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Transport of a power plant tracer-plume over Grand Canyon National Park

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TRANSPORT OF A POWER PLANT TRACER-PLUME OVER GRAND CANYON NATIONAL PARK

A Thesis

Presented to

The Faculty of the Department of Meteorology

San Jose State University

in Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Jun Chen

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ABSTRACT

TRANSPORT OF A POWER PLANT TRACER-PLUME OVER GRAND CANYON NATIONAL PARK

by Jun Chen

Meteorological and air quality data, as well as surface tracer concentration values, were collected during 1990 to assess the impacts of Navajo Generating Station (NGS) emissions on Grand Canyon National Park (GCNP) air quality. These data have been used in the present investigation to determinate between direct and indirect transport routes taken by the NGS plume to produce measured high tracer concentration events at GCNP.

The meteorological data were used as input into a three-dimensional mass-consistent wind model, whose output was used as input into a horizontal forward-trajectory model. Calculated polluted air locations were compared with observed surface tracer concentration values.

Results show that complex-terrain features affect local wind flow patterns during winter in the Grand Canyon area. Local channeling, decoupled canyon winds, and slope and valley flows dominate in the region when synoptic systems are weak. Direct NGS plume transport to GCNP occurs with northeasterly plume-height winds, while indirect transport to the park is caused by wind direction shifts associated with passing synoptic systems. Calculated polluted air mass positions along the modeled streak lines matched measured surface tracer observations in both space and time.

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The 1990 Navajo Generating Station Visibility Study field program, whose data used in the current analysis, was funded by the Salt River Project. Many organizations were responsible for the design, data collection, and data analysis phases of the study, which was coordinated by AeroVironment. STI was responsible for collection and analysis of meteorological and aircraft data.

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1. INTRODUCTION

Impact from the Navajo Generating Station (NGS) on air quality at Grand Canyon National Park (GCNP) was studied during the 1990 Winter NGS Visibility Field Study. In order to study the transport of the NGS plume to GCNP, it is necessary to understand the results obtained from previous observational and modeling studies carried out in similar complex terrain areas.

a. Observational studies

Planetary boundary layer (PBL) structure in complex terrain areas can trap and transport pollutants with minimum dilution (Clements *et al.* 1989). Evolution of the daytime convective boundary layer (CBL) and of the nighttime nocturnal boundary layer (NBL), coupled with complex local thermal wind systems and topographic channeling, produces complex pollutant transport and diffusion processes. Solar radiation, long-wave radiation, and convective fluxes can vary significantly from site to site in such regions (Whiteman *et al.* 1989a, b), resulting in local daytime up-slope and nighttime down-slope flows, along-axis valley and mountain winds, and nighttime valley inversions (Atkinson 1981).

The critical regional air quality problem in the complex terrain areas of southwest U. S., which contain many National Parks, is impairment to local visibility, which is generally good due to low humidity values and limited local anthropogenic pollutant sources (Braaten 1981). Airport visibility at 12 sites in the Grand Canyon National Park (GCNP) area from the 1950s to the 1970s, however, showed a 10-30% deterioration (Trijonis 1979), equivalent to an average increase in extinction (beyond blue-sky scattering) of 45%.

Analysis of historical visibility data in GCNP area by Linak and Peterson (1981) found a high correlation between low visibility values and high concentrations of small secondary sulfate particles. Such particles are effective in reducing visibility, as scattering efficiency is inversely related to aerosol size (Malm 1979). They also found no significant difference between urban and rural values. This suggests that such particles, which can remain suspended for days to weeks (Hall 1981), were transported into the region over long distances.

These hypotheses were confirmed by the VISTTA (Blumenthal *et al.* 1981) and VIEW (Pitchford *et al.* 1981) field observation programs, in which surface visibility impacts of atmospheric aerosols in the Grand Canyon region were determined from airborne measurements of background meteorological conditions and aerosol properties (Cahill *et al.* 1981; Macias *et al.* 1981a, b). Visual air quality was found best in winter and worst in spring (Malm *et al.* 1981). Near homogenous aerosol concentrations were observed throughout the VISTTA aircraft spirals (to about 3000 m MSL) on hazy days. This was due to long range transport and/or the strong afternoon vertical mixing common in desert environments (Hering *et al.* 1981).

Tracer studies by Macias *et al.* (1981b), Pitchford *et al.* (1981), and Hering *et al.* (1981) documented that summer pollutants in the Grand Canyon area result primarily from long range transport and transformation of Los Angeles basin industrial and urban emissions during periods of slow moving surface synoptic anticyclones (Braaten 1981). The visibility model of Blumenthal *et al.* (1981) showed that secondary aerosol effects only become important for travel distances beyond 100 km, due to the dry conditions in the Grand Canyon area.

Summer long range transport from the Los Angeles basin begins when the prevailing westerlies are enhanced during summer by the formation of a thermal low over the interior California deserts. The 2000 m tall San Gabriel Mountains chain on the eastern edge of the basin ejects pollutants vertically to the 800 mb level (Wakimoto and McElroy 1986). Transport into the Southwest then occurs in association with winds from the Pacific High.

With a second ridge of high pressure centered over the Rocky Mountains, pollution from Los Angeles either stagnates before reaching the Grand Canyon area or passes south of it. The resulting southeasterly flow aloft then advects moist tropical Gulf of Mexico air into the Grand Canyon region (Hoffer *et al.* 1981) and advects pollution from southern Arizona smelters into the Grand Canyon area (Braaten 1981).

In contrast, project SCENES air quality and visibility data collected at 19 locations around the Grand Canyon indicated that anticyclonic surface conditions were not usually associated with low visibility winter episodes (Kalkstein *et al.* 1989). Analysis of 1986 winter SCENES data by Markowski *et al.* (1989) found high ventilation rates in Glen Canyon (Fig. 1). These arose from mountain-flow convergence that induced vertical motions out from the top of the stable boundary layer and into the westerly synoptic flow above.

A special SCENES field program (WHITEX) in January and February 1987 assessed the contribution of emissions from the coal fired power plant at the Navajo Generating Station (NGS) to winter visibility impairment at the GCNP, Canyonlands National Parks, and Glen Canyon National Recreation Area (Malm *et al.* 1988, 1989). Results suggested that NGS emissions travel to the SW a

distance of 100 km (Fig. 1) to the Grand Canyon area, build up over 3-5 day periods, and are advected out of the area during frontal passages.

