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DISCUSSION

COMMENTS ON "A SYNOPTIC CLIMATOLOGICAL ANALYSIS OF AIR QUALITY IN THE GRAND CANYON NATIONAL PARK"

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This note is written to comment on the paper by Davis and Gay (1993, henceforth referred to as DG), in which DG have ignored surface synoptic data sets. The inclusion of these data would permit a more accurate characterization of air quality influences on Grand Canyon National Park. They cannot provide a more accurate definition of air quality by adding synoptic classes based on upper air analyses alone. Their categories are defined exclusively in terms of analyses provided by 21 rawinsonde stations located throughout western U.S.A. and Mexico. They ignore, however, the more numerous surface observation stations which are the only data that can be used to define the pressure field over this region at the surface. During the winter, in particular, the movement of air below the synoptic inversion, which can often be of a different direction than the 500 mb winds, is not considered at all in DG. Atmospheric flow in this layer below the inversion exerts a significant influence on pollutant transport from surface-based sources. Using rawinsonde data alone, Doty and Perkey (1993) have shown the failure of the operational rawinsonde network to characterize transport paths even in the flatter eastern United States, as a result of the sparse spatial representation and limited (12 h) time sampling of the rawinsonde network. This conclusion is also supported by work presented in Kahl and Samson (1986, 1988) and Walmsley and Mailhot (1983) in which the spatial and temporal resolution of the Standard National Weather Service twice daily rawinsonde observations over the eastern United States were found to lack the necessary resolution in determining transport paths during the Cross Appalachian Tracer Experiment (CAPTEX) under relatively calm synoptic conditions. It is important to also note that the spatial resolution of the rawinsonde network in the east is more dense than in the western United States. Therefore, the conclusions of these authors relative to the limitations of rawinsonde analyses would be expected to be even more valid for the western United States where the resolution of the network is coarser and complex terrain effects are also more significant. This is a serious omission which limits the value of the DG study, and results in erroneous conclusions which are illustrated in the next sections.

DG also misinterpreted the use of the synoptic classification in the WHITEX study (Malm *et al*., 1989). The climatological analysis used in WHITEX is a proven, valuable approach to assess synoptic weather categories as reported in Yarnal (1993) and Barry and Perry (1973). Using the surface pressure analyses and frontal positions, the six synoptic classes discussed in Pielke *et al.* (1987) are further decomposed into geostrophic wind direction and speed classes. Whether or not the Grand Canyon receives pollution from a source such as the Navajo Generating Station (NGS) depends on the flow direction below a synoptic inversion assuming that the effective stack height is below that level. The effective stack height at NGS is generally between 450 and 1050 m above ground level in the wintertime (Whiteman *et al*., 1991). Whether there is an accumulation of pollution near this industrial site and then a transport towards the southwest depends on both the antecedent surface weather patterns, and flow speed and direction below any synoptic and/or local generated thermodynamic inversion.

To demonstrate the seriousness of their oversight, we categorize the 16 periods of highest sulfur levels at Hopi Point, as reported in Malm *et al.* (1989), according to their synoptic 500 mb maps and corresponding class definitions. The dates of these events are given in Table 1.

In order to illustrate the often present directional difference between the surface and 500 mb flow at a point near the Navajo Generating Station a synoptic classification processor was utilized. European Center for Medium Range Weather Forecasting (ECMWF) 2.5° latitude/longitude synoptic-scale data were used to compute the wind speed and direction at the surface and 500 mb at 12 GMT on dates when the high pollution levels were recorded (45 in all; see Table 1). The geostrophic surface level wind speed and direction were calculated from the mean sea level pressure gradient. The 500 mb flow information was taken directly from the data set. The synoptic processor also was employed to perform an objective classification based on the synoptic classes discussed earlier.

Shown in Table 1 are the dates of high pollution events followed by the classes as objectively and subjectively determined. The last three columns show the geostrophic wind direction at the surface, for the subjective and objective analysis, respectively, and the analyzed model winds at 500 mb. The results indicate that there was agreement in synoptic classification (Columns 2 and 3) for 80% of the days, demonstrating the objective skill of the processor in describing the subjectively determined synoptic categories. Disagreements between the two are associated with transition zones between categories, and the occasional anomalous pattern.

In order to validate the wind directions evaluated by the objective processor, a comparison to the subjectively diagnosed wind directions can be made from Table 1. Neglecting the calm days (11 total), the direction agreed on 15 out of the 34 case days. While the direction used is allowed to vary 45° in either direction (e.g. easterly geostrophic wind is considered in agreement with a northeasterly or a southeasterly geostrophic surface wind), a total of 32 out of the 34 days are in agreement. The only day with disagreement (14 February, 1987) involves a case where the surface front is located very

