INTEGRATED ANALYSIS OF PHYSICAL AND BIOLOGICAL PAN-ARCTIC CHANGE

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Abstract. We investigate the recent large changes that have occurred in the Arctic over the period of 1965–1995 through examination of 86 regionally-dispersed time series representing seven data types: climate indices, atmosphere, ocean, terrestrial, sea ice, fisheries, and other biological data. To our knowledge, this is the first semi-quantitative analysis of Arctic data that spans multiple disciplines and geographic regions. Although visual inspection and Principal Component Analysis of the data collection indicate that Arctic change is complex, three patterns are evident. The temporal pattern of change calculated as the first Principal Component (PC1), representing 23% of the variance, has a single regime-like shift near 1989 based on a large number of time series, which include projections from a strong stratospheric vortex in spring, the Arctic Oscillation, sea ice declines in several regions, and changes in selected mammal, bird, and fish populations. The pattern based on the second Principal Component (PC2) shows interdecadal variability over the Arctic Ocean Basin north of 70° N; this variability is observed in surface wind fields, sea ice, and ocean circulation, with the most recent shift near 1989. Contributions to PC1 cover a larger geographic area than PC2, and are consistent with a recent amplification of the interdecadal mode due to polar processes such as increased incidence of cold stratospheric temperature anomalies or internal feedbacks. Most land processes – such as snow cover, greenness, Siberian runoff, permafrost temperatures – and certain subarctic sea ice records show a third pattern of a linear trend over the 30-year interval, which is qualitatively different than either PC1 or PC2. These variables are from lower latitudes and often integrate the atmospheric or oceanographic influence over several seasons including summer. That more than half of the data collection projects strongly onto one of the three patterns, suggests that the Arctic is responding as a coherent system over the previous three decades. However, no single index or class of observations exclusively tracks change in the Arctic, a conclusion that emerges from a multivariate analysis.

1. Introduction

The Arctic has undergone significant shifts in surface temperatures over the last century (Polyakov et al., 2002) and demonstrable environmental changes have occurred over the previous three decades. These changes have made it difficult for those who live and work in the north to anticipate the course of these changes or at least determine their potential range. There is evidence that changes in midlatitudes are increasingly connected to those in the Arctic. Areal coverage of sea ice has

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diminished and sea-level pressures in the central Arctic have decreased. Warmer surface temperatures are observed in northern Europe during winter and Alaska and northwest Canada during spring. There is an increase in the frequency of years with colder than normal temperature in the lower stratosphere over high latitudes. Permafrost temperatures have risen in Siberia and Alaska with increased erosion. Satellite estimates of 'greening' have increased over both the eastern and western hemispheres, with less snow cover, longer growing seasons and changes in the character of the tundra. The influence of warm Atlantic water in the Arctic Ocean became more widespread and intense in the 1990s, with implications for the upper water column. Many of these changes are noted in Serreze et al. (2000) and Dickson et al. (2000). These changes are robust, and many other biological and physical changes are suggested – increases in cod in the Barents Sea shrimp off of southern Greenland, and caribou populations in North America, and declines and redistributions of marine mammal populations, although the causes for these changes are less certain (Ottersen et al., 2001). Primary references for these changes will be provided later in Table II.

It has been hypothesized that the present changes in the Arctic are interrelated (Morison et al., 2001), and are associated with a rising trend in the Arctic Oscillation (AO) since the 1960s (Thompson and Wallace, 1998). Here the AO phenomenon is used to broadly describe the strengthening and increased zonality of the polar vortex as shown by the AO index and related teleconnection indices. Determining whether the covariability of these changes are coincidental or have a causal link is of major importance. In this paper we examine these changes from a heuristic perspective, based on examination of 86 representative biotic and abiotic time series from the Arctic and subarctic.

The advantage of such a pan-Arctic study, which spans multiple scientific disciplines, is that the credibility for analyzing and possibly detecting change in the Arctic is increased by considering multiple lines of evidence (Parmesan and Yohe, 2003). Ideally, there would be two important interpretations of our approach. If lines of evidence are independent, then combining this information into one metric increases the level of confidence. Alternatively, if there is a high decree of covariability between them, further investigation is needed to understand the potential causality between the records. In practice, each record has uncertainties in its measurement value and regional representativeness. Also, because Arctic change is poorly understood, each record may project only partially onto the important underlying processes. Thus use of multiple lines of evidence may provide a better representation of change than a single variable or index.

There are three major difficulties with this approach. The most obvious is the use of short records. Most records in our data collection span less then 35 years. While many of the time series show a trend during this period, it is known for atmospheric temperature that the value of the trend depends on record length (Polyakov, 2002). Since only some series have long records, our interpretation is limited by the short records; this is particularly true for biology. A second issue is that short records can show trends, and thus covariably between records, for a variety of reasons. Some series can be related through nonlinear processes that are not easily detected by linear analyses, for example, lags in the data or a short physical event that results in an ecosystem reorganization which persists for many years. The third difficulty is the large autocorrelation in several series. This is either explicit in averaging in a few indices or implicit in certain biological or chemical time series (CO_2 for example). Correlation-based analyses may favor these later time series over those with large interannual variability.

Thus we approach the analyses from the point of view of a screening process. We use the degree of dissimilarity of the time series as a way of reducing the dimensionality of the data collection. In the end, each time series represents its own underlying process. Finally we investigate commonalities of the reduced data set.

2. The Unaami Data Collection

The Study of Environmental Arctic Change (SEARCH) is a U.S. interagency program with international connections focused on understanding recent large-scale changes in the Arctic. The SEARCH Science Plan* has given the name Unaami, the Yup'ik word for tomorrow, to the complex of intertwined pan-Arctic changes. Although it appears that many of these changes are interrelated, the causal relation between them, their feedbacks and long-term impacts are far from certain. To this end we have selected 86 representative time series for a data collection for further investigation.** We have chosen data that represent diverse regions and seven data types: climate indices, surface and upper atmosphere, ocean , sea ice, terrestrial, fisheries, and other biological indicators (Figure 1). The complete set of time series is listed in Appendix A.

The Unaami data collection is a representative subset of Arctic data bases. For example, time series are included for all major regions of sea-ice variability, as determined by primary authors. Data are included for different species in all major fisheries. Our goal in assembling the Unaami data collection was to have yearly coverage for at least 1975 through 1995, although many of the time series extend to 1965 and earlier (Figure 2). Our criteria of yearly sampling excluded some important Arctic change examples where measurements were only available in several years in the 1970s or early 1980s, and a few years in the 1990s, e.g., subsurface Arctic ocean temperatures, observed sea ice thickness, and tundra carbon flux. We have included, however, mammal population data which had regular, but not yearly, sampling. We have not smoothed the data by combining values into annual means. We consider that assessment of trends without smoothing lends greater insight to the analyses. Thus patterns of surface and upper air temperature

* SEARCH Science Plan, 2001, http://psc.apl.washington.edu/search
** Unaami web site, http://www.unaami.noaa.gov

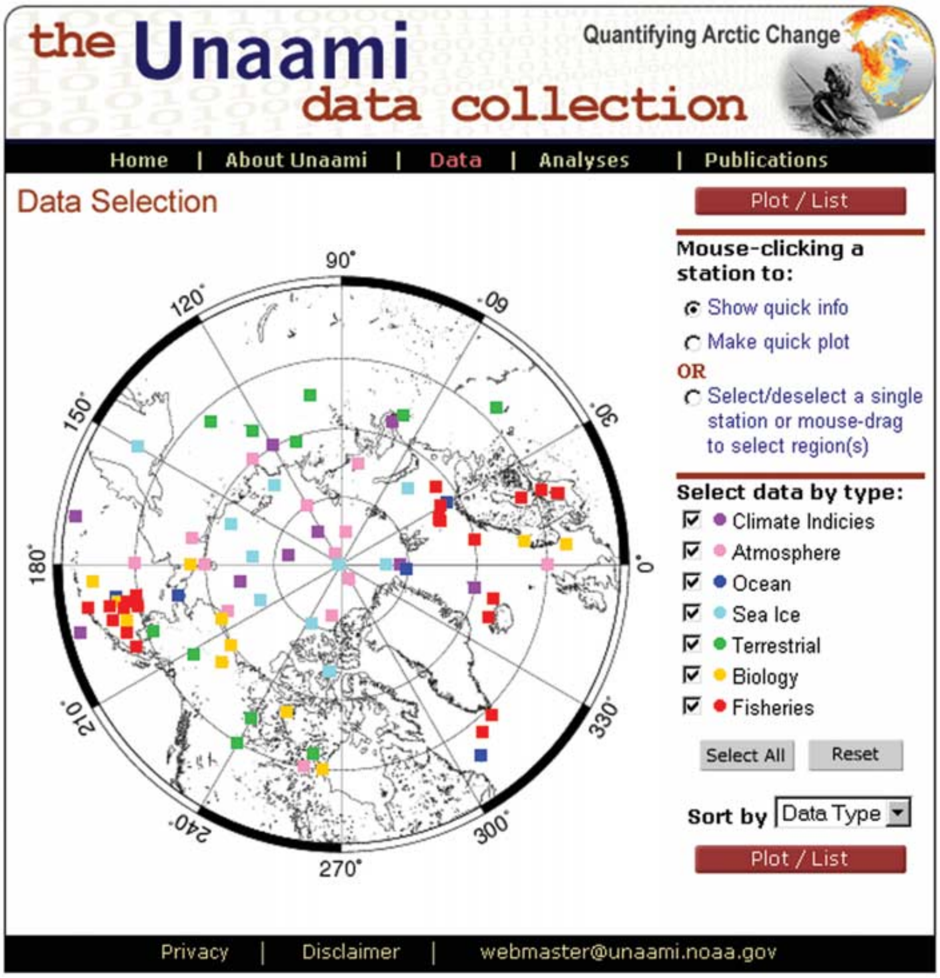

Figure 1. Website showing the seven data types and approximate geographic location of the 86 time series in the data collection. 'Unaami' is the Yupik word for 'tomorrow'.

were kept as separate time series for winter or springtime values. Many biological variables represent year classes or summer values. Sea ice extent data for different regions was included for the season which showed the largest changes.

Most of the time series represent data from published sources. Some series are derivable from primary sources such as the NCEP/NCAR reanalysis (Kalnay et al., 1996), and others are obtained directly from the investigator. All metadata, including contact information, is provided on the Unaami web site. Several of the time series, such as primary productivity and fisheries recruitment, have been renormalized so that they are better suited to a multivariate linear analysis (Hare and Mantua, 2000).

