Docket No, UG-06____
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BEFORE THE

WASHINGTON UTILITIES & TRANSPORTATION COMMISSION

UG-06____

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Exhibit ___(PWM-2) – Trends in Temperature and Precipitation in the Pacific Northwest During the Twentieth Century
Exhibit ___(PWM-3) - Monthly Graphs Of Cascades Four Weather Stations
Exhibit ___(PWM-4) – Normal Heating Degree Days

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Trends in Temperature and Precipitation in the Pacific Northwest During the Twentieth Century

Abstract

Documenting long-term trends or persistent shifts in temperature and precipitation is important for understanding present and future changes in flora and fauna. Carefully adjusted datasets for climate records in the USA and Canada are combined and used here to describe the spatial and seasonal variation in trends in the maritime, central, and Rocky Mountain climatic zones of the Pacific Northwest. Trends during the 20th century in annually averaged temperature (0.7°C–0.9°C) and precipitation (13%–38%) exceed the global averages. Largest warming rates occurred in the maritime zone and in winter and at lower elevations in all zones, and smallest warming rates occurred in autumn and in the Rockies. Largest increases in precipitation (upwards of 60% per century) were observed in the dry areas in northeast Washington and south central British Columbia. Increases in precipitation were largest in spring, but were also large in summer in the central and Rocky Mountain climatic zones. These trends have already had profound impacts on streamflow and on certain plant species in the region (Cayan et al. 2001), and other important impacts remain to be discovered. The warming observed in winter and spring can be attributed partially to climatic variations over the Pacific Ocean, and the buildup of greenhouse gases probably also plays an important role.

Introduction

In the last ~150 yr, humans have enhanced the natural greenhouse effect of the atmosphere by increasing the quantities of key greenhouse gases. Carbon dioxide has increased 32% because of the burning of fossil fuels and deforestation, and methane has increased by 151% because of agriculture (chiefly cattle and rice paddies) and other human sources (Prentice et al. 2001). Other greenhouse gases have also increased, including CF_4, C_2F_6, and SF_6, whose human sources exceed natural sources by a factor of 1,000 or more, and some (e.g., the chlorofluorocarbons) that have no natural sources (Prather et al. 2001). In the global mean, CO_2 accounts for 60% of the radiative forcing by greenhouse gases, and CH_4 20% (Ramaswamy et al. 2001).

During the 20th century, globally averaged surface temperature rose 0.6°±0.2°C, with most of the warming occurring in two intervals: between 1910 and 1945, and between 1976 and 2000 (Folland et al. 2001). Most evidence confirms that at least some of the rise in temperature can be attributed to the buildup of greenhouse gases (Mitchell et al., 2001). In addition to these instrumental records, evidence from a variety of natural systems also confirm recent warming: reductions in springtime northern hemisphere snow cover by 10%, in sea ice extent, and in length of most glaciers (Folland et al. 2001); changes in range of various flora and fauna, and timing of migration of diverse species (Walther et al. 2002). In western North America, warming has advanced the arrival of spring by 1-2 wk in the past 50 yr as indicated by various hydrologic and phenologic metrics (Cayan et al. 2001), and has reduced springtime snowpack in the Pacific Northwest (PNW) especially at elevations below about 1800 m (Mote 2003a).

Several studies (Easterling et al. 2000, Zhang et al. 2000, Folland et al. 2001) have displayed maps of trends in temperature and precipitation at the national or global scale, which show that temperature and precipitation have risen in the PNW during the 20th century. Southern British Columbia warmed substantially (roughly 0.5°-1.5°C), especially at night and in winter, and precipitation increased in all seasons in amounts between 5% and 35% (Zhang et al., 2000). It is difficult, however, to quantify regional or subregional trends from national maps like those shown by Zhang et al. (2000) especially when the distinction between adjacent colors is poor. Mote et al. (1999) presented maps and analysis for the U.S. part of the PNW, for which temperature rose 0.8°C and precipitation 14% during the 20th century.

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This article provides a regional focus for climatic trends in the PNW that may be useful for understanding other environmental changes and trends, augmenting the above-mentioned national- or global-scale studies. Also, this article emphasizes that the PNW is ecologically connected across the U.S.-Canada border. Mote (2003b) combined U.S. and Canadian data and examined the spatial and elevational dependence of the trends; this article uses more recent data for the USA, adds stations in western Montana, provides a basis for combining the datasets, and examines seasonal and interannual characteristics of the variability and trends.

Data and Methods

For this study I circumscribe the Pacific Northwest by the Continental Divide, the 111° meridian, and the latitudes 42° and 55°. This definition encompasses Washington, Oregon, and Idaho in their entirety, southern and central British Columbia, and a portion of western Montana. I use station data compiled and adjusted separately by the U.S and Canadian climate centers.

For the Canadian portion of the study area, I use the Historical Canadian Climate Database (HCCD) (Vincent and Gullett 1999), which has 32 stations with temperature records and 81 stations with precipitation records. For the U.S. portion of the study area I use the Historical Climate Network (USHCN) (Karl et al. 1990), which has 122 stations with temperature records and 84 stations with precipitation records. The period of record with best coverage (Figure 1) is roughly 1925-2000 for USHCN and 1950-1995 for HCCD, although for both datasets a majority of stations have periods of record beginning by 1920. Many stations have gaps in their precipitation records as indicated by the fluctuating totals. In this paper I will compare trends at different locations over the period of record 1930-1995 and areally combined trends over different periods of record; results (especially for temperature) are relatively insensitive to period of record.

Weather stations were not originally intended for monitoring long-term trends, and therefore these datasets have been adjusted to account for factors that can influence measurements, including changes in instrument, changes in observing practices, and relocation of the station. For example, weather observations at Vancouver, Washington (Figure 2) have a varied history. This station has the earliest measurements in the USHCN database for the Northwest. Measurements began in December 1849 at Fort Vancouver, were discontinued in 1868, resumed for a few years around 1890, resumed again in 1895, and continued without major interruption until 1966. In mid-1966

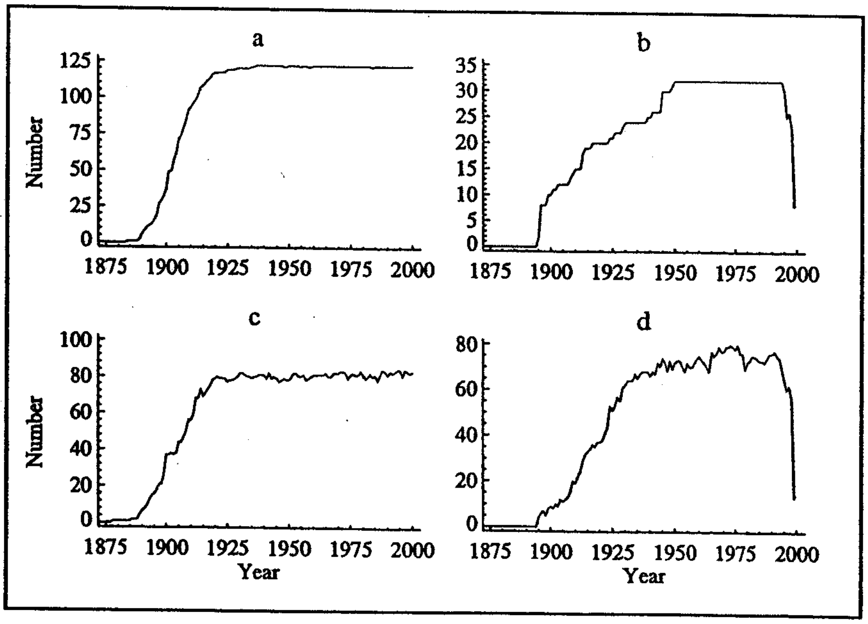

Figure 1. Number of stations reporting annual mean temperature (a, b) or precipitation (c, d) in each year for the USHCN dataset (a, c) and the HCCD dataset (b, d).

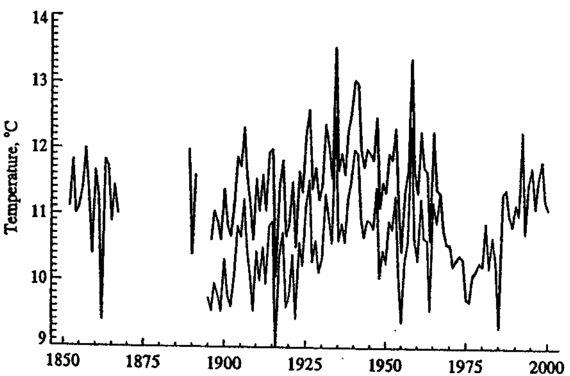

Figure 2. Annual mean temperature at Vancouver, Washington, showing the difference between unadjusted (upper) and adjusted (lower, shorter) station records in the USHCN dataset. In 1966 the station was moved about 4 km, and the new site had a lower annual mean temperature; the earlier record was adjusted to reflect this change. After 1966 the two time series are nearly identical. Adjustments at other stations were almost all smaller than those shown here.

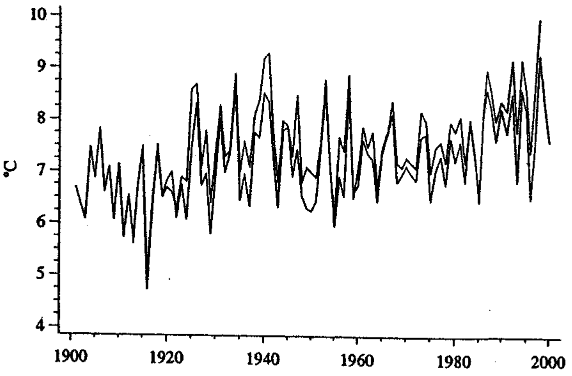

Figure 3. Comparison of annual mean temperature at Porthill, Idaho (lower), period of record 1901-2000 from the USHCN dataset, and Creston, British Columbia (upper), period of record 1913-1998 from the HCCD dataset. The two stations are about 10 km apart and both records have been adjusted to remove various time-dependent biases.

the station was moved 4.6 km northeast, and at the new location, the mean temperature was approximately 1°C lower, so that the earlier part of the data record was adjusted downward to be consistent. (Adjustments related to station changes are always applied to the earlier part of the record so that new observations can be added with no further adjustments.) The measurements before 1888 were not performed with a properly sheltered, min-max thermometer and are excluded. Differences between adjusted and unadjusted records were typically much smaller than this example, and few had such dramatic step changes.

One concern about combining the USHCN and HCCD databases is that somewhat different procedures were used by the two national climate centers in processing and adjusting station data. An indication of consistency between datasets can be derived by comparing proximate stations, like Porthill, Idaho, and Creston, British Columbia, which are 10 km apart (Porthill is 56m lower in elevation). Their annual temperature records (Figure 3) are correlated at 0.94 and have nearly identical trends (1.3° and 1.5°C). The difference in means (0.4°C) is not statistically significant. From this limited comparison, combining the datasets seems reasonable.

To examine the temporal (seasonal, interannual, and longer-term fluctuations) characteristics of the temperature variations, it is necessary to combine or aggregate the station data in some way. Various approaches have been used in previous studies, including averaging in latitude-longitude bins (Easterling et al. 2000, Zhang et al. 2000), averaging in climate divisions and then weighting by area of climate division to form a regional average (Mote et al. 1999), or thinning the stations to a more nearly uniform density (Frich et al. 2002). In this study, following Mote (2003b), I divide the Northwest into three broad climatic and ecological zones: the maritime zone, encompassing stations west of the crest of the Cascade mountains and those in British Columbia lying in or west of the coastal mountains; the Rockies, encompassing stations in north-central and eastern British Columbia, Montana, and most of Idaho; and the central zone, encompassing stations in eastern Washington, eastern Oregon, the Snake River Plain, a few other moderate-elevation (<1160m) stations in western Idaho, and south-central British Columbia south of Kamloops. Monthly mean temperatures in each zone are calculated using only those stations with nearly continuous records from 1920 to 1999, to ensure that no spurious trend will arise as a result of changes in the population of stations used from year to year. Values before 1920 are calculated from stations as available and are plotted but not included in the analysis.

