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Climatology of persistent deep stable layers in Utah's Salt Lake Valley, USA

S. Zhong[1], X. Xu[1], X. Bian[2], and W. Lu[1]

[1]Department of Geography, Michigan State University, East Lansing, Michigan USA
[2]USDA Forest Service Northern Research Station, East Lansing, Michigan, USA

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Abstract. The characteristics of winter season persistent deep stable layers (PDSLs) over Utah's Salt Lake Valley are examined using 30-year twice daily rawinsonde soundings. The results highlight the basic climatological characteristics of the PDSLs, including the strengths of the inversion, the frequency of the occurrence, and the duration of the events. The data analyses also reveal linear trend, interannual variability, as well as the relationship between the interannual variability of PDSLs and the variability of large-scale circulations. Finally, the study investigates the large-scale atmosphere conditions accompanying the formation and destruction of the PDSL episodes.

1 Introduction

Persistent deep stable layers (PDSL) are frequent wintertime phenomena in basins and valleys of the Intermountain West of the United States (Wolyn and Mckee, 1989; Reeve and Stensrud, 2009). The strong static stability decouples the air within the basin/valley from layers aloft, which often leads to stagnation and limits atmospheric dispersion (Vosper and Brown, 2008; Smith et al., 2010). Cold and sometimes moist air, being trapped in basins or valleys by PDSL, favors the formation of fog, drizzle, or freezing rain, which can be hazardous for ground transportation as well as aviation. Accurate forecasting of the formation and removal of these PDSLs has proven to be one of the many challenges of mountain weather forecasting (Smith et al., 1997; Zängl, 2005).

In this study, we perform climatological analyses of winter season PDSLs over the Salt Lake Valley (SLV) in Utah, USA. The objectives are to determine the basic climate characteristics of PDSLs, understand their interannual variability and trend, and understand the synoptic conditions that accompany the buildup and breakup of PDSLs.

Correspondence to: S. Zhong
(zhongs@msu.edu)

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2 Site, data, and method

The SLV (Fig. 1) is bordered by high terrain on three sides: the Oquirrh Mountains to the west, the Wasatch Range to the east, and the Traverse Range to the south. The highest peak along the Wasatch Range has an elevation of 3300 m above mean sea level (MSL), approximately 2000 m above the valley floor. The valley opens up to the north with the Great Salt Lake to the northwest.

The analysis employed winter-season (defined here as the beginning of November through the end of February), twice-daily rawinsonde soundings launched from the Salt Lake City International Airport in the north central part of the SLV (Fig. 1) for the period of 1979 to 2009.

For this study, a PDSL event is defined as $\frac{\partial\theta}{\partial z}\Big|_{z_2-z_1} > 0.0033\,^\circ\mathrm{C\,m^{-1}}$ (Z_1 and Z_2 are 850-hPa and 700-hPa geopotential heights) is satisfied by at least three consecutive soundings. This is equivalent to the condition that the temperature lapse rate between 850 and 700 hPa is less than the moist adiabatic lapse rate; in other words, the atmosphere is absolutely stable. All PDSL events are further classified into three categories based on the value of the potential temperature gradient: a strong PDSL event if

$$\frac{\partial\theta}{\partial z}\Big|_{z_2-a_1} > 0.017\,^\circ\mathrm{C\,m^{-1}};$$

a weak event if

$$0.0033\,^\circ\mathrm{C\,m^{-1}} < \frac{\partial\theta}{\partial z}\Big|_{z_2-a_1} \le 0.009\,^\circ\mathrm{C\,m^{-1}};$$

and a moderate event, otherwise.

