

Reply to Editor and list of major changes:

Dear Editor, we have now revised our manuscript based on your and the reviewers suggestions. We agree with the reviewers' suggestions and addressed all of their concerns in the revised manuscript.

1. We have clarified the motivation of our study and also the novelty of our contribution compared to those of earlier studies including the IPCC reports in introduction section. Although, the attribution of climatic conditions and detection of the anthropogenic signal based on models is now a mature discipline, two analyses still remain rare: (1) data-based detection and attribution of climate indices (e.g., temperature) is rare because there are not many high quality long-term observations of various climate system indicators, and (2) the impact attribution, i.e., quantitative attribution of the observed impacts (e.g., sea ice decline) to relative contributions from anthropogenic forcing and natural variability is still rare. The first is about detection and attribution of climate variables, understandably mostly temperature and the second is the detection and attribution of the observed impacts on physical, biological, and human domains.

For the second aspect not only are the requirements of observed data more complex and the number of influencing drivers potentially more numerous, but the attribution problem presents additional challenges, including the need to synthesise information from a much broader range of disciplines. The IPCC's Fifth Assessment Report (AR5) concludes that impacts of recent regional changes in climate on natural and human systems are documented across the globe, yet studies explicitly linking these observations to anthropogenic forcing and natural variability are scarce. To this regard, our study is a novel and significant contribution to literature. We have modified the second paragraph of the introduction section to make the focus more clear in the new version of the manuscript.

2. We have recalculated all p-values, trends and correlation coefficients in the new manuscript to check discrepancies in software (R, EXCEL, ...) mainly arising from truncation of decimal places in the new manuscript. There is no major change on the manuscript to this regard.
3. We have added Table 1 for data summary and variable categorization.
4. We have added definitions for driver and response variables, variable categories, “temperature mediation“ phrase, “satellite era“ phrase, and related terms.
5. We have listed the negative and positive contributions of sea ice decline to net positive carbon uptake one-by-one in section 3.5
6. We have added further clarification of tables and figures in captions and footnotes. We have interlinked tables and figures in the footnotes to make the results more clear.
7. We have also thoroughly checked the manuscript for wordings, phrases, missing references,... and corrected whenever it was appropriate.
8. Finally, it should be noted that our manuscript is one of the first (together with recent efforts) to quantitatively attribute climate change impacts to natural variability and anthropogenic drivers using several observations.

Reply to Anonymous Referee #1:

We thank the anonymous referee #1 for very positive overall comments on our manuscript. We reply below after each numbered comments.

The paper uses different environmental datasets to link the coherent changes and trends in CO₂, snow cover, spring phenology and thaw, solar radiation, Scandinavian Pattern, and North Atlantic Oscillation, solar radiation. Authors tries to give us a relatively full picture on the relation between these different variable but their internal coherence in the change among land, cryosphere, and ocean to natural and human induced climate variability and change. The study fits the central theme of the journal ESD. Because this study tries to give a big picture and thus it is understandable that many more details are missed and some statements have no data to support and needs other further studies are needed. I suggest the paper accepted for publication with minor revision.

Thank you very much for the positive comments.

From line 5 to line 10, the below relevant key papers should be cited.

A. Angert et al. (2005). Drier summers cancel out the CO₂ uptake enhancement induced by warmer springs. Proceedings of the National Academy of Sciences, 102: 10823-10827.

A. L. Westerling, H. G. Hidalgo, D. R. Cayan, T. W. Swetnam (2006). Warming and earlier spring increase western U.S. forest wildfire activity. Science, 313: 940-943.

P. J. van Mantgem, N. L. Stephenson, J. C. Byrne, L. D. Daniels, J. F. Franklin, P. Z. Ful, M. E. Harmon, A. J. Larson, J. M. Smith, A. H. Taylor, T. T. Veblen (2009). Widespread increase of tree mortality rates in the western United States. Science, 323: 521-542.

W. A. Kurz, et al. (2008). Mountain pine beetle and forest carbon feedback to climate change. Nature, 452: 987-990.

We have included the suggested references in the new version of the manuscript

Reply to Anonymous Referee #2:

We thank the reviewer for the time she/he spent and for providing very helpful and extensive comments, which helped us improve the manuscript. We reply below after each numbered comments.

1. In this paper, the authors selected a lot of indicators of land, cryosphere and ocean from different observational datasets to assess their changes over time, in particular focusing on interannual variability. They also analyzed the relationships with each other to show how different components of earth's climate system are responding to forcings and attributed these observed changes to natural variability and anthropogenic forcings. Major comments: The authors attempted to provide a comprehensive assessment of current changes in climate system, which is kind of a mini version IPCC report. Overall this is really a big topic because almost each part can be an individual research field. In this case, it is understandable that the analysis for each part cannot go very deep. I just have a feeling that the authors put much stuff in the paper but I am so sure what is actually "new" out of the results. Because for all changes detected, there are numerous related papers from those specialized fields that not only detected such change but also studied the mechanisms. So the authors really have to make it clear and emphasize what is new in this paper compared with other similar research, which is something I didn't get so far after reading it.

We have given extensive background on the scope of the study in the introduction. Although, the attribution of climatic conditions and detection of the anthropogenic signal based on models is now a mature discipline, two analyses still remain rare: (1) data-based detection and attribution of climate indices (e.g., temperature) is rare because there are not many high quality long-term observations of various climate system indicators, and (2) the impact attribution, i.e., quantitative attribution of the observed impacts (e.g., sea ice decline) to relative contributions of anthropogenic forcing and natural variability is still rare. The first is about detection and attribution of climate variables, understandably mostly temperature and the second is the detection and attribution of the observed impacts on physical, biological, and human domains.

For the second aspect, the key literature (e.g., Parmesan et al. *Ecol. Lett.*, 16, 58-71, 2013; Rosenzweig et al. *Nature*, 453, 353-357, 2008; Stone et al. *Clim. Change*, 121, 381-395, 2013; Poloczanska et al. *Nature Clim. Change*, 3, 919-925, 2013) suggest that for impacts, not only are the requirements of observed data more complex and the number of influencing drivers potentially more numerous, but the attribution problem presents additional challenges, including the need to synthesise information from a much broader range of disciplines. The IPCC's Fifth Assessment Report (AR5) concludes that impacts of recent regional changes in climate on natural and human systems are documented across the globe, yet studies explicitly linking these observations to anthropogenic forcing and natural variability are scarce. To this regard, our study is a novel and significant contribution to literature. We have modified the second paragraph of introduction section to make the focus more clear in the new version of the manuscript.

2. I don't quite understand the rationale for these particular indicators chosen in this study. Why it has to be these indicators instead of others to represent land, biosphere and ocean, as well as the forcings? Any strong reasons for these indicators? And how well are they in representing land, biosphere and ocean? The authors need to explain their considerations when choosing these indicators. To me some variables are not very relevant. For example, it seems cosmic ray doesn't really matter to climate change, and I didn't see any benefits of including Stratospheric Aerosol Optical Thickness in the analysis. For land, I think there are many more important indicators like extreme events, precipitation, vegetation productivity, and hydrology variables that need to be evaluated but are missing here. For phenology, the authors only use few variables to reflect the spring phenology, while summer and autumn phenology are not included. These questions again are related to the authors' motivation and purpose.

We provided extensive rationale in the last three paragraphs of the introduction for why we selected the variables included in the current study. For example, detection and attribution study on extreme events and precipitation is rather mathematically impossible to assess to first order in a deterministic sense. Another example, spring phenology is much easier to estimate accurately and responds to first order to temperature change than the slow browning in autumn therefore we have excluded variables which may carry over large uncertainty in the assessment. We further average many of the variables to diminish random errors. Missing drivers, due to lack of high quality long-term time series, are attributed in our study to unexplained variances. We have explained all these in detail in the last three paragraphs of the introduction and we believe that any further explanation will make the manuscript unreadable. We here quote the last two sentences of the introduction section which give brief explanation for the use of the selected variables: "We have selected several indicators for which high-quality, long time series satellite observations, with high retrieval accuracy, covering most or all of the Northern Hemisphere are available, and relate to temperature. This is because temperature fulfils the key assumption of detection and attribution studies where the response to external forcing is a deterministic change and to first order, and signals and noise superimpose linearly (Meehl et al., 2003)." We have modified these sentences from the last version to include "high retrieval accuracy"

3. There are many terms or categories used in the paper relating to the selected variables but have never been defined explicitly. Since there are 15+ variables in the paper, so without clearly defined, it may cause some confusions especially when the authors refer to something like "forcing and response variables" "natural variability and anthropogenic forcing variables" and "teleconnection variables". In many cases, I don't know what exactly these terms indicate to.

We have regrouped the variables, and added Table 1 for summary of definitions and categories. We have also modified the wordings of categories in the revised manuscript. Thank you very much for this constructive comment. We have rephrased the phrase "response and forcing variables" into "response and driving variables" throughout the manuscript. We have defined the "response and driving variables" in the second sentence of section 2 in the new version of the manuscript.

4. The overall presentation needs to be improved before publication. One problem is that figures and tables are not well integrated into the text. The table and figures are very informative but it seems a lot of information has not been

conveyed effectively into text. For example, there isn't much discussion about Figure 3 in the text. Tables and figures are complex with lots of numbers and curves, so the meanings are not easy to interpret directly. And because of this, in many cases, I got lost when the authors refer a sentence to a figure. When I look back at the figure/table, I don't know from where the authors' statement gets its support. One solution is to explicitly describe the key features or patterns in table/figure and directly referring them in the text.

We have indicated the panels in figures and section of tables wherever appropriate in the texts in the new version of the manuscript.

5. Minor comments: P2 L2-4: Hasn't the IPCC report provided enough quantitative evidence to attribute observed change to human and natural forcings? For future climate projection, the differences among models are substantial, but models do pretty well in simulating historical changes. I have seen a lot of attribution studies so from my perspective they are not rare. Maybe the authors should be more specific on this point.

Please see detailed answers to question 1 for this suggestion. We have also modified the introduction section to address this concern. Basically detection and attribution of climate change (mainly temperature), and detection and attribution of climate change impact are quite different topic. Our manuscript covers the latter topic, which needs analysis of large sets of data from several domains of disciplines. The added explanation in the revised manuscript in the 2nd paragraph of introduction is as follows: " Previous studies on change detection and attribution of both climatic condition and its impact on physical and biological systems often focused on a single or few climatic (e.g., National Research Council, 1983; Wigley and Barnett, 1990; IPCC, 2007, 2014b) or response indicator variables (e.g., Rosenzweig et al., 2008; Parmesan et al., 2013; Stone et al., 2013; Poloczanska et al., 2013) with the analysis of mechanisms. However, the test for a coherent detection and attribution of impacts of climate change requires observations of consistent patterns across natural systems, including the need to synthesise information from a much broader range of disciplines. Therefore, with accumulation of satellite observations over the last three decades, we here synthesize datasets across several physical and biological systems to test the relative roles of natural variability and anthropogenic forcing on impacts of recent climate change."

6. L16 and L17: What aspects of human and natural systems have these studies looked at in regard to the climate change impacts? It is better to provide direct information or a summary from these papers, because listing only the author names has very little practical meanings to readers.

We have provided a summary of each cited paper in the new version of the manuscript.

7. L30-33: Please explain how the variations in solar radiation and cosmic rays can influence global climate trends.

We have provided detailed explanations as to how solar radiation and cosmic rays affect earth climate in the new version of the manuscript.

8. P3 L12-17: What are the considerations for choosing these particular indicators rather than many alternative indicators? For example, for land indicators, any particular reasons for not including vegetation greenness or productivity? And for

phenology, why only spring is included? Since the title is about coherence, does that mean any indicators that exhibit inconsistent response among land, cryosphere, and ocean responses are naturally excluded in the analysis? What about these inconsistencies?

Please see the answers to question 2 for this suggestion. For example vegetation greenness or productivity as estimated from the growing season integrated NDVI may be affected not only by temperature but also precipitation and drought regimes in summer time unlike the spring phenology estimate in the northern hemisphere which mostly responds to changes in temperature. All the indicator variables we selected respond to temperature at least to the first order. Temperature fulfils the key assumption of detection and attribution studies where the response to external forcing is a deterministic change and to first order. We explained this in the last paragraphs of the introduction section

9. For section 2, it is better to have a summary table including all these variables, their categories, with additional information (e.g., gridded or station data, sources, time span, etc.). When introducing each variable in the text, group them into proper category that is consistent in the following content, such as land, ice, ocean, response, forcing, natural or anthropogenic factors.

