An Integrated Index of Recent Pan-Arctic Climate Change

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Abstract

We investigate climatic changes that have occurred in the Arctic over the period 1982–2017 through examination of ten observational cryospheric time series, and develop a new quantitative composite Arctic Climate Change Index (*ACCI*). Using Factor Analysis highlights joint trends of winter temperature increases and sea ice loss, tundra shifts, and secondarily summer sea ice loss, spring snow loss, and Greenland land ice loss. An Arctic-wide atmospheric circulation index (Arctic Oscillation) was not selected as a joint contributor. Distinct Arctic change began in 1990 and the trend increases after 2005 to the end of the series. That most variables of the collection project onto a single pattern of change suggests that the Arctic is responding as a coherent system over the previous three decades. However, no single index exclusively tracks change in the Arctic, a conclusion that emerges from a multivariate analysis. A composite quantitative index *(ACCI)* is useful to document the co-variability of systematic Arctic change.

1. Introduction and History

This paper addresses two themes from the last 30 years: Arctic change and the use of composite indicators. Shifts in Arctic climate due to increased greenhouse gases were inferred in modeling as early as the 1980s (Manabe and Stouffer 1980) and later suggested from observations (Serreze et al. 2000, Overland et al. 2004). Consensus on observed Arctic change was not obtained until the mid-2000s due to differences between types of Arctic records, regional differences, year-to-year internal variability, and the importance of shifts in large scale atmospheric wind distributions (Arctic Oscillation, AO) (Serreze 2018). In the mid-2000s a state of consilience was reached: when multiple sources of evidence were in agreement. The reality of Arctic change was supported by a convergence of observational evidence, the end of a strong positive AO pattern, combined with causality provided through modeling of Arctic amplification from CO_2 increases (ACIA 2005).

The early-2000s saw several studies that enumerated multiple lines of evidence. However, the issue of external CO_2 forcing versus internal climate variability was not firmly resolved. From Serreze et al. (2000): "Taken together, these results paint a reasonably coherent picture of change, but their interpretation as signals of enhanced greenhouse warming is open to debate." From Hinzman et al. (2005): "the biocomplexity of the Arctic system has highlighted and challenged a paucity of integrated scientific knowledge." Overland (2009) posed the question, "How do we know we are not wrong?", that CO_2 was the driver of Arctic change. The answer was through multiple scientific method standards: Evidentiary (consilience), Performance (consistent, predictive), and Community (provides the best explanation among competing hypotheses, rejection of speculative hypotheses). The abstract of Overpeck et al. (2005) was

similar: “there seem to be few, if any processes or feedbacks within the Arctic system that are capable of altering the trajectory toward this super interglacial state.”

A second theme we consider is a search for composite indicators. In some disciplines with a large number of potential indicators there is a desire to reduce the dimensionality of the information, such as the development of an “ecosystem health” index (Palmer and Febria 2012). For fisheries management there was the challenge of too many potential indicators and the need for a sensible compositing of information (Rice and Rochet 2005). Further there is a desire to search for a common factor for a set of indicators, either an underlying multi-variate response or a cause due to external forcing; such is a motivation for an *Arctic climate change index (ACCI)*.

There are drawbacks to composites, as there may be no clear definition of what the index represents. There should be a clear understanding of the joint process to be resolved (Mazziotta and Pareto 2013). Another issue are shortcomings in mathematical compositing techniques such as Principal Component Analysis (PCA). PCA emphasizes fitting overall variance, rather than the covariability between processes as does Factor Analysis. There can be violated statistical assumptions such as auto-correlated time series and widely-different variances in multiple variables. These mathematical limitations work against the assumption of different single indicators having comparable weights in the integrated analysis, the scientific goal of compositing. Thus the Arctic ReportCard, initiated in 2006, chose not to composite, instead lists seven vital sign components of the Arctic system. Zador and Siddon (2016) chose ten observational indicators from sea ice through fish abundance to characterize the ecosystem status of the Bering Sea. These metrics provide separate understandable indicators that then allow the

user of the information to draw their own system-wide conclusions. However, a viable integrated index of change that represents an underlying composite structure, such as an *ACCI* for the Arctic, is a worthy goal.

