exist, whereas in the vicinity of extratropical cyclones (i.e., pre-cold frontal conditions) long range transport is usually more important.[10] The direction of geostrophic wind is along the lines of constant pressure with higher pressure to the right and lower pressure to the left. The speed is directly proportional to the pressure gradient. This synoptic pressure gradient, determined from surface meteorological stations, is expected to exert a major forcing on pollutant transport in the lowest levels of the atmosphere. Near the center of a large high pressure, the pressure gradient is weak, thus the geostrophic winds are weak also. Sinking air associated with these polar highs leads to temperature inversions aloft and thus poor low-level dispersion. In areas such as the region in and around the WHITEX study area (see Figure 8.1), where the terrain is very complex, poor dispersion can be compounded when air becomes trapped within a canyon or valley. In the winter, when the sun angle is low and there may be snow cover on the ground, stagnation can be quite pronounced.

In this chapter, light geostrophic winds will be defined as geostrophic wind speeds less than 2.5 m s^{-1}, moderately weak as 2.5 - 5 m s^{-1}, moderately strong as 5 - 10 m s^{-1} and strong as geostrophic winds greater than 10 m s^{-1}. Daily weather maps[14] for 5:00 am Mountain Standard Time for the days which are discussed in this chapter can be found in Appendix 8A. Also, the transport mechanisms discussed for any high S/SO_4 event in this chapter represents what is believed to be the primary transport mechanism for an event, and is not meant to exclude the possibility of other secondary transport mechanisms within an event unless so specified.

Photographs taken during extreme sulfur episodes from Desert View Watch Tower which is near the east end of the south rim of the Grand Canyon, looking towards either Page and Navajo Mountain (northeasterly) or Mount Trumbull (westerly) are included in the back of this chapter. The photographs are arranged in two groups with the WHITEX pictures in the first group and the historic photos in the second group. Within each group, the pictures are in chronological order.

8.2 Extreme Sulfur Episodes During WHITEX

During the 6-week WHITEX field study there were three high SO_4 events and two extended periods of very low SO_4 at Hopi Point. Figure 8.2 shows the fine ($< 2.5\ \mu m$) SO_4 ion concentration from the IMPROVE sampler at Hopi Point with time represented in Julian days (JD). (Refer to Chapter 3 for a detailed description of the particulate monitoring.) In this section, the meteorology during the time periods of extreme (highest and lowest) sulfur is examined to determine what type of weather patterns were associated with each.

8.2.1 High Sulfur Episodes

February 9 - February 14, 1987

The episode with the longest duration and the second highest SO_4 ion concentrations measured at Hopi Point occurred during this time period between February 9 (JD 40) and February 14 (JD 45).

Analysis of the meteorological conditions during this time period shows that these days were at the end of a relatively long stagnant period which began on February 5 after the passage of a weak cold front and lasted for 9 days. (Surface and 500 mb weather maps for this time period can be found in Appendix 8A.) From February 6 to February 8 (JD 37–39), the geostrophic winds near the surface were moderately strong from the southeast. The geostrophic winds on these three days suggest long range transport of an airmass originating in southern Arizona (smelters) to be transported to locations south of the WHITEX study area; possibly along a line from southern Arizona to the southern tip of Nevada. The strong southeast surface geostrophic winds during

