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Variability and trends in seasonal snow cover in Ontario from 1980 to 2010 detected using remote sensing

Responding to Climate Change Through Partnership

Ontario

Variability and trends in seasonal snow cover in Ontario from 1980 to 2010 detected using remote sensing

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Cover image: Snow cover in Algonquin Provincial Park (Photo credit: Robert A. Metcalfe)

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Summary

Historical trends in temperature and precipitation have been widely used to assess potential effects of climate change in Ontario but trends in snow cover have received less attention. Seasonal snow cover strongly influences Ontario's climate, is a key component of the water balance, governs the annual hydrograph shape (timing and magnitude of streamflow), influences ecosystem processes and aquatic and terrestrial population dynamics, and affects water supply, public safety, and recreational activities. Expected changes in the extent and volume of snow in response to a changing climate are not obvious because snowfall and snow cover are affected by both air temperature and precipitation. While global and continental scale assessments of changes in snow cover exist, this study focused on documenting the variability and changes in monthly snow water equivalent (SWE) and snow cover extent (SCE) in Ontario over the recent climate normal period (1980–2010). The large study area and data record required for analysis warranted the use of satellite-based products. Several indicators were used to assess changes in snowpack conditions at provincial and secondary watershed scales and the non-parametric Mann-Kendall (MK) test was used to detect monotonic trends in SWE, SCE, and climate variables for the 30-year study period.

A significant decreasing trend of ≈-9 mm or -6.4% per decade was observed in the water year maximum SWE for the province. Trends for the secondary watersheds showed that i) negative trends dominate (78%); ii) no positive trends were significant; and iii) several watersheds had negative trends at the 90 and 95% confidence level, including much of northwestern Ontario. The rate of change observed in the annual maximum SWE in watersheds with significant negative trends ranged from -1.2 to -2.0 mm per year, averaging -1.7 mm. These rates are associated with a 36 to 60 mm change in 30 years, which is 5 to 10% of the annual precipitation in those watersheds.

Strong relationships were observed between SWE and climate variables for the secondary watersheds. This includes the ratio of seasonal maximum SWE to total precipitation as a function of the mean seasonal minimum air temperature. A transition zone was identified in minimum seasonal air temperature above which the proportion of rain in total precipitation increases and SWE decreases. Watersheds most vulnerable to the greatest changes in SWE for small changes in air temperature and precipitation were identified as those in the transition zone and bordering the lower limit (i.e., -6.8 °C). The strong negative relationship supports a first order estimate of the SWE:total precipitation ratio given future predictions of air temperature and the delineation of regions using the noted isotherms where snowpack accumulation is more vulnerable to a warming climate.

While Globsnow-derived estimates of maximum SWE provided a relatively stable indication of changing snow conditions in Ontario, interpretation of the SCE data was complicated by discontinuity in the climate data record. Earlier snow detection and earlier losses of total snow cover were observed in SCE after 2000 but it is unclear how much of this shift in timing is attributable to changes in precipitation and temperature versus changes in remote sensing technology.

Recommendations for further analyses and refinements to validate the results, quantify uncertainty in indicator metrics, provide improved data on snow cover extent, and apply the results to specific resource management activities are provided.

Sommaire

Variabilité et tendances saisonnières de la couverture de neige en Ontario, de 1980 à 2010, selon les relevés de télédétection

Les tendances historiques de température et de précipitations ont largement servi à évaluer les effets éventuels du changement climatique en Ontario, mais on a accordé moins d'attention aux tendances touchant la couverture de neige. La couverture de neige saisonnière influence fortement le climat de l'Ontario; elle est un élément clé de l'équilibre hydrique et, en même temps, régit le profil hydrographique annuel (moment et ampleur de l'écoulement fluviatile), en plus d'influer sur les processus de l'écosystème et la dynamique des populations aquatiques et terrestres ainsi que sur l'approvisionnement en eau, la sécurité publique et les activités de loisirs. Les prévisions de changements touchant l'étendue et le volume de neige en réponse à un climat changeant ne sont pas évidentes, car les chutes de neige et la couverture neigeuse dépendent à la fois de la température de l'air et des précipitations. Même si nous disposons d'évaluations mondiales et continentales des changements dans la couverture de neige, la présente étude visait à documenter la variabilité et les changements dans l'équivalent eau-neige (EEN) et l'étendue de la couverture neigeuse (ECN) en Ontario au cours de la période climatique normale récente (1989-2010). L'étendue de la zone d'étude et le volume des enregistrements de données requis aux fins de l'analyse justifiaient le recours à des produits reposant sur les satellites. Plusieurs indicateurs ont servi à évaluer les changements dans l'état du manteau neigeux et des bassins hydrographiques secondaires à l'échelle de la province, et le test non paramétrique de Mann-Kendall (MK) a permis de déceler les tendances monotones de l'EEN et de l'ECN et les variables climatiques pour les 30 années de la période d'étude.

Nous avons observé une tendance significative à la baisse de ≈-9 mm ou -6,4 % par décennie dans l'EEN maximal de l'année hydrologique pour la province. Les tendances relatives aux bassins hydrographiques secondaires indiquaient i) que les tendances négatives dominent (78 %); ii) qu'aucune tendance positive n'était importante; iii) que plusieurs bassins hydrographiques affichaient des tendances négatives au coefficient de confiance de 90 et 95 %, y compris une bonne partie du Nord-Ouest de l'Ontario. Le taux de changement observé dans l'EEN maximum des bassins hydrographiques affichant des tendances négatives importantes allait de -1,2 à -2 mm par an, pour une moyenne de 1,77 mm. Ces taux sont associés à des changements trentenaires de 36 à 60 mm, soit de 5 à 10 % des précipitations annuelles dans ces bassins hydrographiques.

D'étroites relations étaient observables entre l'EEN et les variables climatiques des bassins hydrographiques secondaires. Mentionnons notamment le rapport de l'EEN saisonnier maximal aux précipitations totales en tant que fonction de la moyenne saisonnière de la température atmosphérique minimum. Une zone de transition a été

observée en ce qui a trait à la température atmosphérique saisonnière moyenne au-delà de laquelle la proportion de pluie dans le total des précipitations augmente et l'EEN diminue. Les bassins hydrographiques les plus exposés aux changements les plus marqués de l'EEN au vu de modestes changements de la température atmosphérique et des précipitations étaient ceux situés dans la zone de transition et proches de la limite inférieure (c.-à-d. -6,8° C). La forte relation négative appuie une estimation d'ordre un de l'EEN : coefficient total de précipitations compte tenu des prévisions futures de la température atmosphérique et de la délimitation des régions utilisant les isothermes indiquées où l'accumulation de neige est plus exposée à un climat en réchauffement.

Même si les estimations de l'EEN maximum dérivées de Globsnow offraient un indice relativement stable de l'évolution des conditions nivales en Ontario, l'interprétation des données de l'ECN est devenue difficile en raison de la discontinuité des enregistrements de données climatiques. Il y a eu après 2000 une détection de neige précoce et de pertes précoces de la couverture de neige totale dans l'ECN, mais il n'est pas possible de savoir clairement quelle est la part de ce décalage dans le temps qui est attribuable aux changements dans les précipitations et la température comparativement aux changements intervenus dans la technologie de télédétection.

Les auteurs fournissent des recommandations dans le sens d'un supplément d'analyses et de perfectionnements pour valider les résultats, quantifier l'incertitude dans les paramètres de mesure, obtenir de meilleures données sur l'étendue de la couverture de neige et appliquer les résultats à des activités précises de gestion des ressources.

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Contents

1.0 Introduction

While historical trends in temperature and precipitation have been widely used to assess potential effects of climate change in Ontario, trends in snow cover have received less attention. Nearly all of Ontario's land mass is snow covered for some of the year while there is total loss of snow cover in the summer. Seasonal snow cover influences climate, the hydrologic cycle, biogeochemical cycling, ecosystem processes, and animal behaviour and adaptation. Snow cover also affects human well-being by providing opportunity for recreational activities and creating potential environmental hazards related to blowing snow (transportation), snow loading (infrastructure), and flooding (infrastructure and private property). Thus, seasonal snow cover has both benefits and costs that affect Ontario's economy.

Snow has a high surface albedo which modifies the surface energy budget, affecting weather (short term) and climate (long term). For example, snow on the ground or in tree canopies reflects much of the incoming solar radiation back into space (EEA 2012). As snow melts, more of this energy is absorbed by these surfaces and the heat given off increases air temperature that, in turn, accelerates melt (i.e., creates a positive feedback loop). Snow cover is also a strong insulator and regulates the transfer of heat between the atmosphere and the ground (Stieglitz et al. 2003). Changes in the timing, duration, density, and depth of snow strongly influence how the air temperature signal penetrates the ground (ground heat flux), which is important for development and maintenance of permafrost and soil respiration (Stieglitz et al. 2003). Permafrost soils sequester significant organic carbon and its thaw may increase carbon dioxide emissions and accelerate climate change (Schuur et al. 2009). Melting snow also delivers heat to the soil, and potential changes in the regulation of soil moisture storage, latent heat flux, and ground insulation can threaten ecosystem structure and stability. Thus, a decrease in snow cover can amplify the effects of climate change (Flanner et al. 2011, Cohen et al. 2014).

Melting snow recharges soil moisture and surface water storage (e.g., lakes and wetlands), produces the most significant annual runoff event in Ontario's streams and rivers, and is a key component of the water balance in Ontario watersheds. The storage and redistribution of water from winter to spring influences how water is managed both as a resource (e.g., volume of reservoirs for waterpower production) and as a hazard to life and property (e.g., road crossings, flood plain mapping).

Snow is also important to Ontario's wildlife (Warren et al. 1998). Newton et al. (2018) summarized several wildlife studies that have used the Snow Network for Ontario Wildlife (SNOW). Snow characteristics directly affect ungulate population dynamics. For example, snow depth is the most important variable of winter severity that influences the movement and forage access of white-tailed deer (*Odocoileus virginianus)* and decreased snow depth at the northern edge of their distribution may result in a northward expansion of their range (Kennedy-Slaney et al. 2018). Kolenosky (1972) used snow depth and snowpack characteristics to help explain predation of white-tailed deer by wolves (*Canis lupus*) in east-central Ontario. Brown (2011) found a significant but weak negative relationship (r^2_{adj}=0.15, p-value=0.017) between calf recruitment and snow depth for moose (*Alces alces*) in Ontario. In aquatic ecosystems, snowmelt increases flow in streams and rivers and water levels in lakes, which provides a strong environmental cue that is imbedded in the life history of many aquatic species. Snowmelt moderates water temperatures, sustains habitat quantity and quality, couples aquatic ecosystems with their riparian areas, and is important for nutrient cycling (Dove-Thompson et al. 2011).

Expected changes in the extent and volume of snow in response to a changing climate is complicated because snowfall is a function of changes in both air temperature and precipitation (Räisänen 2008). In addition, snow cover is a spatially and temporally integrated response to snowfall and snowmelt events (Brown and Mote 2009). In general, changes to snow cover in southern locations are expected to be related more to changes in air temperature. This includes effects on precipitation phase and more frequent winter melt events that decrease snow cover duration (SCD) and snow water equivalent (SWE). The former will be most prevalent in shoulder months (Oct-Nov, Mar-Apr) where increases in air temperature will increase the proportion of precipitation falling as rain. In more northern locations where increases in air temperature will occur below 0℃, changes are expected to be related more to increases in atmospheric water vapour and precipitation, increasing SCD and SWE.

Warmer winter air temperature may inhibit lakes from freezing over, particularly the Great Lakes, making more moisture available to the atmosphere during the mid-winter months when warmer air temperatures will increase the capacity of the atmosphere to hold water vapour. In transitional areas, an increase in mid-winter SWE may offset decreases in SCD and maintain snow cover longer than expected. Although SCD may decrease, greater SWE combined with faster melting may increase the risk of more spring runoff. While higher air temperatures are often associated with increased rainfall and decreased snowfall, local climatologies may obscure expected changes. In some areas of the province snowfall may increase, at least temporarily. In addition, direct relationships between warming air temperatures and changing snow conditions can be obscured by regional and temporal climate variability related to oceanic teleconnections and changes to jet stream behaviour (Brown and Goodison 1996, Cohen et al. 2014. Mudryk et al. 2018). Examining how SCD and SWE have been changing in Ontario is needed to increase understanding of how these processes are reflected in regions across the province.

Annual and interannual variations in snow cover extent (SCE), specifically SCD are key indicators of climate change (Robinson et al. 1993, Brown and Mote 2009, Estilow et al. 2015). Analyzing trends over time provides insight to understand whether climate is changing beyond the typical year-to-year variability. Understanding baseline conditions in the context of existing trends supports interpretation of potential vulnerabilities of a changing climate. Improved information on snow cover will inform understanding of the potential impacts and risks related to changing snow conditions in Ontario.

2.0 Background

The earliest snow survey recorded in the provincial snow survey database maintained by the government’s Surface Water Monitoring Centre (SWMC) was in Ear Falls, Ontario, in 1933 (Beaton 2018, SWMC, pers. comm.). Currently, manual surveys of snow depth and snow water equivalent are conducted bi-weekly in winter at 270 locations throughout the province to support flood forecasting. Surveys are conducted by Ministry of Natural Resources and Forestry districts, conservation authorities, Ontario Power Generation, and Parks Canada. Snow depth has been collected at 90 Environment and Climate Change Canada climate stations in Ontario using automated acoustic sensors, with 74 stations currently active (Gallant 2018, SWMC, pers. comm.). Weekly manual measurements at snow courses are also collected at ≈59 locations across the province as part of the Snow Network for Ontario Wildlife (SNOW; Warren et al. 1998). Earliest satellite observations of SCE in Ontario were available beginning in 1972 with the weekly National Oceanic and Atmospheric Administration (NOAA) snow charts (Robinson et al. 1993) and since 1979 for SWE (Takala et al. 2011). The difference in the satellite records reflects that SCE was originally derived from optical data while SWE is derived from passive microwave data. Satellite observations of snow characteristics have shown value in providing greater temporal and spatial coverage and more consistent estimates compared with ground measurements, although ground-based measurements remain vital for validation.

2.1 Objective

The purpose of this study was to elucidate historic variability, trends, and regional patterns in Ontario's seasonal snow cover. This information helps to identify and understand the risks associated with changing snow conditions in the province, including changes in SWE and SCE. The study replicates and extends the analyses on SWE and SCE by EEA (2012, 2017) in an annual indicator-based report on climate change, impacts, and vulnerability in Europe that includes a comprehensive assessment of the cryosphere (all permanent or seasonal snow and ice on land; in the seas, rivers and lakes; and in the ground).

Specific objectives of this study included documenting and interpreting changes in i) the maximum seasonal SWE, ii) the maximum SWE prior to melt, iii) the timing of snow cover onset in autumn, iv) the timing of melt in spring, and v) the extent of snow covered area.

Snowfall and snow cover are a function of changes in both air temperature and precipitation (Räisänen 2008, Brown and Mote 2009) and large-scale responses of snow cover to a warming climate are linked to projected changes in these variables (IPCC 2014). Thus, changes in monthly air temperature and precipitation were analyzed along with the snow data to help understand the processes driving temporal and spatial patterns of snow in the province.

3.0 Methods

Satellite-based products were used for the analysis because they provide observed estimates of the historical snow cover record, a consistent and reproducible method, and full spatial coverage for the province. The selected products also provide the long-term time series necessary to produce meaningful statistics on trends and variability for studying changes in snow characteristics and climate (Takala et al. 2011). No validation was conducted on the satellite-based products used in the study, but numerous validation studies exist that address the data limitations (e.g., Brown and Derksen 2013, Hancock et al. 2013, Estilow et al. 2015, Mudryk et al. 2015, Larue et al. 2017). Change in snow cover characteristics can be assessed without being hampered by issues related to accuracy of the estimates by focusing on long-term measures of a variable that has a known and consistent bias or known changes in the bias. To assess specific effects of changes in the magnitude of these variables (i.e., mm of water available to refill reservoirs), the sources and magnitude of biases would need to be addressed, which is outside the scope of this report.

Analysis was focused primarily at provincial scale. Where resolution of the data allowed, assessments were also conducted at the secondary watershed scale to elucidate regional differences. This scale is considerably smaller than the continental and hemispherical scales often associated with similar assessments using the same data products. Water years (Oct 1 to Sep 30) for the period 1980 to 2010 were used in the assessment. For example, the 1981 water year includes data from Oct 1, 1980 to Sept 30, 1981. In this case, snow cover data was assessed for the months of October thorough May for each water year, also referred to in this study as a season (e.g., maximum seasonal SWE). The 30 years of data used in the study provides a sufficient length of record to assess trends and follows the World Meteorological Organisation recommendation of using the most recent 3 decades to represent a benchmark or reference against which current and future conditions can be assessed (WMO 2017).

3.1 Snow water equivalent

Monthly SWE data was acquired from the European Space Agency's Globsnow data product (http://www.globsnow.info/swe/) in NetCDF format (Takala et al. 2011). SWE is the product of snow depth (SD) and snow density (ρ) and is the equivalent depth of water (mm) that would result if the snowpack was melted in place. Globsnow has shown consistent performance with stable uncertainty characteristics over its entire 30+ years of record (Luojus et al. 2014). The Globsnow SWE record is derived using a data assimilation approach, based on methods by Pulliainen (2006) and Takala et al. (2011), that combines space-borne passive radiometer data (SMMR, SSM/I, and SSMIS) with ground-based synoptic observations of snow depth. The method uses the difference in brightness temperatures (T_B) of 2 wavelengths of radiation naturally emitted from the ground. Shorter wavelengths (≈19 GHz) are insensitive to snow and pass directly through the snowpack. However, longer wavelengths (≈37 GHz) are scattered by snow grains and therefore sensitive to snow depth and structure. Differences between the brightness temperatures are measured over a ≈25 km^2 grid cell, with larger differences associated with higher SWE.

The SWE record is produced daily for the northern hemisphere. A weekly aggregated SWE is calculated each day using the daily product and a 7-day sliding window whereby the SWE estimate for the current day is calculated using the mean of the previous 6 days and the current day. This approach effectively smooths out the noise in the daily data (Takala et al. 2011). A monthly SWE product is calculated using the average and maximum SWE from the weekly aggregated data for each calendar month. Each monthly NetCDF file contains 2 variables: monthly mean SWE and monthly maximum SWE for the northern hemisphere. These variables were converted to a raster format using ArcGIS.

An ArcGIS shapefile of the province's boundary (OMNR 2008) was re-projected to match the native raster files and to clip out the raster cells covering Ontario. The Ontario boundary shapefile was buffered by 25 km to ensure all pixels that partially fell within Ontario would be selected. Areas denoted as water by Globsnow (i.e., values of -1) were excluded from the analysis. The subsequent clipped rasters covering an area of 977,500 km^2 were re-projected into Nad83 Lambert azimuthal equal area for further analysis. An example of a monthly GlobSnow data product is shown in Figure 1. In addition to provincial summaries of SWE, the spatial resolution of the Globsnow product allowed summaries based on Ontario's 28 secondary watersheds to explore regional variability (Figure 2).

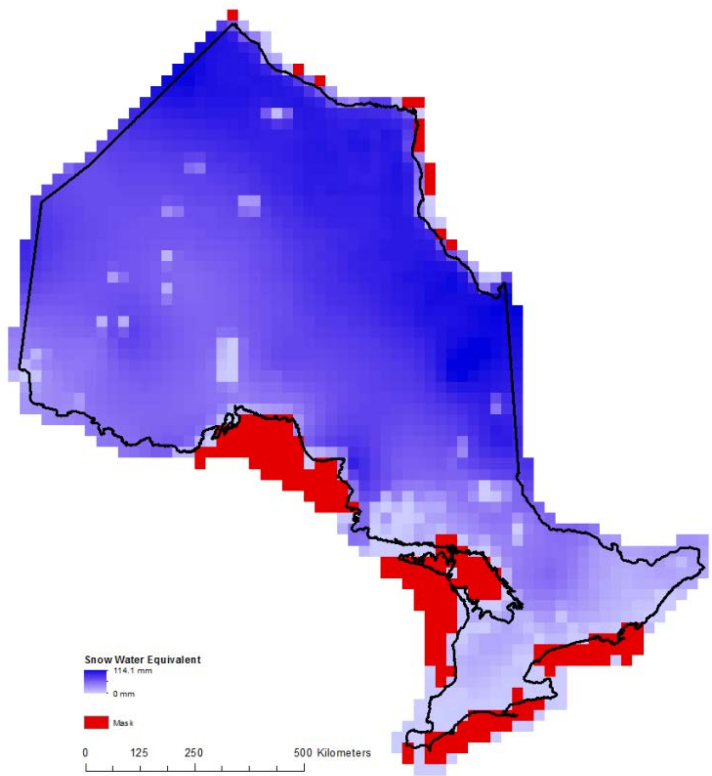

Figure 1. Example of Globsnow data for Ontario, March 1995. Land areas not covered by a pixel were denoted as water in the Globsnow product and masked out; larger inland lakes not masked out are evident as having lower snow water equivalent (SWE) values relative to adjacent areas.

3.2 Snow cover extent

To assess the length and timing of snow cover, monthly and weekly snow cover extent (SCE) data for Ontario was obtained from the Northern Hemisphere (NH) Snow Cover Extent (SCE) climate data record (CDR) developed by the National Oceanic and Atmospheric Administration (NOAA) curated by Rutgers University Global Snow Lab (http://climate.rutgers.edu/snowcover/) (Robinson et al. 2012, Estilow et al. 2015). The

Figure 2. The 28 secondary watersheds of Ontario used to assess regional variability in the Globsnow snow water extent record.

SCE CDR is weekly snow cover extent data digitized into a polar stereographic projection. Its spatial resolution varies by latitude, with a resolution of 190.6 km at 60° latitude (Estilow et al. 2015). The weekly data is based on daily observations with the SCE recorded on the last day of the map week that was cloud free (Robinson and Frei 2000). The SCE is recorded as a binary variable (snow/no snow) for each grid cell and, before 1999, was manually derived by trained meteorologists using multiple visible-band satellite observations. In this case, cells that were interpreted to be at least 50% snow covered were designated as snow covered and cells less than 50% covered designated as snow free (Robinson 1993). From June 1999 onward, the CDR is based on daily measurements from the higher resolution (24 km) Interactive Multisensor Snow and Ice

Mapping System (IMS) (Ramsay 1998, Helfrich et al. 2007). To maintain a consistent record, the original weekly CDR grid cell resolution is used and is designated as snow covered if ≥42% of the IMS land pixels in the cell indicate snow (Estilow et al. 2015). Land pixels are identified using a binary land/water mask developed by Robinson et al. (1993) and adopted by NOAA. The 42% threshold using Monday IMS areas was found to best match the weekly SCE areas when historical and IMS SCE methods were compared for an overlapping period between June 1997 and May 1999 (Estilow et al. 2015). Monthly SCE is determined by weighting the weekly areas based on the number of days of a map week falling in a given month and calculating an average (Robinson 1993, Robinson and Frei 2000). Allchin and Déry (2017) preferred the term snow-dominated area to recognize that a grid cell was not necessarily 100% snow covered.

The coverage of the SCE CDR gridded data product for Ontario is shown in Figure 3. Land areas of the province not covered were identified as water pixels in the NOAA mask or had >50% of their area outside the Ontario border. For grid cells that included land and water, only land areas were used to determine if a grid cell was snow covered. For example, for a SCE cell to indicate snow cover, at least 42% of the IMS land cells in the cell must have snow values (Estilow et al. 2015).

Figure 3. Distribution of the snow cover extent climate data record grid cells across Ontario.

3.3 Climate data

Historical gridded data sets of total monthly precipitation (mm), mean monthly temperature (℃), and mean monthly minimum temperature (℃) at 10 km spatial resolution were acquired from the Canadian Forest Service (CFS) for each water year season of the 30-year study period. The grids were derived by interpolating Environment Canada climate station data using ANUSPLIN as described by McKenney et al. (2006).

3.4 Data processing

Several indicators were used to assess changes in SWE and SCE (Table 1). Mean monthly maximum SWE for the period of record was calculated for the province and the 28 secondary watersheds of Ontario using zonal statistics in ArcGIS Spatial Analyst and the respective ArcGIS shape files (OMNR 2010). These were used to calculate the maximum water year SWE and the March maximum SWE. Similarly, total monthly precipitation, mean monthly temperature, and mean monthly minimum temperature were calculated for each secondary watershed for each season for the study period using the historical climate grids.

Table 1. Summary of indicators for snow water equivalent (SWE) and snow cover extent used to assess changing snow conditions. (DOY=day-of-year)

Attribute/Indicator	Description
Snow water equivalent	
Maximum SWE	The maximum value observed in the monthly maximum SWE data for the water year.
March maximum SWE	The maximum value for March observed in the monthly maximum SWE data for the water year.
Snow cover extent	
Snow cover extent	Mean areal snow cover extent for the province for a month or season.
Start of snow cover	Water year DOY for the first day of the first week of snow cover.
End of snow cover	Water year DOY for the last day of the last week of snow cover.
Season length	The number of weeks between the first and last occurrence of snow cover in a water year and may include weeks where no snow cover was recorded.
Weeks snow covered	The number of weeks in a water year with snow cover; does not include weeks without snow cover.
Continuous snow cover	The number of weeks with continuous snow cover

General snow cover conditions were examined using the mean monthly and mean seasonal snow cover extent. Timing of the initial and final occurrence of snow cover was calculated using the water year day-of-year (DOY). The start of snow cover was calculated as DOY for the first day of the first week of snow cover. Similarly, final occurrence of snow cover was calculated as DOY for the last day of the last week of snow cover. Indicators of snow cover duration measured in weeks include i) season length, ii) time snow covered, and iii) length of continuous snow cover. The coarse resolution of the SCE CDR precluded summaries using secondary watersheds because the grid cells were large relative to the size of the watersheds. As an alternative, individual grid cells were used to examine regional variability in SCE. Because of the large grid cell area over which the data is aggregated, results are best interpreted based on larger spatial patterns rather than the response of individual cells.

The non-parametric Mann-Kendall (MK) test was used to detect monotonic trends in SWE, SCE, and climate variables for the 30-year record. A conservative version of a modified MK (Yue and Wang 2004) was used for time series with significant serial correlation, estimated using Anderson (1942). Time series with serial correlation increases the chance of detecting a significant trend when one does not exist because the number of observations is artificially inflated. Where serial correlation was detected in a time series, both the unadjusted and adjusted p-values are provided. Trend lines were fitted using the Sen's slope estimator method (Sen 1968) to estimate the magnitude of change over the study period.

Relationships between SWE and SCE and climate variables were examined using multiple regression and multivariate adaptive regression splines (MARS).

4.0 Results

4.1 Snow water equivalent

Decreasing trends were observed in both the water year maximum SWE (≈-9 mm or -6.4% per decade) and maximum March SWE (≈-8 mm or -5.5% per decade) for the province but only the former was significant ($p<0.1$) (figures 4 and 5, respectively). The maximum SWE occurred in March in 21 of the 30 years and in February the other 9 years. January, February, and May were the only months with significant negative trends ($p<0.1$) in maximum SWE (Appendix 1).

Mean monthly maximum SWE for the 28 secondary watersheds in Ontario shows variability in magnitude, timing, and rates of accumulation and ablation that highlight regional differences driven by latitude and moisture sources (Figure 6). These apparent patterns were investigated using a k-means cluster analysis on the mean monthly SWE, mean monthly maximum SWE, and the mean SWE coefficient of variation to group the secondary watersheds into 5 distinct classes (Figure 7).