Overland et al. (2004) composited 86 regionally-dispersed Arctic time series representing seven data types over the period of 1965–1995. The first Principal Component had a single regime-like shift near 1989 based on 40% of the available time series, which included a strong stratospheric polar vortex, sea ice declines in several regions, and changes in selected mammal, bird, and fish populations. The short duration between the 1989 shift and the end of the analysis did not allow a choice between the prediction of a continuing Arctic shift perhaps forced by CO_2, or a potential sub-decadal reversal of the shift based on internal variability. Such multi-disciplinary results provided an incentive for an integrated Arctic observing program (SEARCH 2001) to detect which hypothesis was more correct, but such an expansive program was not carried out (Serreze 2018). With 20 more years of data and an interest in underlying Arctic-wide co-variability, it is appropriate to re-investigate Arctic time series for common factors, an integrated *Arctic Climate Change Index*.

2. Methods

A recent Arctic Assessment has been completed, the *Snow, Water, Ice and Permafrost in the Arctic* (SWIPA2017) Report (AMAP 2017). SWIPA2017 took the view of providing information on multiple Arctic climate elements culminating in a time series comparison of six indicators beginning in 1970-1982 with yearly resolution (AMAP 2017, Figure 11.2). This set of initiators has been updated and expanded as in the companion paper by Box et al. (submitted, this issue).

The set of time series we use are listed in Table 1 and graphed in Figure 1. We start with an updated set of cryospheric indicators from SWIPA2017, shift the season on air temperature to winter, and add a winter atmospheric circulation indicator (AO) and winter sea ice. Data are from 1982-2017, limited by the start of the tundra NDVI greenness time series. Our goal is to seek an underlying integrated Arctic climate variability that provides insight into Arctic change over the previous thirty-six years (1982-2017). Factor Analysis is used, as our objective is concerned with explaining the covariance structure among the observed variables.

The main tool is Factor Analysis using standard available software (*Factoran* from Matlab-Mathworks; https://www.mathworks.com/help/stats/factoran.html). The software computes the maximum likelihood estimate of the factor loadings matrix, Λ, in the factor analysis model

$x = \mu + \Lambda f + e$

where x is the vector of observed variables, Λ is the constant d-by-m matrix of factor loadings, f is the vector of independent common factors, and μ and e are the means and independent factors; x is of length d, the number of years of data used in the study, and f is of length m, the number of factors to be considered in the analysis. We are interested in the loading of each observational variable with the each factor, and the time series of the separate factors as latent variables representing integrated Arctic climate change. We removed the mean and normalized each time series by its variance, but did not temporally detrend. Significance of individual contributions is based on their factor loadings: 0.30 is the minimum consideration level and 0.50 is practically significant https://pdfs.semanticscholar.org/5c2c/470955b07c065f478da56b1bdffd1b057520.pdf.

Although the mathematics of Factor Analysis preforms selection of covariant time series, one must first choose an initial set of relevant variables, an ensemble of choice. Overland et al. (2004) composited 86 regionally-dispersed Arctic time series representing seven data types. Here we concentrate on cryospheric related variables. A question is when to terminate the selection process. We started with the list from SWIPA2017 and added the Arctic Oscillation as an additional forcing variable. We used the quality of the time series as a criterion for terminating the initial selection process. For example precipitation and cloud fields were suggested but were not included due to low confidence (Lader et al. 2016, Liu and Key 2016). Burn area is a potential indicator, but was not included as its distribution is highly non-Gaussian with a few major event years; this time series would not be conducive to statistical methods.