To examine connections between PNW climate variability and North Pacific climatic variations, I perform regression analysis of these Northwest climate data using a time series of the North Pacific Index (Trenberth and Hurrell, 1994). The North Pacific Index (NPI) is defined as the mean sea level pressure over the region 30°-60°N, 160°E-140°W, and I use here the NPI value corresponding to the season being analyzed. Regression analysis (von Storch and Zwiers, 2001) identifies linear relationships between variables, much like correlation analysis but with the dimensions of the original variable (°C for temperature, cm for precipitation) preserved. Analyses are performed over the period 1920-2000, and statistical significance ($P<0.05$) is determined using the method of Bretherton et al. (1999) to estimate number of degrees of freedom, accounting for the structure of the serial autocorrelation function.

Results

Temperature Trends

As a first look at temperature trends, I plot at each station the 1930-1995 trend using linear least squares fit (Figure 4). At the vast majority of sta-

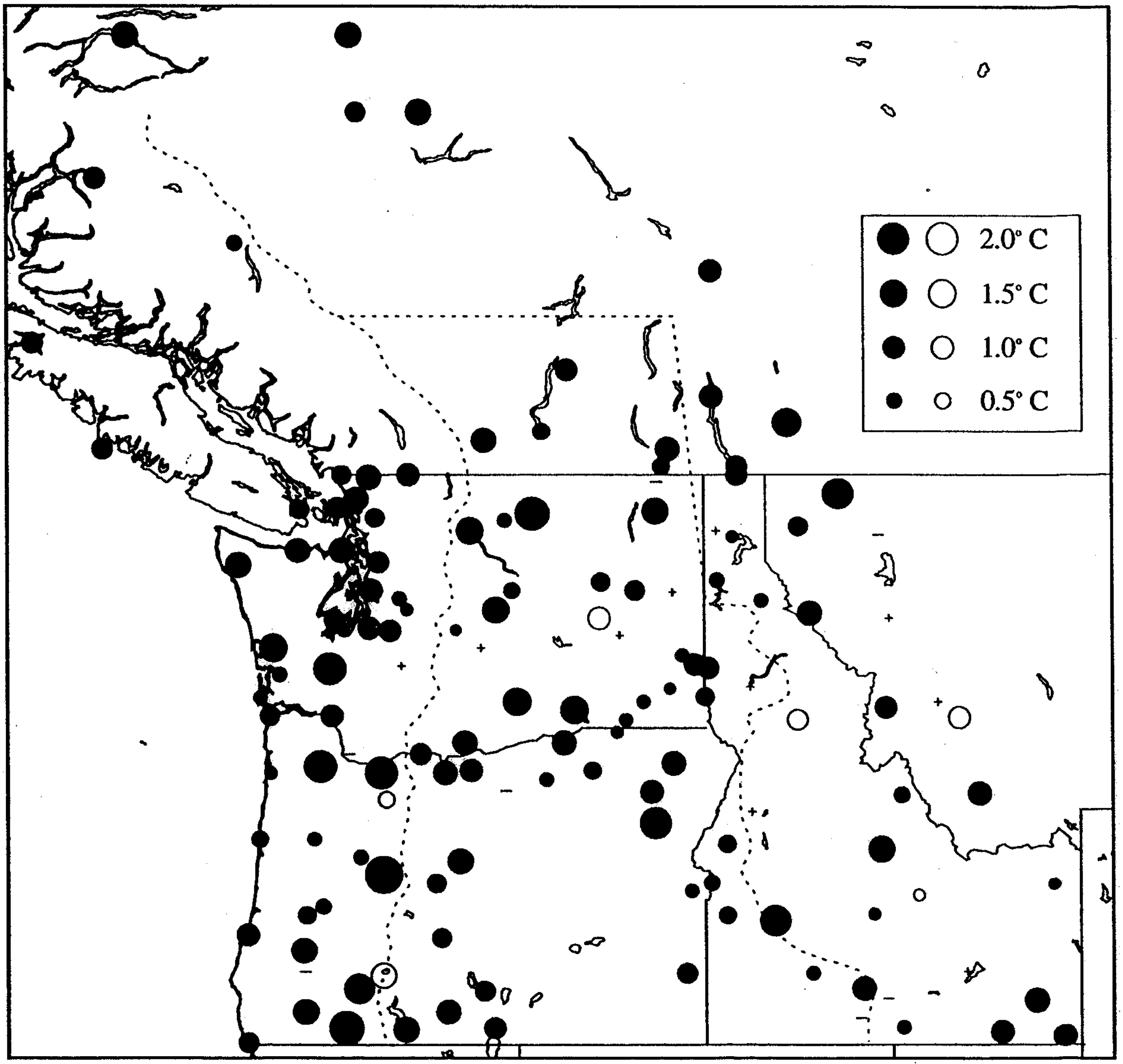

Figure 4. Linear trends in annual temperature at each station. Trends are calculated for the period from 1930 to the end of the record (must be at least 1995) and scaled to give temperature change per 100 yr. Positive trends are shown as filled circles and negative trends as open circles, and the area of the circle is proportional to the magnitude of the trend as indicated in the legend. But trends between 0 and 0.25° C are marked with a '+' and trends between –0.25 and 0° C are marked with a '–'. Dotted curves show the boundaries of climatic zones used in Figures 6 and 9.

tions in the Northwest, the temperature trends have been positive. In each of the four states, but not in British Columbia, trends have been negative at a handful of stations. Stations in and near urban and rural areas have similar trends, and in each state the largest warming trend is in a rural area or small town.

To indicate how the trends depend on the period of record, Figure 5 shows quantile distributions of total change from year indicated to the end of the record. For no choice of starting point are more than 10% of trends negative. A starting point of 1925 yields the largest fraction of negative trends, the smallest mean changes, and the smallest trends. For starting years from 1925 to about 1945, both the mode and the mean increase gradually from about 0.5°C to 1°C.

From the monthly mean temperatures calculated for each climatic, time series and linear trends in monthly, seasonal, and annual temperatures are calculated; Figure 6 shows the results for seasonal and annual temperatures in each climatic zone. The trend in annual average temperature decreases from the maritime zone (0.91°C) to the central zone (0.83°C) to the Rockies (0.73°C), and in all zones the trend is large and somewhat greater than the global average trend over the 20th century (0.6°C), but is only significant in the central zone. In all three zones, trends are largest in winter (January-February-March) and in all but the maritime zone trends in other seasons are small. Trends are smallest in autumn (October-November-December) in all three zones.

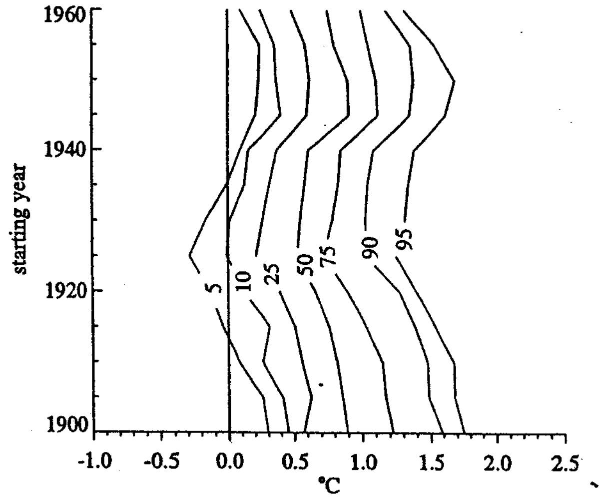

Figure 5. Quantiles (e.g., 50 = 50%) in the distribution of linear trends, evaluated for each starting year at 5-yr intervals as total changes from then to the ending year (required to be at least 1996). The number of stations included in the analysis increases with time as indicated in Figure 1.

Interannual variations in the region's climate are coherent: The three time series of annual temperature (top row) are significantly correlated (0.90 for maritime and Rockies, 0.85 for maritime and central, 0.96 for central and Rockies). The extreme years tend to be similar among the zones: 1955 and 1985 are among the coldest in all three zones, and 1934 and 1992 are among the warmest. The extreme years are often determined by only one season: 1985 had an unusually cold autumn, especially in the Central zone, and 1934 was an unusually warm winter in all zones. In all zones the 1990s were the warmest decade, warmer than any other decade by about 0.4°C-0.5°C; these differences are statistically significant for the maritime and central zones.

Climatic patterns over the Pacific Ocean play an important role in year-to-year climatic variations, and hence potentially influence long-term trends as well. As described earlier, I regressed each of the time series of temperature shown in Figure 6 on the north Pacific index (NPI); the linear trend in the regressed values is then expressed as a fraction of the trend in the data (NPI fraction of trend). Table 1 shows the correlation coefficient and NPI fraction of trend for the annual mean and the winter season, when correlations and trends are significant. The NPI explains 30-40% of the

TABLE 1. Correlations between North Pacific Index (NPI) and temperature, and fraction of the trend attributable to NPI, for the annual mean and winter. In other seasons either the correlation or the trend fails a significance test.

	Maritime		Central		Rockies	
	Correlation	Fraction	Correlation	Fraction	Correlation	Fraction
Annual	-0.69	11%	-0.52	11%	-0.55	12%
JFM	-0.79	41%	-0.63	36%	-0.65	32%