Watersheds in the south accumulate snow more gradually in autumn, have less SWE, and melt snow faster in spring (Class 1). Exceptions include secondary watersheds in traditional snowbelt areas (e.g., eastern Georgian Bay) and in the Ottawa Valley (e.g., central Ottawa, lower Ottawa, and upper St. Lawrence), which accumulate twice as much SWE but lose it by the end of April (Class 2). Watersheds in northwestern Ontario (Class 4) accumulate more SWE in autumn and retain a snowpack later in spring (mean May SWE of ≈21 mm), owing to the colder air temperatures in the shoulder seasons at these latitudes. Watersheds in northeastern Ontario (Class 5) have slightly lower rates of accumulation in autumn compared to the more northern watersheds in Class 4 but accumulate the greatest SWE and have the greatest melt rates in spring. Class 5 also includes all secondary watersheds in the Moose River basin. Watersheds in Class 3 can

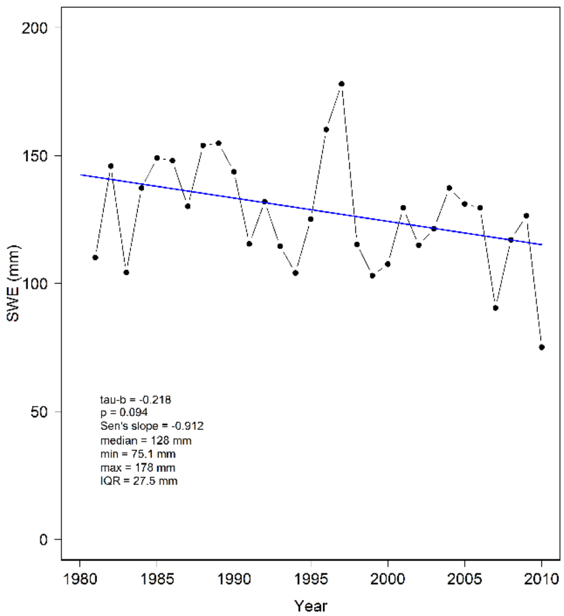

Figure 4. Satellite-derived mean water year maximum snow water equivalent (SWE) in Ontario.

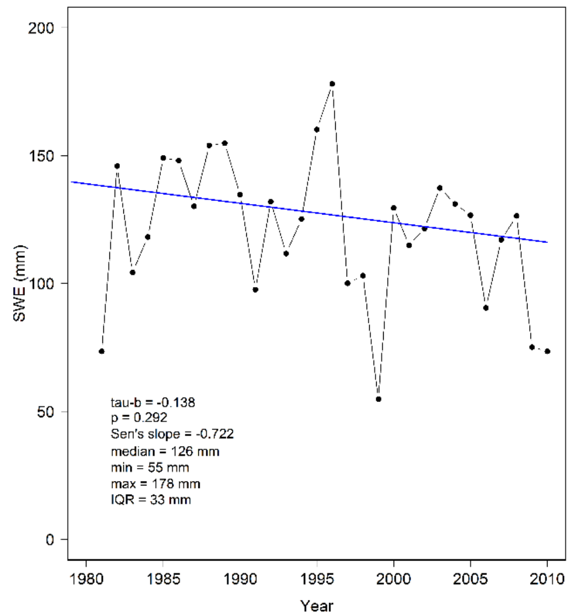

Figure 5. Satellite-derived mean water year March maximum snow water equivalent (SWE) in Ontario.

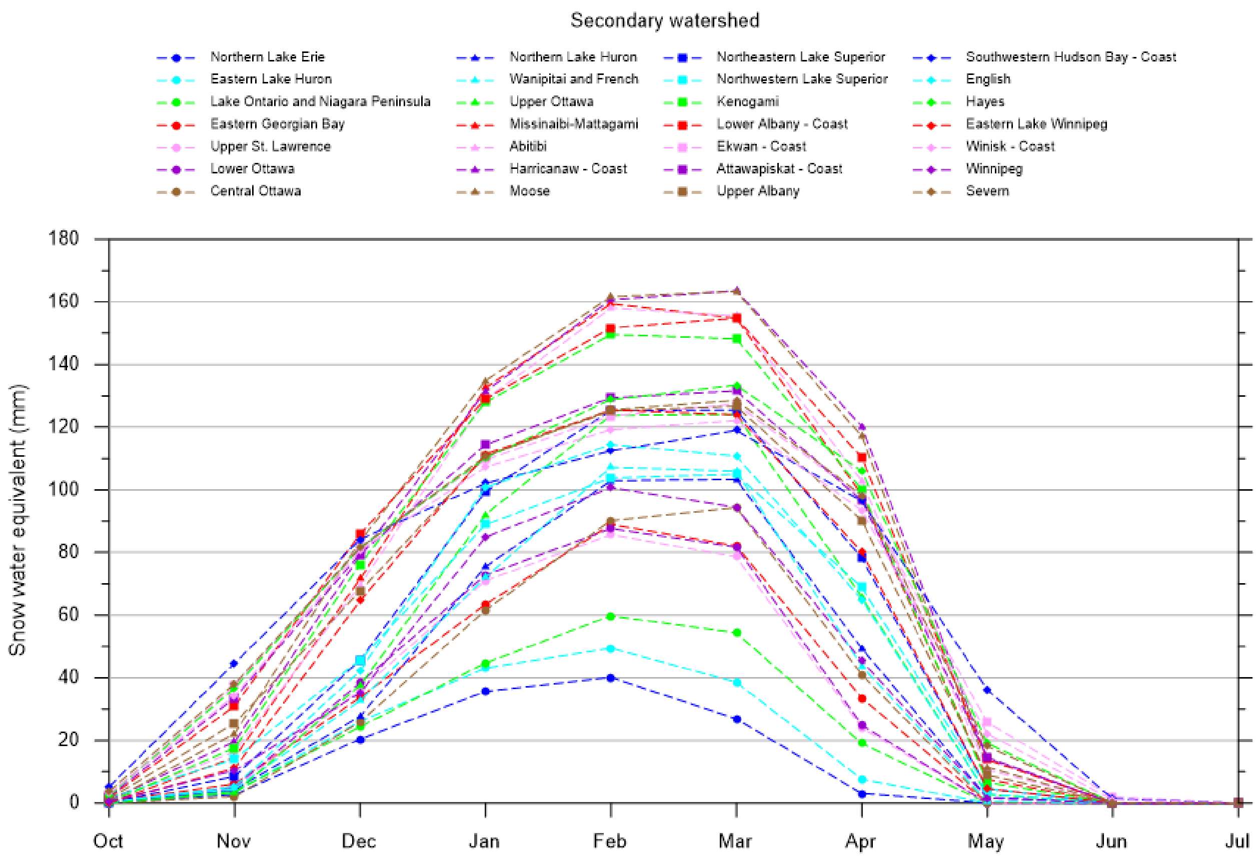

Figure 6. Mean monthly maximum snow water equivalent for 28 secondary watersheds for water years 1981 to 2010.

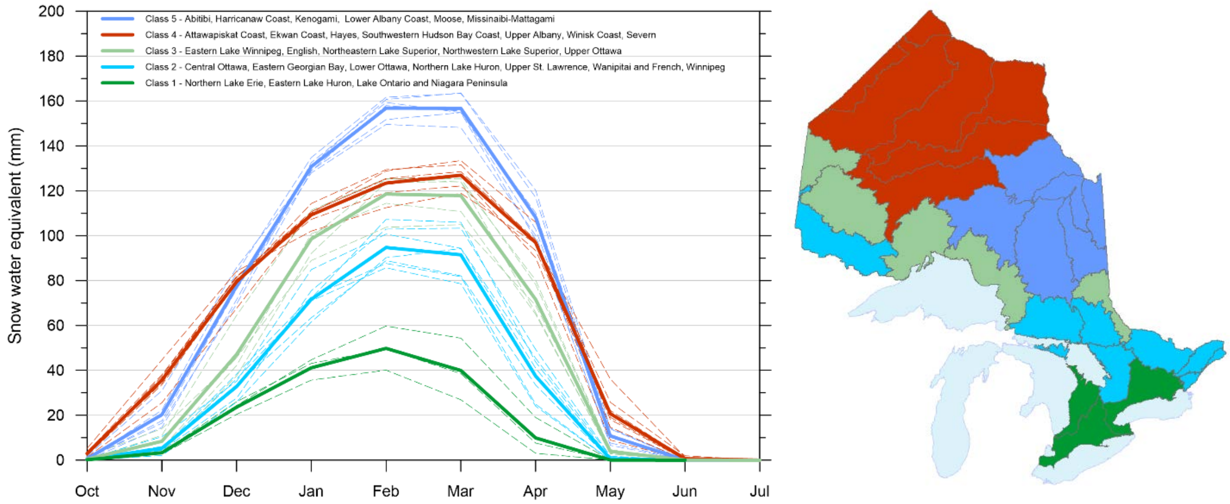

Figure 7. Mean monthly maximum snow water equivalent (SWE) for the 28 secondary watersheds in Ontario classified into 5 groups based on the mean maximum SWE, mean SWE, and mean SWE coefficient of variability (bold lines represent group means); map illustrates physical location of the classes.

be characterized as transitional, with autumn accumulation rates comparable to the more southern watersheds but maximum SWE that approaches that of the watersheds in Class 5. For 15 of the 28 watersheds, maximum SWE peaked in March with the remaining peaking in February. Ten watersheds had February and March maximum SWE within 2 mm of one another. Generally, the month with the maximum annual SWE transitions from February to March from southern to northern watersheds, with all Class 4 watersheds peaking in March.

Trends in the water year maximum SWE for the secondary watersheds are summarized in Figure 8 and detailed in Appendix 2. Although no definitive regional patterns were evident, it is noteworthy that i) negative trends dominated the province (78%); ii) no positive trends were significant; and iii) negative trends were observed for 32% of the watersheds (at 90 and 95% confidence levels), including much of northwestern Ontario. The average and max tau-b was -0.181 and -0.402 for negative trends and 0.034 and 0.122 for positive trends, respectively. Thus, not only were positive trends not significant, the correlations were considerably weaker relative to the strength of the negative trends. Those trends identified as significant were primarily in northern watersheds that flow into James and Hudson bays and have the largest maximum SWE in the province. The rate of change occurring in the annual maximum SWE in watersheds with significant trends, estimated using the Sen's slope, ranged between -1.2 and -2.0 mm per year, averaging -1.7 mm. These rates were associated with a 36 to 60 mm change in 30 years, which is 5 to 10% of the annual precipitation in the respective watersheds.

An examination of monthly trends in maximum SWE for each secondary watershed is provided in Appendix 3 and summarized in figures 9 and 10. Trends were negative for

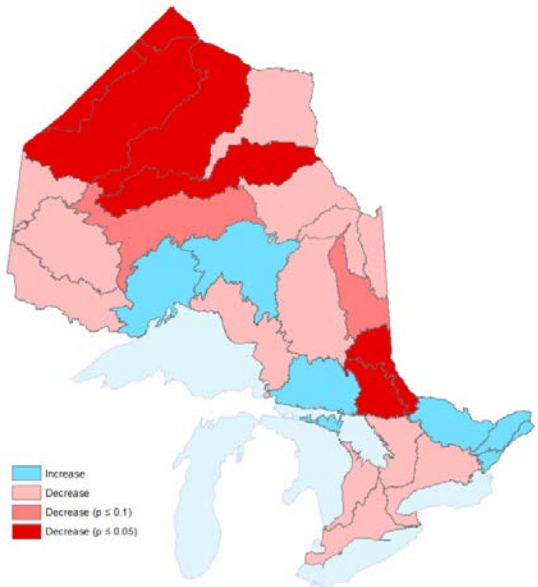

Figure 8. Trends in maximum snow water equivalent for secondary watersheds in Ontario for water years 1981 to 2010.

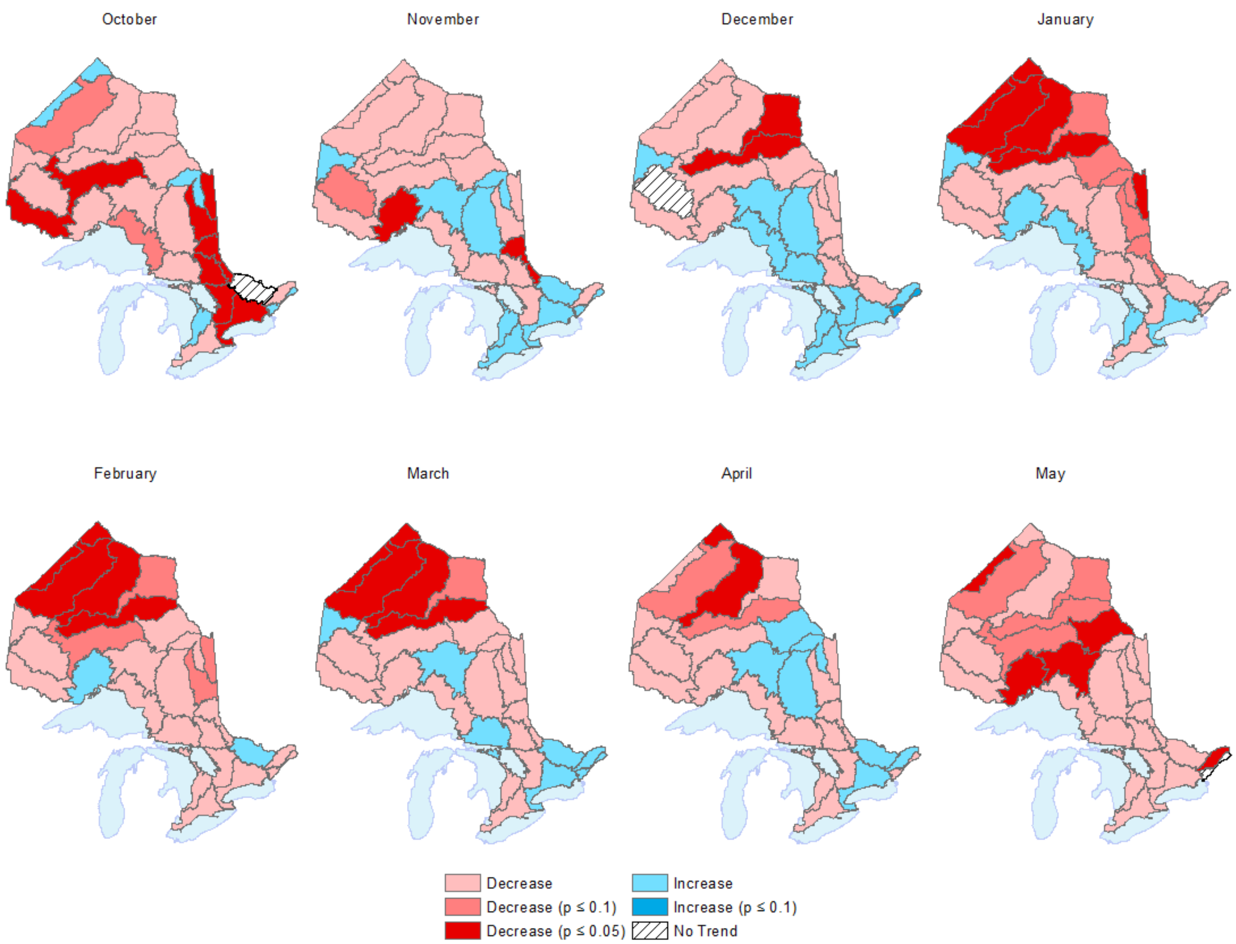

Figure 9. Trends in monthly mean maximum snow water equivalent for secondary watersheds in Ontario for water years 1981 to 2010.

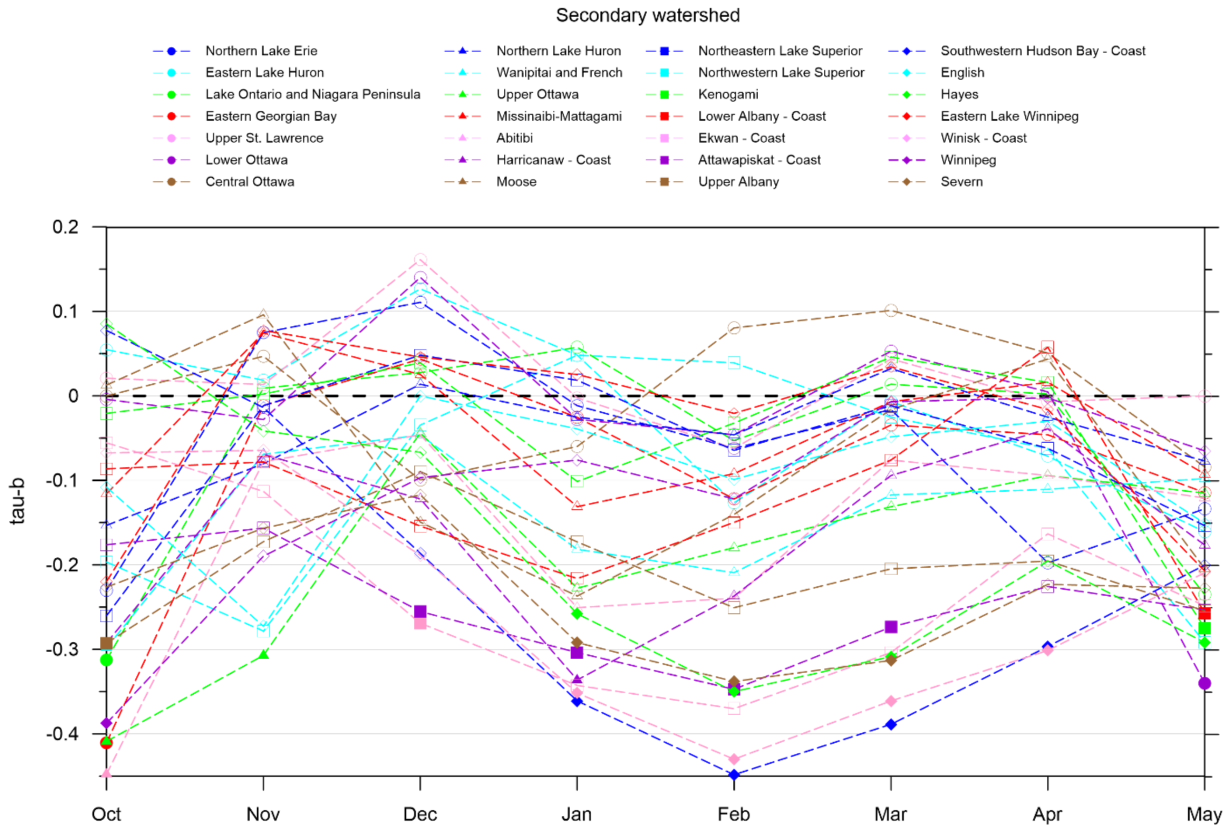

Figure 10. Trends in monthly maximum snow water equivalent shown by Mann-Kendall tau-b values for 28 secondary watersheds for water years 1981 to 2010. Solid symbols indicate a significant trend at the 90% confidence level.

78% of all monthly maximum SWE and 19% of those were significant ($p \leq 0.10$). Seven secondary watersheds with no significant trend in annual maximum SWE (Figure 8) had at least 1 month with a significant decreasing trend ($p \leq 0.10$), including the Kenogami which had a positive trend in annual maximum SWE (Figure 8).

Changes in monthly minimum air temperature (Figure 11) and total monthly precipitation (Figure 12) were investigated to determine if trends in climate forcing variables could explain observed trends in SWE and SCE. Monthly minimum air temperature was used because it produced the strongest correlations in multiple regressions compared with monthly mean and maximum air temperature. Generally, monthly minimum air temperatures across the province increased from 1980 to 2010 during the season and increased over much of the province in the shoulder months of October and May, which is more relevant to processes governing snow accumulation and melt in northern Ontario. Only decreasing trends in monthly minimum air temperature were significant. Both increasing and decreasing trends in monthly total precipitation were observed across the province, with the former being significant in more instances.

Many secondary watersheds had both increasing and decreasing non-significant monthly trends suggesting minimal change. Notable exceptions include northeastern Lake Superior with a decreasing trend in every month, 3 of which were significant, and northwestern Lake Superior with decreasing trends in all but 1 month. Also of interest are the increasing trends in southern Ontario in March and April, which align with

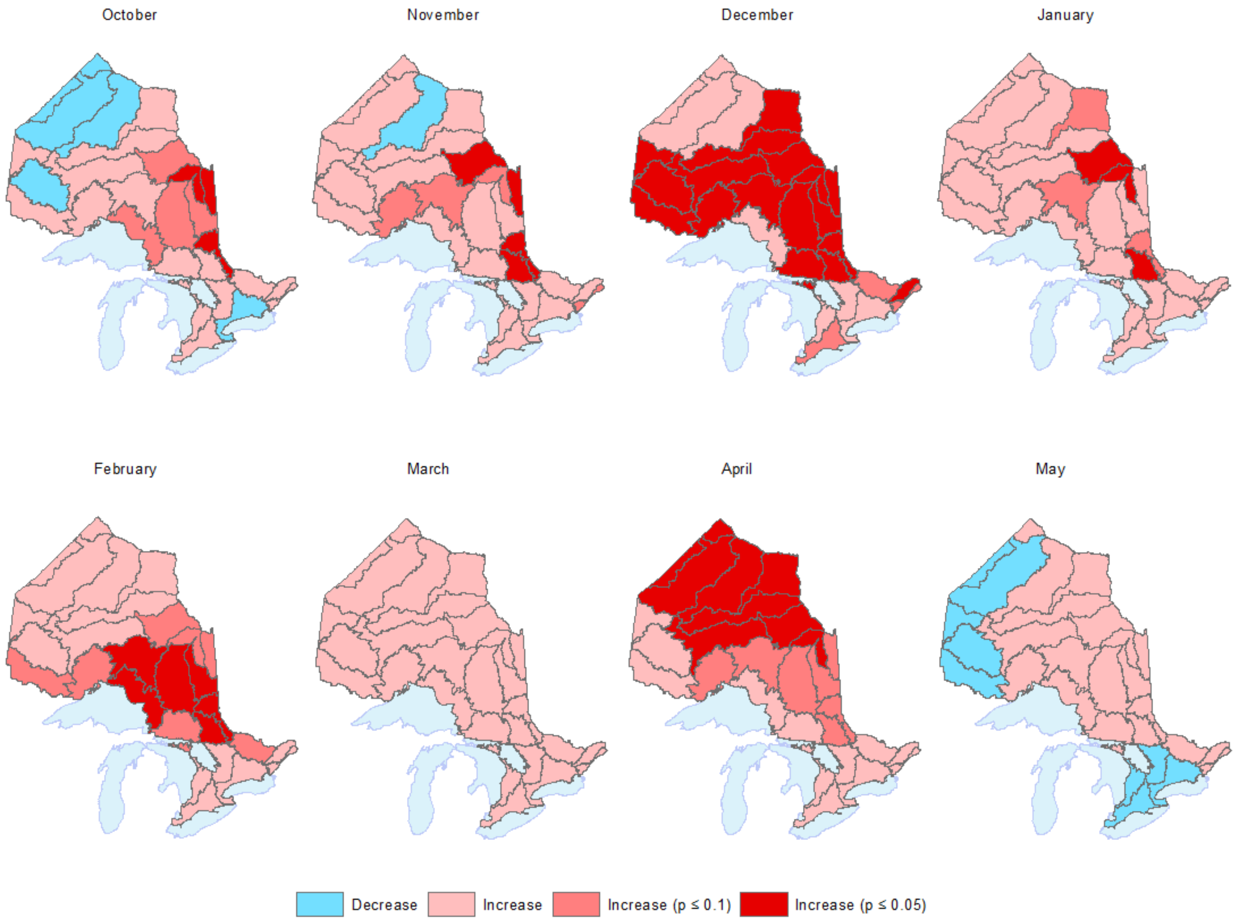

Figure 11. Trends in monthly minimum air temperature for secondary watersheds in Ontario for water years 1981 to 2010.

increasing air temperature trends. These trends may be associated with increased rain-on-snow events during spring melt that are often the mechanism for extreme high flow events.

The relationship among minimum air temperature, total precipitation, and annual maximum SWE using the mean of all the monthly values for each season over the 30-year record shows 2 distinct groups of watersheds separated by a transition zone between -6.8 ℃ and -4.8 ℃, identified using multivariate adaptive regression splines (MARS) (Figure 13). The plotting position of the sites illustrates that average seasonal precipitation and temperature generally decrease from south to north. Thus, the average winter precipitation and temperatures shown on the graph reflect provincial weather patterns. In cold, dry regions where mean minimum seasonal air temperatures are less than -6.8 ℃, total precipitation and SWE increase with increasing temperature. This may be caused by air masses with more capacity to retain moisture as temperature rises but temperatures are such that precipitation still falls primarily as snow. In warmer, wetter regions where mean minimum seasonal air temperature exceeds -4.8 ℃, total precipitation still increases with increasing temperature, although at a lower rate, but

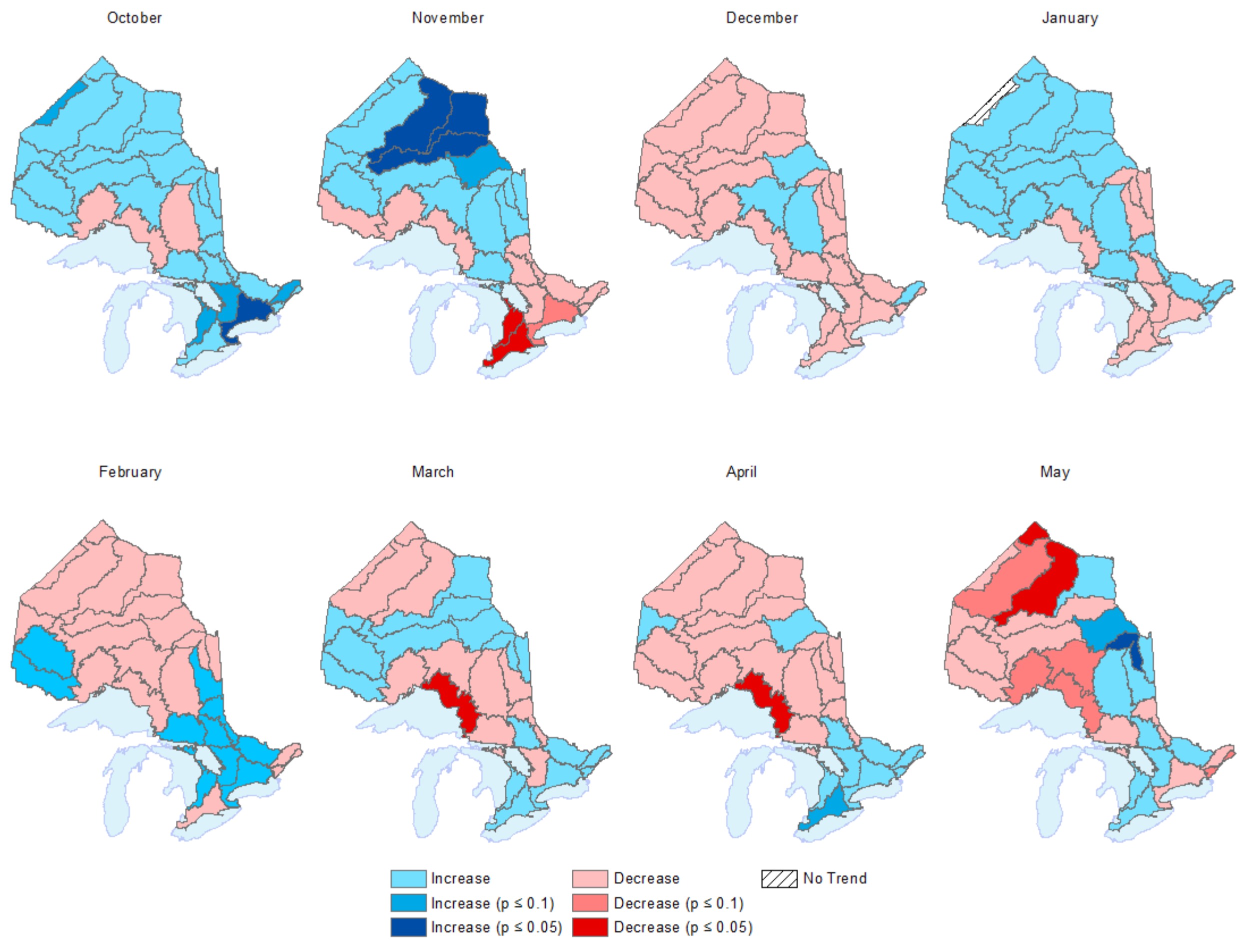

Figure 12. Trends in monthly total precipitation for secondary watersheds in Ontario for water years 1981 to 2010.

