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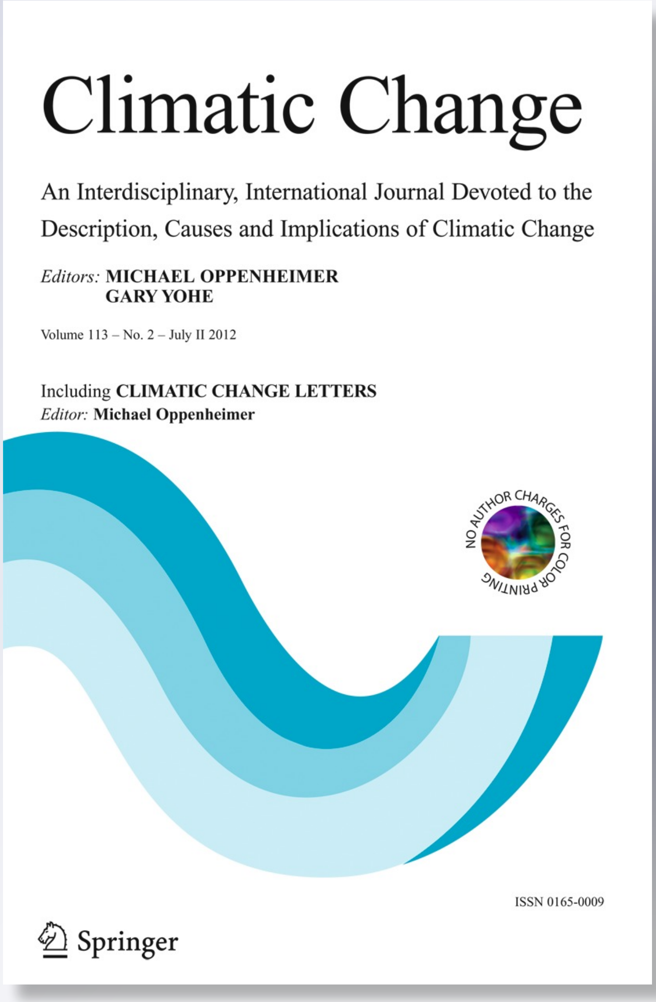

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Growing season expansion and related changes in monthly temperature and growing degree days in the Inter-Montane Desert of the San Luis Valley, Colorado

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Abstract Most climate change studies on high elevation ecosystems identify changes in biota, while several report abiotic factors. However, very few report expansion of the freeze-free period, or discuss monthly changes of temperature and growing degree days (GDD) during the growing season. This study provides initial data on agriculturally-related aspects of climate change during the growing season (M-J-J-A-S) in the inter-montane desert of the San Luis Valley (SLV), Colorado. Temperature data were gathered from 7 climate stations within the SLV. Based on ordinal days, the last vernal freeze is occurring ($p<0.05$) earlier at 3 stations than in prior years, ranging between 5.52 and 11.86 days during 1981–2007. Significantly-later autumnal freezes are occurring at 5 stations by 5.95–18.10 days, while expansion of the freeze-free period was significantly longer at all stations by 7.20–24.21 days. The freeze-free period averaged about 93 days prior to the 1980s, but now averages about 107 days. Increases ($p<0.05$) in daily mean, maximum, minimum temperature occurred at nearly all stations for each month. Increases in GDD_{10}, $GDD_{4.4}$ (potato) and $GDD_{5.5}$ (alfalfa) also occurred at nearly all stations for all months during 1994–2007. Higher temperatures increase the number of GDD, quickening crop growth and maturity, and potentially reducing yield and quality unless varieties are adapted to changes and water is available for the season extension and increased evapotranspiration.

1 Introduction

A critical element determining suitability and type of agricultural production in a given area is the local prevailing annual climatic conditions. Climate determines the freeze-free period,

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mean minimum and mean maximum daily temperature, number of growing degree days (GDD), precipitation patterns, and even soil types. Climate change can impact local growing conditions by changing the date of the last vernal and first autumnal freeze, length of the growing season, daily temperature and number of GDD. The prevailing theory of climate change and global mean temperature rise is emissions of anthropogenic carbon dioxide (CO_2), methane (CH_4), and nitrous and sulfurous oxides (NO_x and SO_x) from fossil fuel combustion. Historical data indicate CO_2 concentrations increased from approximately 280 parts per million (ppm) in the 1800's to about 379 ppm today (IPCC 2007), resulting in an increase in global mean annual temperature of approximately 0.74±0.2 °C, and a decreased daily temperature asymmetry (IPCC 2007, Hansen et al. 2006). Mean annual maximum temperature increased by about 0.1 °C per decade, compared to a 0.2 °C per decade for mean annual minimum temperature (Hansen et al. 2006).

The aforementioned changes are global averages, but climate change is not globally homogenous (Hansen and Lebedeff 1987; IPCC 2007). Changes in climate have occurred at different rates between latitudes (Hansen and Lebedeff 1987; Giorgi et al. 1994; Hansen et al. 2001) and altitudes (Bucher and Dessens 1991; Weber et al. 1994; Diaz and Bradley 1997; Rebetez and Dobbertin 2004). Dettinger and Cayan (1995) speculate that, prior to 1995, higher elevations exhibited less sensitivity to climate change. This is consistent with IPCC (2001) data, which indicates a slower rate of temperature increase at upper altitudes of the atmosphere than for surface temperatures. Rebetez and Dobbertin (2004) also reported a possible lag effect of climate change in sub-alpine regions, noting that climate-related die-offs of Scots pine (*Pinus sylvestris*) lagged global temperature trends by about 15 years.

1.1 Agricultural implications of climate change

The impacts of climate change on agriculture are variable, according to location and topic. Potential benefits of climate change include atmospheric fertilization by higher CO_2 concentration. This has been shown to increase photosynthetic activity, growth and water use efficiency (Drake et al. 1997; Ainsworth and Long 2005). Increased temperatures also can lengthen the growing season and reduce risks of late freezes. More GDD also can reduce crop production time frames and even possibly allow planting more than one crop per year.

Negative impacts of climate change include increased crop water needs because of increased crop growth rates and evapotranspiration, and reduced soil moisture content, resulting from increased temperature (Rosenzweig et al. 2000). Pollen death from high temperatures may cause low yields from poor pollination (Angevin et al. 2008). Crop yield reduction also can occur from forced early maturation; more GDD reduce the length of time between germination and senescence (Singh et al. 1998). Additional negative impacts include climate-induced changes in synchrony of beneficial insects with pests and pollination or distribution, range and voltinism of insect pests, and disease distribution and emergence (Bale et al. 2002; Ward and Masters 2007; Maggioni and Lipman 2010).

Based on their carbon utilization pathways, agricultural crops are generally categorized into 3 types: C_3, C_4 and CAM (Sombroek and Gommes 1996). C_3 plants are adapted to more mesic and lower light intensity regions, while C_4 and CAM plants are adapted to regions with higher light levels and more arid conditions. The latter can utilize CO_2 in a manner that reduces water stress under arid conditions. Common C_3 agricultural crops include alfalfa, barley, oats, wheat, beans (including soy), sweet and white potatoes and rice. Common C_4 agricultural crops include maize, millet, sorghum and sugarcane; while CAM agricultural and horticultural crops include orchids, blue agave, onions and pineapple. Some experimental models indicate climate change will reduce yields of C_3 crops and increase yields of C_4 and CAM crops (Easterling et al. 1993; Singh et al. 1998), although there is equivocation on the topic.

