by the temperature structure, is around 2–2.5 km for the presented hour. Finally, it is worth noting that the details of the near-ground wind and temperature structure are not evident in the figure because of the vertical resolution used in the plots.

Cross-Valley Flow—Pollutant Transport

Four illustrations of transport features are provided for this situation. Three releases in the morning hours and one in the evening, including a case in which turbulence effects were ignored, are shown.

Figure 3 provides the dispersion feature involved with a 0900 LST release (Case 1). The volume of the particles is located initially at the eastern boundary (see Figure 4a) of the domain with a depth of 600 m and a horizontal extent of three grid intervals (15 km). The vol-

Table II. List of transport case studies. u indicates horizontal advection is included; w indicates vertical advection is included; T indicates turbulence is included.

Case	Release hour (LST)	Release location	Forcing	Figure No.
<i>Cross-valley transport</i>				
1	0900	Southeast boundary	u, w	3
2	0500	Southeast boundary	u, w, T	4
3	1100	Southeast boundary	u, w, T	5
4	2100	Southeast boundary	u, w, T	6
<i>Along-valley transport</i>				
5	0500	Middle of valley	u, w	8
6	0500	Middle of valley	u, w, T	9
7	2100	Middle of valley	u, w, T	10

Figure 3. Features of pollutant particles dispersion at several selected hours for a release at 0900 LST. Southeasterly synoptic flow; only advection is considered (Case 1).

ume is differentiated graphically into three layers, enabling an evaluation of the mesoscale impact on each layer separately. The particles are advected by the u (cross-valley wind component) and w (wind vertical velocity) with the turbulent contributions ignored (i.e., $u' = w' = 0$). The motivation for this simulation is the evaluation of the importance of the advection processes as compared to the turbulence processes in the studied cases. This objective can be accomplished by a comparison of the dispersion features presented for Case 1 with those obtained in the cases in which turbulence is considered. By 1200 LST the simulated pollutant mass is vented upward intensely in the convergence zone. By 1500 LST upward venting within the convergence zone is involved with the α layer particles, while the β and γ layer particles, which had been advected to the middle of the valley are sinking in the downward vertical velocities there. By 1800 LST the α layer particles also become trapped in the sinking motion, with the β and γ particles located at the low elevations of the valley as a result of the downward venting. Affected by the final stage of the daytime upslope circulation, the sinking particles were advected westward, while the β and γ particles were advected eastward and vented up the western edge of the convergence zone. As the nocturnal circulation is established following sunset, the particles effected by the reversal in the valley flow and their interaction with the synoptic flow, result toward the end of the night in the particle distribution shown for 0300 LST in Figure 3d.

Case 2 is equivalent to Case 1 except

for the incorporation of turbulence, and particles were released at 0500 LST (Figure 4). By 1100 LST the particles were advected somewhat down slope. The strong vertical mixing within the boundary layer is pronounced; however, the vertical velocity impact illustrated in Case 1 is still noticeable in the particle distributions. At 1700 LST the particles become mixed within the deeper boundary layer along both

slopes; however, the southeastern portion is somewhat deeper as this region is affected by upward venting within the convergence zone. The synoptic flow over the shallow drainage flow during the night causes the pollutant mass to reduce its depth and to be advected gradually out of the domain as illustrated in Figure 4d.

Case 3 is the same as Case 2 except the release of the particles was at 1100 LST; thus, the impact of the daytime valley circulation in this case would appear immediately following the release. By 1400 (Figure 5a) the particles were advected somewhat in the downslope direction. The mass is noticeably affected by the upward and downward velocities at the slope convergence location and the mid-valley divergence zone following the patterns illustrated in Figure 3. It is worth pointing out that the sinking motion above the valley causes the particles aloft to be vented downward, otherwise, particles may not have been trapped within the valley. The dominance of the convergence/divergence effects leads by 1700 LST to a division of the mass into two branches (Figure 5b). Similar nocturnal features shown in Case 2 are also obtained for this case, while the mass is advected gradually toward the northwest and out of the domain (Figure 5c,d).

