Chapter 11

Long-Term Trends in Climate and Climate-Related Drivers

In this chapter, we first describe common methods to measure climate and climate-related drivers and our rationale for the selection of variables in this book. We then show graphs of climate data through time for each site and summary maps at the continental scale.

Methods of Measurements and Selection of Variables

Climate has been monitored throughout the United States since President Grant started the National Weather Service in 1870. Numerous standardized measurement locations exist on land, in streams and lakes, and in the coastal ocean. In this report, we focus on contemporary climate records (late 1880s to present) obtained from standardized instruments and stations located at or near the research sites described in this book.

For land sites, standardized data were obtained from meteorological stations either located and maintained at a research site or at a nearby airport or city and maintained, in most cases, by the National Weather Service (NWS) and archived by the National Climate Data Center. The NWS station at the nearest city was used for coastal sites. For terrestrial sites, the onsite station was used unless a longer record was available from a nearby NWS station with similar climate. In some cases, we used onsite data combined with NWS data to obtain a longer-term weather record.

Standards are used at all sites for daily measurements of minimum and maximum air temperature (°C), precipitation (mm), relative humidity (%), wind speed (m/sec) and direction (from 0 to 360°), and solar radiation (MJ/m^2) (WMO 2008). Other measurements, such as soil temperature (°C) and soil moisture (% or cm water per cm soil) often have site-specific criteria for depth and timing that make cross-site comparisons difficult. Here, we show climate data for all 50 sites for four variables most commonly used by ecologists (minimum, maximum, and average air temperature, and precipitation) (Greenland 1986). For each variable, we calculated the mean across all days in each year of the record to focus on long-term trends in annual values. Data for climate variables can be found on the Internet, either on individual research site home pages or on the EcoTrends website (http://www.ecotrends.info).

We show two additional measures of climate that are particularly useful in comparing ecosystems. First, the Palmer Drought Severity Index (PDSI) was obtained for all sites where calculations are available (http://www7.ncdc.noaa.gov/CDO/cdo); this analysis excludes sites in Alaska, Antarctica, French Polynesia, and Puerto Rico. This index uses air temperature and rainfall information as well as soil properties to estimate monthly moisture supply and demand as a measure of departure from the mean condition at a site (Palmer 1965, Heim 2002). The PDSI is standardized to local climate to allow sites to be compared for relative drought or rainfall conditions. A value of 0 is normal; drought is shown by negative numbers. Drought severity increases with the absolute value of the negative number (-3 is moderate drought; -4 is extreme drought). Excess rain is shown by the magnitude of the positive number (for example, 2 is moderate rainfall). Second, we calculated Walter-Lieth climate diagrams for each site using monthly total precipitation and average air temperature values, scaled two to one respectively. These diagrams allow climate seasonality to be compared among sites using standardized diagrams. Shading of the diagrams are used to illustrate dry or wet months (see figure 11-1).

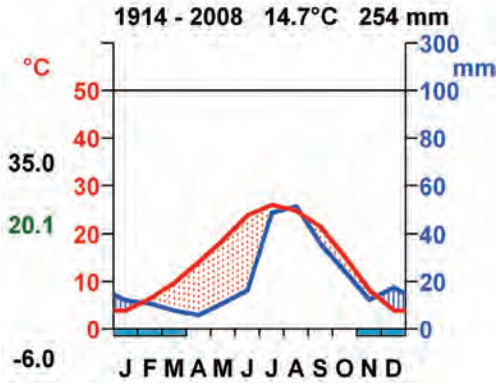


Figure 11-1. Example of a Walter-Lieth climate diagram for one site, Jornada (JRN). Mean monthly temperature in degrees Celsius (left axis, red) is plotted with precipitation in millimeters (right axis, blue) for each month in the year (bottom axis, J-D = January-December). Areas shaded in speckled red indicate dry months; areas with blue vertical lines indicate wet months. Dark blue bars at the bottom of the diagram indicate months with possible frost. The title gives range of years the data fall within, the average annual temperature, and the average annual precipitation. Black and green numbers on the left axis, from top to bottom, are the mean maximum temperature of the hottest month (black), the mean daily temperature range (green), and the mean minimum temperature of the coldest month (black), respectively.

In water, five common measurements are illustrated. Streamflow is measured daily in liters per second by gauges located within streams using standards determined by the U.S. Geological Survey (Buchanan and Somers 1969). Sea level (meters), as shown here, is measured in coastal oceans using tide gauges that measure sea surface height relative to a nearby geodetic benchmark. Ice duration is the number of days in a year on which a lake is ice covered. Water clarity or transparency is measured using a Secchi disk in oceans and lakes (Hutchinson 1957). A circular disk mounted on a line is lowered slowly in the water, and the depth at which the pattern on the disk is no longer visible is the Secchi depth (meters), which is proportional to the average light extinction coefficient. Standard methods for lake monitoring are available from the U.S. Environmental Protection Agency (http://www.epa.gov/OWOW/monitoring). Water temperature (^{o}C) is measured at a near-surface depth in streams, lakes, and oceans using thermometry or temperature probes.

Graphs Showing Long-Term Trends

The remainder of this chapter is devoted to showing trends in climate and climate-related drivers displayed in two ways to provide a sense of change across a range of spatial scales (continent, site) for each variable. First, we provide a summary of trends at the continental scale using maps that show either the mean across years or the slope of the regression line (if significant) across time for each of four variables collected at all sites (precipitation and minimum, average, and maximum air temperature). Slopes are shown using either red (positive) or blue (negative) bars; the height of the bar is the magnitude of the slope. Following the continental-scale maps for precipitation and temperature, we show site-scale data through time using four panels: (1) annual average minimum, mean, and maximum air temperature, (2) annual precipitation, (3) annual PDSI, and (4) monthly average air temperature and precipitation in a Walter-Lieth diagram. For panels 1 and 2, a solid line indicates a significant positive or negative trend through time ($p \leq 0.05$) based on simple linear regression, uncorrected for autocorrelation. The site graphs are organized by ecosystem type to allow comparisons of sites in the same ecosystem. Five additional variables are shown for sites where these data are collected: ice duration, sea level, streamflow, water clarity (Secchi depth), and surface water temperature. For variables with many sites (sea level height, streamflow), continental-scale maps of averages and slopes are shown. For all five variables, site-scale graphs through time are embedded within a continental map, and the same regression statistics are shown as in the previous panels. Long-term means and regression coefficients can be found in appendices 2 through 4.

Summary

A few noteworthy trends can be seen in these graphs. Air temperatures are increasing in at least one variable (minimum, mean, maximum) for 27 of the 50 sites. Although effects of global warming may be most dramatic and most visible to the public at high latitudes in the Arctic and Antarctic, much of North America is experiencing increases in air temperatures. In addition, sea level is increasing at all 11 coastal sites. This combination of increasing global change drivers (air and water temperature, sea level) can be expected to have more serious ecological impacts than individual drivers acting alone. Coastal waters and lakes may be susceptible to factors that increase water temperature: Increases in water temperature at three sites (CCE, SBC, and NTL) were not found in water bodies in other parts of the country or at high latitudes. Additional sites would have to be sampled to confirm this spatial pattern. Observing these trends in climate across multiple ecosystems across continents is only possible with spatially extensive, long-term data collection and analysis, such as provided by the EcoTrends Project.

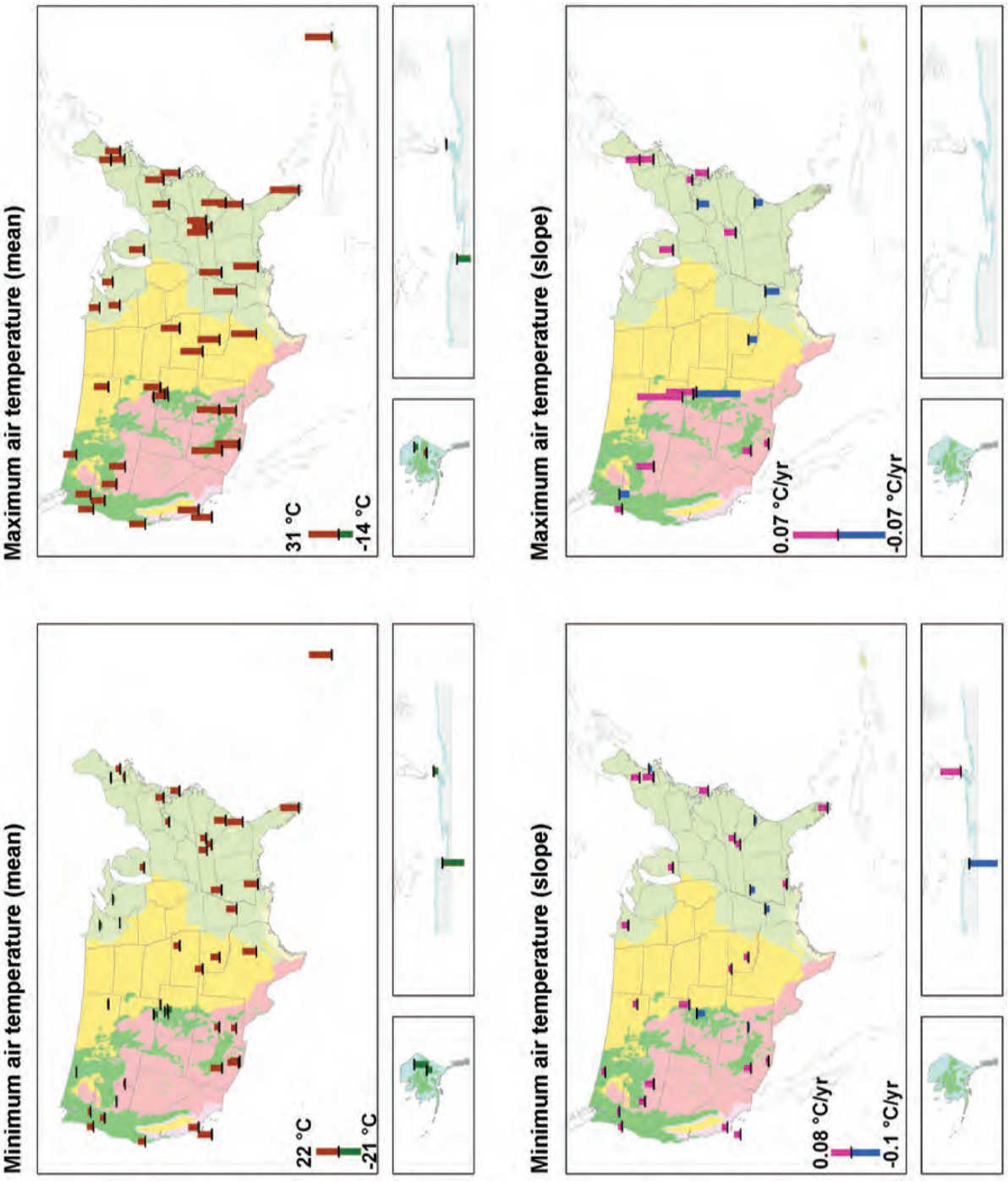


Figure 11-2. Top panels: continental patterns of long-term average annual minimum and maximum air temperature (°C) for all sites. (Positive values are red; negative values are green.) Bottom panels: slopes of significant regression lines ($p < 0.05$). (Positive values are pink; negative values are blue.) Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

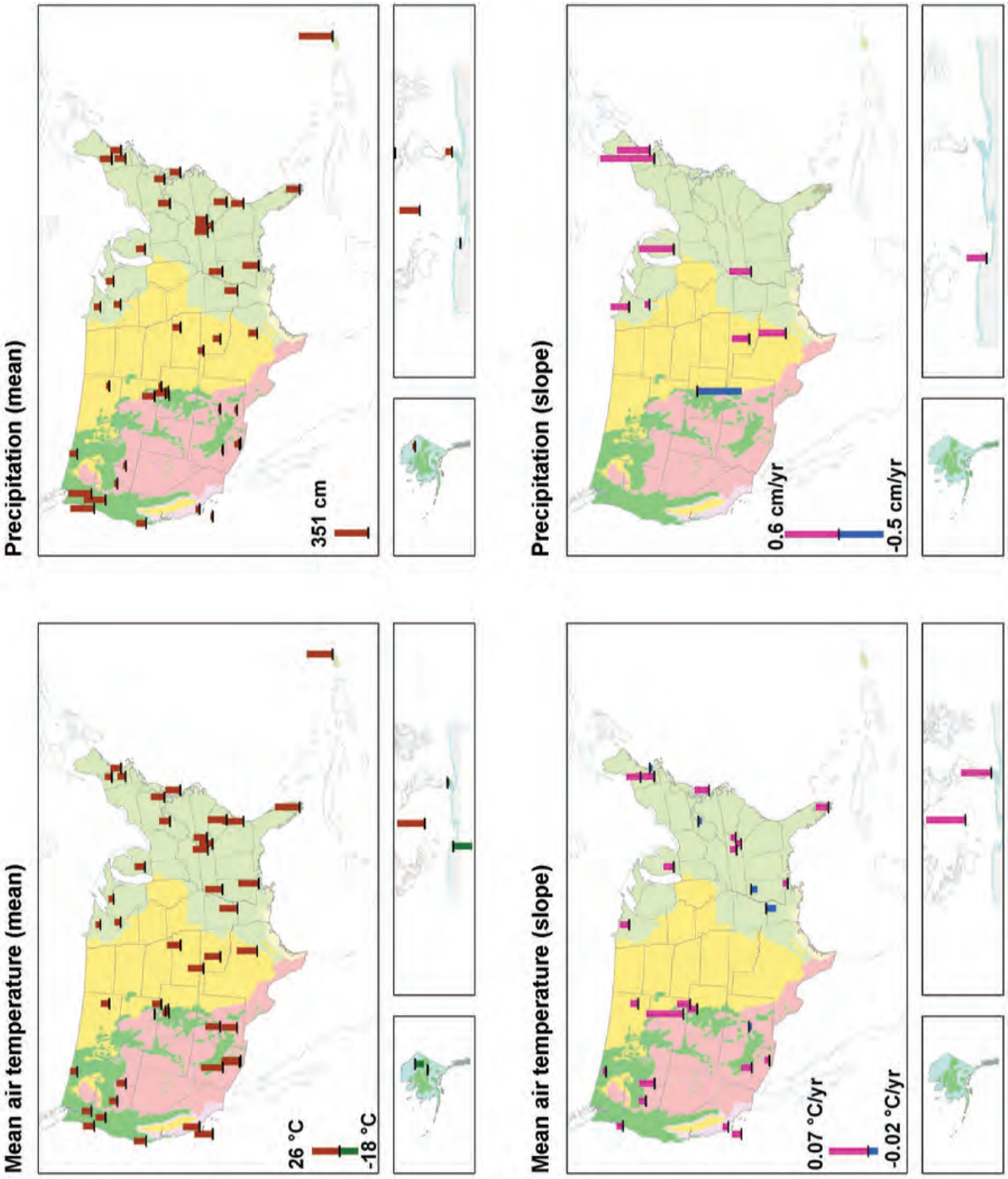


Figure 11-3. Top panels: continental patterns of long-term average annual mean air temperature (°C) and annual precipitation (cm) for all sites. (Positive values are red; negative values are green). Bottom panels: slopes of significant regression lines ($p < 0.05$). (Positive values are pink; negative values are blue.) Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