Regardless, increased temperatures are expected to exacerbate needs for agricultural irrigation, because increases in crop evapotranspiration also are expected to occur (Adams 1989; Schimmelpfennig et al. 1996; Fischer et al. 1996; Ramirez and Finnerty 1996). Although Ramirez and Finnerty (1996) point out crop production will need additional water to reduce impacts of increased temperatures, they also indicated costs may be offset as increased CO_2 concentrations may result in a greater income per hectare as crop production increases. Alternatively, higher daily temperatures may affect crop pollination, or speed maturation, at the cost of yield (weight/volume). Applied climate change scenarios support this and indicate temperature increases will cause worldwide decreases in crop production. In the U.S. variable production outcomes are predicted based on regional precipitation changes (Fischer et al. 1996; Reilly et al. 2003). Once again, the data is equivocal (Fischer et al. 1996; Sombroek and Gommes 1996).

Studies of Midwestern plains agricultural production by Easterling et al. (1993, 2001) found almost all negative effects of climate change, i.e. changes in precipitation pattern and increased temperature and evapotranspiration, will be offset by higher yields and growth from increased CO_2 concentrations, if agricultural modifications such as crop adaptations, synchrony and adaptive technologies are also implemented. Similarly, by employing those modifications in central European agriculture, Finger and Schmid (2008) estimate higher yields and income with increased CO_2 concentrations.

1.2 Changes in phenology

Temperature triggers changes in phenology and the presence (or absence) of beneficial insects and pests. Many studies report climate change related shifts in phenology of insects, crop and pest plants, and disease distributions, synchrony and emergence, insect fecundity or disease virility (Bradley et al. 1999; Chakraborty et al. 2000; Rosenzweig et al. 2000; Beaubien and Freeland 2000; McCarty 2001; Walther et al. 2002; Thuiller et al. 2005; IPCC 2007). Adverse impacts manifest as increases in insect abundance, wider or new distribution and prevalence, increased voltinism and changes in synchrony (Manzer et al. 1987; Porter et al. 1991; Colbach et al. 1997; Woiwod 1997; Fleming and Candau 1998; Rosenzweig et al. 2000; Losey and Vaughan 2006). Changes in insect prey/predator synchrony relationships have potential to cause severe economic losses. Worldwide insect pollinators, parasitoids and predators account for about $300 billion dollars in ecosystems services and in the U.S. account for $52 billion in natural capital (Pimentel et al. 1997).

Observations of plant phenology indicate early flowering is occurring in several species (Beaubien and Freeland 2000), with bloom times occurring 8.2–19.8 days earlier for several species (Bradley et al. 1999; Cayan et al. 2001). These phenological changes indicate the growing season in the northern hemisphere has increased by 7–12 days (Keeling et al. 1996; Myneni et al. 1997; Menzel and Fabian 1999; Walther et al. 2002).

1.3 Growing degree days

Phenological advancement can be numerically quantified and used to predict or estimate timing of developmental stages of a particular species. It is calculated as the sum of accumulated heat units necessary for a particular organism to develop. These heat units are commonly referred to as growing degree days (GDD). As early as 1735, René-Antoine Ferchault de Réaumur (de Reaumur 1735) introduced the concept of growing degree days when he recognized temperature affected phenology. He postulated organisms need to accumulate a number of heat units unique to the organism in order to initiate growth, development and maturity. This concept is extensively used in agriculture to estimate days to crop germination, bloom or maturity (Hartz and Moore 1978; Snyder et al. 1999; Kim et al. 2000) or to predict regional distributions of organisms (e.g., crops, insects, plant pests).

Growing degree days are calculated from daily mean temperature data from which a base value is subtracted. The base values (denoted by subscript) are unique to each species and represent the lower temperature threshold for growth (Breazeale et al. 1999; Derscheid and Lytle 1981). Similarly, a maximum temperature threshold is present, above which the organism's metabolism is suspended. The maximum and minimum temperature thresholds are used to derive the GDD specific for each species or specific agricultural varietal.

Principle crops of the San Luis Valley are C_3 crops; namely alfalfa/grass hay, potato, mixed cereals and vegetables. GDD_{10} can generally be used for crops in most cases, $GDD_{5.5}$ is specifically used for alfalfa and $GDD_{4.4}$ for potatoes and cereals (the subscript base equals the lower temperature threshold, expressed in °C). Because of variability among species and crops, climate change may not affect each equally, but benefit some while harming others. As an example, GDD_{10} crops' maximum and minimum thresholds are 30 °C and 10 °C, with growth estimated to occur only within this range, whereas alfalfa (a $GDD_{5.5}$ crop) starts growing at 5.5 °C and continues until 45 °C is reached. Thus, increased temperature may benefit GDD_{10} by increasing the number of days minimum daily temperature is reached. In contrast, it would suspend growth at times when the maximum daily temperature is reached, neither would affect $GDD_{5.5}$ crops.

There are well known and understood relationships between GDD and crop production, plant growth and insect development (Hartz and Moore 1978; Frank and Hofmann 1989; Ojeda-Bustamante et al. 2004). Several developmental stages are triggered by accumulated GDD including, thermal dormancy, a period of time when germination, leaf unfurling (bud burst) or bloom set are suspended, until triggered by temperature changes (Cannell and Smith 1983; Snyder et al. 1999; Grundy et al. 2000) and the initiation of seed/fruit maturation and senescence (Snyder et al. 1999; Aber et al. 1995). Ramankutty et al. (2002) have utilized GDD to predict an agricultural region's sensitivity to climate change. GDD are also used to estimate emergence of agricultural pests and disease (Pscheidt and Stevenson 1988; Kim et al. 2000) and their distribution or changes in distribution (Rosenzweig et al. 2000).

2 Objectives

The goal of this study is to address climate variables and their potential effects on agriculture in the San Luis Valley (SLV), located just below the headwaters of the Rio Grande Basin. Few studies have reported an expansion of the freeze-free period or changes in growing season monthly temperature and GDD resulting from climate change. Further, very few studies report changes in montane or sub-alpine ecosystems, none having been directed to changes in the San Luis Valley. This study sought to determine what increases in length of the growing season, increases in monthly temperature, and GDD occurred in the SLV during the mid– to late– 20th and early–21st Centuries. The growing season in the SLV is defined as May thru September, the primary months for heat accumulation. The freeze-free period is defined as that which occurs between the last vernal freeze and first fall freeze.

3 Study area

Located in south-central Colorado, the SLV is roughly bisected by the Rio Grande. The river originates in the western San Juan Mountains, which form the western boundary of the SLV, while the Sangre de Cristo Mountains form the eastern boundary. The elevation of the SLV is approximately 2300 m. The region regularly experiences low wintertime temperatures extremes of below -20 °C, and even as low as -40 °C (NCDC a, b), ranking in the top 20 coldest locations in North America (King 2007). Warm season temperatures reach the 30s °C, although the warm season only lasts 90–110 days.

Located in the rain shadow of the San Juan Mountains, the Valley receives less than 20 cm of precipitation annually, while the mountains to the west receive 100–200 cm of precipitation annually. Although arid, the Valley is a major agricultural region for the State of Colorado, producing the majority of the state potato crop (14,000–30,000 ha), and a large portion of its alfalfa crop (80,000–100,000 ha) (CSU 2003a). Irrigated agriculture covers more than 1.4 million ha, accounts for more than 30% of the Valley economy and 50% of local employment, which makes it the dominant industry (SLVDG 2002). The Valley's arid condition results in agriculture being entirely dependent on irrigation (CSU 2003b).

Climate stations in the SLV used in this study were selected on the basis of several criteria, including location, length of record, and period of record common to all stations (Table 1). The earliest common date for all stations was 1958, with the common period of record being 1958–2007. Three stations are located along the Rio Grande riparian zone: Del Norte 2E (2396.9 m elevation), Monte Vista 2 W (2344.5 m elevation), and Alamosa AP (2296.1 m elevation) (in upstream to downstream order). Two stations, Manassa (2343.9 m elevation) and Center 4SSW (2338.7 m elevation), are located south and north, respectively, in the interior of the Valley, while two stations, Blanca 4NW (2349.7 m elevation) and Great Sand Dunes National Park (GSDNP) (2475.0 m elevation), are located north and south, respectively, along the eastern edge of the Valley. The locations of the stations are shown in Fig. 1.

