Deep Stable Layers in the Intermountain Western United States

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ABSTRACT

A deep stable layer (DSL) is a layer much deeper than a typical nocturnal inversion with stabilities not frequently found over a sizable portion of the lowest 1.5 km. They have traits that can cause the stagnation of cold air in basins, i.e., light winds at the surface even if moderately strong winds aloft are present, and the restriction of the growth of daytime convective boundary layers. The objective definition used in this study is that, if 65% of the lowest 1.5 km of the 1200 UTC [0500 mountain standard time (MST)] sounding has a lapse rate of 2.5°C km^{-1} or less, then the day is under the influence of a DSL. A climatology of days under the influence of a DSL was performed at four sites in the intermountain western United States: Grand Junction, Colorado; Salt Lake City, Utah; Winnemucca, Nevada; and Boise, Idaho. The DSL is a wintertime phenomenon with 10% to 20% of the days in December and January at the four stations being under the influence of a DSL. Successive days with a DSL present lead to episodes of varying lengths. Episodes of three days or longer occurred at least once each year at Boise and Grand Junction and at least once every two years at Salt Lake City and Winnemucca. An episode of 8 days duration occurred at Grand Junction.

A DSL episode that occurred in December 1980 was examined in depth to gain insight into the life cycle of a DSL. Synoptic-scale warming above 1 to 1.5 km and weak surface heating were important for the initiation of the episode. The longwave radiation properties of a persistent fog layer and weak surface heating were important physical processes for maintaining and prolonging the episode. From the episode it is hypothesized that DSLs form when warming aloft traps relatively cold air near the surface, decoupling it from the rest of the atmosphere. The barriers surrounding the basins are important for the formation of a DSL because they prevent the horizontal movement of the cold air. DSLs have important implications for air quality, episodes of persistent fog, and surface temperature forecasts.

1. Introduction

Complex terrain has profound influences on the movement of surface air masses which are stable. Mountain barriers can prevent the movement of very stable, relatively cold air masses into a region. The barrier's influences can also have the opposite effect. If a stable air mass moves into or develops within the region or if warming aloft greatly increases the stability of the air mass, the complex terrain can prevent the stable, relatively cold air from leaving the region.

This study will examine an atmospheric condition defined as a deep stable layer (DSL) in the intermountain western United States. DSLs are deep layers of at least moderate stability that are deeper than typical nocturnal inversions. The deep layer of stability has two traits which can cause the stagnation of relatively cold air in basins. The stability can cause light winds at the surface even if there are moderately strong winds aloft and they can cause a shallow daytime convective boundary layer (CBL).

DSLs are studied at Salt Lake City, Utah; Boise, Idaho; Winnemucca, Nevada; and Grand Junction, Colorado. Figure 1 shows the location of these intermountain region stations. The four stations are located in basins. In this study a "basin" refers to a broad, fairly deep valley where the destruction of a nocturnal inversion proceeds like the destruction over flat terrain. Unlike deep, relatively narrow mountain valleys, buoyant flows up the slope of the surrounding terrain are not important for the destruction of a nocturnal inversion (see Bader and McKee 1985).

There have been many studies of persistent fog episodes and poor air quality which were associated with deep layers of stability in complex terrain. Willett (1928) found that for high inversion fog in Europe, the mean temperature was −2°C at the surface, −4.7°C at 700 m and 0°C at 1270 m. Lockhart (1943) studied high inversion fog in the Central Valley of California. He indicated that, during formation of the episode, warming and drying occurred at a station 4209 feet MSL while no trend occurred in the valley. Once the fog formed, it remained in the Central Valley until a disturbance moved over the region causing the fog and associated inversion to dissipate. Holets and Swanson (1981) indicated that the change in potential temperature with height in a high inversion fog episode was 29 K km^{-1} and that this inversion above the fog layer had a thickness of 1000 m or less. Yu and Pielke (1986)

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FIG. 1. Locations of the stations used in this study.

in their study of air pollution in the Lake Powell region of Utah showed several soundings on days with poor visibility. These days had deep layers of moderate stability. The use of a fully dynamic mesoscale model showed that "recirculation" of pollutants in the cold stagnant air occurred without a sizable amount of pollutants leaving the region.

In this paper the rationale for the objective definition of a DSL will be stated. Then, using this definition, 25 years of National Weather Service (NWS) sounding data at the four intermountain region stations will be examined to develop a climatology of DSLs. One extensive DSL episode will be examined in depth to provide insight into the important factors for the initiation, continuation, and termination of DSL episodes. From this episode the physical processes that form a DSL will be hypothesized. Finally, the influence that DSLs have on air quality, fog episodes, and surface temperature forecasting will be discussed.

2. Deep stable layer definition

The DSL definition is comprised of a depth and lapse rate criteria. The depth criteria identifies layers of stability much deeper than typical nocturnal inversions. The lapse rate criteria eliminates the possibility of buoyancy-induced motions and isolates one group of soundings with relatively strong static stabilities, which do not occur frequently over significant depths of the lower atmosphere. Days satisfying the definition have two traits that can cause the stagnation of air in basins in the intermountain west. First, the layer will severely hamper the mechanically induced vertical mixing of momentum except when a strong wind shear is present. Second, the layer will require a substantial sensible heat input at the surface to form a deep daytime CBL.

The definition of a DSL used in this study is that if 65% of the lowest 1.5 km of the 1200 UTC [0500 Mountain Standard Time (mst)] sounding has a lapse rate of 2.5°C km^{-1} or less the day is under the influence of a DSL. The climatological study of sounding data done by Holzworth and Fisher (1979) showed that at least 75% of the 1200 UTC soundings in the intermountain west had surface-based inversion depths of 500 m or less and that more than half of the soundings had surface-based inversions of 250 m or less. The DSL definition examines a layer much deeper than a typical nocturnal inversion, and the depth of the sounding which must satisfy the minimum stability criteria is at least twice as deep as a typical nocturnal inversion.

