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STUDY OF DENSE FOG AT THE SALT LAKE CITY INTERNATIONAL AIRPORT AND ITS IMPACTS TO AVIATION

Jonathan Slemmer
National Weather Service (NWS) Center Weather Service Unit (CWSU)*
Salt Lake City, Utah

(*currently affiliated with NWS Aviation Weather Center, Kansas City, MO)

Introduction

This study will investigate dense fog at the Salt Lake City International Airport (SLC) and its impacts on aviation. For the purposes of this paper, "dense fog" is defined as a *reported surface visibility equal to or less than one-quarter statue mile (SM) without precipitation other than snow grains*. SLC lies at the bottom of the Salt Lake Valley just to the southeast of the Great Salt Lake (GSL), and is surrounded by higher terrain in all directions except generally to its northwest. This valley is particularly susceptible to dense fog during the winter when strong and persistent temperature inversions in association with the surrounding mountains, act as horizontal barriers to trap cold and moist air near the surface. As the moisture, cold air, and pollution accumulate near the surface, the air becomes stagnant enough to produce ideal conditions for the formation of dense fog.� Since just over 1000 airplanes on average depart and arrive daily from SLC[1], dense fog occurrences as brief as a couple of hours can delay or stop air traffic both locally and nationwide, causing substantial monetary losses to the commercial airlines in lost time, fuel, and additional aircraft maintenance.

Many dense fog studies have concentrated on detecting dense fog events using satellite imagery. There is a comprehensive paper on dense fog climatology along the United States west coast (Leipper 1994), but this study has limited application to the inter-mountain region. A thorough paper on dense fog climatology for Spokane, Washington (Frisbie 1995) was used as a basis for the SLC dense fog climatology presented here. The meteorological conditions that contribute to the development of persistent dense fog episodes in the inter-mountain region is covered by Wolyn and McKee (1989). Several studies have looked at dense fog in northern Utah, including building a local dense fog climatology (Alder 1998), examining dense fog triggers (Hogan 1998), and the influences of the size of GSL on dense fog events (Hill 1988).

The history of observations and climatology of dense fog at SLC will be discussed first. A comparison of surface visibility versus Runway Visual Range (RVR) and surface visibility versus tower visibility follows. Some interesting cases of the conditions leading to the formation of dense fog during the 2000-01 and 2001-

02 Great Basin winters will then be presented.

Dense Fog Climatology

The SLC dense fog climatology was derived from 30 years of surface observations beginning in July 1971 and ending in June 2001. Even though the surface observing site has moved several times since 1971 (Alder et al. 1998), the sites have been located relatively close together in the southeastern part of SLC, thus allowing for generally consistent observation locations. The station was initially located at 174 North and 2300 West at the southeastern side of the airport with reporting by a human observer. On March 8, 1978, the station was moved approximately 1300 feet north, placing the station on the eastern edge of the airport. On August 11, 1994, the station was moved approximately 1900 feet to the south on the extreme southeast corner of the airport. Since November 1996, observations have been taken by an ASOS (Automated Surface Observing System) located between runways on the southern end of the airport.

Since precipitation such as snow and rain can further reduce visibilities resulting in an inflated dense fog frequency, dense fog in this climatology is defined as visibilites of one-quarter statue mile or less without precipitation except for snow grains. Only hourly observations were used in this climatology since several special observations reporting dense fog within an hour would produce an inflated dense fog frequency. While these restrictions will not capture dense fog reported between hourly observations, it should capture the most significant events.

The average number of hourly dense fog occurrences per season is 58 (Fig. 1). Hourly dense fog occurrences have been as high as 266 in 1980-81 and as low as 0 in 1977-78. Four seasons had more than double the average occurring in 1975-76, 1980-81, 1984-85, and 1991-92. Eleven seasons had less than 15 hours of dense fog including 1971-72, 1973-74, 1974-75, 1976-78, 1978-79, 1981-82, 1993-94, 1994-95, 1995-96, 1996-97, 1998-99. Every dense fog season since 1993-94 has had below normal hourly dense fog occurrences. Hill (1988) suggests that the size of GSL may influence the amount of moisture in the air resulting in more dense fog when GSL levels are higher and areal coverage is greater. However, the greatest and least seasonal frequency of dense fog at SLC in this study occurred in 1980-81 and 1977-78, respectively, when GSL levels were near normal historical levels(USGS 2004; see http://ut.water.usgs.gov/infores/gsl.intro.html). There are probably more significant contributions to the development of dense fog such as the presence of Deep Stable Layers (DSL=s; Wolyn and McKee 1989). It's important to note that the 2000-2001 season had 106 observations with dense fog reports although only 49 of these observations (46 percent) were reported at the surface.� This is due to dense fog being reported at the tower and not at the surface sensor. Similarly, the 1999-2000 and 2001-02 seasons had numerous observations reporting dense fog at the tower but not the surface. This will be discussed later in this paper.