Meteorological field measurements during a cold period from 7-12 February 1989 by Porch *et al.* (1990) showed persistent easterly or northeasterly winds near NGS through a depth of nearly 1 km. The extent, persistence, and direction of these winds suggested that they represented a drainage flow down the Colorado River that would carry the NGS plume towards the GCNP.

Analysis of WHITEX data by the National Park Service (NPS) implied that NGS emissions were responsible for a significant portion of winter anthropogenic visibility impairment at GCNP (NRC 1990). Environment Protection Agency (NRC 1990) analysis of the same data showed that a 90% reduction of NGS SO₂ emissions would result in visibility improvement at Hopi Point (Fig. 1) in GCNP on 100 days per winter. The ability of WHITEX data to quantitatively link visibility impairment at Hopi Point to NGS emissions was challenged, however, by Richards *et al.* (1991) on the grounds that WHITEX had not been designed as an attribution study and that its focus had not been GCNP.

b. Meteorological modeling

The spatial and temporal distributions of meteorological fields needed to model atmospheric pollutant transport and diffusion processes in complex terrain areas can be constructed from interpolated observational data or from outputs from atmospheric models.

Interpolation of meteorological fields from relatively few observations can be carried out by a variety of diagnostic mathematical interpolation techniques (Sherman 1978) that first interpolate observations to produce initial grid point

values in a model domain. These values are then adjusted to satisfy selected physical constraints, *e. g.*, three-dimensional mass continuity.

Goodin *et al.* (1979) surveyed three classes of interpolation schemes. The simplest one, *weighted interpolation methods*, assumes that interpolated grid values are a weighted average of surrounding data values, with weight values given as functions of the distance (r) between the observation and the grid point. The most complex class, *optimum interpolations*, require historical data records, and have been used to initialize global and synoptic scale circulation models (Gandin 1965).

The intermediate class, *polynomial interpolation*, determines a least-square fit polynomial (usually r^2) to the observational data points, a good compromise between computational cost and accuracy (Goodin *et al.* 1979). The diagnostic models discussed below use such a technique.

Least-square methods were applied to constant pressure surface height analysis by the extension of cubic spline approximations to horizontal surfaces by Colin (1984). Data were from a non-uniform grid, and analytic solutions were obtained. Results correlated well with satellite imagery.

A finite-differenced mass-consistent wind model (MATHEW) was developed by Sherman (1978) using the variational analysis technique of Sasaki (1958). A finite element version of MATHEW (called FEMASS) was developed by Tuerpe *et al.* (1978). Finite elements should be superior to finite differencing in modeling atmospheric flows, due to their enhanced capabilities in representing terrain, but a comparative study by Rodriguez (1979) found the two models to perform equally well.

In complex terrain areas, additional constraints are sometime considered, e. g., constraints associated with topographic slope, atmospheric stability, or horizontal temperature gradient. Such effects were incorporated in models used by the air quality study of Yocke *et al.* (1978), wind power study of Erasmus (1986), and model development study of Barnard *et al.* (1987).

The WOCSS complex terrain mass consistent wind model of Ludwig *et al.* (1991) incorporated atmospheric stability effects on vertical streamline displacement via the critical dividing-streamline concept. Comparisons by Thykier-Nielsen *et al.* (1990) had shown that wind fields from such models are at least as good as those from linearized prognostic spectral models.

Time-varying PBL meteorological fields can also be obtained from solutions of the atmospheric dynamic equations using numerical techniques. Drainage flows in the 1988 ASCOT program were simulated by Leone and Lee (1989) with a nonhydrostatic finite-element model. Simulated nocturnal down-valley circulation systems compared well with observations. The HOTMAC higher order turbulence model of Yamada and Bunker (1989) successfully simulated the strong wind directional shears and temperature gradients observed in the 1988 ASCOT program.

The prognostic model of Mahrer and Pielke (1976) was used by Physick (1986) to model flows *within* idealized Grand Canyon topography during cloudless periods, when canyon meteorology is not affected by passing synoptic scale fronts. Predicted upward motions above its sidewalls, and downward daytime motions at its center, agreed well with values obtained from aircraft observations by Sinclair and Dattore (1987).

The hydrostatic, terrain following coordinate system model of Pielke and Martin (1981) was applied in the complex terrain area of the Lake Powell Basin by Yu and Pielke (1986). They found that during winter time polar high stagnation episodes, local thermal wind systems occurred within the basin, and that layered haze occurred most frequently with SW winds.

Meteorological output from either the above discussed diagnostic or prognostic model types can be used as input for the variety of air quality dispersion models discussed below.

c. Dispersion modeling

Air quality simulation models predict air pollutant concentration patterns based on mathematical algorithms for both pollutant emissions and meteorological factors. Such models are either Eulerian or Lagrangian in formulation. In general, Eulerian models contain computational grid cells, while Lagrangian models are grid-free (Boybeyi 1990).

Eulerian models generally solve the three-dimensional advection-diffusion equation in a fixed grid, and include the contribution of various physical and chemical sources and sinks. Models differ in their spatial resolutions, boundary conditions, numerical techniques, simplifying assumptions, and/or turbulence and other physical parameterizations.

Lagrangian model emissions are represented by discrete elements (dimensionless points or volumes) transported by the local mean wind and diffused by its turbulent component (Holdeman 1980). Point type Lagrangian models generally use particle-in-cell (PIC) or Monte Carlo methods, while volume approaches use puff techniques. A limitation of PIC methods is that they

have an Eulerian aspect, because a grid must be established to determine concentration gradients.

Monte Carlo particles move independently from each other (Watson and Barr 1976; Hanna 1981), with dispersion resulting from the use of many particles. While other dispersion modeling techniques require input quantities that are not directly measurable (e. g., eddy diffusivities), Monte Carlo methods require only statistics directly obtainable from measurable velocities. Point type Lagrangian models are computer intensive, however, as they require release of a large number of particles.

