CSCE Annual Conference
Growing with youth – Croître avec les jeunes

Laval (Greater Montreal)
June 12 - 15, 2019

TEMPERATURE CONTROLS OF THE FREEZE AND THAW PATTERNS IN QUEBEC

Hatami, S.[1,2] and Nazemi, A.[1]
[1]Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Quebec, Canada.
[2] s_hatam@encs.concordia.ca

Abstract: Accurate quantification of Freeze and Thaw (FT) dynamics is essential for better understanding of environmental processes and socio-economic activities across cold regions. However, climate variability and change can significantly perturb the characteristics of FT patterns, which can in turn result in profound alterations in land-surface characteristics. Investigating the control of temperature on FT is therefore an important step toward advising effective adaptation strategies for future human developments at higher latitudes. There are, however, a number of deficiencies associated with in-situ measurement of FT in terms of temporal and spatial extent of data as well as limitations in extending the local data to regional knowledge. To avoid these gaps, we use gridded remotely sensed FT data record and pair them with gridded surface air temperature data to quantify the association between temperature and FT patterns across Quebec during 1979 to 2016. We study the joint dependence between annual temperature and FT patterns and analyze its variability over time and space. Considering the changes in copula parameters, we address the role of geographic characteristics on altering the temperature control on FT. The copula methodology is employed to formally quantify temperature control on FT dynamics at the annual scale. We conclude that copulas provides a generic tool for assessing the future FT according to future projections of temperature.

Keywords: Freeze and Thaw dynamics, Gridded remotely sensed data, Copula, Climate variability and change

1 INTRODUCTION

Landscape Freeze and Thaw (FT) is one of most important cryosphere processes in cold region. This is due to the impacts of FT on formation of environmental processes and socio-economic activities (Williams, et al. 2015; Entekhabi et al. 2004). Although many hydroclimate variables such as snow depth and precipitation are effective on FT patterns, the timing and distribution of FT dynamics are majorly controlled by near surface air temperature (Frauenfeld et al. 2004). As a result, the changes in air temperature can perturb the characteristics of FT patterns over time and space. These changes are specifically observed across northern regions and during cold season (Henry 2008). There are, however, known deficiencies in in-situ data measurements such as being constraint in capturing spatial and temporal patterns of climate and FT states through the usage of station-scale measurements, particularly at higher latitudes with extremely sparse measurement network (Takala et al. 2009). Furthermore, interpolating the available data from weather stations into data-sparse regions can result in ignoring the role of geographic characteristics on the FT patters, particularly over larger scales (Williams et al. 2000). Satellite microwave data can overcome the limitations of in-situ measurmens by providing a synoptic monitoring technology for understanding the spatiotemporal variability of FT patterns. Continuous, remotely sensed time series of daily FT states have become recently available (Park et al. 2016) and can be paired with gridded temperature data to explore the statistical association between temperature and FT patterns. To evaluate the control of temperature on FT formally, their joint dependencies must be taken into account. Copula provides a powerful statistical framework for modeling these interdependencies (Nazemi and Elshorbagy 2012). In this study, the copula methodology is employed to quantify the temperature control on different FT characteristics over Quebec. To showcase the utility of copula methodology, we address the impacts of 1° warming on annual FT characteristics over different spatial scales and within different time period.