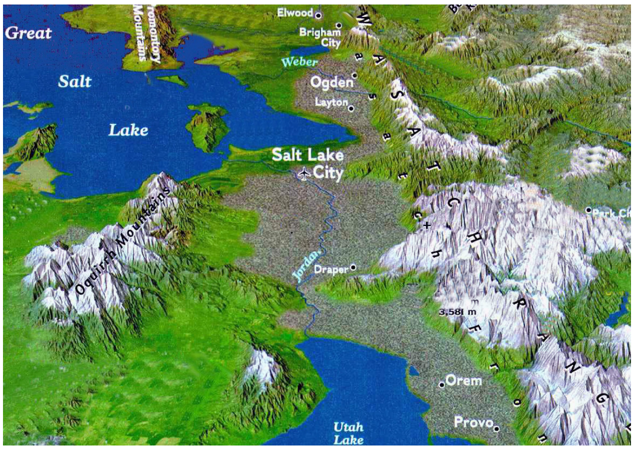

Figure 1. The Salt Lake Valley of Utah, USA (NASA Satellite Image; Courtesy of Frank Ludwig).

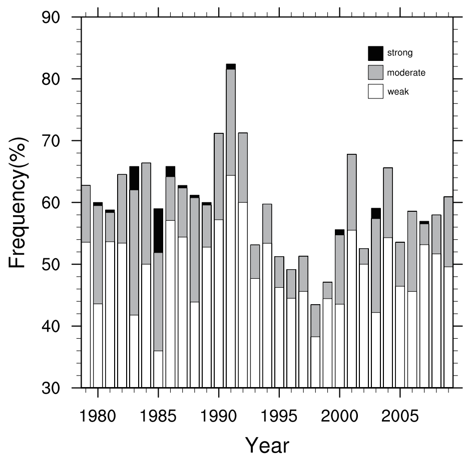

Figure 2. Winter season mean frequency of PDSL occurrence for the period of 1979–2009.

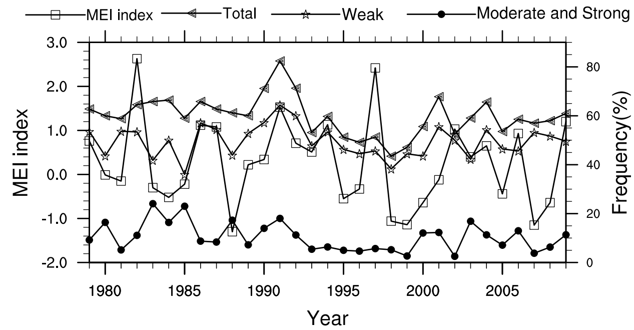

Figure 3. The frequency of PDSL events and the MEI index.

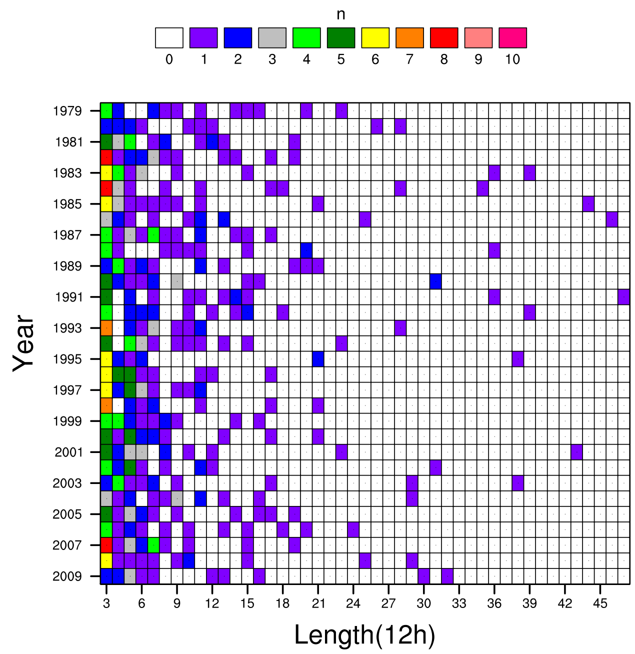

Figure 4. The length of PDSLs and the frequency of their occurrence. The color represents the number of times a PDSL of given length occurs in the year.