Volume element techniques, such as segmented plumes or puffs, are less computer intensive than other Lagrangian techniques, as fewer elements are required. Segmented plumes are composed of continuous pieces, each of which represents emissions over a specific time period (Bass 1980). The center point of each segment is advected with the prevailing local wind. Within each segment, pollutants are assumed to have two-dimensional Gaussian distributions (Bankley and Bass 1979).

The Lagrangian Adaptive Volume Plume (AVP) model of Ludwig *et al.* (1989) and Boybeyi (1990) approximates a continuous plume by a series of discrete volumes that change shape in response to vertical wind shear and changes of atmospheric stability with height. Horizontal and temporal changes in meteorological parameters are accounted for by the use of local meteorological conditions along the trajectories.

Meteorological inputs required by an air quality dispersion model for simulations under complex meteorological conditions can be provided by either diagnostic mass consistent or prognostic dynamic PBL models. For example,

the three-dimensional prognostic RAMS model was used to simulate pollutant streak lines in sea-breeze circulations over Chesapeake Bay (Segal *et al.* 1982). Topographic effects were included in the model in similar studies over Florida (McNider and Pielke 1979).

Meteorological output from the prognostic three-dimensional URBMET PBL model of Bornstein *et al.* (1987a) was used in the three-dimensional Eulerian urban air pollution dispersion model of Shir and Shieh (1974) to simulate sulfur-dioxide concentrations from point and area source emissions during sea-breeze circulations over New York City (Bornstein *et al.* 1987b). Results from the PBL and dispersion models reproduced observed sea breeze frontal characteristics and correctly simulated observed three-dimensional time varying sulfur dioxide concentration fields.

Mass-consistent wind flow models are more frequently linked to dispersion models than are dynamic models, as they require less computer power. A two-dimensional vertically integrated version of the mass-consistent MATHEW model (MASCON) was developed by Dickerson (1978) to provide meteorological input to the LIRAQ multi-box dispersion model of MacCracken and Sauter (1975) to simulate carbon dioxide concentrations the San Francisco Bay Area. Three-dimensional MATHEW provided transport velocities to the ADPIC particle-in-cell code of Lange (1978) to simulate data from the 1980 ASCOT program (Porch and Rodriguez 1987). Modeled surface concentration patterns corresponded well with observed tracer data.

Pollutant transport to GCNP under a variety of meteorological situations has been simulated using the non-hydrostatic RAMS prognostic meteorological model linked to a Lagrangian particle model. In one such investigation,

MOHAVE Study data were used by Stocker *et al.* (1992) to construct backward trajectories for a receptor-modeling study that evaluated the spatial distribution of regional integrated influence-functions at six National Parks in Utah, Arizona, Nevada, and California. During the four-day November 1991 simulation period, mesoscale thermal forcing was minimal due to passage of a synoptic frontal system. Results showed that during this period, the Hopi Point site at GCNP was only influenced by emissions in a corridor that stretched from Utah to Oregon.

The same modeling system, in conjunction with MOHAVE data, was used by Uliasz *et al.* (1993) to study impacts of a variety of western source regions on pollutant concentrations at several southwestern National Parks. Results from the one day shown (11 February 1992) indicated that west to east transport of pollutants only from the LA Basin and from the Mohave Power Plant reached the Meadview site at GCNP. A similar study of the stably stratified, SW flow period of 10-13 February 1987 by Poulos and Pielke (1994) used WHITEX data. Results, however, showed the LA Basin as not a major source of pollutants at the Park for that period, as its plume was advected along a path that passed NW of GCNP.

Wintertime pollutant transport from NGS to GCNP (Fig. 2) was studied by Gray *et al.* (1991) using the hydrostatic MM4 mesoscale meteorological model to drive the regional RTM transport model. Simulations were carried out for two northeasterly flow-period episodes from the 1990 Winter NGS Visibility Field Study in order to evaluate the effects of NGS emissions on tracer and sulfate concentrations. Results showed that NGS emissions produced significant im-

pacts on GCNP sulfate concentrations during several periods with high observed values.

As previous field studies had not conclusively demonstrated a causal relationship between NGS plume transport and wintertime GCNP visibility impairment, the 1990 Winter NGS Visibility Field Study was undertaken to determine the possibility of such events. Surface and upper air meteorological, concentration, and tracer data were collected during this study.

The current research uses this meteorological data set as input into a three-dimensional mass-consistent wind model, a two-dimensional horizontal forward trajectory model, and a simplified Gaussian puff-growth model to perform a detailed analysis of the transport of the NGS plume to GCNP during a four-day period. Results are compared with the observed surface tracer concentration values.

2. METHODOLOGY

The current research uses three months of surface and upper air wind observations from the 1990 NGS Visibility Study as input to the California Air Resources Board (CARB) diagnostic mesoscale wind flow model. Resulting mass consistent horizontal velocity fields were input into the CARB trajectory model to calculate continuous plume-height streak lines to determine when NGS emissions were directed towards GCNP. Horizontal puff-growth along the streak lines was represented using computed neutral stability horizontal diffusion coefficients.

a. Models

The three-dimensional mass-consistent terrain-following diagnostic wind model used in the current study was developed by Goodin *et al.* (1980) for the Los Angeles basin air pollution study and subsequently modified by CARB; the top of the model was arbitrarily set at 2000 m. The model consists of a number of grid layers of variable depths, each of which is divided into volumes with equal horizontal extents. Both horizontal wind components (u, v) are located at grid volume centers, while vertical velocity components (w) are displaced one half grid point in the vertical.

The surface wind field at the lowest grid level (anemometer height) is first constructed by interpolation of measured surface velocities using the inverse distance-squared (r^{-2}) weighting of Goodin *et al.* (1979) over a fixed specified radius of influence. Topographic influences are accounted for via a local terrain adjustment technique similar to that of Anderson (1971, 1973).

Upper air u and v wind sounding data are then vertically interpolated to model levels located between the lowest and highest observational levels. Quasi-cubic Hermite polynomials are then used to horizontally interpolate upper air u and v values to horizontal grid locations. The generally weak horizontal gradients in measured upper level wind values (relative to those near the surface) makes highly accurate interpolation procedures unnecessary. As a result, r^{-1} weighting was used at these levels, as it produces smoother fields than r^{-2} weighting.