We agree with the referee comment. We made a summary Table (Table 1) in the new version of the manuscript as suggested. We also follow the reviewer's suggestion and use consistent categories of variables throughout the text and other tables.

10. L20: Please point out the location of Point Barrow since not everyone is familiar with this place. Also for Kiel station. Giving their latitude and longitude would be enough.

We have provided the geo-location information for both stations in the new version of the manuscript.

11. L27: Please define satellite era.

We added satellite era definition in the last paragraph of the introduction section as follows: "The satellite era begins in year 1980, the starting year for continuous full global coverage observations of atmosphere, and land and ocean surfaces."

12. L31: Missing reference for SSM/I data? Every dataset needs to come with a source.

We have provided references for each dataset in the new version of the manuscript (see Table 1).

13. P4 L10: Why only use the flower bloom day of Canada? Phenology has quite large regional difference. I am not sure if the flower bloom day of Canada is a suitable indicator for the entire northern hemisphere. How many stations are there and what is their spatial coverage?

Canada-only integrated spring indicator helps to study the impact of natural variability; particularly the North Atlantic Oscillation (NAO) and the Scandinavia Pattern (SCA) which have a contrasting impacts on vegetation activity on the North American and Eurasian parts of the circumpolar region (see Fig. 4). We have provided further details on the flowering phenology data in the new version of the manuscript. The cited reference (Gonsamo et al. Sci. Rep., 3, 2239, 2013) provides details of the datasets. We also add the following sentence to make this clear in the first paragraph of section 3.2: "FFB,

unlike hemispheric averaged spring indices such as SOS and ST, shows the contrasting roles of NAO and SCA on North American and Eurasian part of the Northern Hemisphere (see Fig. 4). “

14. L29: Undefined acronym TOPEX, VIRGO, SOHO, ACRIM.

We have provided the full names in the new version of the manuscript.

15. L23-29: What is the spatial coverage of RAD?

We have now provided the type, spatial coverage, time span and source reference of each variable in Table 1.

16. P6 L15: Why anomalies are calculated only for winter and why trends are removed here?

Teleconnection indices are already anomalies from long-term normals, the normal period being always updated to reflect the background (for example externally forced changes in sea temperature or atmospheric pressure). We use the common approach, where winter, defined here as December of the preceding year and January, February and March of the current year, because (i) most of the leading teleconnection indices are only active during the northern hemisphere winter, and (ii) they are indicator of the climatic regime to come during the ensuing growing seasons (e.g., Gonsamo et al. *Glob Change Biol.* doi:10.1111/gcb.13258; Gonsamo, A., and Chen, J. M. *Proc. Natl. Acad. Sci. USA*, 112, E2265–E2266, 2015). The long-term sum effect of the natural climatic oscillation on climate variables should be zero. Therefore, we remove trends to enforce this zero sum impact for the data period we studied for each variable. We have provided this explanation in the new version of the manuscript.

17. Table 1: I felt Table 1 is difficult to understand. Perhaps Table 1 can be reorganized in a way that variables are grouped into response and forcing variables, or other meaningful categories. I don't understand what different shades actually mean here. Adding a new row and a column to specify the name of each category is helpful. Also, I don't understand how the number in italic bold font represents both long-term and interannual co-variability. Some of correlations make very little physical sense. For example, it shows 63% interannual variability of temperature can be explained by spring thaw, while 29% interannual variability of spring thaw can be explained by temperature. Even 63% is higher, but it has little physical meaning because we know it is temperature variability that drives spring thaw but not the opposite.

The shades indicated different categories of variables such as temperature, biosphere indicators, greenhouse gases, and natural variability. We have added category column and row in Tables 1 and 2 in the new version of the manuscript. We have also provided a separate Table to explain each variable (see answer to question 9).

We have also modified the table caption as follows: “Table 1. Percent interannual (lower left) and long-term (upper right) variances in indicator A explained by indicator B or vice versa.” We have also added further details about the presented values in the Table in the footnote.

The table is a simple square of the Pearson correlation coefficient matrix from correlation analyses based on detrended data (lower left) and raw data (upper right) as such A does not necessarily drive B or vice versa. The italic bold font represents a pair of correlation for which both long-term and interannual covariability shows statistically significant

relationship. This way we partially avoid spurious correlation from further discussion and interpretation if there is no correlation both for raw and detrended datasets.

We also figured out different software such as R, EXCEL, EXCEL with VB gave slightly different Pearson correlation and p-value results for the slope significance for linear relationship with two tails particularly related to decreasing the decimal of p-value into two digits ($p=0.05$) for deeming significant due to cut-offs without proper rounding. We have recalculated all p-values and Pearson correlations, for both Table 2 and Figures 2 and 3. Another source of discrepancy came from the fact that Figures 1 and 2 are based on the entire available data series period while all of the tables were calculated based on the most common data series record period (i.e., 1982-2011). Now we have put the data record period for analyses in each Table heading and also added the source of discrepancies in correlation amounts in the footnote of Table 2.

18. For analysis section in P7: How did the datasets with different temporal periods treated in the correlation analysis of interannual variability and trends, by using the overlapping period?

Each interannual analysis is done based on detrended datasets using the common period of pair of variables. We have added the following text in the Analysis section in the new version of the manuscript: “All interannual variability assessments were done based on detrended time series at annual time scale using the common base period of each pair of analysis.

19. P7 L5: Have the response and forcing variables here clearly defined earlier in the manuscript?

We have rephrased the phrase “response and forcing variables” into “response and driving variables” throughout the manuscript. We have also added table 1 with variables’ summary and categories. We have defined the “response and driving variables” in the second sentence of section 2 in the new version of the manuscript.

20. L15-17: How many PCAs are selected? Maybe Table 2 should be referred here.

As presented in Table 3, 4, and Fig. 5, different numbers of PCAs and different outputs of PCA were used in each analysis. We believe citing results section in the method section may add confusion. We provided detailed captions for each table and figure to explain how the PCAs are used throughout the manuscript.

21. L24-25 I don’t understand the meaning of “temperature mediation”? This has been frequently mentioned in the paper but I didn’t see any explanations prior its appearance.

We added definition of “temperature mediation” at the end of introduction section in the new version of the manuscript. The term “temperature mediation” refers to the impacts of natural and anthropogenic driving variables on the response variables primarily through changes in temperature (as opposed to changes in precipitation, radiation and associated variables such as cloudiness and humidity). For example, in table 4, the explained variance derived from a PCA and stepwise regression analyses in column 4 include the temperature mediation by that the explanatory variables include radiation, teleconnection and temperature. On the other hand, column 3 gives the results of explained variances by radiation and teleconnection without temperature mediation.

22. P8 L3: Such four categories should be defined or mentioned earlier in dataset sections.

We have modified the sentence. Here the “groups” are organized for presenting the results but not necessarily based on the categories (which we have defined in the modified manuscript) of each variable. Please see answers to questions 9, 17 and 19 for further detail.

23. L12: It obvious that both RF of WMGHG (steady rise) and temperature (with fluctuation) increased through time (1980-2010), I don’t understand where the “highly correlated” come from.

We have modified the sentence as follows in the new version of the manuscript: “During the study period, the radiative effects from the increased WMGHG concentrations follow the rise in global surface temperatures (all $p < 0.1 \times 10^{-7}$), whereas the solar irradiance is not and has an overall declining trend (Fig. 1(b)).

24. L21-25: Which exact number in Table 1 is referred to support “significantly correlated” in this sentence “ST and SOS are also significantly correlated with temperature after data detrending (Table 1) indicating both long-term and interannual covariability ($p < 0.01$)”. Because there are two sets of numbers: A explained by B and B explained by A, I don’t know which one of them is the case here. According to Table 1, there is no significant correlation between FEB and T, but in figure 2(b) they show some kind of co-variability. Why do these two places show inconsistency with each other?

Please see answers to questions 17 for this suggestion. The interannual covariability is given in the lower-left and the long-term covariability in upper-right sections of Table 1. We just figured out different software such as R, EXCEL, EXCEL with VB gave slightly different p-value results for the slope significance for linear relationship with two tails particularly related to decreasing the decimal of p-value into two digits ($p=0.05$) for deeming significant due to cut-offs without proper rounding. This affected FFB because the actual p-value was close to threshold ($p=0.05$). The effect on others is minimal because the p-values are either much smaller or larger than the threshold. We have recalculated all p-values and Pearson correlations, for both Table 2 and Figures 2 and 3. Another source of discrepancy came from the fact that Figures 1 and 2 are based on the entire available data series period while all of the tables were calculated based on the most common data series record period (i.e., 1982-2011). Now we have put the data record period for analyses in each Table heading.

25. Table 2: Please add full name of each variable. It is very hard to remember these acronyms since too many of them are contained in the paper.

We have added the full name of each variable in caption footnote in the new version of the manuscript.

26. L30-31: I don’t know how this statement comes out of Table 2. And again, what is the temperature mediation? Without explaining this term in the beginning, I cannot quite follow the rest of this paragraph.

Please see answers for question 21 regarding definition of temperature mediation. The statement on L30-31 is from Table 3 not Table 2. Table 3 provide the explained variance of land, cryosphere and ocean indicators by natural variability and anthropogenic forcing with and without temperature mediation calculated from the detrended data.

27. Figure 4. It seems the growing season annually integrated normalized difference vegetation index (NDVI) appears here but is not chosen as an indicator. Why is that?

We use the integrated NDVI only to discuss some of the peculiar results. For the reason why we have not included the integrated NDVI in the main analysis please see answers to question 8.

28. Table 2: Please clearly define land, cryosphere and ocean “indicators”, and natural variability and anthropogenic forcing “variables” throughout the paper. It is unclear from the table that which variable belongs to what category, especially when they are referred in the text.

Thank you for this comment. We have now clearly defined the variables in the new version of the manuscript. Please also see answers to several of your suggestions above related to this. We have also added Table 1 per your suggestion to make the categories clear.

29. P11 L13: I suggest listing the “several explanations” one by one (first, second. . .) for clarity.

Thank you very much. We have now provided the explanations one by one as suggested in the new version of the manuscript.

L26: By what criteria these variables grouped into three sets are considered to be coherent for their interannual pattern?

Basically (from the original manuscript), Table 2 gives us the first results of coherence assessment in light of total variances by the variables considered in this study (well unexplained variances from missing drivers remain). Variables which load on the same axis are coherent. Table 1 gives further support whether or not the loadings in Table 2 are statistical artefact of projection into a low dimensional subspace, by that the variables should at least show either or both long-term and interannual covariability which is statistically significant. We have now modified this part in the revised manuscript and we base the coherence analysis only on the Table 2 (now Table 3) results from variables that have at least 30 years of observations.

Overall, we have tried our best to address each and every concern you raised. Our manuscript has really improved by your suggestions to the greater extent. We therefore thank you very much for your time and inputs.

Coherence among the Northern Hemisphere land, cryosphere, and ocean responses to natural variability and anthropogenic forcing during the satellite era

A. Gonsamo¹, J. M. Chen¹, D.T. Shindell², and G.P. Asner³

¹Department of Geography and Planning, University of Toronto, Toronto, ON, Canada

²Nicholas School of the Environment, Duke University, Durham, USA

³Department of Global Ecology, Carnegie Institution for Science, Stanford, USA

Correspondence to: A. Gonsamo (gonsamoa@geog.utoronto.ca)

Abstract. A lack of long-term measurements across Earth's biological and physical systems has made observation-based detection and attribution of climate change impacts to anthropogenic forcing and natural variability difficult. Here we explore coherence among land, cryosphere and ocean responses to recent climate change using three decades (1980–2012) of observational satellite and field data throughout the Northern Hemisphere. Our results show coherent interannual variability among snow cover, spring phenology, solar radiation, Scandinavian Pattern, and North Atlantic Oscillation. The interannual variability of the atmospheric peak-to-trough CO₂ amplitude is mostly impacted by temperature-mediated effects of El Niño/Southern Oscillation (ENSO) and Pacific/ North American Pattern (PNA), whereas CO₂ concentration is affected by Polar Pattern control on sea ice extent dynamics. This is assuming the trend in anthropogenic CO₂ emission remains constant, or the interannual changes in the trends are negligible. Our analysis suggests that sea ice decline-related CO₂ release may outweigh increased CO₂ uptake through longer growing seasons and higher temperatures. The direct effects of variation in solar radiation and leading teleconnections, at least in part via their impacts on temperature, dominate the interannual variability of land, cryosphere and ocean indicators. Our results reveal a coherent long-term changes in multiple physical and biological systems that are consistent with anthropogenic forcing of Earth's climate and inconsistent with natural drivers.