3 Results and discussions

3.1 Frequency of occurrence

PDSL is a frequent winter season phenomenon over the SLV. As shown in Fig. 2, the winter season mean PDSL frequency of occurrence ranges from 44% in 1998 to 83% in 1991, with considerable interannual variability. Weak PDSLs are much more frequent than the stronger events except for four winters when the frequency of moderate PDSLs slightly exceeds that of weak ones. Strong PDSLs are rare events. An analysis of the relationship between the interannual variability of PDSL frequency and large-scale circulation indices (Fig. 3) revealed a weak correlation ($r = 0.4365$, $P < 0.05$) between the interannual variation of the frequency of the weak PDSLs and the MEI index, a composite El Niño-Southern Oscillation (ENSO) index with positive (negative) values representing the warm (cold) ENSO phase. No clear relationship, however, is detected between MEI and the interannual variability of the frequency of the moderate or strong PDSL events. The linear trend analysis (not shown) indicates no trend for the weak PDSL events, but a slight downward trend for the moderate and strong events.

3.2 PDSL length

How long do PDSL events last? As shown in Fig. 4, a PDSL may last from 1.5 day (3 consecutive 12 h soundings) to a little over 3 weeks (42 consecutive 12 h soundings). As expected, the longer PDSL events occur much less frequently than shorter ones. With a few exceptions, PDSL events lasting longer than 1 week rarely happen twice in a single year. PDSL events shorter than 1 week account for 86% of the total

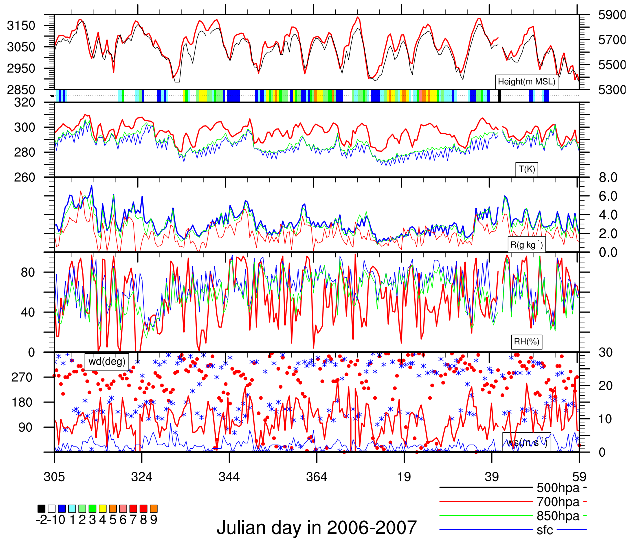

Figure 5. Time series of geopotential height (top), potential temperature (2nd from the top), mixing ratio (middle), relative humidity (2nd from the bottom), and wind speed/direction (bottom). The color bar indicates inversion strength (−2 missing data, and −1 no inversion).

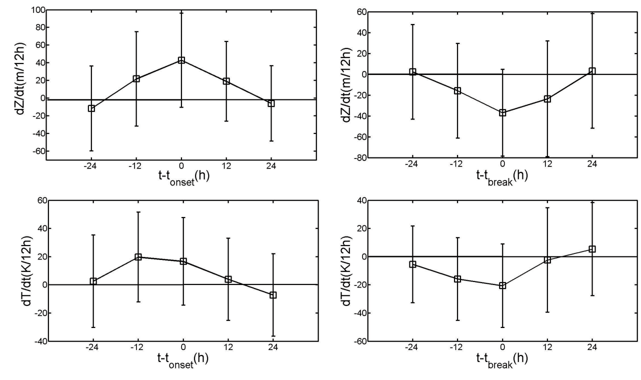

Figure 6. The mean time rate of change and the standard deviation of 500-hPa geopotential heights (top two) and 700-hPa temperature (bottom two) 24 h prior to and after the onset and breakup of a PDSL.