Case 4 is the same as Cases 2 and 3; however, particles are released at 2100 LST (Figure 6). By 0600 LST the presented particle distribution had been established mostly due to horizontal

Figure 4. Features of pollutant particles dispersion at several selected hours for a release at 0500 LST. Southeasterly synoptic flow; advection and turbulence are considered (Case 2).

Figure 5. Features of pollutant particles dispersion at several selected hours for a release at 1100 LST. Southeasterly synoptic flow; advection and turbulence are considered (Case 3).

and vertical transport (as diffusion by the nocturnal turbulence is small). Venting upwards of the α particles due to flow convergence at the bottom of the valley occurred, while the β and γ layers largely conserve their initial configuration by that hour. At 0900 LST (Figure 6b) vertical mixing mostly affects the α and β layers, which still maintain a noticeable differentiation from the γ layer particles. By 1200 LST vertical mixing affects all layers; however, the γ particles, which during the earlier hours were advected faster, are at the front of the advected polluted mass, toward the northwest boundary. The α and β particles being trapped in the valley are affected by thermally-induced winds from both slopes at this hour. Significant advection of the pollutant mass during the next hours is evident by the pollutant distribution at 2100 LST. By that hour the γ particles had been advected out of the domain, while some of the α and β particles were still trapped in the valley.

Along-Valley Flow—Meteorological Fields

A geostrophic wind of 2.5 ms^{-1} along the valley direction (i.e., southwest synoptic flow) is considered in this section. A small contribution of the synoptic flow to a cross-valley component occurred in the boundary layer (i.e., due to Ekman wind turning); however, the cross-slope wind component is primarily

induced by thermal effects. The simulation began around sunset. Since in this case the synoptic flow is along valley, unlike the previous simulation, the nighttime and daytime thermally induced cross valley winds are anticipated to be altered only slightly by the synoptic along-valley flow.

The meteorological fields at 0500 LST (providing an illustration of the

meteorological fields at night), are illustrated in Figure 7. Shallow drainage flow layers are evident from Figures 7a,c. Similar to the previous case study (i.e., the cross-valley simulation), a shallow nocturnal surface inversion also occurs (Figure 7e).

By 1400 LST a classical thermally-induced circulation had developed along both slopes as evident by the u component wind distribution (Figure 7b). The vertical velocity pattern (Figure 7d) illustrates the vertical branch of the mesoscale circulation. The characteristics of the potential temperature (Figure 7f) are similar to those reported for the cross-valley synoptic flow case study.

Along-Valley Flow—Pollutant Transport

In this situation a volume of particles is initially located in the lower elevation of the valley. It might reflect a portion of a larger volume covering the valley. Since the synoptic flow is southwesterly (i.e., along the valley), its impact on cross-valley transport is minor as pointed out previously. Therefore, only the development of cross-valley thermal flows, in addition to turbulence, are expected to cause an alteration in the spatial distribution of the particles in the cross-valley direction.

In the along-valley synoptic flow, the initial location of the pollutant mass is indicated in Figure 9a. Figure 8 presents the development involved with Case 5 where negligible vertical velocity is simulated with a 0500 LST release. At 0800 LST the α and β layers were most noticeably affected as the upslope flows began. By 1400 LST most of the α

Figure 6. Features of pollutant particles dispersion at several selected hours for a release at 2100 LST. Southeasterly synoptic flow; advection and turbulence are considered (Case 4).

Figure 7. The same as Figure 1 except for the along-valley synoptic transport case (southwesterly synoptic flow).

particles were advected toward the boundaries of the domain, but were decelerating in the east, at the convergence zone. The α layer particles were affected by a less intense upslope and their advection toward the boundaries was slower.

Figure 9 presents a time sequence for Case 6 of the alteration of mass (initially released at 0500 LST) including diffusion by turbulence processes which should cause alterations in the basic features as obtained in the previous case. Following 9 hours from the release (Figure 9b), the development of upslope flows and a well mixed layer were evident by the generation of two separate and well mixed pollutant volumes along the slopes. The α , β and γ layer particles were vertically well mixed up to an elevation of about 2.5 km above the valley bottom. Additional impact of the daytime upslope on the particle distribution was seen at 1700 LST. It consists of the generation of a relatively clear at-

mosphere at the valley bottom, as well as the advection of some of the particles out of the domain, mostly from the western boundary where the upslope flows were stronger. In the nocturnal period, relatively strong but shallow drainage flow was capped by a deep but light reversal flow aloft. This led to a

trapping of the pollutant mass over the valley 24 hours following the release (0500 LST second day).

