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Interannual Variations in Snowfall and Continuous Snow Cover Duration in Pelso, Central Finland, Linked to Teleconnection Patterns, 1944-2010

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Abstract**—**Climate warming would increase rainfall by shifting precipitation falling form from snow to rain, and would accelerate snow cover disappearing by increasing snowpack. Using temperature and precipitation data in the temperature-index snowmelt model, we evaluated variability of snowfall and continuous snow cover duration (CSCD) during 1944-2010 over Pelso, central Finland. Mann-Kendall non-parametric test determined that annual precipitation increased by 2.69 (mm/year, $p<0.05$) during the study period, but no clear trend in annual temperature. Both annual rainfall and snowfall increased by 1.67 and 0.78 (mm/year, $p<0.05$), respectively. CSCD was generally about 205 days from 14 October to 6 May. No clear trend was found in CSCD over Pelso. Spearman's rank correlation showed most significant relationships of annual snowfall with the East Atlantic (EA) pattern, and CSCD with the East Atlantic/West Russia (EA/WR) pattern. Increased precipitation with no warming temperature caused the rainfall and snowfall to increase, while no effects on CSCD.

Keywords**—**Variations, snowfall, snow cover duration, temperature-index snowmelt model, teleconnection patterns.

I. INTRODUCTION

SPATIALLY and temporally interactions of snow cover with surface thermal energy budget, atmospheric dynamics, and soli thermal energy conditions make the snow cover as a main component of global hydrologic cycle and climatic systems [1], [2]. Hence, variations in the snow cover basically change the water storage ability of snowpack, or in broader term affects the water management systems such as reservoirs [3]. Since 1969, the models about climate theory have considered the snow cover as a function of temperature [4]. The snow cover sensitivity to the temperature [5] proposes its strong negative relationship with average global temperature increasing [6]; however, this relationship could be changed in different regions.

At high latitudes of Northern Hemisphere, increases in temperature and precipitation are predicted by many climate models [7]. The warming would like to change precipitation form from snow to rain, and to increase melting rate and evaporation from snowpack. Both of these warming impacts resulted in reduction of snowfall as well as snow cover expand and duration, while increases in precipitation could make available enough snowfall for snow cover development. In northern Europe, changes in both precipitation and temperature, as main meteorological variables affecting the snowfall and snow cover duration, are associated with substantial variations in teleconnection patterns [8] that are defined as persistent modes of atmospheric circulation above a large area for a relative long time.

The goal of this paper is generally to investigate dependencies of variations in snowfall and continuous snow cover duration on climate variability and teleconnection indices in central Finland. To achieve this goal, four specific objectives are recognized: (1) to analyze a 65-water year (1 Sep-31 Aug) record of precipitation and temperature, that exposes the climate variability; (2) to determine changes in precipitation form from snow to rain and vice versa; (3) to identify changes in continuous snow cover duration, and; (4) to evaluate correlations of precipitation, temperature, rainfall, snowfall, and continuous snow cover duration with different teleconnection patterns.

II. STUDY AREA AND DATA

Study area is Peslo located in central Finland (Fig. 1) where mean annual temperature and precipitation were respectively about 1-2°C and 600-650 mm for winter time during calendar-based years from 1981 to 2010 [9]. Daily precipitation and temperature data (1944-2010) at Vaala Pelso weather station were obtained from Finnish Meteorological Institute (FMI) to use in this study. The station is located at coordinates of 64.5000° N and 26.4667° E (Fig. 1). The measurement of precipitation was done by a Wild gauge, but it was changed to a Tretjakov gauge by 1981 in order to measure solid precipitation more precisely. The measured snow water equivalent (SWE) data from November 1950 to December 2010 at Pelso snow course measurement located about 20 km northwest of Vaala Pelso station were found from the Environmental and Spatial Information Services (OIVA) website (http://wwwp2.ymparisto.fi/scripts/oiva.asp).