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) attributed many recently observed changes in Earth's physical and biological systems to climate change (IPCC, 2014a, b). Several modelling and observation-based studies show that contemporary climate change has already affected plant phenology (Angert et al., 2005, Parmesan and Yohe, 2003; Walther et al., 2002; Parmesan, 2006), range and distribution of species (Kelly and Goulden, 2008; Parmesan and Yohe, 2003; Walther et al., 2002; Parmesan, 2006; Post et al., 2009), species extinction (Parmesan, 2006), phytoplankton (Montes-Hugo et al., 2009), ocean variability (Santer et al., 1995; Pierce et al., 2012), forest disturbances (Harmon et al., 2009, Kurz et al., 2008, Westerling et al., 2006), and sea ice (Stroeve et al., 2012; Post et al., 2013). These studies (e.g., Kelly and Goulden,

2008; Parmesan and Yohe, 2003; Walther et al., 2002; Parmesan, 2006; Post et al., 2009; Montes-Hugo et al., 2009; Stroeve et al., 2012; Post et al., 2013; Pierce et al., 2012; Santer et al., 1995) provide compelling scientific evidence for a pronounced impact of recent climate change; however, studies quantitatively attributing the observed impacts in natural systems to relative contributions of anthropogenic forcing and natural variability are rare (e.g., Stone et al., 2013), and differences between models and observations have been well understood but not resolved (Fyfe et al., 2013). These differences, caused by a combination of modelling errors in expected differences in internal variability between models and the stochastic climate system with limited knowledge on processes and mechanisms involved in external forcing and climate model response, make disentangling the relative roles of natural variability and anthropogenic forcing challenging (e.g., Fyfe et al., 2013; Hegerl and Zwiers, 2011).

Observation-based causal attribution analysis of recent biosphere responses to climate change (e.g., Parmesan and Yohe, 2003; Parmesan, 2006; Walther et al., 2002; Kelly and Goulden, 2008; Post et al., 2013; Wu et al., 2011; Menzel et al., 2006; Montes-Hugo et al., 2009) is further complicated because of a lack of long-term observational data across life supporting natural systems to attribute the detected climate change impacts to natural variability and anthropogenic forcing. Although the attribution of climatic conditions and detection of the anthropogenic signal is now a mature discipline going back several decades (e.g., National Research Council, 1983; Wigley and Barnett, 1990; IPCC, 2007, 2014b), detection and attribution of climate change impacts on human and natural systems started only **recently** (e.g., **attribution of physical and biological impacts to warming, Rosenzweig et al., 2008; methodological framework for climate change impact attribution in conservation and ecological research, Parmesan et al., 2013; conceptual framework to detect and attribute effects of climate change, Stone et al., 2013; climate change impacts on marine life, Poloczanska et al., 2013**). For detection and attribution of climate change impact assessments to work, understanding of numerous drivers, which may not often have additive interactions, are required along with observational data across a broader range of Earth's systems (Stone et al., 2013; Parmesan et al., 2013). **Previous studies on change detection and attribution of both climatic condition and its impact on physical and biological systems often focused on a single or few climatic** (e.g., National Research Council, 1983; Wigley and Barnett, 1990; IPCC, 2007, 2014b) **or response indicator variables** (e.g., Rosenzweig et al., 2008; Parmesan et al., 2013; Stone et al., 2013; Poloczanska et al., 2013) **with the analysis of mechanisms. However, the test for a coherent detection and attribution of impacts of climate change requires observations of consistent patterns across natural systems, including the need to synthesise information from a much broader range of disciplines. Therefore, with** accumulation of satellite observations over the last three decades, we here synthesize datasets across several physical and biological systems to test the relative roles of natural variability and anthropogenic forcing on impacts of recent climate change. Our aim is not to explain the entire observed variances, but rather to study the relative contribution of each of the examined driving variables on interannual changes and long-term trends of physical and biological systems. Furthermore, we study the auto-association among the response **and driving variables** in a way that best explains the observed variances. Unexplained variances remain, and may be attributed to missing drivers, errors in data, or methodological difficulties in capturing feedbacks and short-term

adaptations in Earth's natural systems. Due to a lack of high quality observational time series, the key missing drivers in our analysis include volcanism and aerosol.

Variations in incoming solar radiation have the potential to influence global climate trends (Rind, 2002; Hameed and Gong, 1994). The rates of incoming solar radiation changes due to different solar cycles and apparently produce corresponding changes in weather and climate on the Earth's surface (Lamb, 1972; Burroughs, 1992). The changes in the amount of incoming solar radiation affects climate, both directly through changes in the rate of solar heating of the Earth and atmosphere, and indirectly, by changing cloud formation (Udelhofen et al., 1999) and ozone patterns since changes in solar cycle affect the solar ultraviolet radiation the most (Hood, 1997). But the extent of responses of climatic, biological, and physical systems to solar variability remains largely untested due to a lack of long time series measurements. It has been suggested that cosmic rays induce low level cloud formation through atmospheric ionization and during periods of low solar activity, more cosmic rays enter the Earth's atmosphere affecting the Earth's climate system (Svensmark and FriisChristensen, 1997; Svensmark, 1998; Carslaw et al., 2002). Solar and cosmic ray activities have now been monitored for the past three decades, and those datasets can be tested for associations with climatic dynamics and biosphere responses.

Here we present the relationships of land, cryosphere and ocean indicators to recent changes in surface temperature, greenhouse gases, internal climatic variability, solar radiation, sunspots, and cosmic rays. While longer-term analyses (e.g. century scale) can sometimes yield better statistics, we focus on the satellite era when data quality far exceeds that of earlier years. The satellite era begins in year 1980, the starting year for continuous full global coverage observations of atmosphere, and land and ocean surfaces. All satellite datasets are spatially averaged time series to partially diminish the effects of stochastic noise. We have selected several indicators for which high-quality, long time series satellite observations, with high retrieval accuracy, covering most or all of the Northern Hemisphere are available, and relate to temperature. This is because temperature fulfils the key assumption of detection and attribution studies where the response to external forcing is a deterministic change and to first order, and signals and noise superimpose linearly (Meehl et al., 2003). We also analyse the relative roles of natural and anthropogenic driving variables on the changes of response variables with and without temperature mediation. The term "temperature mediation" refers to the impacts of natural and anthropogenic driving variables on the response variables primarily through changes in temperature (as opposed to changes in precipitation, radiation and associated variables such as cloudiness and humidity).

2 Observations

We use several observational satellite and field data throughout the Northern Hemisphere including temperature, cryosphere indicators, land indicators, ocean indicators, external anthropogenic forcing indicators, external natural forcing indicators, and internal climatic variability indicators (Table 1). In total we use 13 driving (external anthropogenic forcing indicators, external natural forcing indicators, and internal climatic variability indicators) and 9 response (temperature, cryosphere indicators, land indicators, and ocean indicators) variables (Table 1). The key land indicators include, satellite-measured

spring thaw (ST) (Barichivich et al., 2013) and start of growing season (SOS) (Barichivich et al., 2013) of the **Northern Hemisphere (>45°N)**, the **Point Barrow station atmospheric CO₂ concentration peak-to-trough amplitude (AMP)**, and field-measured first flower bloom (FFB) day of Canada (Gonsamo et al., 2013). The cryosphere indicators include, satellite-measured sea ice concentration (SIC) and extent (SIE) of the Northern Hemisphere (>31°N), and snow cover (SC) of the Northern Hemisphere (0°N –90°N). Satellite-measured sea level (SL) of the Northern Hemisphere (0°N –90°N) was also included as **ocean indicator** to assess the response of open water bodies to climate change.

The forcing and natural variability **indicators include: Point Barrow station atmospheric CO₂ concentration (PPM); sunspot number (SP), satellite-measured solar irradiance (RAD); cosmic ray (CR) counts at Kiel station; and eight leading National Oceanic and Atmospheric Administration (NOAA) Northern Hemisphere teleconnection indices: the North Atlantic Oscillation (NAO), East Atlantic Pattern (EA), West Pacific Pattern (WP), Pacific/North American Pattern (PNA), East Atlantic/West Russia Pattern (WR), Scandinavia Pattern (SCA), Polar/Eurasia Pattern (POL), and El Niño/Southern Oscillation (ENSO)-Niño 3.4 index (NINO)**. We have also included sets of well-mixed global greenhouse gases (WMGHG), GISS global stratospheric aerosol optical thickness at 550nm, Atlantic Multidecadal Oscillation (AMO), and total solar irradiance to identify the relative roles of large-scale and long-term forcing and decadal internal climate variability during the satellite era. **For surface temperature, we use the Goddard Institute for Space Studies (GISS) analysis of Northern Hemisphere (0°N –90°N) (Hansen et al., 2010). Details and summary of each variable are given below and in Table 1, respectively.**

Spring thaw

The spring thaw (ST) day of year was estimated from the daily combined freeze-thaw dynamics as the first day when at least 12 out of 15 consecutive days were classified as non-frozen (am and pm thawed) between January and June (Barichivich et al., 2013; Kim et al., 2012; Xu et al., 2013) based on global microwave observations from morning (am) and afternoon (pm) equatorial crossings of the Special Sensor Microwave Imager (SSM/I). The ST dataset is for **Northern Hemisphere (>45°N)** for the period of 1988–2007.

Start of growing season

The start of season (SOS) day of year is calculated from the biweekly 8 km third generation (NDVI3g) Normalized Difference Vegetation Index (NDVI) data set produced from **Advanced Very High Resolution Radiometer (AVHRR)** observations by the Global Inventory Modeling and Mapping Studies (GIMMS) group at NASA Goddard Space Flight Center to characterize the photosynthetic growing season of the **Northern Hemisphere (>45°N)** for 1982–2011 (Xu et al., 2013). SOS was calculated from maximum rate (inflection point) of green-up as determined by the first derivative of the seasonal curve of smoothed NDVI data (Barichivich et al., 2013).

First flower bloom day of Canada

The first flower bloom (FFB) day of Canada is obtained from phenology records of PlantWatch Canada Citizen Science network. FFB is defined as a plant stage at which the first flower buds have opened in an observed tree or shrub or in a patch of smaller plants. We have selected only the FFB day records observed by at least five observers at a minimum of five different locations in order to remove observer bias for 19 Canadian plant species recorded by several observers across Canada between years 2001 and 2012 totalling 1,784 unique site-year data points (Gonsamo et al., 2013).

Sea ice extent and concentration

Annual means calculated from the daily sea ice extent (SIE) and concentration (SIC) observations are obtained from the Scanning Multichannel Microwave Radiometer (SMMR; 1980–August 1987) and the Special Sensor Microwave/Imager (SSM/I; July 1987 to present) onboard the Nimbus-7 satellite and Defense Meteorological Satellite Program, respectively. The data are provided by the National Snow and Ice Data Center (NSIDC) (Fetterer et al., 2009). SIC is the fraction of Ocean area covered by sea ice whereas SIE is the total area covered by at least 15 percent of ice. The SIE and SIC datasets are for the Northern Hemisphere (>31°N) for the period of 1980–2012.

Snow cover

Annual means calculated from the monthly mean snow cover (SC) extent (Robinson et al., 2012) are obtained from the Rutgers University Global Snow Lab (Available at <http://climate.rutgers.edu/snowcover>). The SC extent is based on AVHRR satellite observations. The SC dataset is for the entire Northern Hemisphere for the period of 1980–2012.