Figure 2 shows a temperature versus height plot in the lowest 2.0 km for three special conditions, the DSL lapse rate criteria, a sounding which meets the DSL criteria, and a sounding which does not meet the criteria. The three special conditions are lapse rates of 9.8°C km^{-1}, 4.0°C km^{-1} and isothermal. The line with a lapse rate of 9.8°C km^{-1} is the dry adiabatic lapse rate. Except for shallow layers, a sounding cannot be less stable than this lapse rate. The line with a lapse rate of 4.0°C km^{-1} is a representative value for moist adiabats at temperatures near 20°C and pressures of 800 mb. (For 0°C and 800 mb the lapse rate is near

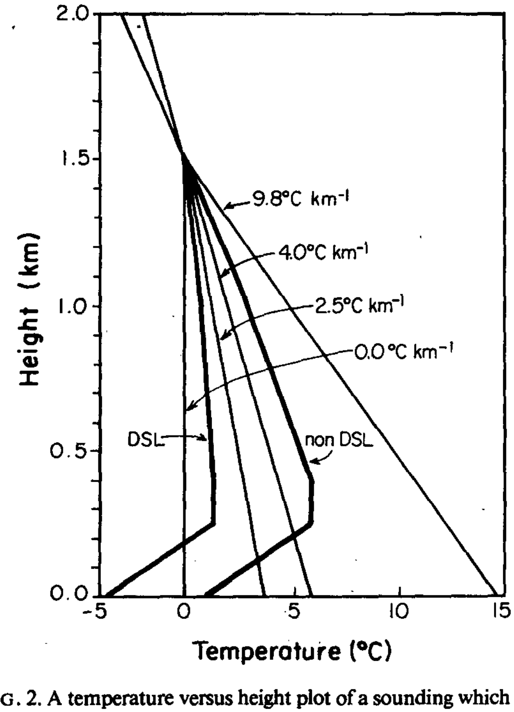

FIG. 2. A temperature versus height plot of a sounding which meets the DSL criteria and one which does not. The lighter lines are lapse rates of 9.8, 4.0, 2.5°C km^{-1}, and isothermal.

5°C km^{-1}). Saturated parcels are buoyant if the lapse rate is greater than moist adiabatic. Using a more stable lapse rate than moist adiabatic ensures that parcels are not buoyant even when saturated. The isothermal lapse rate defines a relative boundary since few soundings have a significant portion of the lowest 1.5 km with lapse rates at least this stable.

The DSL definition is in the region between moist adiabatic and isothermal lapse rates. Soundings that meet the DSL definition have a significant portion of the layer above a surface-based inversion (or other thermal structure) and below 1.5 km with lapse rates less (more stable) than 2.5°C km^{-1}. These soundings comprise a set of days formed by a strong stabilizing action in the atmosphere. The two soundings in Fig. 3 with bold lines illustrate the difference between a sounding which meets the DSL (to the left) and one which does not meet the definition. The energy required to bring each to the adiabatic lapse rate is strikingly different. Sensitivity of the frequency of the number of DSL days to the depth and lapse rate criteria are shown in Figs. 3 and 4. Figure 3 shows the mean percentage change in the number of DSL days using different lapse rate criteria for the four stations in the study for the years 1960–64. The curve is shaped like a negative exponent. The 2.5°C km^{-1} lapse rate is on the edge of a region where the number of days identified increases rapidly for larger lapse rates. For example, decreasing the lapse rate to 2.0°C km^{-1} results in only 19%–26% fewer days meeting the DSL definition while increasing the lapse rate to 3.0°C km^{-1} results in 22%–45% more days meeting the definition. Using the isothermal lapse rate decreases the number of days by 43%–68% while using 4.0°C km^{-1} increases the number of days by 81%–167%. The 2.5°C km^{-1} lapse rate appears to identify one group of days with deep layers of stability which does not commonly occur. Choosing a smaller lapse rate, like isothermal, will identify less days of a similar nature while a larger lapse rate may start to identify days in a different regime.

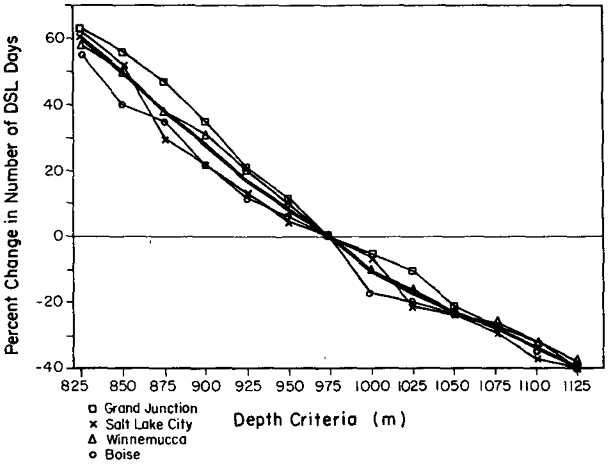

FIG. 4. As in Fig. 3 but for depth criteria.

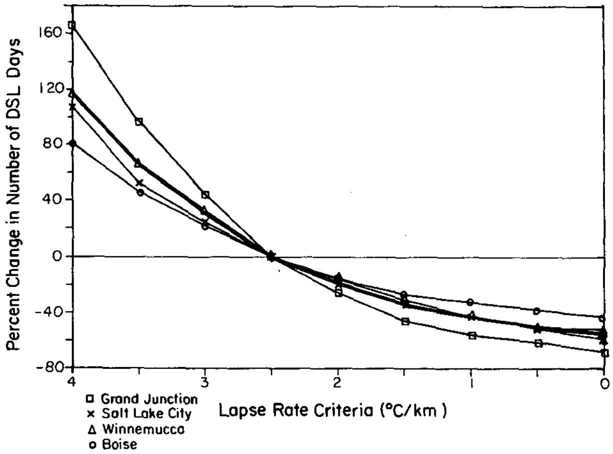

FIG. 3. The mean percentage change (bold line) for the four stations in the number of DSL days for different lapse rate criteria. The lighter lines show the percentage change for individual stations.

Figure 4 shows a similar graph for the depth criteria. The depth criteria has more of a linear shape than the lapse rate criteria. Changing the depth criteria by 25 m will alter the number of DSL days by 5%–11% while a change of 50 m will alter the number of days by 10%–21%. The slope of the lines connecting the mean percentage change is almost exactly linear for depth ranges 825–925 m and 1025–1125 m with the lines in these two regions having different slopes. It is interesting to note that the depth criteria (975 m) is in a transition region between two different meteorological regimes.