The teleconnection patterns of North Atlantic Oscillation (NAO), East Atlantic (EA), West Pacific (WP), East Pacific/

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North Pacific (EP/NP), Pacific/North American (PNA), East Atlantic/West Russia (EA/WR), Scandinavia (SCAND), Tropical/Northern Hemisphere (TNH), Polar/Euroasia (POL), Pacific Transition (PT), and Arctic Oscillation (AO) were used in this study. The Climate Prediction Centre (CPC) website (http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml) provides main information about all these teleconnections. Based on the 1981-2010 climatology, the standardized monthly values of these indices during which they are prominent in a year, are available for the period from 1950 to 2011 on the CPC website.

III. Methods

Using measured daily precipitation and mean temperature data from Vaala Pelso weather station, daily snow water equivalent (SWE) was simulated by the empirical temperature-index snowmelt model. The model assumes a linear relationship between snow melting and temperature. Main outputs from the model for this study were snowfall, rainfall and SWE.

This model has been discussed in details in [10]. Eleven parameters (Table I) were selected for model calibration using nonlinear least squares method between simulated and measured SWE for the period November 1950-April 1980. The model was also validated based on the simulated and measured SWE data from December 1980 to December 2010.

In this study, annual term refers to a water year from 1 September to 31 August. In addition, continuous snow cover duration is number of days in which the snow water equivalent is continuously more than zero mm (SWE > 0 mm) during the water year. Trends in annual values were calculated by Mann-Kendall non-parametric test [11]. Correlation analyses were done based on Spearman's rank correlation that is precise for small data series because it does not follow any specific probability distribution of variables and also assumes no linear relationship between them [11].

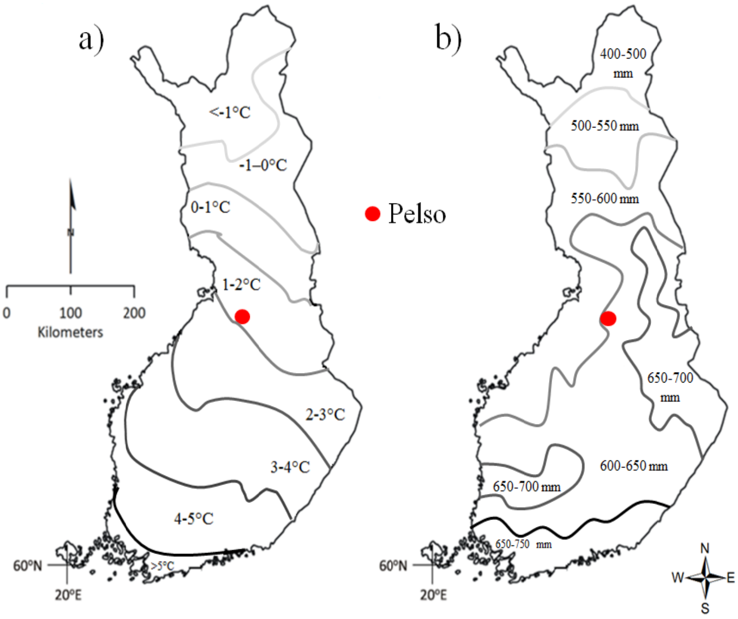

Fig. 1 Study area in Finland's map of (a) average annual temperature (°C) and (b) average annual precipitation (mm), during 1981-2010 Compiled based on [9]

TABLE I
SELECTED PARAMETERS FOR CALIBRATION OF THE TEMPERATURE-INDEX SNOWMELT MODEL

Parameter	Description	Lower bound*	Upper bound*	Initial value	Calibrated value (Nov 1950- Apr 1980)
Tmin	Snowfall base temperature (°C)	-6.100	0.000	-0.830	-3.534
Tmax	Rainfall base temperature (°C)	-0.100	3.500	-0.100	2.500
Csnow	Snowfall correction coefficient	1.050	1.800	1.100	1.241
Crain	Rainfall correction coefficient	1.010	1.400	1.030	1.358
Kd	Degree-day factor (mm °C-1 day-1)	0.800	14.00	1.410	3.180
Tmelt	Snowmelt base temperature (°C)	-0.50	2.100	0.000	0.821
r	Liquid water retention capacity	0.020	0.520	0.029	0.029
Kf	Refreezing coefficient (mm °C-e day-1)	0.020	5.100	3.500	1.216
Tf	Refreezing base temperature	-5.000	-0.001	0.000	-2.339
e	Exponent	0.001	1.000	0.000	0.116
E	Evaporation from snow	0.001	0.500	0.000	0.012

*From literature ([10]).