2 DATA AND CASE STUDY

The FT data used in this study consists of classified remotely-sensed FT data, available from the newest version of FT Earth System Data Record (FT-ESDR; Kim et al., 2011). The data is based on retrieval of bi-daily FT states, using calibrated bi-daily (AM and PM) brightness temperature (Nghiem et al. 2012). Brightness temperature is essentially a physical temperature related to land-surface thermal emission. The changes in emissivity due to its sensitivity to water content in snow or ice as well as available information on temperature across the landscape enable the usage of brightness temperature in detection and mapping of FT. The daily FT state in relation to brightness temperature is then classified into four discrete classes, namely frozen (AM and PM frozen), non-frozen (AM and PM non-frozen), transitional (AM frozen and PM non-frozen) and inverse-transitional (AM non-frozen and PM frozen). This data is available publically at the daily scale and at 25 km × 25 km spatial resolution for the period of 1979 to 2016 (McDonald et al. 2004; check https://doi.org/10.5067/MEASURES/CRYOSPHERE/nsidc-0477.004). From this data, we extracted number of frozen (NF) and number of thawed (NT) days in each year (September- August) and paired it with historical gridded maximum and minimum daily temperature provided by Global Meteorological Forcing Dataset (http://hydrology.princeton.edu/data.pgf.php; see Sheffield et al. 2006) during the same period. The average of mean daily temperature over each year (September- August) is then obtained as the mean yearly temperature (T_{mean}) in each grid. Indeed, the yearly data period starts from September 1979 (beginning of FT year of 1980) to August 2016 (end of FT year of 2016). We then re-gridded the temperature data using the *k*-nearest neighbourhood to match them with FT gridded data. We then analyze the dependency between annual FT variables (i.e. NF and NT) and annual T_{mean} across Quebec and its eight ecozones, namely Arctic Cordillera (AC), Northern Arctic (NA), Southern Arctic (SA), Taiga Shield (TS), Boreal Shield (BS), Atlantic Maritime (AM), Mixed Wood Plains (MWP) and Hudson Plains (HP). Addressing temperature control on FT patterns over Quebec, the largest province in Canada, has a large diversity in climate and vegetation type over this region. This diversity can cause divergent environmental responses to climate change, which can impact the frequency and extent of FT patterns in different ways. Accurate quantification of changes in FT patterns different ecozones can be therefore essential for sustainable development in Quebec.

3 METHODOLOGY

We first analyze the statistical dependence between considered FT variable with T_{mean} using Kendall's Tau dependence coefficient (Kendall 1938) over the period of 1980 to 2016. To explore the potential changes in the dependence in time, we also divided the total period into two equal 18-year periods, one from 1980 to 1997 and the other from 1998 to 2016. We then use copula methodology to assess the temperature control on FT characteristics over different ecozones and Quebec as a whole. The copula methodology provides a powerful tool to model the joint dependencies among random variables, stating that the joint cumulative distribution function of any given pair of continuous random variables $(\boldsymbol{X}, \boldsymbol{Y})$, can be written as follows (Genest and Favre 2007):

$$[1] \quad H(\boldsymbol{X}, \boldsymbol{Y}) = C\big(F(\boldsymbol{X}), G(\boldsymbol{Y})\big)$$

where $H(\boldsymbol{X}, \boldsymbol{Y})$ is the joint dependence; $F(\boldsymbol{X})$ and $G(\boldsymbol{Y})$ are the marginal distributions; and C is the copula function. C is a continuous function, coupling a set of cumulative marginal distributions to form a cumulative joint distribution. Gaussian, Frank and Clayton copula families are analyzed to find the best competitive copula model. To provide a notion for alterations in dependencies with latitude, longitude and elevation, we developed a set of regional copula models based on all grid cells, located in each of the eight ecozones. The copula parameter for each ecozone is then compared with the average geographic characteristics of that ecozone to inspect the role of geographic characteristics on altering the temperature control on the FT variables. Using the regional copula models developed, we then address what 1° warming means to FT variables across different ecozones based on the dependence observed in the whole period as well as the first and the second half-periods. For this purpose, the probability distribution of NF and NT are obtained based on the long-term T_{mean} and 1° warmer climate (long-term T_{mean}+1°) across two different ecozones over Quebec. The same analysis is performed to derive the probability of the FT characteristics in one particular ecozone but over two different time episodes to find the impacts of warming on interdependencies between temperature and FT patterns over time.

4 RESULTS AND DISCUSSION

4.1 Dependency between FT Characteristics and Mean Temperature

Figure 1 summarizes the results of the dependency analysis between the annual mean temperature and the number of frozen days (first row) and thawed days (second row) in each year. Red color spectrum is an indicator of positive dependencies while blue color shows negative Kendall's Tau dependence coefficient at the grid scale. We also look into the potential change in the dependency between temperature and FT characteristics by recalculating the dependence in the first and second half of the study periods. Based on the results, high number of grids are showing significant dependency between the NF and NT with T_{mean}, which is observed over 90 and 84 percent of grids, respectively, during the whole data period. Having said that, the dependency between FT characteristics and temperature is variant over considered time episodes, specifically across southern and central Quebec. In the Boreal Shield for instance, the number of grids with significant dependencies between NF and mean annual temperature is almost doubled in second half period, in comparison to the first half.