3. Results

Table 1 lists the loading of each of ten Arctic climate variables with the derived factors given the *a priori* assumption of six factors, the maximum number of factors as designated by the computer program. Factor 1 has high loadings with multiple indicators: winter surface air temperature, winter sea ice extent, northern Alaska permafrost temperatures, and smaller but relevant loadings with tundra greenness (satellite maximum NDVI), summer sea ice extent, and Greenland land ice mass balance. There are near zero correlation with winter AO, spring snow days, and Alaska glaciers. Factor 2 also shows the influence from multiple variables, especially Greenland ice, snow, and summer sea ice. Factors 3-5 indicate the strong presence of single variable components: Spitzbergen glaciers, Alaska glaciers, and AO (loading weights of 0.71, 0.94 and 0.80). Factor 6 shows low loadings for all Arctic climate variables and suggests the stopping point in the analysis. A factor that corresponds to a single Arctic time series does not imply that it is unimportant, just that it is varying independently of the larger data set. This is

also evident from inspection of the time series (Fig. 1); Alaskan glaciers shows large variance and the AO, after large values in the early 1990s, has a flat trend.

As suggested by the literature on Factor Analysis (Johnson 1998), it is advisable to remove variable that represent single factors. This is clear for Alaska glaciers and AO; there is also a case for removing Spitzbergen glaciers. Greenland ice has a strong weight on Factor 2 and two additional variables also contribute to Factor 2. Greenland has a non-zero contribution to Factor 1. These points argue for keeping Greenland ice in the analysis. Thus we remove Alaska and Spitzbergen glaciers and the AO, and repeat the Factor Analysis with seven variables and two factors (Table 2). An additional Factor Analysis that included precipitation (not shown) indicated a relation between AO and Arctic-wide precipitation.

Table 2 shows the factor loadings of each variable with Factor 1 of >|0.8| for winter temperatures and winter sea ice, and >|0.5| for tundra, summer sea ice, and Greenland ice. All variables have some weight on Factor 2 with loadings of >|0.6| for summer sea ice, Greenland ice, and snow cover. When three Factors were specified with seven variables (not shown), the loadings of all variables with Factor 3 were <|0.5| indicating that most covariability information is carried by the new Factors 1 and 2.

Figure 2 shows the time series of Factor 1 and Factor 2. We consider Factor 1 as a candidate for an *Arctic Climate Change index (ACCI)*, as all variables participate except for snow, with weights >|0.5|. Inspection of the *ACCI* time series has a first increase in 1990 followed by 1991, 1993 and 1995. This also corresponds to the change point of 1989 found in Overland et al.

(2004). A second rise (increasing trend) occurs after 2004. Factor 2 has substantial weights from summer sea ice, snow, and Greenland ice. Although there is a suggestion of decadal variability in Factor 2, inspection of the original time series variables (Fig. 1), suggest that Factor 2 acts more as a correction term to the more piece-wise linear Factor 1 than indicating separate physical forcing of the variables associated with Factor 2. Snow days, summer sea ice, and Greenland land ice mass balance time series deviate from a linear trend, having little change before 2000 and having a large shift in the late 2000s.

4. Discussion and Conclusion

Northern Alaskan permafrost temperatures, winter sea ice extent, and tundra greenness (satellite maximum NDVI) follow winter surface air temperatures over the period of record since 1982. Summer sea ice extent, spring snow days, and Greenland ice sheet mass balance impact have increasing trends after 2005. Atmospheric circulation does not play an important role in long term Arctic change, as do temperature related increases. This separation of atmospheric circulation forcing from temperature forcing of Arctic change was also noted by Screen et al. (2018) and references there in.

Factor Analysis based on the covariability matrix is a suitable objective method to establish a composite *Arctic Climate Change Index (ACCI)*. It was able to suggest removing variables from an original *ad hoc* set of indicators, based on lack of covariability (AO) or a noisy signal (Alaskan glaciers). The number of relevant Factors was determined by terminated the analysis at a third Factor with low loadings for all variables. Although the *ACCI* was upward trending, with winter sea ice negatively correlated, the time series was not uniformly increasing, rather there

was an increased trend after 2004. The second Factor, while representing variability from more than one original variable, was more of a correction for the shape of the individual time series, rather than indicating a separate decadal variability signal. In the case of Arctic climate, a composite *ACCI* quantitative index is useful to demonstrate the covariability of a system-wide Arctic change. Six of the seven cryospheric time series project onto *ACCI*. *ACCI* is an integrated index of value in quantifying the reality and importance of the overall Arctic contribution to global change.