4 Methods

Daily maximum, minimum and mean temperature data were compiled from National Climate Data Center (NCDC a) COOP data for the years 1958–2007. The data was used to develop GDD and test for changes in GDD, maximum, minimum and mean monthly temperatures. Growing degree days were calculated for 3 bases: 10, 4.4 and 5.5. To determine changes in the freeze-free period, the ordinal day for the last vernal freeze

Table 1 Location and elevation of SLV sampling stations (Mix 2010)

Stations	Location	Elevation (m)
Valley floor stations		
Alamosa AP	37 °26′N/105 °52′W	2296.1
Blanca	4NW 37 °29′N/105 °34′W	2349.7
Center	4SSW 37 °42′N/106 °09′W	2338.7
Del Norte	2E 37 °40′N/106 °19′W	2396.9
GSDNP*	37 °44′N/105 °31′W	2475.0
Manassa	37 °10′N/105 °56′W	2343.9
Monte Vista	2 W 37 °35′N/106 °11′W	2344.5

*Great Sand Dunes National Park

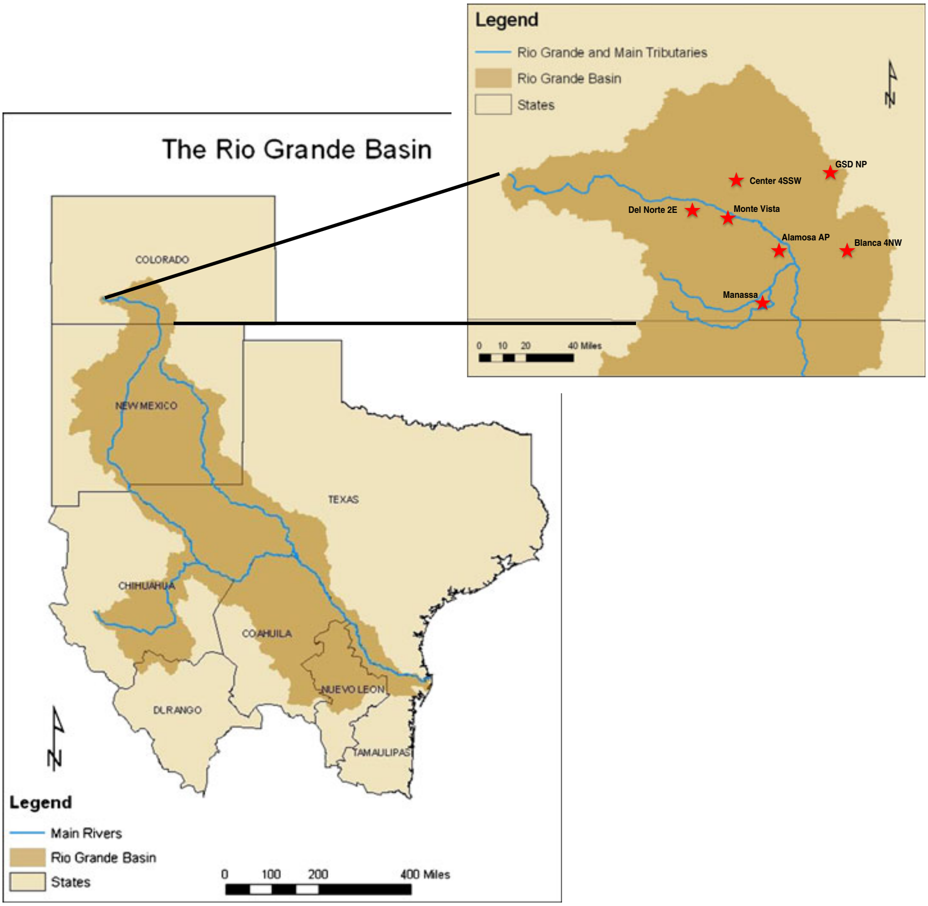

Fig. 1 Locations of sampling stations in San Luis Valley, Colorado (*source*: basin image from River Systems Institute at Texas State University, inset from the State of Colorado Decision Support System)

(minimum temperature at or below 0 °C) and first autumnal freeze of each year were identified. Frost-free days were not used because it is an event that can occur at various temperatures depending on humidity and wind speed, and occurrences would have to be estimated; therefore days with a minimum temperature of 0 °C were indicators for freeze. The last day with 0 °C or less determined the start of the freeze-free period as did the first occurrence of an autumnal day with 0 °C or less.

The formula used to convert daily minimum and maximum temperatures to GDD can be used for non-specific crops (GDD_{10}) or for specific crops such as alfalfa ($GDD_{5.5}$) or potatoes ($GDD_{4.4}$), the latter two are the most important crops in the SLV. The formula for deriving GDD is as follows: $GDD_x = [(T_{max} + T_{min})/2] - X$, where T_{max} = maximum temperature; T_{min} = minimum temperature; and X = base temperature threshold. For non-specific crops, the maximum and minimum temperature thresholds applied would be 30 °C and 10 °C. All temperature data exceeding the maximum is reduced to 30 °C, while the values below 10 °C were raised to 10 °C, since no growth occurs above or below the threshold values. For potatoes the maximum and minimum temperature thresholds are 30 °C and 4.4 °C, respectively, and for alfalfa, the maximum and minimum temperature thresholds are 43.3 °C and 5.5 °C, respectively.

Change point analysis was utilized to identify point(s) in the data record where values departed significantly from previous values. For freeze-free data the actual ordinal day on which the last vernal or first autumnal freeze occurred was utilized. For the freeze-free period, the sum of freeze-free days for each year was utilized. For GDD bases and temperature the annual mean temperature values were utilized.

Change point analysis utilizes an iterative cumulative sum (CUSUM) procedure in combination with the bootstrapping method of analysis (Wayne Taylor, pers comm.). The CUSUM chart starts and ends at zero with the maximum distance from which the CUSUM chart deviates from zero being the measure of change. It then compares the CUSUM chart of the original data with the CUSUM charts of random reordering of the data (bootstraps) to determine if there is a difference indicating a significant change. Because of this bootstrapping approach, the method is distribution free. If a change is detected, the time of the change is estimated and the data split at the change point. The analysis is then repeated on each segment to detect further changes. As a result more than one set of data is identified as being statistically separate from other sets. Each set or sequence has a statistical distribution more similar to the data within than to data in other sets of the same series. One or more points are estimated that define the moment of change or shift in distribution and a range of points is provided as the likeliest period for change, along with the previous and new mean values. Previous studies have indicated that changes in the means of time series data can be identified using this method (Page 1955, 1957; Pettitt 1979; Taylor 2008). Change point analysis has been used also in several climate studies to identify points of departure from mean values (Craddock 1979; Buishand 1981; Salinger and Mullan 1999).

Utilizing periods identified by change point analysis, a one-tailed *t*-test was performed to determine if the ordinal day of the last vernal and first autumnal freeze were significantly earlier or later during the period 1994–2007. Significance was set at $p<0.05$. Similarly, the numbers of days of the freeze-free period were tested to determine if that period had extended significantly during 1994–2007. Finally, mean monthly temperature values and GDD for each base were tested to determine if they were significantly higher during the latter period than the earlier period at all stations.

Because GDD are predicated on daily, accumulated heat units, the use of daily data is essential for this study. Identifying the last vernal and first autumnal freezes can only be done with daily data. It is also essential to use daily temperature values to analyze changes in monthly temperatures in the short growing season of the SLV. At the same time, because there is no reliable method for correcting long-term daily data (Menne and Duchon 2000; Alexander et al. 2006), the data set used in this study does contain some inhomogeneities.