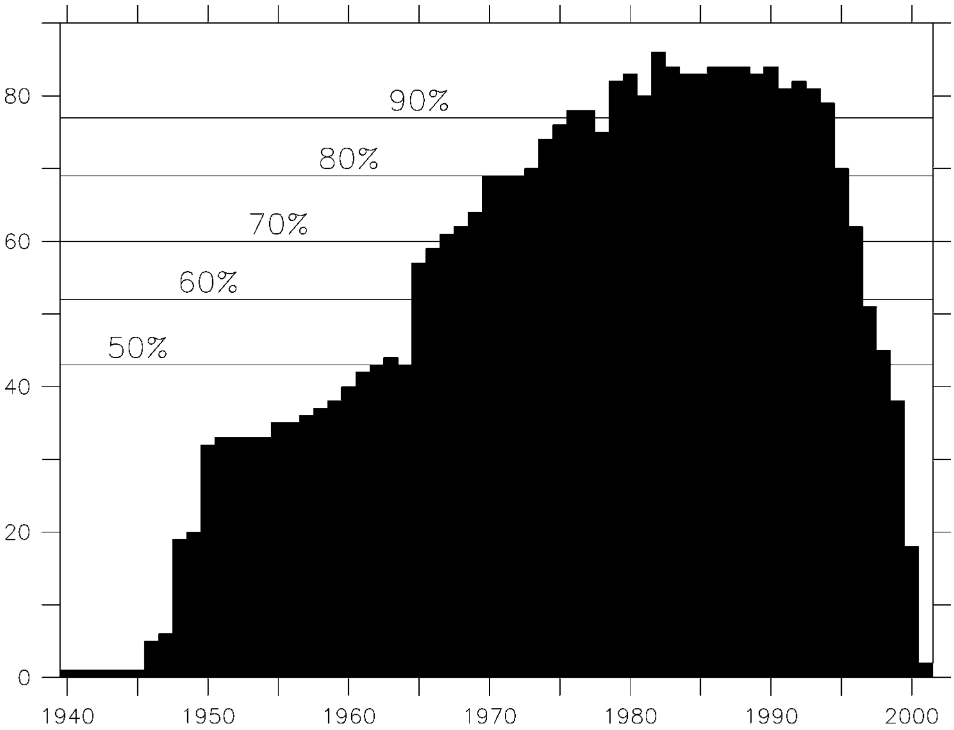

Figure 2. Temporal coverage for the 86 time series in the data collection.

3. Initial Results

The primary analysis technique is Principal Component Analysis (PCA), which is used to isolate common modes of variability in the data set. PCA has three types of output: (1) principal components (PC), which give the temporal structure of the isolated modes; (2) eigenvectors (also called Empirical Orthogonal Functions), which provide the loading or importance of each variable to that particular PC time series; and (3) the eigenvalues, which indicate the fraction of total data variance represented by each PC mode. The first PC time series explains the greatest amount of total variance of the combined dataset, and each successive PC explains the largest amount of residual variance, subject to the mathematical constraint that the subsequent EOFs are orthogonal to the earlier set. PCA is not the only approach to multivariate analyses. Multidimensional scaling, for example, focuses on data sets that tend to cluster in groups. We have chosen PCA as a method that would emphasize joint variation within the data collection, with the loadings (or projections) representing the importance of individual time series to the associated PC.

As an initial screening process, we applied PCA to the correlation matrix of the 86 time series. This was done for both the 1975–1995 and 1965–1995 periods; this represents the trade-off between complete coverage versus longer records as

Table I

Percent variance explained from an PCA analysis of the correlation matrix

	Mode				
	1	2	3	4	5
86 series 1975–95	29.0	11.4	8.2	6.7	5.8
86 series 1965–95	23.3	12.0	8.9	6.3	5.2

noted in Figure 2. The percent variance explained for each mode, based on the eigenvalues is listed in Table I; the first two PCs are selected as significant based on the method of North et al. (1982).

The first principal component (PC1) for the years 1965–1995 is shown in Figure 3. It can be interpreted as a regime shift over these 30 years with an increase in the magnitude of the slope near 1989. Note that the weights of the individual time series contributions can be positive or negative so that the increase in PC1 can represent either an increase or decrease in the individual contributing time series. The correlation of each series with PC1 is shown in the lower part of Figure 3. Shapes represent data types and colors represent absolute values of the magnitudes; a key to the representative location of all variables is provided in the appendix. Forty of the 86 series have an correlation >0.5 with PC1. It should be noted that every data type and every region of the Arctic are represented by strong correlations with PC1 >0.5. The shape of PC1 is similar for the shorter period of 1975–1995.

The second principal component (PC2) and correlation map for the years 1965–1995 are shown in Figure 4. It shows a minus-plus-minus structure with breaks near the mid 1970s and 1990. While many of the time series have this structure, one must keep in mind that PC2 is also mathematically constrained to be orthogonal to PC1. Fourteen of the series have an ABS $(r) > 0.5$ with PC2. The shape of PC2 is necessary in understanding the difference in using 20 years of data (1975–1995) and using 30 years (1965–1995). Both PC1 and PC2 have shifts near 1989. Inclusion of the additional 10 years of data is important because it suggests interdecadal shape in PC2 in contrast to the more linear or regime shape of PC1. Both PC1 and PC2 are consistent with a major discontinuity in the late 1980s, while their behavior in the 1970s provides a contrast between the two modes. Thus care must be taken in interpreting the 20-year records. Here we encounter the limitation of multivariate retrospective analysis of Arctic change in that few pan-Arctic records exist before the 1960s. With roughly one and a half cycles for PC2, one cannot fix an absolute time scale, but it could be considered as part of an interdecadal or decadal mode.

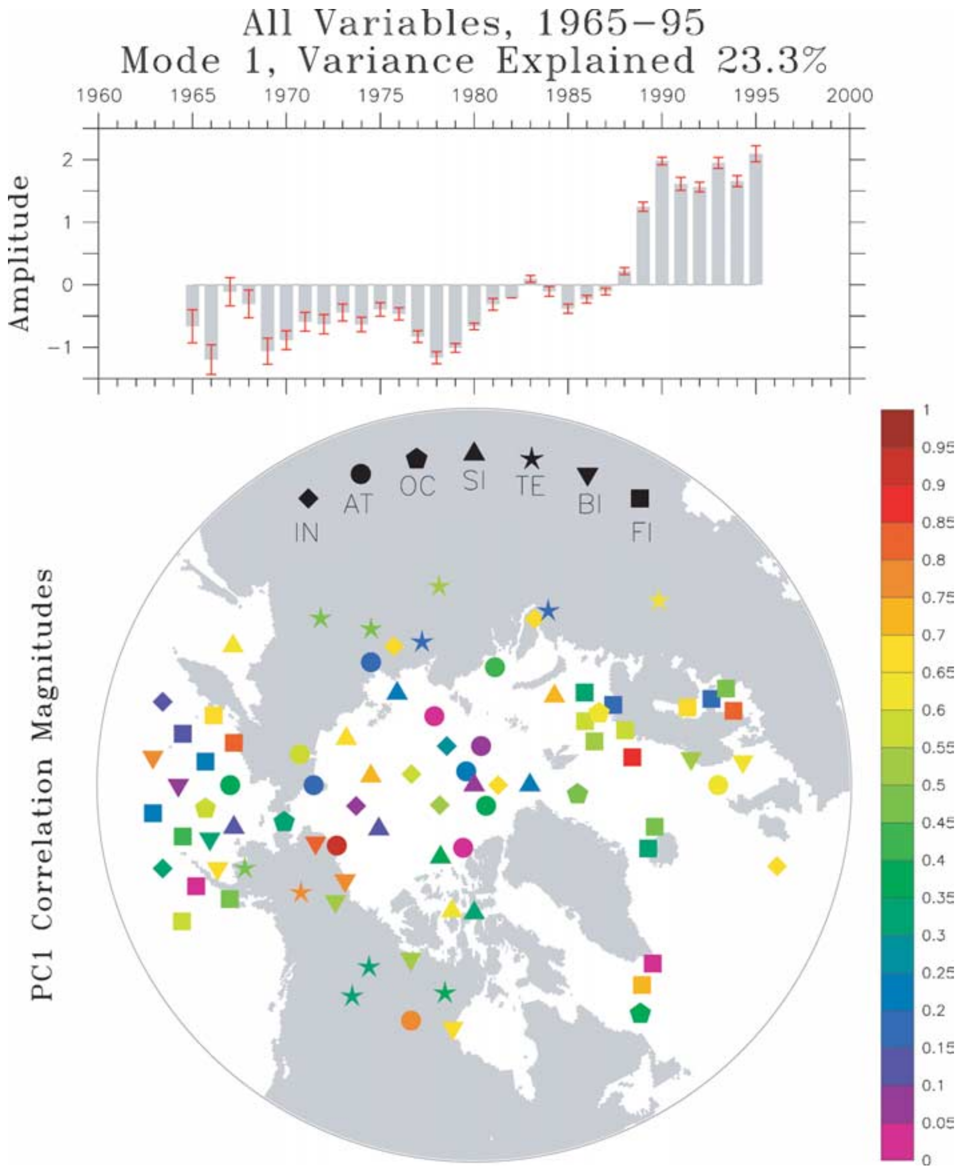

Figure 3. (top) The first principal component time history (PC1) for the entire data collection. Note the single 'regime-like' change near 1989. Error bars represent the estimated influence of missing values in the data collection. (bottom) The correlation magnitude of each time series with (PC1). A location key is provided in the appendix. Note that a wide variety of data types and locations contribute to PC1.

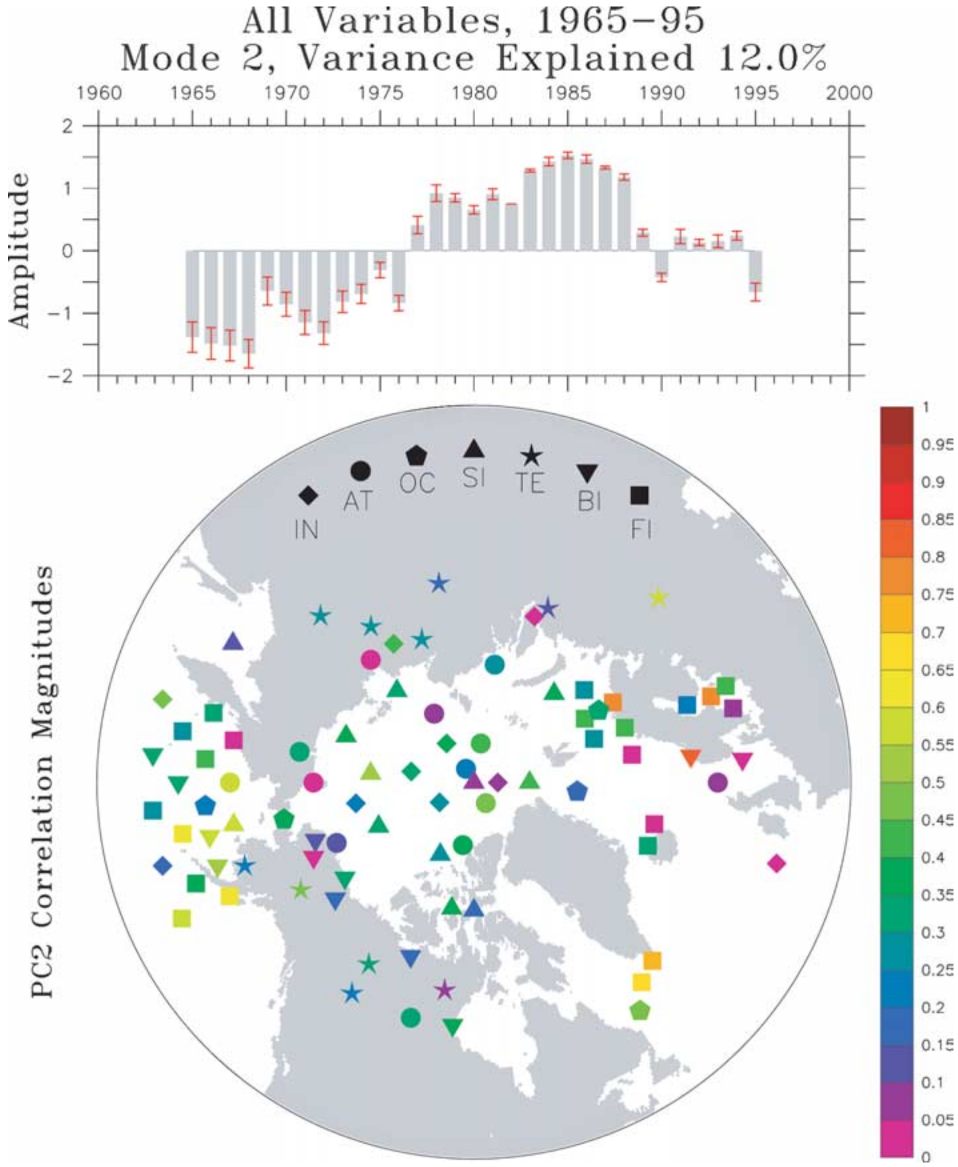

Figure 4. Same as Figure 3, but for the second Principal Component (PC2).