Other key factors in the choice of a definition are to identify days which would likely have the traits of light surface winds even with moderately strong winds aloft and shallow daytime CBLs. The Richardson number given in Panofsky and Dutton (1984) is

$$R_i = \frac{g}{T} \frac{(\gamma_d - \gamma)}{(\partial v/\partial z)^2}, \qquad (1)$$

where

R_i	Richardson number,
g	gravity,
T	temperature,
γ_d	dry adiabatic lapse rate,
γ	the lapse rate of the atmosphere,
v	wind speed,
z	height.

Panofsky and Dutton (1984) state that when using rawinsondes a bulk Richardson number of 1.0 is needed to get clear air turbulence. With a temperature of 273 K and a lapse rate of 2.5°C km^{-1} a wind shear of 16 m s^{-1}/km is needed to get a bulk Richardson number equal to 1.0. The depth criteria in the present definition of a DSL will allow for a sufficiently deep layer of stable air so that vertical momentum transfer will not occur easily. Since the objective DSL definition requires a

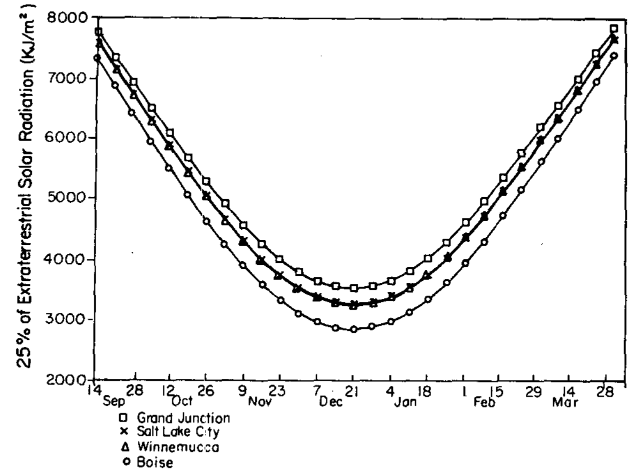

FIG. 5. Twenty-five percent of the daily extraterrestrial solar radiation at the four stations from 14 September 1980 to 28 March 1981.

fairly large wind shear to have vertical mixing of momentum, it is likely that the cold air in the basin will have only light wind speeds even if the winds above the basin are relatively strong.

Figure 5 shows 25% of the daily incoming solar radiation at the top of the atmosphere for the four intermountain region stations. (Using 25% of the radiation will be shown later to be a good estimate.) Comparing this figure to two hypothetical soundings will demonstrate that a sizable amount of surface heating needed to form a CBL when a DSL is present. A sounding which minimally meets the DSL requirements has a lapse rate of 2.5°C km^{-1} from the surface upward. To form a CBL up to 500, 750, and 1000 m requires a surface sensible heat flux of 1835, 2753, and 3671 kJ m^{-2}, respectively. During the low sun season 25% of the incoming solar radiation is not much greater than the amount needed to form a CBL up to 1000 m.

A surface-based nocturnal inversion often is present at the morning sounding. When a 250 m deep surface inversion with a strength of 10°C km^{-1} (a "weak" surface inversion as defined by Holzworth and Fisher 1979) is inserted into the sounding, the amount of energy required to form a CBL to 500, 750, and 1000 m becomes 2220.0, 3139.7, and 4057.4 kJ m^{-2}, respectively. Figure 5 shows that for an 8 week period centered on the solstice at Grand Junction, 10 weeks at Salt Lake City and Winnemucca, and for 13 weeks at Boise the 25% of the incoming solar radiation is below the amount to form a CBL to 1000 m. A sounding with a weak surface-based inversion and a layer above which barely meets the DSL lapse rate criteria likely would not be able to form a daytime CBL deep enough to destroy the DSL by surface sensible heat flux alone during the low sun season.

3. Deep stable layer climatology

National Weather Service rawinsonde data from 1959 to 1983 at Salt Lake City, Utah; Boise, Idaho; Winnemucca, Nevada; and Grand Junction, Colorado were examined to determine the days on which DSLs were present. Unlike previous studies (i.e., Holzworth 1962, 1967) where climatologies of mean soundings were developed, we are identifying specific days with deep layers of moderate stability. The data includes temperature and moisture at the mandatory and significant levels which according to the Manual for Radiosonde Coding (1968) can represent the temperature profile to an accuracy of at least 2°C and humidity to 10% below 300 mb when a straight line connects these points.

Table 1 shows the number of DSL days by month at the four intermountain region stations. The distribution is very similar for all the stations. In December and January 10% to 20% of the days met the objective DSL definition while from April to September less than 2% of the days were DSL days. Table 2 shows the length of DSL episodes. Days with missing or bad data were

TABLE 1. Monthly distribution of DSL days and percentage of DSL days in all days of the period of record from 1959 to 1983.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
					Grand Junction								
Number of days	151	33	4	3	5	6	4	6	9	16	37	143	417
Percentage	20	5	1	<1	1	1	1	1	1	2	5	18	
					Salt Lake City								
Number of days	83	30	8	3	2	4	3	2	4	25	49	85	298
Percentage	11	4	1	<1	<1	1	<1	<1	1	3	7	11	
					Winnemucca								
Number of days	119	40	6	0	9	0	4	3	7	35	76	117	417
Percentage	15	6	1	0	1	0	1	<1	1	5	10	15	
					Boise								
Number of days	118	51	8	6	3	6	14	3	8	53	76	116	462
Percentage	15	7	1	1	<1	1	2	<1	1	7	10	15	

TABLE 2. Monthly distribution of DSL episodes of various length (number of days) over the period of record from 1959 to 1983.