Nevertheless, the daily data from these stations represent the 'best available' data for this study. The NCDC provided monthly and annual data for each station adjusted for inhomogeneities. The adjusted annual temperature data set was used for change point analysis. However, daily temperature data were used in the statistical analysis as that analysis was based on changes in daily values, i.e. GDD. Because of the presence of inhomogeneities the estimate of changes is more likely conservation in this study. For the same reason the freeze free period also may be fractionally longer. Nonetheless, the results of this study reflect changes in GDD, temperature and the freeze free period that may have potentially important impacts on the agricultural community of the SLV.

5 Results

5.1 Change point analysis

The results of change point analysis for the freeze-free period and temperature values are shown in Tables 2 and 3. The column "Change point year" shows the likeliest year the cumulative sum of the means is significantly different from the previous mean

Table 2 Results of change point analysis of vernal and autumnal freeze dates and freeze-free period for stations on the floor of the San Luis Valley, Colorado (Mix 2010)

Station	Change point year	Confidence interval	Confidence level	Before	After
Alamosa AP					
Last vernal freeze	No change	–	–	–	–
First autumnal freeze	No change	–	–	–	–
Freeze free period	1982	1962–2002	92	91.8	99.2
Blanca 4NW					
Last vernal freeze	1991	1979–1999	98	161.2	150.0
First autumnal freeze	1974	1967–1983	95	249.7	261.3
Freeze free period	1993	1979–1998	93	95.0	114.2
Center 4SSW					
Last vernal freeze	1985	1974–1993	99	163.8	152.0
First autumnal freeze	1981	1973–1985	100	248.1	261.7
Freeze free period	1983	1977–1988	100	85.3	109.0
Del Norte 2E					
Last vernal freeze	1963	1962–1975	99	144.2	156.7
	1985	1980–1992	99	156.6	143.6
	2001	1996–2003	93	143.6	160.3
First autumnal freeze	1973	1959–2001	93	256.1	263.6
Freeze free period	1978	1973–1986	99	104.5	119.0
	2001	1999–2001	94	119.0	90.2
GSDNP					
Last vernal freeze	1967	1965–1967	100	145.3	170.2
	1977	1977–1979	100	170.2	143.3
First autumnal freeze	No change	–	–	–	–
Freeze free period	1978	1968–1992	97	100.3	120.7
Manassa					
Last vernal freeze	1988	1974–1996	97	164.0	152.5
First autumnal freeze	1981	1977–1984	100	242.1	260.2
Freeze free period	1988	1984–1991	100	81.7	109.0
Monte Vista 2 W					
Last vernal freeze	1965	1962–1971	91	163.4	151.0
	1977	1975–1977	99	151.0	168.4
	1986	1986–1995	99	168.4	153.5
First autumnal freeze	1982	1964–1991	99	250.2	260.9
Freeze free period	1965	1960–1985	96	82.6	102.5

Table 3 Results of change point analysis for temperature variables at stations on the floor of the San Luis Valley, Colorado (Mix 2010)

Station	Change point year	Confidence interval	Confidence level	Before	After
Alamosa AP					
Maximum	1900	1990	93	15.9	17.2
	1903	1903–1906	92	17.2	14.9
	1999	1985–2003	97	14.9	16.0
Minimum	no change				
Mean	1994	1962–2001	100	5.1	5.7
Blanca 4NW					
Maximum	1909	1906–1913	100	14.1	13.0
	1921	1918–1926	99	13.0	14.3
	1964	1923–1992	94	14.3	14.0
	1994	1990–1996	100	14.0	15.6
Minimum	1994	1987–1996	99	-3.2	-2.3
Mean	1908	1904–1911	100	5.6	4.8
	1921	1919–1943	93	4.8	5.5
	1994	1990–1996	100	5.5	6.7
Center 4SSW					
Maximum	1905	1903–1909	100	15.9	14.2
	1999	1983–2003	92	14.2	15.2
Minimum	1994	1987–1999	100	-3.8	-2.8
Mean	1911	1907–1924	93	5.9	5.2
	1994	1988–2000	98	5.2	6.1
Del Norte 2E					
Maximum	1903	1901–1905	100	14.4	12.9
	1933	1921–1957	98	12.9	13.5
	1960	1949–1970	98	13.5	12.7
	1994	1989–1999	100	12.7	13.9
Minimum	1994	1989–1999	100	-4.3	-3.4
Mean	1994	1986–1999	100	4.4	5.3
GSDNP					
Maximum	1903	1901–1906	99	14.5	13.0
	1994	1987–1997	100	13.0	14.0
Minimum	1950	1916–1958	95	-1.3	-1.9
	1964	1960–1973	100	-1.9	-1.6
	1994	1992–1995	100	-1.6	-0.4
Mean	1912	1906–1924	91	6.4	5.8
	1994	1990–1996	100	5.8	6.9
Manassa					
Maximum	1918	1916–1920	100	14.6	13.1
	1934	1932–1945	100	13.1	14.2
	1994	1979–1999	96	14.2	15.2
Minimum	1954	1949–1961	100	-5.1	-4.1
	1994	1991–1996	100	-4.1	-2.7

Table 3 (continued)

Station	Change point year	Confidence interval	Confidence level	Before	After
Mean	1912	1901–1919	97	4.9	4.3
	1923	1913–1944	94	4.3	4.1
	1945	1940–1952	100	4.1	5.0
	1994	1990–1997	100	5.0	6.3
Monte Vista 2 W					
Maximum	1911	1906–1918	98	15.0	13.7
	1994	1991–1997	100	13.7	15.4
Minimum	1994	1984–2001	94	-4.9	-4.1
Mean	1912	1906–1924	99	5.1	4.4
	1994	1990–1998	100	4.4	5.6

values. However, a few stations indicated multiple change points for some variables and a few change points were indicated for the same year. The column "Confidence interval" indicates a broader range of years in which the change might have occurred.

The first change point analysis identified periods with significantly different ordinal days for the freeze-free periods. There was, however, no single definitive "Change point year" for the freeze-free period, last vernal or first autumnal freeze at all stations (Table 2). In this instance, the freeze-free period "Confidence interval" dates were used to estimate a change point common for all stations in order to approximate a system wide change. The estimation was accomplished by averaging the years in order to find the most parsimonious year included in the "Confidence interval" span of years for the SLV as a whole system. Using the above process it was concluded the years 1980–1981 represented the likeliest system wide change point, and the periods 1958–1980 and 1981–2007 were utilized for analysis. Since the freeze-free period is defined by days with minimum temperature above 0 °C, a minor temperature shift can result in change; therefore it should be expected, as climate warms, subtle changes will be detected earlier than changes in annual mean temperature. This is evident in comparison to the following change points in temperature and GDD bases.

The annual temperature change point analysis indicated 1993–1994 as the most parsimonious change point. Eighteen of 45 change point years were 1994, 6 of which were the only change points identified for the parameters: maximum, minimum or mean. Further, change point years for 5 of 7 stations listed 1994 as a change point year for all temperature parameters. Mix et al. (2011a) previously utilized the same process to identify change points in annual temperature data from the same stations; however the data in that study was corrected for inhomogeneities and reconstructed to 1895. The result of that study also indicated the period 1993–1994 as the likeliest system wide change point (Table 3). Change points for GDD were estimated based on the annual temperature change points. These are a function of daily temperature and therefore must be factored from daily data. At this time, daily temperature data from stations cannot be adjusted for inhomogeneity, therefore, the annual temperature change point served as proxy for GDD change points. This was felt to be a more conservative approach.