A major issue for PCA is the impact of data gaps in the middle and end of the records. We address this sensitivity in three ways. First, we compared PCA for the 21-year and 31-year periods, which showed similar PC time series for mode 1 and 2 in the period of overlap. Second, we used the method of Davis (1976) to permit the calculation of PC time series in the presence of data gaps. This method also provides an associated square error estimate of the uncertainty of the PC at each time value. This error is zero when all variables are present in a given year.

The error bars on the PC time series in Figures 3 and 4 are greatest for the years with reduced data coverage (1965–1974) as expected, but show that extending the analysis to include the relatively less sampled earlier period is warranted. The average uncertainty in PC amplitudes due to missing data is less than 11% for PC1 and 12% for PC2. A third approach is to fill the missing data values in the data collection before the PCA analysis using a Monte Carlo approach (D. Percival, 2003, personal communication). This method produced PC time series for mode 1 and 2 similar to those presented based on the Davis method.

The time series that make major contributions to the PCA are listed in Table II and many are displayed in Figure 5. Table II lists their primary season and location, principal reference and whether they represent primarily a trend, regime-like character or interdecadal oscillation. Figure 5 plots the time series with the 1/3 largest values in red and the 1/3 lowest values in green; if the time series showed a decrease over time we have inverted the series and noted this with a star (*). There is an overall shift from green to red over the 30-year period across the different data types. The major variability is on a decadal rather than interannual scale. The next sections present a discussion of the response of different data types in more detail.

4. Atmospheric and Climate Indices

Because many climate indices relate directly to atmospheric circulation, we have combined this category into one group with atmospheric time series. However, we have separated CO_2 and ozone into a separate group, as they represent atmospheric chemistry, and show a different trend shape than the time series representing atmospheric circulation.

The observations of CO_2 at Barrow and Ozone over Canada show a correlation with PC1. Stratospheric ozone levels, as represented by five Canadian stations, have decreased steadily from 1970 to the late 1990s, and now appear stabilized at a lower level due in part to the reduction in CFC use. It is estimated that it will take at least several decades for ozone to return to previous values (Weatherhead et al., 2000). Carbon dioxide as represented by the Barrow Alaska observatory record has steadily increased over the period; CO_2 is now estimated to be at levels which are higher than at any time in the past 20 million years, and the increase continues (Pearson and Palmer, 2000). Increases of CO_2 in models (Shindell, 2003) show a contribution toward cooling of the stratosphere. Ozone chemistry is understood to contribute to cooler stratospheric temperatures through positive feedback mechanisms (Randall and Wu, 1999). However, the importance of these results is controversial (Graf et al., 1998; Gillett et al., 2002). As we will note in the next paragraphs, an increase in the frequency of cold temperature anomalies and increased stratospheric winds occurred in the 1990s, which are coupled to atmospheric changes in the lower troposphere. CO_2 and O_3 have linear trends and

Table II

A subset of the Unaami data collection which represents major Arctic change 1965–1995

Variable	Season	Location	Principal reference	Trend type	Latest change
Global chemistry					
CO_2		Barrow TBP	Peterson 1986	Trend	Up
Stratospheric ozone		Canada	Fergusson 1998	Trend	Down
Atmosphere and indices					
Polar vortex 50 hPa	Dec–Apr		Graf 2000	Regime	Up
Arctic oscillation	Nov–Mar		Thompson 1998	Regime	Up
Zonal wind 300 hPa	Jan–Mar	N Atlantic	Wang/PMEL 2002 PC	Regime	Up
North Atlantic Oscillation	Dec–Mar		Hurrell 2001	Regime	Up
200 hPa air temps (mode 1)	March		Wang/PMEL 2002 PC	Regime	Down
925 hPa air temps (mode 2)	April		Wang/PMEL 2002 PC	Trend	Up
Surface vorticity	2-yr mean		Walsh 1996	Interdecadal	Up
Siberian High	Jan–Mar		Savelieva 2000	Interdecadal	Down
Arctic Ocean sea-level gradient			Proshutinsky 1999	Interdecadal	Up
‘E’ (meridional) index			Savelieva 2000	Trend	Down
‘W’ (meridional) index			Savelieva 2000	Trend	Up
Zonal wind 300 hPa	Jan–Mar	N Pacific	Wang/PMEL 2002 PC	Pacific/regime	Up
Aleutian low	Jan–Mar		Trenberth 1994	Pacific	Up
Sea ice					
Thickness	September	E Siberia	Holloway/AES 2002 PC	Regime Down	
Thickness	September	Fram Strait	Holloway/AES 2002 PC	Interdecadal	Down
Extent	Summer	Arctic	Parkinson 1999	Regime	Down
Extent	Spring	Barents	Parkinson 1999	Trend	Down
Extent	Winter	Okhotsk	Parkinson 1999	Trend	Down
Duration	Summer	Resolute Bay	Flato 1996	Trend	Up
Extent	Spring	Bering Sea	Wyllie-Echevarria 1998	Pacific	Down
Oceanic					
Water temps	January	Kola Peninsula	Dickson 2000	Interdecadal	Up
SST	Jan–Mar	Labrador Sea	Salo/PMEL 2002 PC	Regime	Down
SST	Winter	Pribilof Is.	Hare 2000	Regime	Down
Transport		Bering Strait	Roach 1995	Trend	Up
Terrestrial					
Greening	Apr–Oct	Eurasia	Zhou 2001	Trend	Up
Greening	Apr–Oct	N America	Zhou 2001	Trend	Up
Snow	February	Eurasia	Rutgers Climate Lab 2002 PC	Trend	Down
Snow	February	N America	Rutgers Climate Lab 2002 PC	Interdecadal	Down
Permafrost temperature	Annual	Alaska	Osterkamp 1999	Trend	Up
Permafrost temperature	Annual	E Siberia	Romanovsky/UAF 2002 PC	Trend	Up
Discharge	Water year	Siberia	Savelieva 2000	Trend	Up
Burn area	Annual	NE Canada	Murphy 2000	Regime	Up
Biological					
Carabou		W Alaska	Griffith/USGS PC	Regime	Up
Black Guillemont		N Alaska	Divoky/UW PC	Regime	Up
Zooplankton		N Sea	Planque 1998	Regime	Up
Red deer			Post 1997	Trend	Up
Benthic invertebrates		Bering	Conners/AFSC 2002 PC	Pacific	Up
Fur seals		Bering	York 2000	Pacific	Down
Fisheries					
Herring		Norway	Statistics Norway 1999	Regime	Up
Shrimp		Greenland	FAO 2001	Trend	Up
Cod		Barents	Ottersen and Loeng 2000	Trend/regime	Up
Cod		Baltic	ICES/ACFM:18 2001	Regime	Down
Turbot		Bering	Hollowed 1998	Pacific/regime	Down
Plaice		Bering	Hollowed 1998	Regime	Down
Chum salmon		Bering	Hare 1999	Interdecadal	Down
Herring		Baltic	Kull 1996	Interdecadal	Down
Redfish		Barents	ICES/ACFM:19 2001	Interdecadal	Down
Halibut		Greenland	ICES/ACFM:20 2001	Interdecadal	Down
Sockeye salmon		Bering	Hare 1999	Pacific	Up
Arrowtooth flounder		Bering	Hollowed 1998	Interdecadal	Down

PC = Personal Communication (see website).

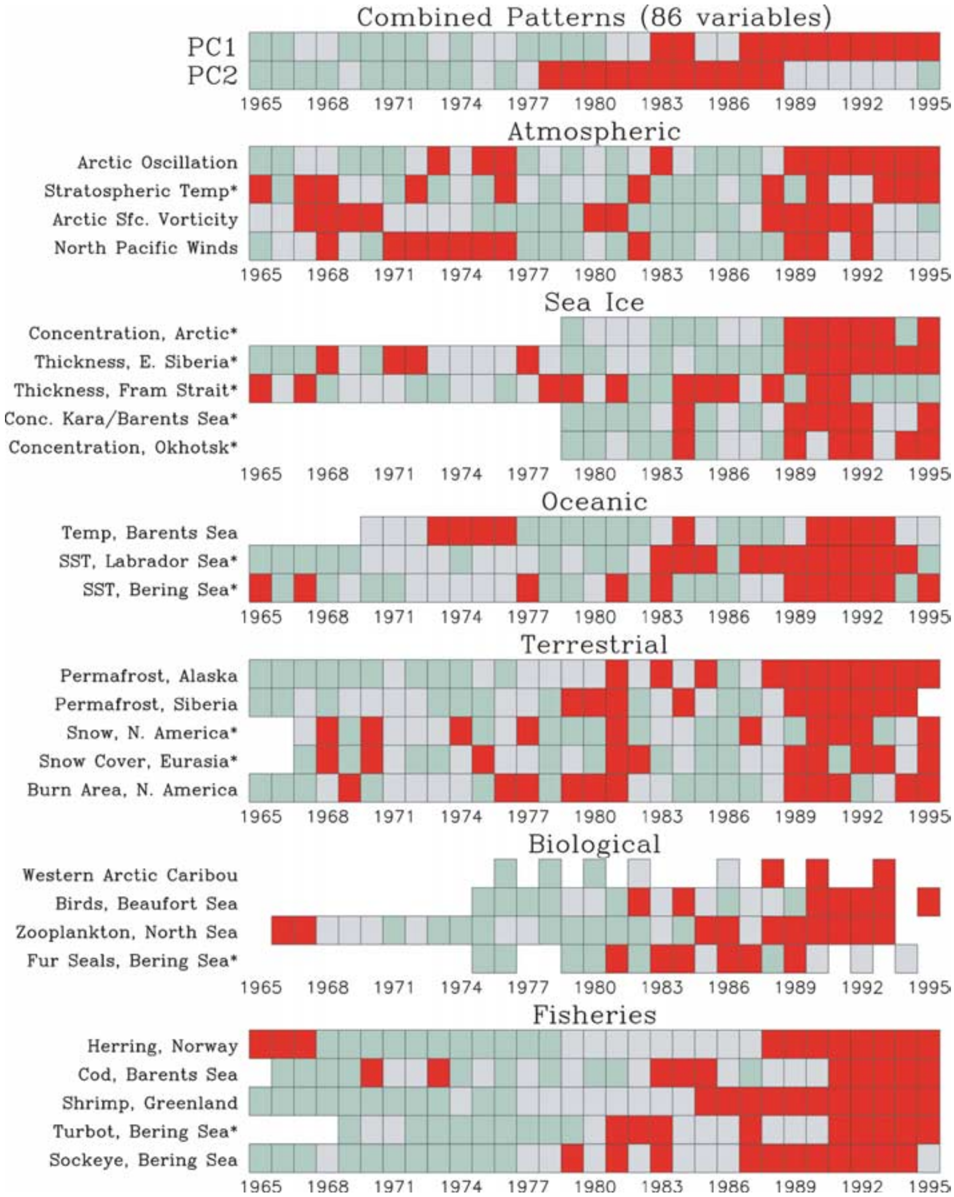

Figure 5. A selection of time series representing six data types that demonstrate Arctic change over the previous three decades. The first two principal components of the larger data set are also shown. Data values are divided into three strata: lowest 1/3 (green), middle (gray), and highest 1/3 (red). To demonstrate covariability over time, some series have been inverted as noted by a star. The complete data collection is described at www.unaami.noaa.gov. Note the shift from green to red for many of the series and that the primary time scale of variability is decadal.

do not show the step-like behavior of many of the other atmospheric variables. However, the trends in CO_2 and O_3 cannot be entirely ruled out as a forcing mechanism through radiative/dynamic processes contributing to the multivariate trend of PC1 in Figure 3.