Sea level

Annual means calculated from 10-day estimates of sea level (SL) are obtained from University of Colorado Sea Level Research Group Research Group (Available at <http://sealevel.colorado.edu>). The SL estimate was derived from the TOPOgraphy EXperiment (TOPEX) and Jason series of satellite radar altimeters calibrated against a network of tide gauges (Nerem et al., 2010). The SL dataset is for entire Northern Hemisphere for the period of 1993–2012.

Surface temperature

The annual mean Northern Hemisphere surface temperature was obtained from the GISS (Hansen et al., 2010) dataset (Available at <http://data.giss.nasa.gov/gistemp>) for the period of 1980–2012. The global GISS and the 2013 reconstruction of Cowtan and Way (Cowtan, 2014) HadCRUT4 hybrid UAH temperature anomalies are shown in Fig. 1b. The Cowtan and Way reconstruction of HadCRUT4 temperature data corrects for the incomplete global coverage, thereby alleviating the cool bias in recent decades (Cowtan, 2014).

Atmospheric CO₂ measurements at Point Barrow station

Monthly averaged atmospheric CO₂ concentrations at Point Barrow station (Alaska, USA, 71.3° N, 156.6° W), based on continuous *in situ* observations, are obtained from the Earth System Research Laboratory (ESRL) of the National Oceanic and Atmospheric Administration (NOAA) (Available at <http://www.esrl.noaa.gov/gmd/dv/data>). Atmospheric CO₂ concentration measurements from *in situ* stations cover the period of 1980–2012. The peak-to-though amplitude (AMP) for an individual year is calculated as a difference between maximum and minimum of monthly means to avoid influences of different curve fitting and data smoothing methods. The annual means of parts per million (PPM) of atmospheric CO₂ concentration were also used in this study.

Sunspot measurements

Annual means calculated from the international daily mean sunspot (SP) number were obtained from the SIDC (Solar Influence Data Center) at World Data Center for the Sunspot Index, Royal Observatory of Belgium (Available at <http://www.sidc.be/sunspot-data>). The sunspot number data used in this study covers the period of 1980–2012 (SIDC-team, 1980-2012).

Solar irradiance

Annual means calculated from version d41_62_1302 daily averaged solar irradiance (W m⁻²) are obtained from Physikalisch-Meteorologisches Observatorium Davos World Radiation Centre (PMODWRC) (Available at <ftp://ftp.pmodwrc.ch/pub/data/irradiance>). The composite algorithm, corrections for the radiometers other than VIRGO (Variability of solar IRradiance and Gravity Oscillations), and detailed methodologies are given in Frohlich and Lean (1998) and Frohlich (2000, 2003, 2006). The Active Cavity Radiometer Irradiance Monitor (ACRIM) II data are used to fill the gap during the Solar and Heliospheric Observatory (SOHO) Vacations in 1998 and early 1999. The solar irradiance (RAD) data used in this study covers the period of 1980–2012. The long-term solar irradiance data shown in Fig. 1c is obtained from (Krivova et al., 2007) for the 1880–1979 period and were merged with the PMODWRC data for 1980–2012.

Cosmic ray measurements at Kiel station, Germany

The hourly pressure corrected cosmic ray (CR) neutron monitor data of Kiel neutron monitoring station (Kiel, Germany, 54.3°N, 10.2°E) is obtained from the National Geophysical Data Center (NGDC) of the National Oceanic and Atmospheric Administration (NOAA) (Available at ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/COSMIC_RAYS/STATION_DATA/Kiel). The annual mean of hourly CR count calculated from hourly data for the period of 1980–2007 was used in this study.

Northern Hemisphere teleconnection indices

We restricted the teleconnection indices to those that dominate the interannual variability of climatic oscillations in phase and amplitude with continental to global scale implications accounting for the most spatial variance of the observed

standardized anomaly (Quadrelli and Wallace, 2004; IPCC, 2007). The eight teleconnection indices (Barnston and Livezey, 1987; Wallace and Gutzler, 1981): North Atlantic Oscillation (NAO), East Atlantic Pattern (EA), West Pacific Pattern (WP), Pacific/ North American Pattern (PNA), East Atlantic/West Russia Pattern (WR), Scandinavia Pattern (SCA), Polar/ Eurasia Pattern (POL), and El Niño/Southern Oscillation (ENSO)-Niño 3.4 index (NINO), are obtained from the National Oceanic and Atmospheric Administration (NOAA) National Weather Service website (Available at <http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml>). We calculated teleconnection index anomalies for each year as a mean value of December of the preceding year and January, February and March of the current year. **We use the common approach, where winter, defined here as December of the preceding year and January, February and March of the current year, because (i) most of the leading teleconnection indices are only active during the Northern Hemisphere winter, and (ii) they are indicator of the climatic regime to come during the ensuing growing seasons (Gonsamo and Chen, 2015; Gonsamo et al., 2016).** We then removed trends from the resulting winter teleconnection index by detrending the time series for the 1982–2011 base period.

Decadal teleconnection index

The Atlantic Multidecadal Oscillation (AMO) index is calculated from Kaplan sea surface temperature (SST) dataset and is obtained from NOAA Earth System Research Laboratory (Available at www.esrl.noaa.gov/psd/data/timeseries/AMO).

Stratospheric Aerosol Optical Thickness

Annual means calculated from monthly mean stratospheric aerosol optical thickness at 550 nm are obtained from the GISS (Sato et al., 1993) dataset (Available at <http://data.giss.nasa.gov/modelforce/strataer>) for the period of 1850–2011. Background aerosols with an optical thickness 0.0001 were added as a lower limit for aerosol amount at all times. The effective radius (R) of the aerosol particles is defined as: $R = 0.20$ (in the state with small optical thickness); otherwise $R = 0.20 + \tau_{\max}(\text{latitude})^{0.75} \times f(t-t_0)$ (μm) (for large volcanoes), where $f(t-t_0)$ is a function of time derived from the observed R for Pinatubo, while keeping the observed values for El Chichon and Pinatubo.

Well-mixed greenhouse gases (WMGHG)

The measurements of 5 major greenhouse gases (CO_2 , CH_4 , N_2O , CFC-12, CFC-11) and 15 minor long-lived halogenated gases (CFC-113, CCl_4 , CH_3CCl_3 , HCFCs 22, 141b and 142b, HFCs 134a, 152a, 23, 143a, and 125, SF_6 , and halons 1211, 1301 and 2402) are obtained from the NOAA annual greenhouse gas index (AGGI) (Available at <http://www.esrl.noaa.gov/gmd/aggi>). The radiative forcing of the 20 well-mixed greenhouse gases (WMGHG) is calculated from a globally distributed network of air sampling sites (Hofmann et al., 2006). The total radiative forcing of the WMGHG is calculated based on IPCC (2001) expressions to convert greenhouse gas changes, relative to 1750, to instantaneous radiative forcing.

Analysis

For both response and **driving** variables, we have included observational datasets within the Northern Hemisphere (0°N – 90°N , 180°E – 180°W) (Fig. 1a) available between 1980 and 2012. We present interannual variability analysis from detrended data to examine correlations at various timescales and minimize the risk of detecting spurious correlations. **All interannual variability assessments were done based on detrended time series at annual time scale using the common base period of each pair of analysis.** Trend analysis based on the raw data are presented only in Figures (2) and (3), to show the long-term trends in both response and driving variables. Our interpretation of the results starts with basic correlation analysis (Table 2) comprising percent explained variance (coefficient of determination) among all variables from both raw and detrended datasets for trend and interannual covariability analyses, respectively. To investigate if the correlations are worthy of interpretation and to illustrate the coherence by analysing which variables are similar (or different), we use the squared loading of the variables (Abdi and Williams, 2010) from orthogonally projected driving and response variables, using principal component analysis (PCA). The squared loading of variables used in this study is alternatively called “squared cosines”. We used a PCA algorithm with Pearson correlation coefficient as index of similarity to remove the effect of scale. Alternatively, this is called normalized PCA. The squared loading of variables can be interpreted numerically as the coefficient of determination between a PCA axis and a given variable, and reveals the internal structure and auto-association among the response and driving variables in a way that best explains the total variance. We use the 95% confidence level from a two-tailed Student’s t-test to identify variables contributing significantly to each PCA axis. Generally speaking, the squared loading of the variables help interpret which variables are significantly coherent from the point of view of total variance analysis. The squared loading of variables that are small and not significant are interpreted as likely an artifact of projection into a low dimensional subspace, or an indication that the observed changes in response and driving variables are not coherent. Furthermore, we use several sets of PCAs (including natural and anthropogenic drivers together and separately with or without temperature mediation) to show the relative contribution of natural variability and anthropogenic forcing, and to predict each of the indicator variables with and without temperature mediation. We follow stepwise regression with Akaike Information Criterion (AIC) using different sets of PCA coordinates as regressors to reduce the effects of multicollinearity. All trend slopes in this study are calculated using a simple least squares linear regression.

3 Results and Discussion

This section starts with the northern hemisphere temperature trend analysis followed by the results and detailed interpretations of four **groups of variables, i.e., spring phenology indicators, snow cover, sea level, and** finally the atmospheric CO_2 dynamics in response to sea ice decline and climate variability.

3.1 Trends in the Northern Hemisphere surface temperature

The Northern Hemisphere experienced increases in surface temperature during the last three decades that are unprecedented in the anthropocene era (Fig. 1a) with climate extremes during the period 1990–2010, which included the warmest decades since the start of modern measurements around 1850 (Fig. 1c). Warming in these recent decades is larger over land than over ocean (Fig. 1a), in part because the ocean responds more slowly than the land due to the ocean's large thermal inertia (Hansen et al., 2010). Warming during the past three decades is enhanced in Eurasia and the Arctic (Fig. 1a). Warming of the ocean surface has been largest over the Arctic Ocean, and smallest and even slightly cooler over the North Pacific Ocean (Fig. 1a), partly due to the La-Niña-like cooling in the tropics affecting the extratropics (Kosaka and Xie, 2013). During the study period, the radiative effects from the increased WMGHG concentrations follow the rise in global surface temperatures (all $p < 0.1 \times 10^{-7}$), whereas the solar irradiance is not and has an overall declining trend (Fig. 1b). The timeframe covered in this study coincides with the period when the global temperature anomalies diverged from trends in solar forcing and the internal climatic oscillation indicated by AMO (Fig. 1c).

3.2 Spring phenology of vegetation and soil thaw

We quantitatively assessed the spring anomalies of the start of growing season (SOS), spring thaw (ST), and first flower bloom (FFB) days. FFB, unlike hemispheric averaged spring indices such as SOS and ST, shows the contrasting roles of NAO and SCA on North American and Eurasian part of the Northern Hemisphere (see Fig. 4). Observed trends include earlier ST (2.1 days/decade) for 1988–2007, SOS (1.07 days/decade) for 1982–2011, and FFB (6.7 days/decade) for 2001–2012 (all $p < 0.05$). Long-term trends of ST and SOS are overwhelmingly correlated with changes in annual mean surface temperature ($p < 0.001$) (Fig. 2b). ST and SOS are also significantly correlated with temperature after data detrending (Table 2) indicating both long-term and interannual covariability ($p < 0.01$). Changes in Canadian FFB are moderately explained by changes in annual mean surface temperature of the Northern Hemisphere (Fig. 2b), although there was, unsurprisingly, a stronger association with Canada's annual mean temperature ($R = -0.85$, $p < 0.001$) (Gonsamo et al., 2013). Associated with post-1998 slow down in surface temperature increase, SOS and ST advanced more slowly, even with slight delays (Fig. 2b). Although the Canadian FFB shows strong correlation with NAO and SCA (Table 2), the stepwise regression selects 9 PCAs for FFB prediction (Fig. 5g,o) and the degrees of freedom becomes zero – indicating that there is no way to affirm or reject the prediction model for FFB. The interannual changes in solar radiation, NAO, and SCA are the most covarying variables with spring phenology anomalies (Table 2 and 3).