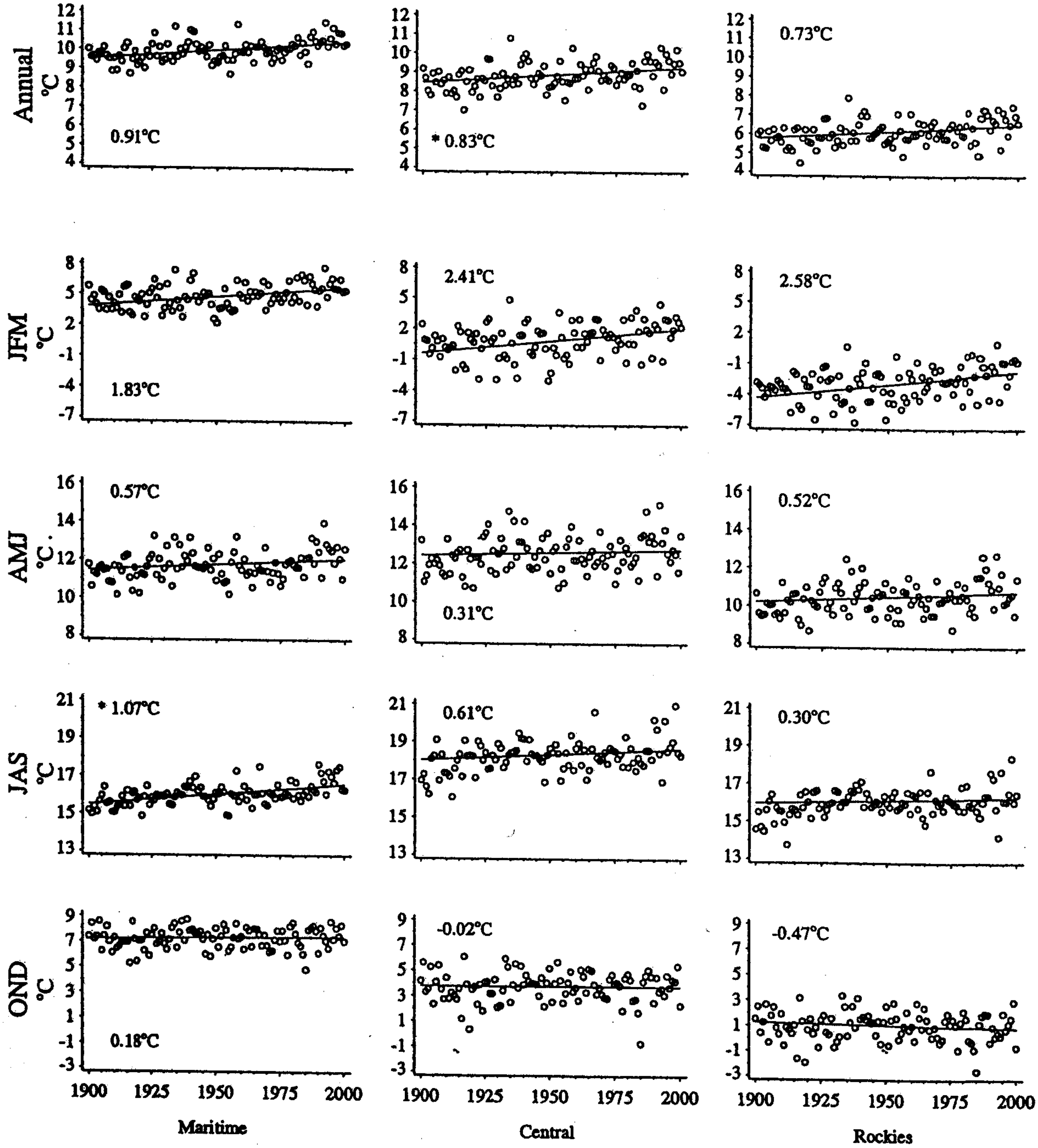

Figure 6. Temperature, averaged over all stations in each of three climate zones (columns, as indicated) for annual mean (top row) and each of four seasons as indicated. The linear trend over the 1920-2000 period, expressed in degrees per century, is indicated in each panel and marked by a '*' if significant at $P < 0.05$. In each row the scale on the ordinate is the same for all three zones. Note that trends in each climate zone are largest in winter (JFM).

large winter trends but only a small portion of the trends in annual mean. For spring, correlations are significant (ranging from –0.35 to –0.45), but trends are not; in other seasons, correlations are not significant.

Precipitation Trends

Although total precipitation at a given location helps determine which flora will be found there, relative (percentage) changes in precipitation are often more relevant for changes in biological pro-

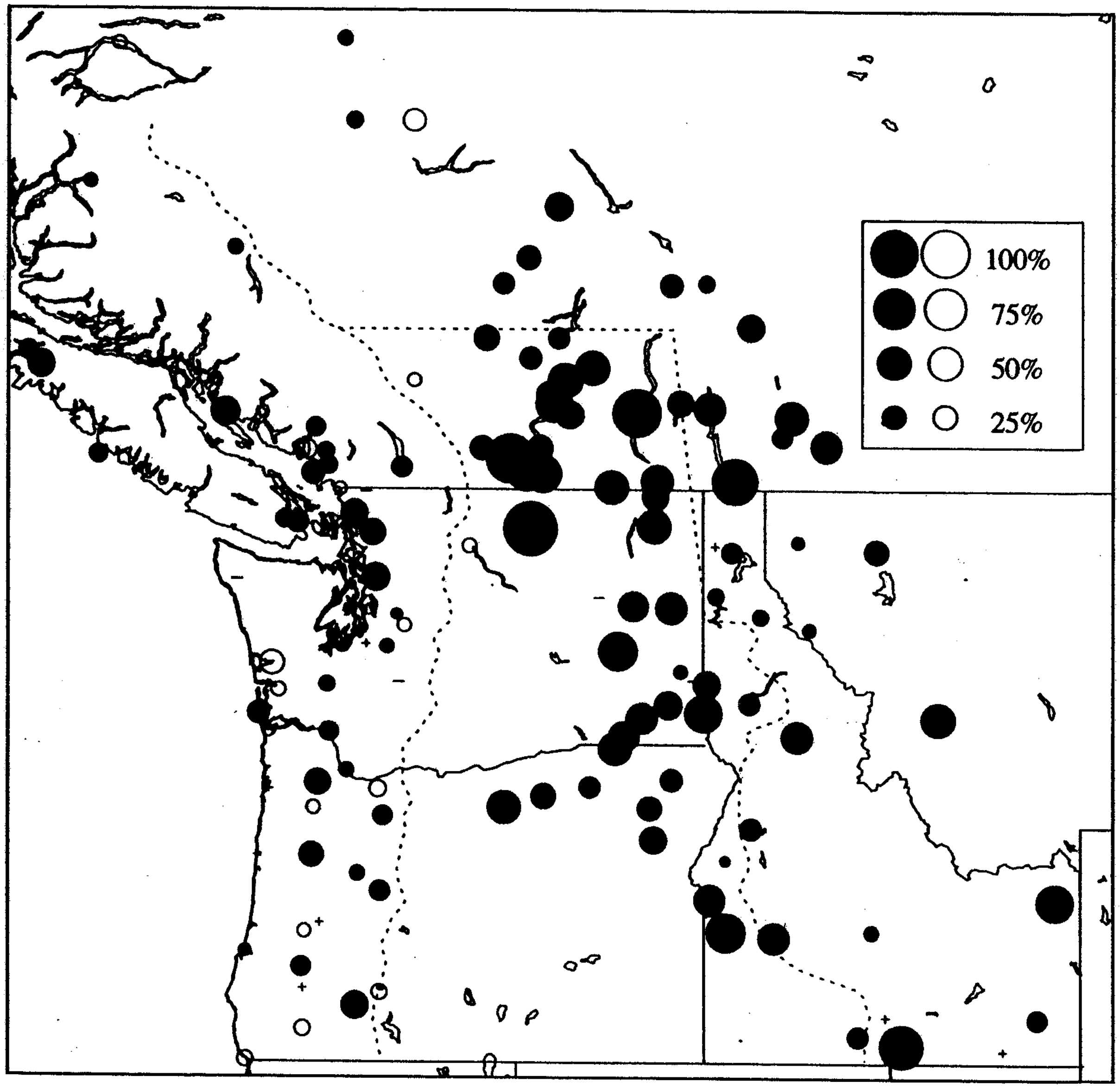

Figure 7. As in Figure 4 but for relative trends in precipitation, calculated for each station as a percentage of the value in 1930. The largest trend, at Conconully, Wash., is 135% per century. Trends between 0 and 5% are marked with a '+' and trends between –5 and 0% are marked with a '–'.

ductivity or functioning. An additional 10 cm of precipitation may be functionally irrelevant at a wet coastal location where 10 cm amounts to 4% of the annual total, but 10 cm may be significant at a dry location with annual precipitation of 20 cm. In this paper I present both absolute and relative trends, but emphasize relative trends.

Like the trends in temperature, trends in precipitation (Figure 7) are overwhelmingly positive over the period 1930-1995. In the maritime zone, most stations show modest relative increases, but some showing decreases are interspersed. Other zones have almost no stations with negative trends. The tenth percentile, median, and ninetieth percentile are –1%, 22%, and 58%, and none of the negative trends is statistically significant.

The most intriguing feature in Figure 7 is the collection of stations in eastern Washington and southeastern BC where precipitation rose significantly, many >60% per century. At Conconully, Washington, annual precipitation rose 135%. At most of these stations, precipitation rose the most during the spring and early summer (April-July).

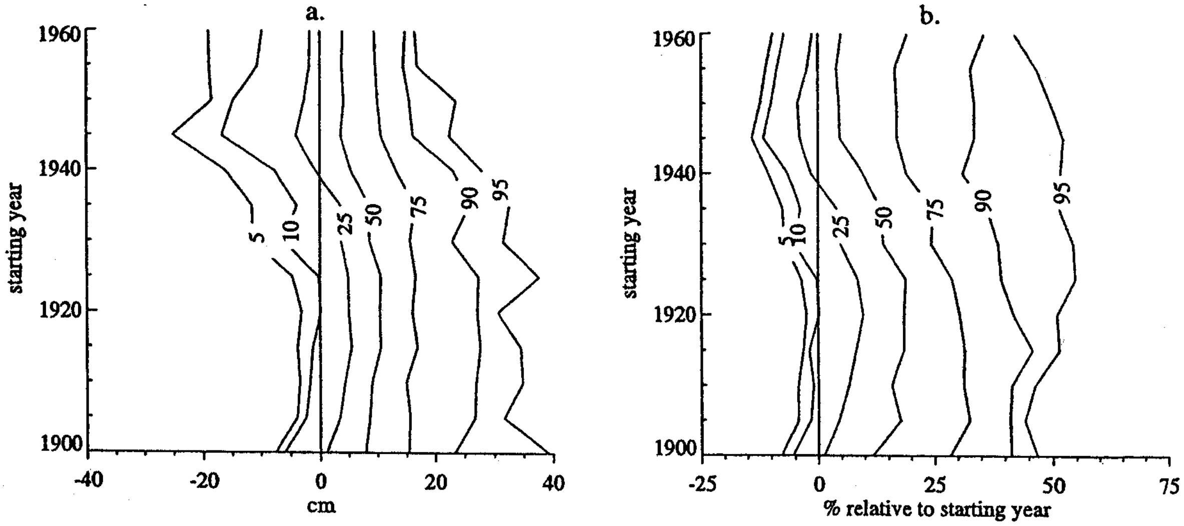

Figure 8. As in Figure 5, but for precipitation expressed as both absolute trends (left) and relative trends (right) over the given period of record.

As with temperature, I plot quantiles of precipitation changes as a function of starting year (Figure 8). The shape of the distribution is somewhat skewed, with steeper changes below the mode than above it, and changes little from 1900 to 1925. In contrast to the monotonic increases in temperature seen in Figure 5, trends in precipitation taken from starting points later in the record (e.g., after 1930) are more likely to be negative because precipitation fluctuates more on interdecadal timescales. Regardless of starting year, the median change is ~5-10 cm. Total relative change is most likely to be in the range of 10-30% before about 1935. Most of the increase in precipitation over the 20th century occurred before 1945, and trends over the second half of the century are somewhat smaller.

Important differences are seen when precipitation variability and trends are examined by season and by zone (Figure 9). As expected from Figure 7, the largest relative trend (38%) is in the central zone, but statistically significant increases occur in spring in the other two zones. Interannual variations in precipitation are significantly correlated among the regions (0.70 between maritime and central, 0.65 between maritime and Rockies, and 0.82 between central and Rockies). The wettest year (1996) was wettest in all three zones. Disparity was greater among the driest years, though the combination of the dry fall in 1976 (the driest in each zone) and fairly dry winter in 1977 in the central zone and the Rockies made the 1976-77 October-March period the driest in the 20th century.

The seasonality of precipitation trends has some interesting features. In all three zones absolute trends are largest and statistically significant in spring, and in the maritime zone the relative trends are largest in spring, too. For the central zone, summertime precipitation increased by about 70% but this increase is not statistically significant. As with temperature, trends are largest in autumn.

Correlations between NPI and precipitation are ≤0.26, and in only one case (wintertime trend in the central climatic zone) statistically significant. The variability and trends in precipitation are not well explained by NPI.