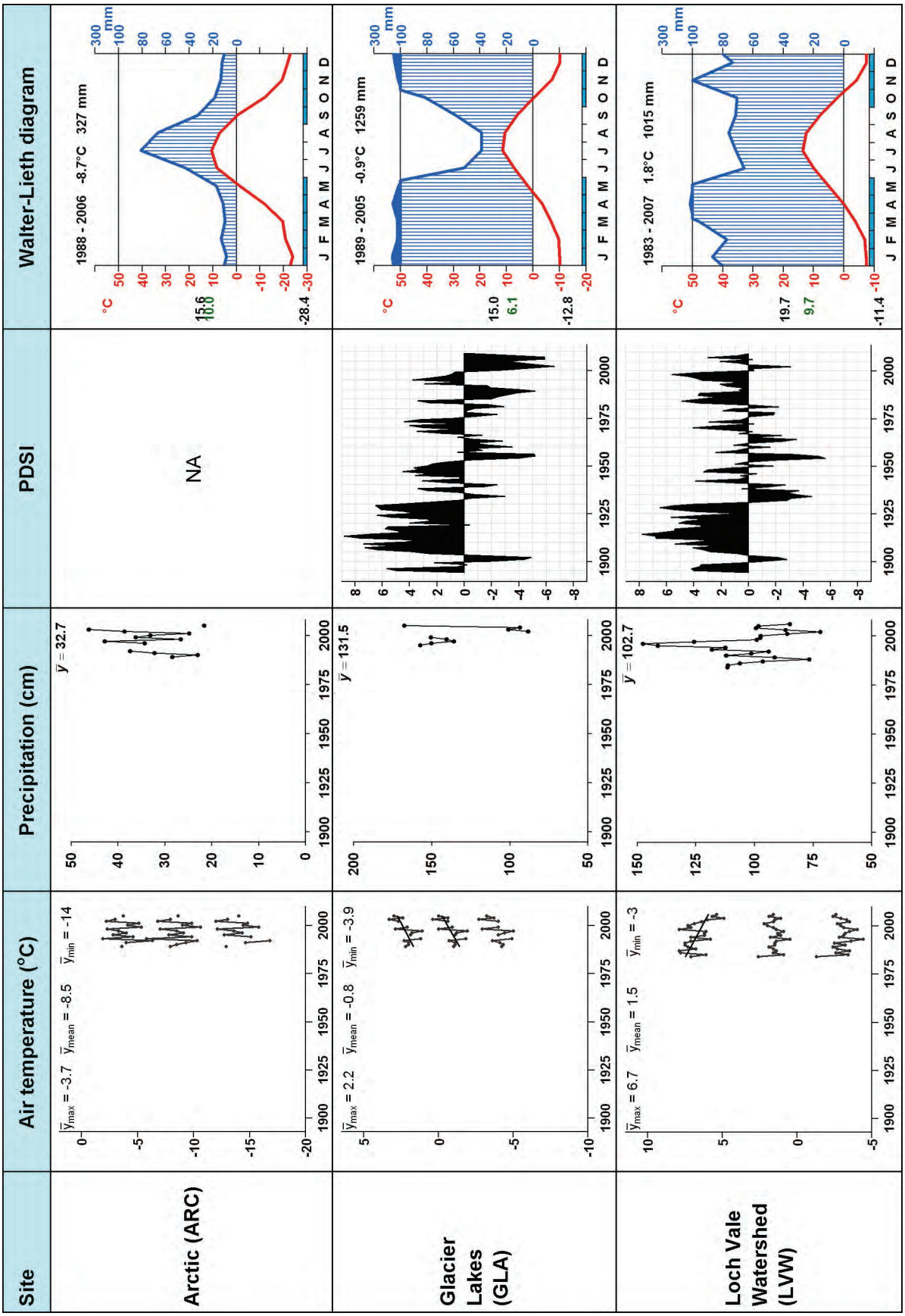


Figure 11-4 (Alpine and Arctic sites) continued next page.

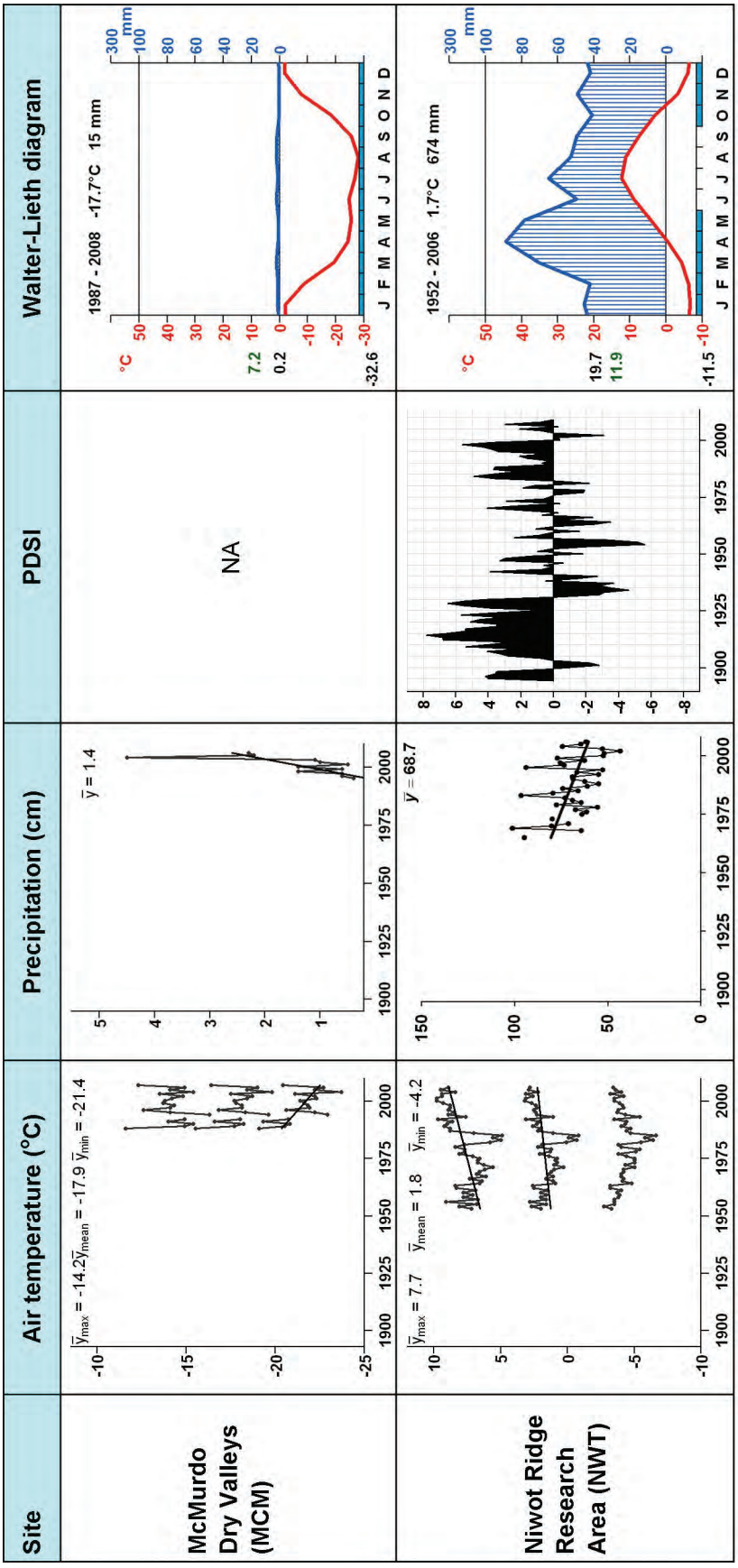


Figure 11-4. Trends for each alpine and arctic site—annual temperature (°C) (minimum, mean, maximum), annual precipitation (cm), annual PDSI, and monthly average precipitation and mean temperature—in a Walter-Lieth diagram. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for minimum, mean, and maximum air temperature and precipitation, respectively, are (NS = non-significant) Arctic (ARC): NS, NS, NS; Glacier Lakes (GLA): NS, 0.071, 0.066; NS; Loch Vale Watershed (LVW): NS, NS, -0.069, NS; McMurdo Dry Valleys (MCM): -0.114, NS, NS, 0.215; and Niwot Ridge Research Area (NWT): NS, 0.019, 0.044, -0.490. Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

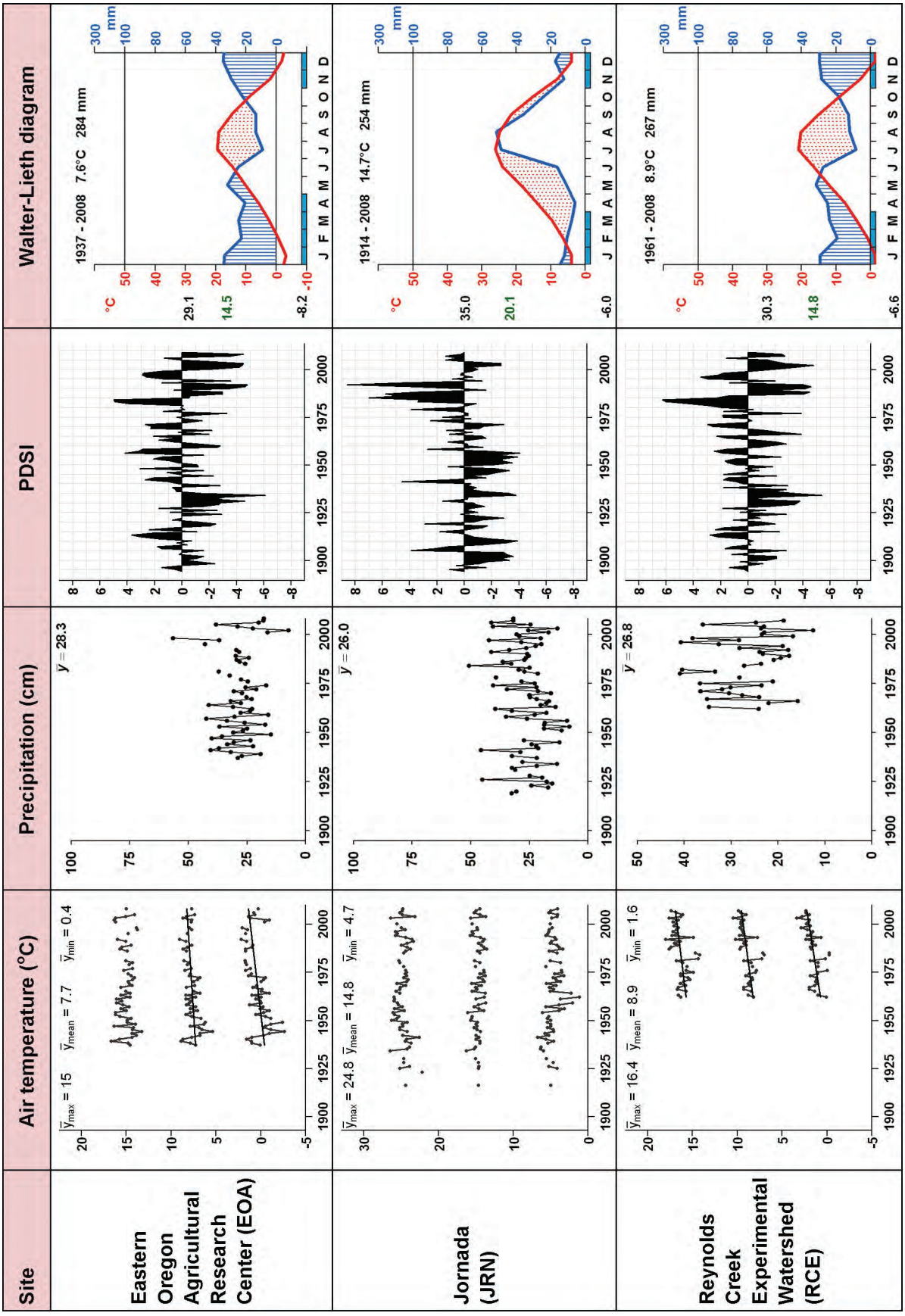


Figure 11-5 (aridland sites) continued next page.

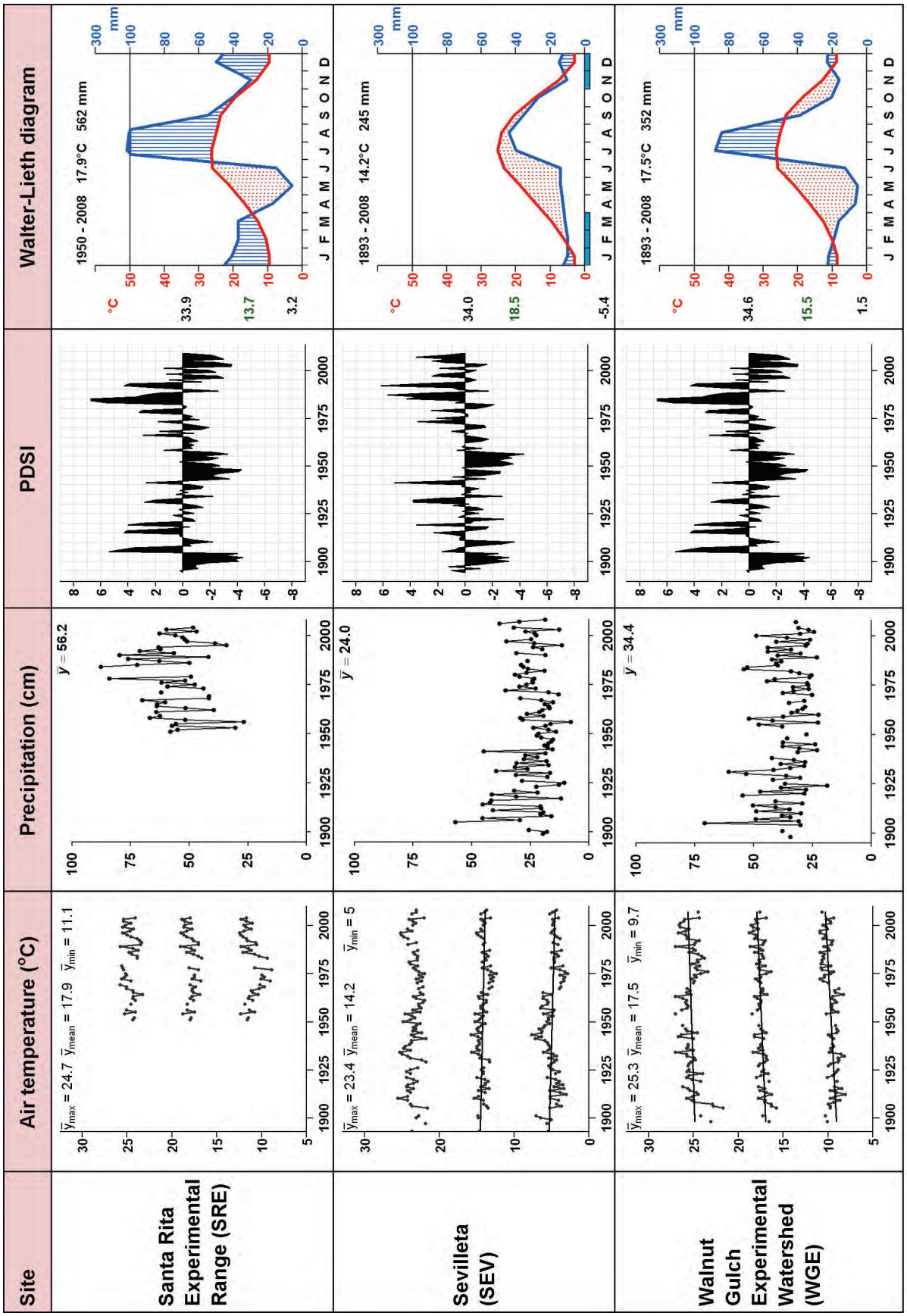


Figure 11-5. Trends for each aridland site—annual temperature (°C) (minimum, mean, maximum), annual precipitation (cm), annual PDSI, and monthly average precipitation and mean temperature—in a Walter-Lieth diagram. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for minimum, mean, and maximum air temperature and precipitation, respectively, are (NS = non-significant) Eastern Oregon Agricultural Research Center (EOA): 0.025, 0.014, NS, NS; Jornada (JRN): NS, NS, NS, NS; Reynolds Creek Experimental (RCE): 0.034, 0.030, 0.026, NS; Sevilleta (SEV): -0.006, -0.006, NS, NS; Santa Rita Experimental Range (SRE): NS, NS, NS, NS; and Walnut Gulch Experimental (WGE): 0.011, 0.009, 0.007, NS. Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