5.2 *T*-test analysis

Ordinal day of the last vernal freeze and first autumnal freeze were analyzed to determine if the 1981–2007 period had significantly earlier last vernal and later first autumnal freezes (Fig. 2, see Table S-1 in Supplementary Online Material). The last vernal freeze occurred significantly earlier only at 2 stations (Center 4SSW; GSDNP) with each occurring 7.75 and 11.86 days earlier, respectively. First autumnal freezes occurred significantly later at all stations, except Del Norte 2E and GSDNP, by 5.95 and 18.1 days. Additionally, the number of days occurring during the freeze-free period was analyzed to determine if the freeze-free period had increased in length during the 1981–2007 period. The freeze-free period significantly increased at all stations, except Del Norte 2E, by 7.3 to 24.2 days, respectively (Fig. 3, see Table S-1 in Supplementary Online Material).

T-test analyses were performed to determine if growing season months of May, June, July, August and September during the period 1994–2007 experienced an increase in temperature values, compared to the period 1958–1993. Data analysis of maximum temperature indicates 3 stations (Blanca 4NW; Del Norte 2E; GSDNP) experienced no significant increases for most months during 1994–2008 compared to 1958–1993 (Fig. 4, see Table S-2 in Supplementary Online Material). With few exceptions, all other stations experienced significant increases in maximum monthly mean temperature; between 0.30 and 1.4 °C. Analysis of minimum temperatures indicated all stations, with limited exceptions, experienced significant increases during all months, ranging between 0.34 and 2.12 °C (Fig. 5, see Table S-3 in Supplementary Online Material). The notable exception to these observations was Del Norte 2E, which experienced significant decreases in minimum temperature during all months except May. Furthermore, analysis of mean temperature indicates 5 of 7 stations experienced

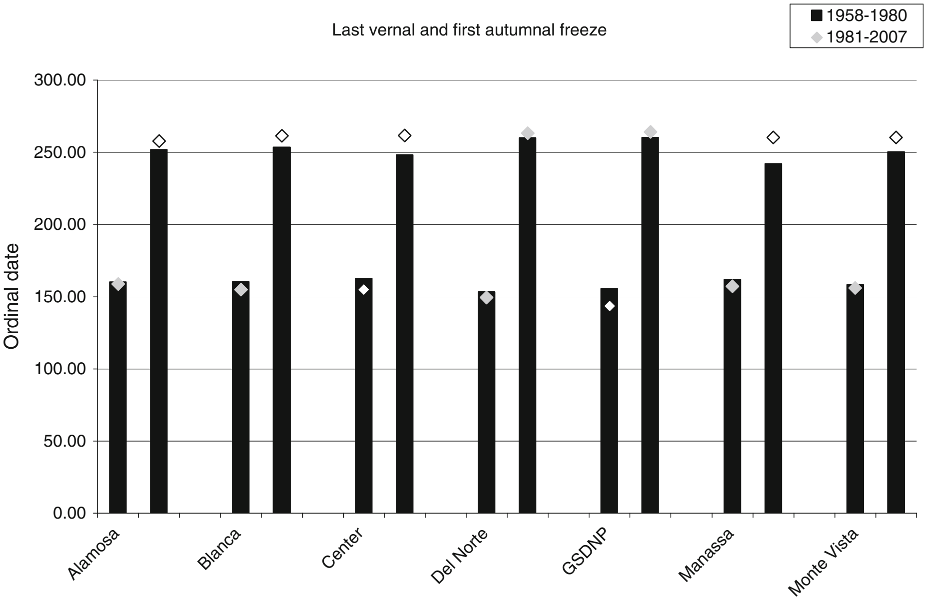

Fig. 2 Comparison of 1958–1993 (*bar*) mean annual freeze dates to 1994–2007 (*diamond*) mean annual freeze dates for each valley floor station in the San Luis Valley, Colorado. The first bar and diamond for each station represents the vernal freeze and the second the autumnal freeze. Open or white diamonds indicate significant differences ($p<0.05$)

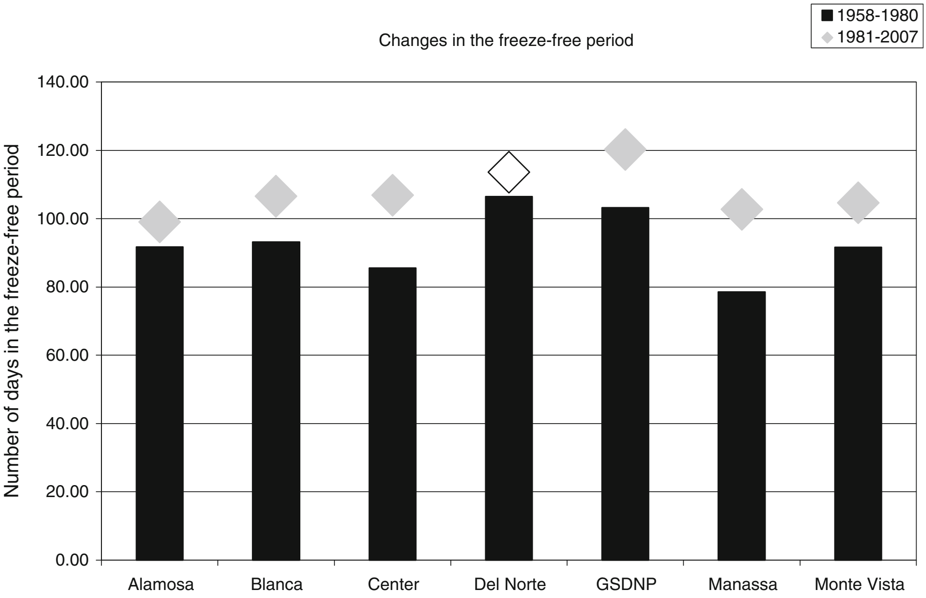

Fig. 3 Comparison of 1958–1993 (*bar*) mean length of freeze-free period to 1994–2007 (*diamond*) for each valley floor station in San Luis Valley, Colorado. Only Del Norte, open diamond, did not have a significantly longer growing season

increases during all months of 0.30–1.64 °C (Fig. 6, see Table S-4 in Supplementary Online Material). Two exceptions were Alamosa AP and Del Norte 2E, the former indicating no

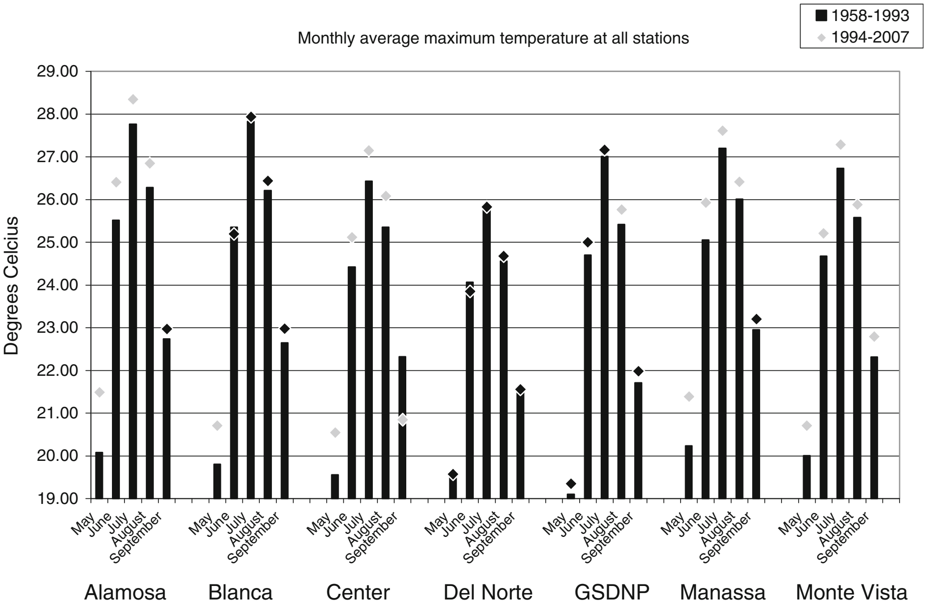

Fig. 4 Comparison of 1958–1993 (*bar*) maximum temperature to 1994–2007 (*diamond*) for each valley floor station in San Luis Valley, Colorado. Black diamonds indicate no significant difference ($p<0.05$)