When the non-steady upper level of the general coordinate system shown in Fig. 3a is assumed constant in time, the terrain-following Cartesian (x,y,z) coordinate system of Fig. 3b results. Normalization of this system results in the terrain influenced coordinates (x, y, ρ) of Fig. 3c that are used in the current formulation. This produces a new vertical velocity W , given by:

$$W = w - u\left(\frac{\partial h}{\partial x} + \rho \frac{\partial \Delta H}{\partial x}\right) - v\left(\frac{\partial h}{\partial y} + \rho \frac{\partial \Delta H}{\partial y}\right), \quad (1)$$

where all symbols are defined in the Appendix. The local vertical distance ΔH between the top of the topography $h(x,y)$ and the model top H is given by

$$\Delta H(x, y) = H(x, y) - h(x, y). \quad (2)$$

while the new normalization vertical coordinate ρ is given by

$$\rho = \frac{z - h(x, y)}{H - h(x, y)}, \quad (3)$$

where ρ ranges between zero and unity.

The following mass continuity equation is integrated vertically to calculate $W(z)$ at the top of each grid layer, based on an assumed zero W value at the surface and on u and v values of grid cells below the given height:

$$\frac{\partial W}{\partial p} + \frac{\partial(u\Delta H)}{\partial x} + \frac{\partial(v\Delta H)}{\partial y} = 0. \quad (4)$$

This technique, however, can produce unrealistically large W values at the model top, when low level divergence is not compensated for in upper parts of the domain. The following three-step Goodin *et al.* (1980) adjustment procedure is thus carried out to reduce the divergence at each level to an acceptable value. The method redistributes excess integrated divergence horizontally and vertically, so that the final vertical velocity at the top of each column is near zero.

First, the following modified five-point smoothing filter is sequentially applied to u - and v -velocity components at any z -level:

$$u_{i,j}^{n+1} = 0.20(u_{i,j}^n + u_{i+1,j}^n + u_{i-1,j}^n + u_{i,j+1}^n + u_{i,j-1}^n)(1 - \alpha) + \alpha u_{i,j}^n, \quad (5)$$

where α either fixes interpolated velocities to observed values at grid points in grid cells that contain an observation site ($\alpha=1$) or changes values at grid points in grid cells without an observational site ($\alpha=0$). Vertical velocities at the top of each layer are next evaluated sequentially from (4) by temporarily disconnecting each vertical layer from all the others. Resulting vertical velocities are held fixed throughout the remaining steps of the divergence reduction procedure.

The final step (developed by CARB) reduces any remaining local divergence $D(x, y, p)$ by application of the following equation individually to each layer:

$$\frac{\partial W}{\partial p} + \Delta H \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) = D(x, y, p). \quad (6)$$

where $D(x, y, \rho)$ is reduced towards zero by subtraction of $D_{i,j,k} \times \frac{\Delta x}{2\Delta z}$ from $u_{i+1,j,k}$, and $D_{i,j,k} \times \frac{\Delta y}{2\Delta z}$ from $v_{i,j+1,k}$. Four passes are required through the horizontal velocity field, in which grid cells are scanned sequentially from left to right, bottom to top, right to left, and top to bottom. As the scans proceed, updated velocity values are incorporated into the procedure, which produces largest adjustments at grid points at the end of each scan. As the global domain total residual is usually reduced by about five orders of magnitude by these scans, this bias is thus insignificant.

The horizontal-trajectory model of CARB uses linear in time interpolation on the hourly output values from the mass consistent wind model. These are then used to calculate forward trajectories for instantaneous NGS pollution-puff releases at 15 minute intervals (starting on the hour). The calculations are carried out at the estimated 600 m simulation-period average observed plume-height level. Streak lines were then constructed by a time sorting of trajectory positions.

All NGS emissions were treated as a single point source, with an assumed position at the wind-model grid-point closest to its actual location. Horizontal dispersion-coefficient values (σ_y) were estimated as a function of travel distance (d) from the following neutral stability equation from Ludwig *et al.* (1989) for each puff-location along the streak line:

$$\sigma_y = 0.128d^{0.9}. \quad (7)$$

Note that neutral stability was assumed, as the calculation was carried out only to show the relative age of polluted air masses along streak lines, as well as to compare observed and estimated times during which NGS tracer emission

impacted GCNP. As one of four different tracers was released each day, each calculated polluted air mass was marked on the same basis.

b. Data

The 1990 Winter NGS Visibility Field Study, conducted in northern Arizona and southern Utah from beginning of January through end of March 1990, was supported by the Salt River Project. The NGS coal-fired power plant is located 6 km ESE of Page, at an elevation of 1330 m MSL (Fig. 1).

While the plant includes three 750 MW units, each venting effluent through individual 236 m tall stacks (Whiteman *et al.* 1990), effluent from individual stacks generally quickly combines into a single large plume (Richards *et al.* 1991). Effective stack height values of the combined plume were calculated using Page airsonde data in the formulation of Briggs (1972). Hourly height values depend on meteorological conditions, but typically ranged from 1800 to 2400 m MSL (Fig. 4a). Aircraft-determined visual estimates of plume height were available during selected daytime hours at distances between 13 and 93 km downwind from the stack. They generally agreed with corresponding calculated values, with a Pearson Product-Moment correlation coefficient of 0.60 (Fig. 4b).

Topographic features in the direct transport path between NGS and GCNP are shown in Fig. 2 and Table 1. For direct transport to GCNP, the plume must pass through 3.5 km wide, 720 m deep Marble Canyon, which is surrounded by three 2000 m evergreen forest plateaus (Kaibab, Paria, and Kaibito); Kaibab has a deep permanent winter snow cover.