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References

ACIA 2005 *Arctic Climate Impact Assessment* ACIA Overview report Cambridge University Press 1020 pp ISBN: 0 521 86509 3

AMAP 2017 *Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017* Arctic Monitoring and Assessment Programme (AMAP) Oslo, Norway 269 pp

Box J E and coauthors 2018 Arctic climate change indicators *ERL* this issue.

Hinzman L D and coauthors 2005 Evidence and implications of recent climate change in northern Alaska and other Arctic regions *Climatic Change* **72** 251-298.

Johnson, D E 1998 *Applied multivariate methods for data analysis* Brooks/Cole Publishing 567 p

Lader R and coauthors 2016 Two-meter temperature and preceipitation form atmospheric reanalysis evaluated for Alaska J Applied Meterol. And Climatology 55 901-922

Liu Y and J Key 2016 Assessment of Arctic Cloud Cover Anomalies in Atmospheric Reanalysis Products Using Satellite Data J. Climate https://doi.org/10.1175/JCLI-D-15-0861.1

Manabe S and Stouffer R J 1980 Sensitivity of a global climate model to an increase of CO_2 concentration in the atmosphere *J. Geophys. Res.* doi:10.1029/JC085iC10p05529

Mazziotta M and Pareto A 2013 Mehtod for constructing composite indicies: one for all and all for one *Rivista Italiana di Economia Demografia e Statistica* **67** (2).

Overland J E, Spillane MC, and Soreide NN 2004 Integrated analysis of physical and biological pan-Arctic change *Climatic Change* **63** 291–322 doi: 10.1023/B:CLIM.0000018512.40506.d2.

Overland J E 2009 The case for global warming in the Arctic In *Influence of Climate Change on the Changing Arctic and Sub-Arctic Conditions* J.C.J. Nihoul and A.G. Kostianoy (eds.), Springer 13-23.

Overpeck J T and coauthors 2005 Arctic system on trajectory to new, seasonally ice-free state. *EOS, Trans AGU* **86** 309-316.

Palmer M A and. Febria C M 2012 The heartbeat of ecosystems *Science* **336** 1393-1394 doi: 10.1126/science.1223250

Rice J C and Rochet M 2005 A framework for selecting a suite of indicators for fisheries management *ICES Journal of Marine Science* **62** 516-527 doi:10.1016/j.icesjms.2005.01.003

Screen, J Bracegirdle TJ and I Simmonds 2018 Polar Climate Change as Manifest in Atmospheric Circulation *Current Climate Change Reports* **4** 383–395 https://doi.org/10.1007/s40641-018-0111-4

SEARCH 2001 *SEARCH Science Plan 2001 – Study of Environmental Arctic Change* Polar Science Center University of Washington, Seattle 91 pp

Serreze M C and coauthors 2000 Observational evidence of recent change in the northern high-latitude environment *Climatic Change* **46** 159-207.

Serreze M C 2018 *Brave New Arctic* Princeton University Press 255pp.

Zador S and Siddon E 2016 Ecosystem Considerations 2016: Status of the Eastern Bering Sea Marine Ecosystem, Stock Assessment and Fishery Evaluation Report North Pacific Fishery Management Council.

Table1: Factor loadings using 6-factors based on 10 time series from 1982-2017. Time series is normalized by their standard deviations, but the linear trend is kept. Arctic cryospheric climate indicators are: Arctic Oscillation for Winter, Winter surface air temperature north of 60 N, Permafrost temperatures for northern Alaska, Tundra greenness index, sea ice extent March, sea ice extent September, number of snow days in spring (May-June), Greenland ice mass balance, Alaskan glacier index, Spitsbergen glacier index. For more details see Box et al. (2018).