SWE decreases. This results from a higher proportion of rain in total precipitation, demonstrated by the strong negative relationship between minimum air temperature and the ratio of snow water equivalent (SWE) to total precipitation (Figure 14). Watersheds most vulnerable to the greatest changes in SWE for small changes in air temperature and precipitation include those in the transition zone and bordering the lower limit (i.e., -6.8 ℃). Values of SWE:total precipitation greater than 1 in Figure 14 could be attributed to several factors, including i) precipitation gauges undercatching snowfall and therefore underestimating total precipitation (English et al. 2017); ii) uncertainty in the gridded precipitation data, particularly in northern regions with fewer climate stations; and iii) error in the Globsnow SWE estimates.

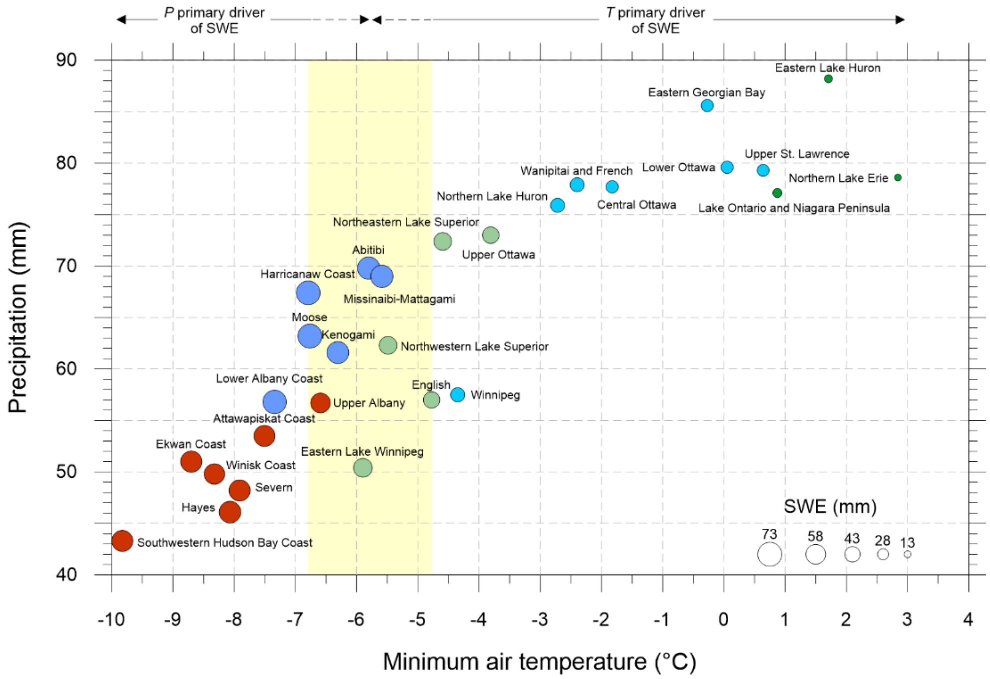

Figure 13. Relationship among mean seasonal total precipitation, mean seasonal minimum air temperature, and mean maximum seasonal snow water equivalent (SWE) for water years 1981 to 2010. Symbol colours refer to the classes identified in Figure 7 and the shaded area bounds the knot points identified in the multivariate adaptive regression splines (MARS) analysis (-6.8 ℃ to -4.8 ℃).

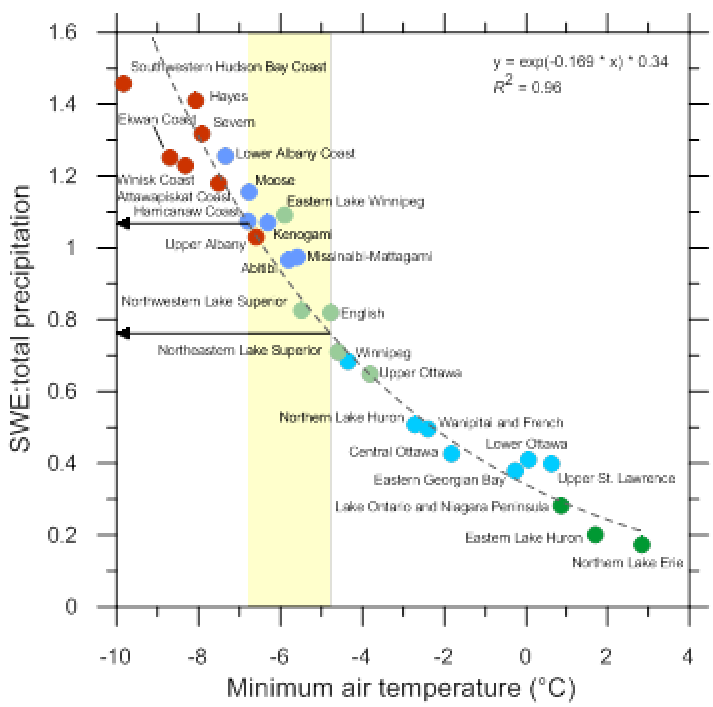

Figure 14. The ratio of maximum seasonal snow water equivalent (SWE) to total precipitation versus mean seasonal minimum air temperature for all secondary basins for water years 1981 to 2010.

4.2 Snow cover extent

Small positive trends in provincial maximum SCE were observed for each season, the largest being in autumn, but none were significant at the 90% confidence level (Figure 15). As expected, variability was higher in autumn and spring and lower in winter. To determine whether seasonal data was masking shorter-term signals, trends in SCE for individual months were also investigated (Figure 16). All monthly trends were positive except for May and no trends were significant at the 90% confidence level. The largest positive trend occurred in October. However, the low tau-b values for all months indicated weak monotonic relationships and suggested no change in SCE for the province over the 30-year period. January and February showed the least variation; this is when snow cover is at its maximum extent in the province. Obvious changes in the timing of snow accumulation in autumn and snowmelt in spring were also not observed.

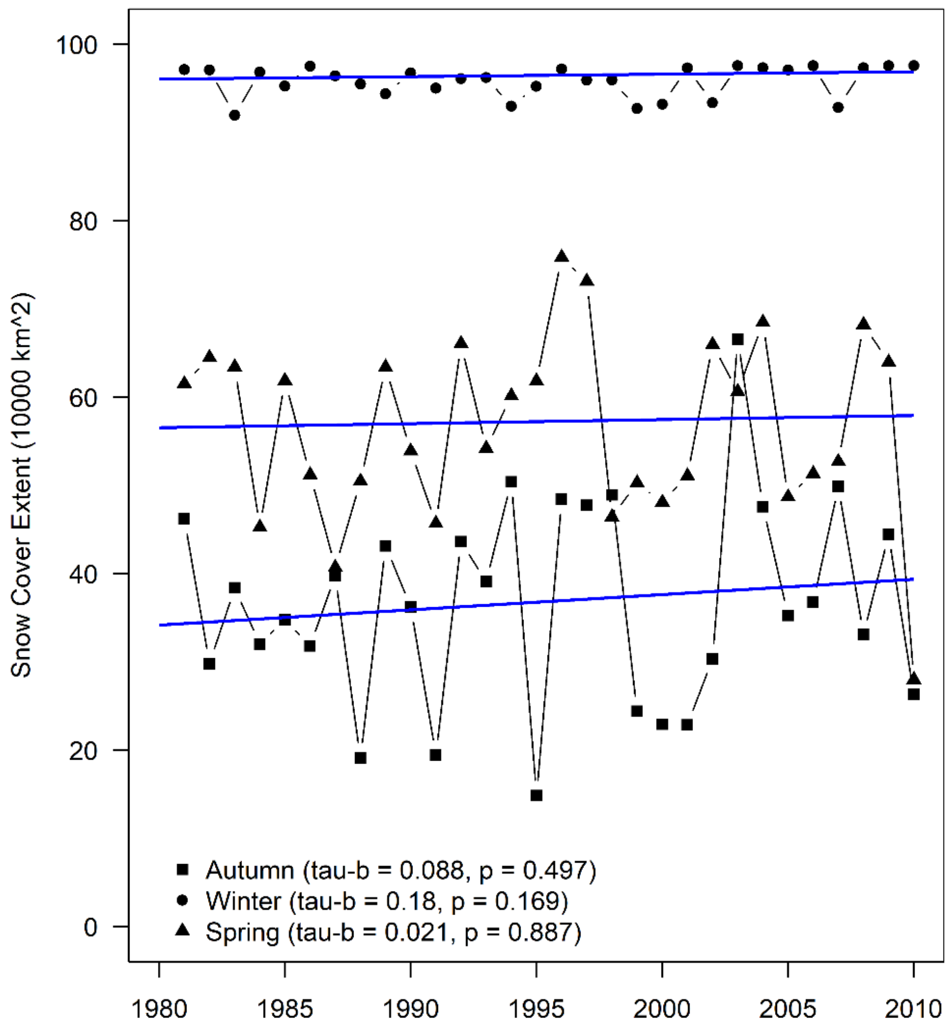

Figure 15. Trends in maximum snow cover extent for Ontario for autumn (October, November), winter (December–February), and spring (March–May) for water years 1981 to 2010.

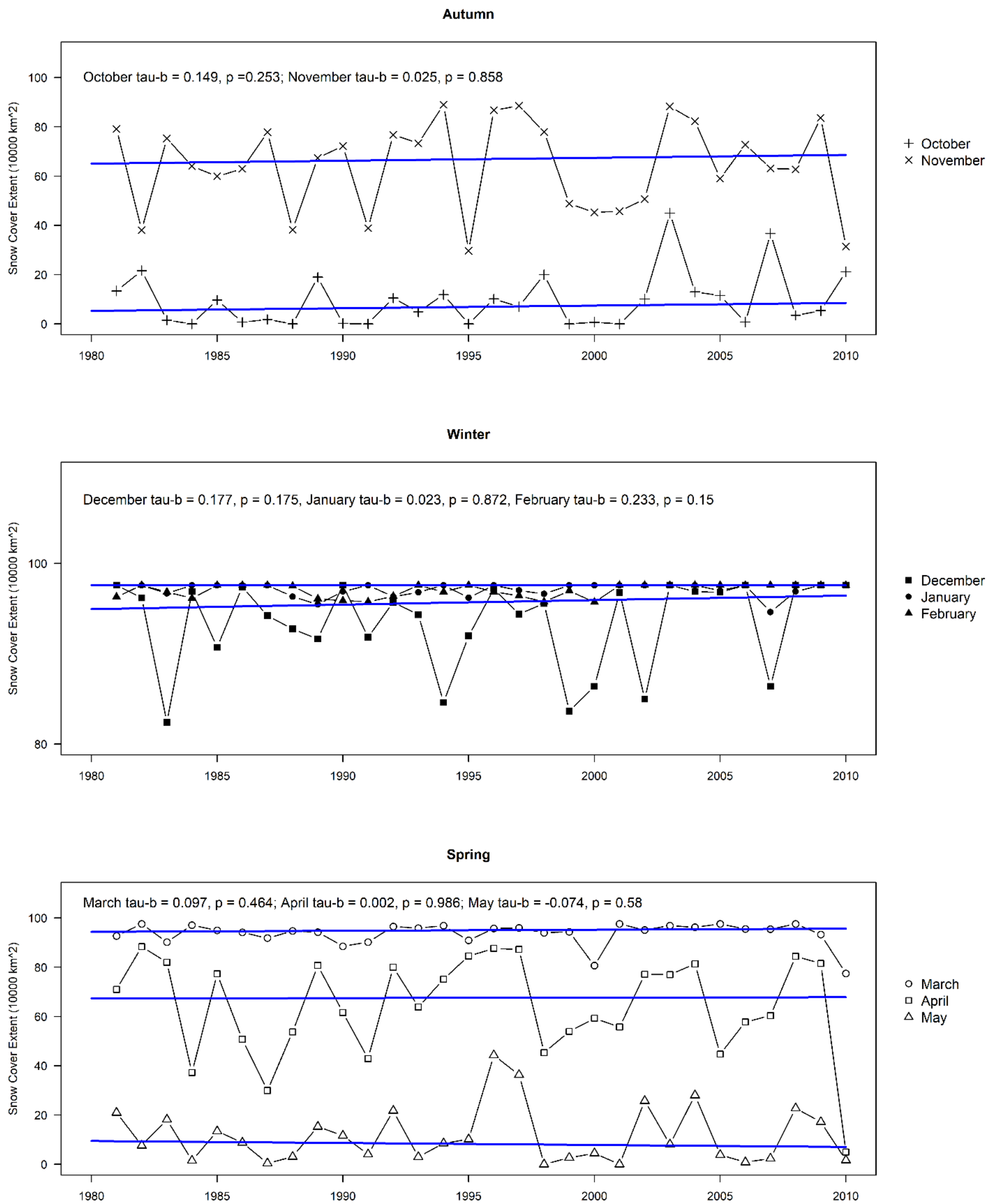

Figure 16. Trends in maximum snow cover (SCE) extent for Ontario by month for water years 1981 to 2010.

(Figure17) although indications of earlier snow detection and earlier snow cover losses were evident after 2000. This agrees with the stronger positive trends observed in October and the negative trends observed in May (Figure 16). No trends in the timing and duration of snow cover in individual SCE CDR grid cells were significant at the 90% confidence level (Figure 18). However, clusters of cells with similar increasing and decreasing trends hint at a regional variability that can be broadly defined by southern, central and northeastern, and northwestern Ontario.

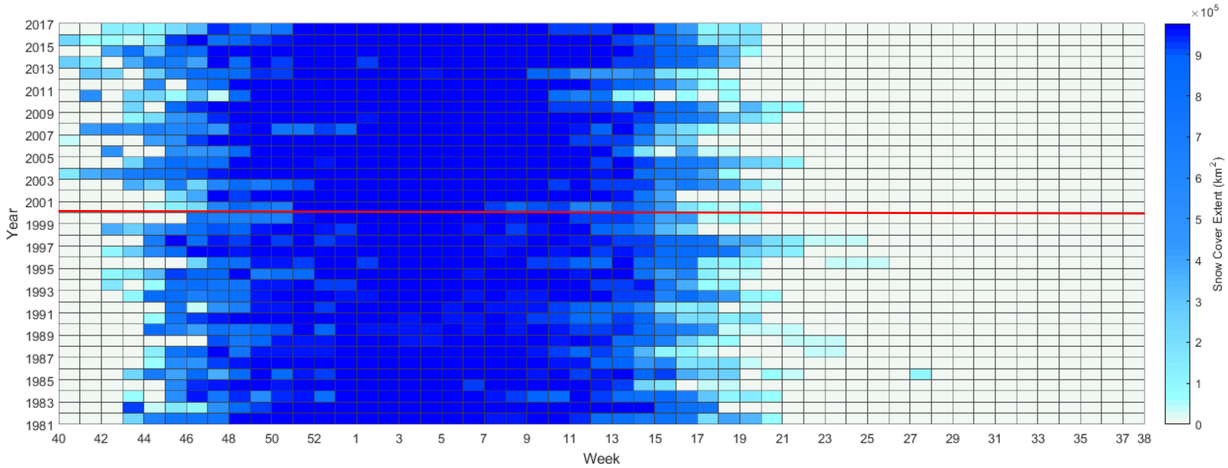

Figure 17. Weekly snow cover extent in Ontario using the snow cover extent (SCE) climate data record shown by week-of-year. The red line designates the change from determining SCE using visible-band satellite observations to using the Interactive Multisensor Snow and Ice Mapping System (IMS) sensor.

4.3 Variability in snow water equivalent and snow cover extent

The decadal coefficient of variation (CV) was used to determine whether the variability in SWE or SCE had increased over the 30-year period (Table 2). Only spring SWE showed increasing variability over the 3 decades while winter SWE and SCE were stable.

5.0 Discussion

The significant decreasing trend observed in the water year maximum SWE (≈-9 mm or -6.4% per decade) for Ontario reported here is less than the decrease of -8.9% per decade observed in March snow mass for Europe over the same period (EEA 2012). However, the results are similar to the decreases, and pattern, observed by Mudryk et al. (2018) over Ontario from 1981 to 2015 using an ensemble of models and GlobSnow. The negative trend in SWE is projected to continue for the 2020 to 2050 period across Canada based on results of a Coupled Model Intercomparison Project (CMIP5) model ensemble using the RCP8.5 forcing scenario (Mudryk et al. 2018). These are averages over significant geographic areas and greater decreases may be occurring locally,

Table 2. Coefficient of variation for snow water equivalent and snow cover extent for the province for each season over 3 decades.

Attribute/timing	1980s	1990s	2000s
Maximum snow water equivalent			
Fall	110.5	90.6	111.7
Winter	29.4	28.4	29.7
Spring	87.2	96.7	102.0
Snow cover extent			
Fall	89.3	95.3	76.6
Winter	3.3	4.4	4.2
Spring	84.3	79.0	87.6

evidenced by a decrease of 20 mm per decade for the Upper Ottawa watershed (Figure A2.3).

The water year maximum SWE provides an indication of the total volume of water to be released from the snowpack into a watershed. Mid-winter or early spring melting may release part of the water stored in a snowpack prior to spring melt, decreasing SWE. This may explain the lower statistical significance of the March trend compared with the annual maximum SWE and differences in their respective magnitudes (figures 4 and 5). This water may not exit a watershed immediately; instead it may infiltrate the soil and refreeze or fill surface depressions and refreeze. In both cases, water may be lost from the snowpack, and therefore not contribute to SWE, but may still influence spring runoff processes and the magnitude, timing, and duration of the spring runoff peak (Metcalfe and Buttle 1999). The March maximum SWE is still relevant because it indicates the water available immediately preceding spring melt, which is important for forecasting floods and assessing potential hazards related to increased runoff in streams and rivers.

Liquid water present in the snow or soil will result in underestimates of SWE from passive microwave sensors such as those used by Globsnow while ice layers resulting from freeze-thaw cycles will result in overestimates (Clifford 2010). The latter is significant because in a warming climate these will likely increase making any decreasing trends observed in this study conservative estimates. It also suggests that maximum seasonal SWE would provide a more accurate estimate of the total snow water inputs to a watershed than the March maximum SWE. Hancock et al. (2013) also found Globsnow to be superior for estimating peak accumulation and the seasonal pattern of SWE development relative to 2 other SWE products. Very close correspondence between annual maximum SWE measured using Globsnow and snow courses in a forested environment in central Ontario for the 2016 and 2017 water years

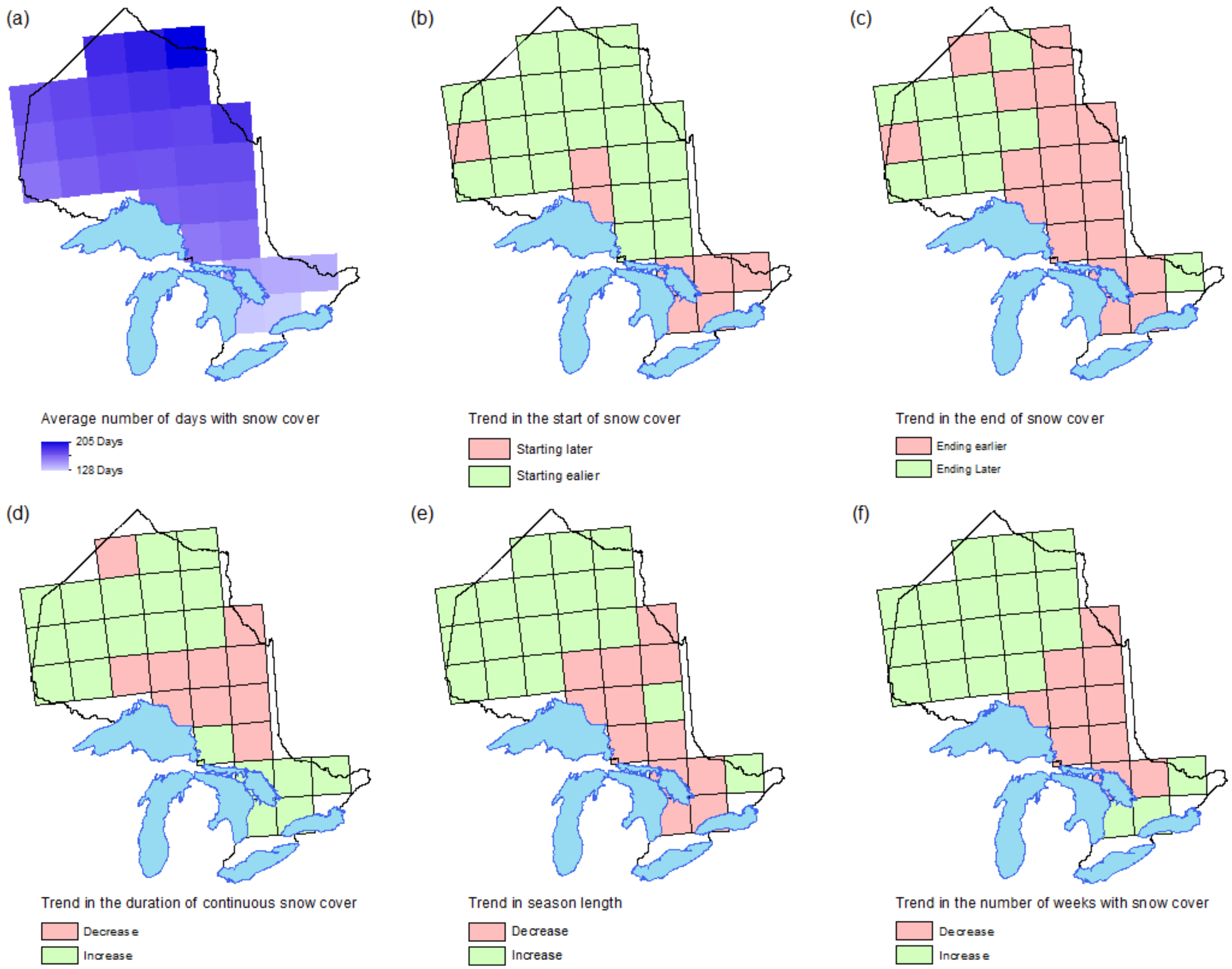

Figure 18. Trends in snow cover timing and duration for each grid cell of the snow cover extent climate data record using weekly data for Ontario (1981–2010 water years) including the a) average number of days with snow cover, b) start of snow cover, c) end of snow cover, d) duration of continuous snow cover, e) season length, and f) number of weeks with snow cover.

have been observed (Beaton 2018, MNRF Surface Water Monitoring Centre, pers. comm.).

The relationship among minimum air temperature, total precipitation, and annual maximum SWE showed 2 distinct groups of watersheds separated by a transition zone between -6.8 ℃ and -4.8 ℃. Similarly, Sospedro-Alfonso and Merryfield (2017) reported a transition zone of -5 ±1 ℃ (mean seasonal air temperature) below which precipitation primarily drives snowpack variability and above which temperature is the main driver. In contrast, Räisänen (2008) found the transition between rising and decreasing SWE in late 20th century, determined using 20 global climate models, was associated with the -20 ℃ November to March mean temperature isotherm. The strong negative relationship observed in this study offers a first order estimate of the SWE:total precipitation ratio given future predictions of air temperature and provides a basis for delineating regions using the noted isotherms where snowpack accumulation is more vulnerable to a warming climate (Sospedro-Alfonso and Merryfield 2017).

While Globsnow-derived estimates of maximum SWE provide a relatively stable indication of changing snow conditions in Ontario, interpretation of the SCE data is complicated by some uncertainties. Earlier snow detection and earlier losses of total snow cover observed in the weekly SCE after 2000 (see Figure 17) aligns with the discontinuity in the NOAA CDR where manual measurements of visible-band satellite observations were replaced by estimates using the IMS sensor. The higher spatial and temporal resolution of the latter led Brown and Derksen (2013) to postulate whether the increasing trend in autumn SCE, which was opposite to those observed in several other reanalyses and climate simulation data sets (Mudryk et al. 2014), and a steeper decreasing trend in spring SCE, is internal to the CDR and caused by improved snow detection in autumn and snow loss in spring. Estilow et al. (2015) acknowledged the observation by Brown and Derksen (2013) but did not provide alternative explanations and claim the transition from weekly to daily maps has not resulted in an artificial step change in spring continental-scale SCE.

A notable increase in the detection of SCE earlier in the season post-1999 and SCE later in the season pre-1999 was observed (Figure 17). However, earlier detection of bare patches over smaller areas during spring melt was not observed. This finding might be explained by a quicker transition from deeper snow to no snow during spring melt resulting in less ambiguous SCE boundaries and less difference between the historical and IMS methods. Also, the reduced SCE reported for the Northern Hemisphere may not be evident in results from this study because the former reflects changes at the most southern extent of the seasonal snow line.

Regional patterns defined by trends in SCE (Figure 18) show some similarity to those reported by Mudryk et al. (2018; Figure 1) for 1981 to 2015 using monthly snow cover fraction estimated using several SWE products. Trends in end of snow cover (Figure 18c) were similar to those observed by Mudryk et al. (2018) for spring (April–June) but earlier trends in the start of snow in Northern Ontario (Figure 18b) were opposite of their autumn trends (October–December).

From a Canadian evaluation of the NOAA CDR with surface observations, Brown and Mote (2009) found that the effect of improvements in mapping over time was an order of magnitude smaller than the observed trends in snow cover duration and therefore unlikely to change conclusions where snow cover is changing the most. Although snow cover duration and timing are expected to provide the largest response to climate change across a range of snow-climate regimes (Brown and Mote 2009), no significant trends were detected in this study.

Interestingly, the trend in earlier start to SCE in northwestern Ontario aligned with increasing precipitation in October and November (Figure 12). Trends in the end of SCE in northwestern and northeastern Ontario (Figure 18c) also aligned well with trends in May monthly minimum air temperature (Figure 11). In southern Ontario, increasing trends in duration of continuous snow cover (Figure 18d) and the number of weeks with snow cover (Figure 18f) that is starting later (Figure 18b) and melting earlier (Figure 18c), aligned with increasing monthly minimum air temperatures (Figure 11) and increasing monthly total precipitation from February to April (Figure 12). The increase in minimum air temperature could be delaying the phase transition of precipitation in autumn (i.e., rainfall to snowfall), expediting it in the spring (i.e., snowfall to rainfall), and making more atmospheric water vapour available in the mid-winter months, particularly from water bodies that remain unfrozen. Thus, although similar changes in SCE were found that coincide with the discontinuity in the data, climate data over the same period also provided a reasonable explanation for observed changes in SCE. Similarly, Cohen et al. (2014) found that the positive trend in October snow cover extent over Eurasia aligned well with temperature patterns associated with the North Atlantic Oscillation/Arctic Oscillation. They proposed that a possible physical mechanism for the increased snow cover was that a warmer Arctic atmosphere could hold more water vapour supplied by increasingly open water when air temperatures remained sufficiently cold for precipitation to fall as snow.