Table 1: Elevation of key topographic features in Fig. 1

Feature	Elevation (m MSL)
NGS stack base	1330
Lake Powell	1128
Kaibab Plateau	2500-2700
Paria Plateau	2000-2150
Kaibito Plateau	1900-2000
Kaiparowits Plateau	2100-2300
Fredonia Pass	1900
Grand Canyon Pass	2000

Surface meteorological observations of wind, temperature, moisture, solar radiation, and precipitation were continuously made at 15 sites. Upper air wind and thermodynamic data were collected at six or 12 hour intervals at five rawinsonde sites, four airsondes sites, and two tether sondes (Whiteman *et al.* 1990; Lindsey *et al.* 1991; Richards *et al.* 1991). In addition, four Doppler sodars and three Doppler radar profilers were operated continuously. Surface and upper air site locations are shown in Fig. 5 and described in Table 2. Regional 700 mb meteorological data during the study period were also obtained from twice-daily National Weather Service (NWS) rawinsonde soundings at Winslow (Fig. 1), 140 km south-southeast of Page at an elevation of 1488 m MSL.

The perfluorocarbon tracer-plume study was begun at 1300 MST on 12 January and continued continuously until 1800 MST on 28 March, with concurrent releases from all three NGS stacks. Four distinct tracers were sequentially released, each over a 24 hour period (after the first day) starting at 1800 MST. Cumulative tracer samples were collected at four hour intervals (starting at 0200 MST) by the surface air quality (tracer and SO₂) monitoring network (Figs. 1 and 5), which consisted of three continuously operated GCNP sites (Hopi Point, Desert View, and Indian Gardens), eight research sites, 15 regional sites, and one

Table 2: Meteorology measurement sites, where x and y are Fig. 8 model-domain grid-coordinates (from Lindsey *et al.* 1990).

Site	Site I.D.	Instrumentation	Latitude (°N)	Longitude (°W)	Altitude (m MSL)	UTM E-W (m)	UTM N-S (m)	x	y
Bullfrog Basin	BUL	S,R	37°31'08"	110°43'30"	1130	524 301	4 152 474	69.7	55.8
Dangling Rope	DNG	S,R,D	37°07'48"	111°04'53"	1155	492 770	4 109 297	63.4	47.1
Cameron	CAM	S,R,D	35°50'54"	111°25'39"	1350	461 397	3 967 207	57.1	18.7
Tusayan	TUS	R	38°58'05"	112°07'35"	2012	398 437	3 980 997	44.6	21.5
Ash Fork	ASH	S,R	35°14'21"	112°29'00"	1588	365 036	3 900 578	37.9	5.4
Cedar Ridge	CDR	S,P,A	36°15'55"	110°40'35"	1786	439 242	4 013 587	52.7	28.0
Mexican Hat	MEX	S,D	37°08'56"	109°51'42"	1271	601 298	4 111 820	85.1	47.6
Fredonia	FDN	S,D	36°56'17"	112°31'46"	1420	364 055	4 089 638	37.7	43.2
Lee's Ferry	LEY	S	36°51'48"	111°36'00"	994	447 500	4 081 000	54.4	41.5
Hopi Point	HOP	S	36°04'16"	112°09'14"	2152	396 526	3 990 824	44.2	23.4
Indian Gardens	ING	S	36°04'45"	112°07'37"	1146	404 137	3 992 372	45.7	23.7
Desert View	DSV	S,L	36°02'29"	111°49'39"	2283	425 551	3 989 018	50.0	23.1
Meadview	MVW	S	35°57'12"	114°05'46"	1070	220 332	3 988 818	8.9	23.0
Buffalo Ranch	BFL	S,T,A	36°28'11"	111°56'43"	1710	413 843	4 034 478	47.6	32.2
Phantom Ranch	PTN	S,P,T,A	40°00'00"	105°00'00"	750	404 653	3 997 253	45.8	24.7
Page	PGA	S,P,A	36°54'00"	111°30'00"	1322	458 492	4 085 327	56.6	42.3

Key to instrumentation:

S Surface
R Rawinsonde
A Airsonde
T Tethersonde
D Doppler Sodar
P Doppler Radar Profiler
L Doppler Lidar

tracer-only sampling site near the NGS plant at Copper Mine (Richards *et al.* 1991).

Intensive observational periods were scheduled whenever the NGS plume was forecast to impact GCNP. During such periods, the data collection program was enhanced to include additional surface-based meteorological and chemical (including sulfate filter values) observations at four-hour intervals, hourly back scatter observations, continuous surface-based Lidar measurements, and hourly aircraft sampling of chemical, meteorological, and tracer parameters. Rawin-

sonde launch frequency was also increased at all four sites (Bullfrog Basin, Dangling Rope, Cameron, and Tusayan) from twice per day to four per day.

3. RESULTS

Direct transport of NGS emittants to GCNP occurs with northerly synoptic-scale flows associated either with low pressure systems passing south of NGS or with the development of high pressure ridges west of NGS (Lindsey *et al.* 1991). Indirect transport, on the other hand, occurs under various scenarios, e. g., when the plume is channeled by topographic features along the Colorado River (Fig. 2), or when it is carried across the canyon by a wind direction shift.

The period of 18-21 January was selected for the current study as the observed winds and surface tracer data showed it contained occurrences of direct, indirect, and non-transport of the NGS plume towards GCNP. These cases arose due to wind direction changes associated with the passage of a synoptic frontal system during the first two days of the period. The following sections describe the study period, using time varying vertical cross sections of the meteorological structure along the direct-transport path between the NGS and GCNP, wind flow model results, computed 600 m level NGS plume streak lines, and observed surface tracer concentrations. Preliminary results of these simulations were presented at the AWMA Annual Meeting by Lindsey *et al.* (1991).

a. Winter climatology

A three month (January to March 1990) summary of 700 mb rawinsonde data at Winslow, AZ (Fig. 6) shows that its height averaged about 3070 m AGL above the highest terrain (located at 3050 m MSL) in the study area. Winds at this level were typically from the W or SW.

Major high pressure events, lasting more than two or three days, occurred around 10 January (Julian Day 10), 21 February (Julian Day 52), and 21 March

(Julian Day 81). When such pressure systems enter the area from the west, 700 mb winds weaken and become northerly or easterly (Whiteman *et al.* 1990), while temperatures rise and humidities fall. With such weak winds aloft, and with strong stable conditions near the surface, circulations below the 700 mb level may be decoupled from the flow aloft and be channeled by local topographic features (Lindsey *et al.* 1991). Under such conditions, the NGS plume will not generally reach GCNP via a direct transport path.