The interannual variability of spring phenology indices are explained more by natural forcing (i.e., solar radiation) and teleconnections than greenhouse gases (GHG) (Table 4). Temperature mediation on interannual variability of spring phenology indices is only apparent with GHG, and less relevant with natural forcing (Table 4). Solar radiation and teleconnections may have non-temperature mediated effects on spring phenology through their impacts on incident solar radiation, cloudiness, precipitation and snowfall. The timing of spring events in many plant life cycles is advancing in

response to climate warming (Parmesan and Yohe, 2003; Parmesan, 2006; Walther et al., 2002; Menzel et al., 2006; Post et al., 2009; Fitter and Fitter, 2002; Barichivich et al., 2013). The observed earlier spring activities (Fig. 2b) of terrestrial ecosystem increase the length of the growing season and consequently the primary productivity of vegetation. This same condition may also increase soil and plant respiration (Piao et al., 2008) and expose plants to widespread late spring frost damage (Hufkens et al., 2012), leading to carbon loss. However, the tradeoffs between increased primary productivity and enhanced ecosystem respiration and soil carbon release related to advancing spring activity remain poorly understood.

NAO and SCA are two of the most dominant teleconnections related to dynamics in terrestrial ecosystems of the Northern Hemisphere (Fig. 4 and Table 2 and 3) (Gonsamo and Chen, 2015; Gonsamo et al., 2016). NAO has strong negative relation with SCA (Table 2), affecting much of Canada and Eurasia, with SCA dominant in Midwestern Europe (Fig. 4). Therefore, we only discuss the NAO results in relation to spring activity. The detrended NAO index is negatively correlated with fluctuations in snow cover ($p < 0.01$), and positively correlated with changes in the FFB days ($p < 0.01$) (see lower left in Table 2). A steeper atmospheric pressure gradient (the high or positive NAO index phase), indicating an intensified Icelandic low, is associated with warmer Northern Hemisphere (mostly Europe and Asia) winter temperatures. This explains the negative relationship between the detrended NAO index and snow cover observed in our analysis (Table 2). Under steeper atmospheric pressure gradient or positive NAO (i.e., negative SCA index) phase when the westerlies in the North Atlantic are shifted poleward, there is enhanced advection of warm air across Northern Europe and Asia, increasing vegetation productivity on this region (Gonsamo and Chen, 2015) (Fig. 4). Continental winter temperatures to the east are raised as a consequence. To the west in northern Canada and Greenland the winters are colder and drier, delaying the Canadian first flower bloom days (Table 2) and overall vegetation productivity (Fig. 4).

3.3 Snow cover

Although the response of snow cover (SC) to global warming is complicated, as snow formation and melt are closely related to a temperature threshold of 0°C (Brown and Mote, 2009), SC is the most predictable indicator (Fig. 5a,i) among the studied variables while teleconnections and solar radiation alone explain more than 74% of the interannual variability (Table 4). The SC decline over the Northern Hemisphere of $0.14 \times 10^6 \text{ km}^2/\text{decade}$ for 1980–2012 was not statistically significant for the region ($p = 0.26$), and showed less interannual variability after the 1998 global warming slowdown (Fig. 2c). Figures 5a,i and Table 4 show that SC is well explained by teleconnections and solar radiation whereas temperature mediation has only a marginal effect. The two leading Northern Hemisphere teleconnections (i.e., NAO and SCA) contribute the biggest natural climatic contributions to the interannual SC variability (see Table 2 and PCA1 column in Table 3). Temperature mediation on interannual variability of SC is only conspicuous with GHG, and less relevant with internal climatic variability (Table 4).

3.4 Sea level

For time scales relevant to anthropogenic warming, the rate of sea level (SL) rise is roughly proportional to the magnitude of warming above the temperatures of the pre-industrial age, with a proportionality constant of 3.4 mm/year per $^{\circ}\text{C}$ (Rahmstorf,

2007). Our analysis of simple linear trend shows that over the past twenty years, Northern Hemisphere SL has risen at a rate of 27 mm/decade for 1993–2012. Natural factors (solar radiation and teleconnections) impacting temperature explains 63% of SL interannual variability (Table 4), while the combination and interactions of all studied driving variables together with temperature explain 78% of the observed variability (Fig. 5h). Although long-term SL rise is related to temperature rise (Fig. 2d) (Rahmstorf, 2007), the interannual variability is mostly controlled by temperature mediated (Fig. 5h,p and Table 4) changes in PNA and WR teleconnections (Table 2). PNA and WR modulate the location and strength of jet streams and fluxes of heat, moisture and momentum and can thus directly warm and expand, or cool and contract large areas of Northern Hemisphere water. Locally, the possible link between SL and teleconnections could be through changes in the surface atmospheric pressure via the inverse barometer effect, and water balance and density changes in response to temperature. Both PNA and WR are highly related to NINO (Table 2), and PNA phases are related to warm and cold Pacific episodes and sea level (Bromirski et al., 2011).

3.5 Atmospheric CO₂ variation in response to sea ice and climate variability

The concentration of Northern Hemisphere atmospheric CO₂ decreases in spring as vegetation grows, and increases in fall when vegetation senesces resulting in an annual peak-to-trough amplitude (AMP) of CO₂ concentration. The seasonal cycles of the Point Barrow CO₂ concentration is mainly explained by dynamics of growing and shrinking extratropical land ecosystems (e.g., Graven et al., 2013; Barichivich et al., 2013). The monthly Point Barrow measurements show that the CO₂ AMP has increased over the last three decades at a rate of 0.96 ppm/decade ($p=1.2\times 10^{-6}$) for 1980–2012. Both CO₂ AMP and concentration (PPM) increases are significantly ($p<0.001$) correlated with the long-term temperature increases (Fig. 2e) but changes in temperature do not directly explain the interannual variability (see lower left Table 2). The interannual variability of CO₂ AMP is explained by large-scale teleconnections such as EA, PNA and NINO and their temperature mediation (Table 3–4), although the direct explanatory power of temperature on CO₂ AMP is negligible (Fig. 5e,m and Table 2). Our results show that there is no direct interannual link between CO₂ AMP and PPM in the Northern Hemisphere – the former is controlled by EA, PNA and NINO and their temperature mediation while the later is controlled by the influence of POL on sea ice dynamics (Table 3). Warm ENSO phases (i.e. positive NINO), coincides with lower CO₂ AMP (Table 2) indicating decreased CO₂ sink capacity which is in agreement with previous finding (Miralles et al., 2013). This decrease of CO₂ sink during positive NINO phase is due to reduced CO₂ uptakes by northern biosphere and may not be linked to sea ice dynamics (Table 3). In other words, the interannual variability of seasonal dynamics of CO₂ concentration is mostly controlled by EA, PNA and NINO influence on temperature while the absolute interannual variability in PPM is controlled by the POL influence on sea ice dynamics (see details below). This is assuming the trend in anthropogenic CO₂ emission remains constant, or the interannual changes in the trends are negligible.

Following a decade with nine of the lowest minima on record, sea ice concentration (SIC) and extent (SIE) have received increased attention in light of climate warming (Post et al., 2013). Over the last three decades there have been rapid declines in both SIE (0.53×10^6 km²/decade) and SIC (1.8%/decade) (both $p<0.5\times 10^{-11}$) for 1980–2012. The decline rate in

SIE is much faster than that of the SIC (Fig. 2a), indicating that sea ice is diminishing more rapidly in areas with thinner ice cover. The rapid decline of SIE is highly correlated with temperature rise ($R=-0.8$, $p<0.2\times 10^{-7}$) (Fig. 2a). Our results show that the interannual variability of SIE and SIC are less controlled by temperature (Table 4), the least predictable indicators (Fig. 5b,c,j,k), more affected by POL teleconnection, and have the biggest direct control on atmospheric CO₂ concentration at Point Barrow but not globally (Table 3). The interannual changes in CO₂ concentration are negatively related to changes in sea ice extent ($p<0.01$) and concentration ($p<0.001$) (see lower left Table 2).

The rapid changes in the Arctic are a consequence of the enhanced warming that the Arctic experiences compared with the rest of the world both on land and in the ocean, caused by a complex interaction of forcing and feedbacks, known as Arctic amplification. Inferring causality between correlated time series is difficult but may be supported when the sea ice response and feedback displays the expected physical understanding. There could be several explanations for the negative relationship between sea ice extent and atmospheric CO₂ concentration. First, water column stratification due to ocean freshening from melting sea ice restrain nutrient availability in Arctic primary productivity (Wassmann et al., 2011). Second, sea ice decline may indirectly contribute to periodic massive pulses of terrestrial carbon release as shown by the link between ice loss and the annual extent of tundra fires in Alaska (Post et al., 2013; Hu et al., 2010). Third, sea ice algae and sub-ice phytoplankton account for more than half of the total annual primary production in the Arctic Ocean (Gosselin et al., 1997), thus the decline in sea ice contributes to substantial loss of habitat for the primary producers. Forth, parallel to changes in the oceanic cryosphere, the lengthening of the growing season and a reduction in snow cover have also been observed in terrestrial ecosystems across the Arctic, which may induce large releases of carbon due to permafrost thaw (Schuur et al., 2011). On the other hand, sea ice decline can also contribute to increased carbon uptake. First, large phytoplankton blooms in the Arctic, where light transmission has increased in recent decades due to the thinning ice cover and proliferation of melt ponds can increase carbon uptake (Arrigo et al., 2012). Several studies show that rapid decline in sea ice related to climate warming is responsible for the increased sub-ice primary production (e.g., Post et al., 2013; Parmentier et al., 2013). Second, solubility-driven sea carbon uptake increases with increased ice-free sea surface. Third, sea ice decline is also strongly linked to longer growing season and increased vegetation productivity of the circumpolar north (>45°N) terrestrial ecosystems (Gonsamo and Chen, 2016) which indicates enhanced carbon uptake by northern plants. Generally speaking, through temperature and sea ice dynamics (Fig. 2a), the ocean may have a large impact on the terrestrial greenhouse gas balance of the Northern Hemisphere: earlier snowmelt and higher land surface temperatures — leading to longer growing seasons — can potentially increase plant uptake of atmospheric CO₂, and these same conditions also increase respiration, permafrost thaw, wildfire, and droughts. Overall, our analysis strongly suggests that the increased carbon loss due to sea ice decline-related processes may outweigh the carbon uptake enhancement through the parallel and concomitant processes, at least during the current climate regime.

The Polar/Eurasia Pattern (POL), which enhances the strength of the circumpolar vortex during its positive phase, is related to gradients in total mass of the atmosphere between polar and continental regions. The ice-albedo feedback due to declining sea ice results in warmer Arctic sea surface temperature, which increases ocean heat content and evaporation in

polar region, further decreasing the temperature gradient of polar and continental regions. This may, in turn, result in strong negative POL phase events that lead to a weaker circumpolar vortex, and the resulting cold air spill will delay the spring vegetation activity of continental areas, reducing the CO₂ sequestration by terrestrial ecosystem. **The negative phase of POL is strongly linked to decreased vegetation productivity of the circumpolar north (>45°N) terrestrial ecosystems (Gonsamo and Chen, 2016).** With disproportionately accelerating warming of the polar region, the negative phase of POL will be prevalent resulting in less sea ice extent, and colder winters in continental areas. Currently, our results suggest that the sea ice loss is linked to net increase in atmospheric CO₂ concentration (Table 2). Given the above explanations, the anticipated sea ice decline in the future may lead to increased atmospheric CO₂ concentration, further strengthening the vicious circle of Arctic amplification.

4 Summary and concluding remarks

Prior to data detrending, our results reveal strong long-term relationships between temperature and several land, ocean and cryosphere indicators (Figures 2 and 3). From Fig. 1, it seems that the atmospheric CO₂ forcing time series has less interannual variability but shows strong long-term relationships with rising temperature. When both the response and driving variables are detrended, the relationship between the long-term trend of temperature and land, ocean and cryosphere, and CO₂ forcing on temperature is partially removed. Consequently, the effects of the rapidly adjusting interannual variability of solar output and teleconnections become evident on several indicator variables. Unlike a single climatic variable such as temperature or precipitation, teleconnections control the entirety of heat, moisture and momentum fluxes, and incidence radiation through their effects on cloudiness (IPCC, 2007). This makes solar output and teleconnections the main drivers of the interannual variability of land, cryosphere and ocean indicators. However, new evidence is emerging regarding external forcing precursors on teleconnections (Fowler et al., 2012; Risbey et al., 2014; Collins, 2005), which may intensify in the midst of long-term climate changes. There is no relationship between solar irradiance and sunspot numbers with key land, cryosphere and ocean indicators (Fig. 3) if the trends are not removed from the datasets. This suggests that the recent trend in solar output has no discernible influence on the trends of the physical and biological systems indicators studied in the current work.