Dense fog is most common in January and December when insolation is at its weakest (Fig. 2, Fig. 3). The average frequency of dense fog reported at the surface in the hourly observations is 3.4 percent in January. Even though insolation typically increases in February, enough cold air and snow cover may be present to create dense fog. November and March have had rare episodes of dense fog while all other months have had statistically insignificant occurrences.

Dense fog occurrences per day (Fig. 4) rapidly increase in the middle of December and fluctuate significantly through the middle of February. These data was smoothed over 9 days to reduce the fluctuations. Three notable peaks occur in mid-December, around the first of the year, and the later part of January. Two big dips are evident in late December and mid-January. The dense fog occurrences from the middle to later part of January gradually decrease through late February. The daily dense fog fluctuations during winter are also supported by Alder (1998) when he looked at the frequency of daily dense fog occurrences from 1928 to

1998. The 1968-96 daily climatology of several upper-air fields (e.g., 500-mb heights, 250-mb winds) obtained from the National Climate Data Center web-site (see http://www.cdc.noaa.gov/cgi-bin/Composites/printpage.pl) were studied corresponding to the dense fog Apeaks and valleys@ in December and January. No significant correlations were found, such as stronger ridging with higher occurrences of daily dense fog. The fog climatology data set may not be large enough to naturally smooth these peaks and valleys.

Dense fog is most common from 0600 to 0800 LST (Local Standard Time) and is least common from 1200 to 1600 LST (Fig 5). A significant decrease in dense fog frequency occurs between 0900 and 1000 LST. Dense fog frequency gradually increases from 1700 through 0700 LST. From 0600 to 0800 LST, the typical year has an average of 4 to 5 occurences of dense fog per hour. From 1200 to 1600 LST, the typically year has an average of one dense fog occurrence per hour.

When wind speeds are not calm (less than 3 kt), dense fog most commonly occurs with a wind direction from the southeast or northwest (Fig. 6). These wind directions are common at SLC nearly any time of the year because of local mountain-valley circulations. When the synoptic scale has little impact on the Salt Lake Valley=s weather and diurnal circulations dominate, the southeast winds last approximately two times as long as the northwest winds during the winter (wind directions of 120 to 190 degrees true occur 49.8 percent of the time while wind directions of 290 to 360 degrees true occur 27.5 percent of the time during the period of December through February). Thus, there is a higher probability of dense fog occurring when there is a northwesterly wind since this tends to advect low level air masses that are colder and have higher relative humidities.

The majority of dense fog occurs when wind speeds are 6 kt or less (Fig. 7). Dense fog is rare when wind speeds are 9 kt or greater, with the highest frequency near 4 kt. This may be a reflection of dense fog advecting in from GSL. The greatest frequency of dense fog occurs when the temperature ranges between 23 to 27 ^{o}F (Fig. 8). Approximately 90 percent of dense fog occurs between 13 to 32 ^{o}F. Dense fog is rare when temperatures get much above freezing.

The average dew point depression when dense fog occurs is 2.2 ^{o}F (Fig. 9). Dew point depressions should be close to zero when dense fog is present, except when fog forms as a result of saturation with respect to ice (Frisbie 1995). Approximately only 3 percent of the dense fog observations in this study were cold enough for conditions to be saturated with respect to ice. However, the climatology revealed some unusually high dew point depressions. Most winters had dew point depressions of 2 ^{o}F or less, but the winters of 1972-73, 1980-81, 1983-84, 1984-85, and 1985-86 had a much greater frequency of high dew point depressions (Fig. 10). It=s surmised that the equipment was poorly calibrated or of low quality during these periods, particularly in the mid 1980=s.

The greatest frequency of dense fog occurs when the altimeter ranges between 30.20 to 30.29 in Hg (Fig. 11). Dense fog usually does not form with an altimeter reading below 29.90 in Hg.

Most dense fog events last for only four consecutive hours or less (Fig. 12). A significant number of dense fog events occur over a period of 5 to 10 hours. One extreme event had 28 consecutive hours of dense fog which began at 0600 LST on December 28, 1980, and ended the following day at 1000 LST.

Surface Visibility versus Tower Visibility

When the visibility decreases to four miles or less and the tower and surface visibilities differ, the lowest visibility becomes the prevailing visibility in the observation while the higher visibility is mentioned in the remarks.

Prior to November 1999, the SLC tower was approximately 100 feet above the ground and located near the middle of the airport property. The frequency of dense fog reports at the tower with no dense fog reported at the surface occurred approximately 9 percent of the time. In these cases, low clouds or dense fog may have reduced the visibility to less than one-quarter mile at the tower, while none was occurring at the surface station.