6.0 Recommendations

This study is the first known analysis of changing snow conditions in Ontario focused at provincial scale. The 2 data products analyzed are the only satellite-derived observations of snow cover with provincial coverage and historical records sufficient to produce meaningful statistics for studying trends and variability related to changes in climate for the period 1980 to 2010. Globsnow SWE is a homogeneous CDR that directly measures radiative properties influenced by snow, uses in situ snow depth observations, and compares well with other reanalysis products and land surface models (Mudryk et al. 2015).

While the NOAA SCE CDR has been widely used to study the effects of climate change, a possible discontinuity in the data and incongruities with other data records (Brown and Derksen 2013) cannot be overlooked. It is unclear how much of the observed shift in the start and end of snow cover are attributable to the data discontinuity or observed trends in temperature and precipitation. However, information on changing snow cover extent is important for understanding potential effects on the surface energy budget, ecosystem processes, animal behaviour and adaptation, and recreational activities.

Future work could use the daily measurements from the higher resolution (24 km) Interactive Multisensor Snow and Ice Mapping System (IMS) directly to estimate indicators of SCE from November 1998 to present. Validation of the remote sensing data sources using historical site data from the Province’s snow survey network and Snow Network for Ontario Wildlife (SNOW) would also help to quantify the uncertainty in the snow indicator metrics. This information would provide a more complete understanding of snow conditions based on the most direct (e.g., snow surveys) and indirect (e.g., Globsnow and IMS) observations from which climate model ensembles could then be assessed.

The strong relationships between SWE and climate variables and ability to estimate the SWE:total precipitation ratio given future predictions of air temperature also warrants closer examination. These relationships could be further refined by following the methods of Sospedro-Alfonso and Merryfield (2017) to relate maximum SWE to more defined periods immediately preceding the date of maximum SWE rather than using the seasonal means. These refinements are required to help detect where hydro-climatic shifts from pluvial-nival (snow) systems to more pluvial-dominated (rain) systems are occurring in the province to help formulate anticipatory adaptive resource management strategies.

It would also be informative to relate Globsnow maximum SWE estimates to other environmental variables directly linked to snowpack conditions such as spring streamflow magnitude and forest fire frequency. This knowledge would be valuable for assessing the potential for using Globsnow data operationally to support various resource management activities.

8.0 Literature cited

Allchin, M.I. and S.J. Déry. 2017. A spatio-temporal analysis of trends in Northern Hemisphere snow dominated area and duration, 1971–2014. Annals of Glaciology 58: 21–35.

Anderson, R.L. 1942. Distribution of the serial correlation coefficients. Annals of Mathematical Statistics 13(1): 1–13.

Brown, G.S. 2011. Patterns and causes of demographic variation in a harvested moose population: Evidence for the effects of climate and density-dependent drivers. Journal of Animal Ecology 80: 1288–1298.

Brown, R.D. and P.W. Mote. 2009. The response of Northern Hemisphere snow cover to a changing climate. Journal of Climate 22: 2124–2145.

Brown, R.D. and C. Derksen 2013. Is Eurasion October snow cover extent increasing? Environ. Res. Lett. 8: 1–7.

Brown, R.D. and B.E. Goodison. 1996. Interannual variability in reconstructed Canadian snow cover, 1915–1992. Journal of Climate 9: 1299–1318.

Cohen, J., Screen, J.A., Furtado, J.C., Barlow, M., Whittleston, D., Coumou, D., Francis, J., Dethloff, K., Entekhabi, D., Overland, J., and J. Jones. 2014. Recent Arctic amplification and extreme mid-latitude weather. Nature Geoscience 7: 627–637.

Clifford, D. 2010. Global estimates of snow water equivalent from passive microwave instruments: History, challenges and future developments. International Journal of Remote Sensing 31(14): 3707–3726.

Dove-Thompson, D., C. Lewis, P.A. Gray, C. Chu and W.I. Dunlop. 2011. A summary of the effects of climate change on Ontario's aquatic ecosystems. Ontario. Ministry of Natural Resources, Applied Research and Development Branch, Peterborough, ON. Climate Change Research Report CCRR-11. 56 p.

English, J., J.J. Luce and R.A. Metcalfe. 2017. OTT Pluvio² L totalizing precipitation gauge: Site selection, installation, and maintenance. Ontario Ministry of Natural Resources and Forestry, Science and Research Branch, Peterborough, ON. Science and Research Technical Manual TM–04. 30 p.

Estilow, T., K. Young, A. and D. Robinson. 2015. A long-term Northern Hemisphere snow cover extent data record for climate studies and monitoring. Earth Systems Science Data 7: 137–142.

[EEA] European Environment Agency. 2012. Climate change, impacts and vulnerability in Europe 2012: An indicator-based report. European Environment Agency Copenhagen, DK. EEA report No 12/2010.

[EEA] European Environment Agency. 2017. Climate change, impacts and vulnerability in Europe 2016: An indicator-based report. European Environment Agency, Copenhagen, DK. EEA report No 1/2017.

Flanner, M.G., K.M. Shell, M. Barlage, D.K. Perovich and M.A. Tschudi. 2011. Radiative forcing and albedo feedback from the Northern Hemisphere cryosphere between 1979 and 2008. Nature Geoscience 4(3): 151–155.

Hancock, S., R. Baxter, J. Evans and B. Huntley. 2013. Evaluating global snow water equivalent products for testing land surface models. Remote Sensing of Environment 128: 107–117.

Helfrich, S., D. McNamara, B. Ramsay, T. Baldwin and T. Kasheta. 2007. Enhancements to, and forthcoming developments in the interactive multisensor snow and ice mapping system (IMS). Hydrological Processes 21: 1576–1586.

[IPCC] Intergovernmental Panel on Climate Change. 2014. Climate change 2014: Synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, CH. 151 p.

Kennedy-Slaney, L., J. Bowman, A. Walpole and B.A. Pond. 2018. Northward bound: The distribution of white-tailed deer in Ontario under a changing climate. Wildlife Research 45: 220–228.

Kolenosky, G.B. 1972. Wolf predation on wintering deer in east-central Ontario. The Journal of Wildlife Management 36: 357–369.

Larue, F., A. Royer, D. De Sève, A. Langlois, A. Roy and L. Brucker. 2017. Validation of GlobSnow-2 snow water equivalent over Eastern Canada. Remote Sensing of Environment 194: 264–277.

Luojus, K., J. Pulliainen, M. Takala, J. Lemmetyinen, M. Kangwa, M. Eskelinen, S. Metsämäki, R. Solberg, A-B. Salberg, G. Bippus, E. Ripper, T. Nagler, C. Derksen, A. Wiesmann, S. Wunderle, F. Hüsler, F. Fontana and N. Foppa. 2014. GlobSnow-2 final report. European Space Agency Study Contract Report V. 1.0/01. <http://www.globsnow.info/docs/GlobSnow_2_Final_Report_release.pdf>; Accessed October 2018.

McKenney, D.W., J.H. Pedlar, P. Papadopol and M.F. Hutchinson. 2006. The development of 1901–2000 historical monthly climate models for Canada and the United States. Agricultural and Forest Meteorology 138: 69–81.

Metcalfe, R.A. and J.M. Buttle. 1999. Semi-distributed water balance dynamics in a small boreal forest basin. Journal of Hydrology 226: 66–87.

Mudryk, L.R., P.J. Kushner and C. Derksen. 2014. Interpreting observed northern hemisphere snow trends with large ensembles of climate simulations. Climate Dynamics 43: 345–359.

Mudryk, L.R., C. Derksen, P.J. Kushner and R. Brown. 2015. Characterization of northern hemisphere snow water equivalent data sets, 1981–2010. Journal of Climate 28: 8037–8051.

Mudryk, L.R., C. Derksen, S. Howell, F. Laliberté, C. Thackeray, R. Sospedra-Alfonso, V. Vionnet, P.J. Kushner and R. Brown. 2018. Canadian snow and sea ice: Historical trends and projections. The Cryosphere 12: 1157–1176.

Newton, E.J., A. Ritz and B.A. Pond. 2018. Can automated monitoring stations replace wildlife snow courses to measure snow depth and winter severity? Ontario Ministry of Natural Resources and Forestry, Science and Research Branch, Peterborough, ON. Science and Research Technical Report TR-24. 14 p. + append.

[OMNR] Ontario Ministry of Natural Resources. 2008. Ontario boundary polygon. Ontario Ministry of Natural Resources, Office of the Surveyor General, Toronto, ON. File ID 0b975965-7325-414f-ac8d-dd3981a9cbe4.

[OMNR] Ontario Ministry of Natural Resources. 2010. Secondary watershed version 2.1.3. Ontario Ministry of Natural Resources, Land Information Ontario, Peterborough, ON.

Pulliainen, J. 2006. Mapping of snow water equivalent and snow depth in boreal and sub-arctic zones by assimilating space-borne microwave radiometer data and ground-based observations. Remote Sensing of Environment 101: 257–269.

Räisänen, J. 2008. Warmer climate: Less or more snow? Climate Dynamics 30: 307–319.

Ramsay, B. 1998. The interactive multisensor snow and ice mapping system. Hydrological Processes 12: 1537–46.

Robinson, D.A. 1993. Monitoring Northern Hemisphere snow cover. Pp. 1-25 *in* Snow Watch ’92: Detection Strategies for Snow and Ice. World Data Centre, US Department of Commerce, National Oceanic and Atmospheric Administration, Boulder, CO. Glaciological Data Report GD-25.

Robinson, D.A., F. Dewey and R. Heim, Jr. 1993. Global snow cover monitoring: An update. British American Meteorological Society 74: 1689–1696.

Robinson, D.A. and A. Frei. 2000. Seasonal variability of Northern Hemisphere snow extent using visible satellite data. The Professional Geographer 52(2): 307–315.

Robinson, D.A., T.W. Estilow and NOAA CDR Program 2012. NOAA climate data record (CDR) of Northern Hemisphere (NH) snow cover extent (SCE), Version 1.v01r01. NOAA National Centers for Environmental Information. [doi: 10.7289/V5N014G9]. Accessed January 29, 2018.

Schuur, E.A.G., J.G. Vogel, K.G. Crummer, H. Lee, J.O. Sickman and T.E. Osterkamp. 2009. The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. Nature 459: 556–559.

Sen, P.K. 1968. Estimates of the regression coefficient based on Kendall's Tau. Journal of the American Statistical Association 63: 1379–1389.

Sospedro-Alfonso, R. and W.J. Merryfield. 2017. Influences of temperature and precipitation on historical and future snowpack variability over the Northern Hemisphere in the second generation Canadian Earth System Model. Journal of Climate 30: 4633–4656.

Stieglitz, M., Déry, S. J., Romanovsky, V. E., and T.E. Osterkamp. 2003. The role of snow cover in the warming of arctic permafrost, Geophys. Res. Lett. 30: 1721.

Takala, M., K. Luojus, J. Pulliainen, C. Derksen, J. Lemmetyinen, J. Kärnä, J. Koskinen and B. Bojkov. 2011. Estimating Northern Hemisphere snow water equivalent for climate research through assimilation of space-borne radiometer data and ground-based measurements. Remote Sensing of Environment 115: 3517–3529.

Warren, R., A.R. Bisset, B.A. Pond and D. Voigt. 1998. The snow network for Ontario wildlife. The why, when, what and how of winter severity assessment in Ontario. Ontario Ministry of Natural Resources, Peterborough, ON. 19 p.

[WMO] World Meteorological Organization 2017. WMO guidelines on the calculation of climate normal. Geneva, CH. WMO-No.1203. 18 p.

Yue, S. and C. Wang. 2004. The Mann-Kendall test modified by effective sample size to detect trend in serially correlated hydrological series. Water Resources Management 18: 201–218.

Appendix 1. Trends in monthly maximum snow water equivalent for the province.

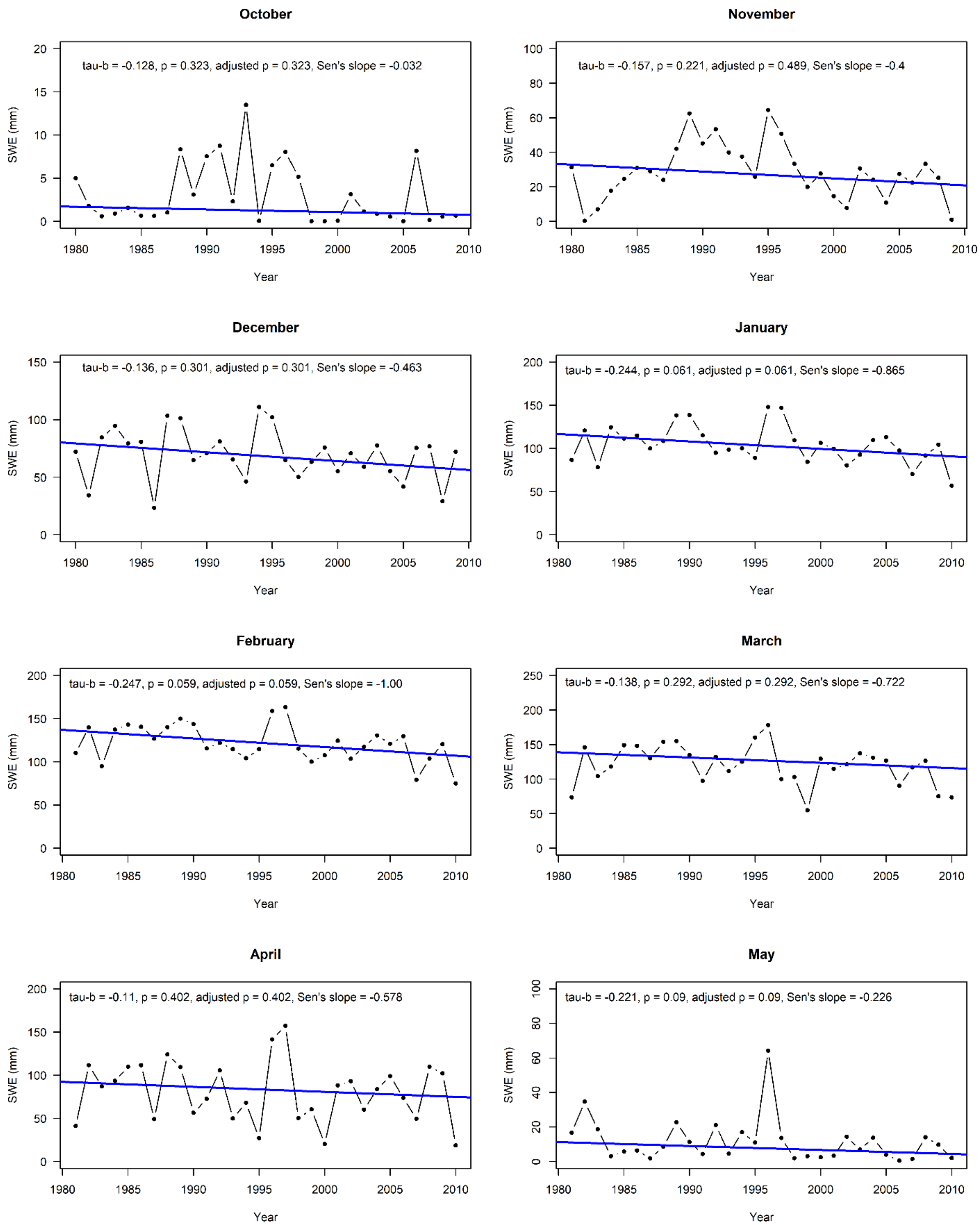

Figure A1.1. Satellite-derived trend in the maximum monthly snow water equivalent (SWE) for Ontario for water years 1981 to 2010.

Appendix 2. Trends in water year maximum snow water equivalent for each secondary watershed.

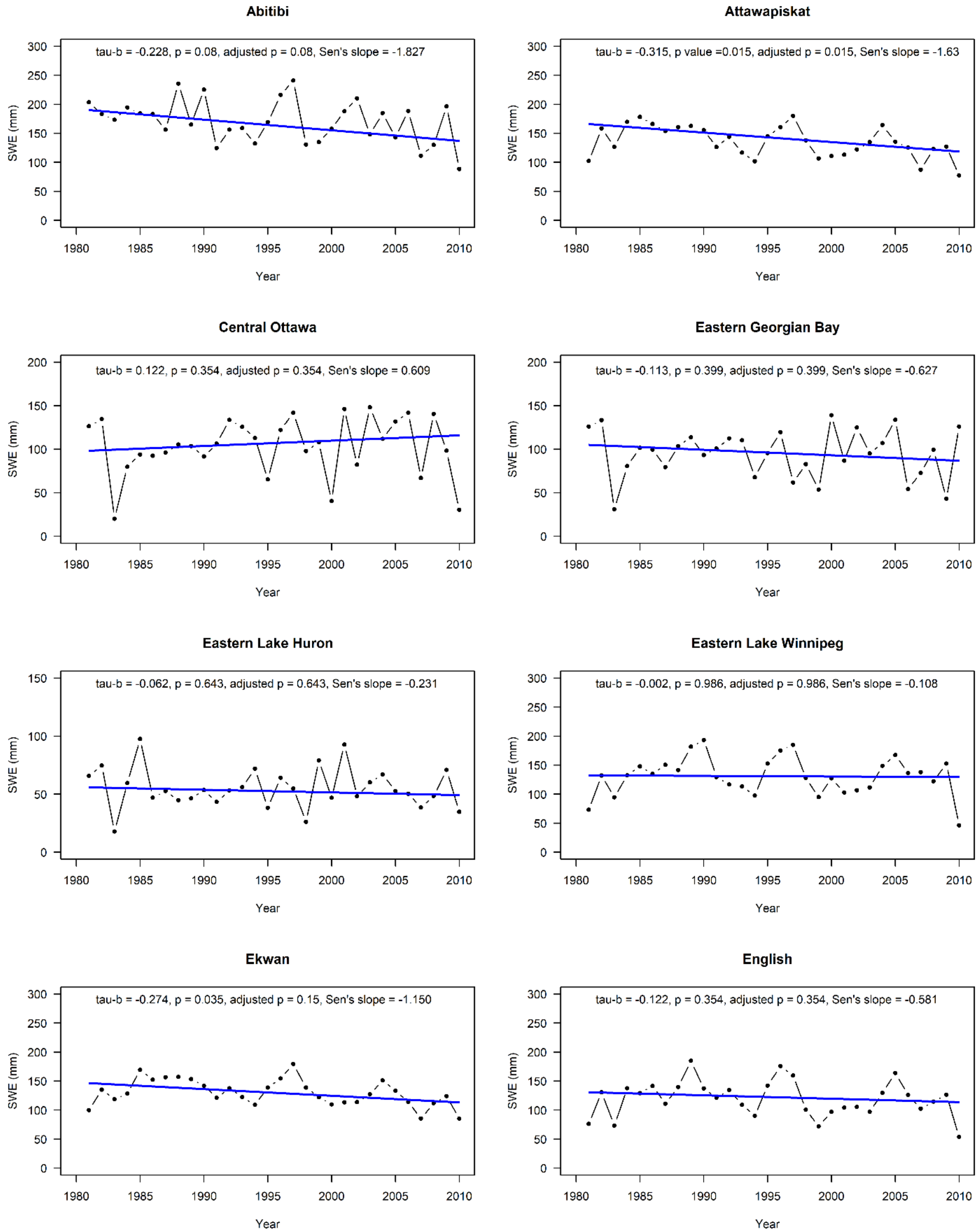

Figure A2.1. Satellite-derived trend in seasonal maximum snow water equivalent (SWE) for eight secondary watersheds for water years 1981 to 2010.

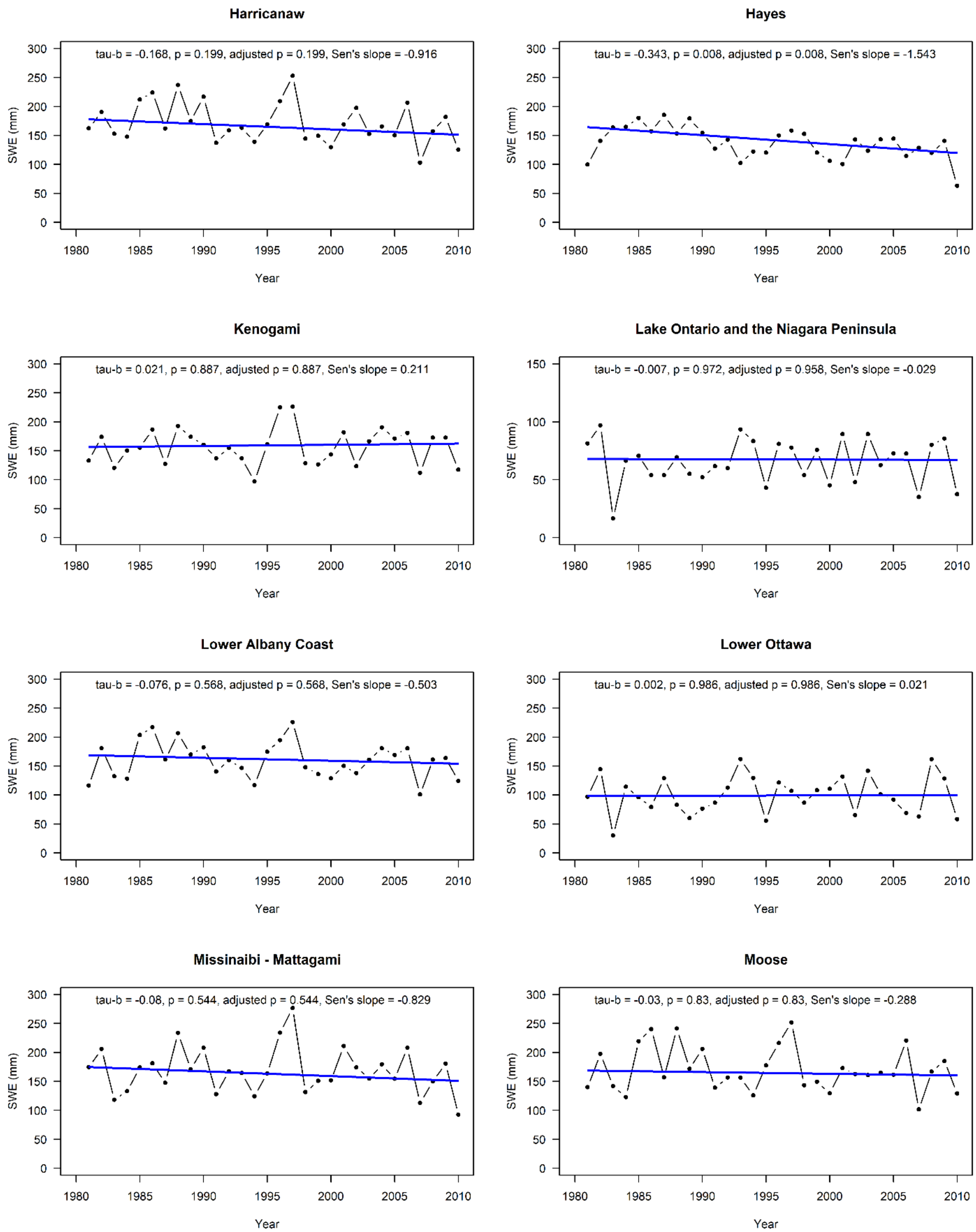

Figure A2.2. Satellite-derived trend in seasonal maximum snow water equivalent (SWE) for eight secondary watersheds for water years 1981 to 2010.

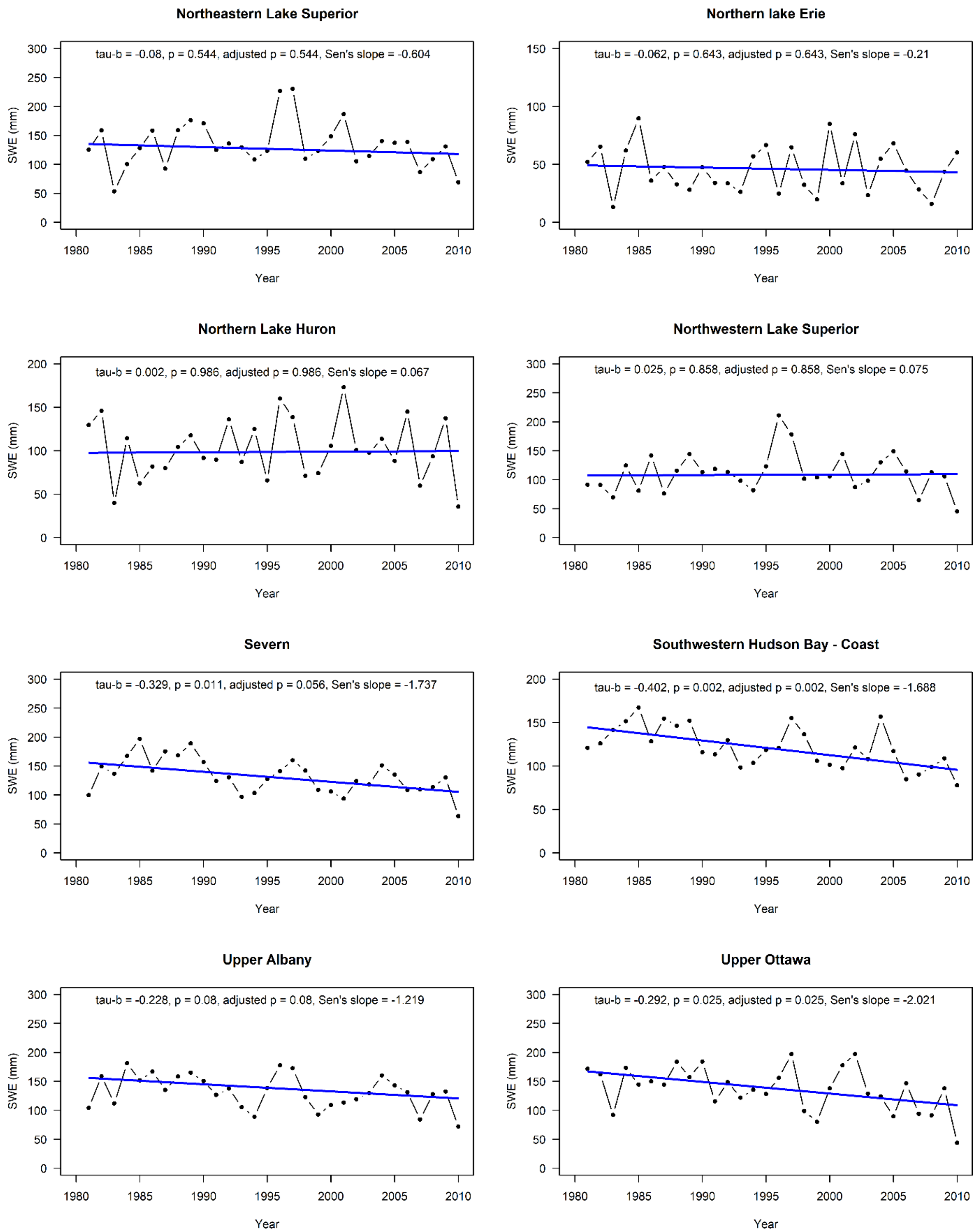

Figure A2.3. Satellite-derived trend in seasonal maximum snow water equivalent (SWE) for eight secondary watersheds for water years 1981 to 2010.