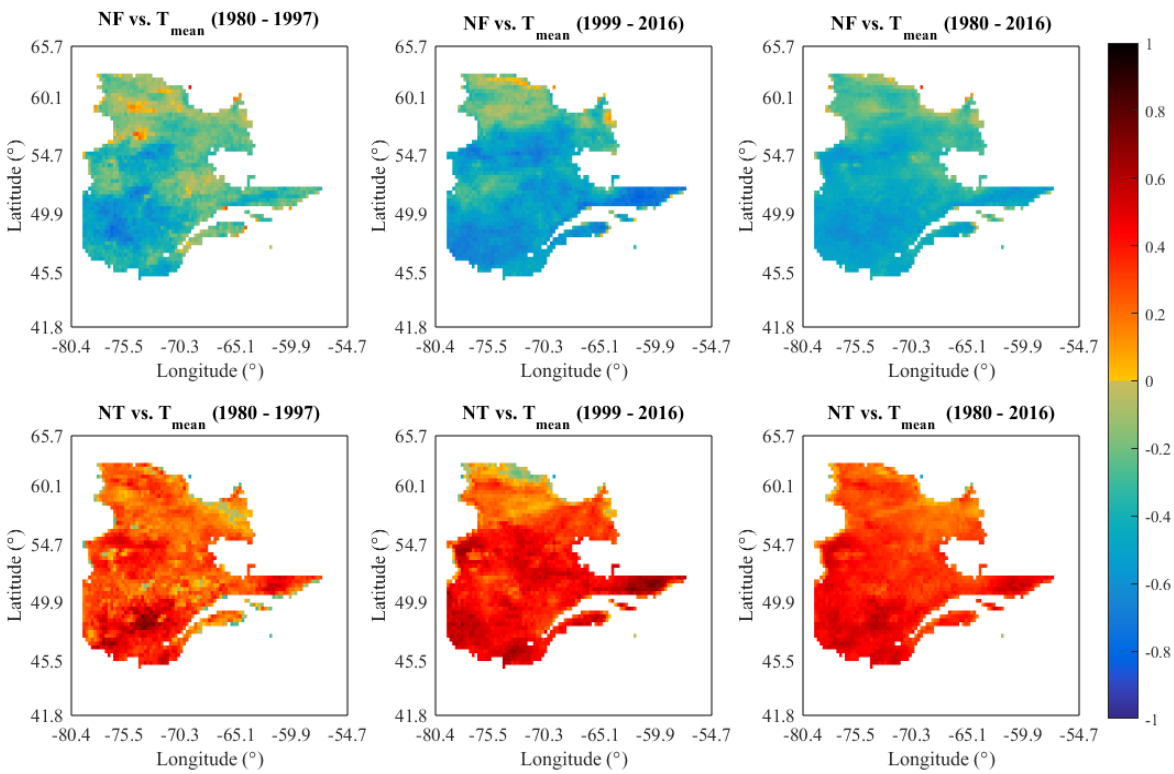

Figure 1: Kendall's tau dependence coefficient between NF and T_{mean} (first row) as well as NT and T_{mean} (second row) over the first half (1980-1997), second half (1998-2016) and whole study period (1980-2016).

4.2 Copula Modelling for Investigating the Temperature Control on FT Characteristics

Based on the results from previous section, there is significant dependence between temperature and FT characteristics over most of the Quebec area; and therefore, there is a copula model that can statistically describe the temperature control on the FT patterns. We compare, three competitive copulas to assess the impacts of change in annual T_{mean} on FT characteristics. For this purpose, the Gaussian, Frank and Clayton copulas are fitted on the data at the grid scale. To fit the copula models, first marginal temperature and FT characteristics should be transformed using their cumulative distributions functions and then copula structures are used to assess the dependencies between marginal distributions. After fitting copula models on marginal data in each grid, the simulated Kendall's Tau is compared to the observed dependence and the error in simulated dependence is calculated. The boxplot of errors in simulated Kendall's Tau over each ecozone are estimated for three copulas – see Figure 2. These boxplots can provide a notion for copula modelling performance to capture the interdependencies between mean annual temperature and FT characteristics in grids over different regional scales (i.e. 8 ecozones and Quebec as a whole). As can be easily investigated, the Clayton copula has considerably lower power in modelling the interdependencies between both NF and T_{mean} as well as NT and T_{mean} due to higher error values in modeled Kendall's Tau (with average error of -0.4 over grids covering Quebec for NF and T_{mean} and average error of roughly 0.1 in Quebec for NT and T_{mean}). Comparing the Gaussian and Frank copula, it can be seen that Frank copula is more robust due to having narrower boxplots over most ecozones as well as across the whole Quebec. As a result, hereafter we limit our discussion only to Frank copula.