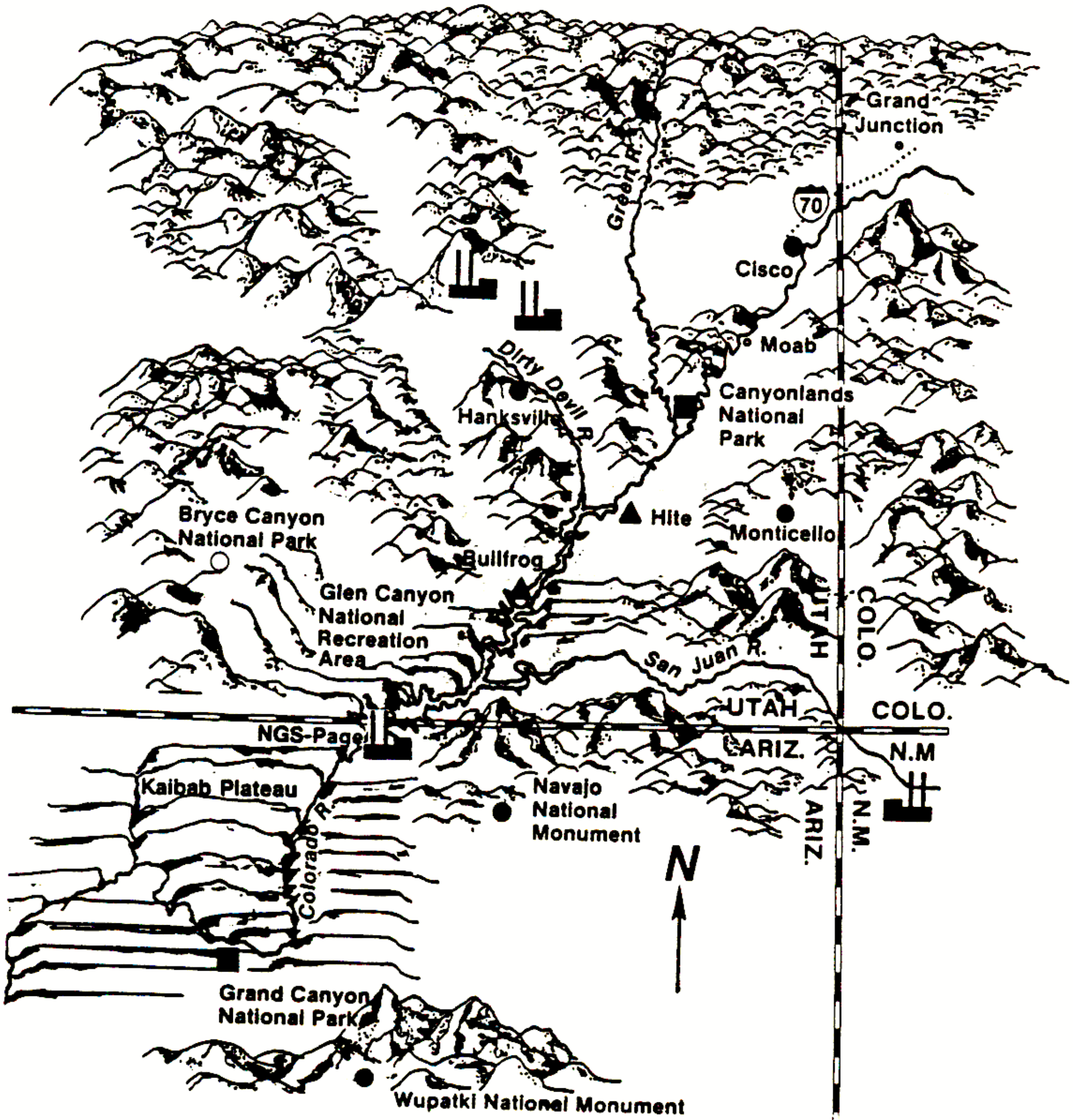

Figure 8.1: Schematic drawing of terrain in the WHITEX study area.

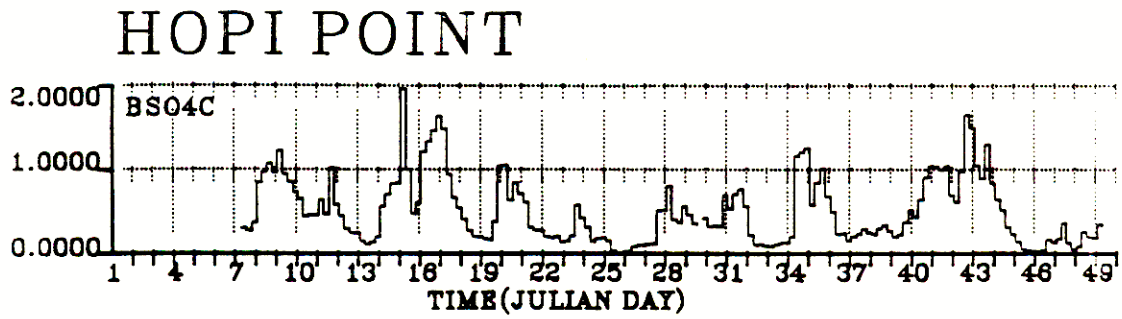

Figure 8.2: Sulfate ion concentration (μg m^{-3}) at Hopi Point for the WHITEX period.