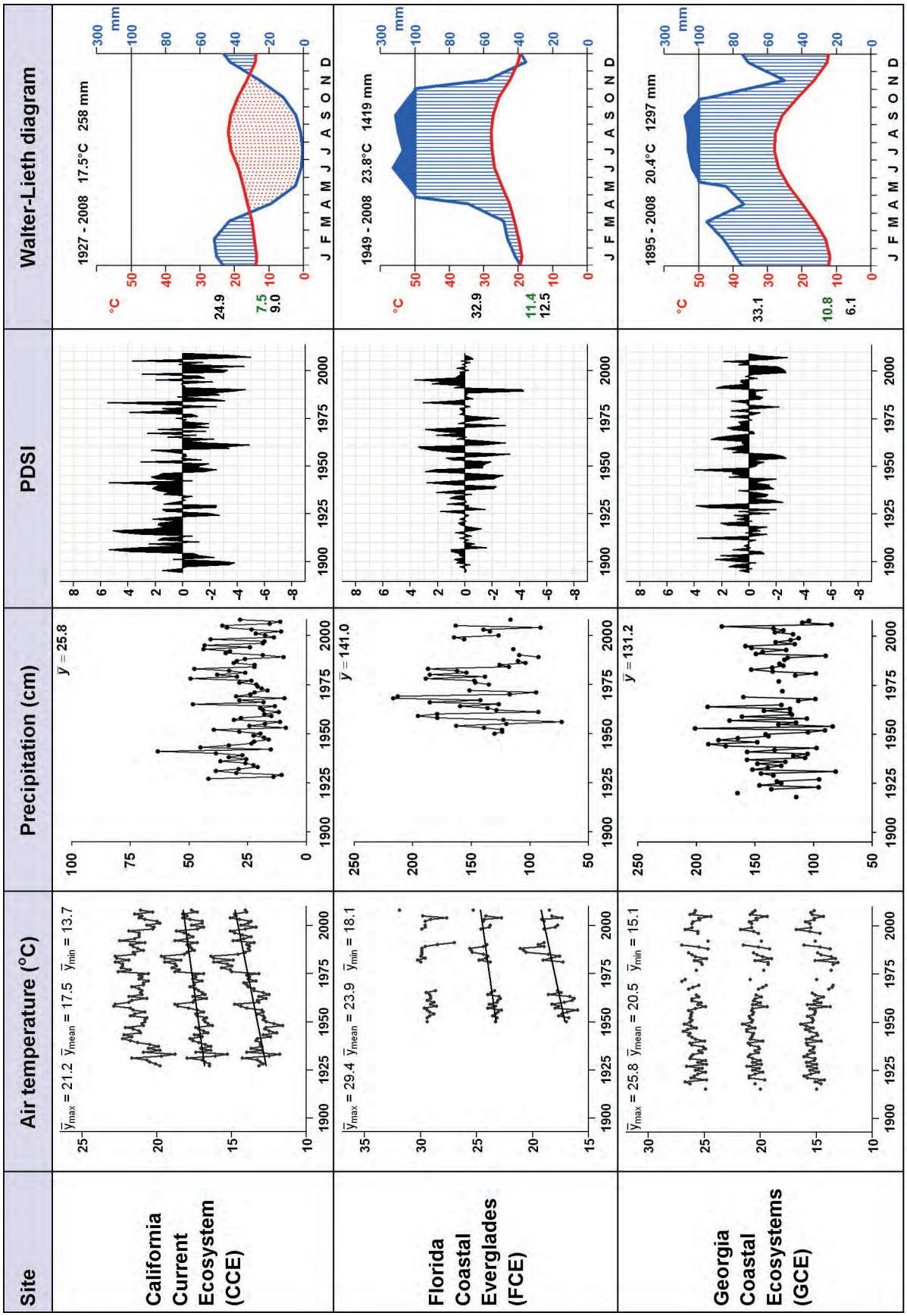
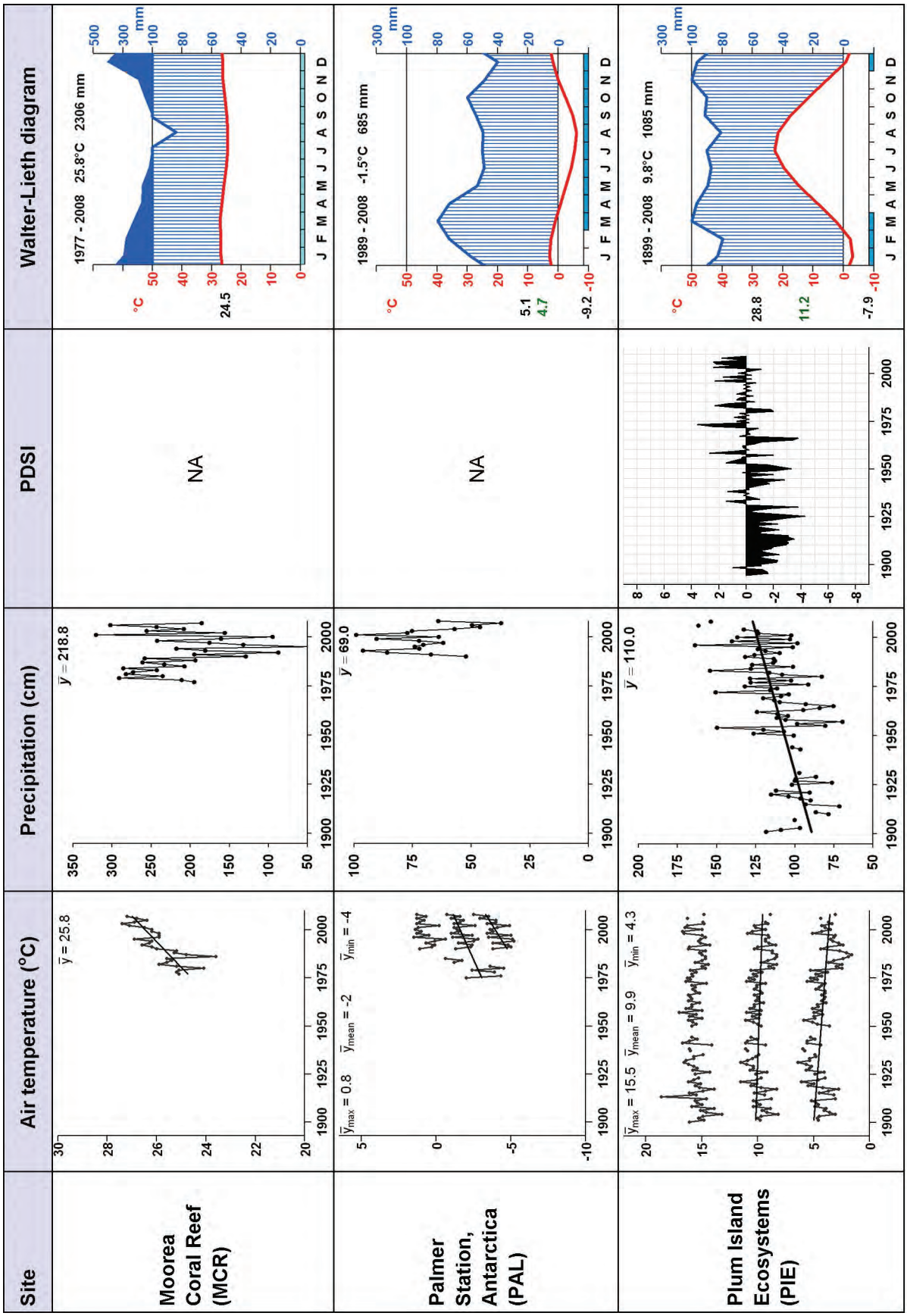


Figure 11-6 (coastal sites) continued next page.



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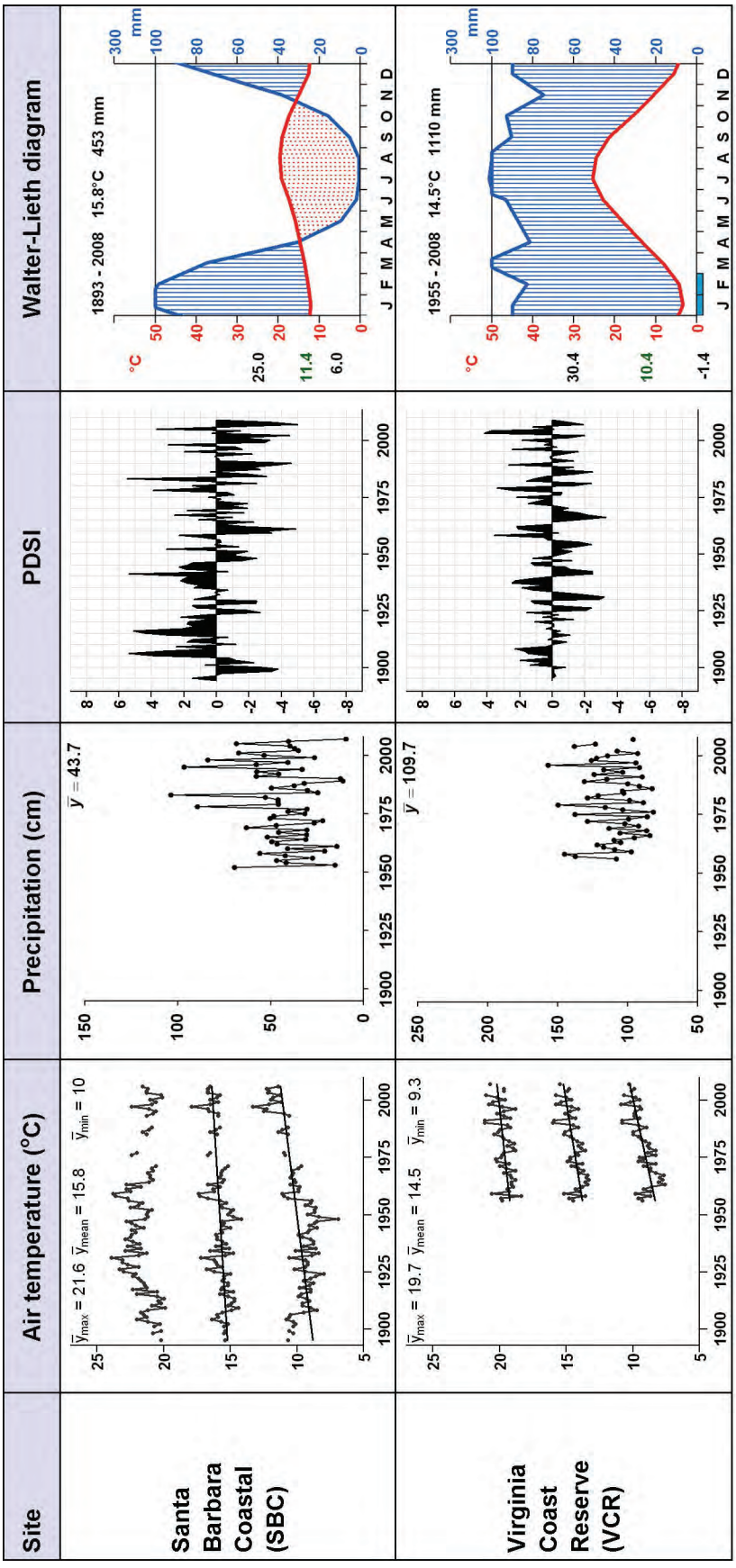


Figure 11-6. Trends for each coastal site—annual temperature (°C) (minimum, mean, maximum), annual precipitation (cm), annual PDSI, and monthly average precipitation and mean temperature—in a Walter-Lieth diagram. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for minimum, mean, and maximum air temperature and precipitation, respectively, are (NA = not available, NS = non-significant) California Current Ecosystem (CCE): 0.026, 0.018, NS, NS; Florida Coastal Everglades (FCE): 0.037, 0.024, NS, NS; Georgia Coastal Ecosystems (GCE): NS, NS, NS, NS; Moorea Coral Reef (MCR): NA, 0.075, NA, NS; Palmer Station, Antarctica (PAL): 0.081, 0.059, NS, NS; Plum Island Ecosystems (PIE): -0.013, -0.006, NS, 0.360; Santa Barbara Coastal (SBC): 0.022, 0.010, NS, NS; and Virginia Coast Reserve (VCR): 0.037, 0.028, 0.019, NS. Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. MCR climate data provided by Météo France en Polynésie Française. Synthesized data from http://www.ecotrends.info.

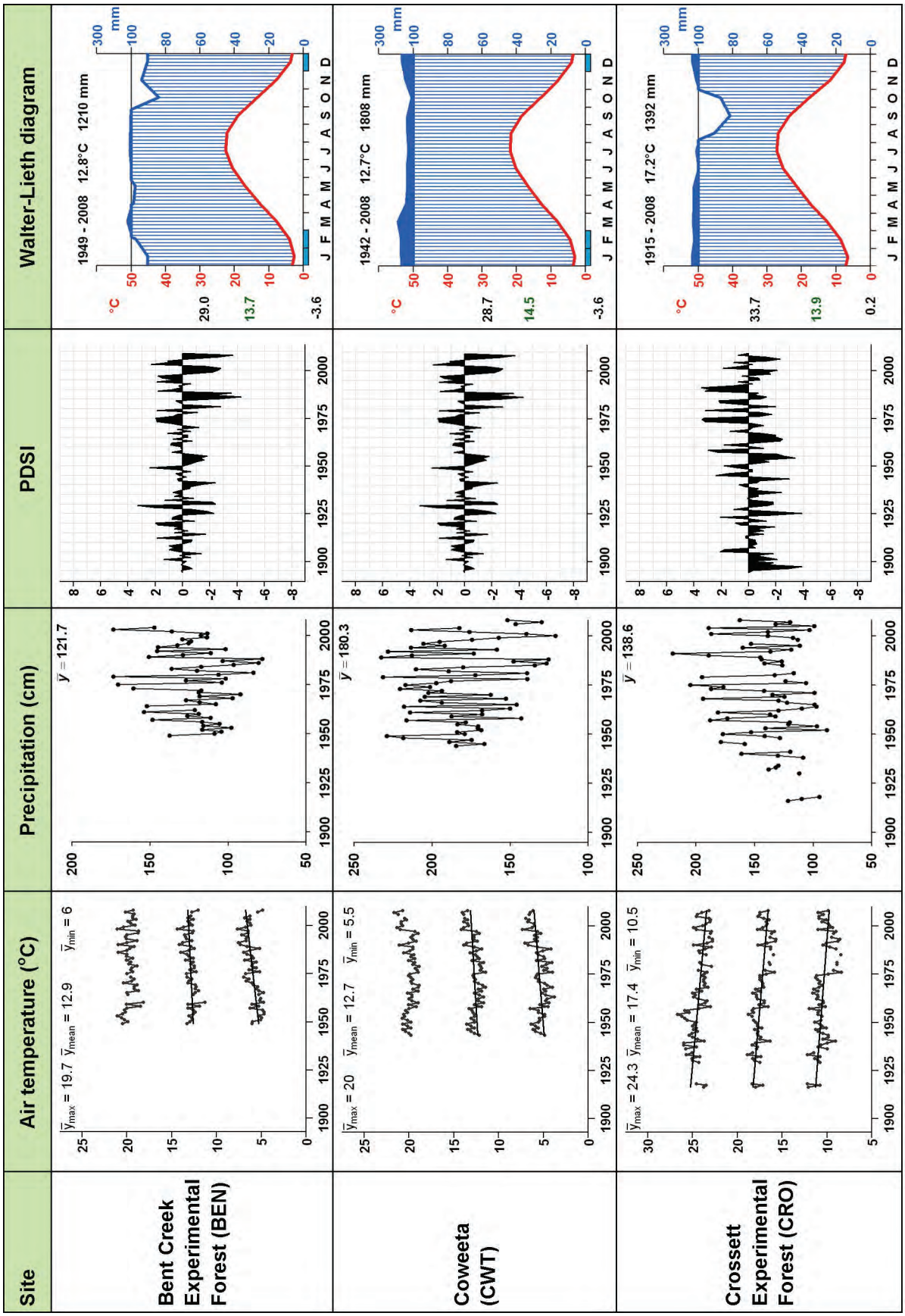
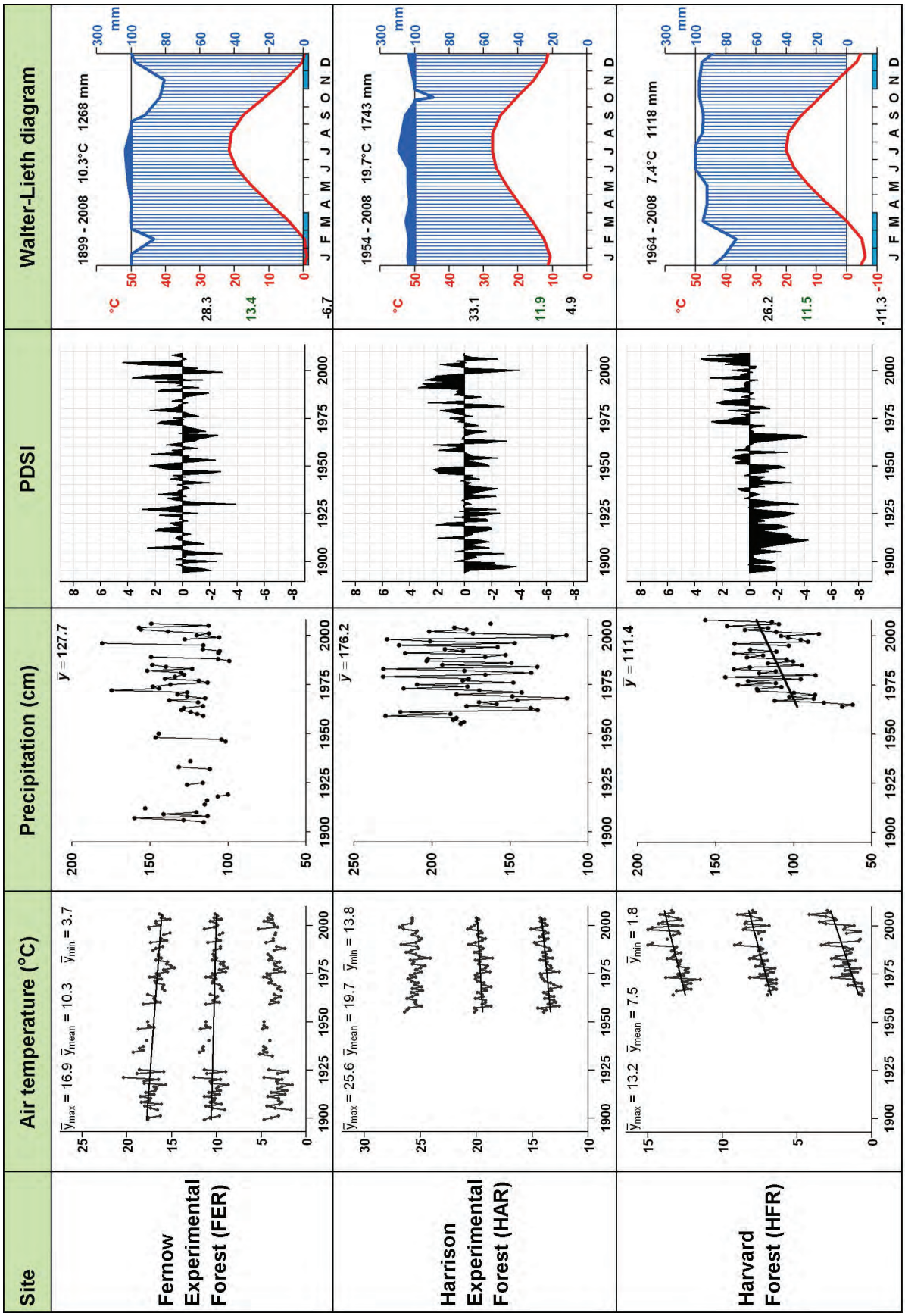


Figure 11-7 (eastern forest sites) continued next page.