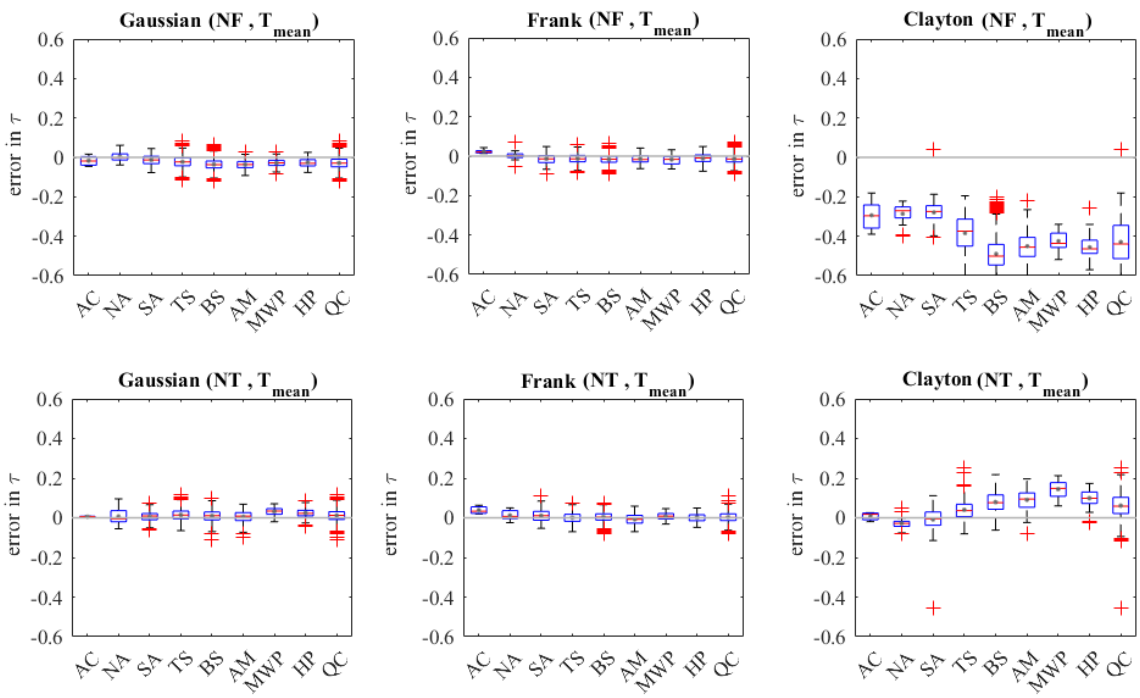

Figure 2: Boxplot of error in reconstructing interdependencies between NF and T_{mean} (first row) as well as NT and T_{mean} (second row) in different Quebec's ecozones and the province of Quebec as a whole using Gaussian (first column), Frank (second column) and Clayton (third column) copulas.

4.3 Alteration in Temperature Control on FT with Geographic Characteristics

To inspect the dependency between geographic dependencies and the Kendall's dependence coefficient, we matched the parameters of regional copula models at each ecozone with area-averaged geographic characteristics, namely latitude, longitude and altitude. The significance of dependencies is also evaluated using the formal *p*-values. Figure 3 illustrates the relationship between regional Frank copula parameter and geographic characteristics at ecozones over three considered time episodes (i.e. 1980-2016, 1980-1998 and 1999-2016). On top of each panel, the Kendall's Tau between regional copula parameter and geographic characteristics over the whole period of study is reported along with the associated *p*-value in parentheses. As can be clearly seen, the latitude is the most significantly dependant geographic characteristic altering the copula parameter and consequently the temperature control on both NF and NT. Considering these observations, it can be argued that the regional dependencies between FT variables and temperature are mostly related to the latitude of corresponding regions comparing to the other two geographic characteristics. Moreover, the results show almost the same patterns over different time episodes.