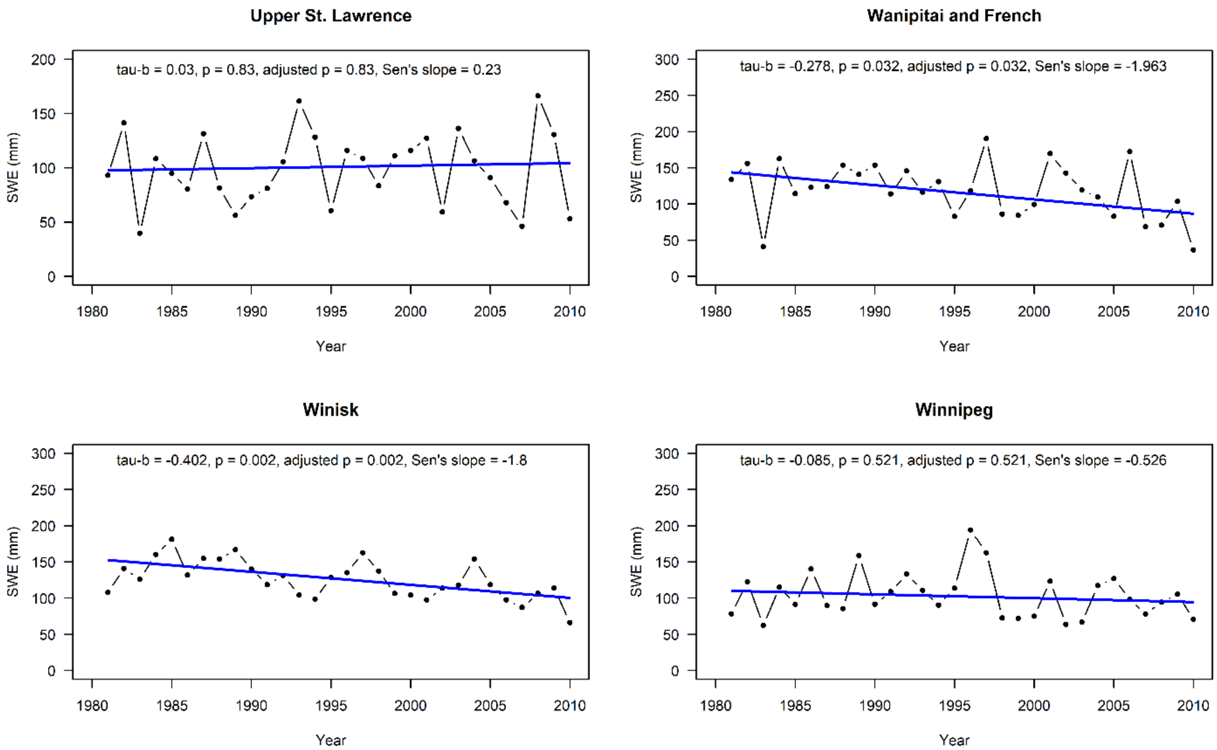

Figure A2.4. Satellite-derived trend in seasonal maximum snow water equivalent (SWE) for four secondary watersheds for water years 1981 to 2010.

Appendix 3: Trends in monthly maximum snow water equivalent for each secondary watershed.

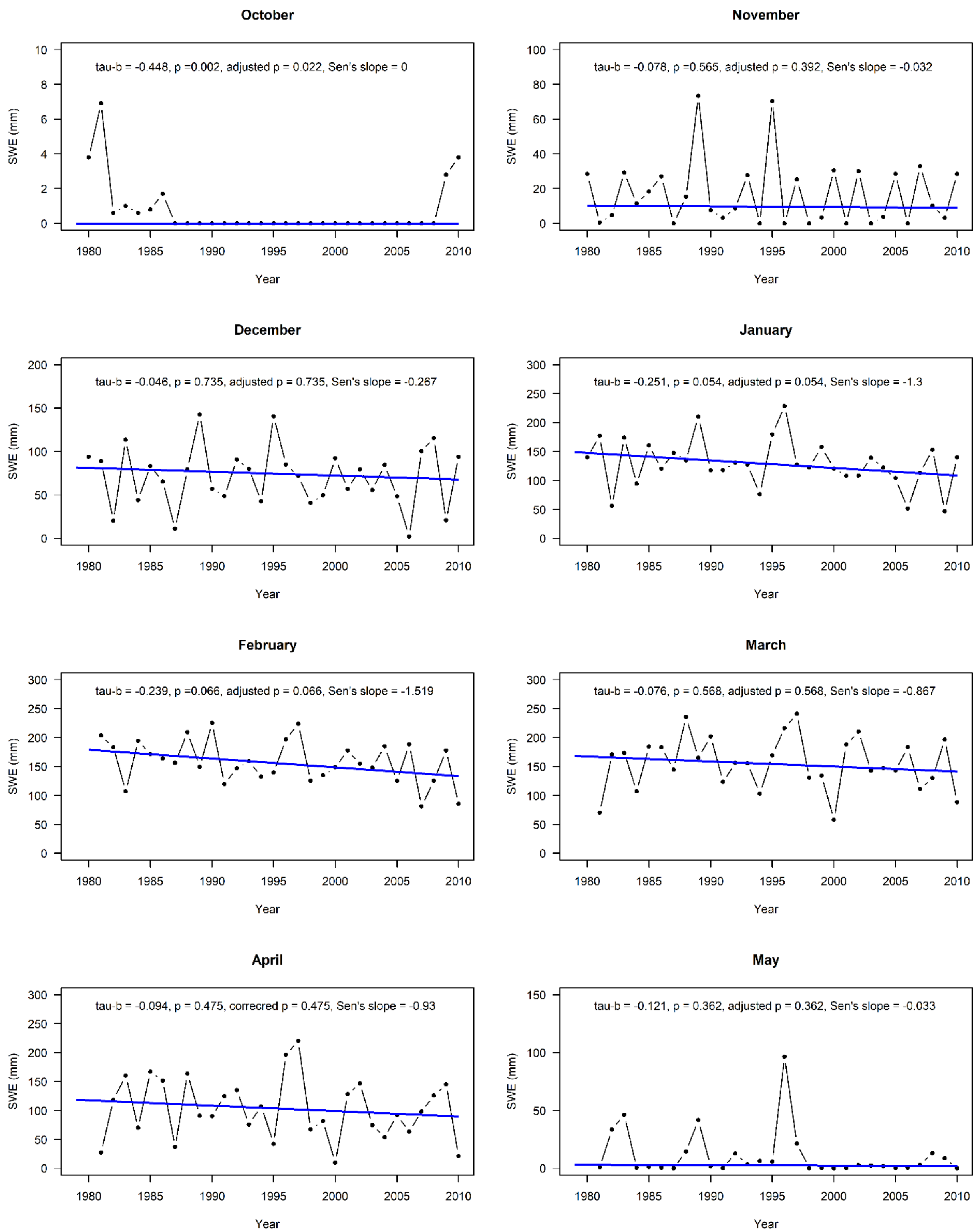

Figure A3.1. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Abitibi watershed for water years 1981 to 2010.

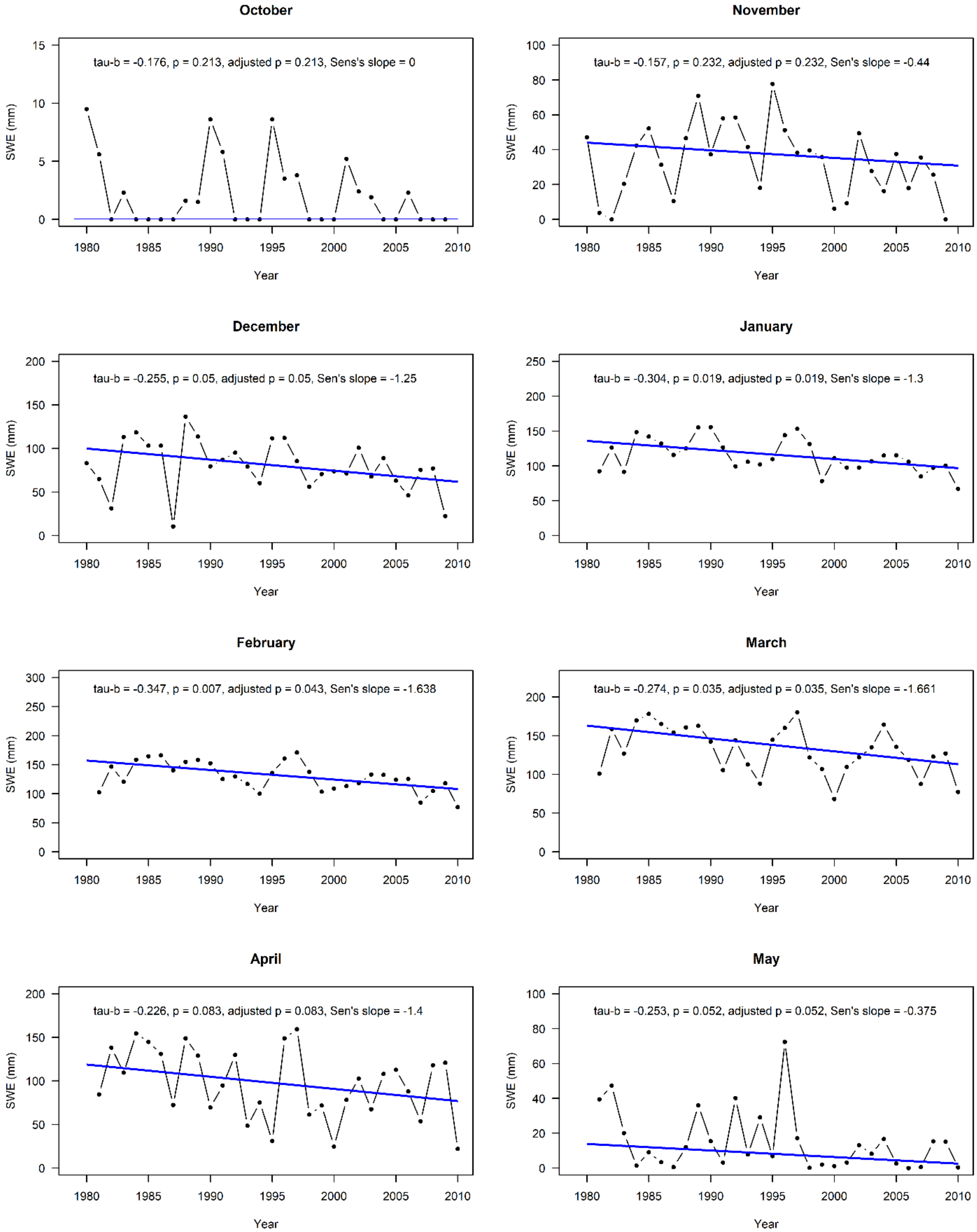

Figure A3.2. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Attawapiskat Coast watershed for water years 1981 to 2010.

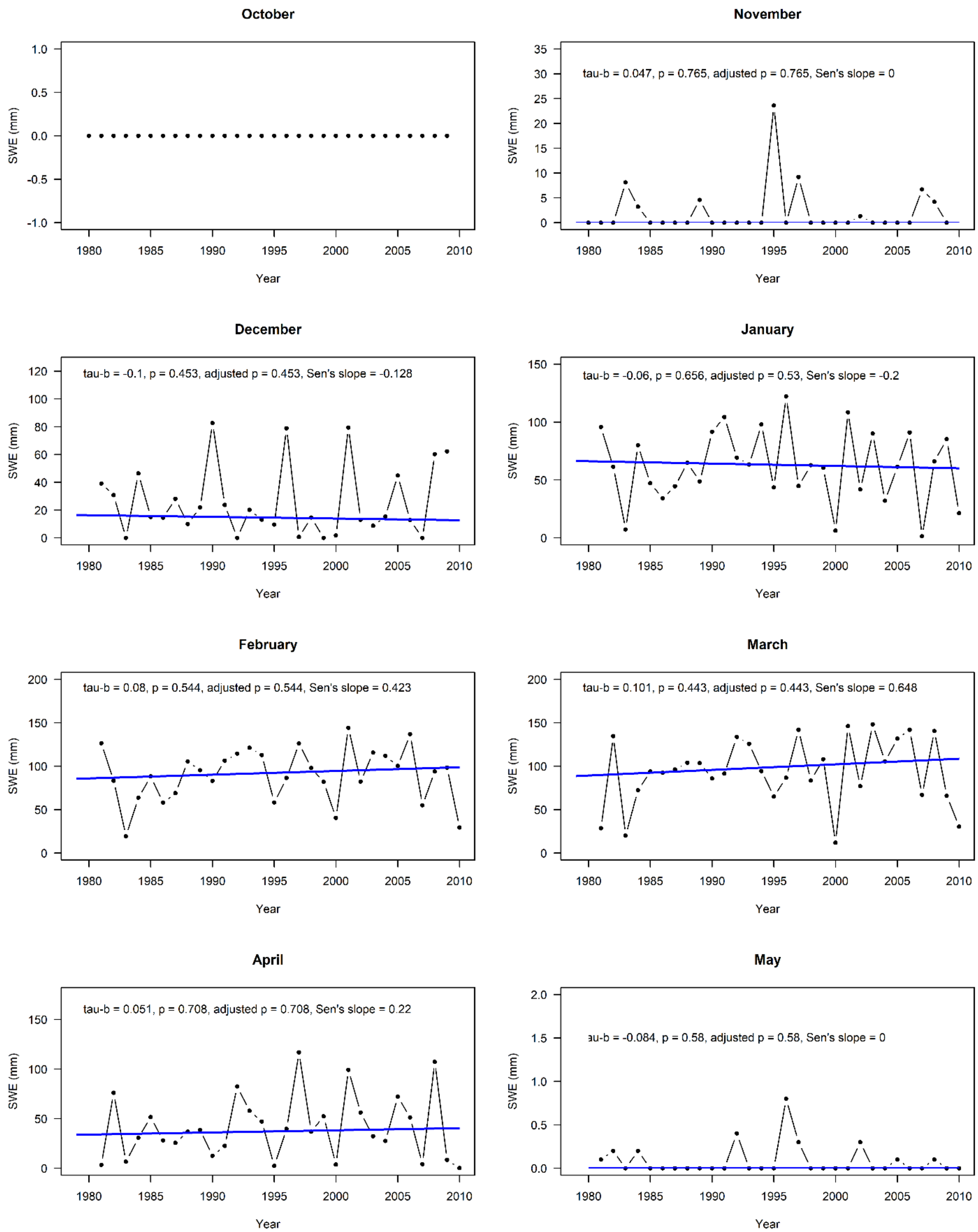

Figure A3.3. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Central Ottawa watershed for water years 1981 to 2010.

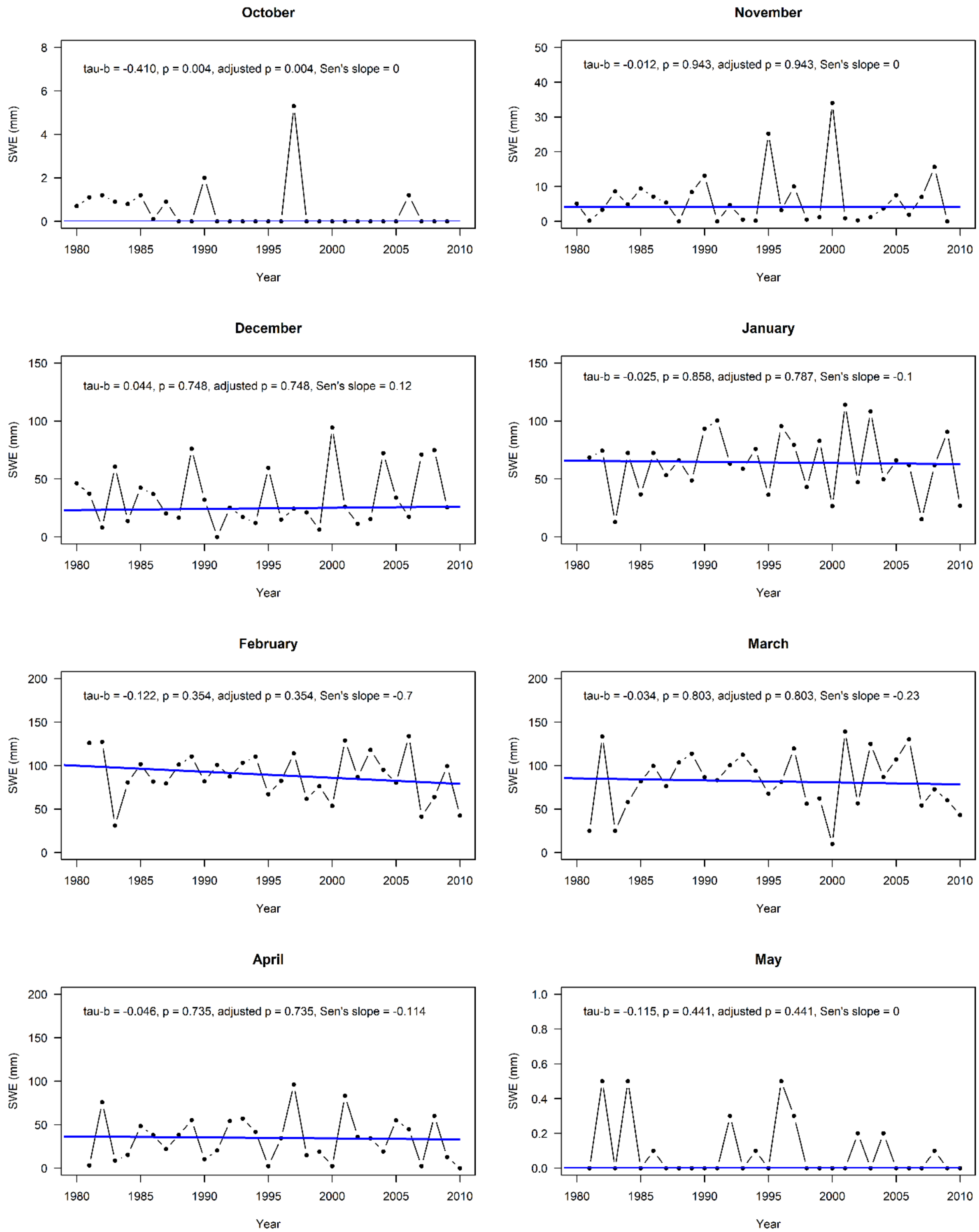

Figure A3.4. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Eastern Georgian Bay watershed for water years 1981 to 2010.

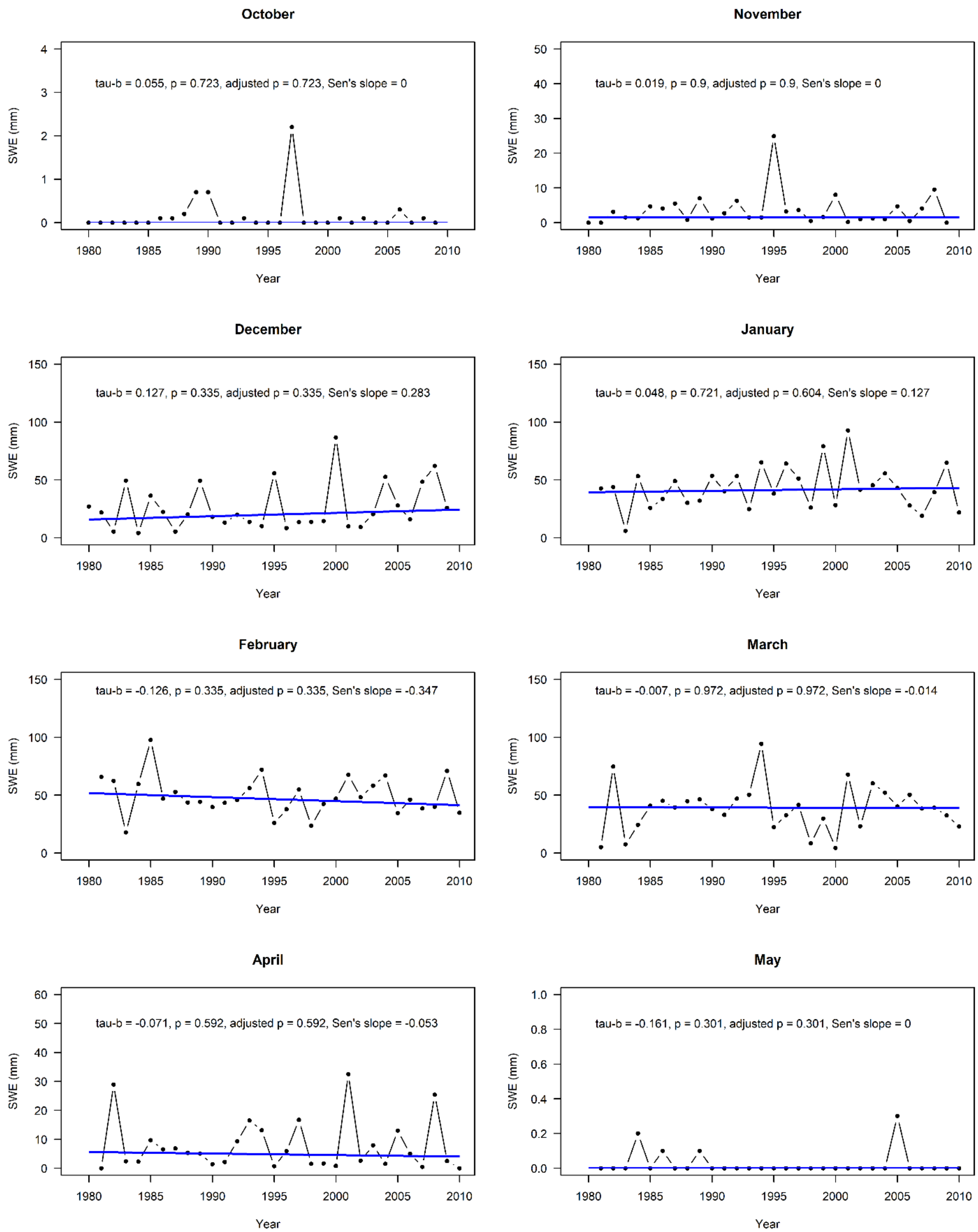

Figure A3.5. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Eastern Lake Huron watershed for water years 1981 to 2010.

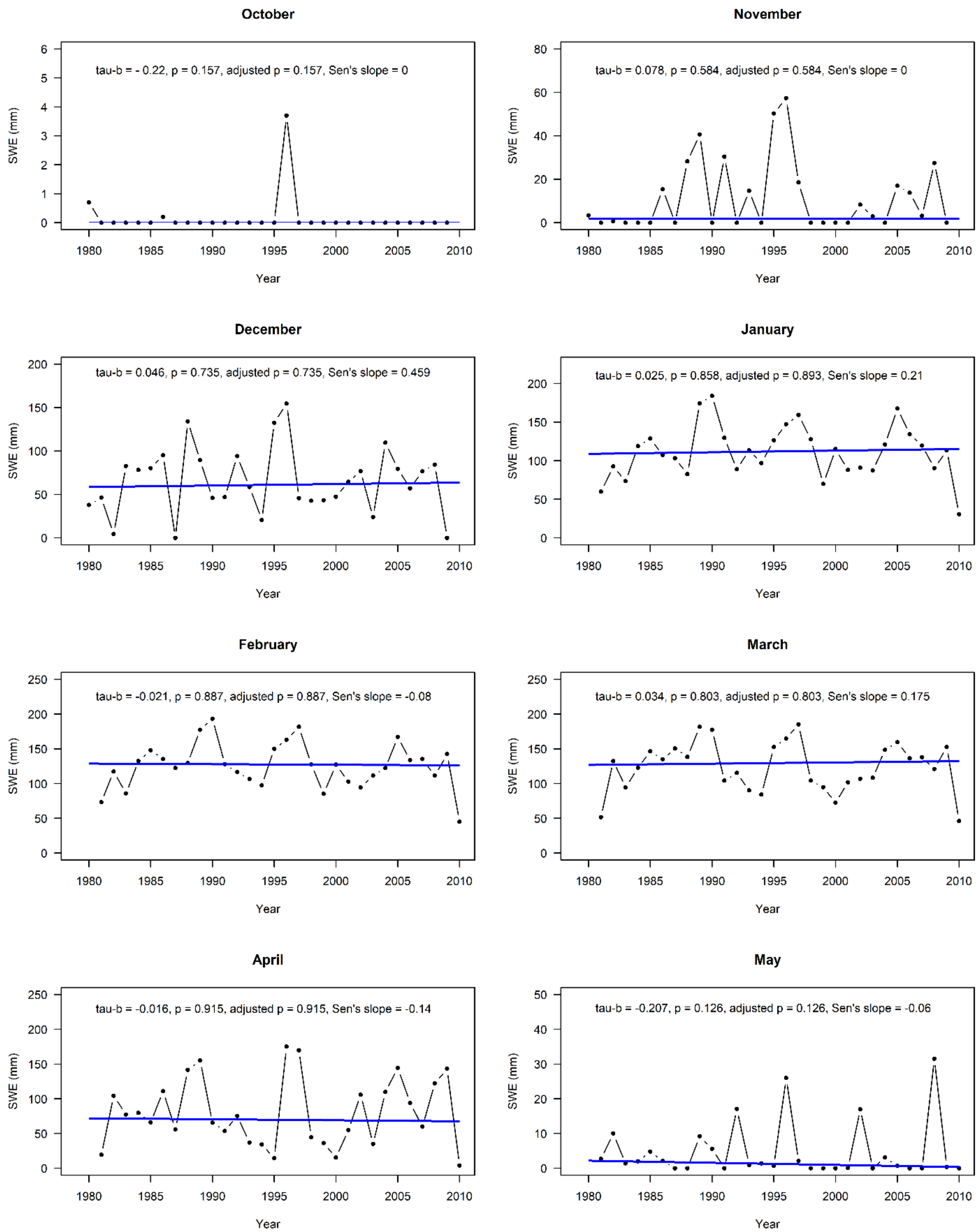

Figure A3.6. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Eastern Lake Winnipeg watershed for water years 1981 to 2010.