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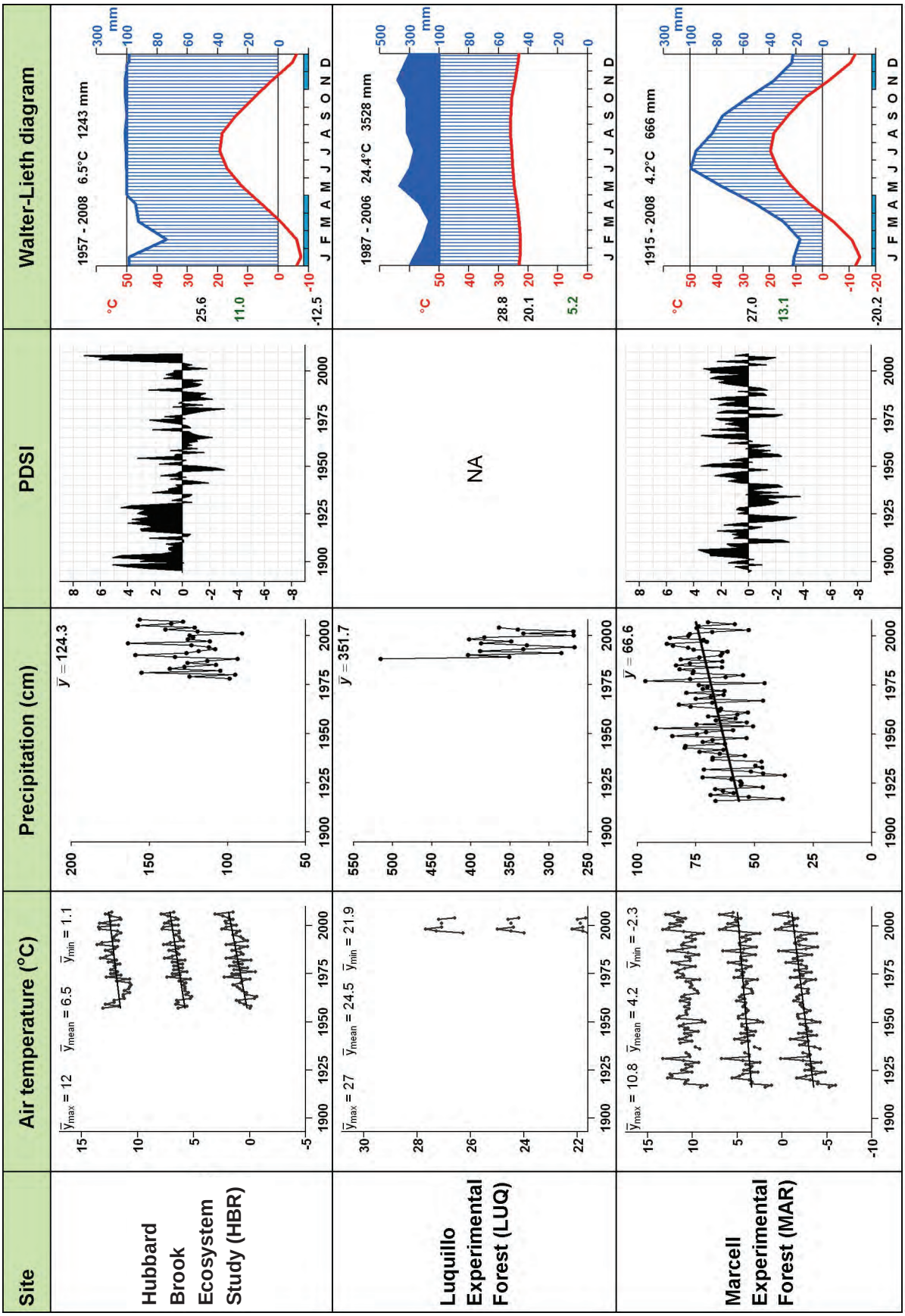

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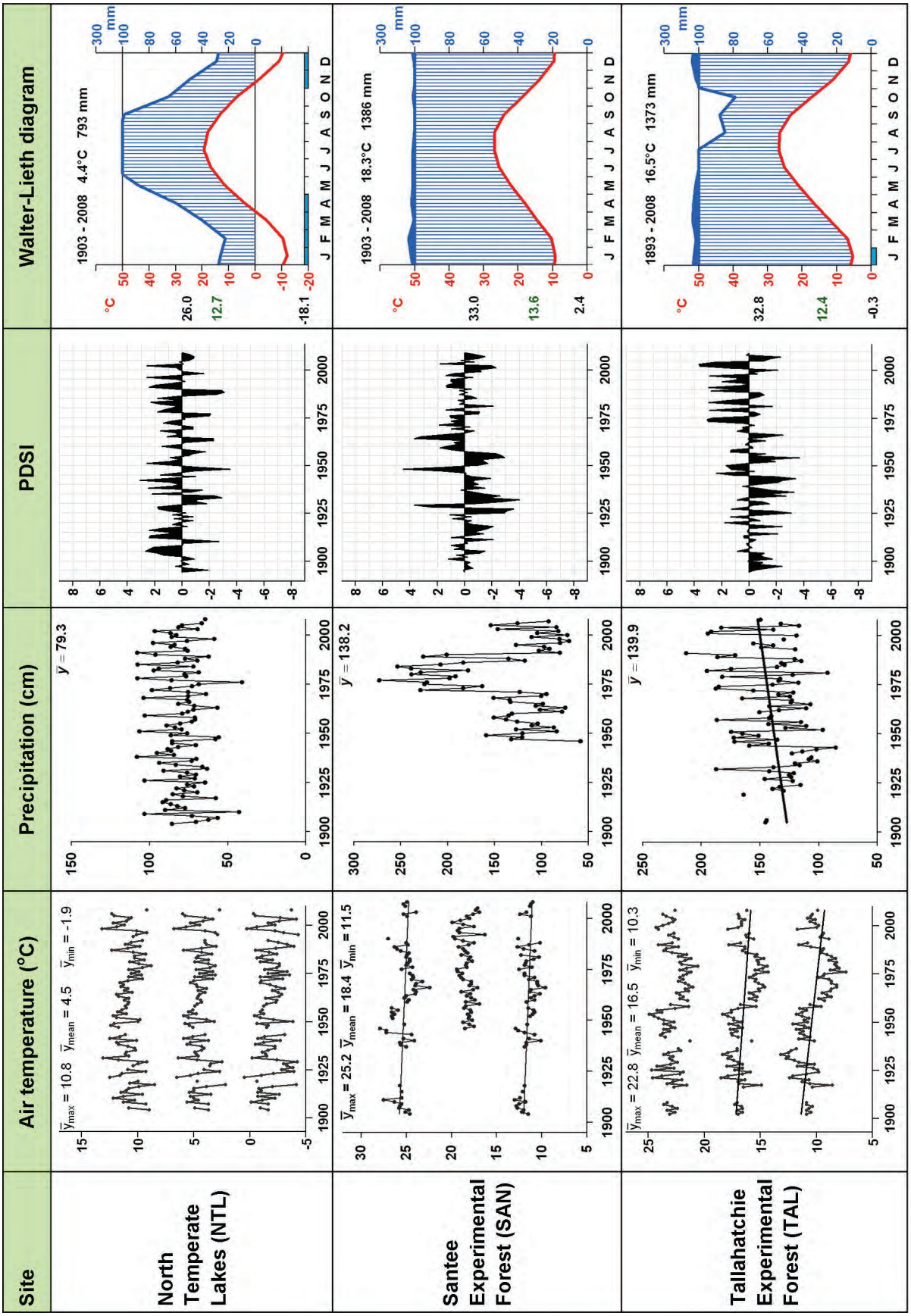

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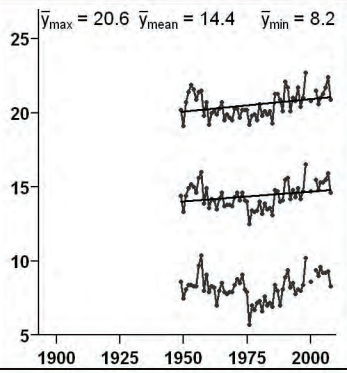
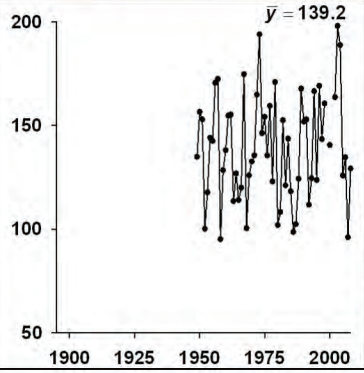
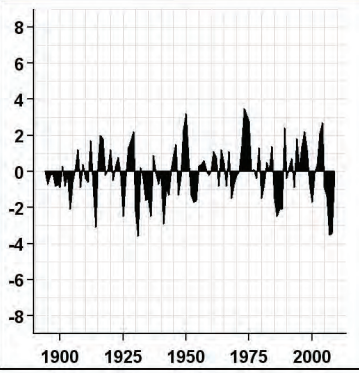
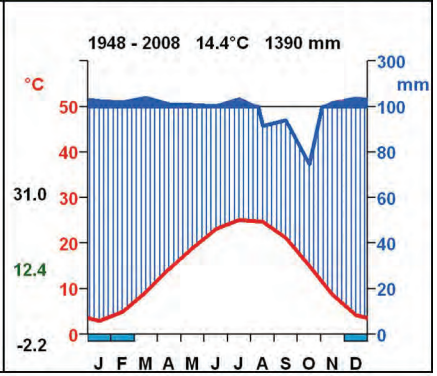
Site	Air temperature (°C)	Precipitation (cm)	PDSI	Walter-Lieth diagram
Walker Branch Watershed (WBW)				

Figure 11-7. Trends for each eastern forest site—annual temperature (°C) (minimum, mean, maximum), annual precipitation (cm), annual PDSI, and monthly average precipitation and mean temperature—in a Walter-Lieth diagram. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for minimum, mean, and maximum air temperature and precipitation, respectively, are (NS = non-significant) Bent Creek Experimental Forest (BEN): 0.025, 0.010, NS, NS; Crossett Experimental Forest (CRO): -0.017, -0.019, -0.021, NS; Coweeta (CWT): 0.017, 0.012, NS, NS; Fernow Experimental Forest (FER): NS, -0.006, -0.017, NS; Harrison Experimental Forest (HAR): 0.016, 0.010, NS, NS; Hubbard Brook Ecosystem Study (HBR): 0.033, 0.027, 0.020, NS; Harvard Forest (HFR): 0.043, 0.034, 0.032, 0.594; Luquillo Experimental Forest (LUQ): NS, NS, NS, NS; Marcell Experimental Forest (MAR): 0.027, 0.017, NS, 0.201; North Temperate Lakes (NTL): NS, NS, NS, NS; Santee Experimental Forest (SAN): -0.009, NS, -0.010, NS; Tallahatchie Experimental Forest (TAL): -0.020, -0.012, NS, 0.240; and Walker Branch Watershed (WBW): NS, 0.013, 0.017, NS. Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

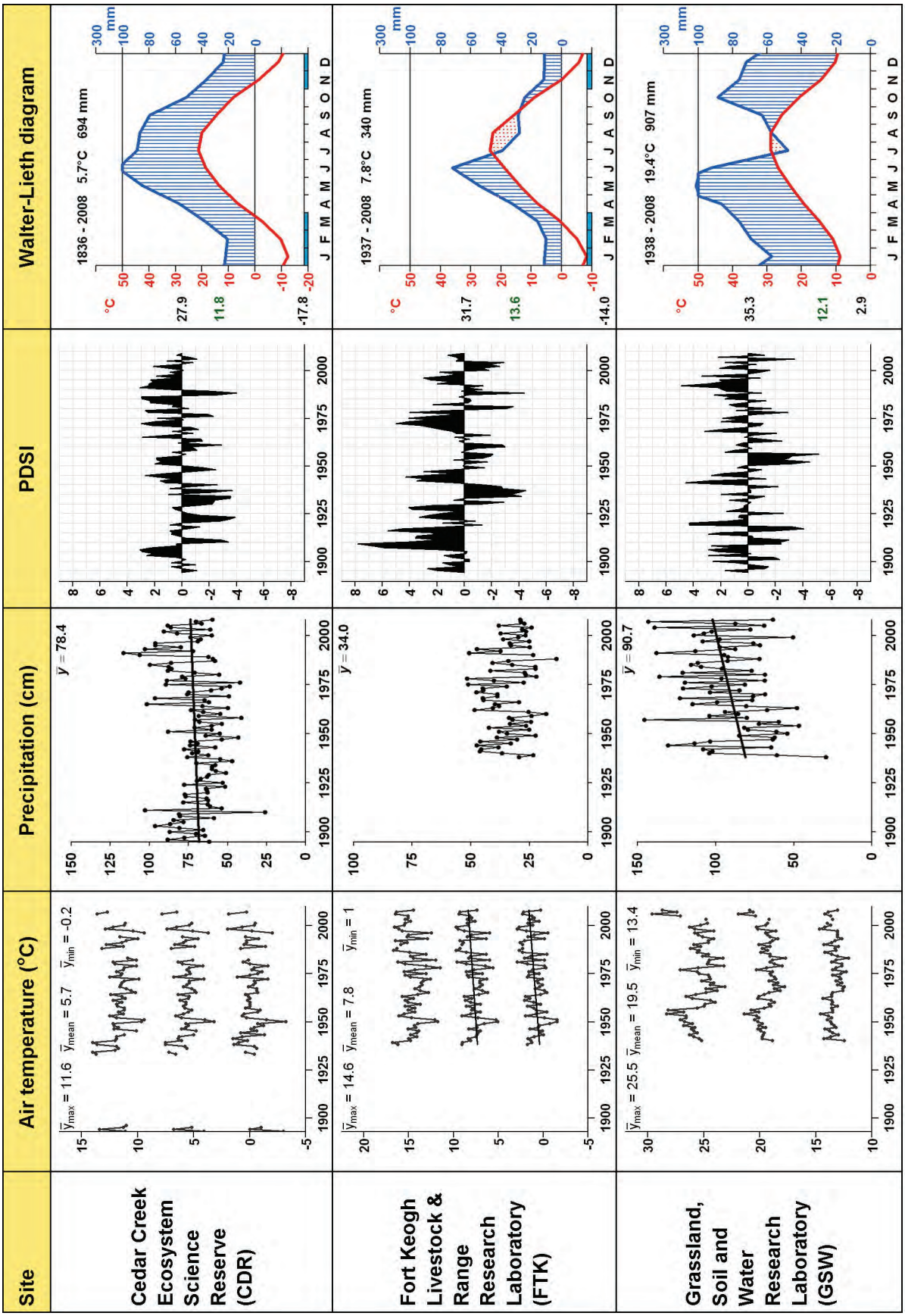


Figure 11-8 (grassland and savanna sites) continued next page.