Discussion

Global temperature and precipitation have increased (Folland et al. 2001), and PNW temperature and precipitation have increased more than the global averages (Figures 4, 6, 7, 9). The long-term fluctuations in temperature are fairly well represented by linear trends, but the long-term fluctuations in precipitation are somewhat more cyclical, partly owing to the Pacific Decadal Oscillation (Mantua et al. 1997). The changes are sufficiently widespread and coherent to rule out factors unrelated to large-scale climate, like land-use change. These trends are undoubtedly real, and the warming is large enough to have signifi-

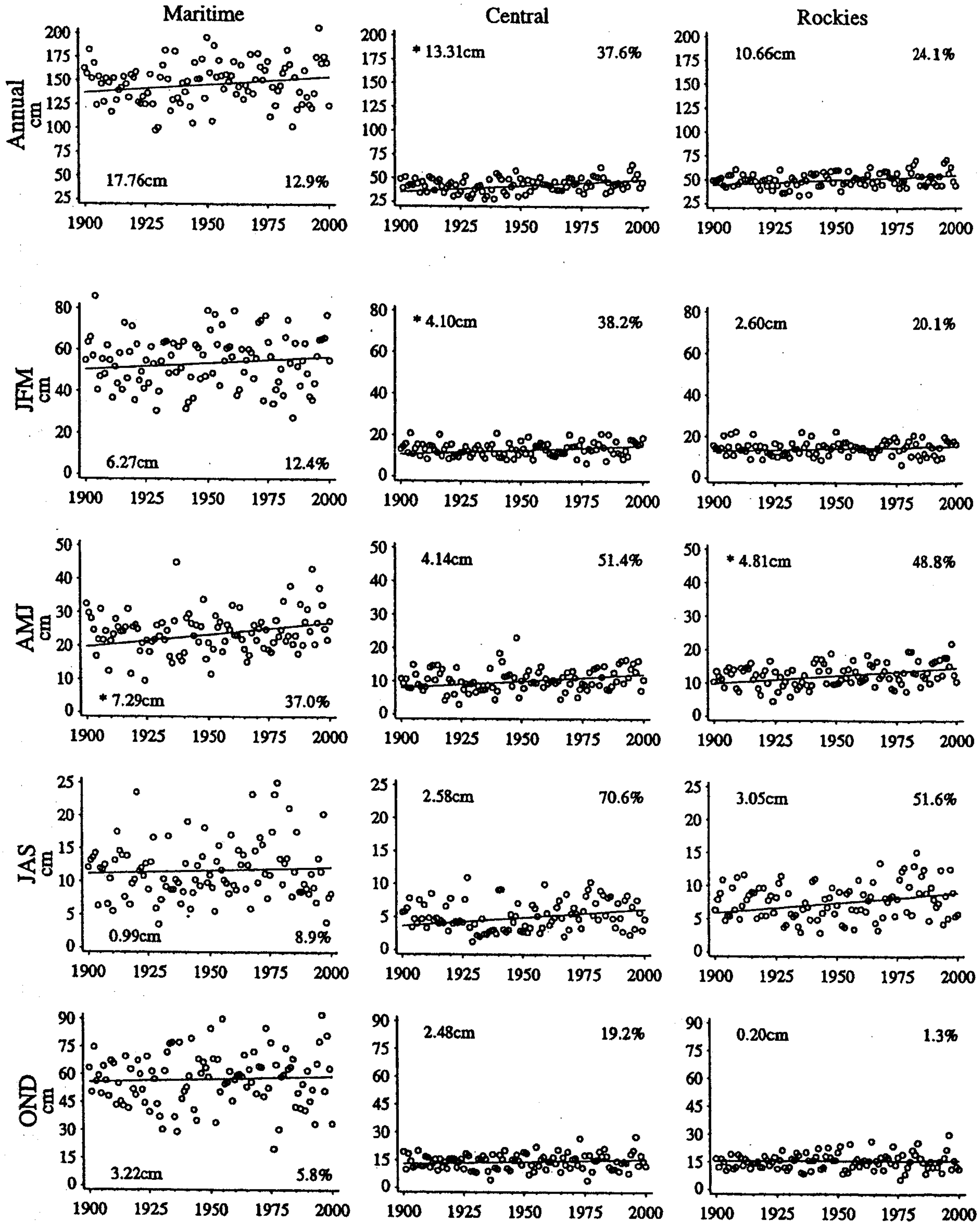

Figure 9. As in Figure 6 but for precipitation. Numerical values of absolute and relative trends are shown in each panel.

cant impacts on the hydrology and ecosystems of the region (Cayan et al. 2001). Several aspects of the trends bear further discussion.

One must use caution in interpreting trends at individual stations owing to possible non-climatic factors. Note, for example, the string of stations just inland of the Oregon coast with trends of alternating sign (Figure 7). Where groups of nearby stations show similar trends, the trends likely reflect genuine climatic trends. In one case, an unusual piece of evidence provides independent confirmation. Crater Lake, Oregon, lies on the crest of the Cascades near Prospect, Oregon (the large positive trend near the California border). The long-term trend in precipitation at Crater Lake was examined by Peterson et al. (1999), who showed that a reconstruction of changes in lake level derived from estimates of precipitation from tree-ring data approximately matches the observed changes in lake level, which dropped ~2 m during the 20th century.

The dependence of these trends on elevation was examined by Mote (2003b). A linear fit of trend to elevation revealed a general decline in both temperature and precipitation trends (both absolute and relative) with elevation, in contrast to expectations from experiments with global (Fyfe and Flato 1999) and regional (Giorgi et al. 1997) climate models. In modeling experiments, the snow-albedo feedback, in which a slight warming near the snowline melts snow and allows the surface to absorb more solar radiation, drives substantial warming in winter and spring, and this warming is enhanced at higher altitudes. Two possible reasons for this discrepancy are 1) since the climate stations are almost all in valley bottoms, the elevational dependence calculated from them does not reflect the elevational dependence in mountainous terrain; 2) other mechanisms (e.g., changes in cloudiness) may overwhelm the snow-albedo feedback. All three climatic zones showed largest trends in winter, consistent with a snow-albedo feedback mechanism, but since the maritime stations rarely experience snow their large trends must be influenced by other factors.

Determining the causes of these trends is difficult, although some possible causes can easily be ruled out. The warming trends are clearly not a spurious by-product of urbanization, since trends in urban areas are no larger than those in rural areas. Although attribution of causes of temperature trends is possible on the scale of continents (Stott and Tett, 1998), it is not yet possible for a region the size of the Pacific Northwest, in part because changes in atmospheric circulation can make one region warm and another cool without changing the global average. Circulation changes, for example associated with the Pacific Decadal Oscillation or El Niño, were represented here by the North Pacific Index and may partly explain the trends in temperature but not precipitation. The positive trends shown here for both temperature and precipitation are roughly consistent with changes simulated by climate models for the 20th century using observed changes in carbon dioxide (Mote et al. 2003).

The observed warming is confirmed by various hydrological and phenological signals (Cayan et al. 2001). Conversely, the changes in temperature have already had an observable effect on key parts of various ecosystems (Cayan et al. 2001, Walther et al. 2002). But one of the most striking observations presented here is of the large increase in precipitation, especially in spring and summer, in the inland Northwest. These increases are especially large in eastern Washington and southern British Columbia, but I know of no evidence that vegetation has responded to these increases in precipitation.

Acknowledgements

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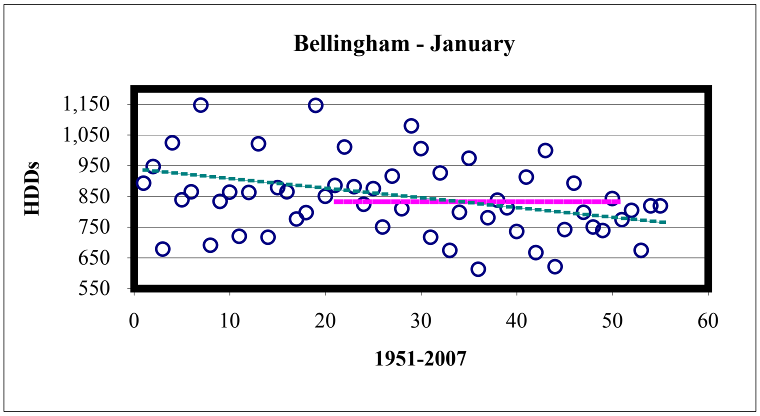
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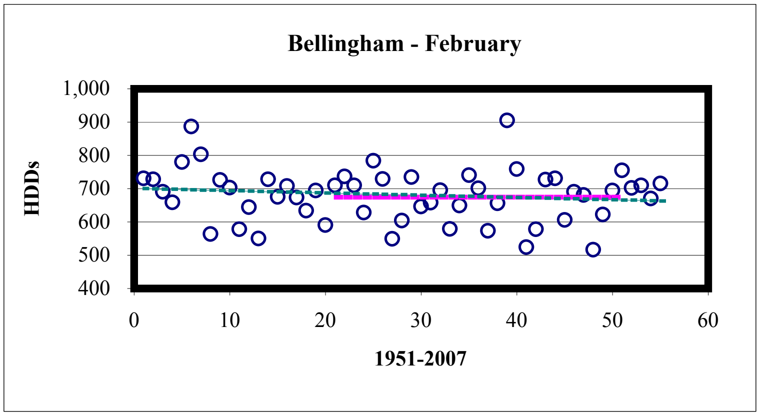
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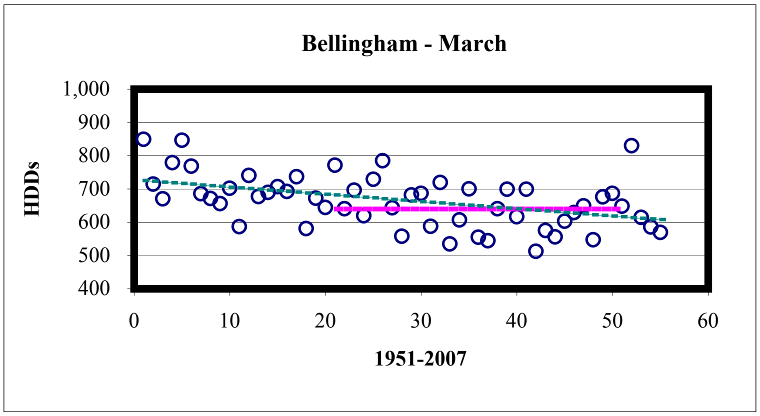
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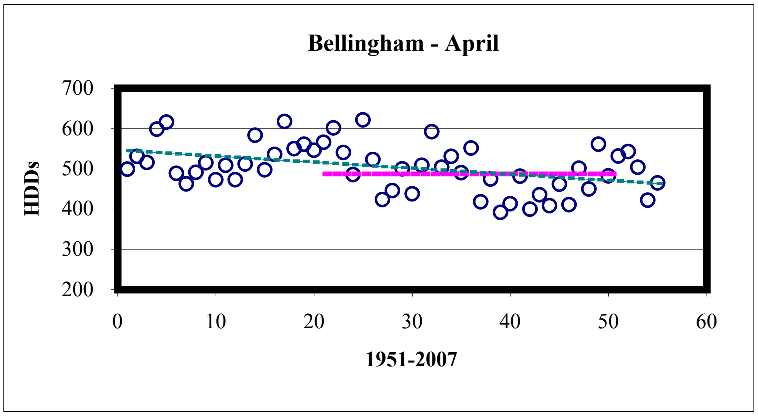
Bellingham - April

○ Actual Monthly HDD
— Average HDD 1971-2000
— Statisical Normal HDD

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Exhibit ___ (PWM-3)
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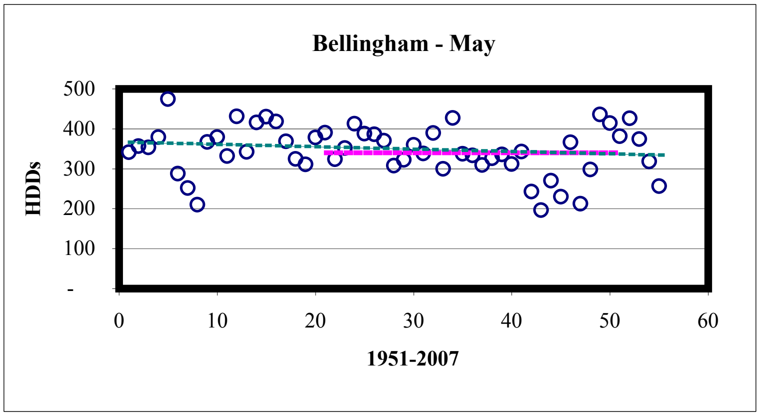