IV. RESULTS

A. Statistical Analysis of Snowmelt Model Performance

Model performance was evaluated by five statistical indicators [12]: the Nash-Sutcliffe coefficient of efficiency (NSE), Percent deviation from measured snow water equivalent (PBIAS), root mean squared errors (RMSE), slope of regression line (S), and coefficient of determination (R2). The model was performed very well for calibration period (Figs. 2 (a) and (c)) when the statistical indicators were NSE = 0.90, PBIAS = 2.89 %, RMSE = 16.35, S = 0.98 and R2 = 0.91. The snowmelt model also showed a very good performance for validation period, see (Figs. 2 (b) and (d)), (NSE = 0.44, PBIAS = -25.11%, RMSE = 39.07, S = 0.97 and R2 = 0.69).

B. Climate Variability

Climate variability was characterized by anomalies of annual precipitation and mean temperature which are deviations from the whole period (1944-2010) average value calling, hereafter, base value. The base values of annual precipitation and mean temperature were equal to 761.25 mm and 1.85°C, respectively (Fig. 3). Trend analysis determined an increasing trend by 2.69 (mm/year, $p<0.05$) in annual precipitation (Fig. 3 (a)), while no significant trend in annual temperature (Fig. 3 (b)). Correlation analysis (Table II) indicated the strongest relationship of annual precipitation with the SCA pattern (rho = -0.44, $p<0.05$), and for annual temperature with the AO index (rho = 0.50, $p<0.05$). The mentioned anomalies for period 1944-2010 and their linkages to the AO and SCA patterns are represented in Figs. 3 (a) and (b), respectively. All statistically significant correlations between annual precipitation and mean temperature with different teleconnection patterns are given in Table II.

C. Precipitation Forms

Base value for annual rainfall was 570.64 mm and for snowfall was equal to 190.62 mm (Figs. 4 (a) and (b)). At 5% significance level, there were increasing trends by 1.67 and 0.78 (mm/year) in annual rainfall and snowfall during water years from 1944 to 2010 (Figs. 4 (a) and (b)), even temperature was unchanged. According to Table II, rainfall was strongly associated with the SCA pattern (rho = -0.37, $p<0.05$) similar to the annual precipitation. In addition, the temperature showed the most significant correlation with the EA pattern (rho = 0.29, $p<0.05$). Both annual rainfall and snowfall anomalies (from 1944 to 2010) and their strongest linkage to the SCA and EA patterns are shown in Figs. 4 (a) and (b), respectively. According to Table II, annual snowfall also showed statistically significant correlations with the SCA pattern (rho = -0.26, $p<0.05$).

D. Continuous Snow Cover Duration

In general, continuous snow cover duration (CSCD) was 205 days from 14th of October to 6th of May. No clear trend was found in CSCD over the period 1944-2010 in Pelso, central Finland (Fig. 4 (c)). Both start and end days of CSCD also showed no significant trends (not presented here). Based on Table II, CSCD was significantly in relation to the EA/WR pattern (rho = 0.27, $p<0.05$) (Fig. 4 (c)). The start day of CSCD showed no significant correlation with different teleconnection patterns considered by this study, but its end day was significantly ($p<0.05$) associated with variations in the AO (rho = -0.26), same teleconnection influencing annual temperature, and POL (rho = 0.25) patterns (Table II). The annual anomalies of CSCD from 1944 to 2010 and their linkage to the EA/WR pattern are represented in Fig. 4 (c).