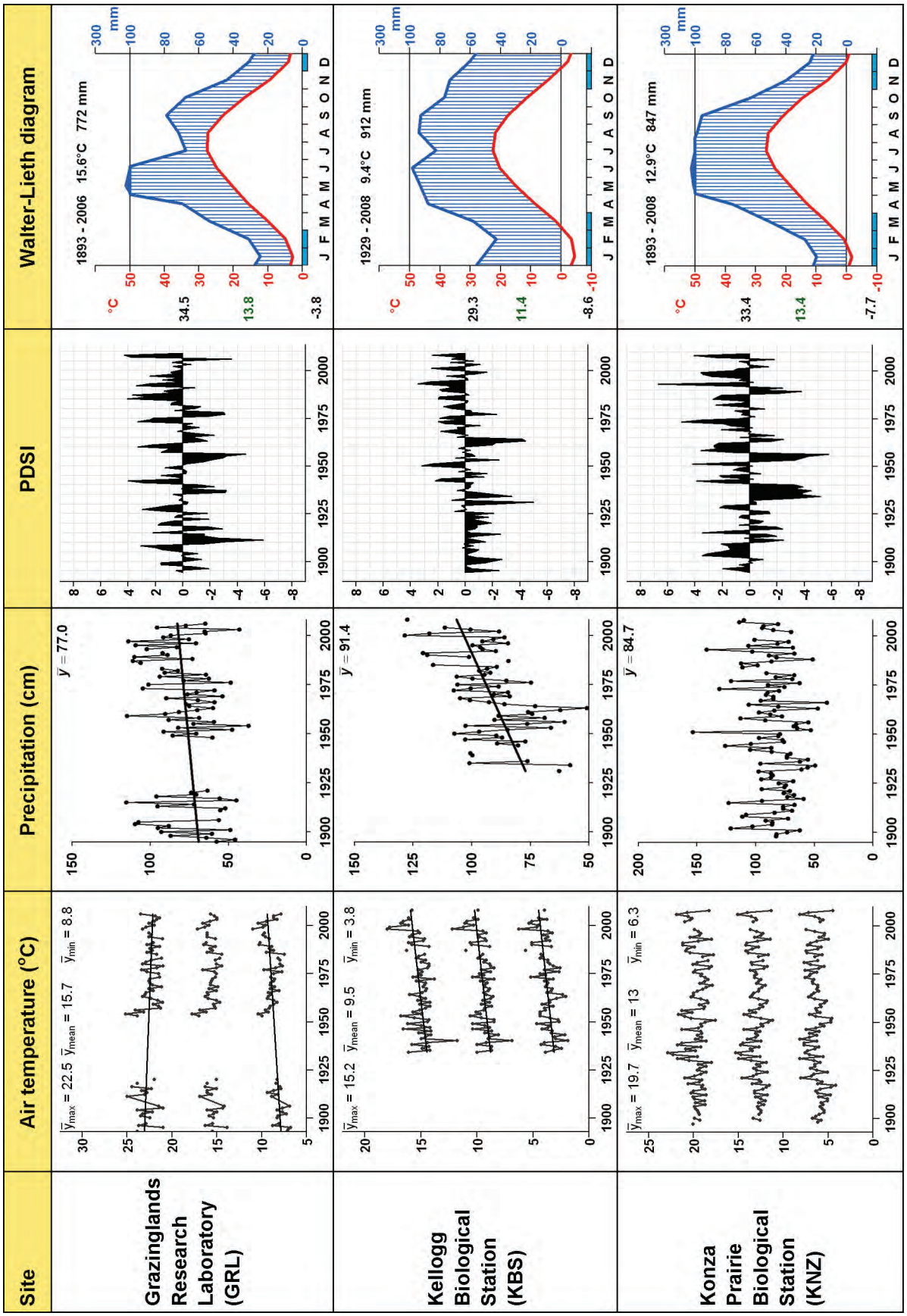


Figure 11-8 (grassland and savanna sites) continued next page.

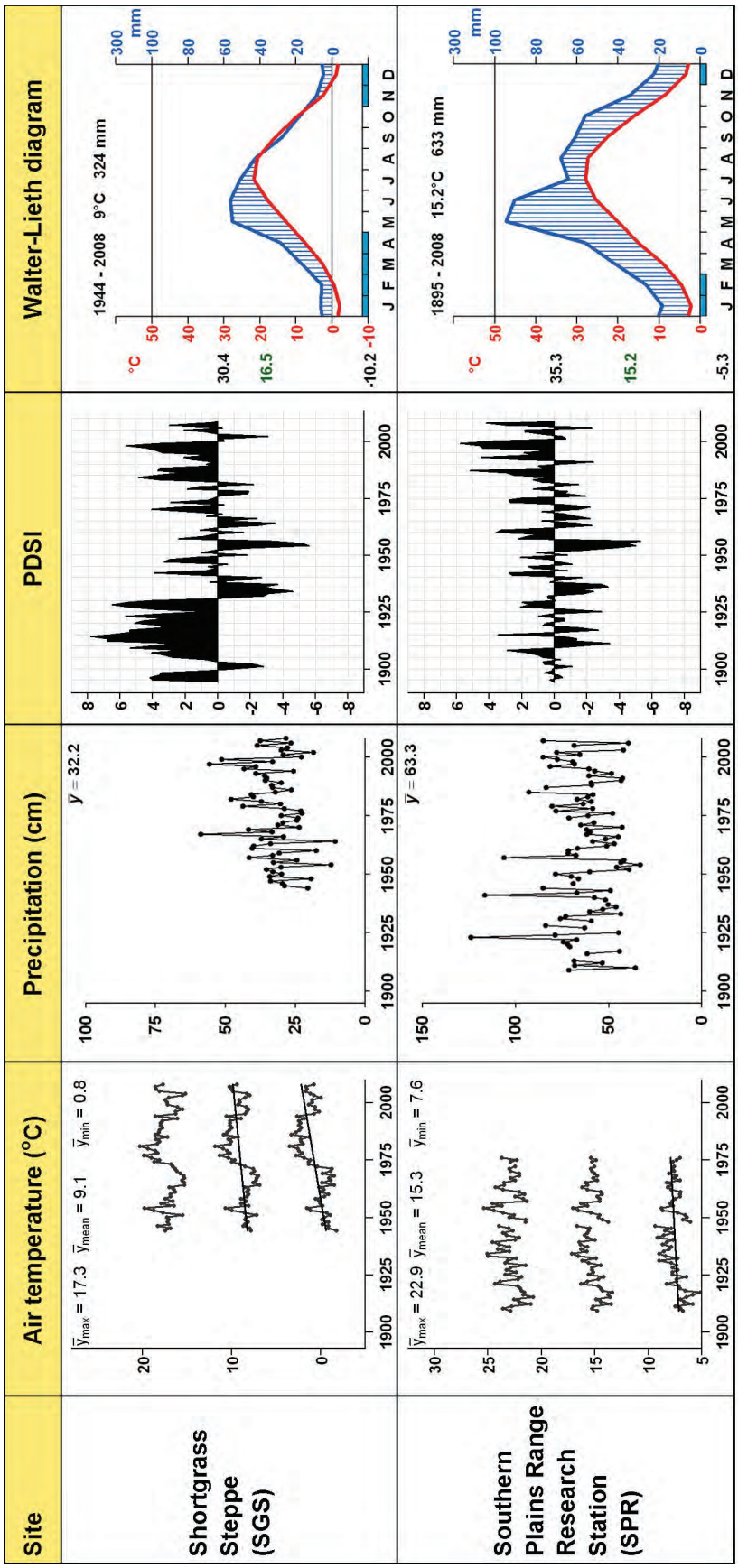


Figure 11-8. Trends for each temperate grassland and savanna site—annual temperature (°C) (minimum, mean, maximum), annual precipitation (cm), annual PDSI, and monthly average precipitation and mean temperature—in a Walter-Lieth diagram. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for minimum, mean, and maximum air temperature and precipitation, respectively, are (NS = non-significant) Cedar Creek Ecosystem Science (CDR): NS, NS, NS, 0.049; Fort Keogh Livestock and Range (FTK): 0.017, 0.015, NS, NS; Grazinglands Research Laboratory (GRL): 0.019, NS, -0.013, 0.191; Grassland, Soil and Water Research Laboratory (GSW): NS, NS, NS, 0.300; Kellogg Biological Station (KBS): 0.019, 0.019, 0.019, 0.380; Konza Prairie Biological Station (KNZ): NS, NS, NS; Shortgrass Steppe (SGS): 0.042, 0.024, NS, NS; and Southern Plains Range Research (SPR): 0.011, NS, NS, NS. Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

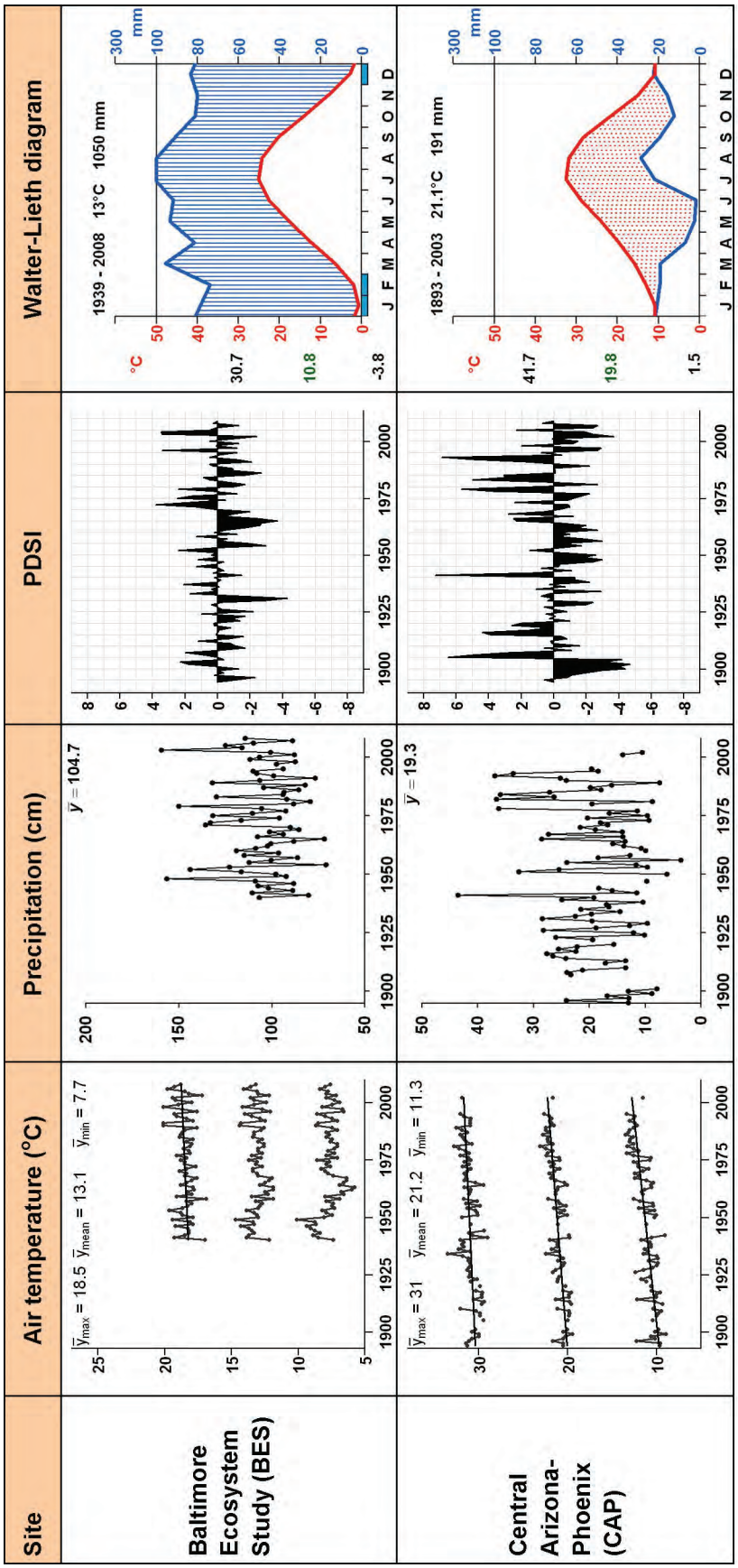


Figure 11-9. Trends for each urban site—annual temperature (°C) (minimum, mean, maximum), annual precipitation (cm), annual PDSI, and monthly average precipitation and mean temperature—in a Walter-Lieth diagram. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for minimum, mean, and maximum air temperature and precipitation, respectively, are (NS = non-significant) Baltimore Ecosystem Study (BES): NS, NS, 0.008, NS and Central Arizona-Phoenix (CAP): 0.028, 0.020, 0.012, NS. Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

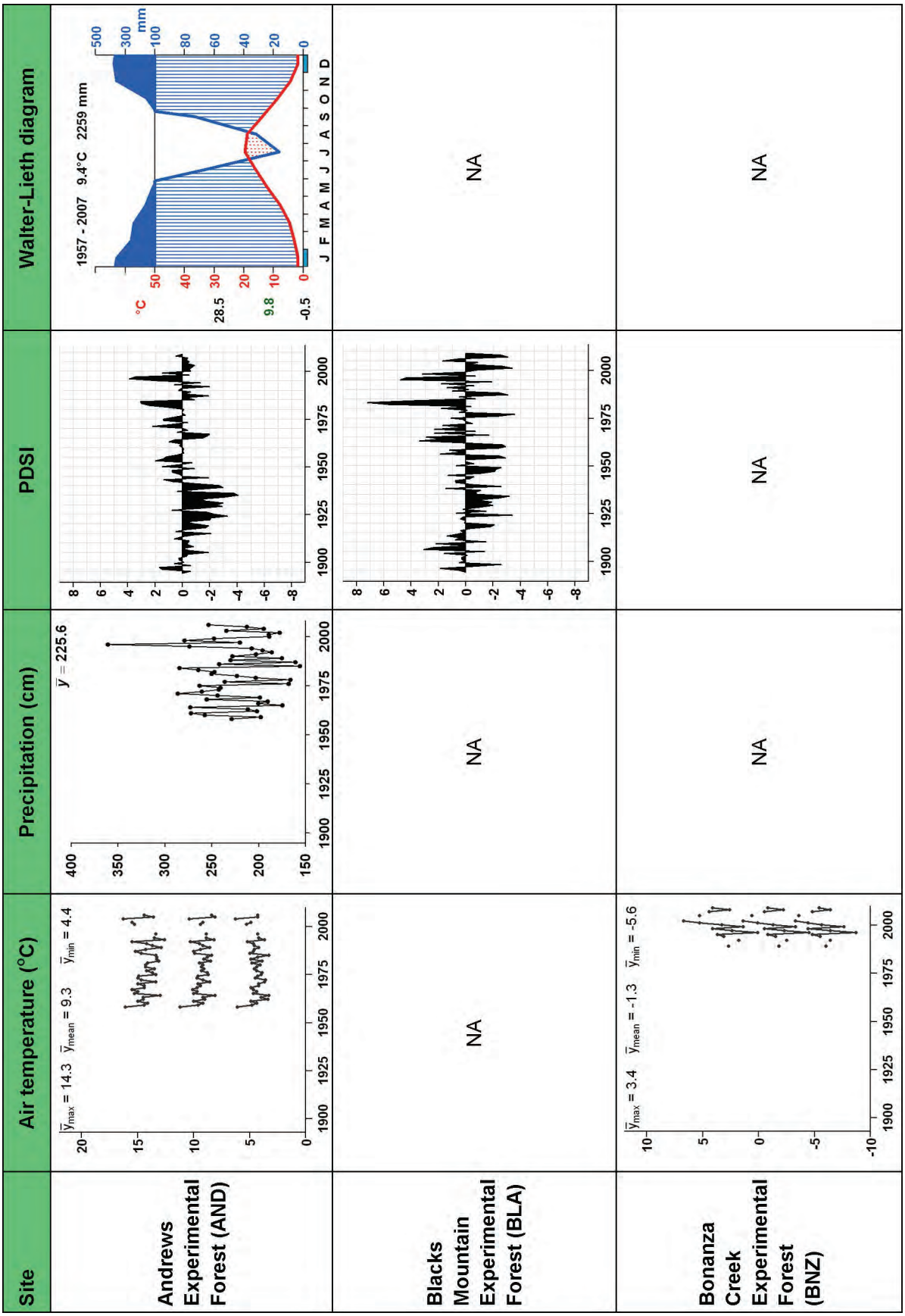


Figure 11-10 (western forest sites) continued next page.