The relation between such traveling upper level weather systems and surface meteorological conditions at GCNP are shown in Fig. 7, which presents a summary (over the same three months) of 700 mb rawinsonde heights measured at Tusayan (Fig. 1) and of the following surface parameters measured at Hopi Point: light scattering by particles (b_{sp}), direct solar radiation, temperature, relative humidity (RH), and precipitation. As expected, upper level trough passages are usually accompanied by cloudiness (and decreased solar radiation), a cessation of southwesterly flow, lower temperatures, higher RH, precipitation, and high b_{sp} readings at Hopi Point. During such conditions, the NGS plume reaches GCNP via a direct and/or indirect transport path. With moist air and intense solar insulation conditions along the transport path, the NGS plume will reach GCNP with a significant fraction of its sulfur dioxide transformed into sulfate aerosols. This results in high b_{sp} and low visibility episode conditions at the park. Without such a photochemical transformation, the mainly sulfur dioxide NGS plume will not impact either b_{sp} or visibility values. Such events are very rare, as compared to low visibility events at the Park that result from west to east long-range transport of pollutants from the Los Angeles Basin.

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period and the one at the end of the study period. Hence the former period was selected for the current analysis.

b. Case study

As reported by Richards et al. (1991), a synoptic scale closed low pressure system passed south of GCNP on 18-19 January. Winds ahead of the low became easterly in the cyclonic circulation around the northern side of the low. As the low passed through the study area, the winds reversed direction, backing to northerly and westerly. The winds reversed direction again on 20 January, becoming northerly and continuing to veer to easterly. This occurred as a 850 mb low moved out of the area to the east, and as a ridge of high pressure formed at the 850 mb level over the area. High relative humidities, cloudiness, and precipitation accompanied the passage of the low throughout the area.

By 21 January, a ridge of high pressure had built over northern Arizona, bringing westerly flow. Descending dry air caused a strong elevated inversion to form over the area.

i. Vertical structure

Measured upper air meteorological data were used to construct a series of vertical cross sections along the Case 1 direct-transport path (Fig. 8) for the 18-21 January study period. The 0400 MST cross section on 18 January (Fig. 9a) shows that data sites along this path include four rawinsondes (ASH, TUS, CDR, and BUL), all three Doppler radar profilers (PTN, CDR, and PGA), and one Doppler sodar (DNG). Note that site ID (upper three letters) and instrument-type (lower three letters) abbreviations along the horizontal axis correspond to entries

in Table 2. Terrain height features (heavy solid line), show (from west to east) the Grand Canyon, Marble Canyon, Lake Powell Basin, and Fiftymile Point (eastern peak). The estimated (Briggs 1972) NGS plume height is indicated by the asterisk above the PGA radar site (located adjacent to the NGS facility). Potential temperature contours (quasi horizontal solid lines) are at 1 K increments, while relative humidity contours (dashed lines) are at 10% increments. Plotted wind vectors represent true horizontal flow directions (even though the cross-section is oriented SSW to NNE), with a speed scale given at lower right of the Figure.

The estimated plume height for this period is about 850 m AGL. Potential temperature contours show weak-to-moderate stable atmospheric conditions over the entire domain during this early morning period, while relative humidity contours show unsaturated conditions throughout the layer. Humidity values generally increase with height, from about 60% near the surface to about 90% at 5 km, as this Pacific Ocean (as determined from NWS 850 mb charts) air mass dries from below during its traverse over the SW desert area.

Flow directions within the Grand Canyon were from the SE, indicative of decoupling from the generally east to northeasterly flows just below the tops of the highest peaks (and thus at plume level). Above this level, directions veer to become more east-northeasterly. Note that the NOAA radar profiler at CDR appears to have malfunctioned at heights above 2200 m MSL during most of the period, although reported directions below this level are consistent with those from all other sites. It is possible that observed upper level winds at this site are associated with vertically propagating gravity waves or are contaminated by ground clutter. Above-canyon speeds generally increased with height, from

about 4 m/s near the surface (average 2 km) to about 12 m/s at 5 km; plume-height speeds above NGS were about 7 m/s.

During the next six hours (not shown), temperature values dropped and then rose at sunrise (about 0800 MST). Wind, temperature, and humidity values at 1000 MST (Fig. 9b) were thus generally similar to those at the previous time. One change, however, is that an expected unstable layer now exists in the lowest 300 m above the surface at Marble Canyon due to solar heating of its eastward facing slope. In addition above 2.5 km, wind speeds are now faster by about 2 m/s, and cyclone-associated wind directions are more from the SE. Speeds are, however, slower (but still from the ENE) at plume level, now lowered to 900 m.

Surface cooling for a few hours after the (not shown) mid-afternoon maximum temperature by 1600 MST (Fig. 9c) resulted in a near neutral surface boundary layer (SBL) with increased relative humidities (up by about 10% from the 75% values at 1000 MST). Wind speeds are, however, now lower, with a 4 m/s value at the plume injection point. Wind directions are still from the NE in the NGS and GCNP areas. The NOAA radar profiler, however, now shows SE winds in the lowest 500 m above the CDR Marble Canyon site, indicative of barrier-induced divergence around Kaibab Plateau; the instrument apparently still malfunctioned at upper levels. Local-channeling wind directions are seen at the DNG and BUL sites, while decoupled winds again exist inside the Grand Canyon. Note, SSW winds are starting to develop below 2500 m at ASH.

By 0400 MST on the 19th (Fig. 10a), SBL potential temperature values had cooled by about 3 K from those in the previous figure, and a surface based radiation inversion had formed at the ASH site up to about 500m. In addition, a

dry westerly flow has penetrated (at elevations up to 4 km) eastward to areas east of Marble Canyon, where the large scale flow has become northerly as the storm system leaves the area. Note the lack of decoupling inside of the Grand Canyon, due to the now generally faster speeds that enhance the downward transport of upper level momentum.

Westerly flow has also penetrated at lower levels in the Lake Powell Basin surrounding the NGS site. At site PGA on the western side of this area, however, near surface winds are from the NNW, but veer to become northerly at plume height (2000m MSL). Upper level winds are also (still) from the NE. The weak winds on the eastern side within the Basin at DNG probably represent the boundary between the westerly and easterly flows. These low speeds represent a reversal of the speed maxima found at this site at the time of the previous figure.