TABLE II

STATISTICALLY SIGNIFICANT ($p<0.05$) SPEARMAN'S RANK CORRELATION (RHO) BETWEEN MAIN VARIABLES AND CLIMATE TELECONNECTION PATTERNS

Variable	NAO	EA	WP	EP/NP	PNA	EA/WR	SCA	TNH	POL	PT	AO
Annual Precipitation							-0.44				0.25
Annual Temperature	0.29					-0.27					0.50
Annual Rainfall							-0.37				
Annual Snowfall		0.29					-0.26				
CSCD start day											
CSCD end day									0.25		-0.26
CSCD						0.27					

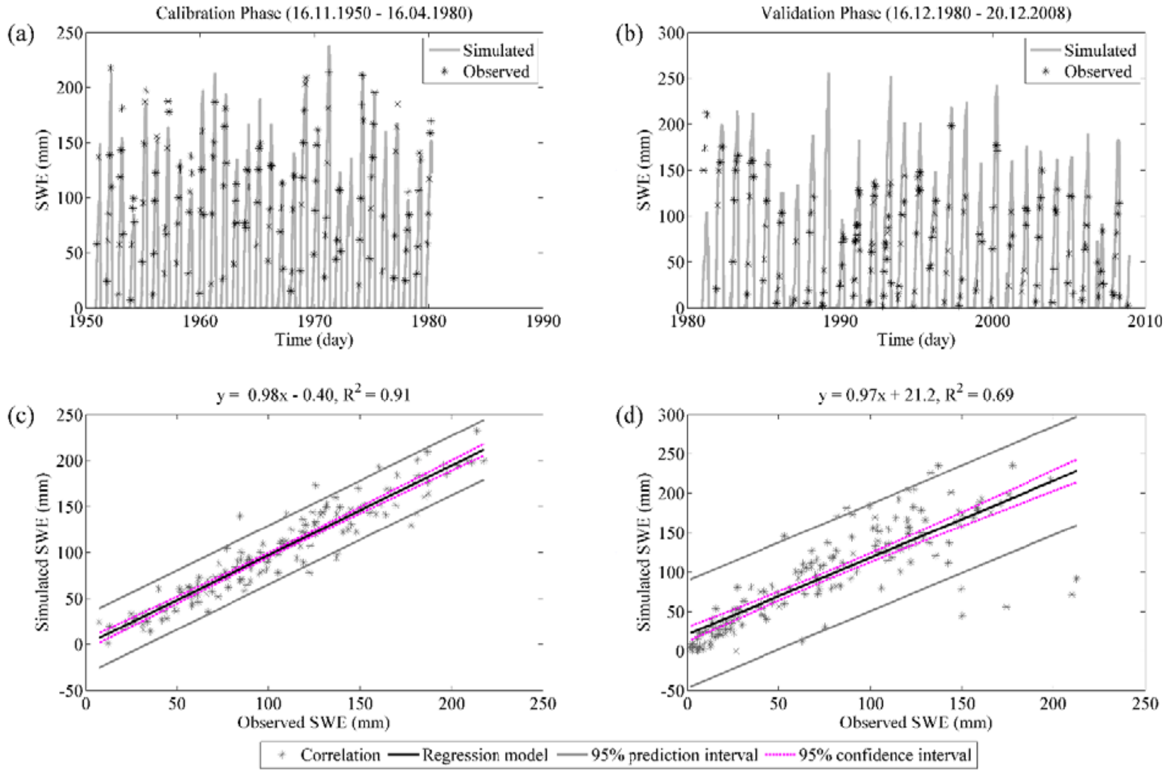

Fig. 2 Comparison of measured and simulated SWE for both (a and c) calibration (1950-1980) and (b and d) validation (1980-2010) phases