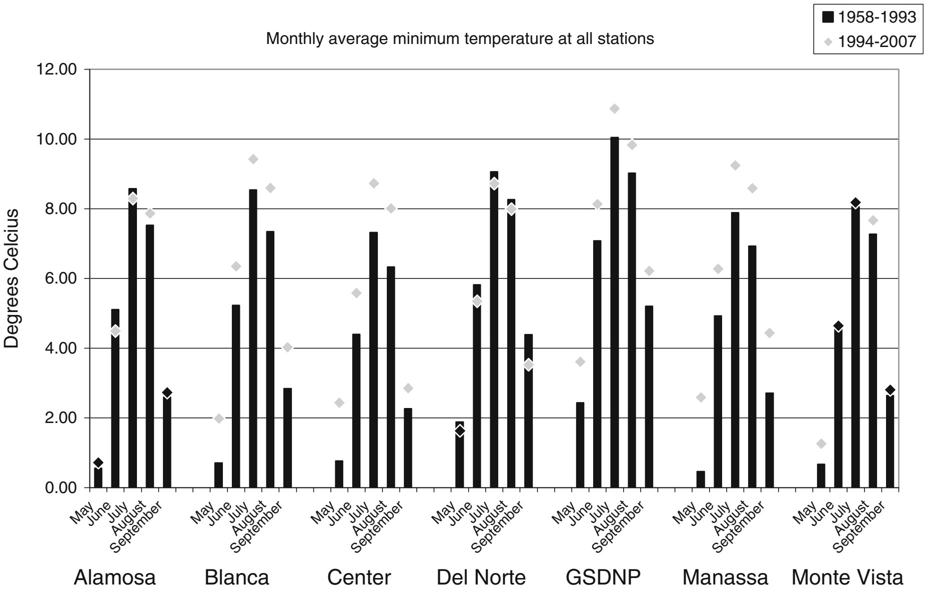

Fig. 5 Comparison of 1958–1993 (*bar*) minimum temperature to 1994–2007 (*diamond*) for each valley floor station in San Luis Valley, Colorado. Black diamonds indicate no significant difference ($p<0.05$)

changes in June, July and September, while Del Norte 2E experienced no change in May, July and August, with data from June and September indicating a significant decrease in monthly mean temperature.

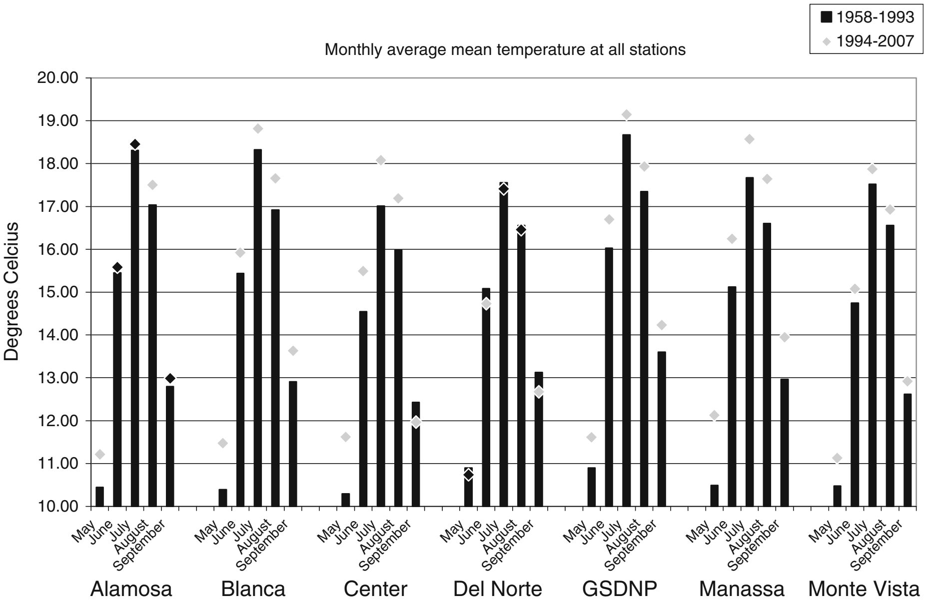

Fig. 6 Comparison of 1958–1993 (*bar*) mean temperature to 1994–2007 (*diamond*) for each valley floor station in San Luis Valley, Colorado. Black diamonds indicate no significant difference ($p<0.05$)

Analyses were performed to determine if GDD had increased during the growing season months of May, June, July, August and September in the period 1994–2007, compared to 1958–1993. The analysis of GDD_{10} indicated all stations experienced significant increases between 0.13 and 0.68 GDD_{10} during nearly every month during the period 1994–2007, compared to 1958–1993 (Fig. 7, see Table S-5 in Supplementary Online Material). Notable exceptions to this pattern included no change for Del Norte 2E during all months, and no changes in June, July and September for Blanca 4NW. The analysis of $GDD_{4.4}$ indicated significant increases for all stations and all months, ranging between 0.23 and 1.08 (Fig. 8, see Table S-6 in Supplementary Online Material). Exceptions to this observation include no change during July at Alamosa AP, and no changes in May, July, August and September at Del Norte 2E, with a significant decrease in $GDD_{4.4}$ for June. The $GDD_{5.5}$ analysis indicated all stations during all months experienced significant increases ranging between 0.19 and 0.97, the exceptions being Blanca 4NW in June, and Del Norte 2E, which exhibited no changes except a significant decrease in June (Fig. 9, see Table S-7 in Supplementary Online Material).

6 Discussion

All major crops of the SLV (alfalfa and other hays, small grains of barley and spring wheat, potatoes, spinach, lettuce and carrots) are freeze resistant, being able to tolerate short periods of temperatures below 0 °C without mortality. For this reason, these crops are typically planted prior to the last freeze (SLVDG 2002). This early planting maximizes the growing season, since they can be germinated and growing by the time the freeze-free period arrives, thereby taking full advantage of warmer temperatures.

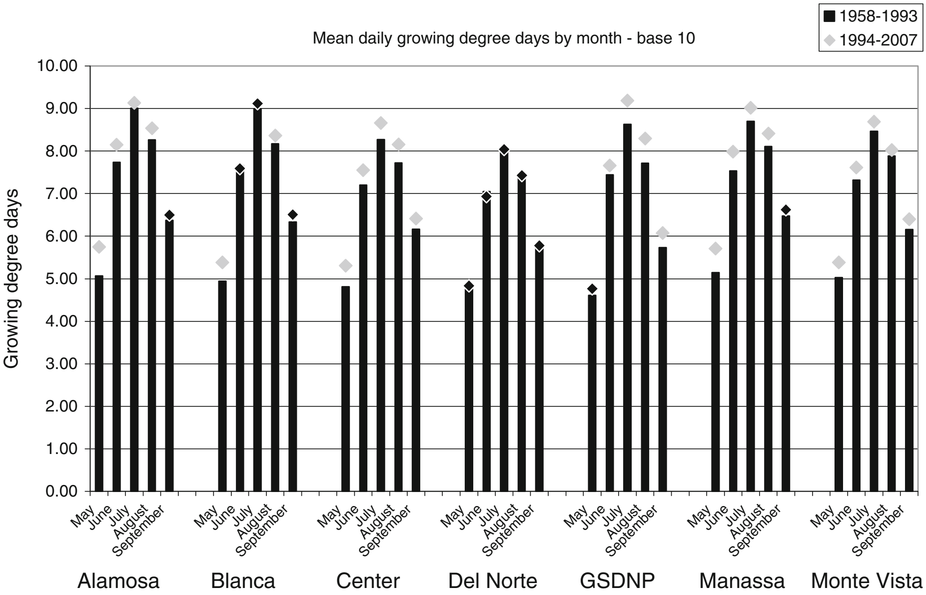

Fig. 7 Comparison of 1958–1993 (*bar*) mean daily GDD_{10} in each month to 1994–2007 (*diamond*) for each valley floor station in San Luis Valley, Colorado. Black diamonds indicate no significant difference ($p<0.05$)