The remainder of the climate indices and atmospheric time series relate to atmospheric circulation. PC1 has major contributions from the Arctic Oscillation (AO), the North Atlantic Oscillation (NAO), the strength of winds in the polar vortex in the lower stratosphere, and the zonal/meridional circulation 'E' and 'W' indices from Russian sources (Rodionov, 1994).

PC2 has contributions from two sub-groups. The first sub-group is centered on the high Arctic: the vorticity of the surface winds near the pole (Walsh et al., 1996), the sea level gradient of the Arctic Ocean from a model (Proshutinsky et al., 1999), and the strength of the Siberian high pressure region. The second sub-group is a North Pacific group of 300 hPa winds at (60° N, 180° W) and the strength of the winter Aleutian low sea-level pressure system, called the North Pacific Index (NPI).

To refine the analyses we performed a PCA on the combined atmospheric and indices group, without CO_2 and O_3. The first seven time series which are strongly weighted on the first Atmospheric Principal Component (APC1) are the AO, the 300 hPa winds over the North Atlantic (60° N, 0° E), the polar vortex, the North Atlantic Oscillation (NAO), the first EOF (zonal) of 200 hPa temperatures in March, the 'E' index, and the second EOF (wave1) of the near-surface 925 hPa temperatures in April (Figure 6a). The second Atmospheric Principal Component (APC2) has the vorticity of surface winds in the high Arctic, the sea level gradient, the second EOF of 200 hPa temperatures in March, and the Siberian high pressure (Figure 6b, top). The third Atmospheric Principal Component (APC3) had the Aleutian low (NPI) and the 300 hPa zonal wind over the Pacific (60° N, 180° W) (Figure 6b, bottom). Thus while the first and second components of the PCA performed on the climate indices/atmospheric data are very similar to the PCA for the entire collection, the PCA on atmospheric data alone did identify a separate Pacific component.

The composite results for the atmosphere/climate indices are summarized by a cross correlation table (Table III). A main feature of Table III is that in general the correlations are not particularly large. This would imply that no single atmospheric index is ideal for representing all Arctic climate variability. As with the atmospheric PCA, we see three groups of variables. The stratospheric polar vortex forms one group (bold in Table III) consisting of the AO, NAO, Atlantic 300 hPa zonal wind, springtime stratospheric (200 hPa) air temperature, and springtime near surface temperatures. The 'E' meridional index is weakly associated with this group. The characteristic common to these time series is a regime-like increase (or decrease) near 1989. The second group (denoted by an underline) as represented by the surface wind vorticity in the high Arctic, relates to the sea level pressure gradient and the Siberian high pressure, all of which are centered near the pole and

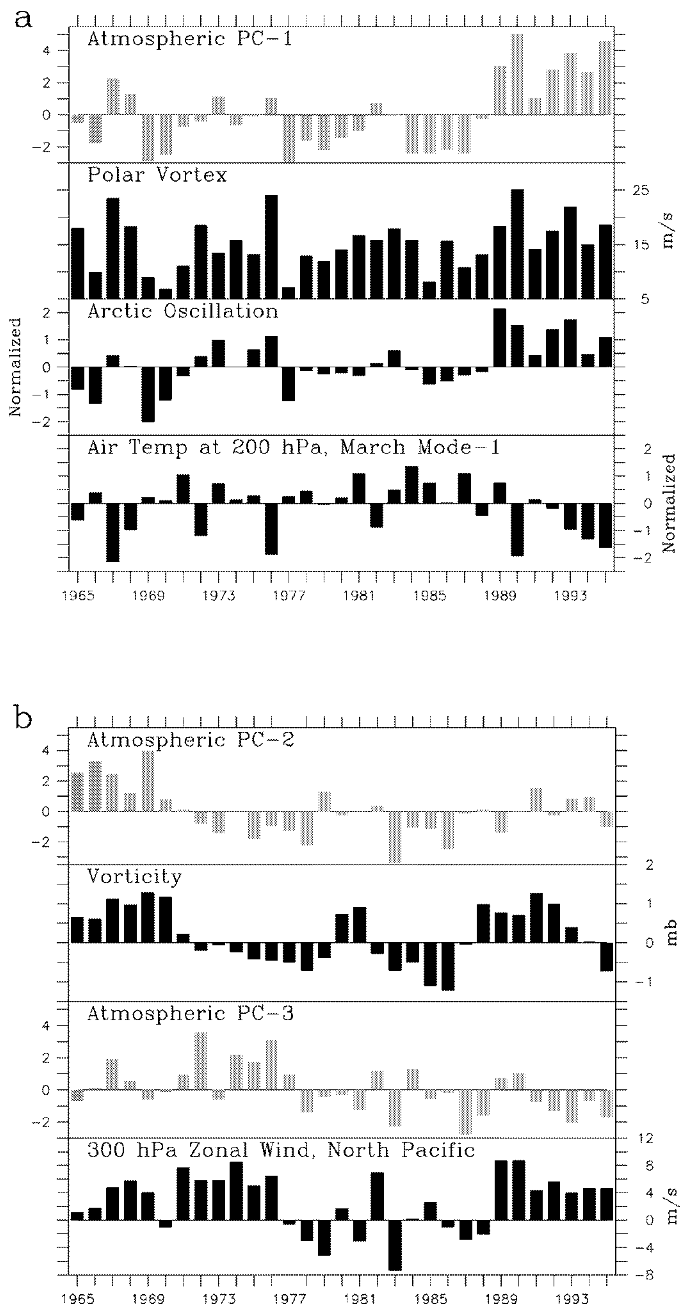

Figure 6. (a) The first Principal Component based on an atmospheric subset of the data (APC1) and the corresponding time series which project onto this mode: stratospheric polar vortex, Arctic Oscillation, and stratospheric temperature anomalies in March (see Table II for more details on the individual time series). (b) (top) The second atmospheric PC mode (APC2) and the surface wind vorticity time series with an interdecadal character. (bottom) The third atmospheric mode (APC3) and zonal wind along 180° longitude; both have a North Pacific regime character after 1976.

Table III

Correlation matrix, 1965–1995 (31 years) for the Atmospheric and Climate Indices data types. Correlations of greater than |0.5| cluster into an Arctic Oscillation group (bold), a central Arctic group (underline), and a Pacific group (italic)

	NDJFM Arctic Oscillation	Dec–Apr mean polar vortex	DJFM North Atlantic Oscillation	JFM 300 hPa zonal wind (N. Atlantic: 60° N, 0° E)	Mar 200 hPa air temp. (EOF1)	Apr 925 hPa air temp. (EOF2)	Annual 'East' Meridional Index (Siberia)	24-Month running mean surface wind vorticity (Arctic Ocean)	Sea level gradient (center of Arctic Basin)	Jan–Mar Siberian high pressure	Jan–Mar North Pacific Index (SLP)	JFM 300 hPa zonal wind (N. Pacific: 60° N, 180° E)
	var1	var2	var3	var4	var5	var6	var7	var8	var9	var10	var11	var12
var1	1.00	**0.76**	**0.86**	**0.76**	–0.36	–0.35	–0.40	–	–	–0.33	–	0.44
var2	**0.76**	1.00	**0.65**	**0.59**	**–0.67**	–0.37	–	–	–0.28	–0.38	–	0.38
var3	**0.86**	**0.65**	1.00	**0.60**	–0.29	–0.34	–0.27	–	–	–0.24	–	0.35
var4	**0.76**	**0.59**	**0.60**	1.00	–0.27	–0.30	–0.42	0.21	–0.41	–0.36	–	0.33
var5	–0.36	**–0.67**	–0.29	1.00	**0.62**	0.23	–	0.39	0.37	–0.33	–0.39	
var6	–0.35	–0.37	–0.34	–0.30	**0.62**	1.00	0.31	–	0.26	–	–	–0.24
var7	–0.40	–	–0.27	–0.42	0.23	0.31	1.00	–	0.47	0.38	–	–
var8	–	–	–	0.21	–	–	–	1.00	–0.65	–0.32	–	0.21
var9	–	–0.28	–	–0.41	0.39	0.26	0.47	–0.65	1.00	0.55	–	–0.24
var10	–0.33	–0.38	–0.24	–0.36	0.37	–	0.38	–0.32	0.55	1.00	–0.22	–0.33
var11	–	–	–	–	–0.33	–	–	–	–	–0.22	1.00	***0.73***
var12	0.44	0.38	0.35	0.33	–0.39	–0.24	–	0.21	–0.24	–0.33	***0.73***	1.00

have a interdecadal character, low in the early 1970s and 1990s and high in the 1980s (or the reverse). The third group (represented with bold italics) is a North Pacific group with the 300 hPa zonal wind (60° N, 180° W) (Figure 6b, bottom) and the North Pacific Index (NPI). These have an interdecadal character with a major shift near 1976, related to the Pacific Decadal Oscillation (Mantua et al., 1997), but also show a shift in the late 1980s similar to PC2. We also note that many pairs of the time series in Table III have modest but significant ($r \sim 0.4$) correlations. For example, the Pacific 300 hPa zonal wind also has a contribution from the polar vortex group. The Siberian high has modest correlations with the other two groups. The AO has a weak association with the temperature fields. Thus each individual physical time series contributes to more than one PC.

PC1 and PC2 for the entire data set and our further detailed analyses of climate indices/atmospheric data suggest four time series shapes or patterns for 1965 through 1995 listed in Table III. The first is a linear increase or decrease and is represented by CO_2 and the 'E' index. The second is a regime-like change near 1989; this includes the polar vortex, AO, and stratosphere spring temperature anomalies. Both of these shapes project onto PC1. The third shape projects onto PC2 and has a interdecadal character where anomaly magnitudes for the 1970s are near those for the 1990s; this includes variables close to the pole such as surface wind vorticity. Also projecting on PC2 is a North Pacific influence which is not strictly Arctic. The North Pacific is characterized by a shift in the mid 1970s, but these series do not strongly correlate with the 'interdecadal' Arctic shape.