Length	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Grand Junction												
1	40	13	2	3	5	6	4	6	10	14	29	41
2	25	4	1	0	0	0	0	0	0	1	2	21
3	10	2	0	0	0	0	0	0	0	0	1	8
4	3	0	0	0	0	0	0	0	0	0	0	2
5	2	0	0	0	0	0	0	0	0	0	0	1
6	2	0	0	0	0	0	0	0	0	0	0	1
7	0	0	0	0	0	0	0	0	0	0	0	1
8	0	0	0	0	0	0	0	0	0	0	0	1
Salt Lake City												
1	29	15	6	3	2	4	3	2	4	19	33	43
2	9	6	1	0	0	0	0	0	0	1	7	16
3	6	1	0	0	0	0	0	0	0	1	0	1
4	1	0	0	0	0	0	0	0	0	0	1	2
5	1	0	0	0	0	0	0	0	0	0	0	0
6	1	0	0	0	0	0	0	0	0	0	0	0
Winnemucca												
1	51	19	6	0	9	0	4	3	7	25	37	59
2	21	6	0	0	0	0	0	0	0	5	11	16
3	7	1	0	0	0	0	0	0	0	0	2	4
4	1	0	0	0	0	0	0	0	0	0	2	2
5	1	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	1	0
Boise												
1	52	20	8	6	3	6	11	3	5	36	40	35
2	11	9	0	0	0	0	0	0	0	6	7	15
3	4	1	0	0	0	0	0	0	1	2	3	11
4	4	0	0	0	0	0	0	0	0	0	2	0
5	3	1	0	0	0	0	0	0	0	0	0	2
6	0	0	0	0	0	0	0	0	0	0	1	0

included in an episode as having a DSL if the episode was at least four days long and if the day was sandwiched between two DSL days. In the 25 years examined, the number of DSL episodes of three days or longer was 15 at Salt Lake City, 21 at Winnemucca, 34 at Grand Junction, and 35 at Boise. The average number of episodes of three days or longer per year was 0.60 at Salt Lake City, 0.84 at Winnemucca, 1.36 at Grand Junction, and 1.40 at Boise.

The examination of the DSL episode that follows will show that the objective definition is "conservative." That is, cold air stagnation may occur on days that do not strictly meet DSL criteria. Consequently, the statistics presented in this section may underestimate the number of days with sufficiently deep layers of stability to cause cold air to stagnate. The results of this climatology as well as the few examples in the introduction of DSL-like phenomenon strongly suggest that DSLs are common occurrences throughout most of the intermountain western United States.

4. Episode

In this section a DSL episode which occurred at the four intermountain region stations from 6 to 23 December 1980 will be examined in detail. Table 3 shows the days which met the objective deep stable layer definition at each location. The analysis will focus on Salt Lake City, which had persistent fog, and Winnemucca, which did not have fog. First, the synoptic situation during the initiation, continuation, and termination of the episode will be discussed. Then, diagrams showing the vertical profiles of potential temperature and winds throughout the episode will be examined.

a. Synoptic situation

Figure 6 shows the 700 mb temperature time history for 6 to 23 December 1980 at the four intermountain region stations. On the 7th and 8th, a deep, cold trough was over the intermountain region providing unsettled weather. By the 9th the upper level trough had moved eastward. For the next several days a warm ridge built into the area causing significant warming at all stations. During this time an eastward progression of warming is evident. On the 13th and 14th a weak "cutoff" low moved over the region resulting in slight cooling aloft. Afterwards, the warm ridge reappeared over the region. On the 17th the ridge began to weaken and by the 21st the flow over the region was nearly zonal. By the 22nd the winds aloft had become stronger as a result of a Pacific storm moving onshore.

TABLE 3. Days which satisfied the objective deep stable layer definition.

Date (December)	Grand Junction	Salt Lake City	Winnemucca	Boise
6				
7				
8				
9			×	×
10		×	×	×
11	×		×	×
12		×		×
13	×		×	×
14	×	×	×	
15	×	×		×
16	×	×		×
17	×	×		×
18	×			×
19				×
20				
21				
22				
23				

b. Isentropic analysis

To gain better insight into the life cycle of the episode, time–height sections of potential temperature and winds were constructed (Figures 7 and 8). Winds are also plotted. Each small barb indicates speeds of 2–3 m s^{-1}, each full barb represents speeds of 4–6 m s^{-1}, and each flag represents speeds of 24–26 m s^{-1}. The shading on the figures represents dew point depressions of 3°C or less. For the rest of this paper the word "day" represents the calendar day at the station. "Morning" refers to the 1200 UTC (0500 MST) sounding and "afternoon" refers to the 0000 UTC (1700 MST) sounding.

To aid in the discussion of the episode, three phases of the deep stable layer episode will be defined. The initiation phase occurs when processes which form a DSL occur. Once a DSL is formed the continuation phase begins. During the continuation phase the DSL may strengthen or weaken, but processes which lead to the final destruction of the episode do not occur. The termination phase starts when processes which lead to the destruction of the episode are first evident.

1) SALT LAKE CITY

Figure 7 shows the isentropic analysis for Salt Lake City. On the 6th there is a deep layer of slight stability up to 5.0 km. Then the initiation phase of the episode starts. Beginning the morning of the 7th, a layer of strong stability and rapid warming appears in the upper part of the sounding. The region of warming descends and by the tenth the base of the stable layer reaches a height of 1.0 km. At this time the continuation phase begins. The adiabats become horizontal between 400 and 1000 m signifying the presence of a deep layer of strong stability. This layer will be called the capping stable layer. From the morning of the 10th through the 12th the air near the surface is very moist but fog does not form. On the 13th a persistent fog layer develops which lasts until the 21st.

On the 14th a "cutoff" low passes over the area. The cooling associated with the disturbance is able to weaken the capping stable layer but not destroy it. After the disturbance passed the capping stable layer reintensifies. The termination phase of the episode begins on the 17th when the warm ridge aloft weakens. During this period the capping stable layer weakens; however, a very strong, shallow inversion remains at the top of the fog layer. Finally, on the 22nd when a strong disturbance influences the area, the fog and the remaining capping stable layer are destroyed. At Boise the episode is very similar to that of Salt Lake City. Note from Table 3 and Fig. 7 that stagnation of relatively cold air in the basin occurred on some of the days which did not meet the objective DSL layer criteria.

2) WINNEMUCCA

Figure 8 shows the isentropic analysis for Winnemucca. The episode has many similarities to the episode at Salt Lake City. On the morning of the 7th, a region of rapid warming first appears. By the morning of the 9th a capping stable layer forms which signifies the beginning of the continuation phase. During this phase a weak disturbance passing over the region does not destroy the capping stable layer. On the morning of the 17th the termination phase begins when significant cooling occurs above 1.0 km. Unlike Salt Lake City, there is not a persistent fog layer, and a CBL forms daily. By the afternoon of the 19th the atmosphere above the daytime boundary layer is only weakly stable. This signifies the end of the episode at Winnemucca.