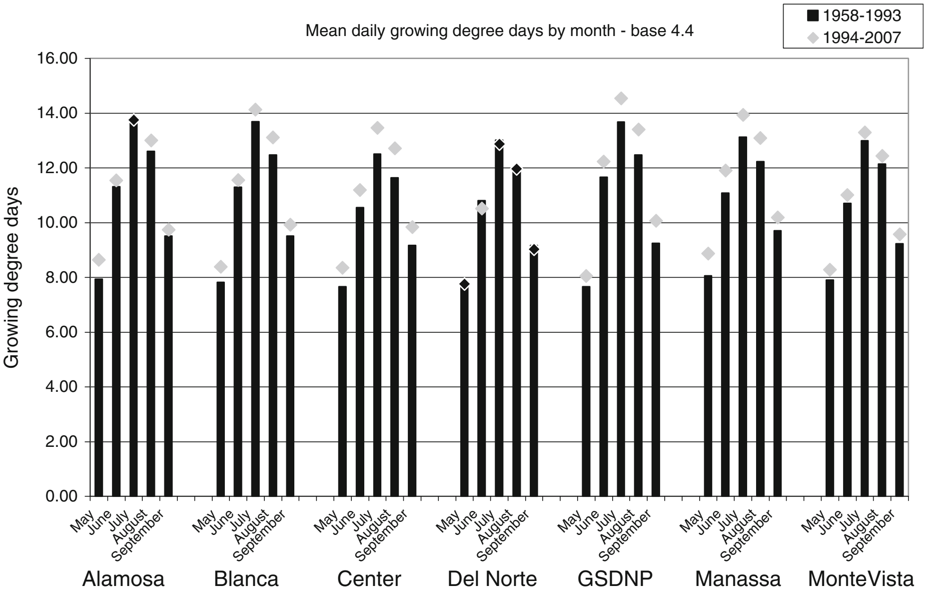

Fig. 8 Comparison of 1958–1993 (*bar*) mean daily $GDD_{4.4}$ in each month to 1994–2007 (*diamond*) for each valley floor station in San Luis Valley, Colorado. Black diamonds indicate no significant difference ($p<0.05$)

Results from this study indicate within the SLV, the freeze-free period has expanded, and GDD and temperature variables have increased in most months of the growing season at most stations. These are not homogeneous increases in time or location. Changes in the

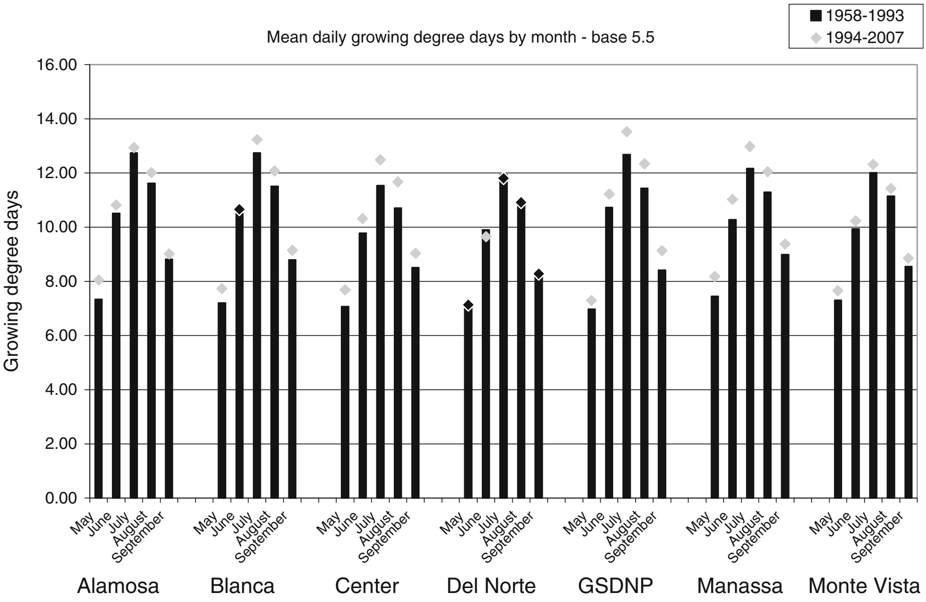

Fig. 9 Comparison of 1958–1993 (*bar*) mean daily $GDD_{5.5}$ in each month to 1994–2007 (*diamond*) for each valley floor station in San Luis Valley, Colorado. Black diamonds indicate no significant difference ($p<0.05$)

length of the freeze-free period have occurred most significantly for the first autumnal freeze date, with little significant change in the earliness of the last vernal freeze date. Similarly, increases in temperature variables and GDD do not indicate homogeneous increases throughout the season.

The freeze free period in the SLV is now longer by about 7–20 days, compared to that for the period 1958–1993. White et al. (2009) found a nominal extension of the growing season in North America by comparing multiple satellite data sources. Feng and Hu (2004) showed a trend toward earlier spring by 4 days in the western United States, while also indicating no change in the Rocky Mountains, in which the SLV is located. Further, Menzel and Fabian (1999) reported an increase in the growing season in Europe by about 10 days over a 30-year period since the early-1960's. Though the Menzel and Fabian (1999) is located in Europe it also reveals 1980 as the date after which the greatest expansion took place. Analysis of the changes in the last vernal and first autumnal freezes indicated the last vernal freezes are arriving earlier for Center 4SSW and GSDNP, and marginally so for Blanca 4NW, by about 8±3 days. The autumnal freeze dates, however, are later by 6–18 days at all but the Del Norte 2E and GSDNP stations. Combining these changes in freeze dates produces the significantly longer growing season noted above. Although the last vernal freeze date typically occurred around June 9 in the earlier period, it now occurs around June 5. The first autumnal freeze, which previously occurred around September 10, now occurs around September 18. In contrast to the findings of Menzel and Fabian (1999), the greater expansion of the growing season in the SLV occurs during the autumnal phase. Their data on European changes only extended to the early-1990's however, whereas the SLV data extends to 2007.

Depending on the magnitude of lengthening, it may provide enough time to grow new crops that require a longer season, or possibly allow for the planting of a second crop. Further, it can reduce planting and harvest time pressures by reducing the threat of late- and early-freezes. With only a few extra days occurring in the spring at 2 or 3 stations, and an increase of several days in the fall at all locations, however, the SLV agricultural community is not likely experiencing a reduction of timing pressures, except at the end of the season. There is the possibility of early maturation with a longer season thus reducing timing pressure, but could come at the expense of reduced yield (Singh et al. 1998).

The analysis of temperature data indicated that increases during the growing season months were highest in May and June. The increased mean daily minimum temperatures potentially indicates a trend toward earlier last vernal freezes; although the change was not always significant, every station did report an earlier mean date for the last vernal freeze (Fig. 2). In contrast, the increased minimum temperatures for September were not as great, although the first autumnal freeze is significantly later at most stations.

The data analysis for the Del Norte 2E station consistently contrasted with general outcomes of other stations. Del Norte is uniquely located, slightly higher in elevation and in the Rio Grande Pass in the San Juan Mountains. The difference in results could be associated with location and presence of air currents flowing down out of the pass. Using annual temperature data, adjusted for inhomogeneities, Mix et al. (2011a) concluded that annual temperature variables at all stations were significantly higher after 1994. Of course, it could be data from Del Norte 2E are not reliable and more likely the trend is similar to other stations.