We found several coherent interannual patterns among related detrended response and driving variables. There are three sets of statistically strong auto-associations of driving and response variables which have **at least 30-years of observations in the Northern Hemisphere** (Table 3): (i) start of season, snow cover, Sun outputs, global well-mixed greenhouse gases (WGMHG), North Atlantic Oscillation (NAO), and Scandinavia Pattern (SCA); (ii) temperature, peak-to-trough CO₂ amplitude, East Atlantic Pattern (EA), Pacific/North American Pattern (PNA), and ENSO; and (iii) sea ice extent and concentration; CO₂ concentration (PPM), and Polar/Eurasia Pattern (POL). Overall, our results show that key land, cryosphere and ocean indicators are behaving as expected if they are responding to rising annual mean surface temperature

and atmospheric CO₂ concentration in the Northern Hemisphere, and global well-mixed greenhouse gases (WMGHG), over the last three decades (Fig. 1b and Fig. 2).

The long-term trend analysis indicates that changes in surface temperature in the last three decades are strongly correlated ($p < 0.05$) with sea ice and sea level, spring phenology and thaw, and atmospheric CO₂ concentration (Fig. 2). Globally, rising temperature is also on a par with increasing radiative forcing of WMGHG (Fig. 1b). Recent changes in the Sun's output, decadal climatic oscillations, sunspot number, and cosmic ray counts have little or no relationship with long-term trends of Northern Hemisphere warming and its effect on land, cryosphere or ocean indicators (Fig. 1 and 2). During the last three decades, the Sun's energy output followed its historical 11-year cycle, with a slight overall decrease (Fig. 1b), temperature anomalies diverged from solar forcing, stratospheric Aerosol, and internal climatic oscillation indicated by the Atlantic Multidecadal Oscillation (Fig. 1c), and the two major volcanic eruptions of the last three decades have had only short cooling effects on climate (Gillett et al., 2012). Therefore, the combination of solar and volcanic activity should actually have led to a slight cooling if they were the primary drivers of long-term trends (Gillett et al., 2012). The recent multidecadal warming of Northern Hemisphere surface temperature cannot be explained by natural variability, or by any known mode of internal variability (Santer et al., 2013a; Santer et al., 2013b) (Fig. 1c). Slow changes in the Earth's tilt and orbit around the Sun are only relevant in time scales of several thousands of years and cannot explain the recent rapid warming. Therefore, the observed rapid climate warming and its impacts on land, cryosphere, and ocean may best be attributed to anthropogenic factors, largely the radiative effects from increased concentrations of WMGHG (Fig. 1b). Despite the apparently slower rate of post-1998 global warming, a coherent pattern of changes across multiple life supporting natural systems is very likely to continue with increasing greenhouse gases.

How robust are our results? Although most of the variables were spatially averaged and multicollinearity was removed, the uncertainties from residual atmospheric effects and calibration errors in satellite data, missing drivers, errors in ground measurements, and methodological difficulty in capturing interactive effects of drivers and short-term feedbacks, are data source specific, difficult to quantify and cannot be ruled out. This work; however, contributes not only to observation-based detection and attribution of changes in climate index (i.e., here temperature), but also to the detection and attribution of impacts of climate changes on physical and biological systems following the 2014 Working Group II IPCC report (IPCC, 2014a) and other recent works (e.g., Rosenzweig et al., 2008; Parmesan et al., 2013; Stone et al., 2013; Poloczanska et al., 2013).

Abbreviations

Temperature = T, snow cover = SC, sea ice extent = SIE, sea ice concentration = SIC, spring thaw = ST, start of growing season = SOS, first flower bloom day = FFB, sea level = SL, peak-to-trough amplitude of CO₂ = AMP, CO₂ concentration = PPM, well-mixed greenhouse gases = WMGHG, sunspot number = SP, solar irradiance = RAD, cosmic ray count = CR, North Atlantic Oscillation = NAO, East Atlantic Pattern = EA, West Pacific Pattern = WP, Pacific/ North American Pattern =

PNA, East Atlantic/West Russia Pattern= WR, Scandinavia Pattern= SCA, Polar/ Eurasia Pattern= POL, ENSO-Niño 3.4 index= NINO.

Acknowledgements

We thank NOAA ESRL Carbon Cycle Cooperative Global Air Sampling Network, NOAA National Geophysical Data Center (NGDC), NOAA Earth System Research Laboratory, NOAA Climate Prediction Center, NASA Goddard Institute for Space Studies, NASA Goddard Space Flight Center, University of Colorado Sea Level Research Group, National Center for Atmospheric Research, Germany Cosmic Ray Monitor, VIRGO Experiment on the ESA/NASA Mission SoHO – version d41_62_1302 data from Physikalisch-Meteorologisches Observatorium Davos und Weltstrahlungszentrum/World Meteorological Organisation, Solar Influences Data Analysis Center, [WDC-SILSO Royal Observatory of Belgium](#), National Snow and Ice Data Center, Joint Institute for the Study of the Atmosphere and Ocean, Rutgers University Global Snow Lab, Compton J. Tucker and the Global Inventory Modeling and Mapping Studies team, and Jonathan Barichivich for making their data available. We thank Eric Post for his constructive comments on an earlier version of the manuscript.

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Table 1. Summary of key variables used in the current study.

Category	Variables (Abbreviation)	Temporal coverage	Spatial coverage	Data references
Temperature	Temperature (T)	1980–2012	Northern Hemisphere (0°N–90°N)	Hansen et al. (2010)
Cryosphere indicators	Snow cover (SC)	1980–2012	Northern Hemisphere (0°N–90°N)	Robinson et al. (2012)
	Sea ice extent (SIE)	1980–2012	Northern Hemisphere (>31°N)	Fetterer et al. (2009)
	Sea ice concentration (SIC)	1980–2012	Northern Hemisphere (>31°N)	Fetterer et al. (2009)
Land indicators	Spring thaw (ST)	1988–2007	Northern Hemisphere (>45°N)	Barichivich et al. (2013)
	Start of growing season (SOS)	1982–2011	Northern Hemisphere (>45°N)	Barichivich et al. (2013)
	First flower bloom (FFB) Atmospheric CO ₂ peak-to-trough amplitude (AMP)	2001–2012 1980–2012	Canada (point data) Station data (Alaska, USA, 71.3° N, 156.6° W)	Gonsamo et al. (2013) This study
Ocean indicators	Sea level (SL)	1993–2012	Northern Hemisphere (0°N–90°N)	Nerem et al. (2010)
External anthropogenic forcing indicators	Atmospheric CO ₂ concentration (PPM)	1980–2012	Station data (Alaska, USA, 71.3° N, 156.6° W)	www.esrl.noaa.gov/gmd/dv/data
	Well-mixed greenhouse gases (WMGHG)	1980–2012	Global (point data)	Hofmann et al. (2006)
External natural forcing indicators	Sunspot number (SP)	1980–2012	Global (point data)	SIDC-team (1980-2012)
	Solar irradiance (RAD)	1980–2012	Point data (satellite based observation)	Frohlich and Lean (1998) and Frohlich (2000, 2003, 2006)
	Cosmic ray counts (CR)	1980–2007	Station data (Kiel, Germany, 54.3°N, 10.2°E)	Steigies et al. (2008)
Internal climatic variability indicators	North Atlantic Oscillation (NAO)	1980–2012	Northern Hemisphere (>20°N)	Barnston and Livezey (1987), and Wallace and Gutzler (1981)
	East Atlantic Pattern (EA)	1980–2012	Northern Hemisphere (>20°N)	Barnston and Livezey (1987), and Wallace and Gutzler (1981)
	West Pacific Pattern (WP)	1980–2012	Northern Hemisphere (>20°N)	Barnston and Livezey (1987), and Wallace and Gutzler (1981)
	Pacific/North American Pattern (PNA)	1980–2012	Northern Hemisphere (>20°N)	Barnston and Livezey (1987), and Wallace and Gutzler (1981)
	East Atlantic/West Russia Pattern (WR)	1980–2012	Northern Hemisphere (>20°N)	Barnston and Livezey (1987), and Wallace and Gutzler (1981)
	Scandinavia Pattern (SCA)	1980–2012	Northern Hemisphere (>20°N)	Barnston and Livezey (1987), and Wallace and Gutzler (1981)
	Polar/Eurasia Pattern (POL)	1980–2012	Northern Hemisphere (>20°N)	Barnston and Livezey (1987), and Wallace and Gutzler (1981)
	El Niño/Southern Oscillation (NINO)	1980–2012	Niño 3.4 region (5°N–5°S, 120°–170°W)	Barnston and Ropelewski (1992)

Table 2. Percent interannual (lower left) and long-term (upper right) variances in indicator A explained by indicator B or vice versa for 1982–2011.

Category	Category	Temperature				Cryosphere indicators				Land indicators				Ocean indicators		External anthropogenic forcing indicators			External natural forcing indicators			Internal climatic variability indicators					
		A	B	T	SC	SIE	SIC	ST	SOS	FFB	AMP	SL	PPM	WMGHG	SP	RAD	CR	NAO	EA	WP	PNA	WR	SCA	POL	NINO		
Temperature	T			-64	-72	-61	-39	-39	27	61	77	79													-20		
Cryosphere indicators	SC																-19								26		
	SIE				88	44			-25	-76	-78	-74	18	24											13		
	SIC				53	46	21		-36	-77	-89	-85	14	19													
Land indicators	ST		-40	21			44				-36	-36													27		
	SOS		-28				61				-19	-23							-26								
	FFB		-41							-41															-51		
	AMP									23	46	45													-17		
Ocean indicators	SL										96	96															
External anthropogenic forcing indicators	PPM				-21	-30						99															
	WMGHG				-22			-18									-18	-20									
External natural forcing indicators	SP			-17				-20				26					92	-76							-18		
	RAD				13			-22				18					90								-18		
	CR									-39							-76	-70									
Internal climatic variability indicators	NAO			-22					43																-55		
	EA	26						-27																	16		
	WP																										
	PNA											-29	25													41	
	WR												23													14 19	
	SCA			27				14	-65								-21	-22							-56		
	POL																								14		
	NINO			-19				25																		16 41 19	

The numbers indicate the statistically significant ($p < 0.05$) coefficient of determination (%), - sign is for negative correlation) from a two tailed Student's t-test. Values in the lower left are the interannual coefficient of determinations after data detrending while values in the upper right are the long-term coefficient of determinations calculated before data detrending.

For interannual correlation analysis, each pair of variables were detrended separately using the common data record period. *The italic bold font represents a pair of correlations for which both long-term and interannual covariability show statistically significant relationship.* Temperature = T, snow cover = SC, sea ice extent = SIE, sea ice concentration = SIC, spring thaw = ST, start of growing season = SOS, first flower bloom day = FFB, sea level = SL, peak-to-trough amplitude of CO₂ = AMP, CO₂ concentration = PPM, WMGHG = well-mixed greenhouse gases, sunspot number = SP, solar irradiance = RAD, and cosmic ray count = CR, NAO = North Atlantic Oscillation, EA = East Atlantic Pattern, WP = West Pacific Pattern, PNA = Pacific/ North American Pattern, WR = East Atlantic/West Russia Pattern, SCA = Scandinavia Pattern, POL = Polar/ Eurasia Pattern, and NINO = ENSO-Niño 3.4 index. *The discrepancies in the amount correlations between Table 2, and Figures 2 and 3 are due to different time period lengths used in both analyses, the former is based on the most common data record period (i.e., 1982–2011) while the latter are based on the entire data record period of each variable.*

Table 3. Squared loading of variables for 1982–2011.