5. Other Physical Variables: Sea Ice, Oceanography, and Terrestrial

5.1. SEA ICE

Sea ice information came primarily from two sources: Passive microwave provides quality records of extent from the late 1970s, and sea ice models provide September thickness estimates. Sea ice models driven by NCEP/NCAR atmospheric reanalyses have improved greatly in the previous decade and we have extracted monthly sea ice thickness values from a model developed at the Institute of Ocean Sciences. Other records included observations at Resolute Bay, Canada. Five of the twelve sea ice time series strongly project on PC1, occurring in the top 28 series which contribute to PC1. The central Arctic (summer) shows a linear decrease but with strong minimums in 1990, 1993, and 1995 (Figure 7a). Modeled September mean sea ice thickness for the East Siberian Sea shows a step-like decrease in thickness for 1988 with low values for the 1990s. Ice cover in the Barents/Kara Seas (spring) shows a linear decrease in extent over time, while on the western side the duration of open water at Resolute Bay has increased since the 1960s and the Okhotsk Sea (winter) shows a linear decrease. PC2 included major contributions from the Central Arctic, Fram Strait, and Bering Sea (Figure 7b). Visual inspection of the Bering

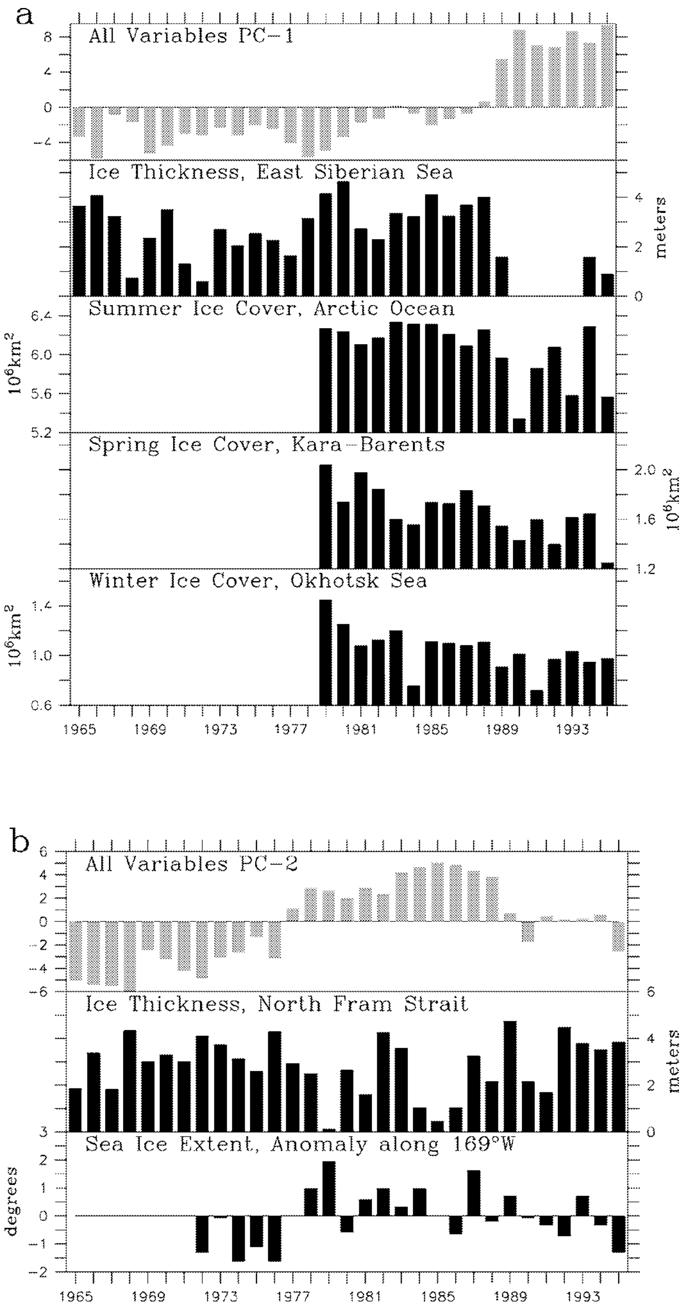

Figure 7. (a) Four sea ice time series which project onto the first Principal Component of the data collection (PC1). Ice thickness in the East Siberian Sea and summer ice cover for the central Arctic basin show reductions beginning in 1989. Spring ice cover in the Kara-Barents Seas and winter ice cover in the Okhotsk Sea show a more linear decrease in ice cover. (b) Modeled September ice thickness near Fram Strait and winter ice extent in the Bering Sea show a more interdecadal pattern and project onto PC2.

Sea ice extent (169° W) may imply a springtime reduction, but it is mathematically a relatively weak signal; it is also related to the Pacific shape. The central Arctic is a short series and thus projects onto both PC1 and PC2. Other locations which are not shown had large interannual variability or interdecadal variability which did not line up with a shift in the late 1980s. In summary, the Siberian shelf and central Arctic extent show a regime-like character while the Barents and Okhotsk seas show a dominant linear trend of reduced sea ice area. Fram Strait modeled ice thickness appears to respond to central Arctic winds associated with PC2.

Sea ice and atmospheric data can be used to trace the time series patterns represented by PC1 and PC2 earlier in the 20th century. This was completed by Venegas and Mysak (2000), who performed a frequency domain analysis of century-long (1903–1994) records of North Atlantic sector sea ice concentration and sea-level pressure poleward of 40° N. The evolutive version of their Local Fractional Variance (LFV) spectrum for sea ice concentration shows that the interdecadal signal for sea ice is significant during the entire record, but shifts slowly toward higher frequencies toward the end of the century (see their Figure 2). The modeling of Proshutinsky et al. (1999) and the analysis of the flux of sea ice out of Fram Strait (Vinje, 2001) also support 20th century interdecadal/decadal (PC2) variability over the Arctic Basin. Goosse et al. (2002) suggest a mechanism based on sea ice/atmospheric feedbacks. Figure 8a, reproduced from Vinje (2001) shows an interdecadal/decadal signal with three maxima since 1950, when the interannual variability is reduced by six year running mean. The symbols ‘C’ and ‘A’ refer to maximum cyclonic or anticyclonic ocean circulation as described by Proshutinsky et al. (1999). Thus the inferred efflux of sea ice out of Fram Strait represents a major 50-year climate record of the interdecadal components in the Arctic Basin.

By contrast, the centennial-long Arctic Oscillation (Figure 8b), which considers sea-level pressure north of 20° N (Thompson and Wallace, 1998), has considerably more variance and trend since 1960 (Feldstein, 2002), a feature also noted in the LFV for sea-level pressure by Venegas and Mysak (2000). Even though the number of reporting weather stations decreases significantly before 1930, the AO time series does support the concept that something unique for the century may have occurred in the 1990s as represented by PC1. Resolution of this point, however, is far from clear. For example, Arctic temperatures and sea-level pressure north of 62° N experienced anomalies in the 1930s as well as the 1990s (Polyakov, 2002).

5.2. OCEAN PARAMETERS

As noted by Dickson et al. (2000), the water column sea temperatures north of the Kola Peninsula in the Barents Sea relate to the increase in the NAO/AO. Figure 9 shows the increase in temperature in 1988, up from the period beginning in 1977. While this time series projected onto PC1, it was also in the top half of time series that projected onto PC2; this PC2 projection can be seen as the warm temperatures in the early 1970s. The second projection on PC1 is a decrease in sea surface

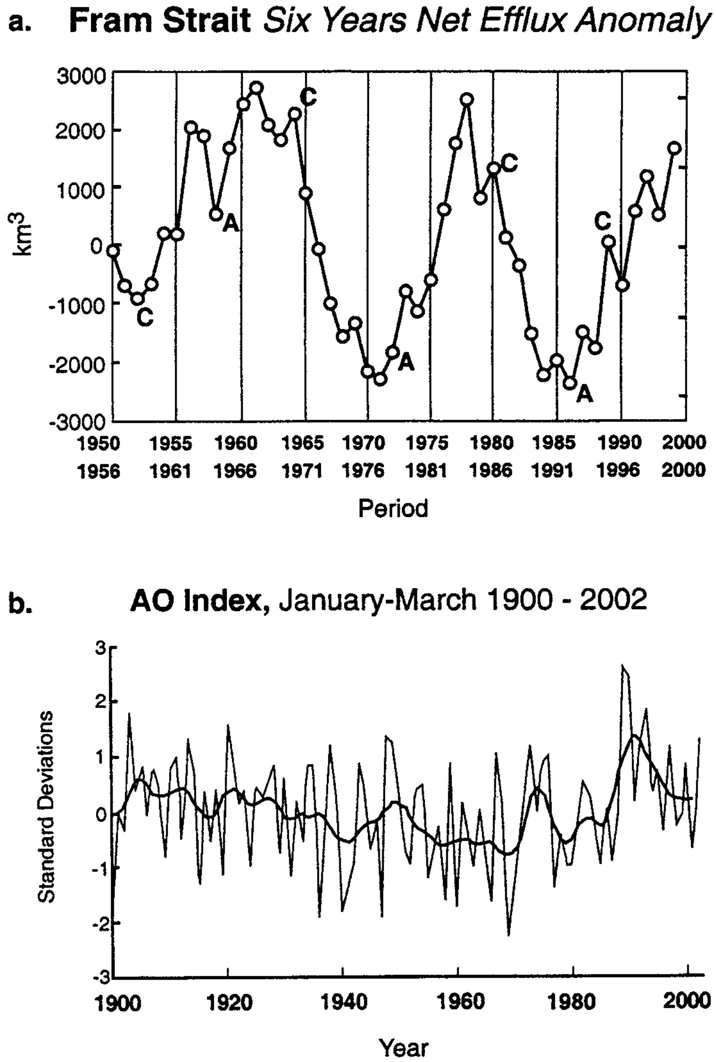

Figure 8. (a) Transport of sea ice exiting Fram Strait, based on wind estimates calibrated by direct sea ice measurements in the 1990s. Data represent six year running means, and show three periods of increased transport since 1950. The 'C' and 'A' represent extremes of the cyclonic/anticyclonic cycle of Proshutinsky et al. (1999). Figure modified from Vinje (2001). (b) The winter Arctic Oscillation index shows an increase in trend and variance toward the end of the 20th century (Feldstein, 2002). Figure updated from Thompson and Wallace (1998).

temperatures near the Pribilof Islands. There is a considerable cooling in the early 1990s as well as the shift to warmer temperatures in the mid 1970s.