this time would prevent mesoscale transport from moving an airmass from the NGS area to Hopi Point. These two influences are a possible explanation for the lower SO_4 readings for these two days (Figure 8.2). February 8 (JD 39), however, had more southerly surface geostrophic winds which became more southerly with height in the lower troposphere over southern Arizona and the WHITEX area. This appears to have produced long range transport from southern Arizona to the WHITEX area as indicated by the ATAD trajectories for this date (see Appendix 6G). A possible reason that the SO_4 measurements were still low on this day is that from the wind speeds obtained on this day, the transport time from southern Arizona to Hopi Point would be on the order of two days. Therefore, a continuation of the brisk southeast surface geostrophic winds and the southerly winds higher up could have produced long range transport from southern Arizona during February 9 (JD 40) and February 10 (JD 41). The long range transport contribution to the SO_4 readings at Hopi Point would most likely be reduced on February 10 (from the February 9 measurements) due to a weakening of the surface pressure gradient (there is some indication of this from the reduction of sulfur in Figure 8.2 for this date in the evening). On February 11 (JD 42), based on the synoptic analysis, the long range contribution would be expected to end due to the lack of any surface geostrophic wind and the dominance of mesoscale circulations. On February 13 (JD 44), the approach of a polar front from the west produced moderately strong southerly geostrophic winds which reduced the SO_4 at Hopi Point somewhat. The polar front then passed through the area on February 14 (JD 45), venting out the pollutants with the strong pressure gradient force associated with the prefrontal conditions. From time lapse photography (see also Photographs 8-11 through 8-16 at the end of this chapter), it can be seen that it was cloudy during much of this time period (presumably due to the upper level trough on the 10th and the approaching front on the 14th) and that the upper and lower level flows were decoupled. At 500 mb, winds were influenced by a low pressure to the northwest during the peak of this event causing geostrophic flow to be southwesterly at this level. The altitude of the wind measurements taken at the Grand Canyon Desert View site during WHITEX was near the boundary between these upper and lower level flow regimes much of the time, so that the measured wind speeds and directions sometimes reflected the surface layer and at other times reflected the higher level flow.

This episode, which produced the longest persistence of high SO_4 days during the WHITEX study, had surface level circulations which were probably being influenced by moderately strong southeast geostrophic winds for the first two days (JD 40–41) and for the remainder a combination of thermally-forced mesoscale circulations and moderately light winds from the northeast at 300 m above the ground. These light northeast winds (2.5 - 5 ms^{-1}) are difficult to classify as either synoptic or mesoscale due to their close proximity to the ground. A preliminary synoptic scale model simulation[13] for this episode was conducted using National Meteorological Center (NMC) data for initialization to determine if the synoptic winds would produce transport from NGS to the Grand Canyon. This simulation showed that the synoptic winds would transport an NGS plume away from the Grand Canyon. The problem with using just NMC data for initialization purposes to simulate low level transport winds in this case is that in the southwest United States, the spatial resolution of upper air rawinsonde sites is very coarse. Therefore, any one individual rawinsonde station is used to represent a very large area. The data used to produce the initial meteorological fields influencing the WHITEX area in this synoptic simulation were primarily only from three stations (Albuquerque, NM; Winslow, AZ; and Grand Junction, CO). This is especially important for this case because the synoptic winds in the lowest levels of the atmosphere during the later stages of this period were light. Thus, a small variation in the pressure distribution at any of the three sites could produce a geostrophic wind from a different direction since the geostrophic wind is defined by the horizontal gradient of pressure on a constant height surface.