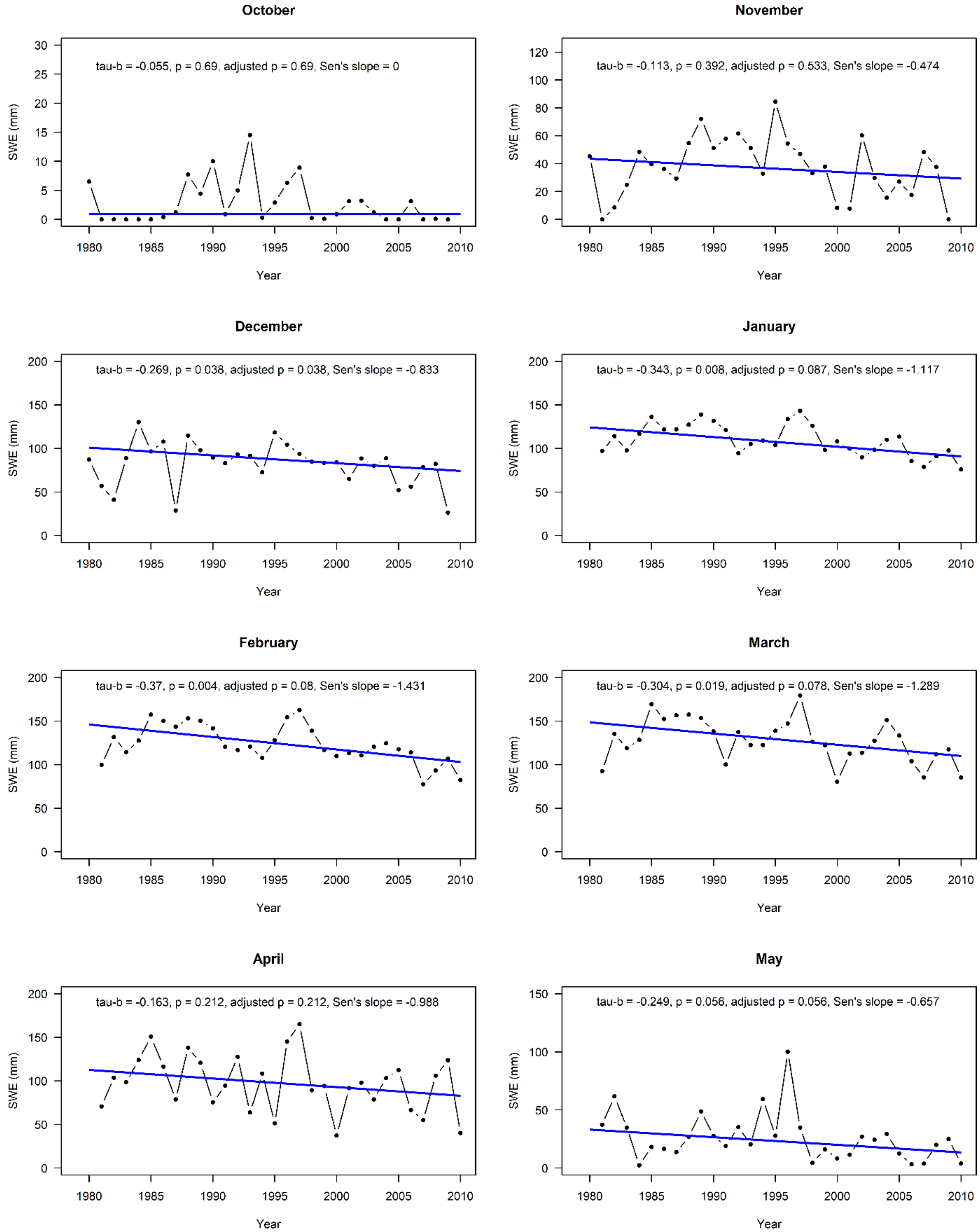

Figure A3.7. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Ekwan Coast watershed for water years 1981 to 2010.

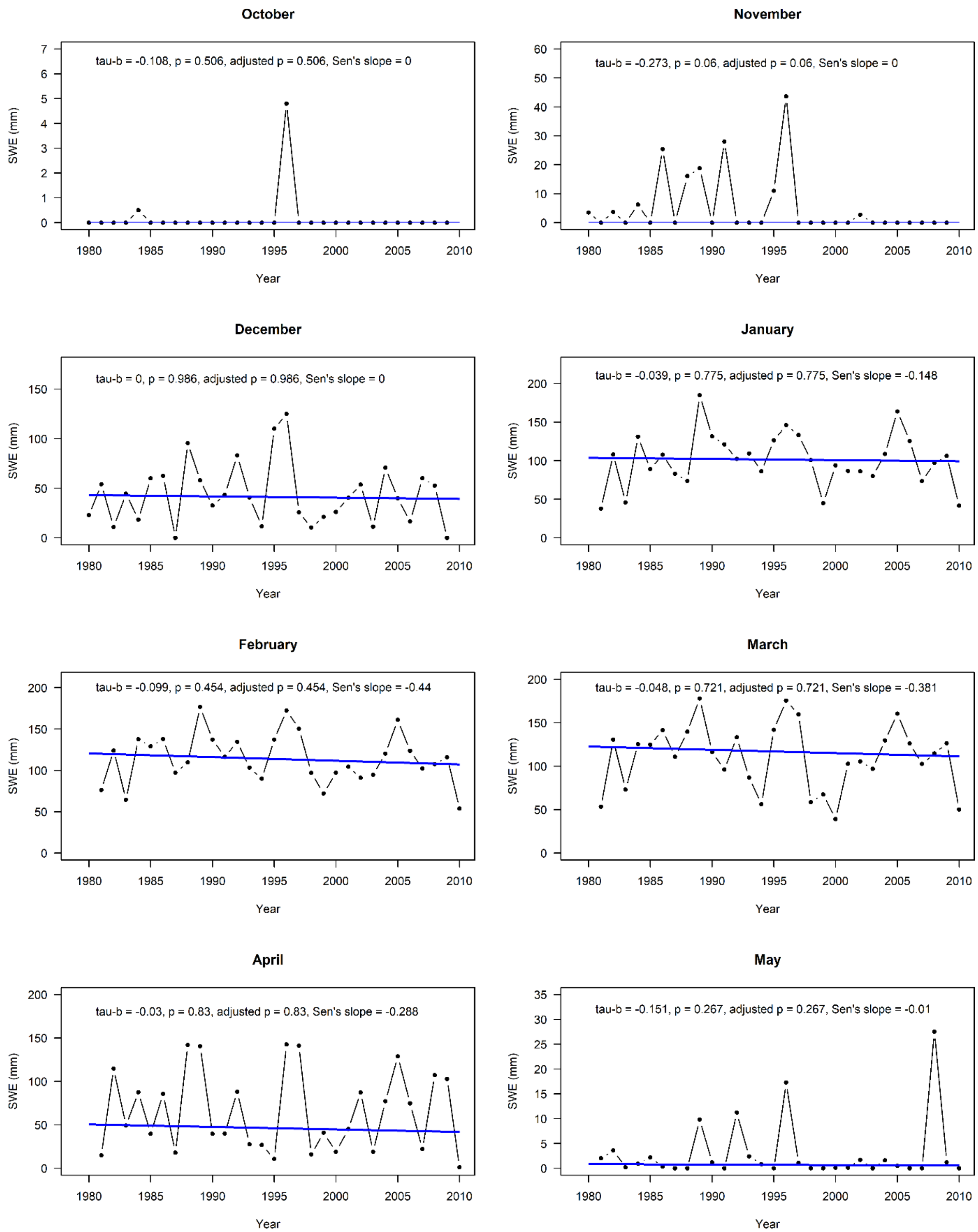

Figure A3.8. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the English watershed for water years 1981 to 2010.

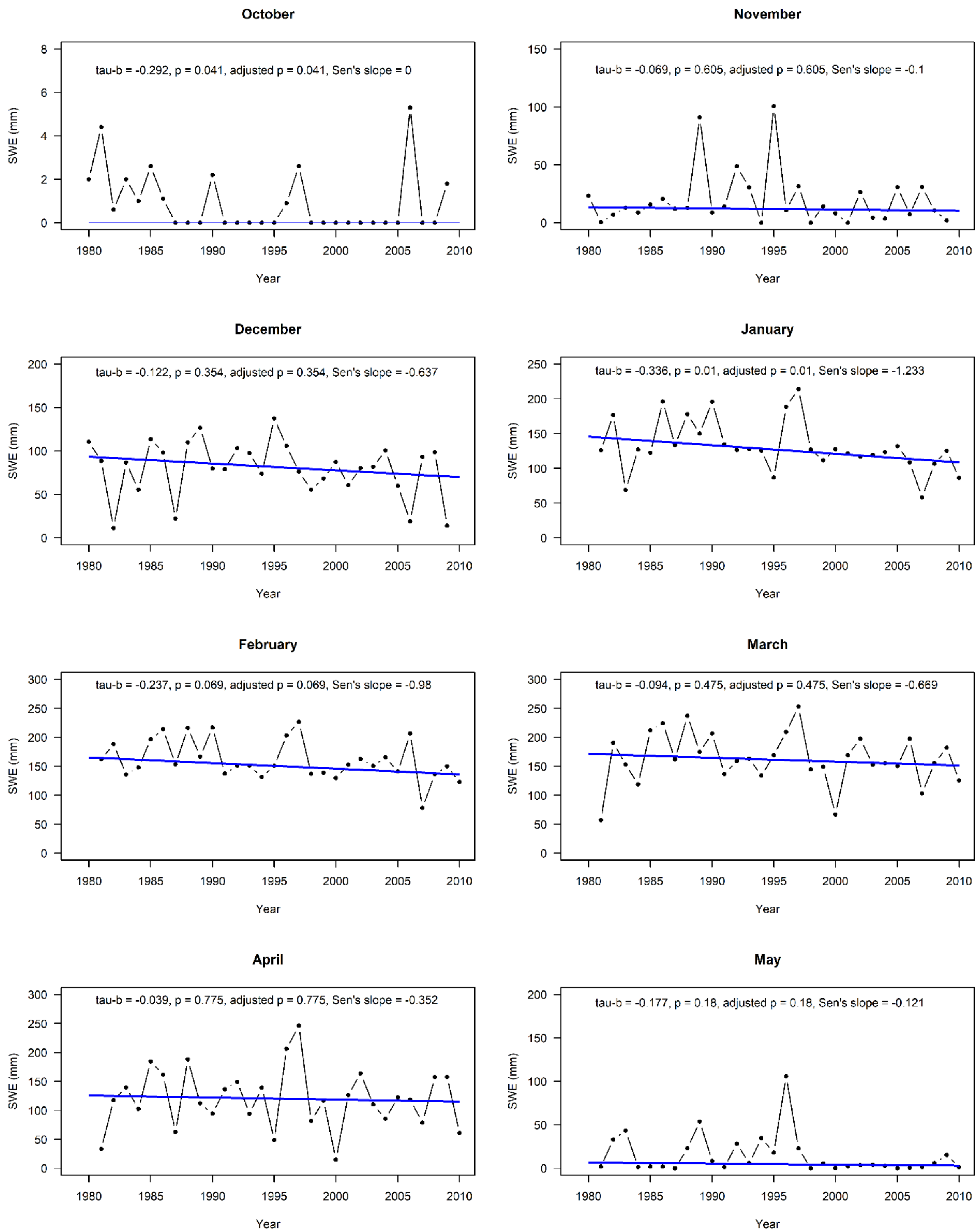

Figure A3.9. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Harricanaw Coast watershed for water years 1981 to 2010.

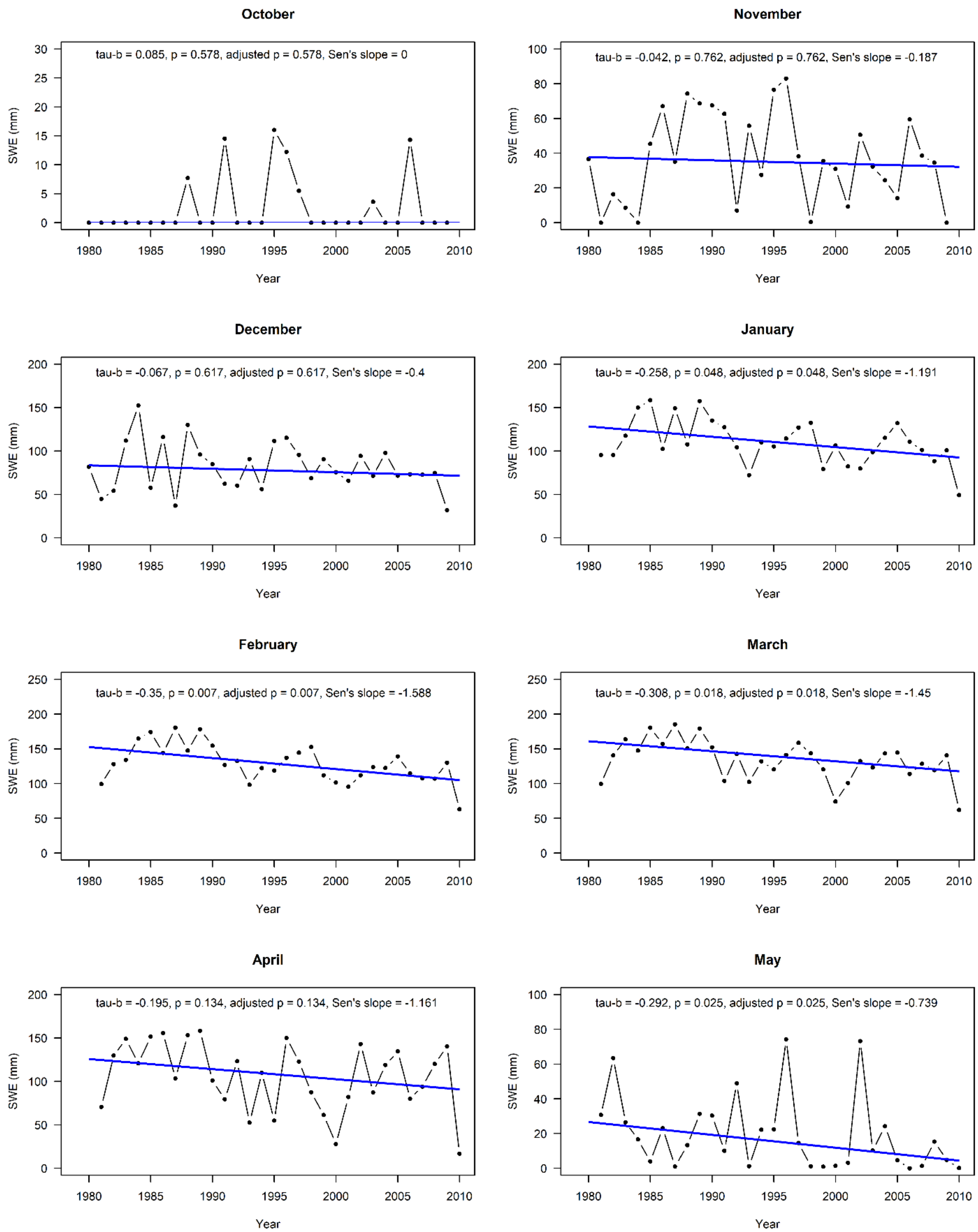

Figure A3.10. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Hayes watershed for water years 1981 to 2010.

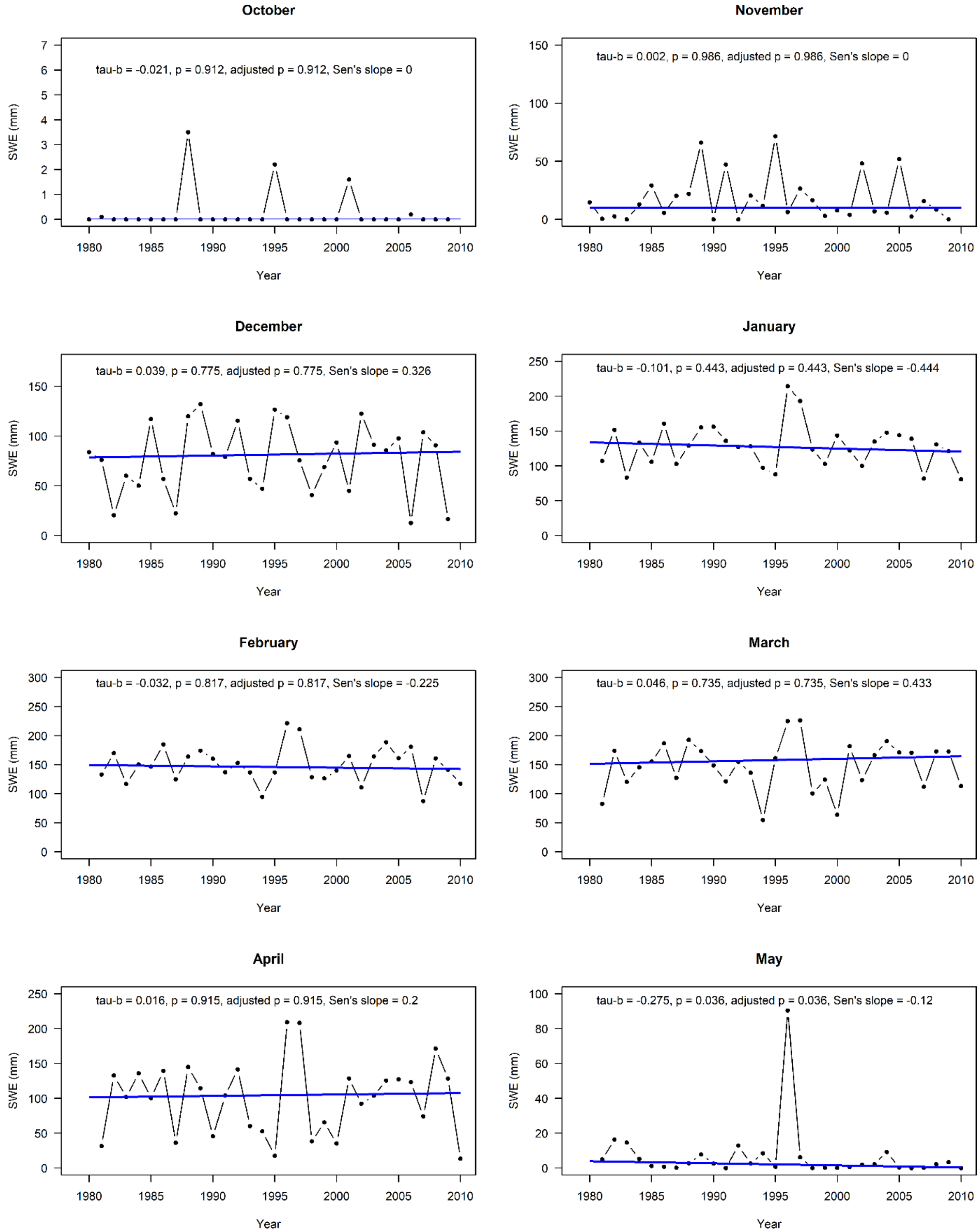

Figure A3.11. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Kenogami watershed for water years 1981 to 2010.

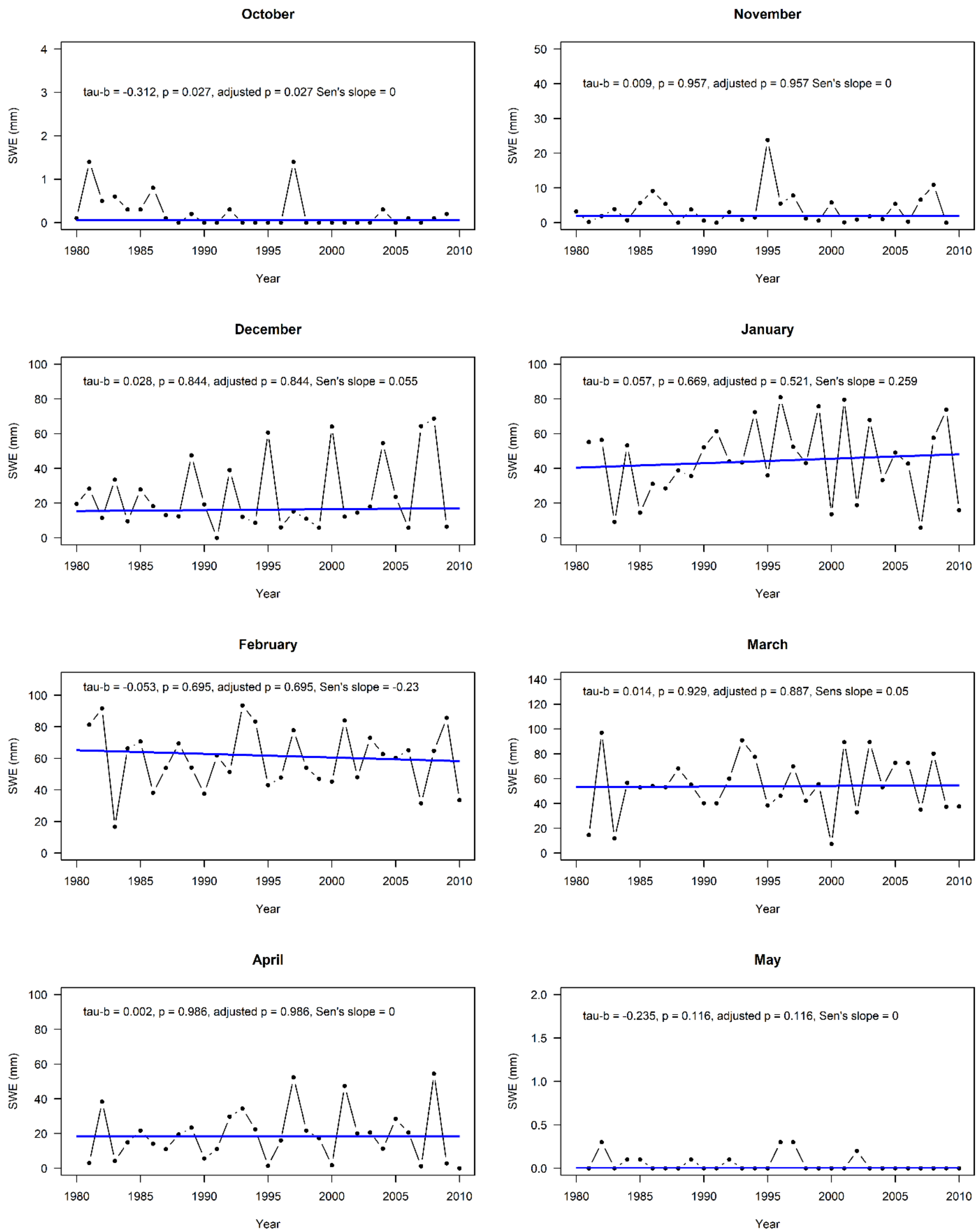

Figure A3.12. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Lake Ontario and Niagara Peninsula watershed for water years 1981 to 2010.

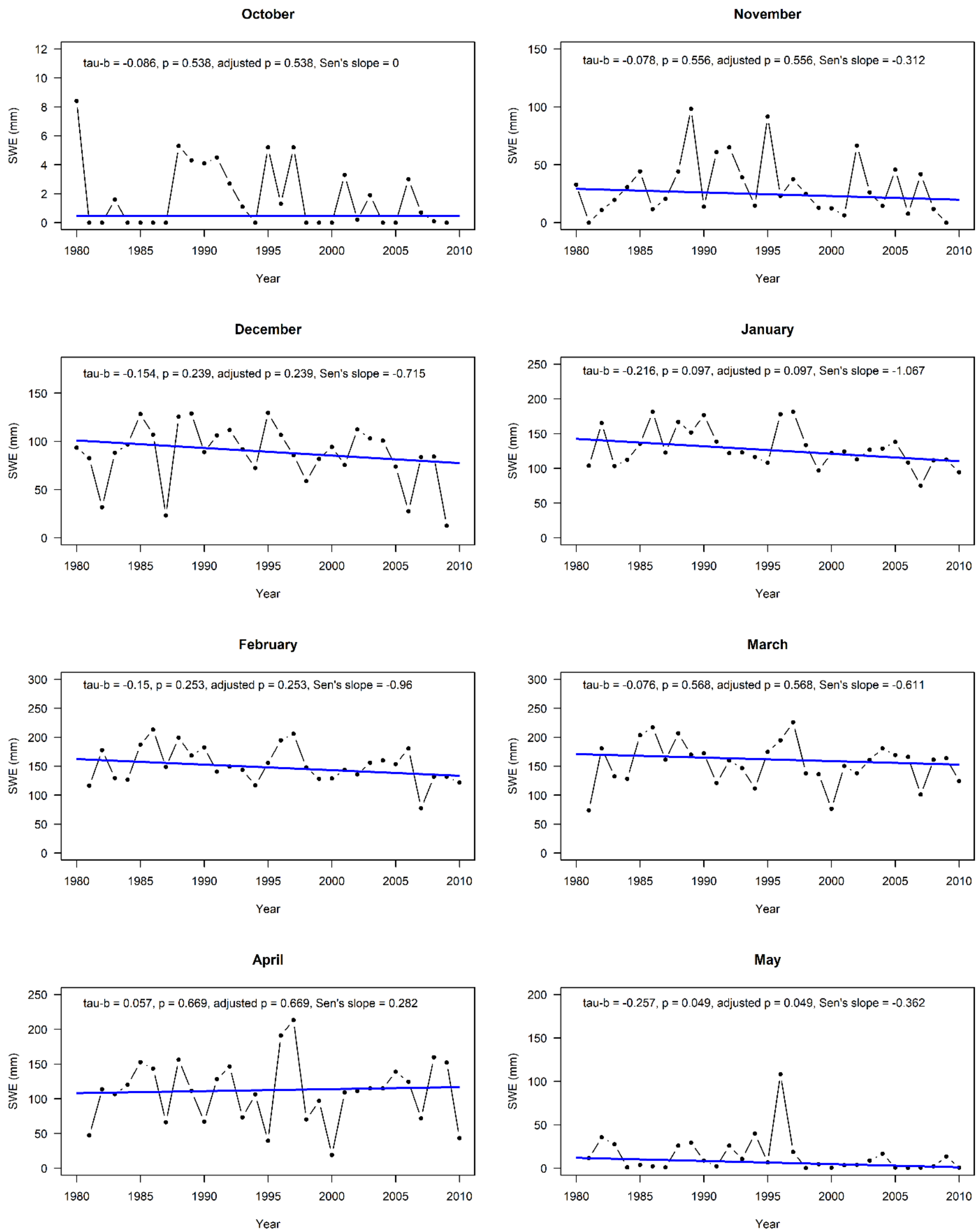

Figure A3.13. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Lower Albany watershed for water years 1981 to 2010.

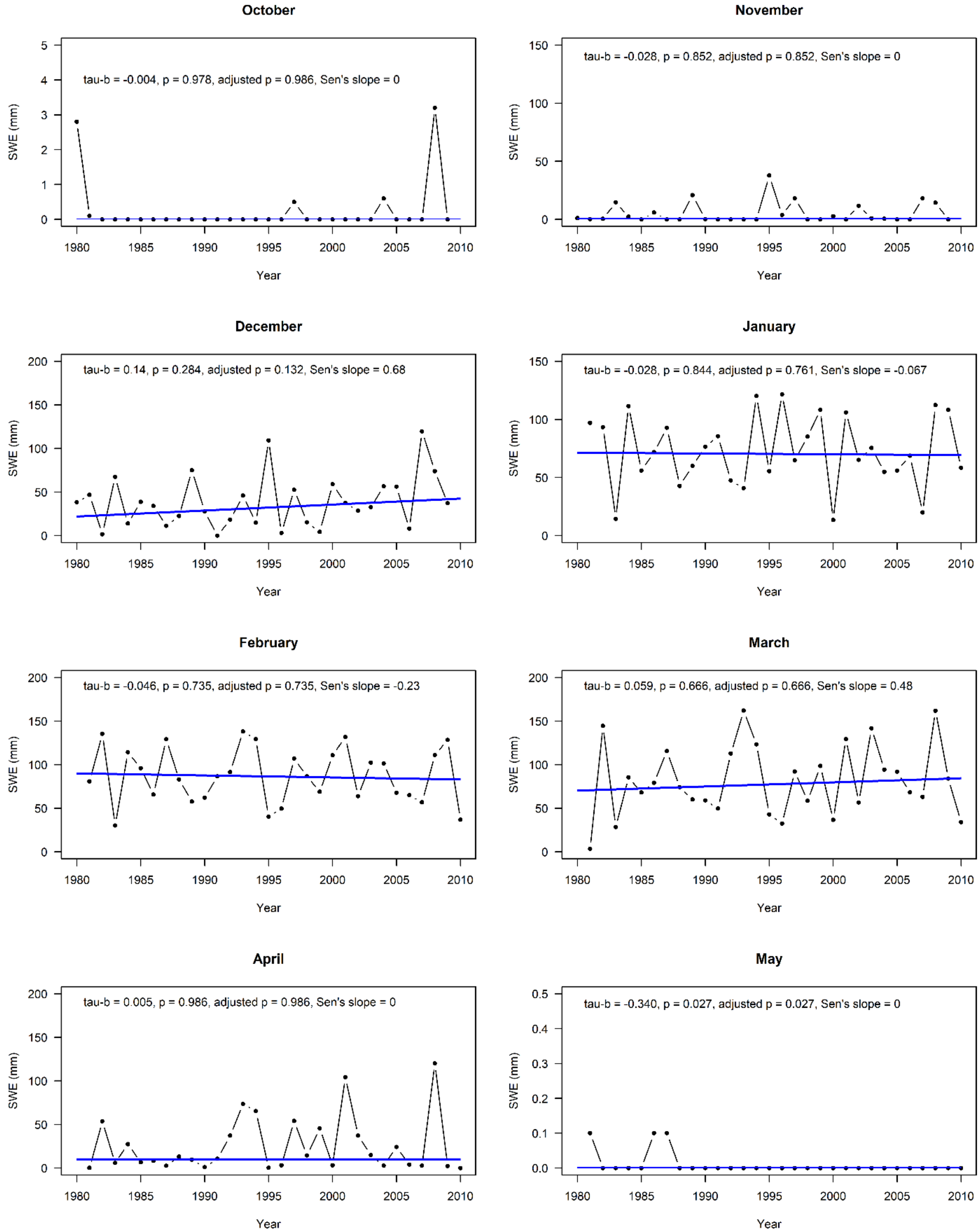

Figure A3.14. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Lower Ottawa watershed for water years 1981 to 2010.