For Case 7, where the release was at 2100 LST, the particular redistribution following 12 hours (0900 LST) is illustrated in Figure 10a. By that time the development of boundary layer vertical mixing and upslope flows were noticeable in the redistribution of the particles. Following an additional 12 hours (2100 LST), the vertically well mixed particles over the valley were similar to those obtained in Case 6 by that hour (Figure 9).

Summary and Conclusions

Two cases of the influence of meso-scale circulation on long range transport that are likely to be involved with the Lake Powell area during the summer were evaluated using a modeling tool. Pollutant mass was represented by particles which were differentiated graphically into three layers (α , β , γ) enabling a more detailed evaluation as to the transport features in each layer. The simulations provide insight as to the impact of valley thermal circulations and dynamic effects in that area on long-range transport. The results also illustrate expected influences on long-range transport of thermally- and dynamically-forced mesoscale flows associated with complex terrain in general. Additional work, of course, is needed to quantify the influence of such characteristics, such as the aspect ratio of the valley, synoptic flow intensity and atmospheric stability (or the Froude number) on the modification of synoptic long-range transport. Three-dimensional simulations of the Lake Powell area, and other geographic regions which incorporate both meso-scale and synoptic influences, and turbulence effects are, of course, needed. Nonetheless, the two-dimensional simulations presented here demonstrate the expected major importance of meso-scale and turbulence effects on long-range transport across complex terrain.

The main conclusions of the present

Figure 8. Features of pollutant particle dispersion at two selected hours for a release at 0500 LST. Southwesterly synoptic flow; only advection is considered (Case 5).

Figure 9. Features of pollutant particle dispersion at several selected hours for a release at 0500 LST. Southwesterly synoptic flow; advection and turbulence are considered (Case 6).

study relevant to long-range transport to the area are:

- Pollutants advected into the Lake Powell area by summer day southeast synoptic flow (i.e., a cross-valley large-scale wind) for the daytime releases were trapped for the simulated period (~ 24 h) in the valley.
- Nighttime releases involved with cross-valley synoptic flow, although trapped in the valley, were transported out of the valley eventually (particularly the elevated polluted layers).
- Vertical and horizontal dilution of the pollution due to the induced thermal circulations distinguish it from the common and simple case of advection along flat terrain. Consequently, as outlined previously, acceleration and deceleration of their center of mass result. With a synoptic flow of 2.5 ms^{-1} and a domain of horizontal extent of 150 km as in the present study, with flat terrain and no mesoscale effects, the pollutants mass would have crossed the entire domain within about 16 hours. This rate of progress is faster than found for the various cross-valley wind cases (i.e., southeasterly wind transport).
- In the cases involved with pollutant mass transport within the valley along its orientation, the transport was affected by cross-valley ther-

mally induced flows, in addition to the turbulence during the daytime hours. The results show that during the daylight hours there is a splitting of the mass into two branches along the slopes, in addition to a vertically well mixed layer. This resulted in a significant dilution of the particles over the domain; however, generally, the particles persisted over the valley area for at least 24 hours.

- The simulations were carried out under the assumption of two-dimensional symmetry of the terrain in the studied area (i.e., a uniform terrain along the valley direction), which is an idealization. Introduc-

Figure 10. Features of pollutant particle dispersion at several selected hours for a release at 2100 LST. Southwesterly synoptic flow; advection and turbulence are considered (Case 7).

ing three-dimensional terrain considerations should lead to various distortions in the features obtained with the two-dimensional simulation. However, general conclusions of the transport/dispersion characteristics in this study should not be changed appreciably.

- Finally, based on the simulated cases, the study indicated the importance of vertical velocities involved with convergence/divergence zones on the vertical venting of pollutants, eventually causing significant alterations in the particle distribution from that which would occur without this venting mechanism.

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M. Segal is a research scientist and R. A. Pielke is a professor in the Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523. C.-H. Yu, deceased, was a graduate student at the same institution. This paper was submitted for peer review November 3, 1986; the revised manuscript was received October 26, 1987.