5. Physical processes

The importance of synoptic scale warming for the initiation of the DSL episode is evident from the case study. During the initiation phase the warming rates at 700 mb, which is about 1.5–2.4 km AGL at the four stations, averaged 3.75 to 5.0°C day^{-1} for a 3–4 day period (see Fig. 6). Since there is little or no condensation induced diabatic heating in this region, the warming aloft is the result of subsidence, horizontal warm advection, or a combination of both processes. The distribution of the resulting heating between the two processes will not be examined in this study.

The importance of physical processes which occur near the surface also are important to the life cycle of the episode. In this section the importance of longwave heating/cooling as well as surface heating to the DSL episode will be evaluated.

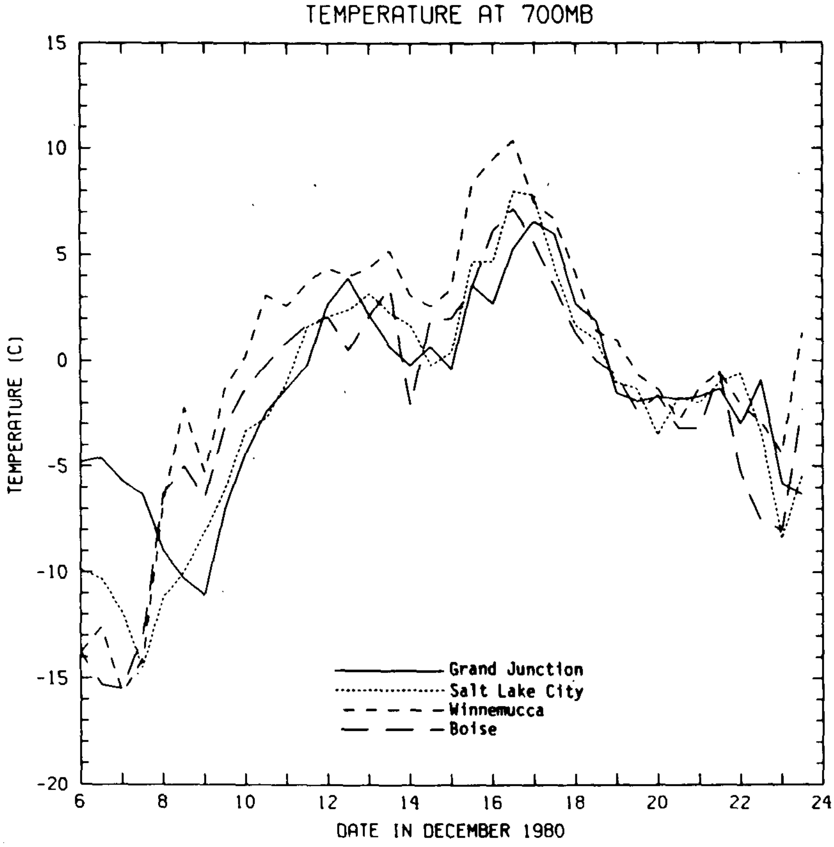

FIG. 6. The temperature at 700 mb for 6–24 December 1980. The data points above the date indicators are from the morning soundings while data between the date indicators are from the afternoon soundings.

a. Longwave heating/cooling

Radiational cooling can have an important influence on the episode by inducing heating or cooling at different heights. Using the IR model described in Cox and Griffith (1979) the upward and downward IR flux along with IR heating rates were calculated for some of the soundings during the episode studied. The carbon dioxide and ozone mixing ratios for the atmosphere and the temperature profile above the sounding are climatological values from McClatchey et al. (1972). The liquid water content of fog used in the IR calculation is 0.025 g m^{-3} and a liquid water content of 0.05 g m^{-3} is used for non-fog clouds. The model was run for three different meteorological situations: cloudless air, a deep fog layer with a cloudless above it, and fog with clouds above it.

1) CLOUDLESS AIR

The IR model was run for two soundings with clear skies as a reference to establish the IR cooling rates for cold, moist surface air beneath warm, dry air and for moist air above dry surface air. Figures 9a and 9b show the soundings and calculated IR heating rates. Generally, throughout the lowest 4.0 km of the atmosphere the magnitude of the IR heating rates are approximately 1.0 to 1.5°C day^{-1} or less and there are not any large vertical gradients in IR heating rates. These calculations indicate that with cloudless skies vertical differences in IR heating rates will not greatly change the overall stability of the atmosphere. These clear air cooling rates, however, may be very important for the formation of deep fog layers which greatly affect the life cycle of the episode.

2) FOG WITH CLOUDLESS AIR ABOVE

Figure 9c shows the morning sounding on 13 December 1980 at Salt Lake City and the calculated IR heating rates. Cooling rates stronger than 10°C day^{-1} occur in the fog layer with slight warming above it. The strong IR cooling provides a source of cold air for the surface fog layer. This cooling not only helps maintain the fog layer, but it can intensify the inversion and provide a mechanism that will help maintain the DSL when other processes which will destroy or weaken it are present.