The question as to whether the 300 m northeast winds seen in the Page soundings were generated by synoptic or mesoscale forcing is a hard question to answer, but with the light geostrophic winds present during this time, it is fairly certain that mesoscale circulations had a major influence on the transport circulations in the WHITEX domain. Thermally-forced mesoscale circulations are created due to differential radiational heating between an elevated ground surface (i.e., mountain) and the ambient atmosphere at some distance away from the elevated ground on a constant horizontal level. Elevated surfaces act as an elevated heat source during the day because the ground warms faster than the free atmosphere at the same height. At night, the opposite is true and the elevated surface cools faster than the free atmosphere. Therefore, less dense warm air moves upslope during the day and cooler denser air moves downslope during the night. This is illustrated in Figure 8.3.

January 14 - January 18, 1987

Figure 8.2 shows this episode began with an increase of the SO_4 ion concentration from a low in the late evening of January 13 tending towards a peak in the concentrations on January 17 in the early morning.

On the day in which the pollutant buildup starts, January 14, the synoptic pattern was in transition between a polar high with strong northeast geostrophic winds and a trough to the east which kept the geostrophic winds from the northeast but weaker (5–10 ms^{-1}). This would indicate transport from the northeast and a weakening of the inversion produced by the polar high which had persisted in this area for six days before the start of this event. The moderately strong northeast geostrophic winds persisted until January 16. At that time, they were replaced by strong northwest winds which would tend to reduce the SO_4 at Hopi Point due to the lack of local sources in that direction (see Figure 8.1). The next day, January 17, the SO_4 measurements increased and the geostrophic wind switched back to a strong northeast geostrophic wind. On January 18, the geostrophic winds weakened and were from the east and there was a gradual decrease in SO_4 concentration at Hopi Point.

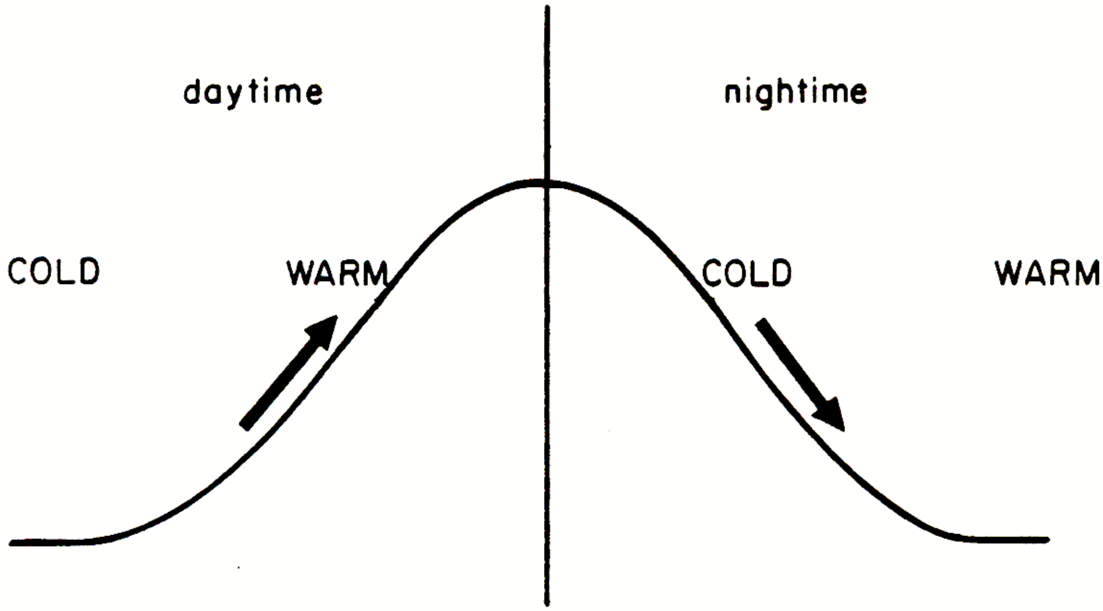

Figure 8.3: Illustration of circulation induced by radiational heating of elevated terrain.