Category	Variables	PCA1	PCA2	PCA3	PCA4	PCA5	PCA6
Temperature	T	0.26	0.40				
Cryosphere indicators	SC	0.40		0.19			0.12
	SIE			0.44			
	SIC			0.59	0.18		
Land indicators	SOS	0.47				0.18	
	AMP		0.44		0.17		
External anthropogenic forcing indicators	PPM			0.50		0.19	
	WMGHG	0.41					
External natural forcing indicators	SP	0.68					0.13
	RAD	0.67					
Internal climatic variability indicators	NAO	0.31			0.24		0.23
	EA	0.22	0.31				
	WP				0.35	0.30	
	PNA		0.58				
	WR			0.22	0.14	0.24	
	SCA	0.47			0.14		
	POL			0.31	0.25	0.14	
	NINO			0.68			
	Eigenvalue	4.21	3.04	2.54	1.70	1.38	1.12
	Variability %	23.38	16.87	14.10	9.44	7.64	6.20
	Cumulative %	23.38	40.24	54.34	63.78	71.42	77.62

Squared loading of the variables. Only variables with at least 30-years of measurements were included in this analysis.

Values in bold correspond for each variable to the factor for which the squared loading is the largest. This Table presents the statistically significant ($p < 0.05$, two tailed Student's t-test) principal component analysis (PCA) squared loading of variables, i.e., the percent explained variance [0–1] between each PCA axis and a variable. Temperature = T, snow cover = SC, sea ice extent = SIE, sea ice concentration = SIC, start of growing season = SOS, peak-to-trough amplitude of CO₂ = AMP, CO₂ concentration = PPM, WMGHG = well-mixed greenhouse gases, sunspot number = SP, solar irradiance = RAD, NAO = North Atlantic Oscillation, EA = East Atlantic Pattern, WP = West Pacific Pattern, PNA = Pacific/ North American Pattern, WR = East Atlantic/West Russia Pattern, SCA = Scandinavia Pattern, POL = Polar/ Eurasia Pattern, and NINO = ENSO-Niño 3.4 index.

Table 4. Explained variance of land, cryosphere and ocean indicators by natural variability and anthropogenic forcing with and without temperature mediation calculated from the detrended data for 1982–2011.

Category	Variables	GHG-T	SR-TEL	SR-TEL-T
Cryosphere indicators	SC	36.6**	73.8***	74***
	SIE	23.7*	32.7*	25.3*
	SIC	35.4**	32.3*	37.9**
Land indicators	SOS	44.4***	46.3**	48.8***
	AMP	4.4	44.2**	52.4**
	ST	29.4*	32*	45.1**
	FFB	42.9*	98.8	100**
Ocean indicators	SL	9.9	51.1**	62.8*

This Table presents the percent explained variance derived from a PCA and stepwise regression analysis of land, cryosphere and ocean indicators by interannual changes in greenhouse gases and temperature (GHG-T); solar radiation and eight leading teleconnections (SR-TEL); and solar radiation, eight leading teleconnections and temperature (SR-TEL-T). Temperature in GHG-T and in SR-TEL-T are included to show the temperature mediated natural variability and anthropogenic forcing. Snow cover = SC, sea ice extent = SIE, sea ice concentration = SIC, start of growing season = SOS, peak-to-trough amplitude of CO₂ = AMP, spring thaw = ST, first flower bloom day = FFB, and sea level = SL. GHG includes concentration (PPM) of atmospheric CO₂ at Point Barrow and 20 global well-mixed greenhouse gases (WGMHG) radiative forcing. SR-TEL includes solar radiation, sunspot numbers and eight leading Northern Hemisphere teleconnection indices. All three sets (columns) of PCA analyses were done separately each only for the selected predicting variables. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, two tailed Student's t-test. The explained variances by combination of all drivers with and without temperature mediation are given in Fig. 5.

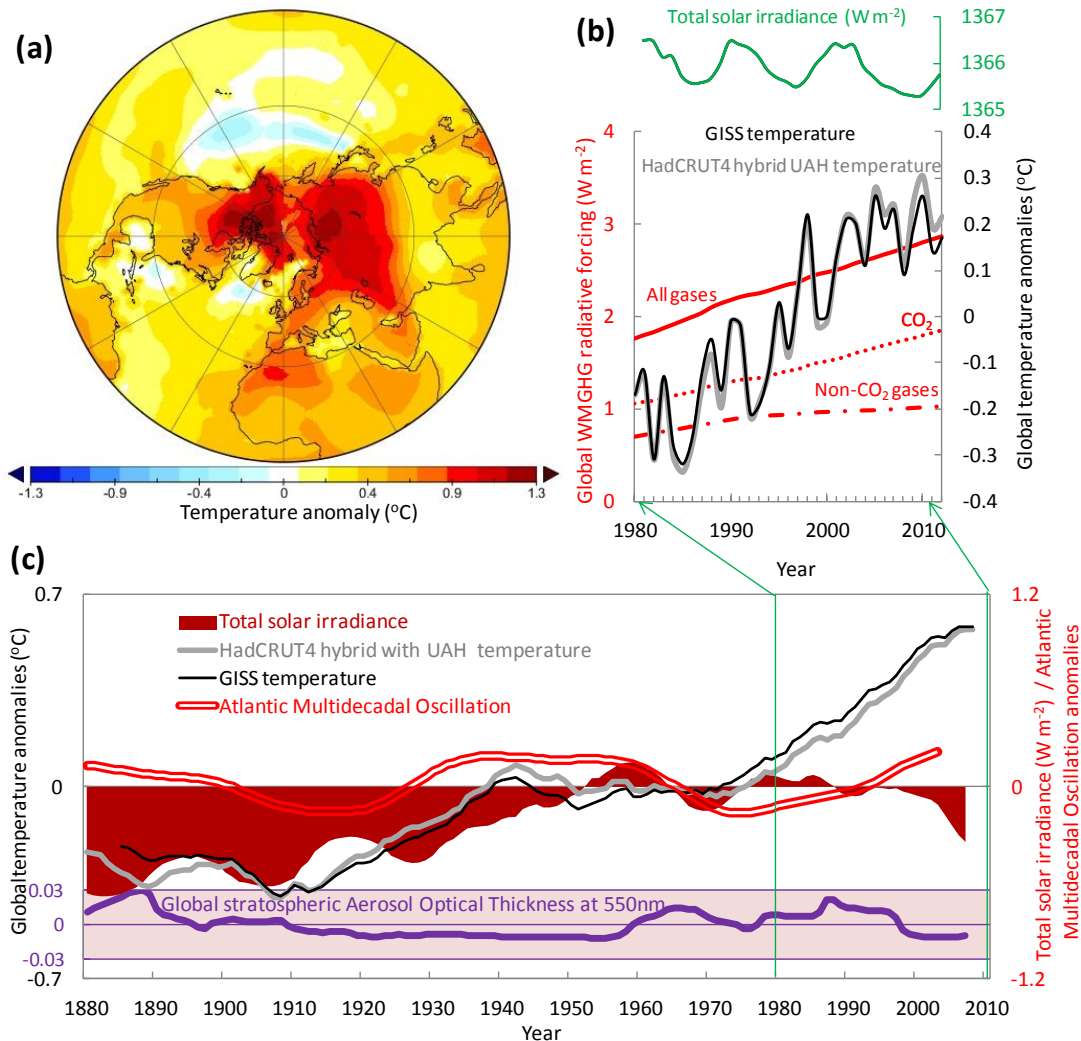


Figure 1. (a) 1980–2012 surface temperature anomaly ($^{\circ}\text{C}$) of Northern Hemisphere relative to 1951–1980 base period. (b) The global mean annual surface temperature anomalies, total solar irradiance, and global well-mixed greenhouse gases (WMGHG) patterns during the satellite era. The WMGHG includes CO_2 , major gases (CH_4 , N_2O , CFC12 and CFC11) and a set of 15 minor long-lived halogenated gases (CFC-113, CCl_4 , CH_3CCl_3 , HCFCs 22, 141b and 142b, HFCs 134a, 152a, 23, 143a, and 125, SF_6 , and halons 1211, 1301 and 2402). Global annual mean surface temperatures relative to 1951–1980 base period from GISS (black) and Cowtan and Way HadCRUT4 hybrid UAH reconstruction (grey), and total solar irradiance are also shown in (b). (c) 11-year moving averages of global annual mean surface temperatures from GISS and Cowtan and Way HadCRUT4 hybrid UAH reconstruction, total solar irradiance, Atlantic Multidecadal Oscillation (AMO) index, and global stratospheric aerosol optical thickness at 550nm anomalies relative to 1951–1980 base period. The zoom-in arrows in (c) show the time period covered in this study when the temperature anomalies diverged from solar forcing and internal climatic variability.

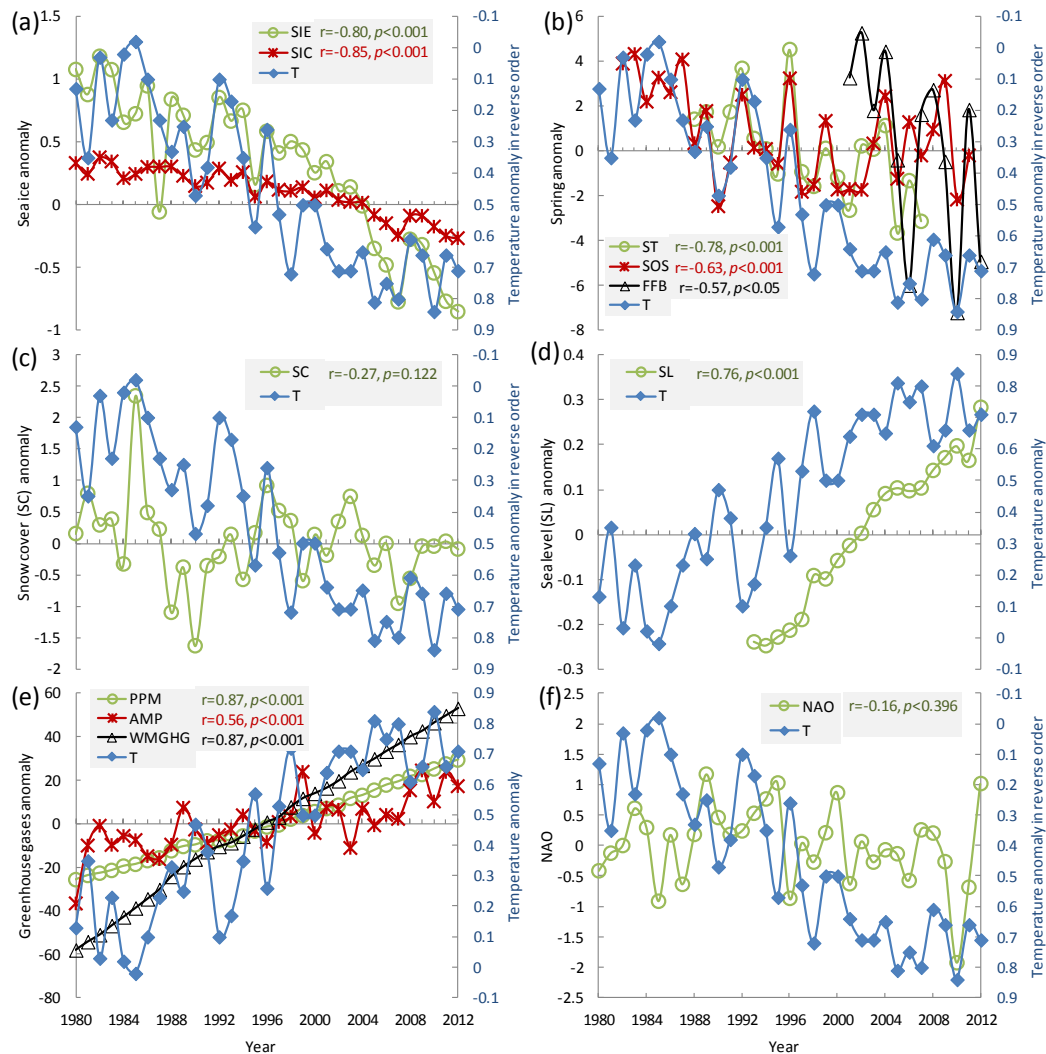


Figure 2. Relationship between land, cryosphere and ocean indicators, and recent trends in surface temperature. Surface temperature anomaly is from the Northern Hemisphere relative to 1951–1980. The r (Pearson correlation coefficient) and p (p -value) are given for long-term relationships between temperature and the plotted variables. (a) Sea ice concentration (SIC) 0 (no ice) to 10 (full ice coverage) anomaly and sea ice extent (SIE) 10^6 km² anomaly of circumpolar Northern Hemisphere region ($>31^\circ\text{N}$) relative to 1993–2012 normals. (b) Spring thaw (ST) and start of growing season (SOS) day anomalies of northern ecosystems ($>45^\circ\text{N}$) relative to 1988–2007 normals (ref. Barichivich et al., 2013, modified) and first flower bloom (FFB) day anomaly of Canada relative to 2001–2012 normals (ref. Gonsamo et al., 2013, modified). (c) Snow cover (SC) 10^6 km² anomaly of Northern Hemisphere relative to 1993–2012 normals. (d) Sea level (SL) 10^2 mm anomaly of Northern Hemisphere relative to 1993–2012 normals. (e) peak-to-trough amplitude (AMP) 10^1 and concentration (PPM) of atmospheric CO₂ at Point Barrow and 20 global well-mixed greenhouse gases (WMGHG) radiative forcing. (f) The North Atlantic Oscillation (NAO) index.