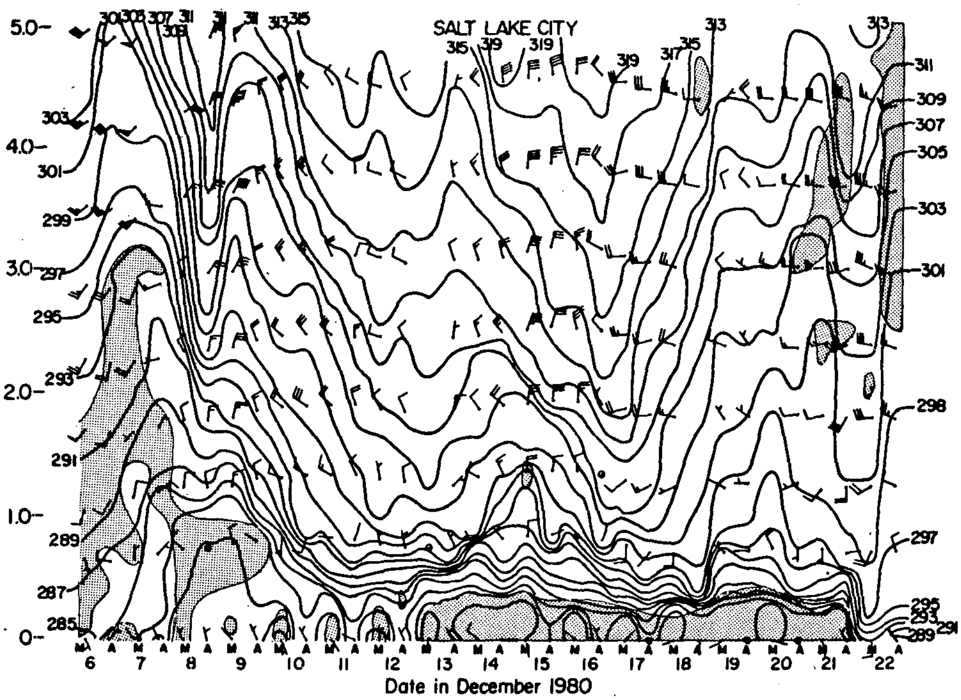

FIG. 7. A time versus height plot of potential temperature and winds for Salt Lake City for 6–23 December 1980. Shaded regions show dew point depressions of 3.0°C or less. "M" refers to the morning sounding and "A" refers to the afternoon sounding.

3) CLOUDS ABOVE FOG LAYER

The afternoon sounding of the 14th and morning sounding of the 15th at Boise have a low, warm cloud above a deep fog layer. During this time a weak disturbance passed over the area and there was a temporary dissipation of the fog layer and warming near the surface. Figures 9d and 9e show the soundings and

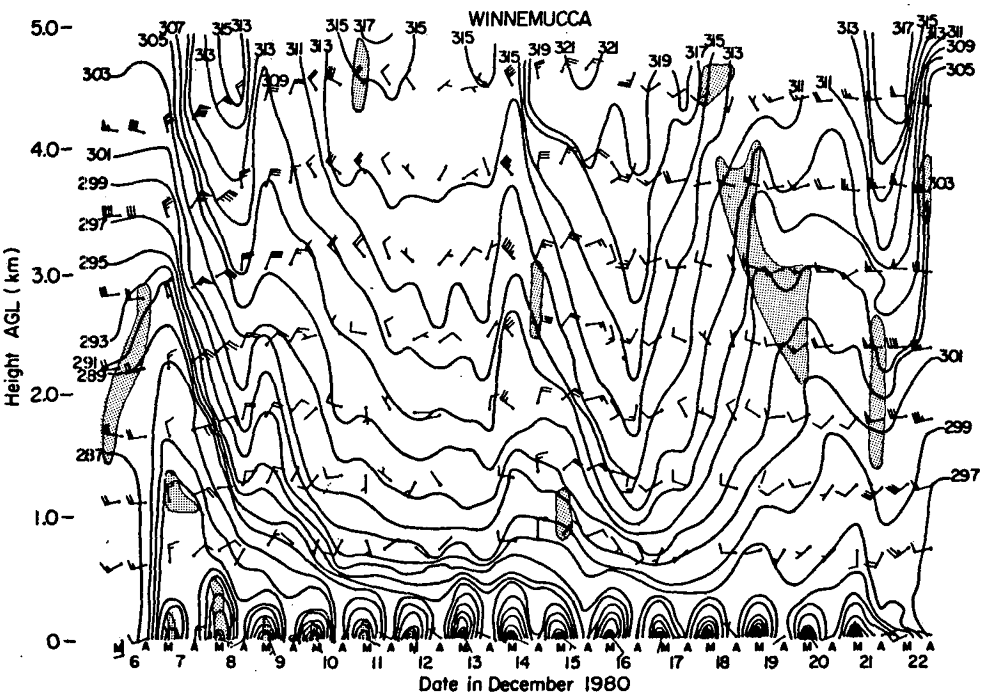

FIG. 8. As in Fig. 7 but for Winnemucca.