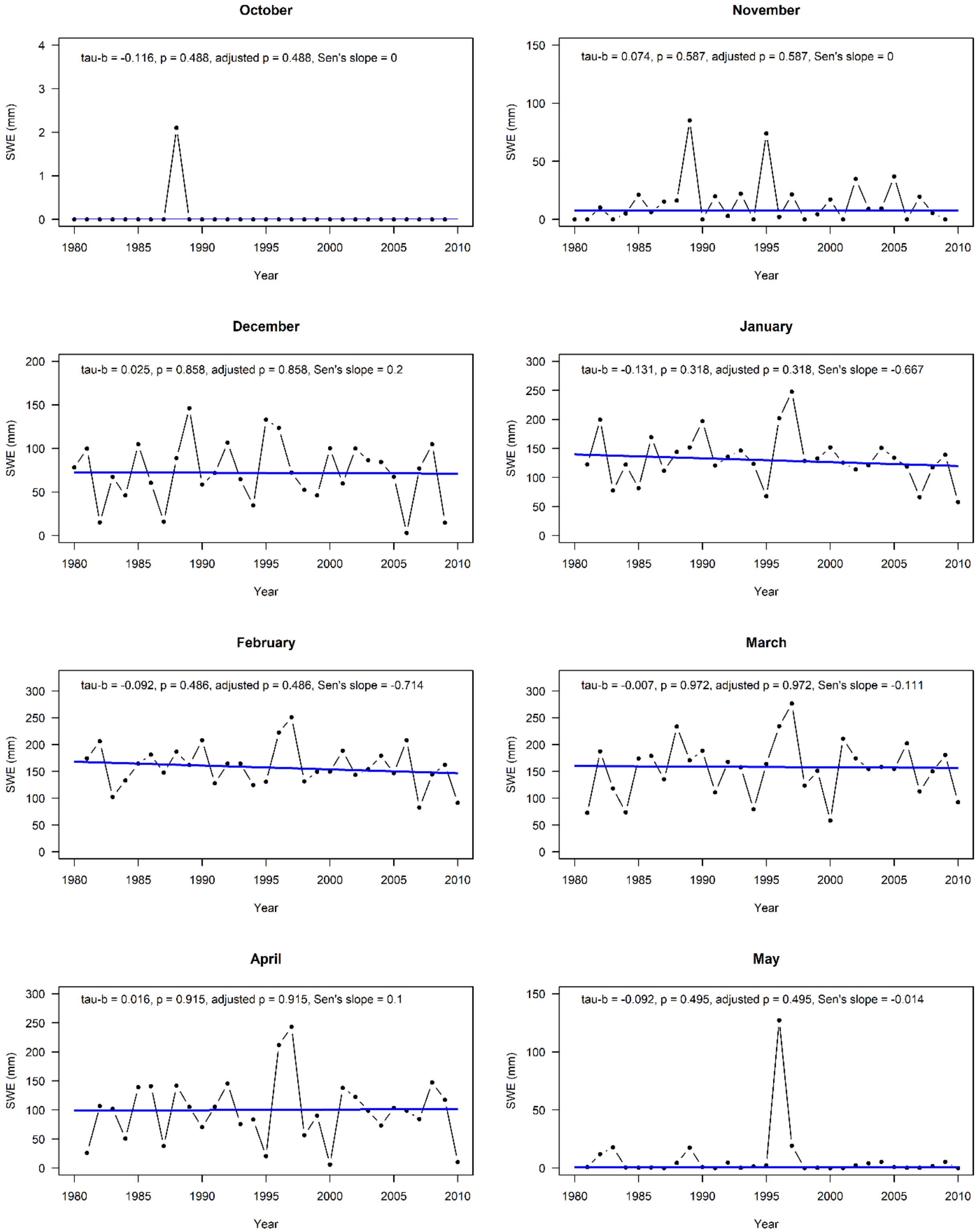

Figure A3.15. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Missinaibi Mattagami watershed for water years 1981 to 2010.

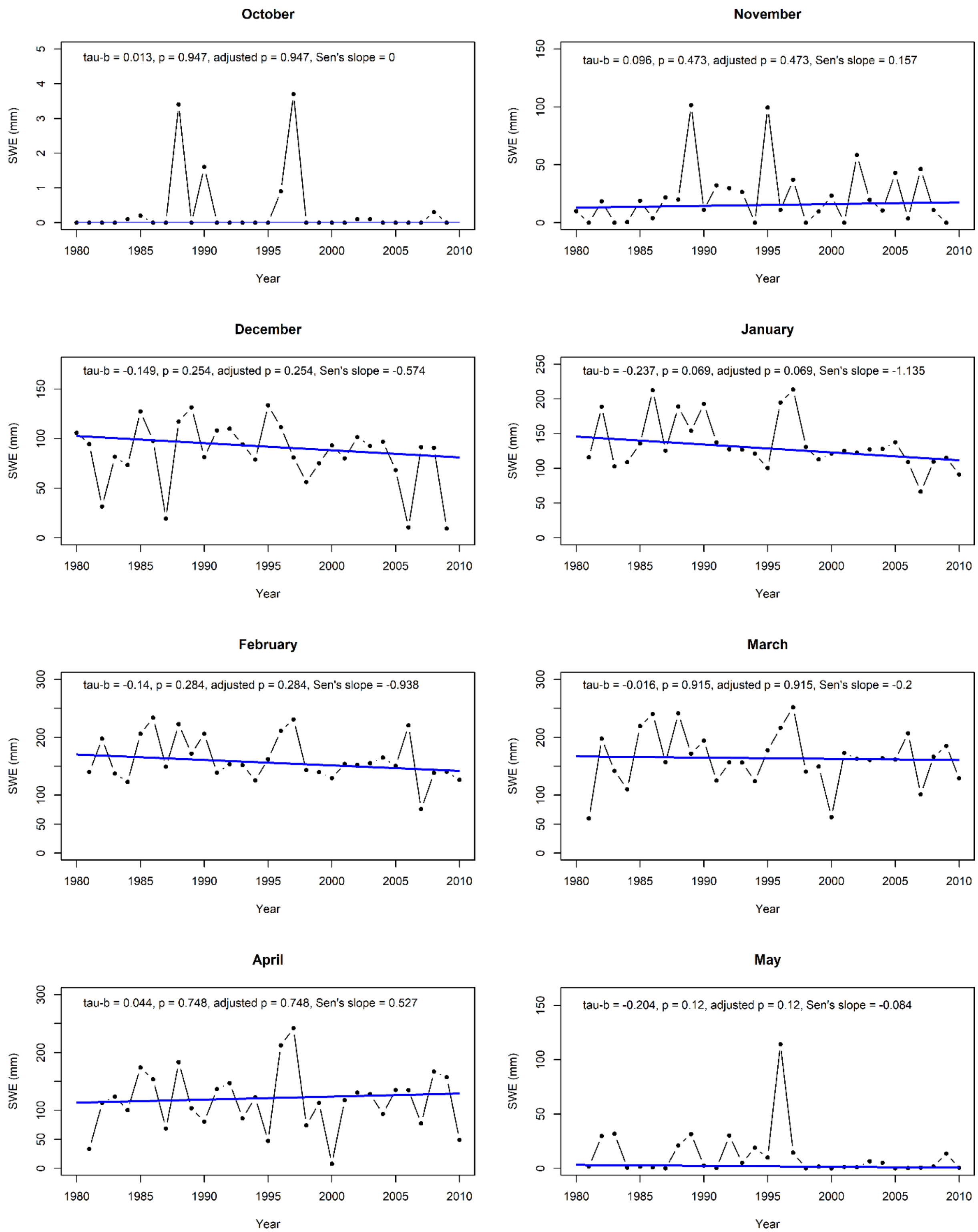

Figure A3.16. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Moose watershed for water years 1981 to 2010.

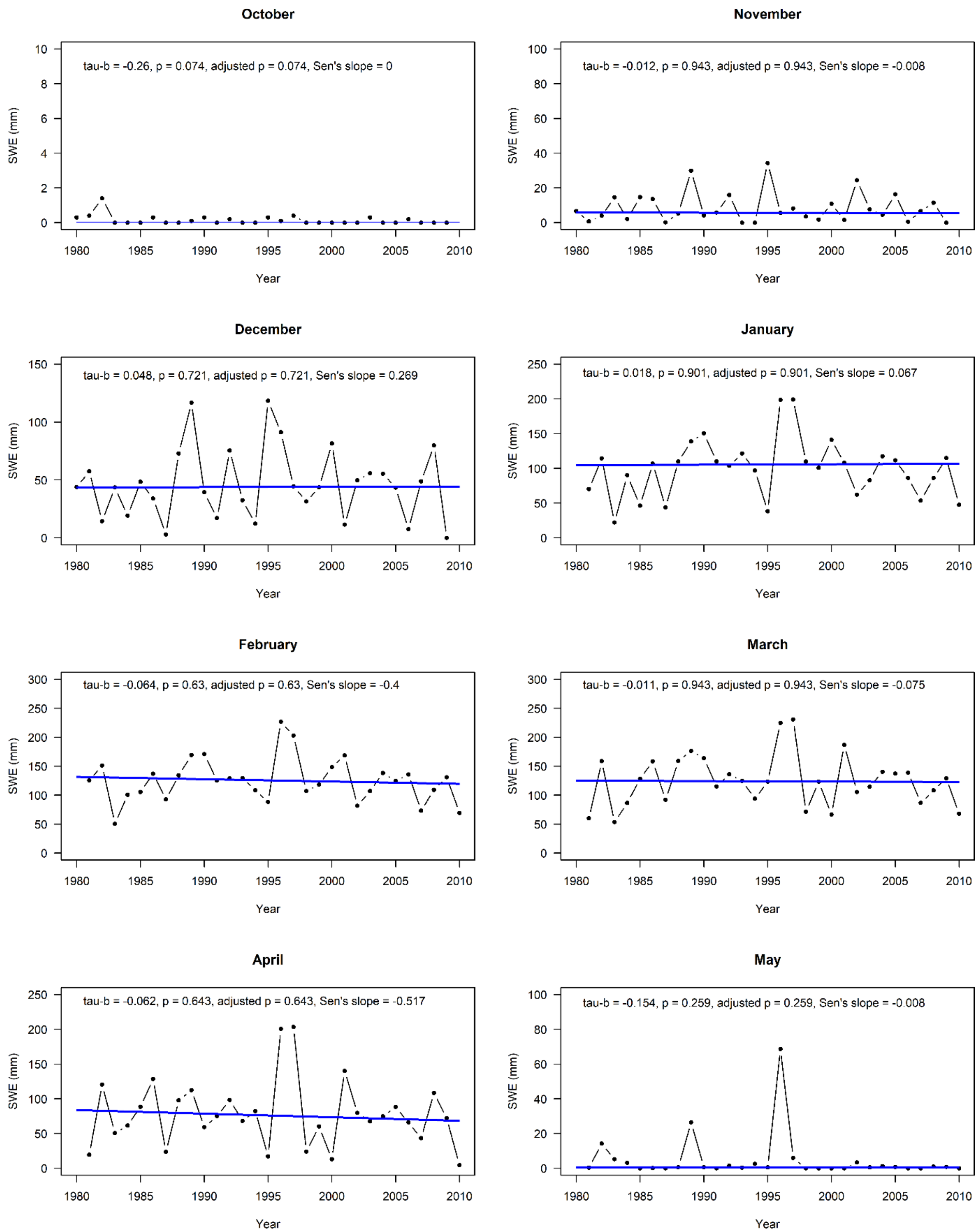

Figure A3.17. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Northeastern Lake Superior watershed for water years 1981 to 2010.

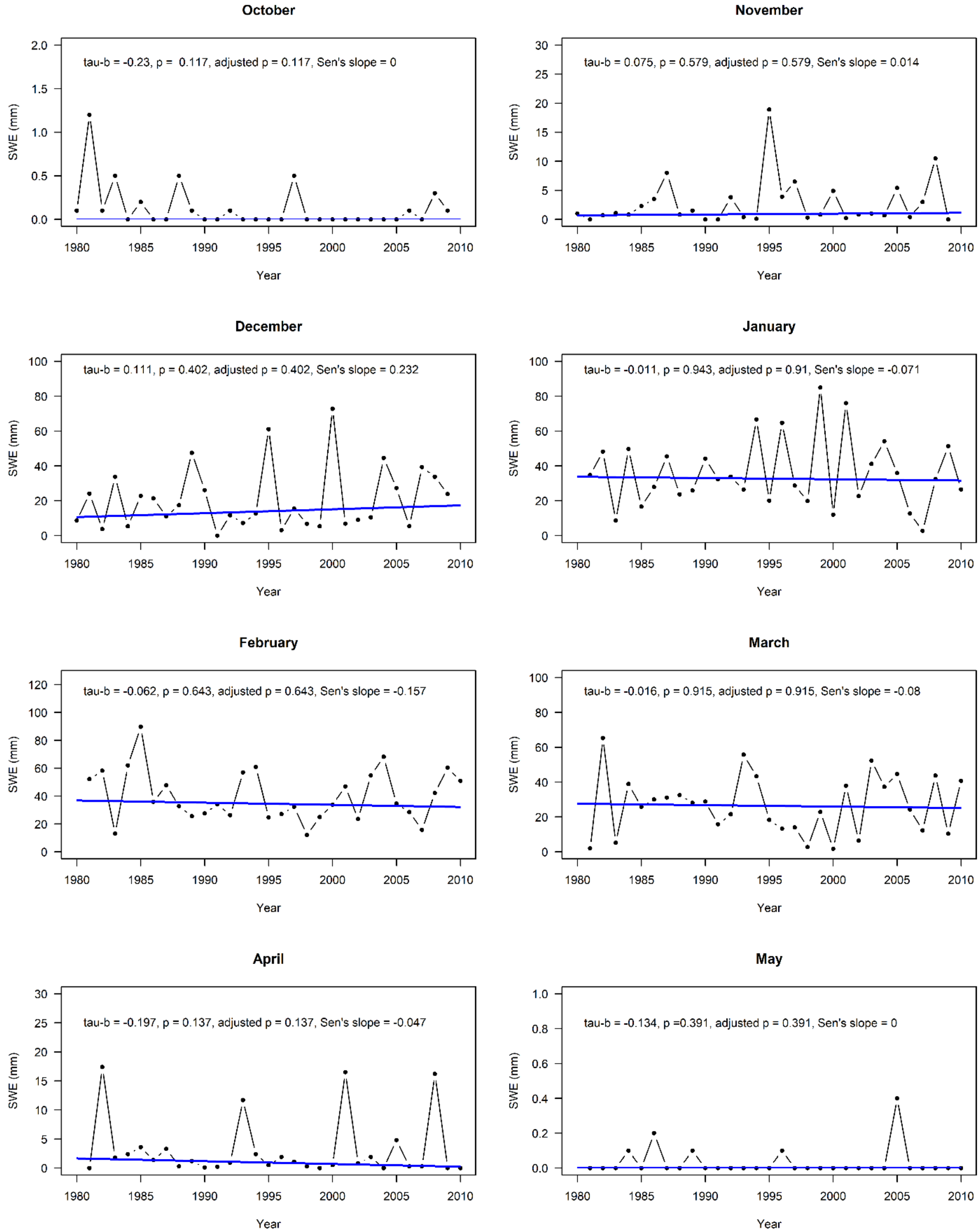

Figure A3.18. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Northern Lake Erie watershed for water years 1981 to 2010.

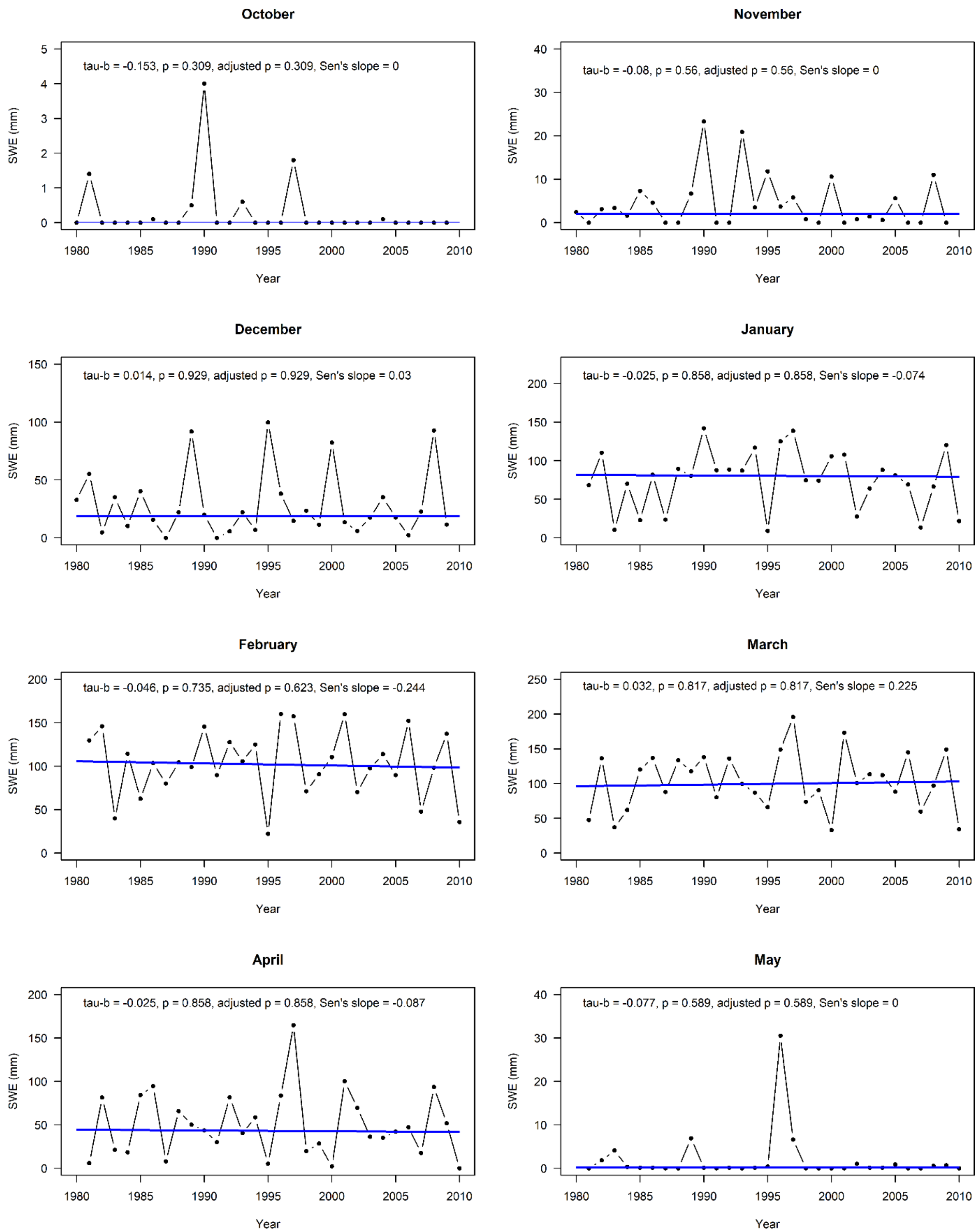

Figure A3.19. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Northern Lake Huron watershed for water years 1981 to 2010.

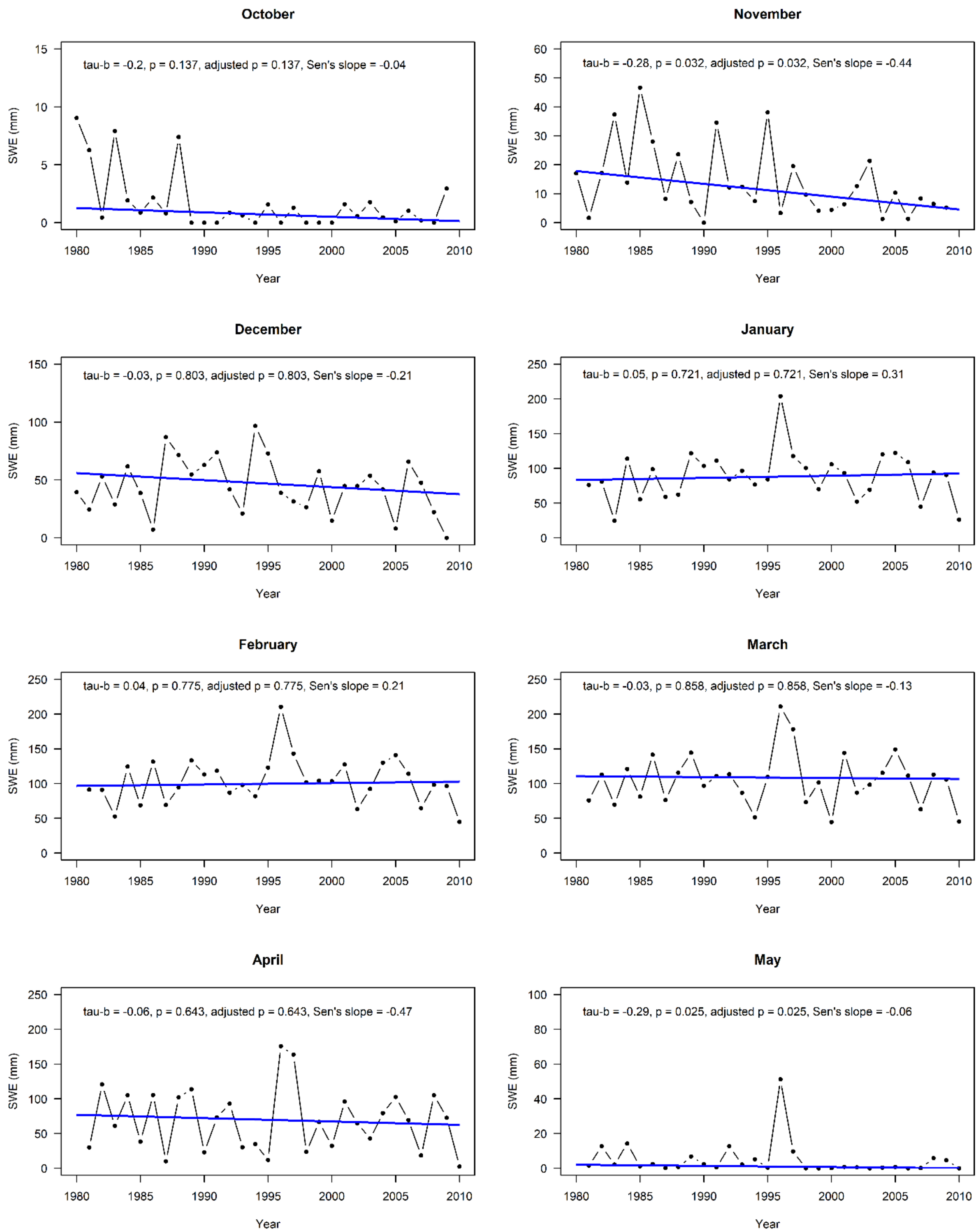

Figure A3.20. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Northwestern Lake Superior watershed for water years 1981 to 2010.

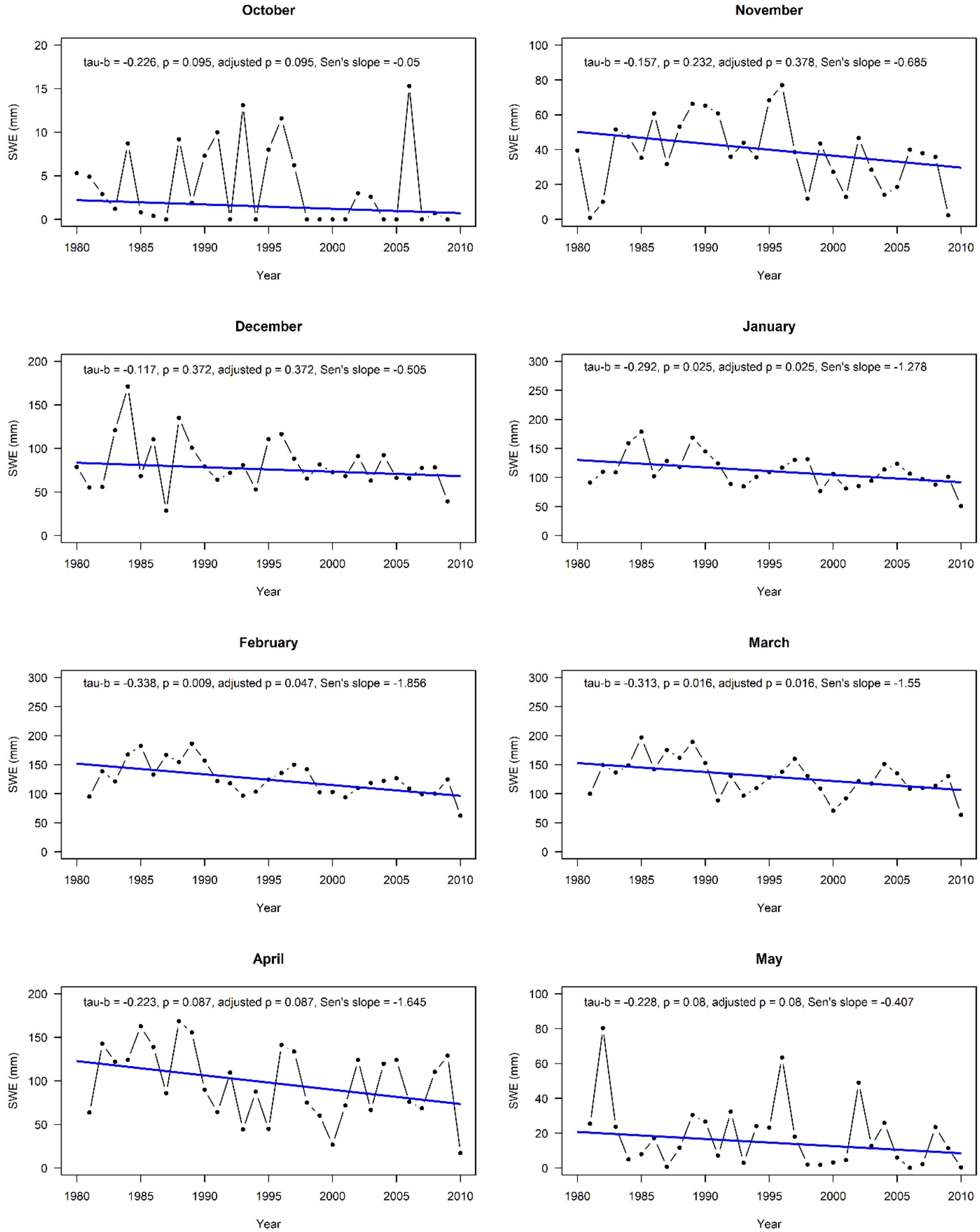

Figure A3.21. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Severn watershed for water years 1981 to 2010.