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor6
AO_DJF	0.014	0.005	0.001	0.000	0.804	0.007
T2m_DJF	0.922	-0.216	0.193	-0.021	0.040	0.242
Permafrost	0.834	-0.254	0.283	0.207	-0.068	-0.207
Tundra_NDVI	0.599	-0.262	0.432	-0.032	-0.091	-0.353
SIE_March	-0.822	0.174	-0.135	-0.288	-0.074	0.100
SIE_Sept	-0.666	0.560	-0.359	-0.080	-0.108	0.208
SnowDay_spr	-0.170	0.448	-0.540	-0.195	-0.136	0.114
GIS_MB	-0.585	0.778	-0.161	-0.084	0.116	-0.035
Glacier_AK	0.153	-0.086	0.257	0.939	-0.001	-0.006
GlacSpibgn	0.263	-0.080	0.710	0.245	-0.052	0.018

Table 2: Factor loadings using 2-factors based on 7 time series from 1982-2017. Time series is normalized by their standard deviations, but the trend is not removed.

	Factor 1	Factor 2
T2m_DJF	0.801	-0.362
Permafrost	0.824	-0.462
Tundra_NDVI	0.561	-0.539
SIE_March	-0.841	0.322
SIE_Sept	-0.580	0.808
SnowDay_spr	-0.191	0.621
GIS_MB	-0.535	0.692