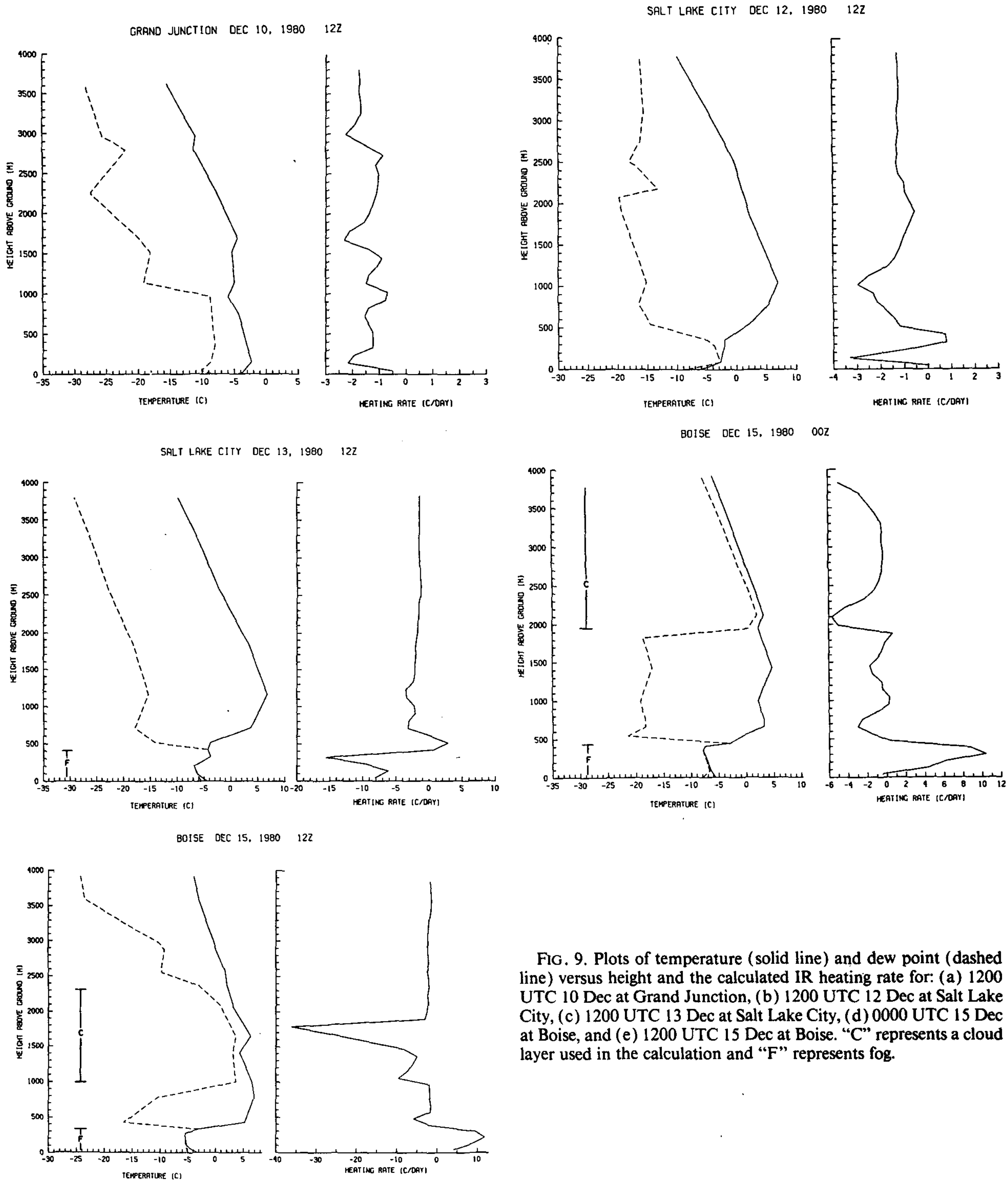

FIG. 9. Plots of temperature (solid line) and dew point (dashed line) versus height and the calculated IR heating rate for: (a) 1200 UTC 10 Dec at Grand Junction, (b) 1200 UTC 12 Dec at Salt Lake City, (c) 1200 UTC 13 Dec at Salt Lake City, (d) 0000 UTC 15 Dec at Boise, and (e) 1200 UTC 15 Dec at Boise. "C" represents a cloud layer used in the calculation and "F" represents fog.

IR heating rates. For both soundings there are warming rates greater than 5°C day^{-1} in the fog layer. The warming in the fog layer could result in the weakening of the overall stability of the atmosphere and dissipation of the fog layer. The influence of the IR heating may help to explain the observed warming at Boise during this time.

b. Surface heating

Figure 10 shows the calculated convective boundary layer (CCBL) heights at Salt Lake City and Winnemucca for this episode. The CCBL is the height at which the potential temperature of the daily surface maximum temperature intersects the 0000 UTC (1700

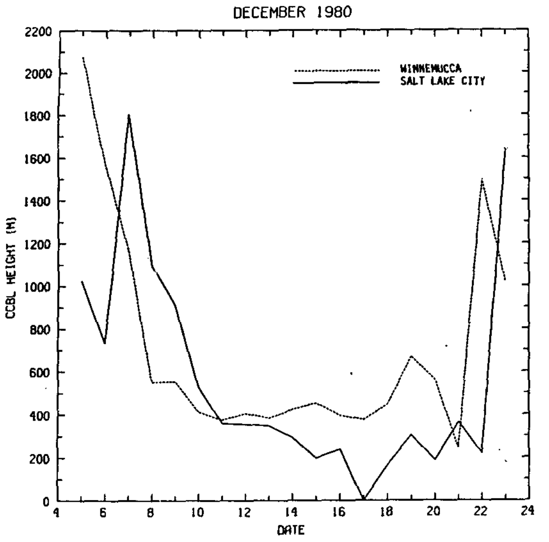

FIG. 10. The CCBL heights at Winnemucca and Salt Lake City for 4–24 December 1980.

MST) sounding. The 0000 UTC sounding was used because it is close to the time of a typical afternoon maximum temperature. The CCBL height is an estimate of the maximum daytime CBL height. The CCBL heights are much lower than the top of the capping stable layer indicating the daytime CBL was not able to mix through the stable layer allowing for the continuation of the DSL episode.

The amount of energy from the surface to the CCBL height between the 1200 UTC sounding and the potential temperature used to calculate the CCBL height is an estimate of the heating needed to form the CBL that day. Figure 11 shows this heating expressed as a percentage of the incoming solar radiation at the top of the atmosphere. During the episode the amount of heating is generally between 20% and 30% at Winnemucca and Grand Junction which are the sites without the persistent fog layer. This shows that using 25% of the incoming solar radiation in the analysis in section 2 is reasonable. The percentages are much smaller at Boise and Salt Lake City on days with a persistent fog layer. With the fog layer present the combination of a high albedo with weak surface heating and IR cooling provide the mechanism to maintain and prolong the episode.

6. Hypothesized life cycle of a DSL episode

During the initiation phase of the episode the atmosphere below 2.0 km was weakly stable and generally cooling. The isentropic analyses show that a deep layer of relatively cold air was present in and above the basins. When warming aloft occurred, the barriers surrounding the basin act as walls restricting the horizontal movement of the relatively cold air near the surface. The deep layer of stability which forms acts as a cap trapping the cold air near the surface and decoupling it from the air aloft. The daytime CBL cannot mix through the capping stable layer and the capping stable layer hampers the vertical transfer of momentum to the surface. Once formed, a weak disturbance could not destroy the capping stable layer. During the termination phase the cooling aloft and some warming near the surface decrease the stability of the atmosphere. The presence of the persistent fog layer strengthens and prolongs the episode by providing a source of IR cooling near the surface and by its high albedo to solar radiation.

7. Implications of deep stable layers

DSLs are associated with the stagnation of relatively cold air in basins. The presence of DSLs can have implications for regional air quality, persistent fog episodes, and surface temperature forecasts. The low daytime CBL along with light winds can provide conditions for potentially poor regional air quality. Figure 12 shows the CCBL height, the mean wind speed below the CCBL height, and the mixing volume for Winnemucca. The mixing volume is the product of the mean wind speed and CCBL height. If this quantity is multiplied by time and a length perpendicular to the wind, it gives an estimate of the volume of air into which pollutants are mixed. Before the episode the mixing volume is large. During the episode the mixing volume decreases drastically and it increases after the episode. Notice that the 12th did not meet the objective DSL definition; yet the three elements remained small so this episode at Winnemucca is at least six days long. The other three stations show a similar pattern. A low mixing volume can allow for the collection of pollutants in a small volume resulting in high pollutant concen-