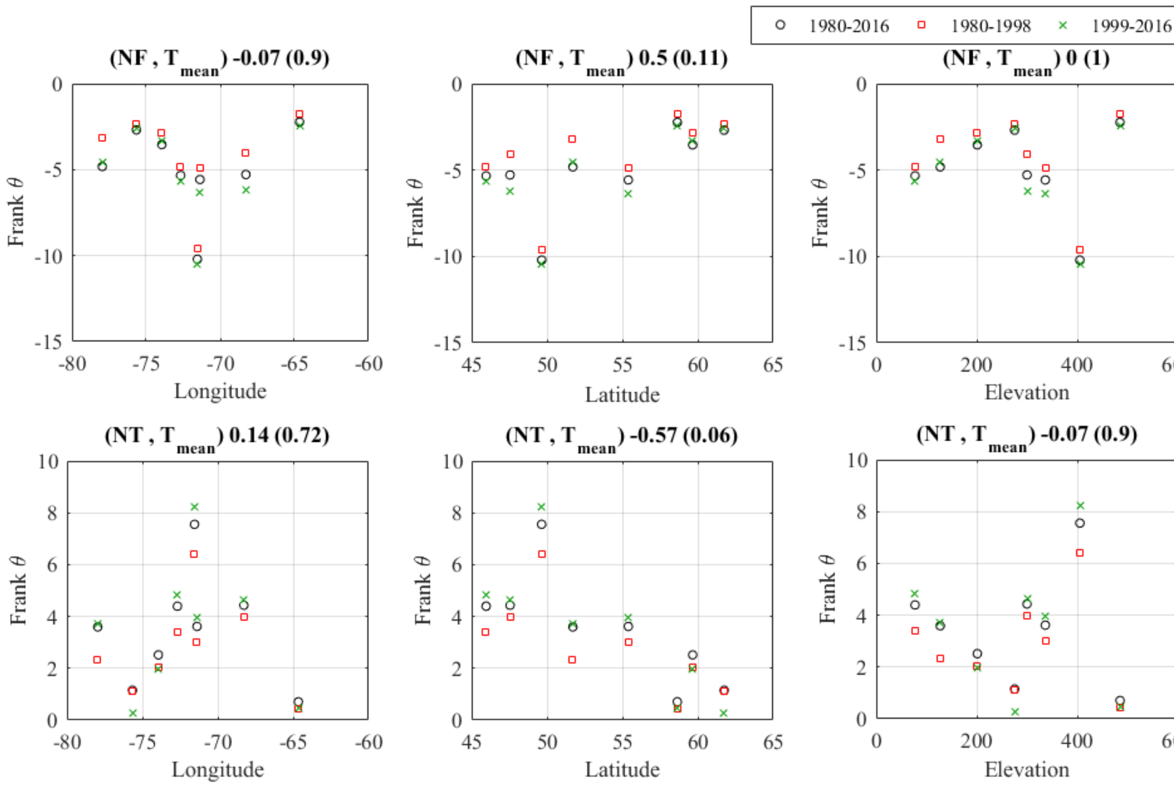

Figure 3: Dependence between the regional copula parameter and three geographic characteristics within different time period; columns are related to longitude, latitude and elevation from left to right whereas rows are related to the copula model parameter fitted on NF and T_{mean} (first row) and NT and T_{mean} (second row).

4.4 Change in FT characteristics in face of 1°C Warming

By having the regional copula models, it would be possible to address the impacts of 1°C warming across each ecozone. To assess these impacts, the probability distribution of NF and NT are obtained based on long-term T_{mean} as well as long-term T_{mean}+1°C across different spatial scales and in different time periods. The analysis is performed once to evaluate the effects of 1°C warmer climate across two different ecozones of Quebec with rather the same area and once over the first and second half-periods over MWP ecozone. The panels in the first row of Figure 4, show the changes in probability of NF and NT while long-term and 1° warmer average temperature is happening across two different ecozones of Quebec (i.e. Mixed Wood Plains and Hudson Palins). The probability distributions clearly illustrate the more vulnerability of both considered FT characteristics across MWP ecozone in case of 1° increase in long-term T_{mean}. To evaluate the temperature control on FT patterns within different time episodes, the imposed shifts in the probability distribution of NF and NT as a result of changes in temperature are also depicted – see second row panels of Figure 4. Based on this comparison, there is a significant difference in shifts of NF and NT probability distributions between two time episodes. This analysis clearly shows the greater shifts in probability distribution of both FT characteristics over the second half of the time period (1999-2016). Considering this observations, it can be argued that the joint dependencies between temperature and FT characteristics are changing over time.