SST anomalies in the Labrador Sea project onto PC2. Warmer temperatures are seen in the mid 1990s after a long period of cold temperatures. While this series has the plus-minus-plus structure of PC2, the transition dates are different from

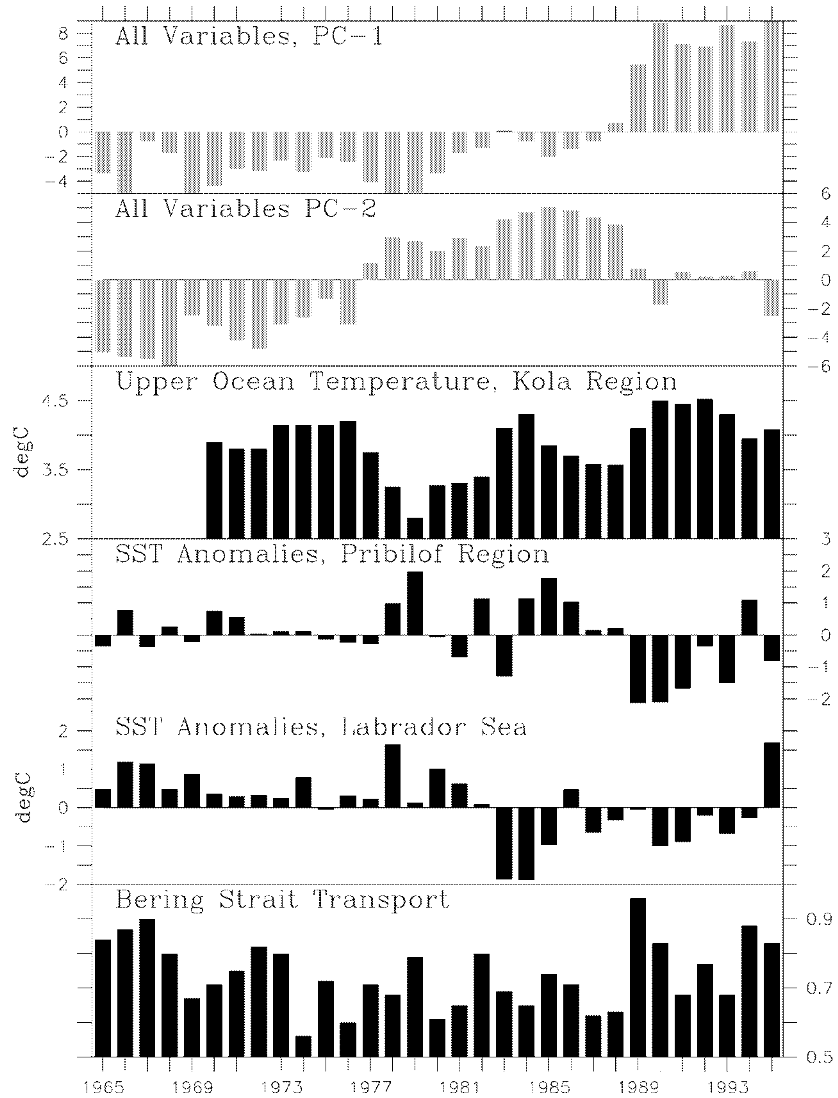

Figure 9. Ocean temperatures in the southern Barents Sea (Kola Peninsula section) project onto both PC1, with a shift in 1989, and PC2 with warmer temperatures in the 1970s. The central Bering Sea sea temperatures (Pribilof region) projects onto PC1 with the 1989 shift. The Laborador Sea SST projects onto PC2, but its major shift in the early 1980s is before the inflection point at 1989. Bering Strait ocean transport also projects weakly onto both PC1 and PC2.

other high latitude series. Bering Strait transport projects weakly onto both PC1 and PC2, but shows a PC1-like increase in the early 1990s.

5.3. LAND PROCESSES

The structure of time series for land processes do project onto PC1, however, inspection of the individual time series suggest a possible different character than other Arctic time series, PC1 or PC2. They represent rather strong linear trends with considerable interannual variability. To this end we have performed PCA on the 11 terrestrial time series for 1965–1995; the first mode (TPC1) represents 36% of the variance (Figure 10, top). The trend, combined with considerable year-to-year fluctuations, is apparent; there is also some echo of a regime-like shift near 1989 similar to PC1. Eight of the eleven time series strongly project onto TPC1. Examples as plotted in Figure 11 are permafrost temperatures in both Alaska and Siberia, snow in Eurasia (February mean), greenness in Eurasia and North America (April–October mean), and Siberian river discharge. Greenness is a measure estimated from two bands of an AVHRR satellite over a summer season. The major exception to this trend is snow cover extent for North America, which is the largest component of the second principal component for terrestrial time series (TPC2); it has more the character of PC2 with low values in the 1970s as well as the 1990s. While TPC2 represents 16% of the variance of terrestrial time series, more than half of the series also have a projection onto this component as suggested by a weak interdecadal component in the time series. Burn area for NW North America shows an upward trend with an episodic character; it projects on the regime-like PC1.

In summary, terrestrial time series show a linear trend with the presence of interannual variability, some interdecadal variability, and shift near 1989. This trend is represented in all terrestrial series to a greater or lesser extent. It is interesting to note that terrestrial time series represent changes in subarctic latitudes and often represent a memory process smoothing out interannual variability from atmospheric forcing. Both greenness and snow cover show areal changes near 60° N, and river discharge into the Arctic Ocean incorporates the influence from more southerly water sheds.

6. Biotic Changes

Biotic changes integrate weather and climate signals over at least a season and possibly over several years, in contrast to atmospheric data which has considerable energy on weekly, seasonal, and interannual scales. Hare and Mantua (2000) conclude for the North Pacific that marine ecosystems appear to filter climate variability strongly and may allow for earlier identification of shifts than is possible by monitoring climate data alone. However, biological data are subject to the influence of population dynamics and human influences in addition to climate influences. In this section we investigate this hypothesis for Arctic data. We sample both lower trophic level and fisheries recruitment time series, which emphasize individual years. In other cases, abundance data provide the primary information.

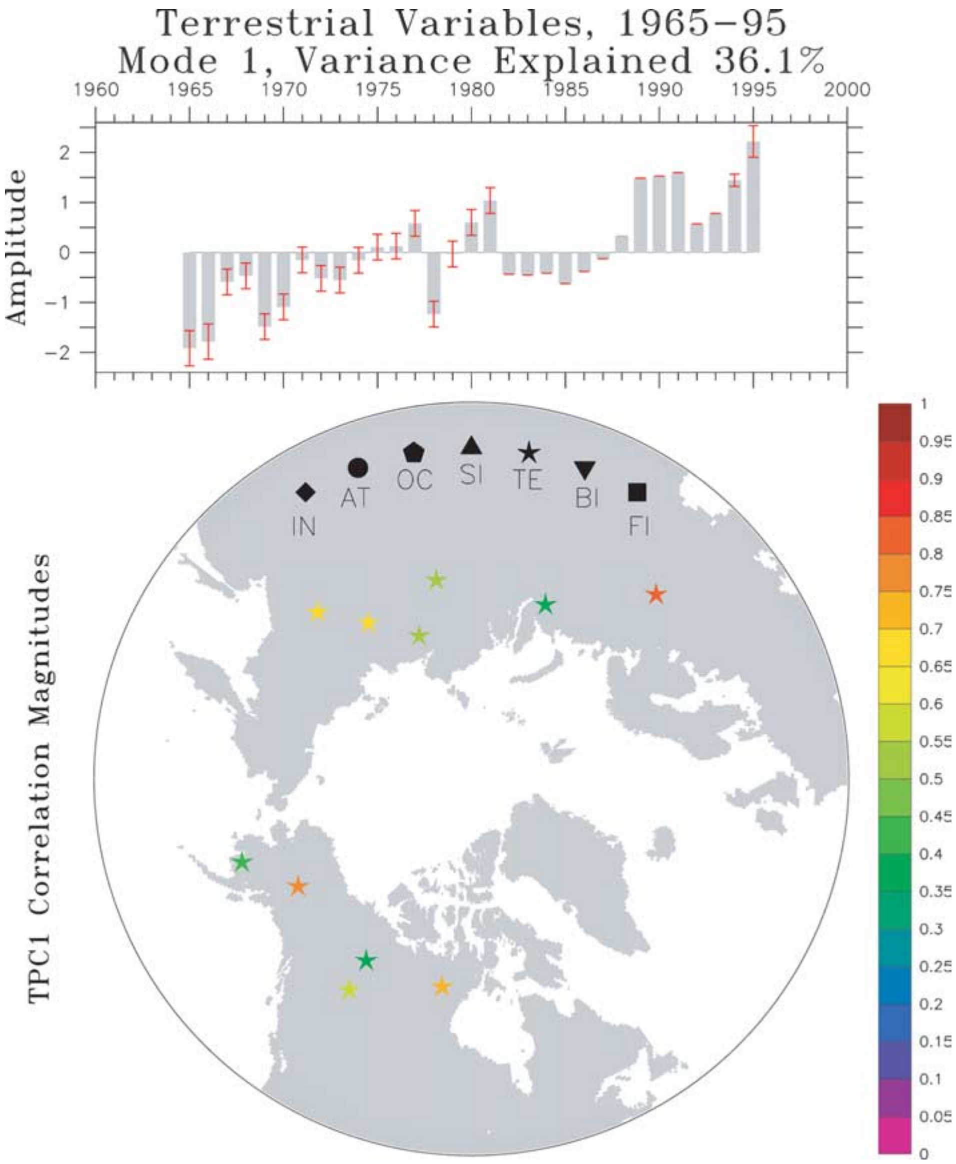

Figure 10. (top) The first Principal Component of the terrestrial time series (TPC1), which shows a linear trend with variability. (bottom) Most of the terrestrial time series project strongly onto TPC1 with correlations greater than 0.5.

6.1. NON FISHERIES DATA

Both biological and fisheries data weight strongly on PC1 and PC2. The western Alaska caribou abundance increases and the date of clutch initiation for Black Guillemont is earlier off the north coast of Alaska in the 1990s compared to earlier decades (Figure 12a), with large contributions to PC1. This step change is

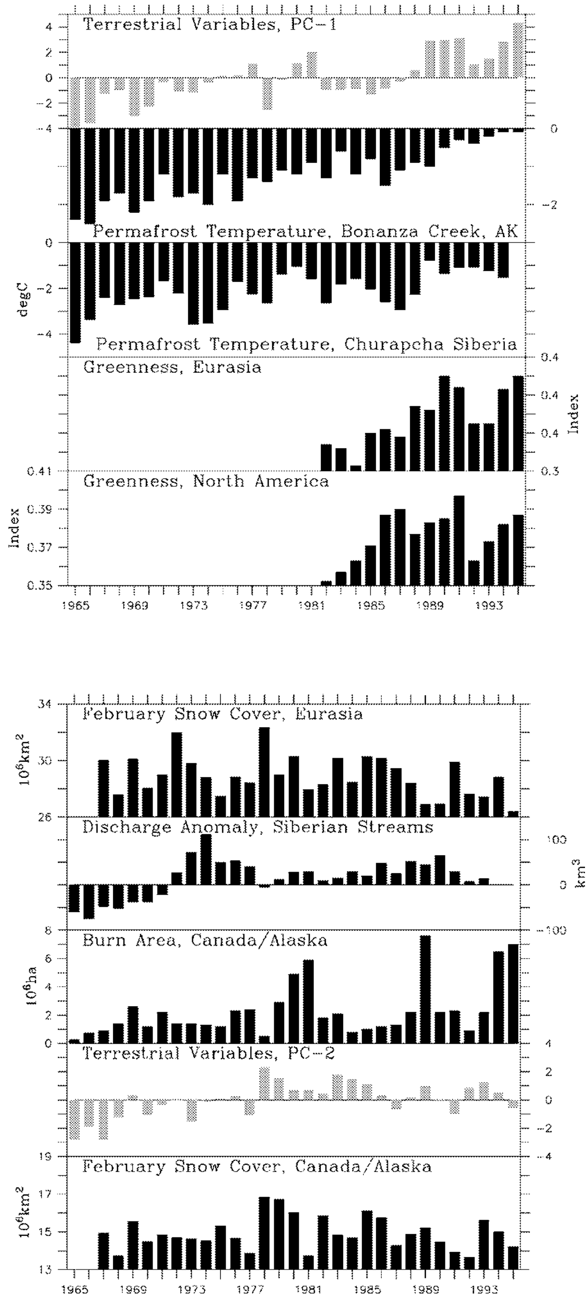

Figure 11. The time series of the first Principal Component of terrestrial time series (TPC1) and the individual time series of permafrost temperatures, satellite estimates of greenness, Siberian runoff, and Eurasian snow cover. All series show a linear trend with interannual variability. North American snow cover had minimums in the 1970s as well as the 1990s and projects on the second Terrestrial Principal Component TPC2. North American burn area projects on TPC1 and shows events in 1980–81, 1989, and 1994–95.