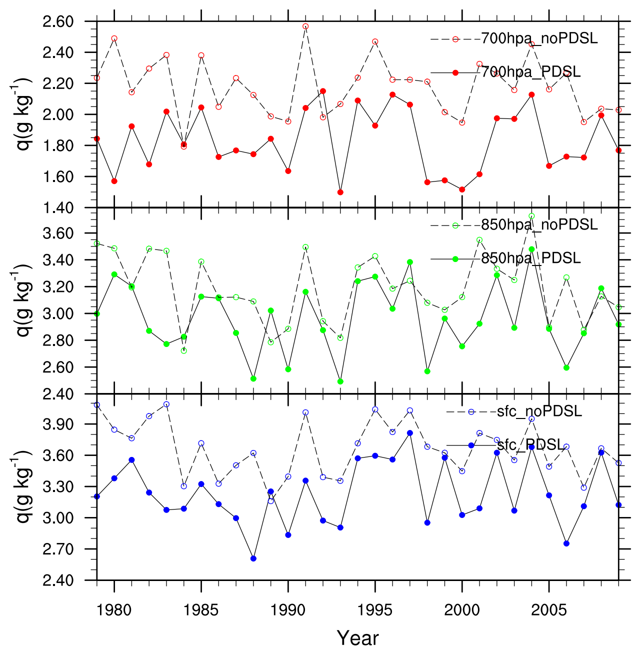

Figure 7. Specific humidity averaged over all PDSL days and all non PDSL days, respectively.

frequency, with the rest of 14% for those lasting longer than 1 week. While it is possible for a PDSL event to last longer than 2 weeks, they are rare events with only 3% frequency of occurrence.

3.3 Synoptic conditions accompanying the buildup and breakup of PDSL

Time series of geopotential height, potential temperature, moisture, and wind at various atmospheric levels are examined for all 30 winters to understand synoptic conditions accompanying PDSL events and an example is shown in Fig. 5 for the winter season of 2006–2007. The buildup (breakup) of PDSLs is usually accompanied by rising (falling) 700-hPa and 500-hPa geopotential heights associated with an approaching ridge (trough) and by 700-hPa warming (cooling). To further illustrate the role of synoptic advection, the mean rate of change of 500-hPa geopotential height and 700-hPa temperature prior to and after the onset and breakup of all PDSL events is examined and the results are shown in Fig. 6. The positive (negative) 500 hPa height advection typically starts 24 h prior to the buildup (breakup) and the rate of height increase (decrease) peaks around the time of the PDSL onset (breakup). Warm (cold) advection also tends to begin 24 h before the buildup (breakup). The rate of 700 hPa warming peaks around 12 h before the onset, and the maximum rate of cooling occurs around the time of breakup.

To understand the influence of wind aloft on the development of PDSLs, the 700-hPa wind speed and direction with/without PDSLs are compared and the results (not shown) reveal a 10–20% wind speed reduction during PDSL events, but no systematic difference in wind direction. A comparison of surface wind with/without PDSLs reveals a considerably lower wind speed in the valley with the presence of PDSLs.

3.4 PDSL and humidity

PDSLs are characterized by consistently lower specific humidity both within and above the valley (Fig. 7), indicating generally drier atmospheric conditions accompanying PDSLs. The relative humidity is always lower at 700 hPa,

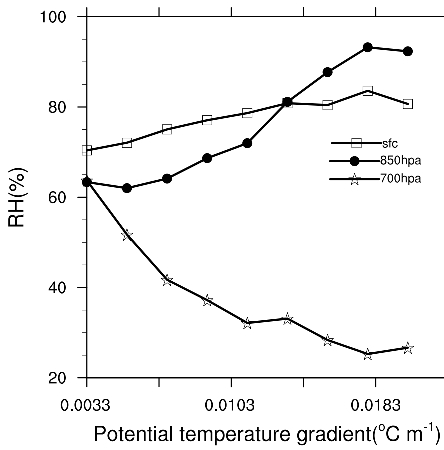

Figure 8. Changes of relative humidity as a function of potential temperature gradient.

a result of both warming and drying, and the stronger the inversion, the lower the relative humidity (Fig. 8). Within the valley, however, the relative humidity is always higher during PDSLs due mainly to colder temperature, and the stronger the inversion, the higher the relatively humidity (Fig. 8). At very strong stability, a further increase in the inversion strength does not lead to a continuing increase or decrease in the relative humidity

4 Future work

The analysis performed here is being extended to other basins and valleys in Western US. The results from different basins/valleys will be compared to determine the spatial variability of the PDSL characteristics.

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