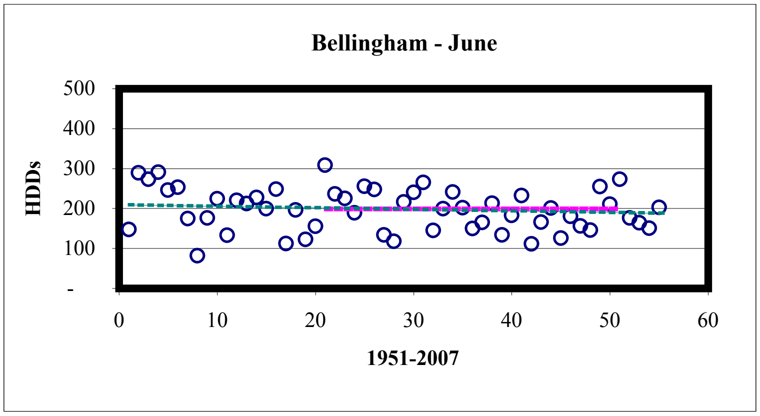

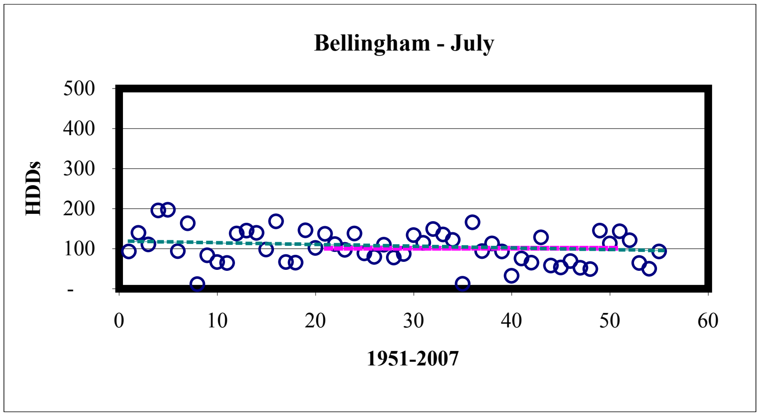

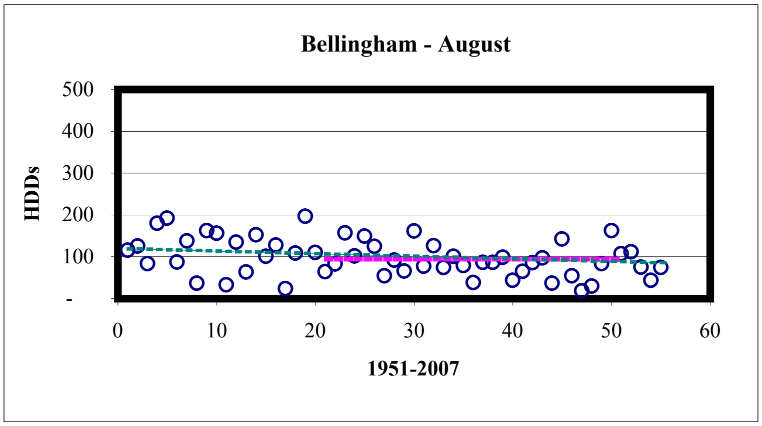

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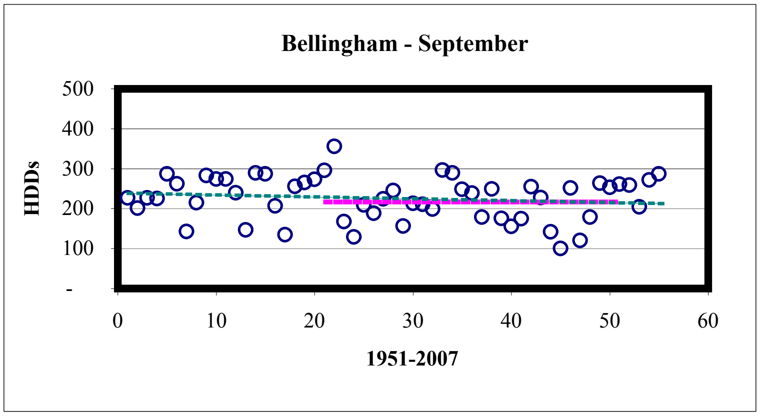
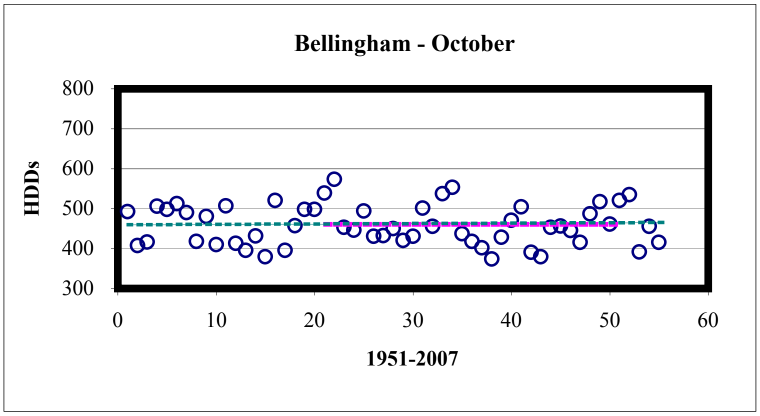
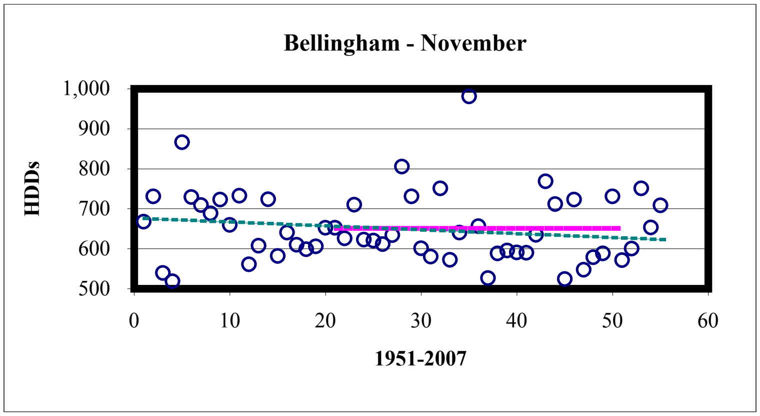
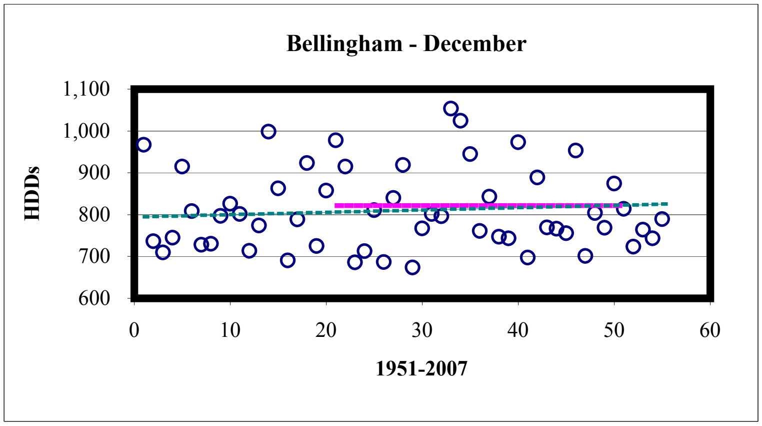
— Statisical Normal HDD