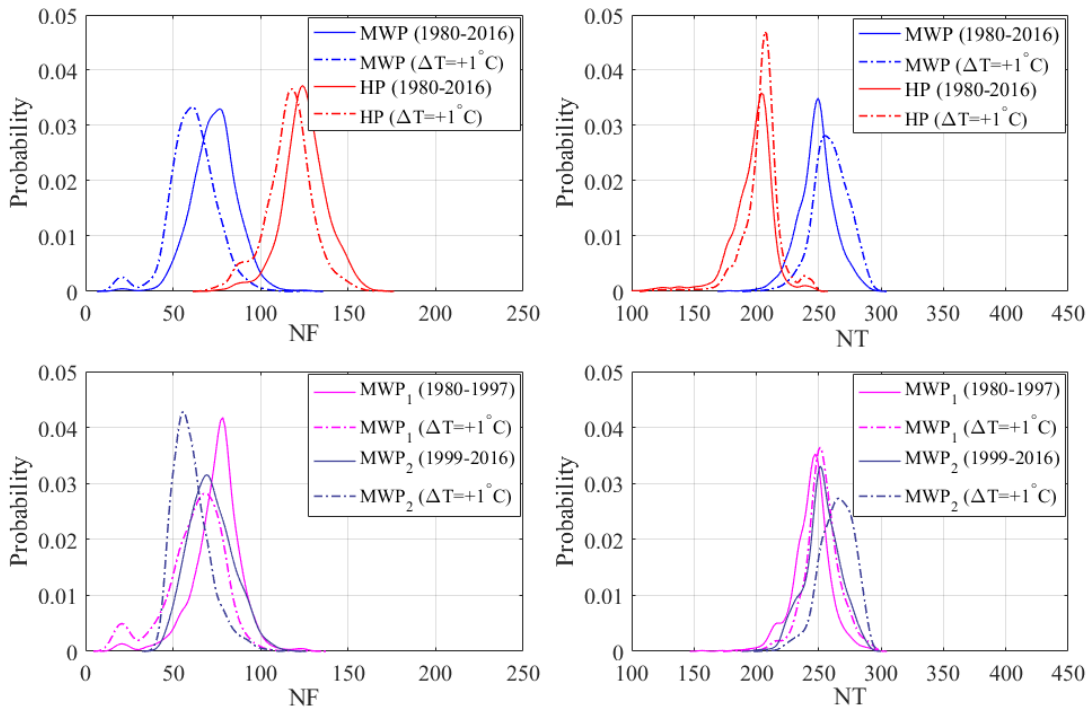

Figure 4: Impacts of 1°C warming on NF (first column) and NT (second column) across different spatial scales (first row) and over different time periods (second row).

5 SUMMARY AND CONCLUSION

Quantifying the temperature controllers of FT patterns is of a great importance for advising a set of effective adaptation strategies for future human developments in cold regions due to the great impact of FT dynamics on hydrological and environmental processes. However, the timing and distribution of this patterns have been subjected to significant change across different temporal and spatial scales. In this study, the copula methodology is employed to provide a notion for temperature control on annual FT characteristics throughout Quebec. We also inspect the alteration in the model parameters with latitude, longitude and elevation as well as the impacts of 1° warming on FT variables across considered spatial scales as well as different time episodes. Considering the results of dependencies between FT characteristics and mean annual temperature, it is concluded that both FT variables are significantly dependent to T_{mean} in more than 84 percent of grids covering the province of Quebec. However, it is noted that these dependencies are variant in different periods. Three competitive copula models are considered to model the joint dependency between FT variables and temperature. Comparing these copula models, it is noted that the Frank copula has significantly better performance in capturing the dependence between temperature and FT characteristics in grid scale across most of the ecozones as well as the Quebec as a whole. Further studies on alterations in model parameters with geographic characteristics, show the latitude as the most significantly dependant geographic characteristic altering the copula parameter at regional-scale and accordingly the temperature control on both NF and NT. Nonetheless, it seems to be no variation in the dependencies between the geographic characteristics and temperature control on FT patterns over different time episodes, at least at the ecozone scale. We also show the vulnerability of FT characteristics to 1° increment in long-term temperature over time and space and concluded that the changes in long-term mean annual temperature do not have the same effects on FT characteristics across different ecozones. Moreover, it is concluded that the positive shift in temperature would be more impactful on probability distribution of both NF and NT during the second half of the study period, showing the possibility of changes in joint dependencies between temperature and FT characteristics over time. Considering our results, the copula modelling can provide a formal basis for assessing the change in FT patterns due to changing temperature. However, further investigations are required to fully establish the copula modelling capability to address the impacts of temperature change on FT patterns in other temporal and/or spatial scales. Studying the control of other hydro-climatic variables (e.g. snow depth) on FT characteristics is another interesting research topic that would be the next step in our future studies.