consistent with earlier spring conditions in northern Alaska (Overland et al., 2002) which relate to the climate variables that contribute to PC1, especially April surface temperatures. However, neither time series extend back to the 1960s. Zooplankton abundance in the North Sea relates to the NAO (Dickson et al., 2000) and to PC1; this time series shows a steady increase since the mid 1970s. The main transition years are different from other series which contribute to PC1, i.e., the mid 1960s and mid 1980s. There was an increase in jellyfish in the Bering in the 1990s, but inspection of the curve suggests a steady exponential increase since the 1970s.

Red deer abundance in Norway (Figure 12b) projects onto PC2 and emphasizes a steady increase from the late 1960s through the mid 1980s with little change from the mid 1980s onward. Post and Stenseth (1999) have discussed the relation of this population change to factors associated with the NAO. A decline in fur seals and an increase in benthic invertebrate populations in the Bering Sea (Figure 12b) have a response to the North Pacific shift in the late 1970s (Atmospheric PC3). The fur seals have a 0.45 correlation with the wintertime Aleutian low (NPI) which emphasizes the 1976 regime shift, and the increase in the summer invertebrate population has a –0.40 correlation with the springtime NPI index. The increase in benthic invertebrates also projects onto the increasing time series represented by PC1 ($r = 0.67$).

6.2. FISHERIES DATA

Fisheries data makes up the largest category of data types. Data covers four main fisheries: Iceland, Barents Sea/Norway, the Baltic Sea, and the Bering Sea. Much of the information on ground fish are recruitment data, i.e., how much biomass is added to the fishery from new fish in each year; these data are actually model results based on sample abundance for different age classes. These estimates are provided by International Council for the Exploration of the Sea (ICES) for the North Atlantic, and by NOAA for the Bering Sea. Other data sources are listed as metadata on the Unaami data collection web site. Many species contribute to PC1, PC2, or both.

With regard to PC1, herring stocks near Norway increased dramatically in 1988 after being low since the mid 1960s (Figure 13a). Cod abundance decreased in 1989 in the Baltic while cod recruitment and lengths increased in 1990 in the Barents Sea, possibly due to warmer ocean temperatures (Kola Peninsula time series) and increased zooplankton in response to the NAO/AO. Shrimp catch off of Greenland has increased since the 1960s and stabilized at large values in the 1990s. This occurred with the cooler temperatures in the western North Atlantic (Labrador Sea time series), which could also relate to AO/NAO shifts. Whether the long-term increase in shrimp since the 1960s is a climate trend is uncertain, as the fishery expanded during this time. Place recruitment in the Bering Sea shows a major regime change in 1990, as does chum salmon catch (Figure 13b). While turbot

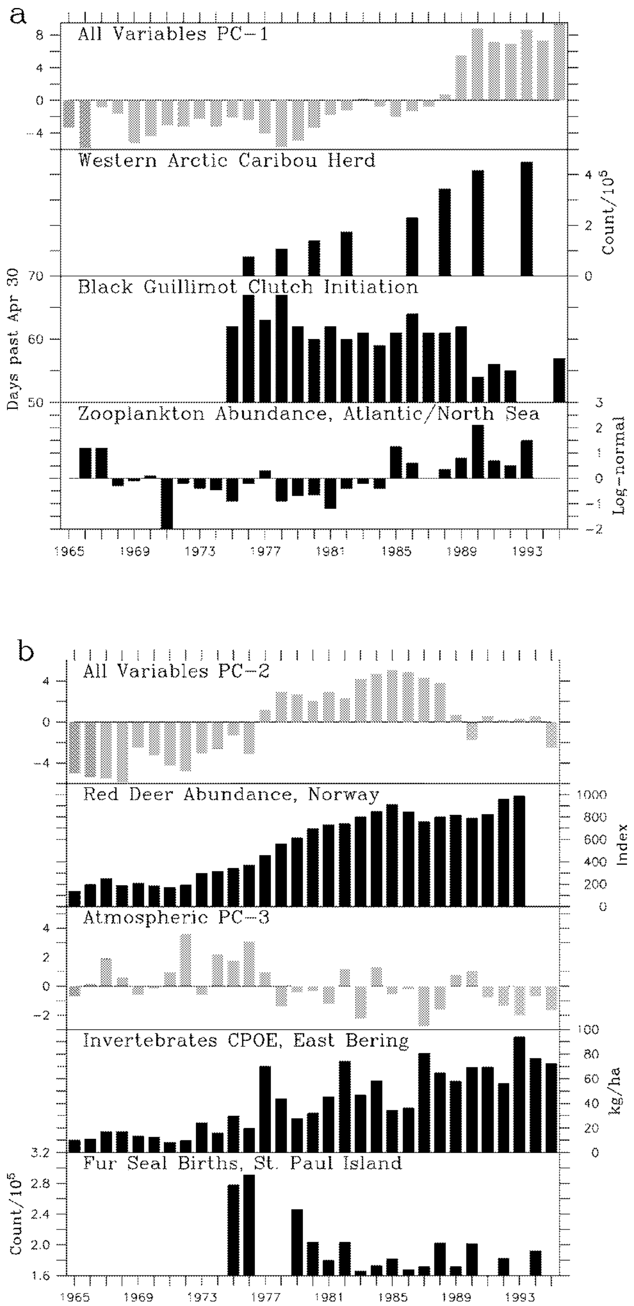

Figure 12. (a) Time series of certain biological species project onto the regime-like (PC1). (b) (top) Despite the trend in abundance of red deer in Norway, the level population from the mid-1980s onward projects onto PC2. (bottom) Along with the North Pacific regime shift in 1976 (APC3), there were changes in bentic invertebrate abundance (up) and fur seal births (down). Invertebrates also project on the Arctic-wide trend of PC1.

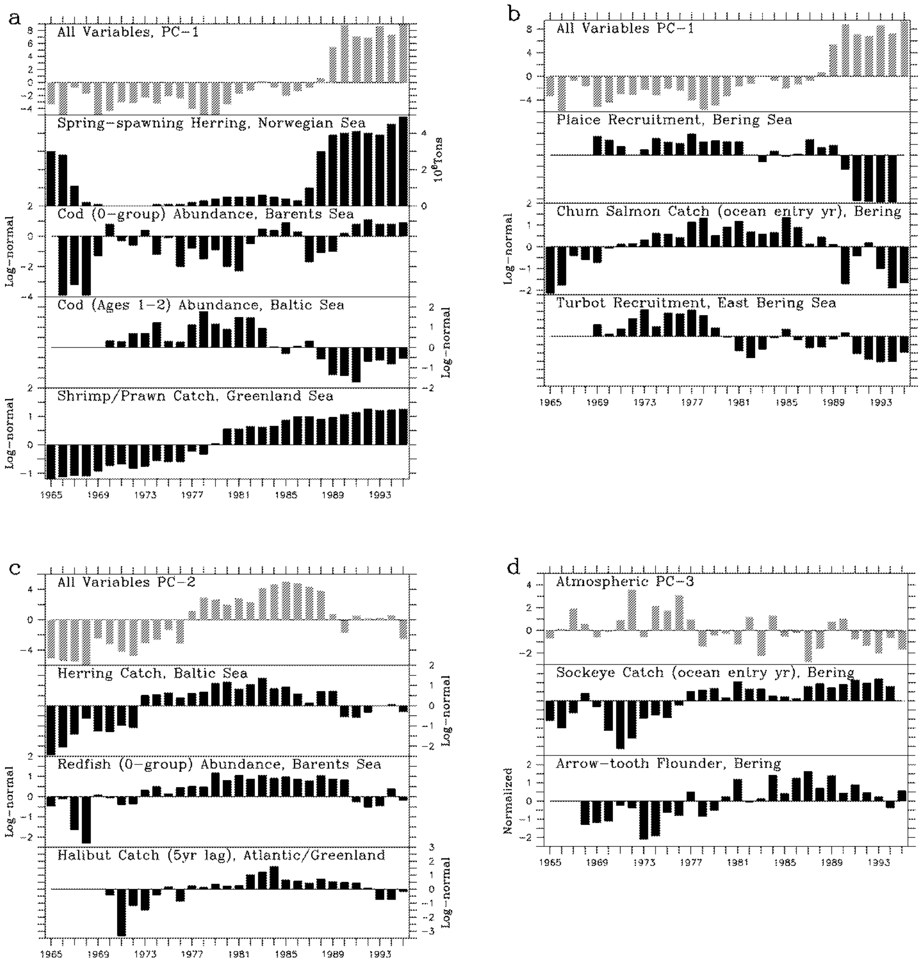

Figure 13. Many fisheries species in the Atlantic (a) and Pacific (b) project onto PC1. (c) Other Atlantic fisheries species show a more interdecadal character (PC2). (d) Two fish species from the Bering Sea project on the North Pacific (APC3) 1976 regime shift pattern.

recruitment in the Bering Sea maps onto PC1 with a decrease after 1990, its main feature is a decline after the North Pacific regime shift in the late 1970s.

After Red Deer in Norway, fisheries data provide the second through seventh largest contributions to PC2. Herring catch in the Baltic Sea, redfish abundance of age-zeros in the Barents Sea, and halibut catch near Greenland all have a interdecadal-like structure (Figure 13c). Sockeye salmon catch and arrowtooth flounder (Figure 13d) in the Bering Sea show a primary change around the time of the late 1970s North Pacific regime shift. Flounder decrease in the early 1990s, but sockeye do not.

A major feature of the fisheries time series is their strong contributions in the PCA. Inspection of the series suggests that these contributions result in part from the large autocorrelation of the recruitment, catch and abundance time series. Whether the autocorrelation in recruitment is related to the modeling procedure and the catch to regulation is beyond the scope of our analysis. While they do appear to provide smooth series of change which often do align with climate variables, the causality of these relations is less certain. There is a plausible NAO/Barents Sea cod link (Dickson et al., 2000) in the North Atlantic, but the fisheries oceanography in other regions is less certain. What is evident is that the smooth fisheries data dominate in a PCA over time series with large interannual variability. Whether this acts as filtering of the climate signal or a preference based on the mathematical process needs further exploration in each fisheries basin. As noted in Section 4, we have conducted a PCA on the climate/atmospheric data and these results independently support the PC1/PC2 character of the climate data.