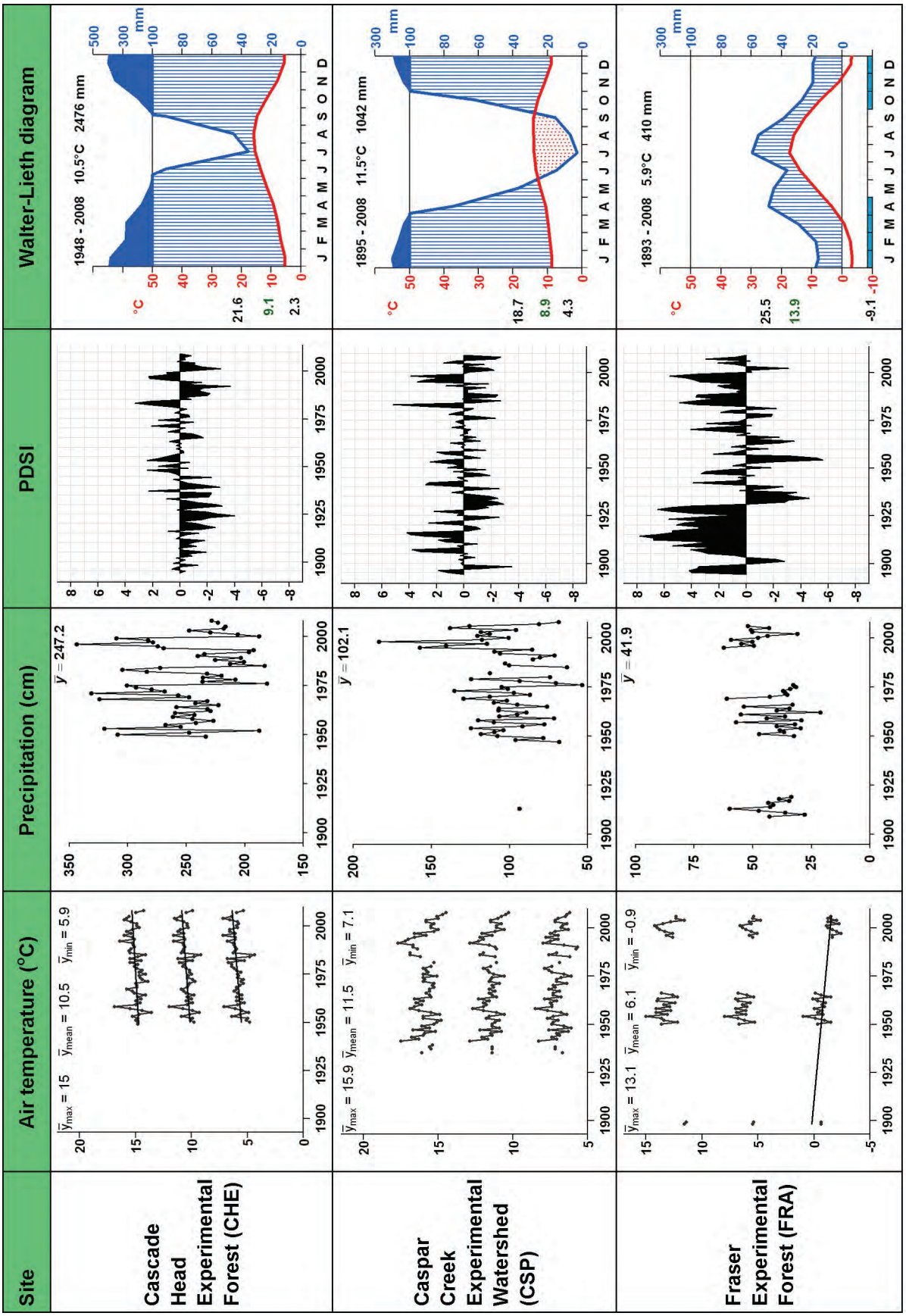


Figure 11-10 (western forest sites) continued next page.

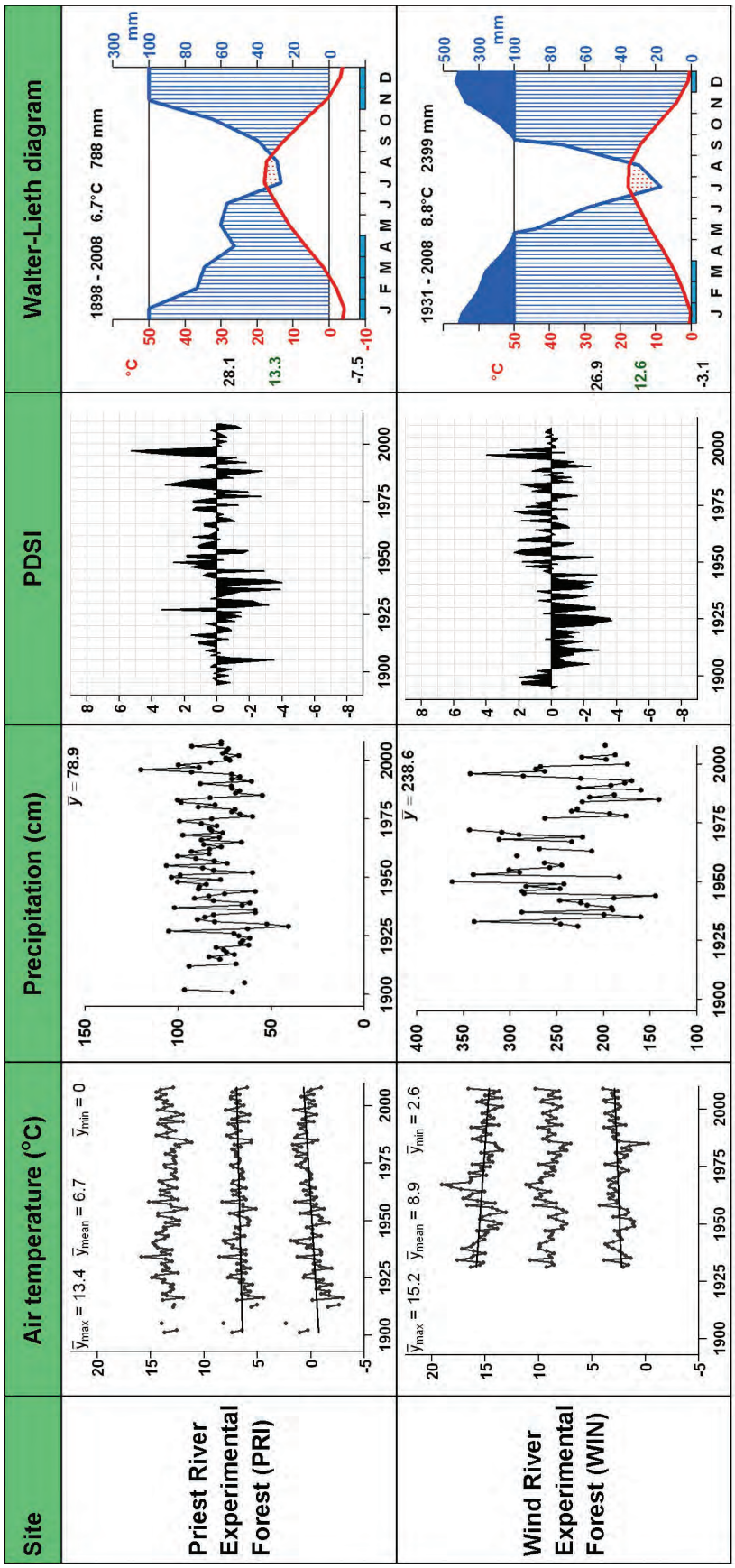


Figure 11-10. Trends for each western forest site—annual temperature (°C) (minimum, mean, maximum), annual precipitation (cm), annual PDSI, and monthly average precipitation and mean temperature—in a Walter-Lieth diagram. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for minimum, mean, and maximum air temperature and precipitation, respectively, are (NA = not available, NS = non-significant) H.J. Andrews Experimental Forest (AND): NS, NS, NS, NS; Blacks Mountain Experimental Forest (BLA): NA, NA, NA, NA; Bonanza Creek Experimental Forest (BNZ): NS, NS, NS, NA; Cascade Head Experimental Forest (CHE): 0.014, 0.012, 0.010, NS; Caspar Creek Experimental Watershed (CSP): NS, NS, NS, NS; Fraser Experimental Forest (FRA): -0.033, NS, NS, NS; Priest River Experimental Forest (PRI): 0.014, 0.006, NS, NS; and Wind River Experimental Forest (WIN): 0.009, NS, -0.015, NS. Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

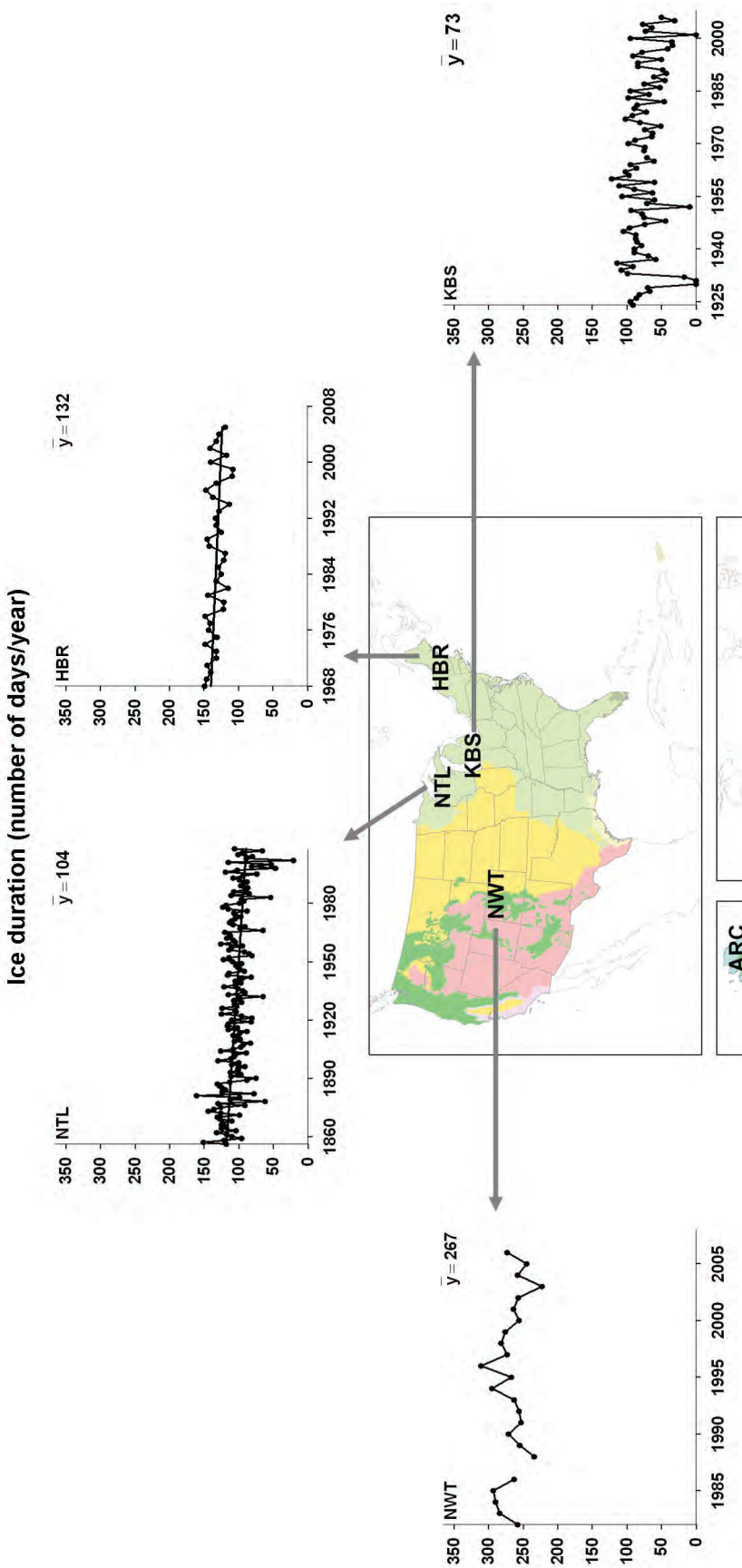


Figure 11-11. Ice duration (number of days per year) through time and the mean number of days per year for six sites with data. Length of the time series differs among sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are Hubbard Brooks Ecosystem Study (HBR) (-0.447) and North Temperate Lakes (NTL) (-0.187). Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

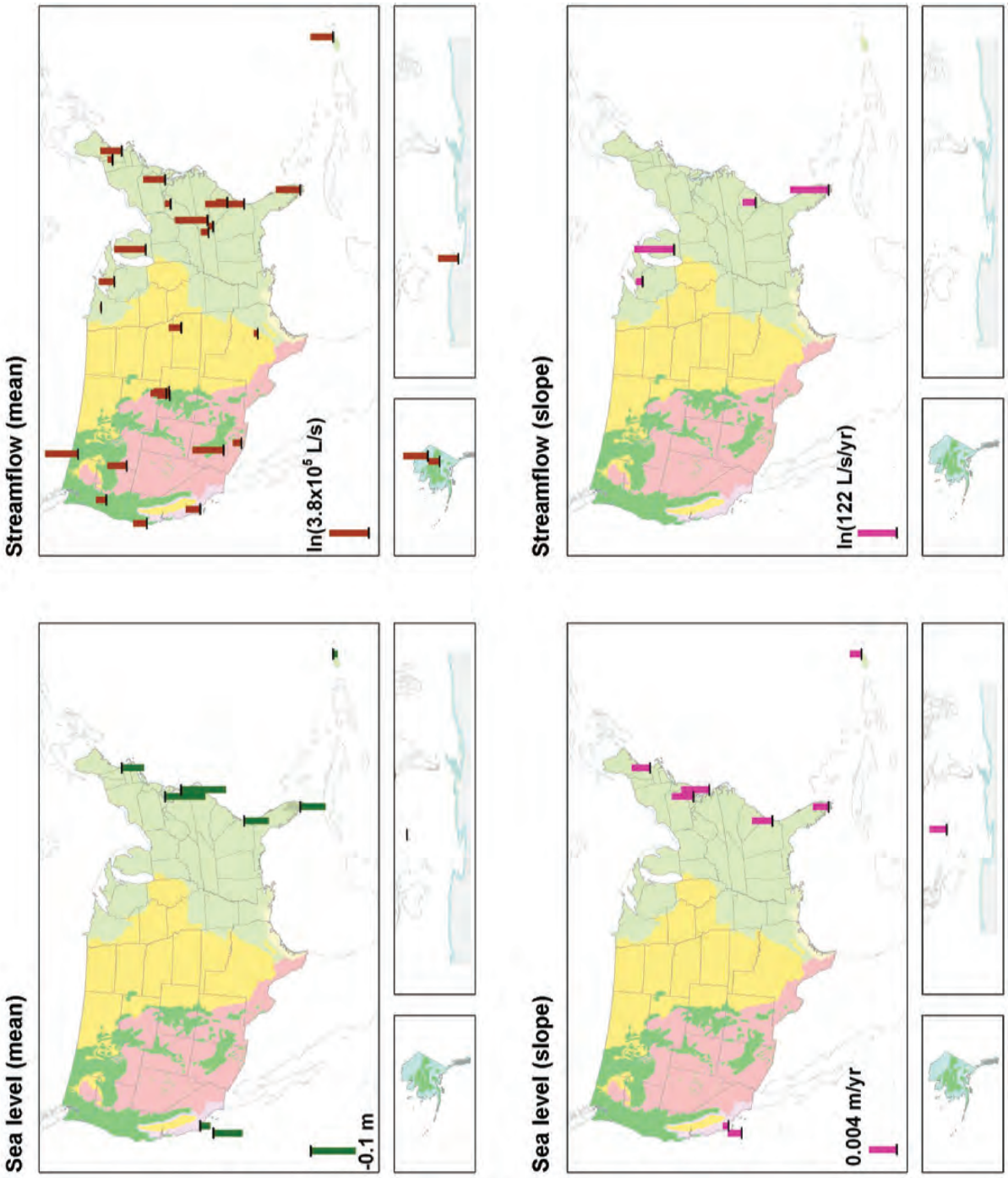


Figure 11-12. Continental patterns in annual mean sea level (m) and streamflow (L/s). Annual mean sea level is defined as the annual arithmetic mean of hourly heights relative to the National Tidal Datum Epoch (the most recent mean sea level datum established by the Center for Operational Oceanographic Products and Services (CO-OPS), currently the mean sea level 1983-2001). (Top panels) long-term averages: positive values are red and negative values are green. (Bottom panels) slopes of significant regression lines ($p < 0.05$): positive values are pink and negative values are blue. For streamflow, the bar height is the ln-transformed value [ln(1+mean), ln(slope)]. Original data from Internet home pages (see table 1-1) and http://www.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