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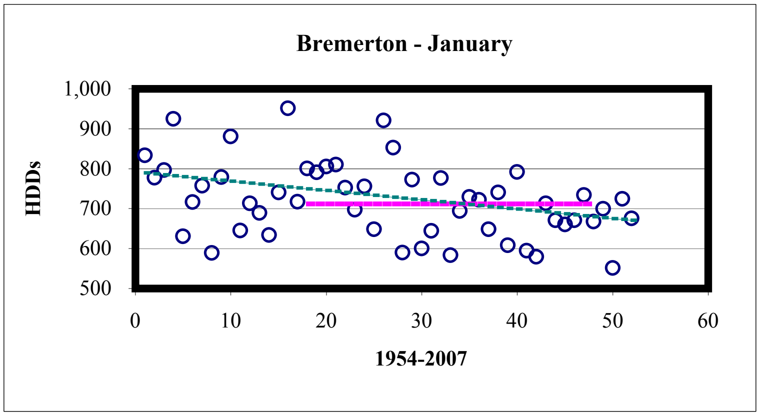
▬ Statisical Normal HDD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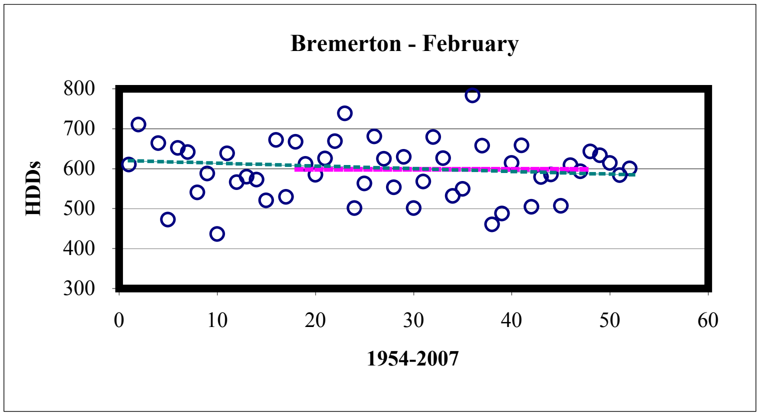
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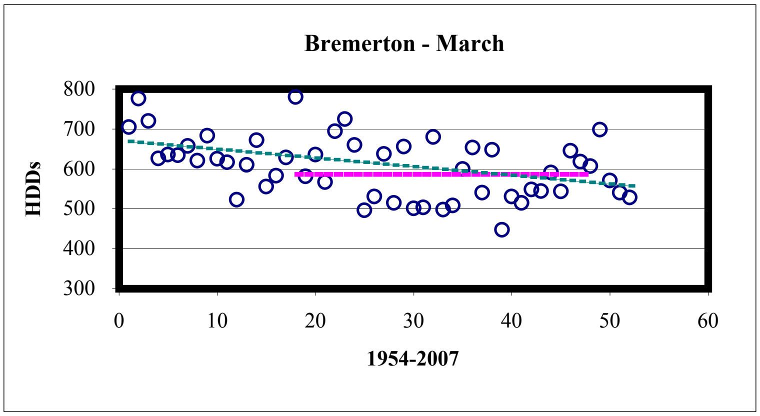
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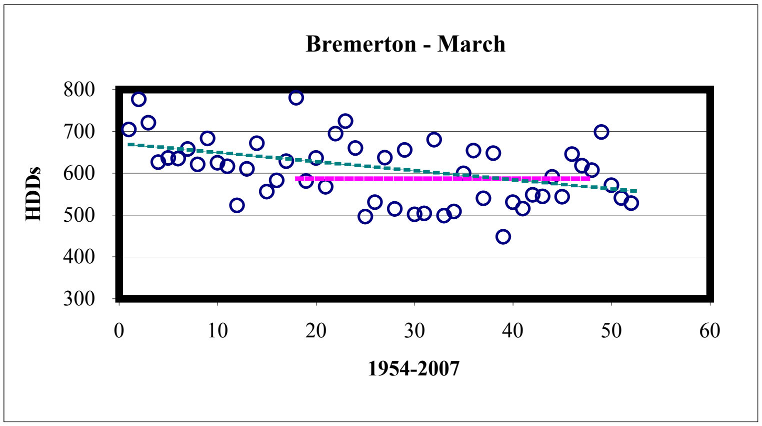
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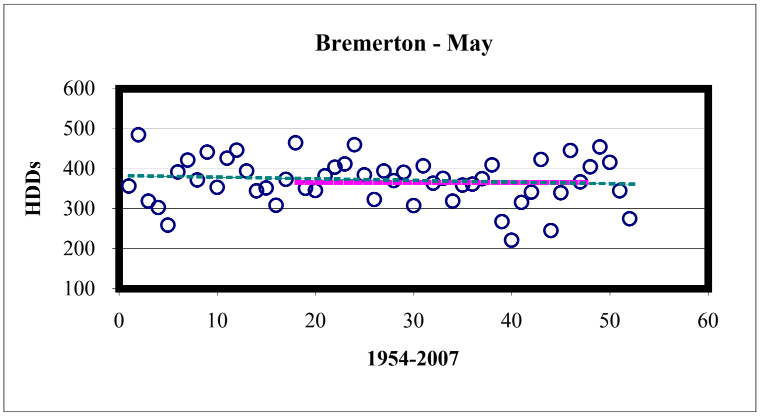
▬ Statisical Normal HDD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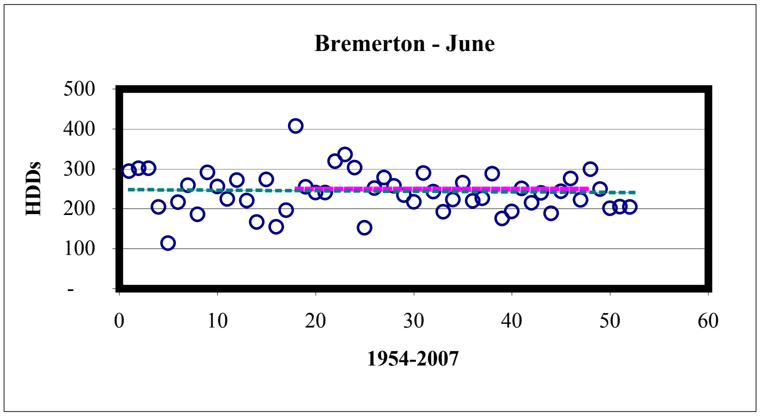
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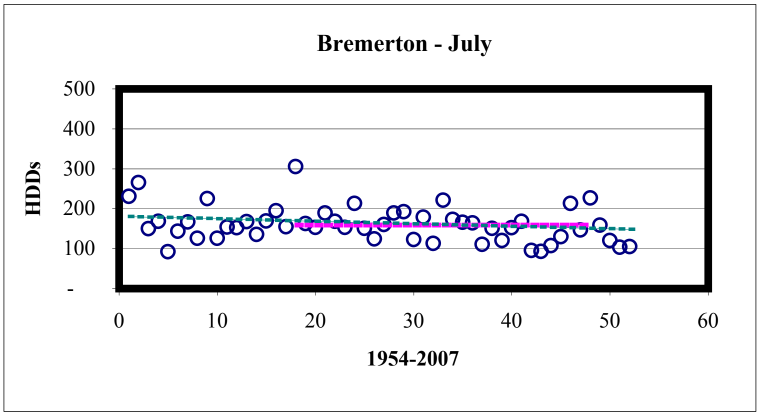
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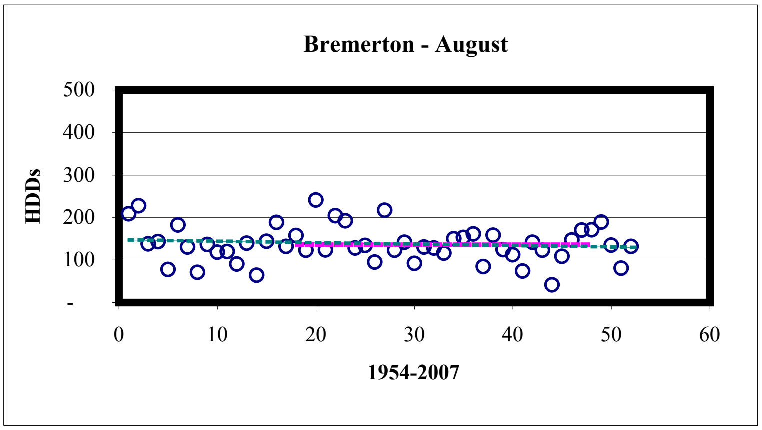
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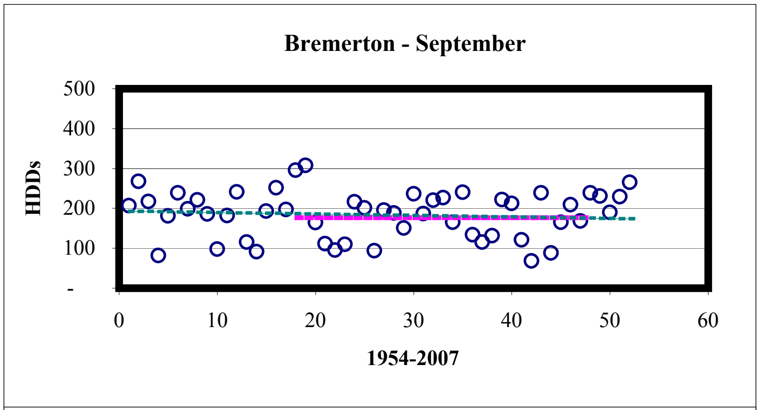
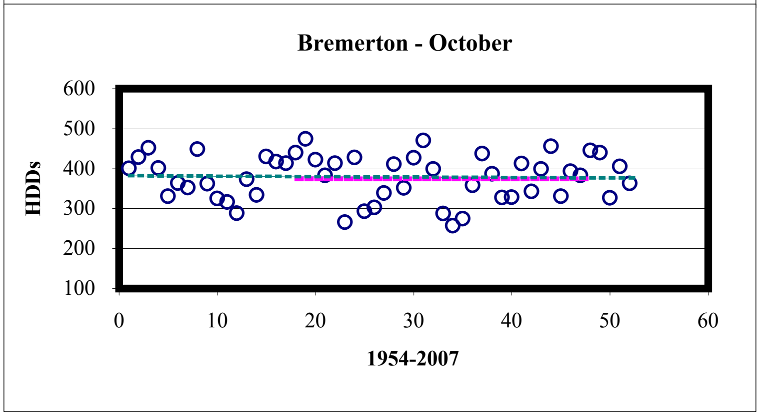
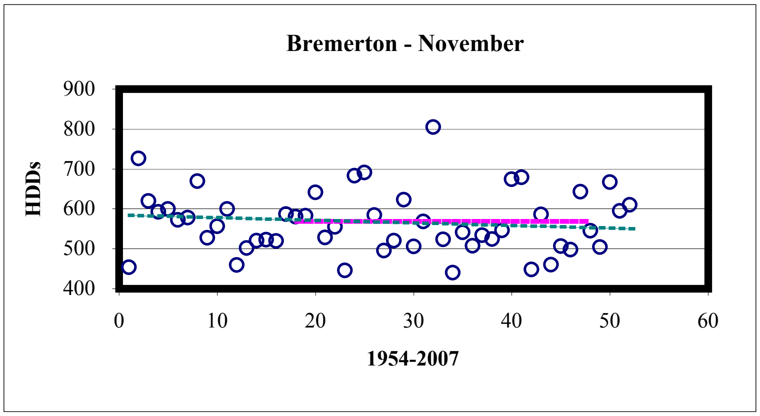
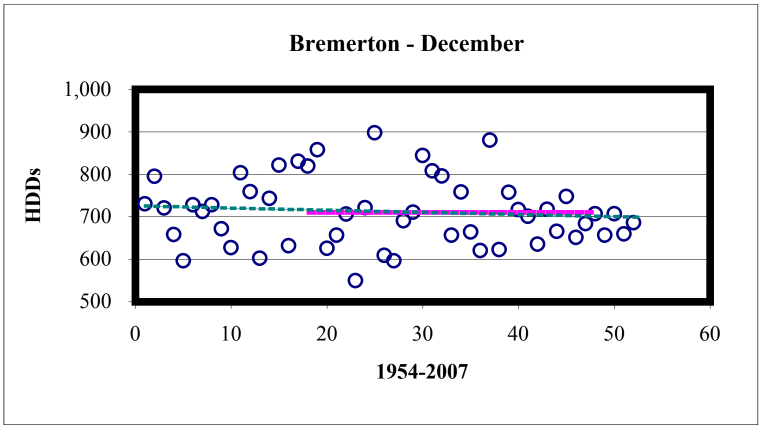
▬ Statisical Normal HDD









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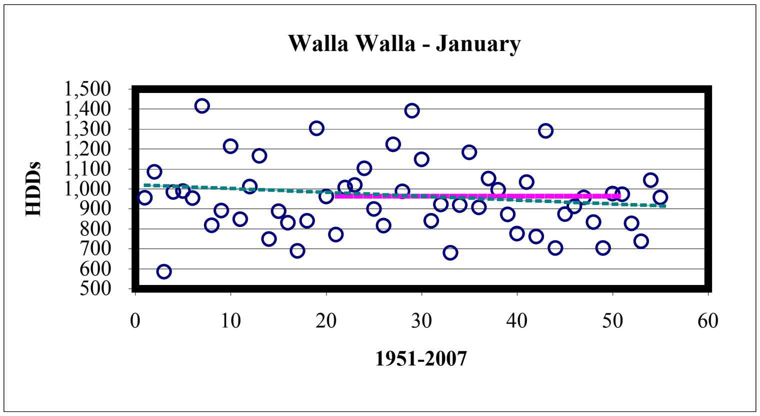