During the high SO_4 period between the afternoon of January 16 until the evening of January 17, clouds were evident in and around the canyon indicating high relative humidity and thus suggesting enhanced conversion of SO_2 to SO_4.

February 3 - February 5, 1987

The synoptic conditions suggest that on February 3 (JD 34) there were light pre-frontal winds from the southwest. The moderately strong geostrophic winds from the northeast associated with postfrontal conditions on February 4 (JD 35) appear to be responsible for the transport of pollution from the northeast to Hopi Point. The light wind polar highs on the first two days of the month apparently allowed a localized pollution buildup to the northeast near NGS before these winds transported the pollutants towards Hopi Point. The polar high is re-established to the north on February 5 with moderately strong easterly and southeasterly winds. Clouds were present during this episode (see Photographs 8-9 and 8-10).

8.2.2 Low Sulfur Episodes

January 25 - 27, 1987

This was a period with low SO_4, beginning midmorning on January 25 and persisting until midmorning on January 27. Preceeding this time period, from January 20 to January 23, strong and moderately strong geostrophic winds persisted over the area with geostrophic flow from the east and southeast for January 21 to January 23. This usually coincides with low concentrations of SO_4 at Hopi Point. Synoptic conditions for January 25 to January 27 indicated the presence of a persistent light wind polar high during which transport would be local in origin and would depend on the local mesoscale flow patterns. Actual surface winds at Desert View during this time period were