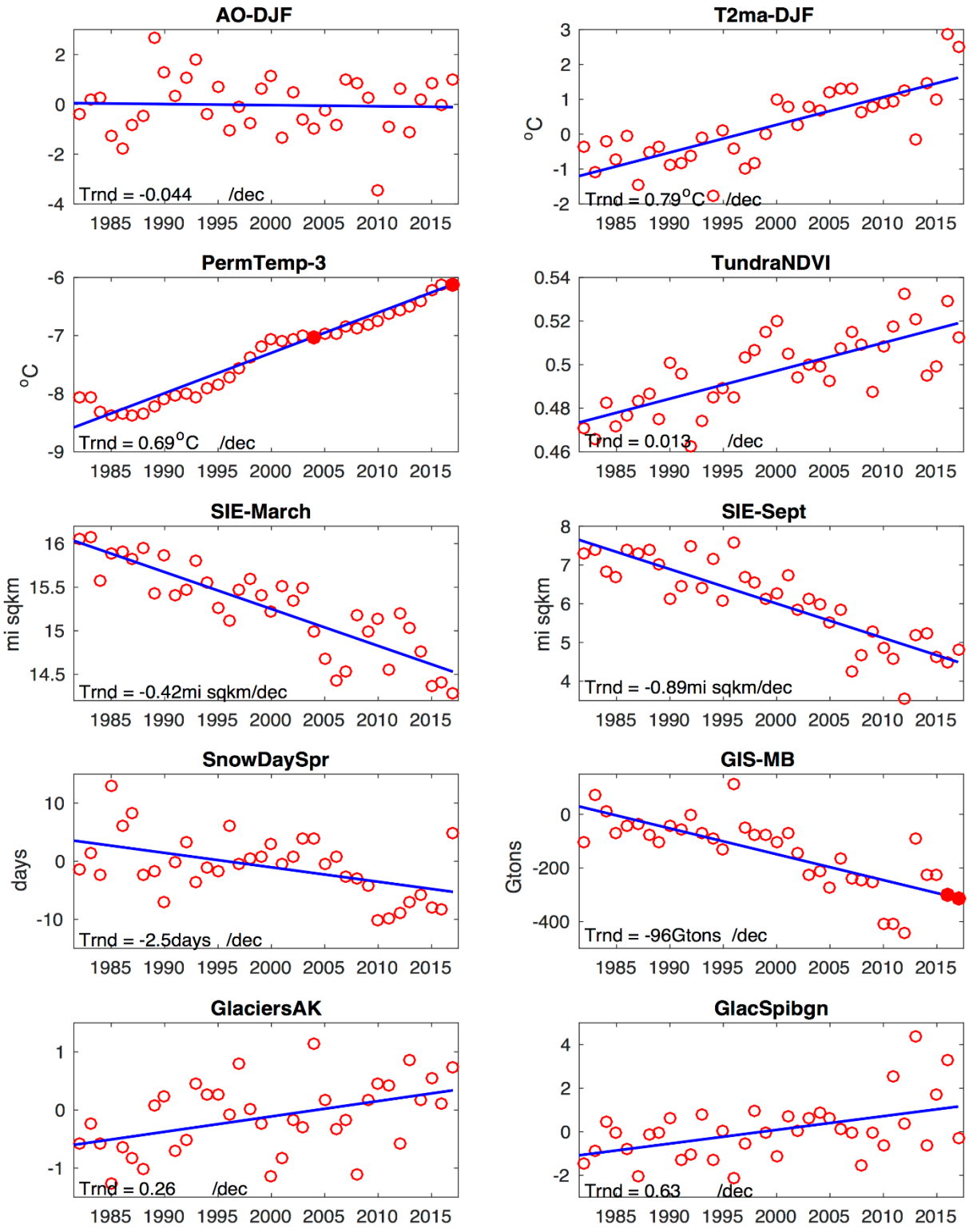

Figure 1. Time series of selected Arctic cryosphere variables shown in open red circle. The solid red circles are values filled by linear trend where the data points are missing. Blue lines indicate the linear trend for 1982-2017 period.

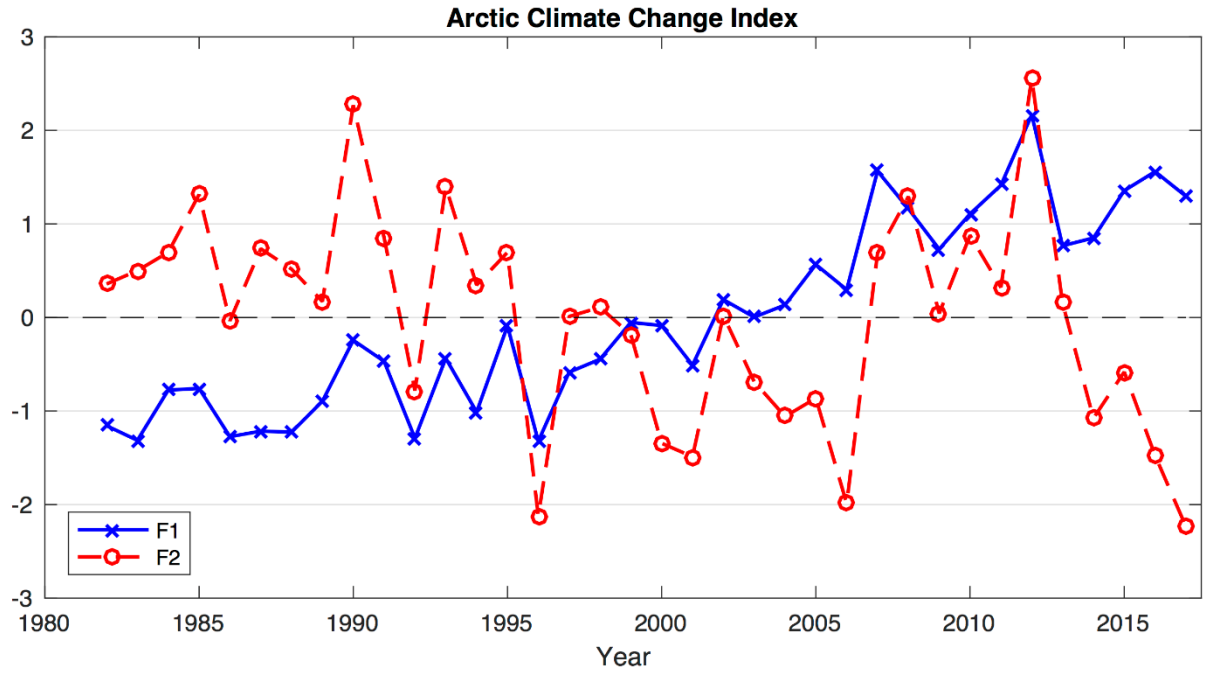

Figure 2. Time series of the two loading factors, F1 and F2. The proposed Arctic Climate Change Index (*ACCI*) is in blue.