REFERENCES

Entekhabi, D., Njoku, E.G., Houser, P., Spencer, M., Doiron, T., Kim, Y., and Smith, J. 2004. The Hydrosphere State (Hydros) Satellite Mission: An Earth System Pathfinder for Global Mapping of Soil Moisture and Land Freeze/thaw. *IEEE Transactions on Geoscience and Remote Sensing*, **42**(10): 2184–95. https://doi.org/10.1109/TGRS.2004.834631.

Frauenfeld, O.W., Zhang, T. and Barry, R.G., 2004. Interdecadal Changes in Seasonal Freeze and Thaw Depths in Russia. *Journal of Geophysical Research,* **109**(D5): D05101. https://doi.org/10.1029/2003JD004245.

Genest, C. and Favre, A-C. 2007. Everything You Always Wanted to Know about Copula Modeling but Were Afraid to Ask. *Journal of Hydrologic Engineering*, **12**(4): 347–68. https://doi.org/10.1061/(ASCE)1084-0699(2007)12:4(347).

Henry, H.A.L. 2008. Climate Change and Soil Freezing Dynamics : Historical Trends and Projected Changes. Climatic Change, **87**: 421–34.

Kendall, A.M G. 1938. A New Measure of Rank Correlation. *Oxford University Press on Behalf of Biometrika Trust*, **30**(1): 81–93.

Kim, Y., Kimball, J.S., Glassy, J., and Du, J. 2017. An Extended Global Earth System Data Record on Daily Landscape Freeze – Thaw Status Determined from Satellite Passive Microwave Remote Sensing. *Earth System Science Data*, **9**(1): 133–47.

McDonald, K.C., Kimball, J.S., Njoku, E., Zimmermann, R. and Zhao, M. 2004. Variability in Springtime Thaw in the Terrestrial High Latitudes: Monitoring a Major Control on the Biospheric Assimilation of Atmospheric CO 2 with Spaceborne Microwave Remote Sensing. *Earth Interactions*, **8**(20): 1–23.

Nazemi, A. and Elshorbagy, A. 2012. Application of Copula Modelling to the Performance Assessment of Reconstructed Watersheds. *Stochastic Environmental Research and Risk Assessment*, **26**(2): 189–205.

Nghiem, S.V., Hall, D.K., Mote, T.L., Tedesco, M., Albert, M.R., Keegan, K., Shuman, C.A., Digirolamo, N. E. and Neumann, G. 2012. The Extreme Melt across the Greenland Ice Sheet in 2012. *Geophysical Research Letters*, **39**(September): 6–11.

Park, H., Kim, Y. and Kimball, J.S. 2016. Widespread Permafrost Vulnerability and Soil Active Layer Increases over the High Northern Latitudes Inferred from Satellite Remote Sensing and Process Model Assessments. *Remote Sensing of Environment*, **175**: 349–58.

Sheffield, J., Goteti, G. and Wood, E.F. 2006. Development of a 50-Year High-Resolution Global Dataset of Meteorological Forcings for Land Surface Modeling. *Journal of Climate*, **19**(13): 3088–3111.

Takala, M., Pulliainen, J., Metsämäki, S.J., and Koskinen, J.T. 2009. Detection of Snowmelt Using Spaceborne Microwave Radiometer Data in Eurasia From 1979 to 2007. *IEEE Transactions on Geoscience and Remote Sensing*, **47**(9): 2996–3007.

Williams, C.M., Henry, H.A.L. and Sinclair, B.J. 2015. Cold Truths: How Winter Drives Responses of Terrestrial Organisms to Climate Change. *Biological Reviews*, **90**(1): 214–35.

Williams, C.N, Basist, A., Peterson, T.C, and Grody, N. 2000. Calibration and Verification of Land Surface Temperature Anomalies Derived from the SSM / I. *Bulletin of the American Meteorological Society*, **81**(9): 2141–56.