Since November 1999, the tower has been located approximately 374 feet above the ground on the northern side of the airport[2]. During the winters of 1999-2000 through 2001-2002, the tower reported dense fog 46 percent of the time, while at the same time the surface had no dense fog. This increase in dense fog occurrences at the tower and not at the surface may be due to the increased height of the tower and the movement of the tower further north. The increased tower height makes the tower more susceptible to reporting low clouds as dense fog. The movement of the tower further north may also make the tower more susceptible to shallow cold pools advecting from GSL.

An aviation forecaster shall forecast a visibility that is representative of expectant *surface* conditions when composing a Terminal Aerodome Forecasts (TAF). Since the tower visibility may not be representative of conditions at the surface, aviation forecasters should be aware that the tower visibility may be reported as the prevailing visibility in the surface observation. Researchers should also realize that a visibility climatology for some sites may be a mixture of surface and tower reports.

Surface Visibility versus Runway Visual Range (RVR)

Though surface visibility is fairly representative of RVR reports, this is not always the case. One of the main reasons for the difference between surface and RVR visibilities is the location of the observations. The ASOS is located at the south central end of SLC, while the RVR=s cover the northern, middle, and southern sections of all the runways. During the winter, dense fog associated with shallow cold pools occasionally advects from around the Great Salt Lake towards SLC. Dramatic temperature drops on the order of 5 to 15 ^{o}F and visibility reductions from greater than 6 SM to less than one-quarter of a statue mile have occurred over periods of a few minutes with these shallow cold pools.

In these cases, RVR sensors on the northern and western ends of the runways frequently report low visibilities before they are reported by ASOS. In some of these cases, dense fog never develops at the southeastern end of the airport. This has produced situations where RVR readings are below 1400 feet for an extended period of time towards the northwestern side of the airport, and surface visibilities in excess of 3 miles at the southeastern end of the airport.

The Federal Aviation Administration (FAA) uses airport RVR thresholds when issuing air traffic ground delays and stops. When dense fog is reducing RVR values enough to have impacts on air traffic operations at SLC, the surface observation occasionally reports no dense fog, and in unusual cases visibilities in excess of 3 SM.

Though RVR data would be of potential use to an aviation forecaster, who can be alerted to the potential development of dense fog at the ASOS, the forecaster is currently unable to access RVR data.

SLC Dense Fog Events (December 2000-January 2001 and December 2001-January 2002)

Prolonged Inversion Case - A persistent inversion formed on 25 December 2000 and continued through approximately 10 January 2001. Dense fog was first reported on the morning of December 28. Most of the dense fog occurred at the surface and tower through December 30 since the cold pool was relatively shallow. As the cold pool deepened with time, the area of fog and low clouds elevated for several days, resulting in dense fog frequently being reported at the tower and not at the surface. In the last few days of this event, the cold pool eventually deepened enough, lifting low clouds even higher and eliminating dense fog at both the surface and tower. This fog event resulted from a DSL.

The dense fog reports occurred primarily between 9 AM LST on December 29, through 10 PM LST on December 31. Fifty-four of 55 hourly observations reported dense fog at SLC during this period. However, 39 of these hours had dense fog only at the tower.

Precipitation Falling into a Weakened Inversion and Shallow Cold Pool Cases - Two dense fog events occurred on 10th and 20th of January 2001. In each of these cases, an approaching weak weather system generated very light precipitation which fell through a weakened inversion and into a shallow cold pool. Several hours after the precipitation ended, dense fog developed. Out of the 13 hours in which dense fog was reported, 1 hour had dense fog only at the tower.

When dense fog was reported at the surface, the RVR=s frequently reported visibilities at or below 1200 feet. The surface high pressure was relatively strong in both cases with altimeter ranges of 29.96 to 29.99 in Hg during the 10 January case, and 30.39 to 30.47 in Hg during the 20 January case. Even though an approaching storm system might be able to weaken an inversion, it may not be strong enough to eliminate the cold pool. If light precipitation falls into the cold pool, the additional moisture may lead to the formation of dense fog.

Shallow Cold Pool Advecting from GSL Cases - Several of the dense fog events, particularly during December 2001 and January 2002, occurred as a result of radiation fog developing over GSL that eventually advected over SLC. Because of slight elevation gains from north and west of SLC to the south and east, the dense fog was sometimes slow to move to the southeast and over the airport.