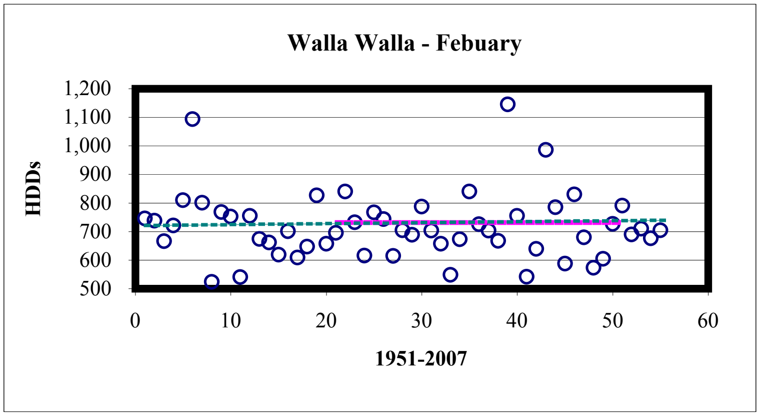

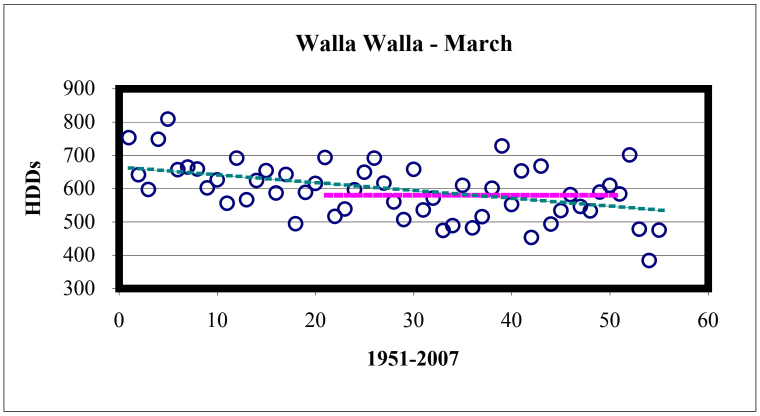

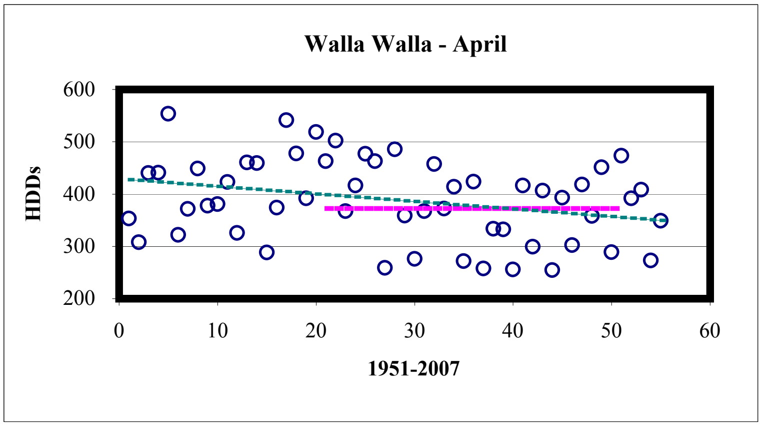

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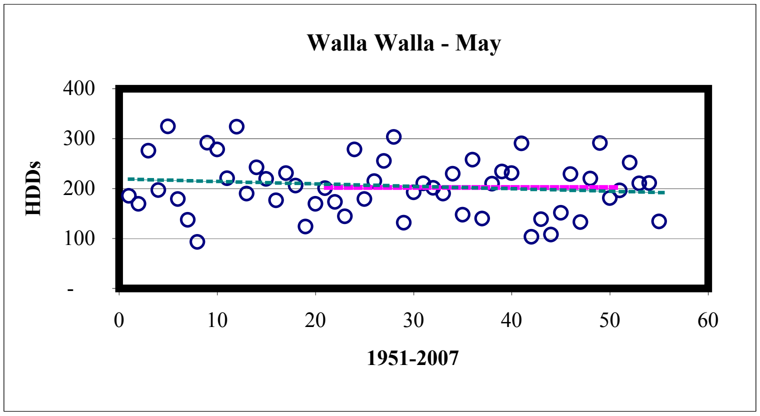

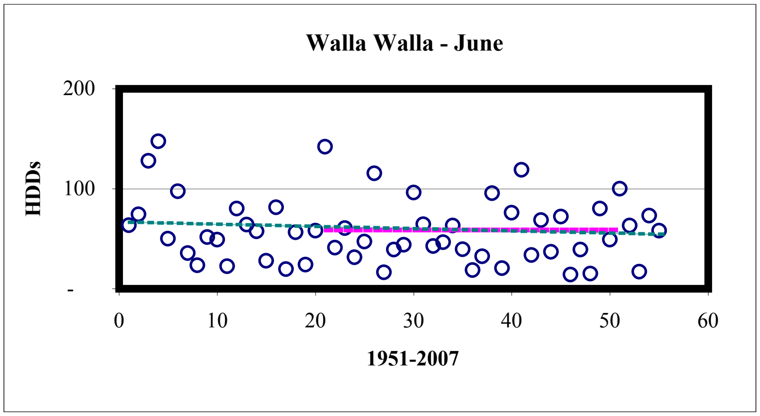

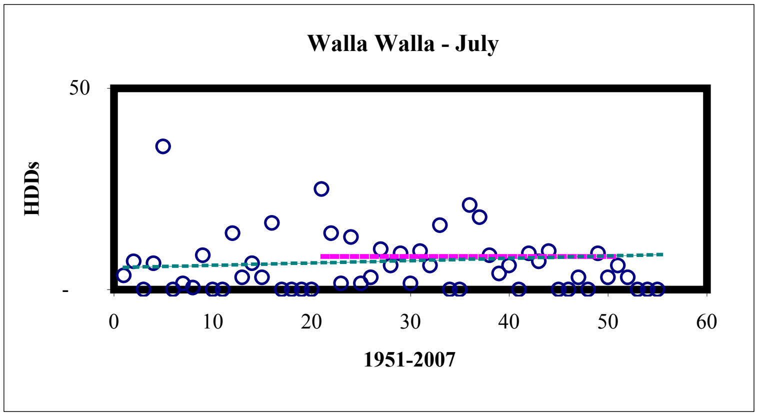

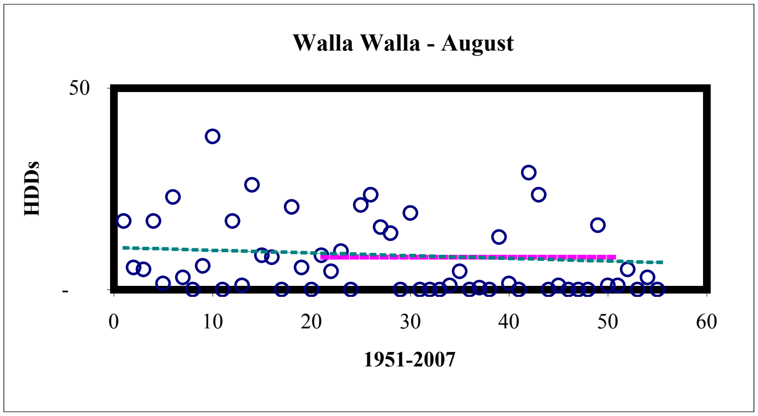

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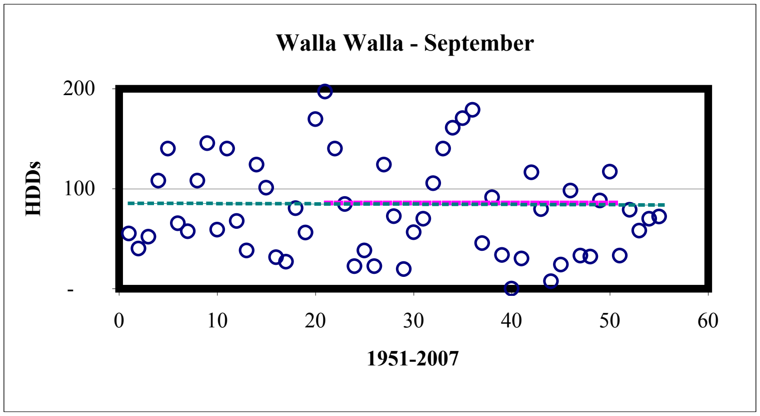

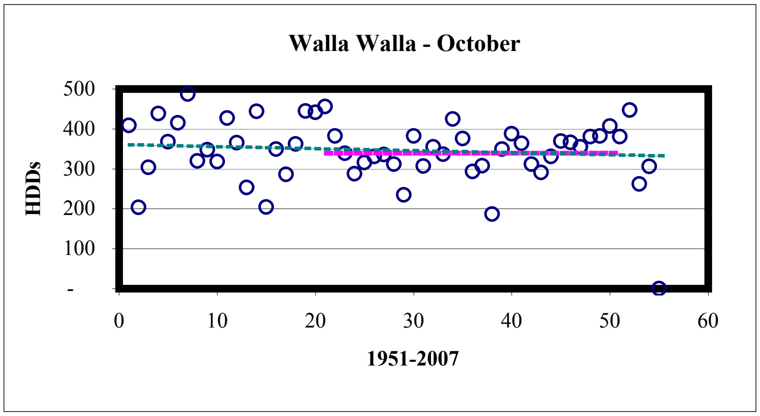

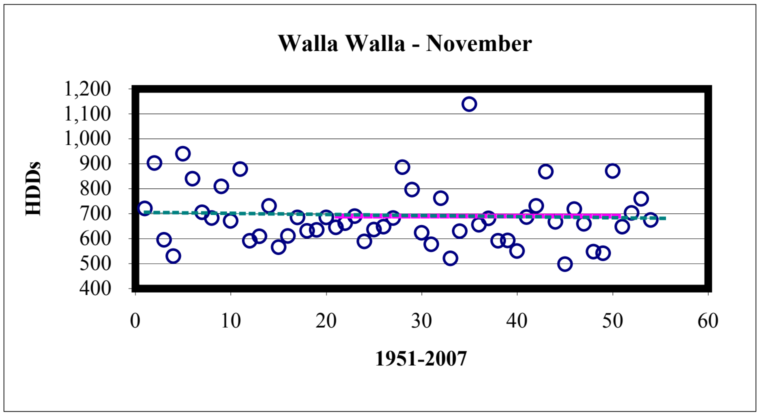

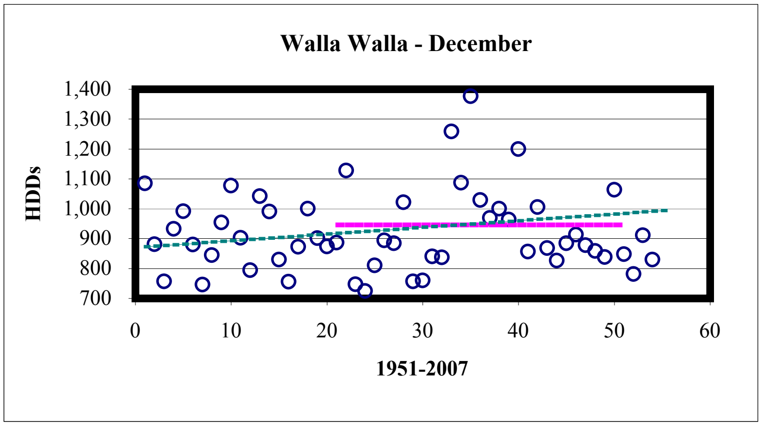

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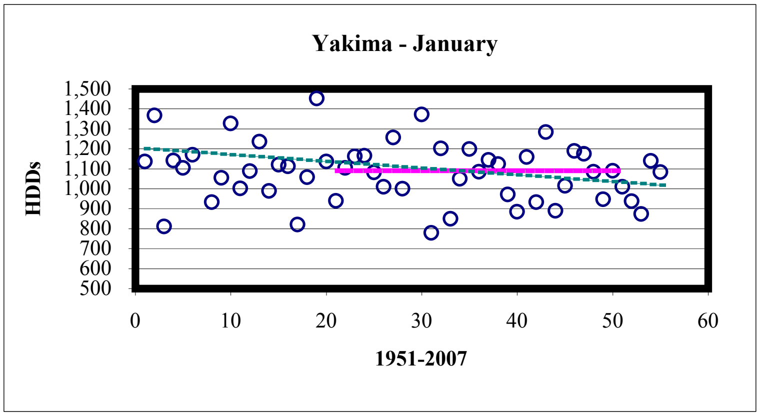