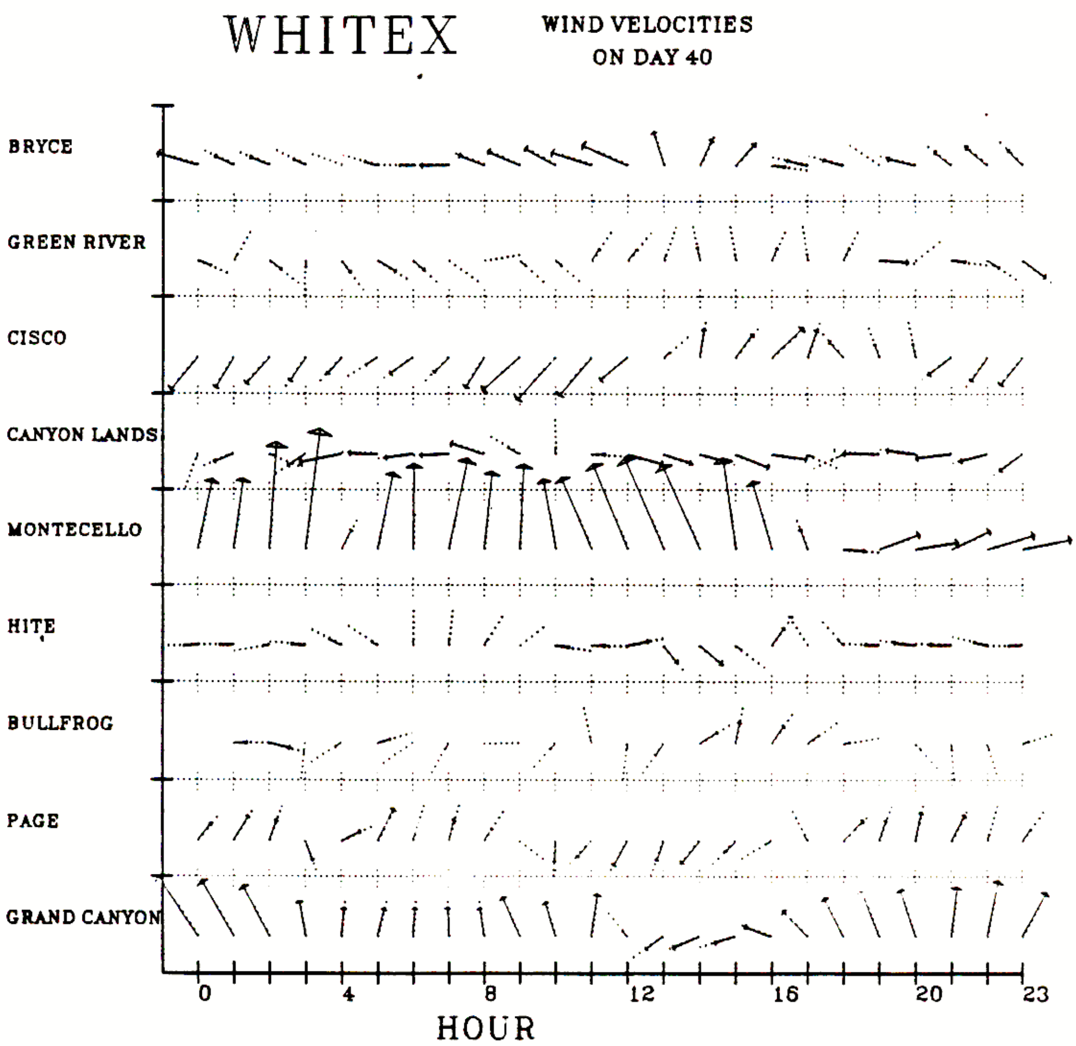

Figure 8.4: Wind vectors at WHITEX sites on Feb. 9, 1987.

mostly from the west and south. There were some high clouds during this period (see Photographs 8-4 through 8-6).

February 1 - February 3, 1987

Figure 8.2 shows persistent low SO_4 values for about two days, beginning on the morning of February 1 (JD 32) and persisting until the morning of February 3 (JD 34). The synoptic conditions suggest that this was again a period consisting of a light wind polar high with the event being not long enough to transport pollutants from surrounding local sources to Hopi Point. Actual surface winds at Desert View were mostly westerly and southwesterly with relatively high speeds (> 5 m s^{-1} for some hours on February 3) during these three days. Skies were clear as can seen in Photographs 8-7 and 8-8.

8.2.3 Summary of WHITEX Episodes

There were three general types of synoptic conditions which transported sulfur from surrounding areas to Hopi Point and thus produced the highest sulfur concentrations at Hopi Point during the WHITEX study of January and February, 1987. These are:

1. A persistent polar high with associated light synoptic winds and subsidence inversion, allowing pollution concentrations to increase near NGS, followed by moderate or strong northeast geostrophic flow which then transports the pollution southwestward toward Hopi Point. The high SO_4 concentrations at Hopi Point occurred during this transport. The January 14 through January 18 and February 3 through February 5 (JD 34–36) episodes can be explained by this mechanism.

2. A persistent (> 2 days) polar high with an associated subsidence inversion and very weak synoptic winds. Actual surface winds are then almost entirely mesoscale terrain induced flow, allowing "sloshing" (see Figure 8.4, Page wind vectors) of the pollutants up and down the canyon between NGS and Hopi Point. Part of the February 9 through February 13 episode can be explained by this mechanism.

3. Long range transport from southern Arizona due to sustained strong south or southwest geostrophic winds. Part of the February 9 through February 13 episode can be explained by this mechanism.

An additional condition which was noted for all three of the high sulfate episodes which occurred during WHITEX was the existence of clouds in and around the area. This suggests that the highest wintertime sulfate concentrations often occur when the relative humidity is high enough to enhance the conversion rate of SO_2 to SO_4 or when there may be in-cloud conversion.

As a further examination of the three high sulfate episodes, the sulfate concentrations at other WHITEX sites were examined for the time periods when sulfate was high at Hopi Point. The absolute concentrations differ between sites due to the differing distances and dispersion between each receptor and NGS, but the relative peaks and low levels in each graph should be consistent with the transport theories. If mechanism 1 was causing the high sulfate concentrations at Hopi Point, then the concentrations of sulfate at Bullfrog, which is north of NGS and Page which is east of NGS would be relatively low during these time periods since the strong northeasterly transport winds are sending the polluted air towards the southwest. As can be seen in Figures 8.5 and 8.6, this is indeed the case for the second two WHITEX SO_4 cases analyzed. If, on the other hand, mechanism 2 or long range transport was causing the high sulfate concentration at Hopi Point, then