Analyses of the GDD in the SLV indicated, with few exceptions, all stations and all months have a greater number of GDD during the 1994–2007 period than prior to that time. This result is similar to results from a Canadian study, which indicated significant increases in GDD had occurred throughout major growing regions (Bonsal et al. 2001). The changes in GDD could lead to asynchrony of pest/prey relationships in several agricultural milieus

(Parmesan 2006). Further, an increase in number of pest generations, and changes in location or migration (i.e., arriving when the crop is sensitive to herbivory), also could manifest as changes in insect phenology occur (Bale et al. 2002). The results from this study indicate about a 1 °C increase in daily mean temperature and 15–20 additional GDD in both May and June, depending on location. The increase in GDD could cause a reduction in crop quality or yield with early maturity, as indicated by Singh et al. (1998).

Potato production in the SLV outranks all other crops in total value at more than $100 million in average annual revenue and $198 million, from 23,430 ha in 2005. Studies of potato insect pests (e.g., peach potato aphid (*Myzus persicae*)) indicate an increase in their abundance with increases in temperature (Bezemer et al. 1998). Fortunately, their parasitoid (*Aphidius matricariae*) also responded with increased fecundity. Diseases of potatoes also have been shown to benefit from increased temperatures and GDD. Infection of potatoes by bacterial ring rot (causal organism *Corynebacterium sepedonicum*) is exacerbated by warmer climatic conditions (Manzer et al. 1987), and the advent of more $GDD_{4.4}$ would provide better conditions for the disease to persist in the SLV. It is predicted late blight (*Phytophthora infestans*) will change distribution and increase virility as northern latitudes warm (Hijmansa et al. 2000). Early blight (*Alternaria solani*) spores become present in the SLV at about 360 GDD, roughly in mid-July (Franc et al. 1983). With the increased $GDD_{4.4}$ found in this study, this occurrence effectively moves the presence of early blight to late-June and the winter wheat pathogen, take-all fungus (*Gaeumannomyces graminis*), begins appearing around 800 GDD (Colbach et al. 1997), which now accumulate about 15–20 days earlier.

In contrast to potato production in 2005 the SLV had approximately 104,000 ha in hay production, more than half being alfalfa. The gross revenue from this crop was $72 million. The May and June $GDD_{5.5}$ at most stations exhibited significant increases of about a 0.5 $GDD_{5.5}$ per 24 hours, effectively adding about 15 additional GDD in those months. This could be beneficial for the crop, by providing additional warmth and time for growth during the short growing season. However, it also potentially increases the need for irrigation. Irrigated alfalfa requires 2–3 acre-feet of water, and significant increases in growth would require increased irrigation (Finnerty and Ramirez 1995). The increased GDD may also indicate insect pests such as spittlebug and aphid species (Auchenorryncha: Cercopidae) (Whittaker and Tribe 1996), and weevils (Coleoptera: Curculionidae) will be able to produce additional generations. Additional $GDD_{5.5}$ are also expected to increase the timing and incidence of verticillium wilt (*Verticillium albo-atrum*) (Boland et al. 2004). As temperatures increase, more irrigation water will be applied, depending on the method employed, i.e. flood, overhead or drip, it has the potential to promote growth of other fungal pathogens. Similarly, GDD_{10} changes occurred, potentially increasing the amount of time available for diseases to infect other SLV crops. However, the studies evaluating the impacts of climate change on crops and their pests are not definitive.

Climate change models indicate insect pests will have greater abundance, new distribution or range, increased voltinism, and are expected to migrate to new regions as the climate shifts (Porter et al. 1991; Brasier and Scott 1994; Woiwod 1997; Hassall et al. 2007). Studies indicate higher temperatures will increase abundance and distribution to higher latitudes of European corn borer (*Ostrinia nubialis*), a common pest of many crops. Lepidopterans are flying earlier under the current increased temperature, resulting in earlier herbivory by their caterpillars. The Fleming and Candau (1998) model of climate change insect interactions predicts increased Spruce budworm outbreaks, which could affect forestry management in Canada.

Information regarding climate change in the San Luis Valley is scant, as are studies on other montane or sub-alpine deserts and ecosystems. Nevertheless, Mix et al. (2011a) reported a lagged increase in temperature response, similar to IPCC (2001) predictions of lower increases in temperature higher in the atmosphere, indicating altitude may provide ameliorating effects from climate change in the short run.

The greatest negative impact likely experienced at this time is increased irrigation. Several studies confirm GDD increases can exacerbate the need for irrigation, since increases in growth will cause a concomitant increase in crop evapotranspiration (Adams 1989; Schimmelpfennig et al. 1996; Ramirez and Finnerty 1996). Herrington (1996) predicts a 12% increase in irrigation demands for every 1.1 °C increase in temperature. The agriculture in the SLV utilizes an average of 750 hm^3 of irrigation water during the growing season, which increased from about 700 hm^3 after 1965 (Mix et al. 2011b). This equates to about a 7% increase in irrigation demand.

The economic importance of risks posed by climate change to agriculture by reducing crop yields because of forced maturity, changes in pest presence, or increased irrigation costs, can be observed easily when viewing SLV crop production statistics. Potato acreage in the SLV in 2005 covered 23,400 ha and yielded 22.2 million cwt, valued at nearly $200 million, equivalent to more than 15 times the gross value of any other SLV crop. Hays, including alfalfa, covered 100,000 ha, valued at nearly $75 million. Small grains and vegetables generate an additional $45 million on the remaining acreage. A small percentage change in the volume or the quality of these crops as a result of climate changes has the potential to cause several million dollar agricultural losses. However, it also should be noted agriculture is constantly adapting with new varietals and hybrids, and there is considerable potential for ongoing adaptive processes to ameliorate any negative impacts of climate change.

7 Conclusion

Analysis of climate change in the SLV indicates the freeze-free period has expanded, that the temperature has risen similarly to global rises, and that GDD are increasing.

The San Luis Valley is an important agricultural system, both locally and regionally. It employs more than 50% of the Valley's inhabitants, being responsible for producing nearly 100% of the state of Colorado's potatoes. The SLV growing season has increased by about 7–24 days at all stations since the early-1980's. The last vernal freeze is occurring significantly earlier at 3 stations by approximately 5–12 days, with the first autumnal freeze occurring significantly later at 5 stations by approximately 6–18 days. Although the last vernal freeze is not occurring significantly earlier for 4 of 7 stations, 6 stations report that May and June exhibit significantly higher mean temperatures. If this is a trend toward a warmer spring, it indicates the last vernal freeze potentially will continue to occur earlier. These analyses also indicate the daily maximum, minimum and mean temperatures at nearly every station in most months of the growing season have increased by about 0.3–1.4 °C, 0.3–1.7 °C and 0.5–1.6 °C, respectively. Further, nearly all stations report significant increases in $GDD_{10,}$ $GDD_{4.4,}$ $GDD_{5.5}$ in most months, 0.15–0.7, 0.2–1.0, and 0.2–0.95, respectively.

The benefits of earlier last vernal freezes include longer crop growing periods, and reduced risk of freeze injury for late plantings. Further, higher temperatures at the onset of the growing season have the potential beneficial impact of increasing the growth rate of young plants, or plants breaking dormancy. Negative impacts of higher temperature and more GDD include bolting in lettuce and spinach crops prior to harvest, longer irrigation periods, potential earlier and increased disease presence. Increased pest insect generations, abundance and potential asynchrony with parasitoid insects also may occur. Further, increases in GDD can cause reduced crop yield from forced maturation, and the crop quality can be reduced, and early senescence may be induced.

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