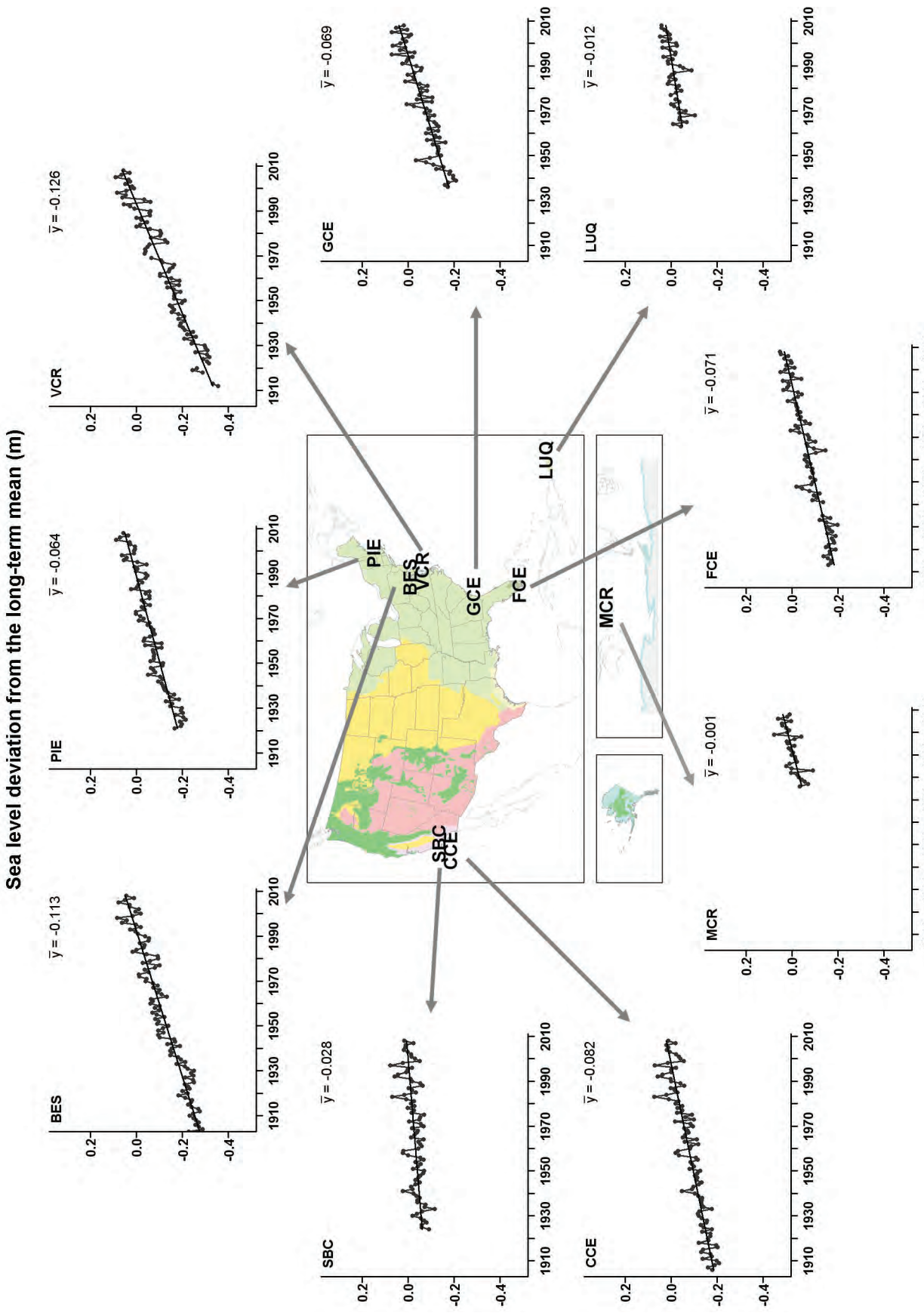


Figure 11-13. Annual mean sea level (m) through time for nine sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are Santa Barbara Coastal (SBC): 0.001; California Current Ecosystem (CCE), Florida Coastal Everglades (FCE), and Luquillo Experimental Forest (LUQ): 0.002; Georgia Coastal Ecosystems (GCE), Moorea Coral Reef (MCR), Plum Island Ecosystems (PIE), and Baltimore Ecosystem Study (BES): 0.003; and Virginia Coast Reserve (VCR): 0.004. Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

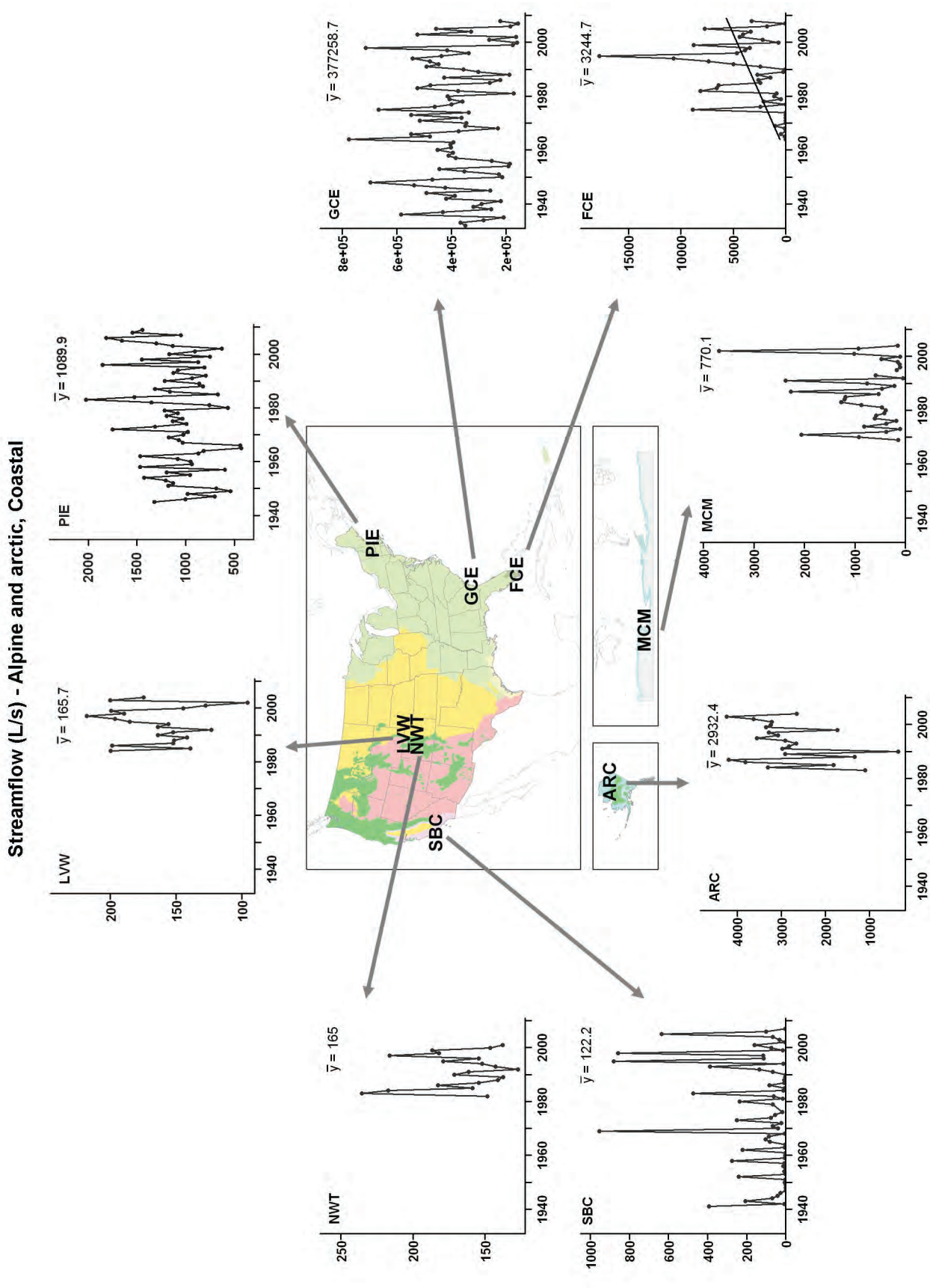


Figure 11-14. Streamflow (L/s) through time for eight alpine and arctic sites and coastal sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slope is Florida Coastal Everglades (FCE) (110.6). Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

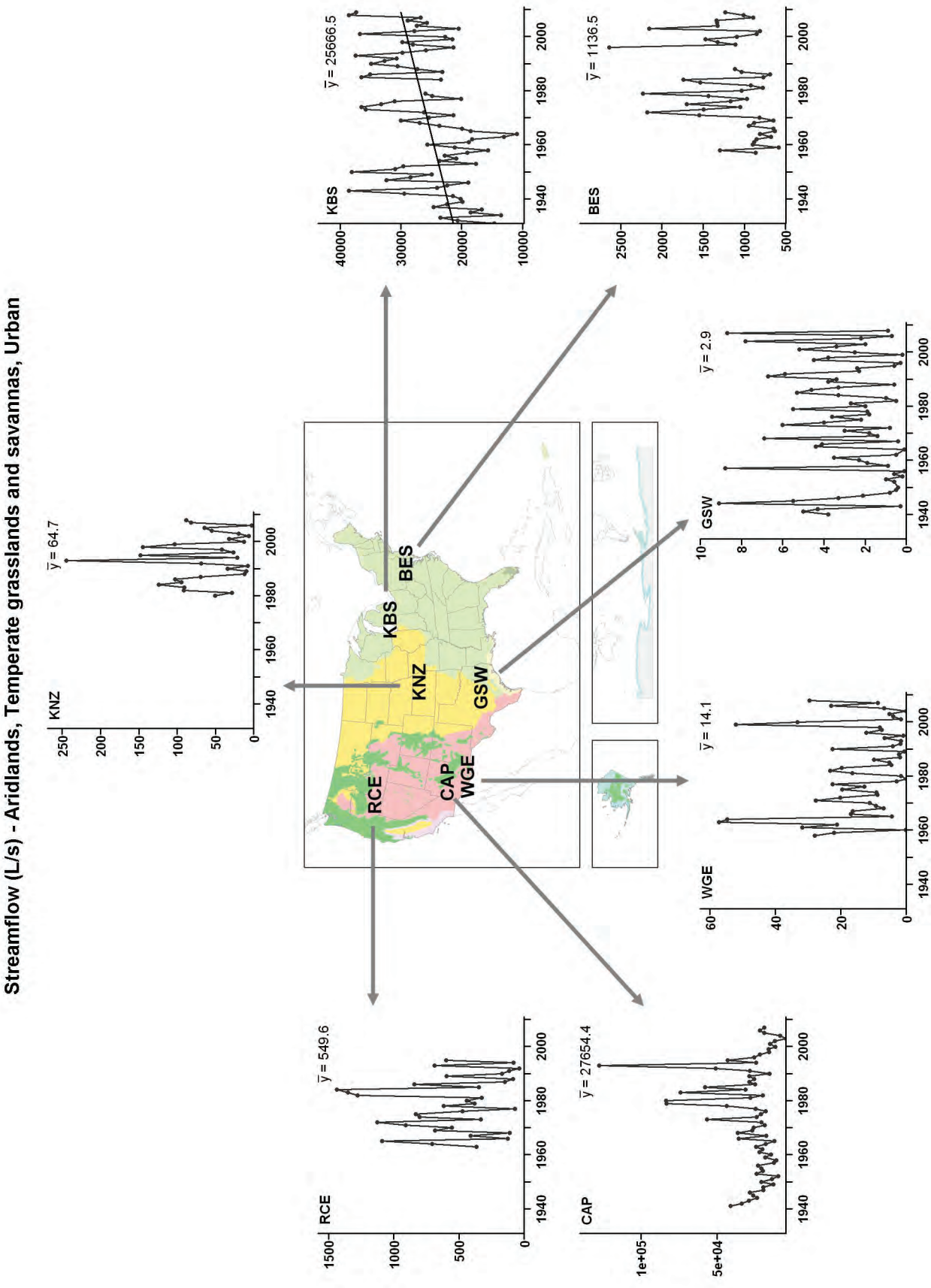


Figure 11-15. Streamflow (L/s) through time for seven aridland, temperate grassland and savanna, and urban sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slope is Kellogg Biological Station (KBS) (122.1). Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

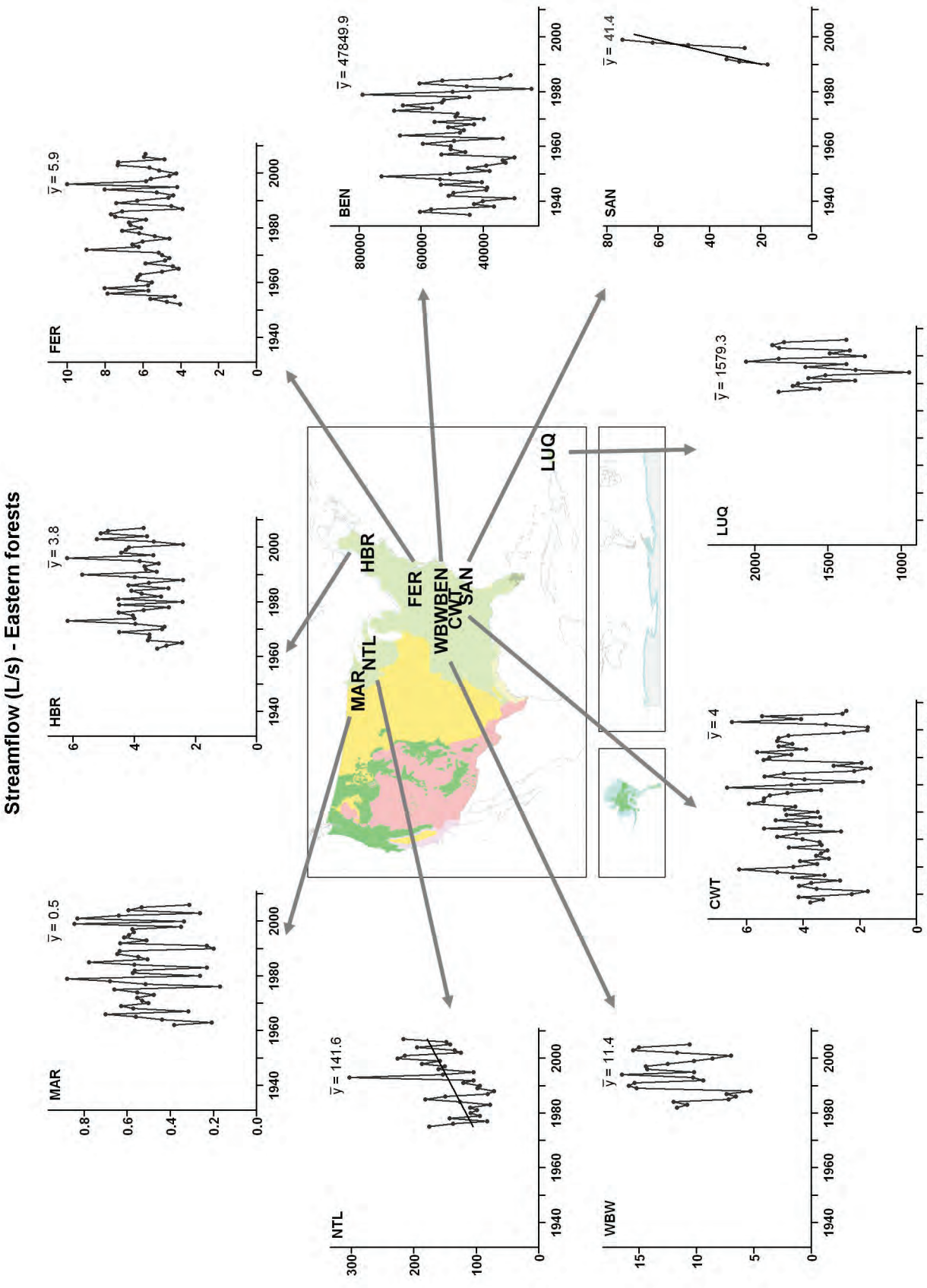


Figure 11-16. Streamflow (L/s) through time for nine eastern forest sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are North Temperate Lakes (NTL) (2.3) and Santee Experimental Forest (SAN) (4.9). Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