Table 1. High pollution events for specified dates

Date	Synoptic class from DG	Synoptic class subjective	Synoptic class objective	$\vec{V}_g$ direction subjective	$\vec{V}_g$ direction objective	$\lvert V_g \rvert$ 500 mb direction
Extreme events during WHITEX						
9–14 February 1987	RR, RR, RB, RR, ZBJ, CP	PH, PH, PH, PH, PH, PrF	PH, PH, PH, PH, PH, PrF	SE, SE, Ca, Ca, SE, SE	SE, SE, SE, SE, S, NW	SW, SW, SW, SW, NW, W
14–18 January 1987	A, A, A, A, A	PH, PoF, PoF, PoF/PH, PH	PoF, WF, PoF, PH, PH	NE, NE, NW, NE, NE	E, E, N, NE, E	W, SW, SW, N, N
3–5 February 1987	ZBJ, STJ, STJ	PH, PoF, PH	PH, PoF, PH	Ca, NE, E	S, E, E	SW, SW, NE
Extreme sulfur events (March 86–May 87)						
17 December 1986	CH	PH	PH	NE	E	SW
20 December 1986	STJ	PoF	WF	SE	SE	SW
24 December 1986	CP	PH	PH	NE	E	NW
1 November 1986	A	PoF	PH	NE	E	SW
15 November 1986	ZSPJ	PH	PH	SE	SE	SW
29 November 1986	STJ	PH	PH	SW	S	W
25 March 1987	A	PoF/PH	PH	NE	E	N
High sulfur events for winter months prior to June 1986						
23–26 November 1982	A, STJ(?), CP, A(?)	Am, PoF, PoF/PH, PH	PH, PH, PH, PH	E, SE, SE, E	E, SE, SE, E	W, SW, SW, N
1–4 November 1983	STJ, STJ, STJ, STJ	PH, Pof/PH, PH, PH	PH, PH, PH, SH	Ca, Ca, E, SE	SE, SE, E, SE	W, SW, E, E
5–8 November 1983	ZPJ, ZPJ, ZSPJ, STJ	PH, PH, PH, PrF/PoF	PH, PH, PH, PH	Ca, Ca, Ca, NE	S, E, S, SW	N, NW, SW, SW
22–25 January 1985	ZBJ(?), ZBJ, STJ, STJ	PH, PH, PoF/PrF, PH	PH, WF, PH, SH	SE, E, E, SE	S, SE, E, SE	SW, W, SW, SW
1–4 March 1986	RR, CH, CH, CH	PH, PoF, PoF/PH, PoF/PH	PH, PH, PH, SH	SE, E, E, SE	S, SE, E, SE	S, SW, NW, E
29 March–1 April 1986	CH, CH, STJ, STJ	PH, PH, PrF/PH, PoF/PH	PH, PH, PH, PH	Ca, Ca, Ca, SE	SE, SE, S, S	S, W, W, SW

PH = polar high; PoF = postfrontal; PrF = prefrontal; SH = subtropical high; WF = pre-warm front; $\vec{V}_g$ = surface geostrophic wind; Ca = calm winds no directional preference and $\vec{V}_g < 2.5\ m\,s^{-1}$; Am = ambiguous. The synoptic classes from DG use the same nomenclature as found in that paper. A question mark indicates that the 500 mb analysis for that date using the DG synoptic classification was not straightforwardly obvious.

close to Grand Canyon National Park with winds ahead of the front being from the southeast and wind behind the front being from the northwest.

The 500 mb wind direction is indicated in the last column of Table 1. The table illustrates that there is a westerly component to the 500 mb wind in 34 out of the 45 case days chosen. This is in contrast to the surface geostrophic winds that show a westerly component in only 2 of the 45 days in both the objective and subjective diagnoses (although they are on different days). On 33 out of the 45 days, the objectively determined geostrophic wind directions are 90° or more out of phase with the 500 mb wind direction. Similarly, the subjectively determined surface geostrophic winds are also more than 90° out of phase with the 500 mb flow directions on 25 out of 33 days (neglecting the days where calm winds were diagnosed). In fact, on 23 of 33 days (neglecting calm days) when winds at 500 mb have a westerly component, winds at the surface have an easterly component! Considering this lack of correlation between wind direction at the surface and 500 mb, obviously, the 500 mb flow field cannot be used in determining dispersion patterns near the surface, including the direction of movement of the NGS plume.

The high pollution events occurred for a range of synoptic classes from the DG study. In the DG paper, they correlate classes SM, CH, and RR with poor air quality, and classes A, CP, ZBJ, and SD with good air quality. The other classes were somewhat in between. In Table 1, of the total of 16 episodes, only four of the high pollution dates were associated with one of DG's poor air quality classes *on any one of the days of the episode*, while four were only associated with the *good air quality cases*!

The reason that the DG scheme fails to adequately represent the high pollution dates is that low-level wind direction was ignored. Fourteen of the 16 episodes had an easterly component or calm surface geostrophic speed on one or more days of the pollution event! Thus any sources in that quadrant, such as NGS, would be a likely source of the pollution observed at the Grand Canyon National Park below the inversion.

It is not surprising that the DG study missed this lack of correlation between the surface and 500 mb flow because they did not appropriately segment their data. Indeed, several years ago when we correlated our synoptic classes (e.g. the polar high) with poor air quality days, but neglected the low-level wind direction, we also did not find a significant correlation.

The conclusion from these comparisons is that simply correlating tropospheric air flow patterns derived from the limited temporal and spatial resolution of the rawinsonde network with surface pollution concentration and lower tropospheric visibility can be grossly misleading. One must be more careful to discriminate the antecedant and current low-level wind direction, and speed, and the thermodynamic stratification to properly characterize the synoptic pattern that results in high levels of pollution from both distant and local sources.

Based on our analysis of the DG paper, while their statistical analysis provides a valuable perspective on flow in the middle troposphere, their conclusions regarding the WHITEX study cannot be supported using such information.

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AUTHORS' REPLY

RESPONSE TO "COMMENTS ON 'A SYNOPTIC CLIMATOLOGICAL ANALYSIS OF AIR QUALITY IN THE GRAND CANYON NATIONAL PARK'"

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The basis of the comment by Pielke *et al.* (1995) is that, in our synoptic climatological analysis of air quality in the Grand Canyon (Davis and Gay, 1993a), we did not include data below the inversion, and thereby produced incorrect results. A careful reading of our paper, and of a preceding paper that describes our synoptic classification procedure in complete