Although many fisheries time series map strongly onto PC1 and PC2, many fisheries time series in each region do not. Therefore it would be difficult to develop a clear single ecosystem index for each region by compositing the fisheries and other physical and biological environmental data.

7. Discussion and Summary

We have presented a large number of time series that represent change in the Arctic based on seven data types. We reduced the number of time series from many Arctic data bases to an Unaami data collection, and then to a further subset using PCA. There are a range of patterns and timing represented by the time series listed in Table II and displayed in Figure 5. The first impression is that changes in the Arctic system over the last three decades are large and that changes are decadal in scale rather than interannual. This includes several degree changes in springtime stratospheric and permafrost temperatures, large areal increases in greenness and decreases in snow cover and ice extent, and order of magnitude changes in abundance or recruitment in many species.

Our analyses reveal certain commonalities. The two patterns based on PC1 and PC2 (Figures 3 and 4) have inflection points near 1989. PC1 transitions from a low value to a high value while PC2 has an interdecadal/decadal character based on the one and one-half cycles spanned by our data collection. The shapes of these patterns are supported by longer records, at least from the 1950s, the AO for PC1 and Fram Strait sea ice efflux for PC2. The main physical variables associated with PC2 are in the high Arctic. One plausible chain of events is that the physical processes that support PC1, most notably the persistence of a strong polar vortex into spring and the Arctic Oscillation index both of which have influences reaching into mid-latitudes, are manifest in amplifying existing modes of climate variability, most notably the high latitude interdecadal/decadal component, e.g., PC2.

The underlying causes for the large number of Arctic changes represented by PC1 is uncertain. The increase in CO_2 and decrease in ozone over the period cannot be entirely ruled out as supporting recent Arctic changes, although this conjecture is controversial. Ozone depletion would be particularly relevant in the Arctic spring. The change in character of the stratospheric temperatures after 1990, with an increase in frequency of cold years, contrasts with the previous five decades (Pawson and Naujokat, 1999; Overland et al., 2002). Internal processes in the Arctic and subarctic such as albedo and cloud radiative feedbacks from decreased ice and snow cover, also can not be ruled out as having an impact. It is difficult to see how these surface processes would couple with the mid-troposphere in summer, but late spring may be an important time; Watanabe and Nitta (1999), Cohen and Entekhabi (1999), and Clark and Serreze (2000) note the importance of lack of Eurasia snow cover on atmospheric circulation, particularly in 1989. Whatever the source, the recent trend and variance increase of the AO can be considered in excess of the level expected from internal variability of the atmosphere using standard statistical tests (Feldstein, 2002). An alternative plausible hypothesis is that the extremes of the 1990s are due to the coincidence of decadal and pentadecadal variability (Polyakov et al., 2002). Choosing between the prediction of an increasing trend represented by PC1, and the reversal of the trend based on the pentadecadal cycle, provides a strong incentive for Arctic observations in the next decade to detect which model is more correct.

Land processes show strong temporal and geographic coherence across most variables: snow cover, greenness, permafrost temperatures in both North America and Eurasia, and Siberian runoff. These series have a distinct linear plus interannual variability character. The ice cover in the Okhotsk and Kara/Barents Seas also had this linear character. The relation of these trends to the more regime or interdecadal character of other climate indices is uncertain. They do represent spring/summer observations and often indicate accumulated influences over several seasons, while climate indices are most pronounced in winter/spring with large interannual variability. A major factor representing year-to-year memory of the land system is the multidecadal increase in shrub abundance (Sturm et al., 2001).

In summary, the climate indices supported by many physical and biological time series show coherent changes across the Arctic and subarctic, representing a regime-like pattern after 1989. These changes may be an amplification of a high-Arctic interdecadal/decadal oscillation pattern. Many land processes and some sea ice data, which emphasize integrated and springtime/summer values, also show geographic coherence across the subarctic, although with a more linear pattern. Many fisheries and other biological time series map onto the principal components of the combined data set, but many do not. More research is needed, especially on the fisheries oceanography, to develop regional ecosystem indices of climate change. In addition to the 1989 regime shift, interdecadal, and terrestrial trend patterns, subarctic regions are also influenced by the North Pacific and the North Atlantic. The Bering Sea has a North Pacific shift around 1976 and the influence of the NAO is often seen in the mid-1980s before the more hemispheric 1989 shift.

Despite their individual character, more than half of the 86 variables in the data collection show considerable projections onto the three Arctic patterns: regime, interdecadal/decadal or linear trend. This suggests that the Arctic is responding to change over the last three decades in a temporally and geographically coherent manner. A conclusion of our pan-Arctic multivariate analysis is that no single index or class of observations exclusively tracks change in the Arctic.

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Appendix A. Unaami Time Series Key (see Figure A1)

Atmospheric

1 CO_2 at Barrow, AK
2 Air Temp 925 hPa April EOF-1
3 Air Temp 925 hPa Dec. EOF-1
4 Air Temp 200 hPa March EOF-1
5 Air Temp 925 hPa April EOF-2
6 Air Temp 925 hPa Dec. EOF-2
7 Air Temp 200 hPa March EOF-2
8 Air Temp 925 hPa Dec. EOF-3
9 Air Temp 925 hPa Dec. EOF-4
10 Siberian High Pressure
11 Ozone, Canada
12 Zonal Wind, 300 hPa, N. Atl.
13 Zonal Wind, 300 hPa, N. Pacific

Biological

14 Bathurst Caribou, NW Terr.
15 Black Guillimot, Alaska
16 Porcupine Caribou, N. Yukon
17 Red deer, Norway
18 Waterfowl, Old Crow Flats, AK
19 Fur seals, Pribilof Is.
20 Invertebrates, Bering Sea
21 Jellyfish Biomass, Bering Sea
22 ‘Q’ Caribou NW Terr. Canada
23 Western Arctic Caribou, Alaska
24 Zooplankton Biomass, Bering S.
25 Zooplankton, North Sea

Fisheries

26 Arrowtooth Flounder, Bering S.
27 Atka Mackeral, Aleutian Is.
28 Capelin Stock, Barents Sea
29 Chinook salmon, West Alaska
30 Chum salmon, Bering Sea
31 Cod abundance, Baltic Sea
32 Cod abundance, Barents Sea
33 Cod length, Barents Sea
34 Cod recruitment, Iceland
35 Haddock abundance, Barents Sea

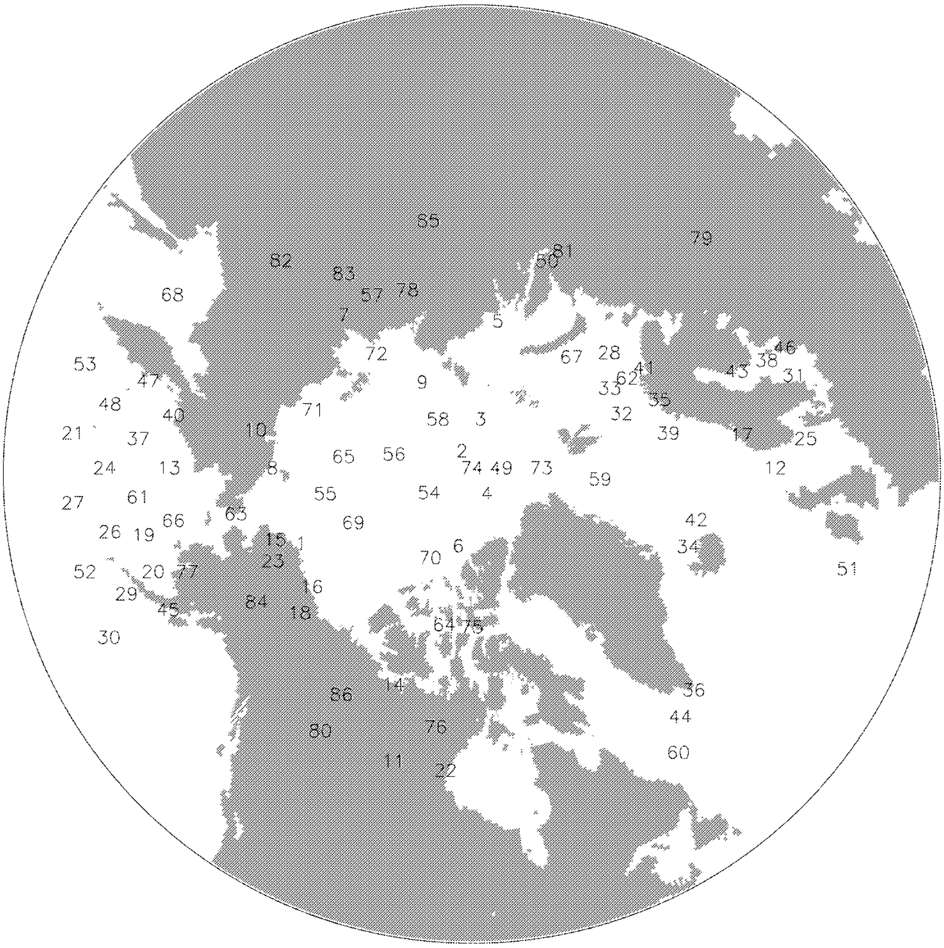

Figure A1. Unaami time series key.

36 Halibut index, Greenland
37 Herring, Bering Sea
38 Herring index, Baltic Sea
39 Herring stock, Norway
40 Plaice, Bering Sea
41 Redfish abundance, Barents Sea
42 Saithe recruitment, Iceland
43 Salmon index, Baltic Sea
44 Shrimp, NW Atlantic
45 Sockeye salmon, Bering Sea
46 Sprat index, Baltic Sea
47 Turbot, Bering Sea
48 Yellowfin sole, Bering Sea

Climate Indices

49 Arctic Oscillation
50 'E' Meridional Index, Siberia
51 North Atlantic Oscillation
52 Aleutian Low (NPI) April–May
53 Aleutian Low (NPI) Jan.–March
54 Polar Vortex
55 SLP Wave 1 phase, Arctic
56 Sea level gradient
57 'W' Zonal Index, Siberia
58 Arctic vorticity

Oceanic

59 Ice Flux to North Atlantic
60 SST anomaly, Labrador Sea
61 SST, Pribilof Is. region
62 Kola sea temperature
63 Bering Strait transport

Sea Ice

64 Open water duration, Resolute B.
65 Summer coverage, Arctic
66 Ice Extent, Bering Sea
67 Coverage, Kara-Barents Sea
68 Coverage, Okhotsk Sea
69 Thickness, Beaufort Sea
70 Thickness, Canadian Archipelago
71 Thickness, East Siberia
72 Thickness, Leptev Sea
73 Thickness, N. Fram Strait
74 Thickness, North Pole
75 Max. Thickness, Resolute Bay

Terrestrial

76 Burn area, Alaska/Canada
77 Discharge, Kusk River, AK
78 Discharge, Siberian rivers
79 Greenness, Eurasia
80 Greenness, North America
81 Time of Ice Melt, Ob River
82 Permafrost Temp., Churapcha
83 Permafrost Temp., Zhigansk
84 Permafrost thickness, Alaska
85 Snow cover, Eurasia
86 Snow cover, North America

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