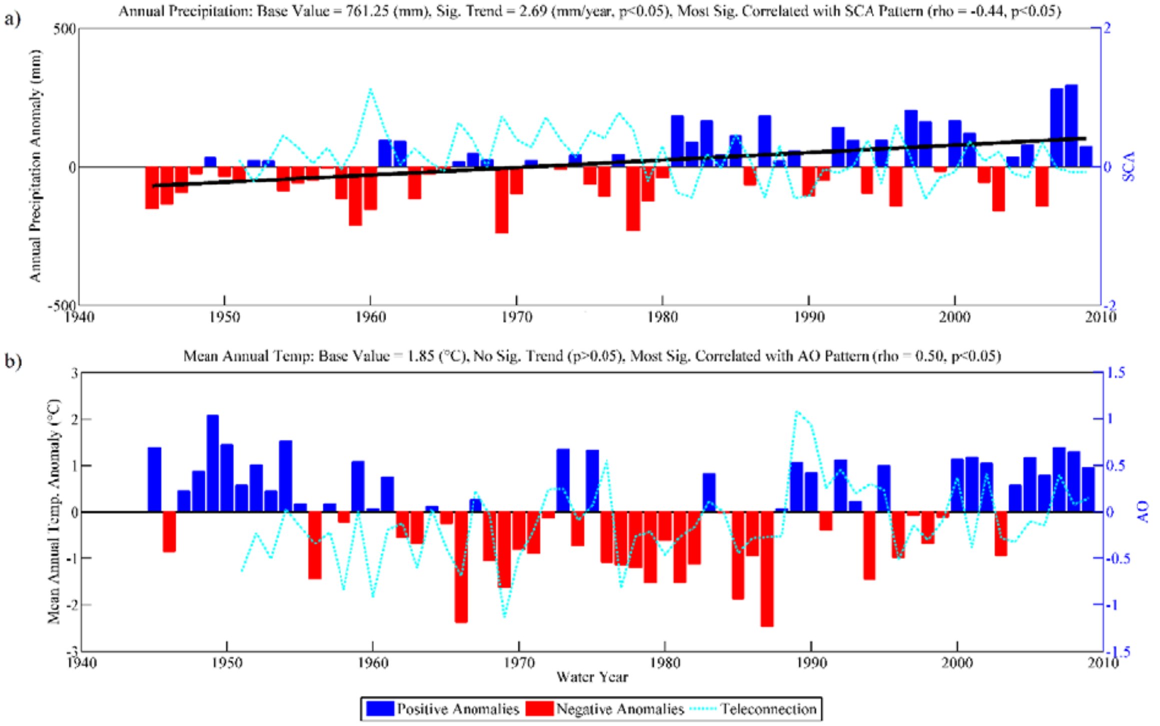

Fig. 3 (a) Annual precipitation anomalies linkage to SCA pattern and (b) annual mean temperature anomalies linkage to the AO index