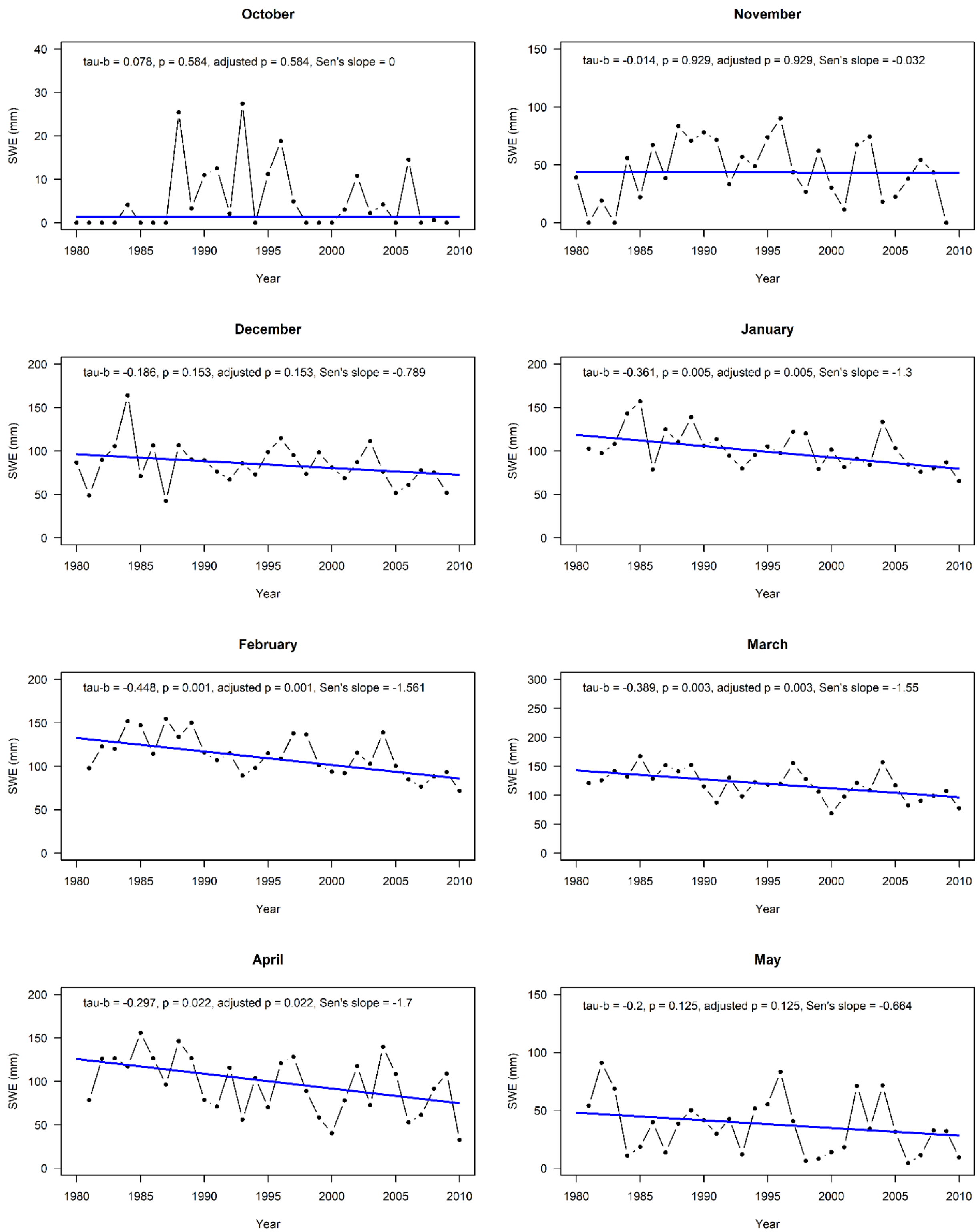

Figure A3.22. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Southwestern Hudson Bay Coast watershed for water years 1981 to 2010.

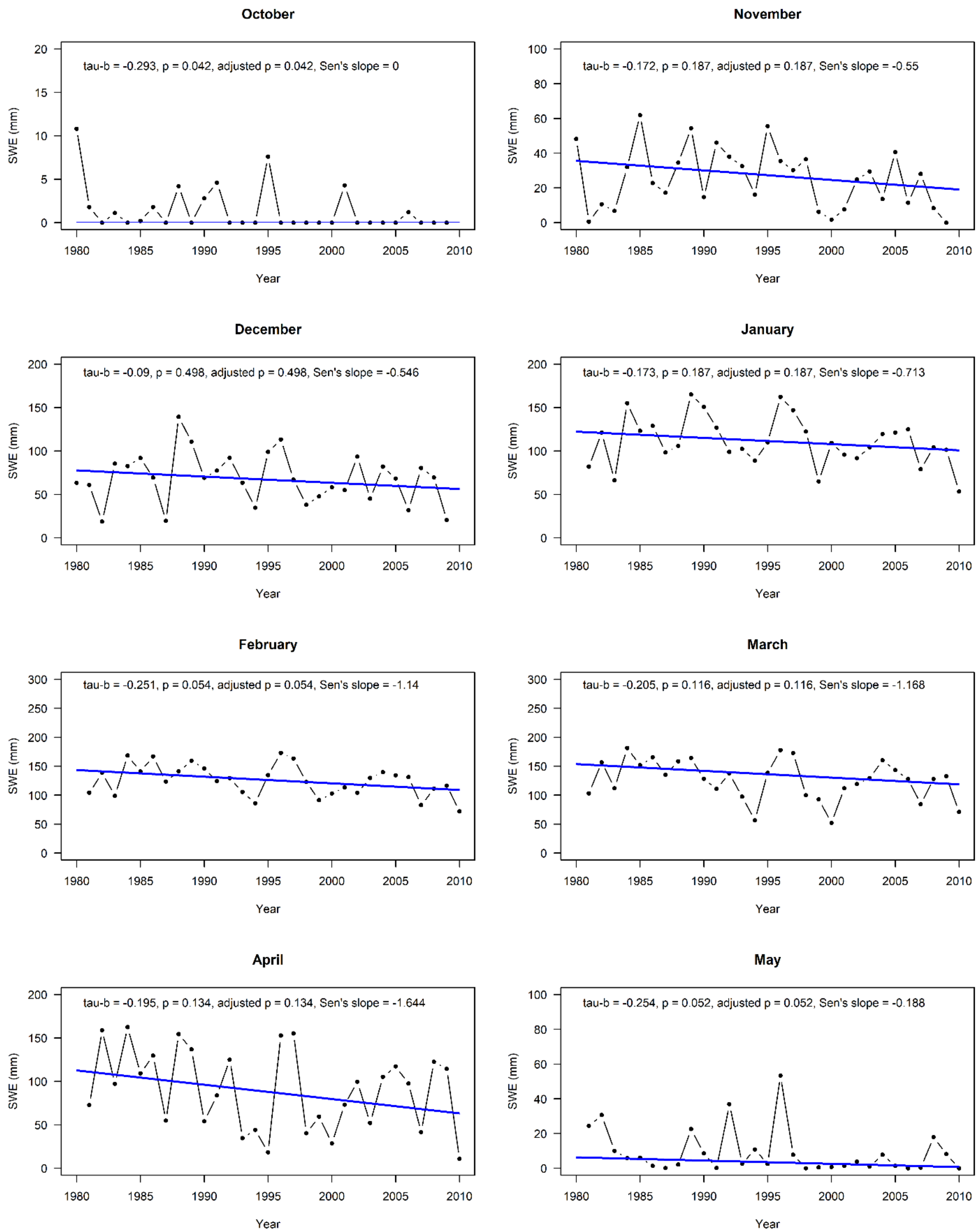

Figure A3.23. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Upper Albany watershed for water years 1981 to 2010.

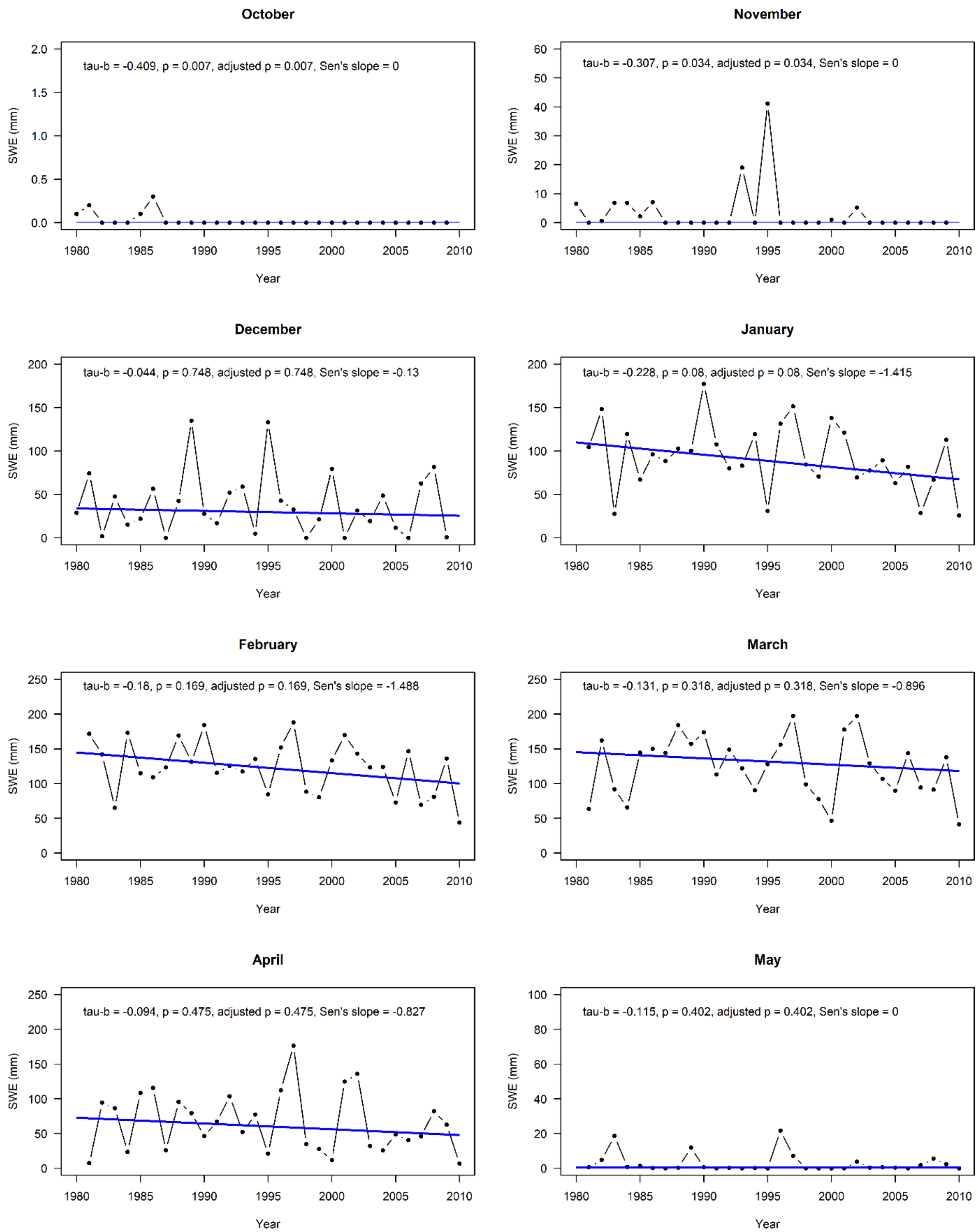

Figure A3.24. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Upper Ottawa watershed for water years 1981 to 2010.

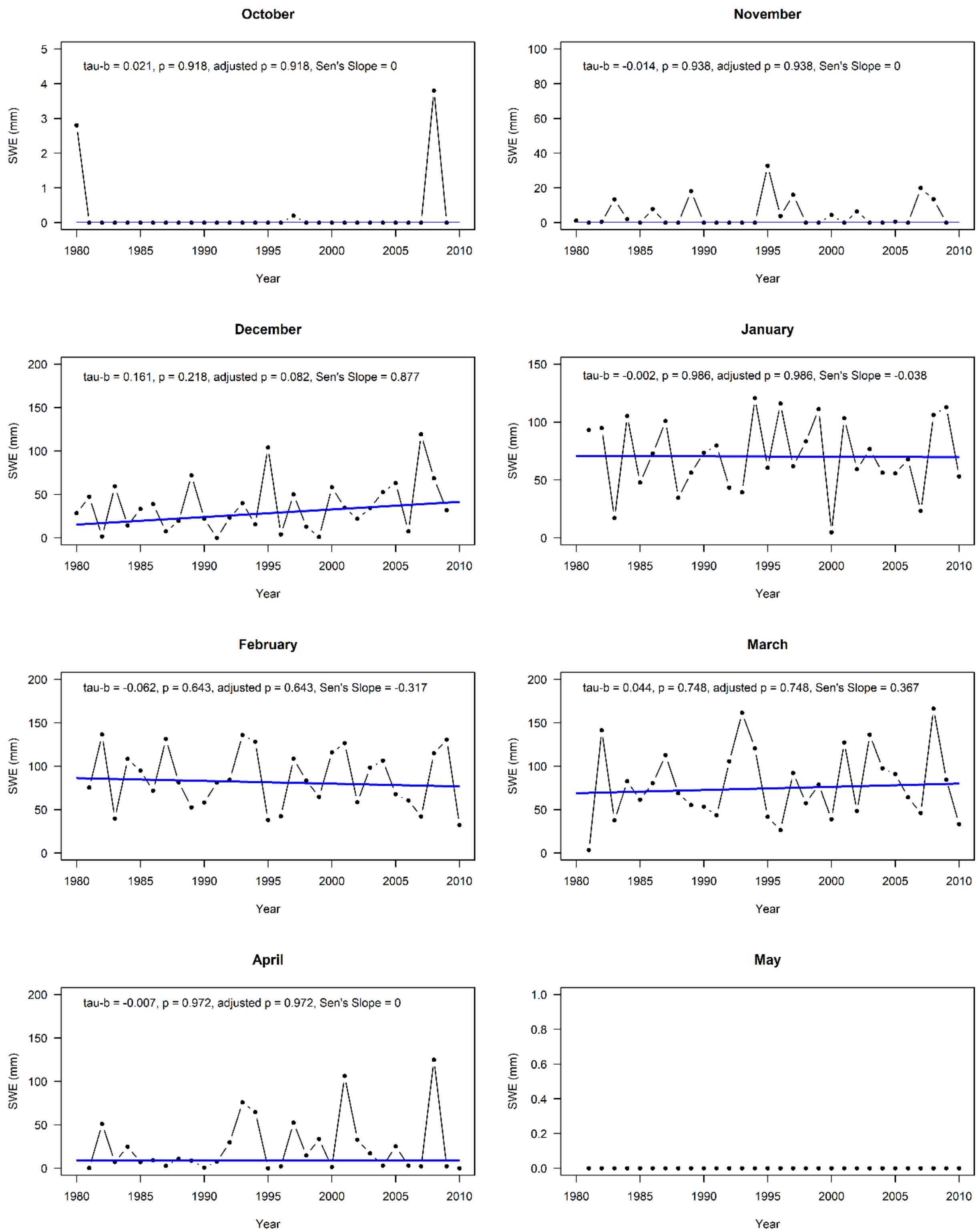

Figure A3.25. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Upper St. Lawrence watershed for water years 1981 to 2010.

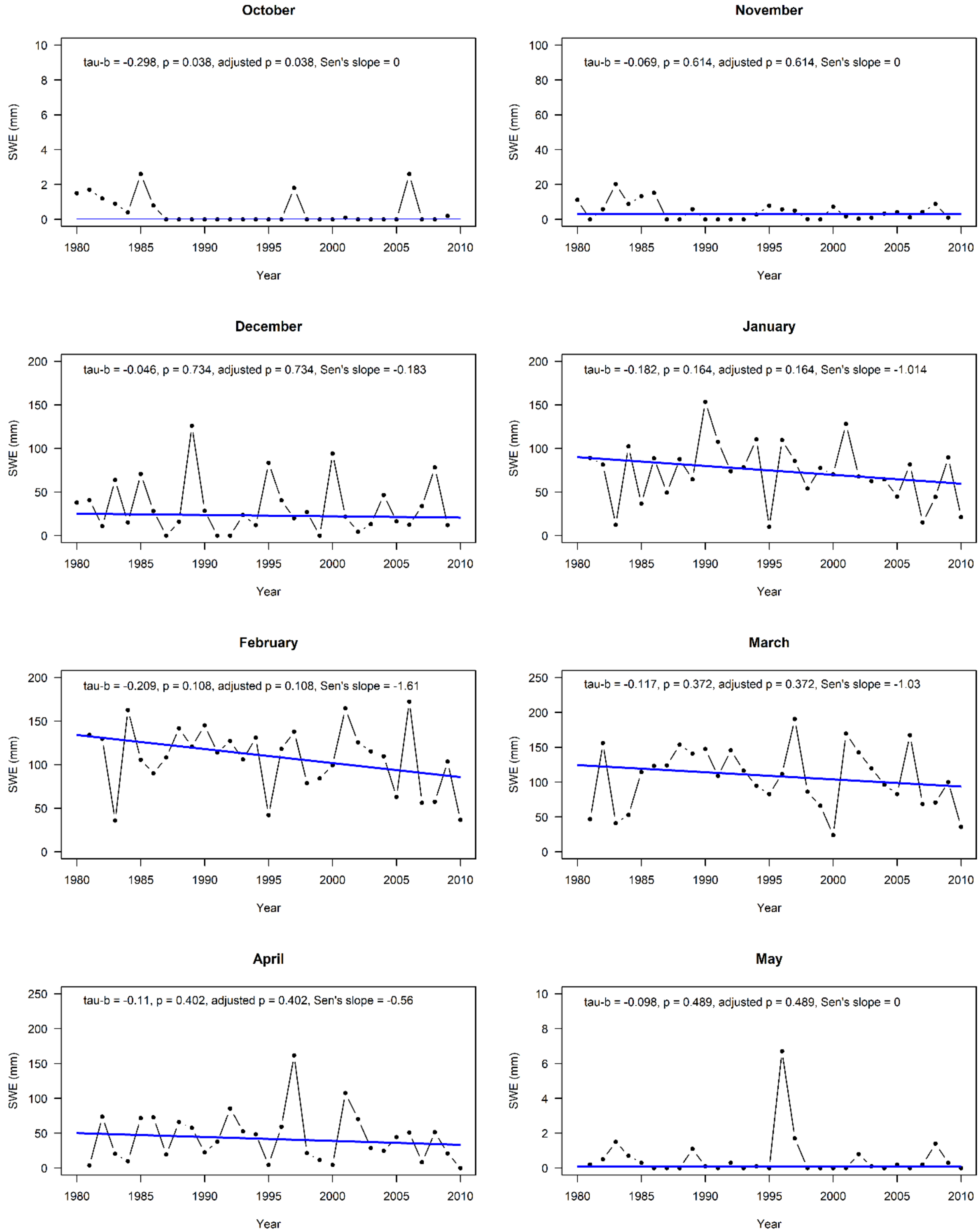

Figure A3.26. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Wanipitai and French watershed for water years 1981 to 2010.

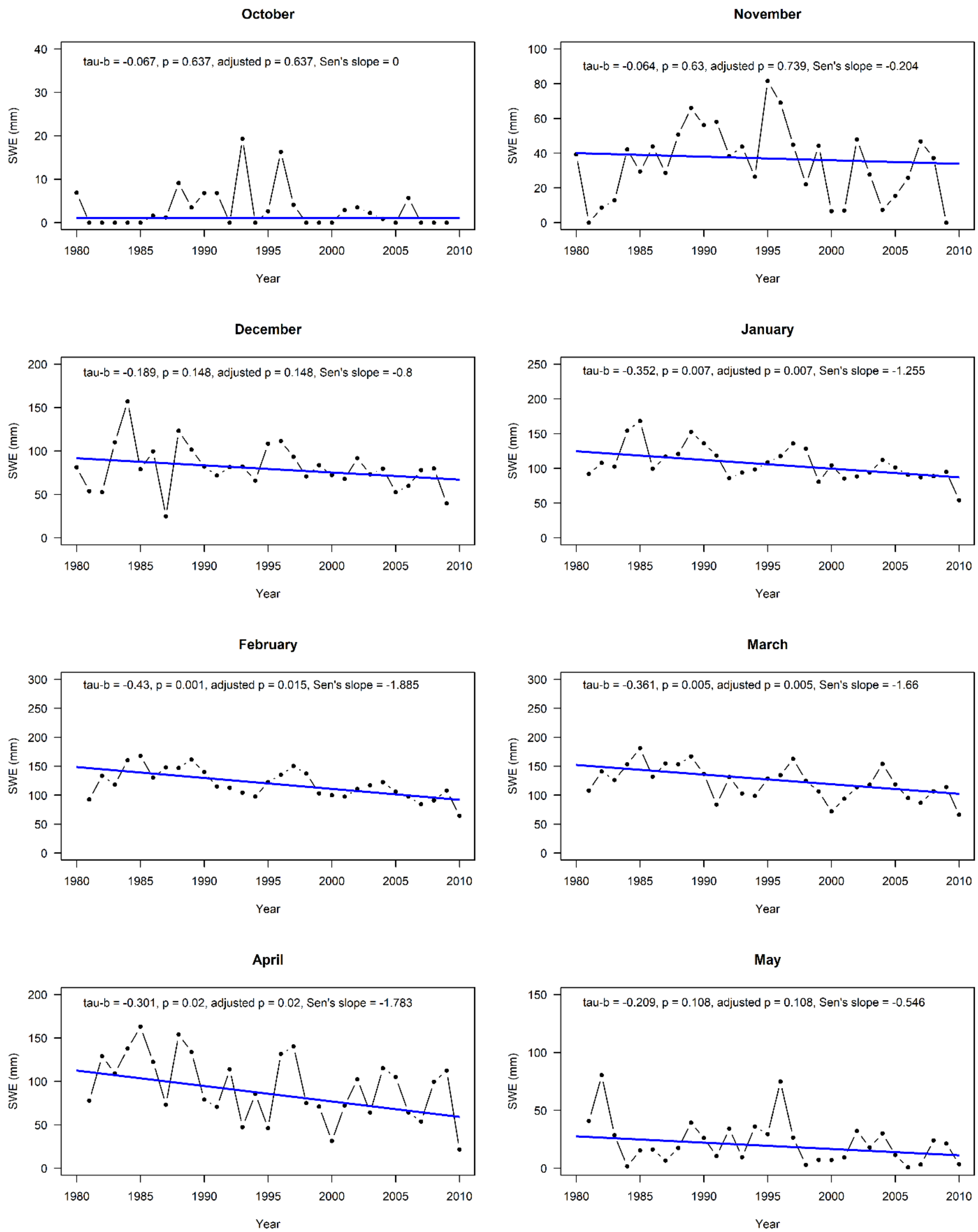

Figure A3.27. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Winisk Coast watershed for water years 1981 to 2010.

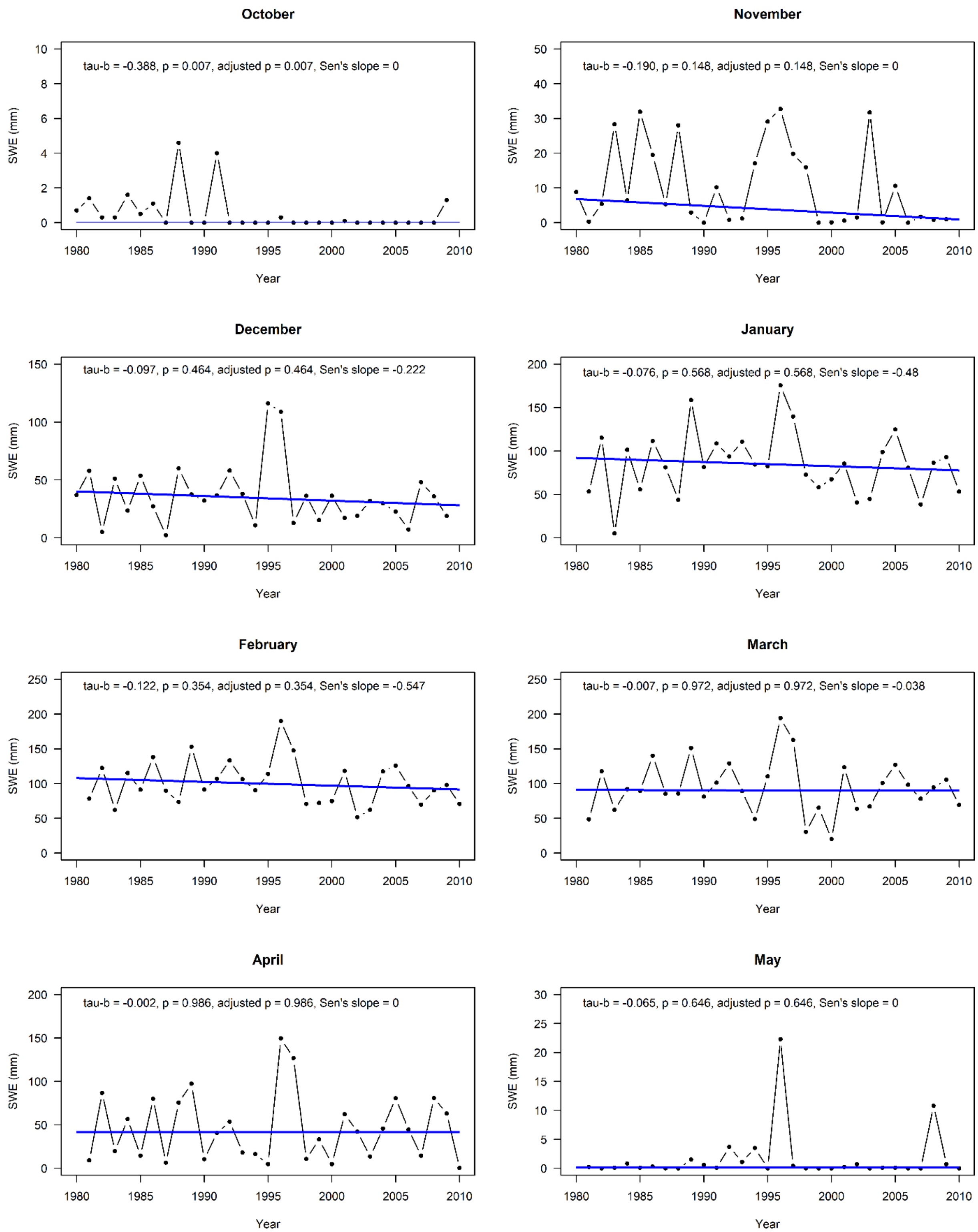

Figure A3.28. Satellite-derived seasonal monthly maximum snow water equivalent (SWE) and trend for the Winnipeg watershed for water years 1981 to 2010.

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