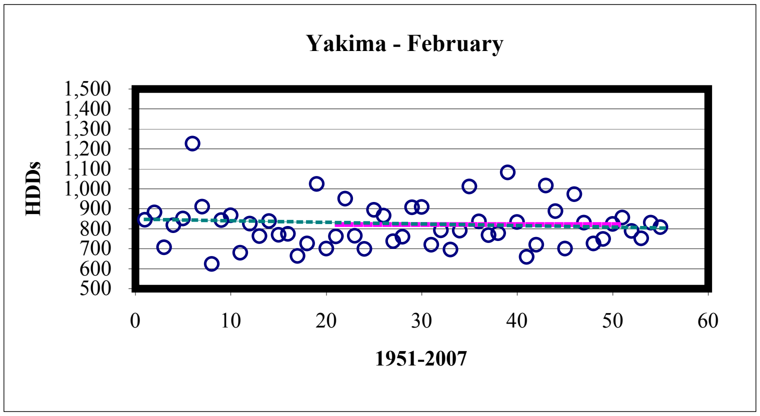

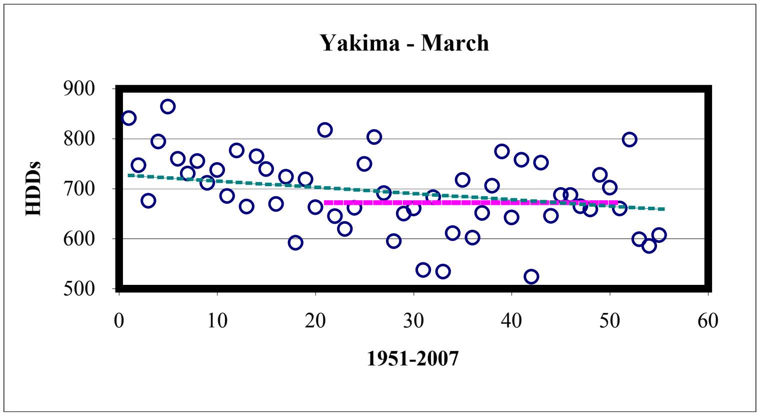

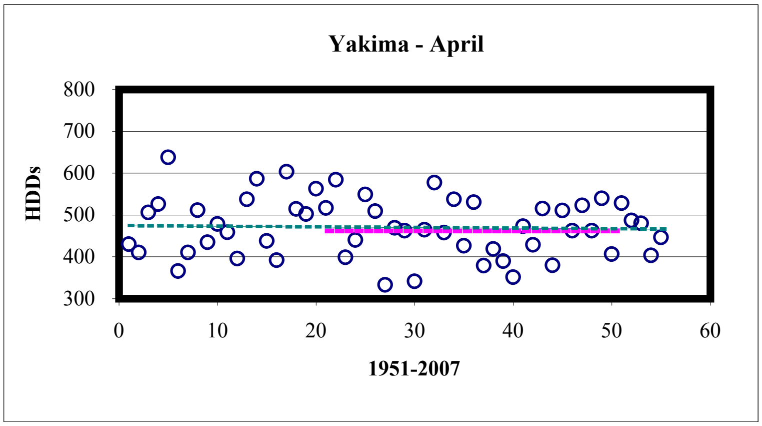

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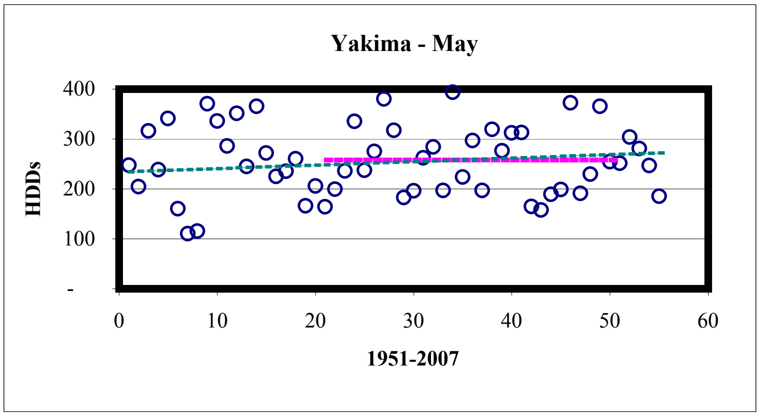

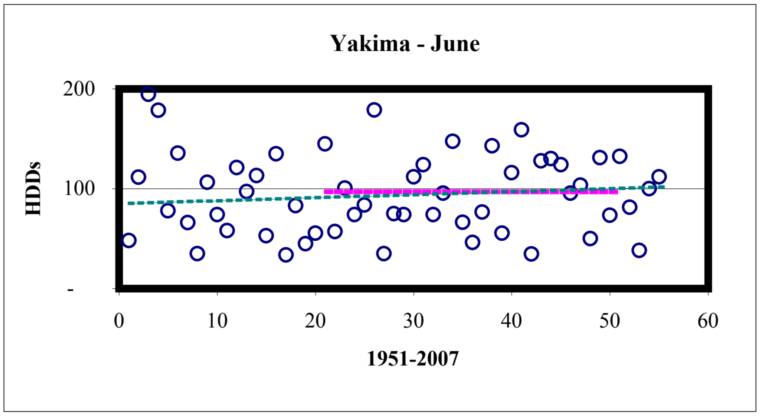

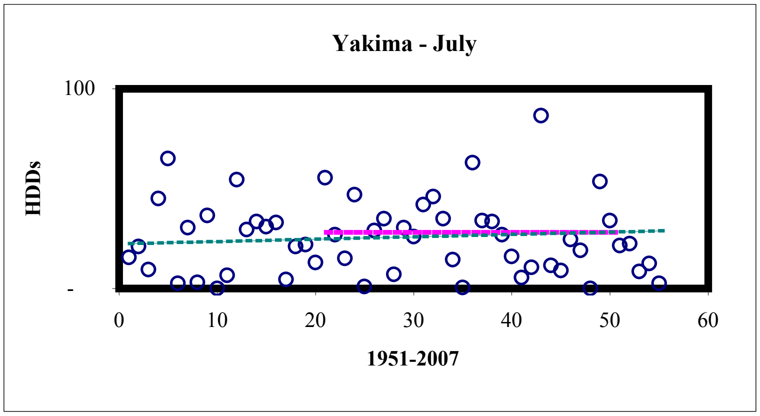

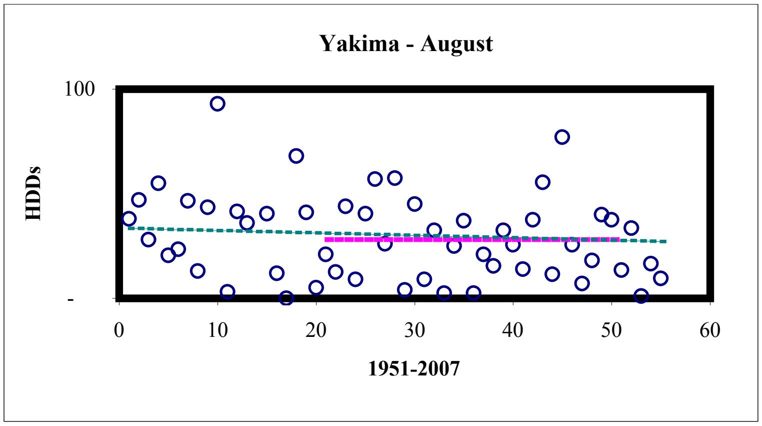

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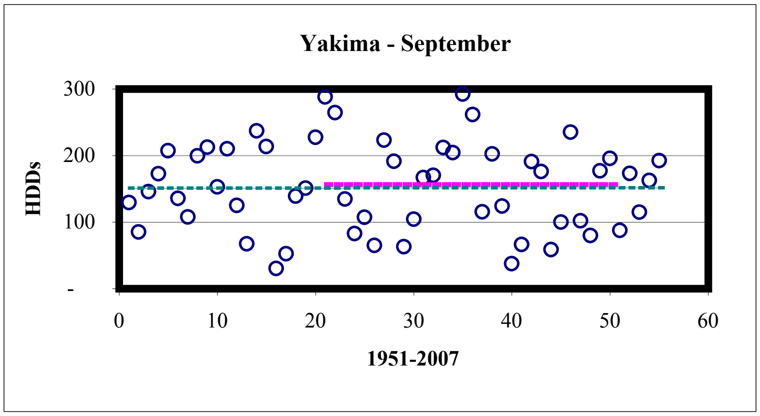

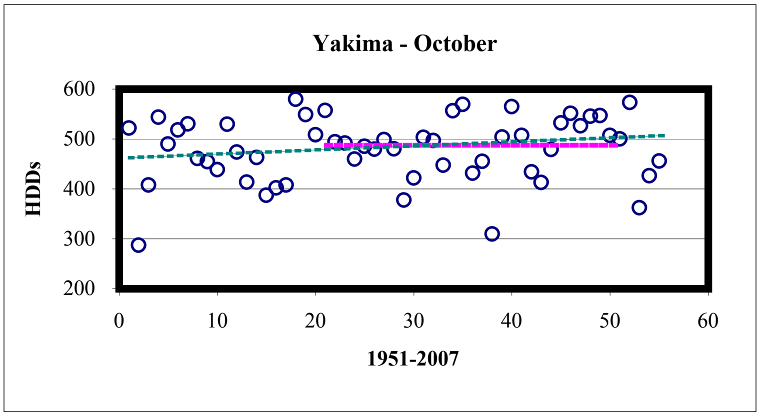

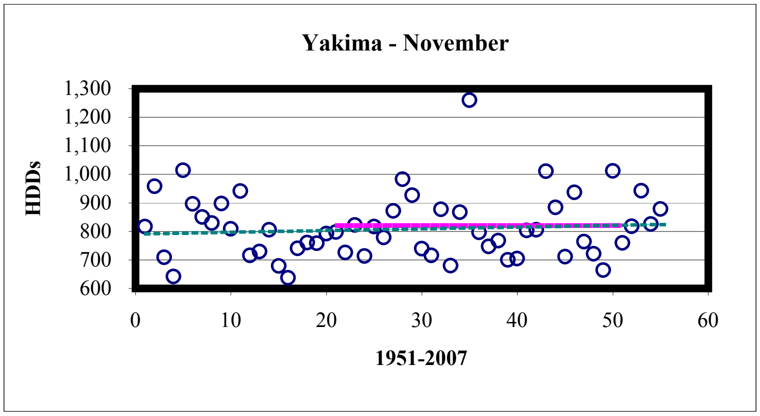

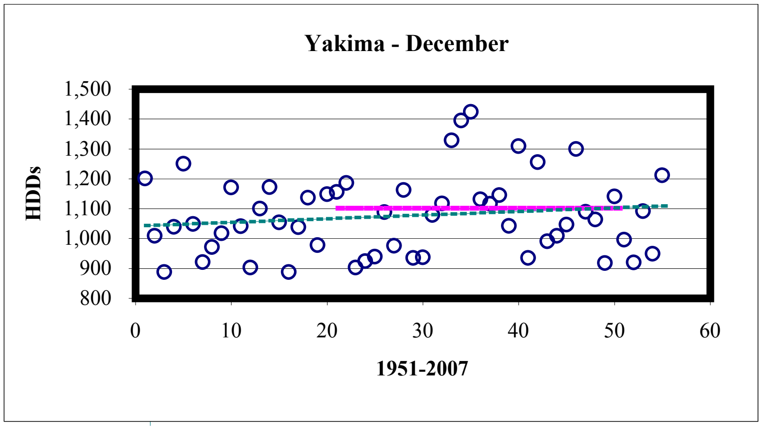

○ Actual Monthly HDD
— Average HDD 1971-2000
— Statisical Normal HDD

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Exhibit ____(PWM-4)
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Normal Heating Degree Days For
Cascade Natural Gas Corporation

Line No.	Month	Bellingham	Bremerton	Walla Walla	Yakima
1	January	756.3	656.5	908.3	1008
2	February	660.8	580.3	740.3	801
3	March	600.8	544.4	527.9	655
4	April	458.8	447.8	345.1	465.7
5	May	332.3	358.9	190.5	274.2
6	June	187	239.6	53.7	102.4
7	July	93.9	144.5	8.8	29.2
8	August	83.6	127.7	6.5	26.8
9	September	210.8	171.7	83.6	151.7
10	October	465.2	375.5	330.8	508.9
11	November	619.8	546	679.7	825.5
12	December	826.5	695.9	1000.2	1112.5
13	Annual	5295.8	4888.8	4875.4	5960.9