At 1600 MST, the entire domain was dominated by the westerly flow (Fig. 10b), which generally brought more stable dry air, as compared with the previously easterly flow. Flows *within* the Grand Canyon and the Lake Powell Basin have not changed as dramatically from those in the previous figure, but plume height has increased by about 200 m.

By 0400 MST on the 20th, the flow pattern in the eastern part of the domain was again shifting (Fig. 11a). Northeasterly flow aloft has begun to enter the eastern domain edge in association with an 850 mb high pressure ridge that formed over the area. At the Briggs plume height level of 1100 m AGL, wind speeds were about 5 m/s in a direction (still) away from GCNP.

By 1600 MST, northeasterly flow covered the entire domain (Fig. 11b) bringing warm dry continental air aloft, where relative humidities have decreased

by almost 20% and potential temperatures have increased by 4 K since 0400 MST. Wind velocities below the plume level (2500 m MSL) are generally decoupled from the stronger upper level flow. A strong inversion layer with a base at 2800 MSL covers the entire area, while a weak superadiabatic SBL exists in Lake Powell Basin.

Two hours past sunset (which occurred at 2000 MST) the elevated inversion layer has strengthened (Fig. 11c), while its base has lowered by about 350 m from its 1600 MST elevation. The area is still dominated by warm dry northeasterly flow, with speeds of 6 m/s above NGS and 10 m/s above the Grand Canyon and Marble Canyon areas at the plume height level (about 1000 m AGL).

These upper level winds and mixing depth values, in addition to the observed surface wind data set described above, are next used as input to the three-dimensional CARB mass consistent wind flow model to produce gridded input wind values for the streak line computations described above.

ii. Model results

A horizontal model calculation domain of 500 by 400 km centered on Page, AZ was selected for the modeling study (Fig. 8). A grid spacing of 5 km in both directions thus resulted in 100 by 80 computational cells. U. S. Geological Survey data were used to obtain the unsmoothed horizontal grid averaged terrain elevations of Fig. 8. Ten unequal vertical layers were specified, which centers located at 10, 150, 300, 450, 600, 750, 900, 1200, 1500, and 2000 m AGL. Note that extra layers are specified in the expected plume height region 600 m AGL.

Diagnostic wind model simulations utilized the following input data sets (discussed above): surface winds, and upper air (radiosonde, radar, and sodar) winds. Spatially-invariant mixing height values were specified. While their temporal variation (Fig. 12) was estimated as the average of all sodar measurements, such values are not particularly robust in complex terrain areas such as GCNP.

Interpolated horizontal wind vectors at 0600 MST on 18 January (plotted at alternate grid points for clarity) from the 600 m AGL level are presented (Figs. 13-16), as this elevation represents the average NGS plume-height (as discussed above). Background terrain contours at intervals of 500 m (up to 3000 m) are also shown. Site NGS represents the power plant, while site HOP represents the most intensively instrumented GCNP site. Measured surface tracer values are plotted as vertical bars with different shadings (key in upper left hand corner of chart) for Tracers 1-4. Simulated emittant time-histories are shown as expanding circles, each having size $\sigma_y(d)$ and a shading that corresponds to its tracer release number.

Note that each wind field was constructed from data collected during the hour previous to the indicated time, while observed tracer concentration values represent four hour integrated values (as discussed above). Also note that when predicted puff locations are compared to observed concentration values at a time corresponding to the beginning of tracer sampling period, observed data from that period are used in the comparison.

Thus the following comparisons between simulated puff locations and observed tracer concentration values will produce an apparent error when predicted puff positions seem to be upwind of a site showing high tracer values.

The high observed values actually resulted when the real plume passed the site latter during the four hour integration period. When simulated puffs seem to be located downwind of a site showing high observed concentration values, those values actually resulted when the real plume passed over the site earlier during the period.

At 0600 MST on 18 January, a winter cyclone was passing south of the study area. Simulated morning winds (Fig. 13a) were thus northeasterly at about 5 m/s in the NGS area, and easterly in the GCNP area and south. Tracer Number 2 emission (released since 1800 MST of previous day) circles show a simulated transport streak-line that is directed to the SW and that passes north of GCNP. Surface tracer observations thus show low values at two GCNP sites (HOP and DSV), while measurements are missing from DNG, FDN, BFL, and CAM.

By 2200 MST, the storm was over the area, and winds were weaker (Fig. 13b) across the domain. Westerly winds have developed over GCNP (as seen in Fig. 9c), but northerly winds still exist in the NE corner. As winds have shifted to northwesterly in the west side of the domain, the modeled plume has been pushed somewhat towards the south.

Most simulated polluted mass circles at 2200 MST still represent tracer Number 2 effluent, but fresh tracer Number 3 has been released (two small new masses near the NGS source). The figure shows that the plume is still located north of GCNP at this time. As 2200 MST represents the start of a new tracer collection period, the high values of Number 2 tracer at site DSV indicate that the plume will reach GCNP sometime during the next four hours (due to the integration period effect discussed above).

Northwesterly winds continue to transport the simulated NGS streak-line southward through GCNP at 0400 MST of 19 January (Fig. 14a). Fresh No. 3 emissions have been continued to be released from NGS, while simulated old No. 2 emissions are shown to have just passed the HOP site via a indirect transported path into the park by the NW flow. As the surface tracer measurements at DSV and HOP show decreasing NGS plume impact for the 0200 to 0600 MST measurement period that brackets this 0400 MST chart, the model has thus underestimated the speed of movement of the plume. The simulated streak-line continues to move east of Hopi Point of GCNP (Fig. 14b) at 1200 MST due to the continued westerly flow in the area. Simulated fresh Tracer 3 emissions thus exit the domain on its east side, and surface tracer measurements show only background values at all sites in the Park.

The eastward moving cyclonic system started to leave the area after 1200 MST on the 19th, as the 850 mb high pressure ridge formed over the area early on the 20th. During the next 24 hours, the northwesterly flow over the domain shifted to northeasterly (as discussed in previous section). At the end of this period at 1200 MST on the 20th, wind speeds were about 3 m/s throughout the domain (Fig. 15a).