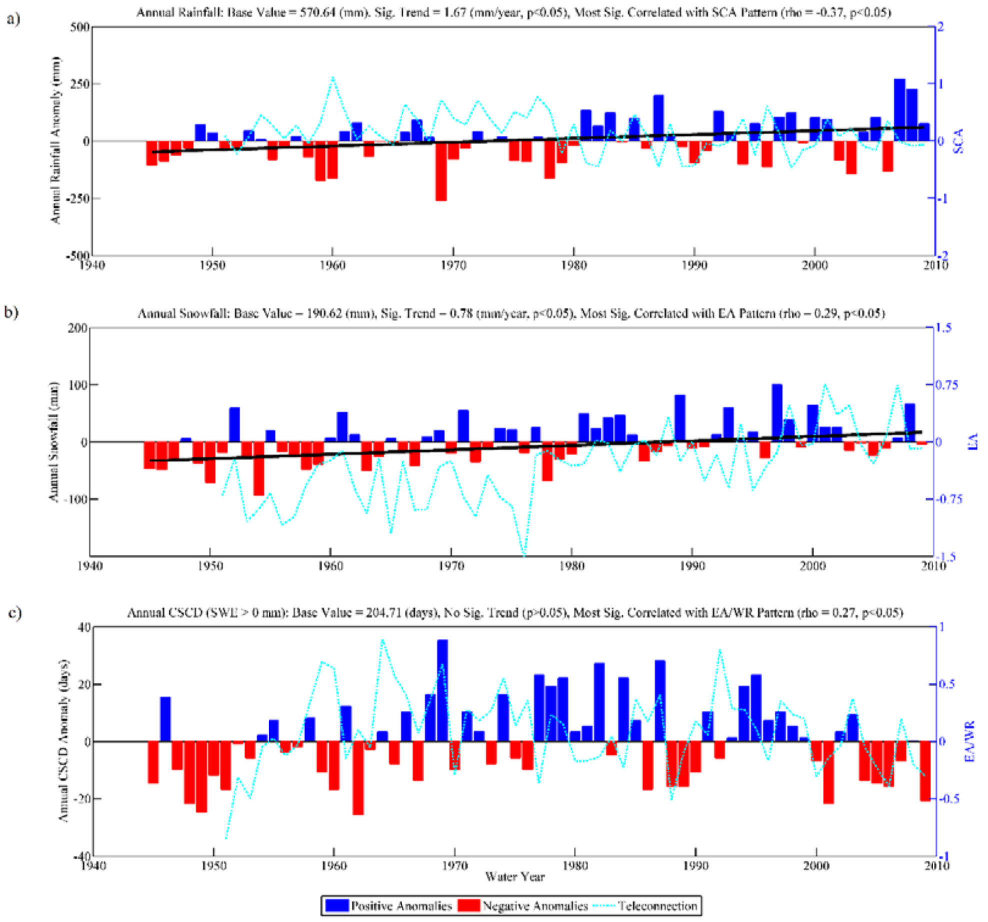

Fig. 4 Time series of (a) Annual rainfall anomalies, (b) annual snowfall anomalies and (c) annual continuous snow cover duration anomalies, with significant trend line and linkages to the strongest influential teleconnections

V. DISCUSSION AND CONCLUSIONS

The empirical snowmelt temperature-index model was calibrated and validated well to simulate snow water equivalent based on data from VaalaPelso weather station, central Finland. Climate variability analysis based on anomalies of annual precipitation and mean temperature determined that annual precipitation increased through the water years from 1944 to 2010, but there was no clear trend in annual mean temperature. Increases in precipitation together with unchanged temperature caused rainfall and snowfall to increase. Increasing trend in precipitation found by this study was in agreement with the study by [13] that showed the annual precipitation increased by 0.92±0.50 (mm/year, $p<0.05$) during last century over Finland. Reference [14] concluded that mean annual temperature on a national scale of Finland has been increased by 0.40±0.20 (°C/decade, $p<0.05$) during 1961-2011. In addition, new projections about climate in Finland estimate increasing trend by 2-6 °C in temperature and by 13-26% in precipitation until the 2080s [15]. Based on these changes, 40-70% decreasing in accumulation of snow is expected over Finland by the end of 21st century [15], [16]. However, the present study determined increases in snowfall over Pelso in central Finland during 1944-2010. This contrast may refer to the projected temperature warming which was not seen during the study period of this study (1944-2010). It seems, in future, increases in precipitation cannot offset effects of temperature warming on snowfall in central Finland.

The Scandinavia (SCA) pattern was the most significant teleconnection influencing annual precipitation, rainfall and partially snowfall in Pelso. The AO index was the most influential teleconnection on variations in annual temperature, and consequently the end day of CSCD. However, CSCD showed interannual variability without significant changes, which was positively associated with the EA pattern in Pelso. Reference [13] reported strong correlation between the EA/WR pattern and annual precipitation in Finland. Reference [14] showed the significant relationships between the AO index and mean annual temperature over Finland. It can be concluded the increases in precipitation, connected to substantial variations in the SCA pattern, intensified annual rainfall and snowfall, while no changes in temperature was resulted in no alterations in CSCD, over Pelso in central Finland.

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