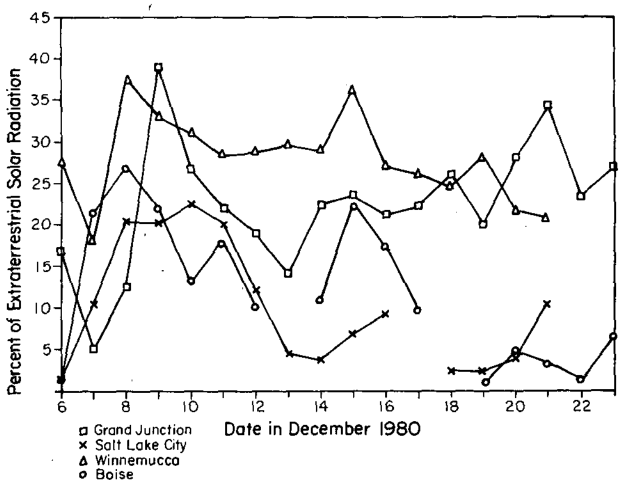

FIG. 11. The percentage of the daily extraterrestrial solar radiation needed to form a CBL to the height and potential temperature of the CCBL.

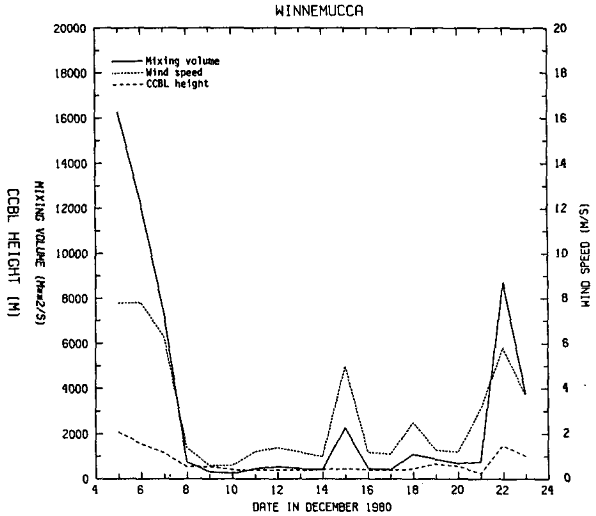

FIG. 12. Mixing volume, wind speed, and CCBL height at Winnemucca for 4–24 December 1980.

trations. The work by Yu and Pielke (1986) indicates that when DSLs are present pollutants will disperse in the basin with little pollution leaving it. Not only do DSLs allow for locally high pollutant concentrations over source regions, but very poor air quality can occur over a significant portion of the basin through the accumulation of pollutants over several days.

Table 4 shows the mixing volumes for December days in the years 1976 to 1980. Nearly all the DSL days had small mixing volumes. There is also a sizable number of non-DSL days with small mixing volumes.

Besides poor air quality, stagnation can also lead to other problems. As seen in the case studies for Salt Lake City and Boise the layer of persistent fog, once formed, may last throughout an entire day and can persist for many days. DSLs can provide the stagnant conditions necessary for the formation and existence of fog.

The presence of DSLs can also be important for surface temperature forecasts. At the four intermountain region stations the mean surface temperature only warmed about 6° to 8°C from 7 December until the end of the episode. By contrast, 700 mb temperatures warmed 15° to 20°C. With the strong warming aloft, objective forecasting indices (such as 500 to 1000 mb thickness or the 700 mb temperature) suggest that surface warming should also be substantial. The knowledge of the presence of a DSL can help the forecaster to properly estimate the change in the mean surface temperature throughout the period.

8. Summary

DSLs in the intermountain western United States are mainly a wintertime phenomenon with episodes of 3 days or longer occurring at least once every two years at Salt Lake City and Winnemucca and at least once a year at Boise and Grand Junction. The case study showed that the objective DSL definition is "conservative" because some days that did not meet the objective definition still had sufficiently deep layers of stability to cause stagnation. DSLs can cause potentially poor regional air quality and are one group of days associated with low mixing volumes at the four stations. DSLs can also be accompanied by episodes of fog which last the entire day. An in depth examination of a DSL episode and the physical processes which may be important to the episode showed the following DSL life cycle.

TABLE 4. The distribution of mixing volumes for December DSL days and non-DSL days from 1976 to 1980.

Mixing volume (10^3 m^2 s^{-1})	Grand Junction		Salt Lake City		Winnemucca		Boise	
	DSL	non-DSL	DSL	non-DSL	DSL	non-DSL	DSL	non-DSL
<1	26	78	12	53	18	24	24	55
1–2	6	23	2	20	8	17	7	20
2–3	0	3	1	17	1	14	1	9
3–4	0	3	0	4	0	9	0	6
4–5	0	1	0	6	0	7	0	7
5–6	0	6	0	7	0	4	0	4
6–7	0	3	0	4	1	3	0	1
7–8	1	1	0	3	0	6	0	1
8–9	0	2	0	3	0	5	0	2
9–10	0	0	0	3	0	3	0	1
10–11	0	1	0	2	0	1	0	2
11–12	0	0	0	1	0	2	0	1
>12	0	4	0	14	0	23	0	12
				Mixing volume				
Mean (m^2 s^{-1})	655	2158	726	4380	1109	8359	755	4892
Standard deviation (m^2 s^{-1})	396	4432	673	7111	1261	12709	542	10721

In the initiation phase a deep layer of cold air was present over the region. A layer of rapid warming descended to form a DSL. The deep layer of stability decoupled the air near the surface from the air aloft. The daytime CBL could not mix through the deep layer of stability and the transfer of momentum aloft to the surface was severely hampered. The barriers surrounding the basin acted as walls restricting the horizontal movement of the cold air near the surface. The deep layer of stability along with the barriers trapped the air in the basin.

The continuation phase had a capping stable layer which did not greatly weaken. In this phase a weak disturbance passed over the region but was not able to destroy the capping stable layer, and weak surface heating prevented the daytime CBL from being sufficiently warm to mix through the capping stable layer. Episodes of fog which last the entire day can occur during this phase and the longwave cooling and high albedo of the fog layer can help maintain or strengthen the DSL.

In the termination phase a weakening of the synoptic-scale ridge aloft allowed disturbances to move over the region with associated cooling aloft. Without the presence of fog the episode ended in two days, while with fog present the episode ended when a strong disturbance moved over the region. The high albedo and strong longwave cooling of the fog layer help prolong the DSL episode.

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