Simulated fresh Tracer 4 emissions at 1200 MST have thus started to move along the direct transport route (to the southwest, as shown in Fig. 8) towards GCNP. The old emissions that constitute the major part of the simulated plume at this time have also been transported to the Park by this flow. This part of the plume is located SE of the fresh emissions part of the plume (due to previous transport), and is thus reaching the Park by an indirect transport route.

Modeled Tracer 4 emissions reached several GCNP sites simultaneously four hours later at 1600 MST (Fig. 15b), when winds at NGS were even weaker (about 2 m/s), but still directed towards GCNP along the direct transport path. Surface measurements verify that Tracer Number 4 did reach the BFL, DSV, and CAM sites (by the indirect trajectory discussed above) sometime during the period from 1400 to 1800 MST.

Simulated newer NGS emissions still covered sites along the direct transport route to GCNP (the BFL site north of the Park and the HOP area of the Park) six hours later at 2200 MST (Fig. 15c). Older emissions, however, continued their southwestward movement past the Park by the weak modeled plume height level winds. The continued observed maximum tracer concentration (valid for the period from 2200 to 0200 MST) at BFL is indicative of the continued direct transport of the fresh plume towards GCNP. Values at CDR and DSV have dropped, as the aged part of the plume has continued its indirect transport westward over HOP, whose measurements are missing at this time.

The simulated NGS streak-line continued to move westward away from all GCNP observation sites (Fig. 16), as a strong easterly wind developed at 0000 MST of 21 January due to the building ridge. Tracer observations (valid for the period of 2200 to 0200 MST) at CDR and DSV both show clean air, while the high concentration values shown at BFL site were measured when the plume was over the site during the early part of the four hour period.

Given both the high quality and relatively dense nature of the surface wind observational network, continuity adjustments by the mass consistent wind model were generally minor during the entire simulation period. Observed winds on the 18th were generally northerly, and the largest adjustments were made at

Site ING located inside the Canyon (Fig. 17). Over the entire domain, adjustments were largest just before midnight at some (but not all) sites near the steepest terrain around the canyon rim. A possible explanation for this effect is that during stable conditions, flows tend to go around topographic features and not over them, as they would during unstable daytime hours. High correlations are seen both between observed and adjusted speeds and directions. The model decreases high observed speeds and increases low observed speeds, while producing a slight cyclonic turning of easterly flows.

On the 19th, surface winds speeds were about the same as those of the previous day, but directions were more westerly (Fig. 18). The adjustments, however, generally showed the same qualitative and quantitative patterns, but correlations are somewhat lower; speed and direction adjustments were hence somewhat larger. By the 20th, surface directions were again more northerly, but speeds were reduced over those of the previous two days (Fig. 19). Difference patterns were again generally unchanged from the previous two days, and correlation values for both speed and direction for this day were intermediate between those from the previous two days.

4. CONCLUSION

Meteorological and air quality data, as well as surface tracer concentration values, were collected during 1990 to assess the impacts of Navajo Generating Station (NGS) emissions on Grand Canyon National Park (GCNP) air quality. These data have been used in the present investigation to determinate between direct and indirect transport routes taken by the NGS plume to produce measured high tracer concentration events at GCNP. Note that such occurrences are relatively rare and short lived (few days to a week), as compared to the more frequent summertime occurrences that result from long range transport from either southern Arizona copper smelters or from Los Angeles.

The meteorological data were used to construct time series plots and vertical cross sections along the direct transport path from NGS to GCNP. The meteorological data were used as input into a three-dimensional mass-consistent wind model, whose output was used as input into a horizontal forward-trajectory model. Calculated polluted air locations were compared with observed surface tracer concentration values.

Results show that complex-terrain features affect local wind flow patterns during winter in the Grand Canyon area. Local channeling, decoupled canyon winds, and slope and valley flows exist in the region when synoptic systems are weak. Direct NGS plume transport to GCNP occurs with northeasterly plume-height winds, while indirect transport to the Park is caused by wind direction shifts associated with passing synoptic systems. Simulated polluted air mass positions along estimated streak lines matched well with measured surface tracer observations in both space and time.

Future studies of NGS plume transport to GCNP should utilize prognostic non-hydrostatic mesoscale wind models linked to Monte Carlo particle plume dispersion models, as was done by Poulos and Pielke (1994) for Los Angeles Basin transport to GCNP. Non-hydrostatic simulations are necessary to study the flow and gravity wave phenomena associated with the steep terrain features found in the GCNP area.

The transport and diffusion processes linked to the photochemical mechanisms associated with the transformation of sulfur dioxide to the sulfate particles responsible for visibility impairment at the Park also need the accuracy of simulation only possible with such non-hydrostatic meteorological models.

These suggested future studies should also investigate observational cases other than the one studied in the present study. These simulations should include other types of indirect transport tracks of NGS emissions to GCNP.

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APPENDIX: LIST OF SYMBOLS

b_{sp}	light scattering by particles
D	remaining local divergence
d	plume travel-distance
H	domain top in untransformed coordinate system
h	height above terrain
RH	relative humidity
r	horizontal distance
t	time
u, v, w	velocity component in x-, y-, and z-coordinate direction, respectively
W	vertical velocity in terrain-following coordinate system
x, y, z	E-W, N-S, and vertical-coordinate direction, respectively
α	filter coefficient (0 or 1)
ρ	normalized relative vertical coordinate
σ_y	horizontal diffusion parameter
ΔH	local vertical distance between H and h
$()^n$	time step index
$()_{i,j,k}$	grid point index in x-, y-, and z-coordinate direction, respectively
$\Delta()$	space increment

Figure 1.

Figure 2.

Figure 3.

(a)

(b)

Figure 4.

Figure 5.

Figure 6.

Figure 7.

Figure 8.

Figure 9a.

Figure 9b.

Figure 9c.

Figure 10a.

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Figure 10b.

Figure 11a.

Figure 11b.

Figure 11c.

Figure 12.

Figure 13a.

Figure 13b.

Figure 14a.

Figure 14b.

Figure 15a.

Figure 15b.

Figure 15c.

Figure 16.

Figure 17.

Figure 18.

Figure 19.