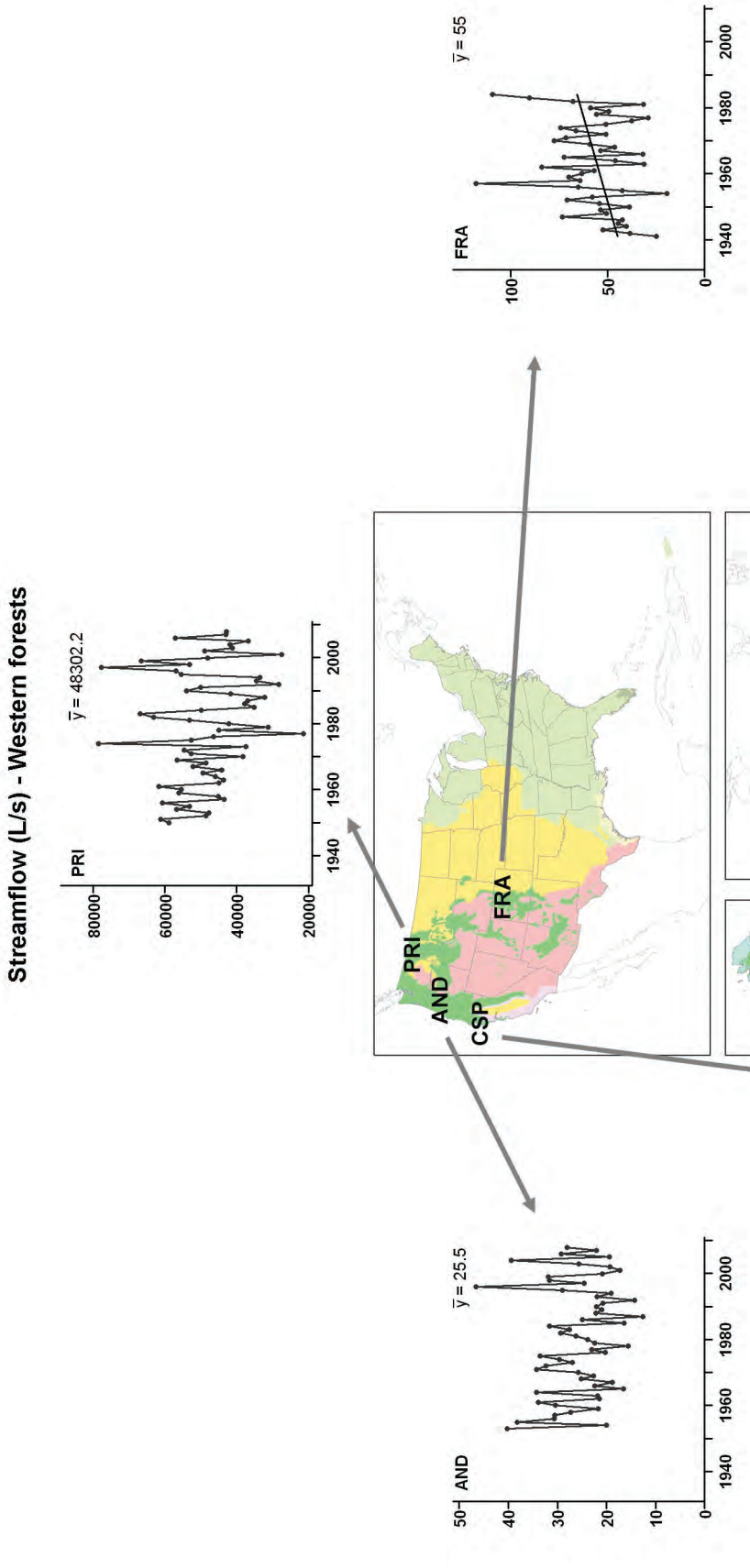


Figure 11-17. Streamflow (L/s) through time for five western forest sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

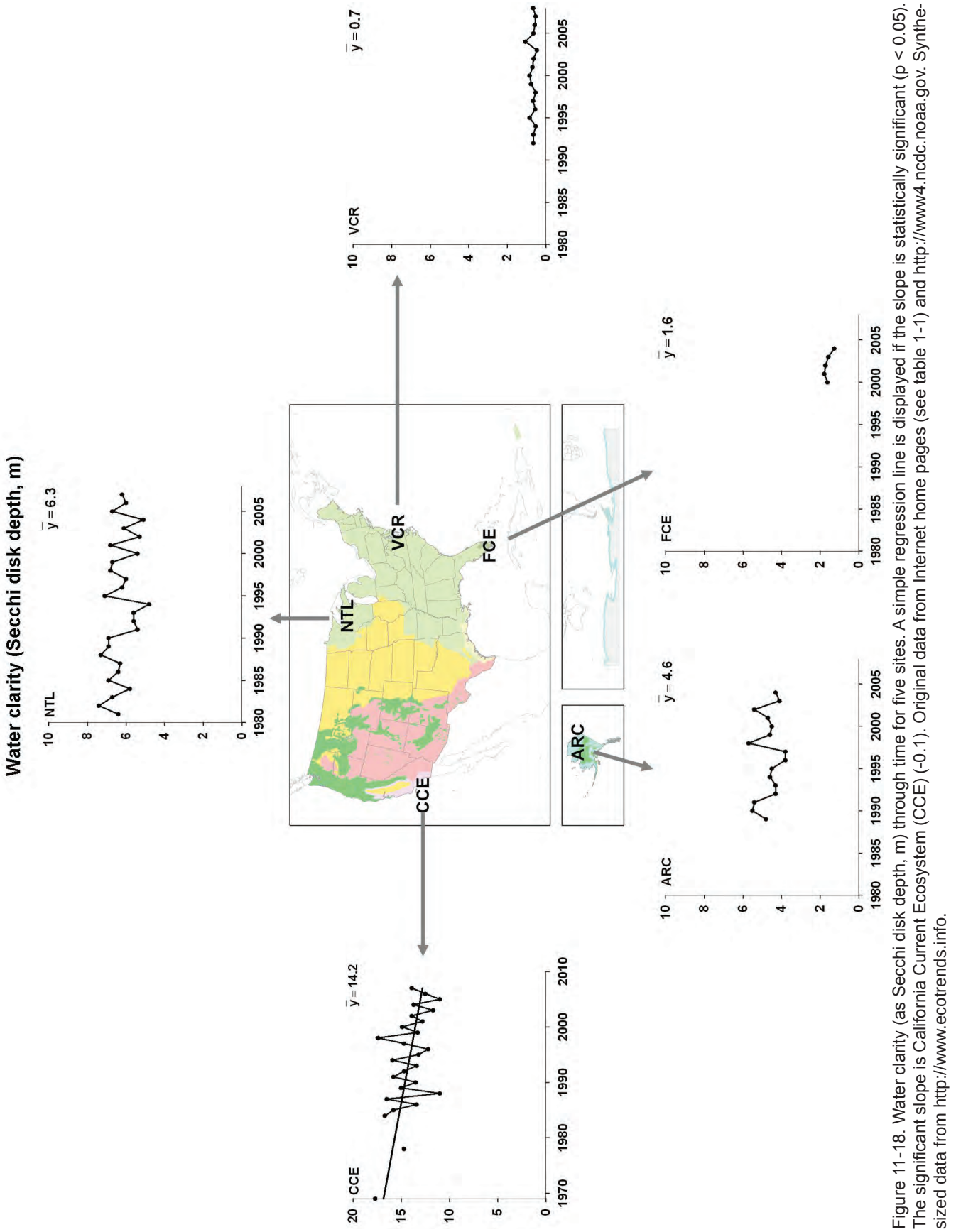


Figure 11-18. Water clarity (as Secchi disk depth, m) through time for five sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slope is California Current Ecosystem (CCE) (-0.1). Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

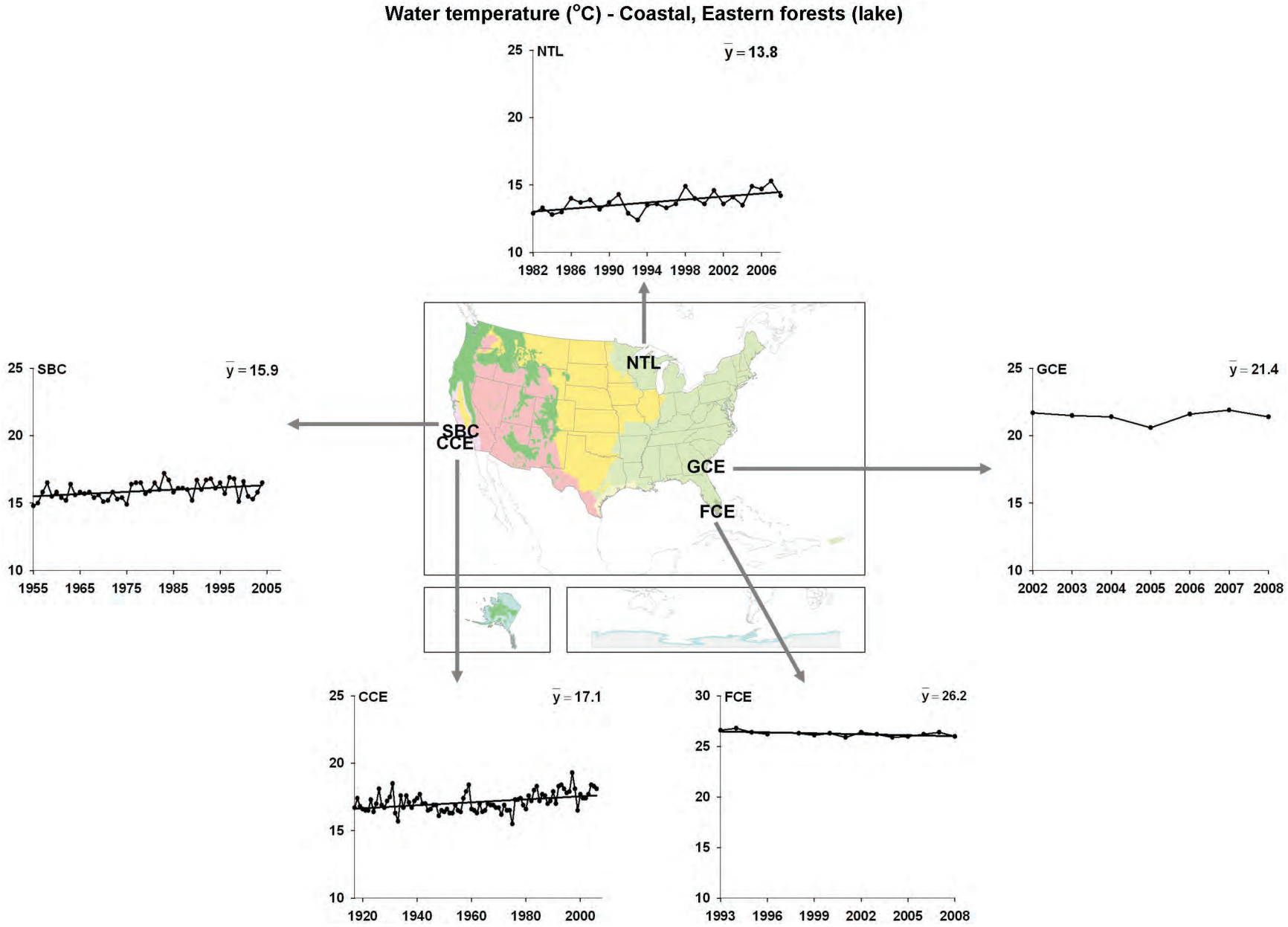


Figure 11-19. Water temperature (°C) through time for five coastal sites and one lake in an eastern forest site. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are: California Current Ecosystem (CCE) (0.01), Florida Coastal Everglades (FCE) (-0.03), Santa Barbara Coastal (SBC) (0.02), and North Temperate Lakes (NTL) (0.06). Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

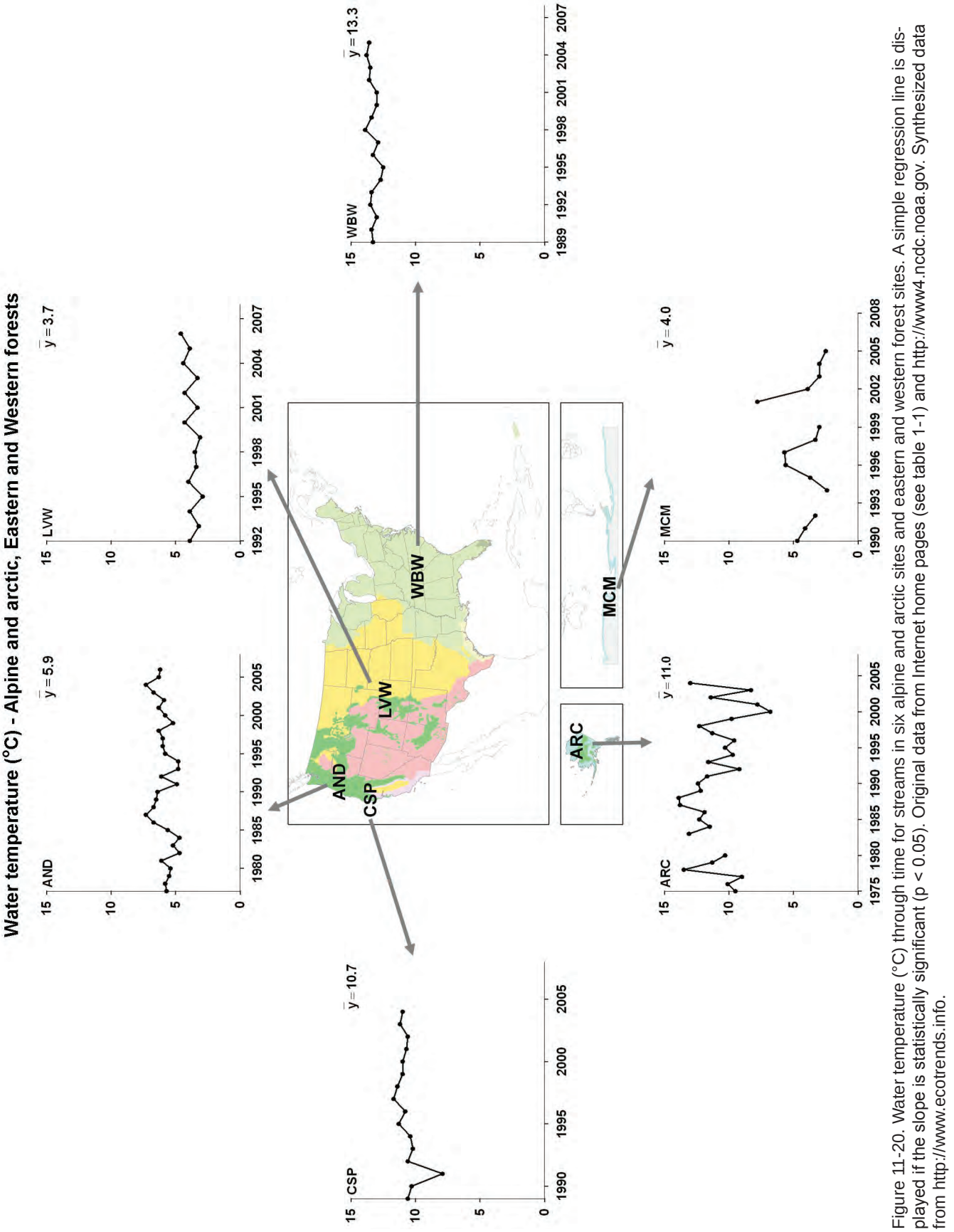


Figure 11-20. Water temperature (°C) through time for streams in six alpine and arctic sites and eastern and western forest sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

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