Larry Burch (Meteorologist in Charge at NWS CWSU SLC) participated in several fog dispersion flights during some of these dense fog advection events from the GSL. On these flights, dry ice was crushed and emitted from the plane around the airport. The dry ice is made of hydroscopic condensation nuclei that cause suspended water droplets to condense and precipitate from the atmosphere as snow grains when temperatures are sufficiently cold. The fog dispersal activities can be effective at significantly increasing visibilities for a period of time. On a couple of these flights, the fog was observed to form Afingers@ near and over GSL (an undulating surface pattern of fog, then clear skies). This shows the development of dense fog can be very sensitive to slight atmospheric differences within a small area.�

When a shallow cold pool with dense fog moves over the airport, a dramatic temperature drop typically occurs. Although these dropping temperatures and visibility reductions usually occur together, their relationship and dependency is unclear. A recent case of a shallow cold pool advecting over the airport from GSL has shown that the temperature can drop dramatically without a great reduction in visibility. An observation from 6:17 AM LST on 30 January 2002 reported a temperature drop of 9 ^{o}F in 21 minutes. The visibility remained at 10 SM, but the RVR on the north end of the airport fell to 3500 feet. By 6:45 AM LST, the temperature warmed slightly and the visibility decreased to 5 SM, with the north end of the airport reporting an RVR of 1600 feet. In addition, a brief deck of broken clouds developed at 100 feet. Thereafter, the visibility and temperature gradually increased.

These cases are particularly difficult to forecast as the shallow cold pools may Aslosh@ (progress and retreat) over the airport several times per event. Operational models have a very difficult time predicting the movement of these shallow cold pools, even in weak flow situations. Typically in these cases, models will forecast a diurnal wind pattern (southeast drainage during the night and morning, and northwest during the afternoon and early evening).

Comparison of Dec 2000-January 2001 and December 2001-January 2002

The period of December 2000 through January 2001 had 54 percent of the dense fog observations reported at only the tower, 43 percent reported at the tower and surface, and 3 percent at only the surface. These statistics were greatly influenced by the DSL event in late December and early January.

The period of December 2001 through January 2002 had much shorter lived fog events and mostly resulted from shallow cold pools advecting from GSL. As a result, dense fog observations as reported at the tower only were much lower than the previous winter at 23 percent. Dense fog was reported at the tower and the surface 54 percent of the time, and 23 percent at the surface only.

Conclusion

This study examined dense fog and its impacts to aviation at the Salt Lake City International Airport. The 30-year dense fog climatology showed the highest occurrence of dense fog to be during the winter when there is a minimum of solar radiation. Dense fog typically formed during the early morning hours when temperatures are on average at their daily minimum. There are an average of 58 hourly occurrences of dense fog per winter. Several winters have had very little dense fog while the winter of 1977-78 had no dense fog reports at all. Dense fog occurrences are most likely when the surface temperature is in the 20=s ^{o}F, the dew point depression is 3 degrees or lower, the wind is 6 kt or less, and the altimeter is 29.90 in Hg or higher. Dense fog most frequently occurs with a southeast or northwest wind, although a northwest wind is preferred. Prolonged dense fog events usually do not exceed 12 consecutive hours in duration, typically beginning in the evening hours and lasting through the morning. In one rare event, dense fog lasted 28 consecutive hours.

Surface observations were used to develop the dense fog climatology. When dense fog is reported in the surface observation, commercial aircraft operations are usually impacted. However, the�FAA uses RVR visibility thresholds for issuing airport ground delays and stops. Surface observation visibilities and RVRs are usually consistent, but can differ significantly due to local effects such as when dense fog advects in from the GSL and to the location of the equipment.

Another potential problem with using surface observations arises when the tower visibility replaces the surface visibility. In these cases, the visibility at the tower becomes less than 4 SM and is less than the surface visibility. Until November of 1999, when the tower visibility was taken approximately 100 feet above the ground, dense fog reported without dense fog at the surface occurred approximately 9 percent of the time. Since then, the tower visibility is reported at 374 feet above the surface, significantly increasing the frequency of dense fog occurring at the tower while not occurring at the surface to 46 percent. This large discrepancy is due to the tower sometimes reporting dense fog while in low clouds. Thus, tower visibility would not be a good indicator of dense fog impacts to SLC air traffic.

Dense fog has also been observed to occur at SLC when deep stable layers form, when precipitation has fallen into a weakened and shallow inversion, and when shallow cold pools advect from the Great Salt Lake. Hogan (1998) has investigated some of the distinct features that may contribute to the formation of dense fog at SLC, such as effects of snow cover, inversion heights, and cloud cover. In the future, additional studies on dense fog events at SLC could classify types, in addition to develop a better understanding of the mechanisms that lead to these and other dense fog events.

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[2] Federal Aviation Administration, Approach Plates for Salt Lake International Airport, April 18, 2002. (return to text)