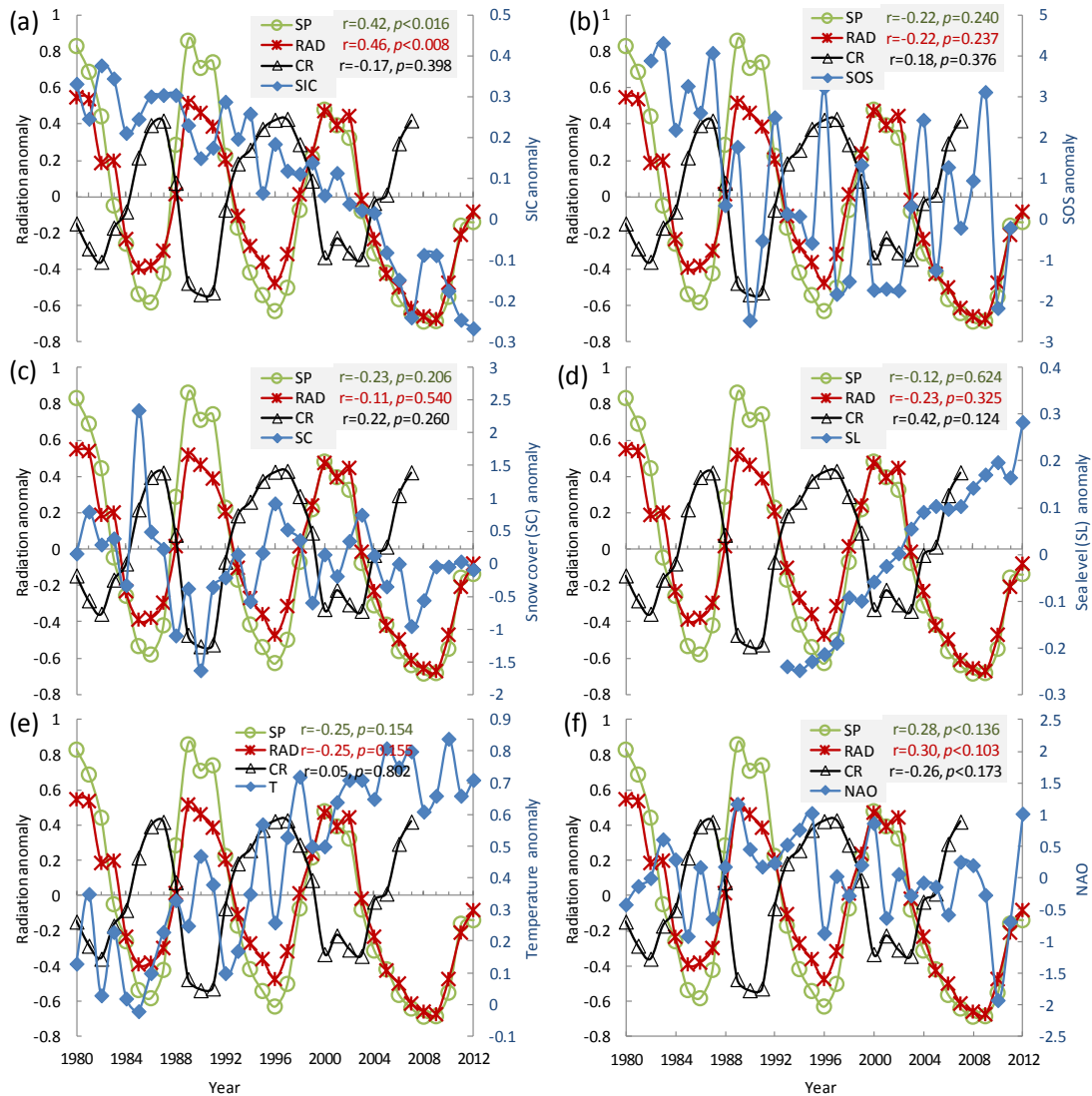


Figure 3. Relationships among temperature, land, cryosphere and ocean indicators, and recent trends in solar radiation, sunspots and cosmic rays. The relationships between anomalies of annual average of daily mean sunspot number (SP), annual average of daily mean solar irradiance (RAD, W m^{-2}), and the Kiel station annual average of hourly cosmic ray (CR) counts relative to 1980–2007 normals and, (a) Sea ice concentration (SIC) 0 (no ice) to 10 (full ice coverage) anomaly of circumpolar Northern Hemisphere region ($>31^\circ\text{N}$) relative to 1993–2012 normals, (b) Start of growing season (SOS) day anomaly of northern ecosystems ($>45^\circ\text{N}$) relative to 1988–2007 normals (ref. Barichivich et al., 2013, modified), (c) Snow cover (SC) 10^6 km^2 anomaly of Northern Hemisphere relative to 1993–2012 normals, (d) Sea level (SL) 10^2 mm anomaly of Northern Hemisphere relative to 1993–2012 normals, (e) Surface temperature anomaly of Northern Hemisphere relative to 1951–1980 normals, (f) The North Atlantic Oscillation (NAO) index. The r (Pearson correlation coefficient) and p (p -value) are given for long-term relationships of SP, RAD, and CR with the plotted variable.

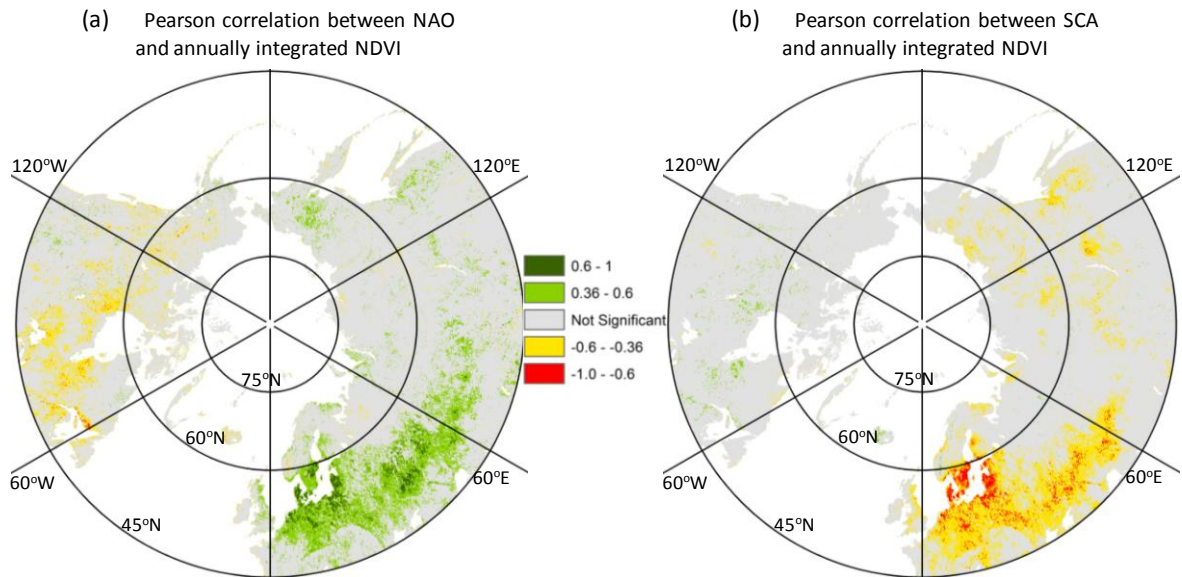


Figure 4. Relationships (values in Pearson correlation coefficient) between the growing season annually integrated normalized difference vegetation index (NDVI) and the North Atlantic Oscillation (NAO) (a), and the Scandinavia Pattern (SCA) (b). Both teleconnection and NDVI datasets were detrended. All colour shaded values are significant at 95% confidence level from a two tailed Student's t-test.

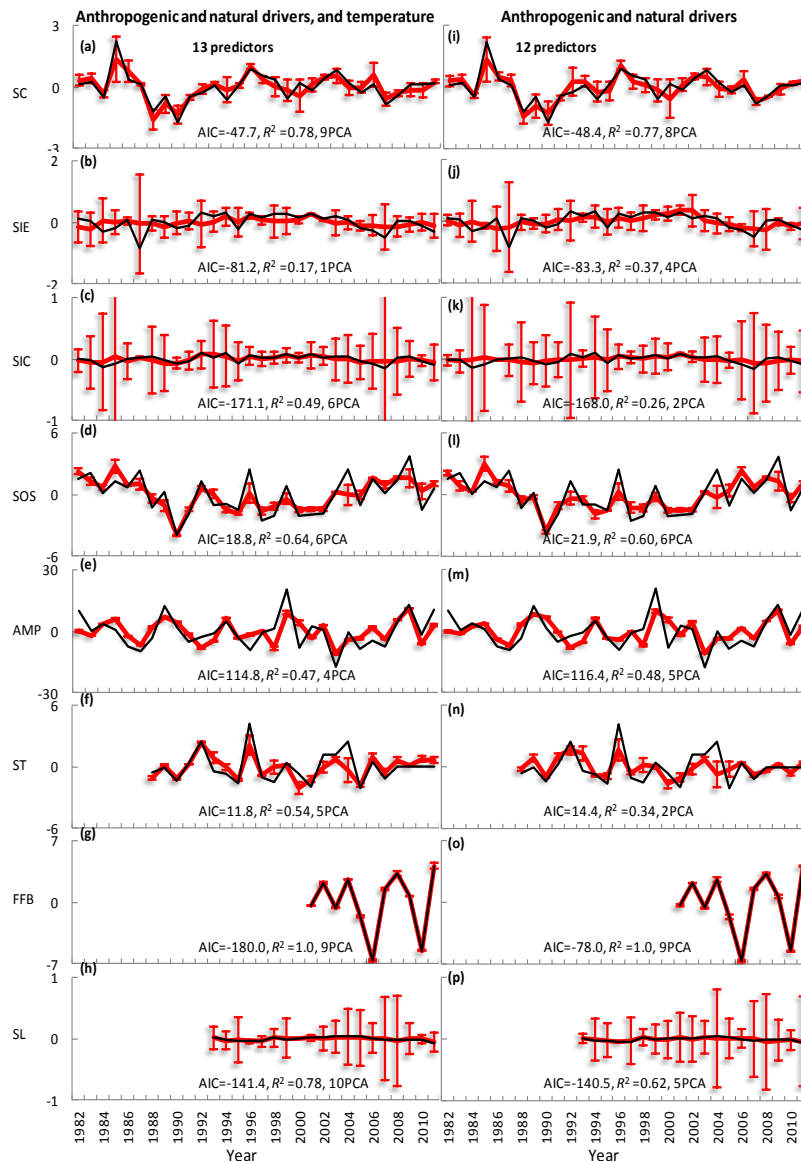


Figure 5. Predicting powers of temperature mediated natural and anthropogenic drivers (left), and only natural and anthropogenic drivers (right). Black line is observed and red line is predicted. Error bars are uncertainty of each prediction measured by standardized error. The predictions were conducted using stepwise regression with Akaike information criterion (AIC) from orthogonal variables transformed by principal component analysis (PCA) against each land, cryosphere and ocean indicator. The number of PCAs selected using the AIC criteria are shown in each panel. Predictors on left panels include the orthogonally transformed PCA variables of temperature, concentration (PPM) of atmospheric CO₂ at Point Barrow, 20 global well-mixed greenhouse gases (WMGHG) radiative forcing, solar radiation, sunspot numbers and eight leading Northern Hemisphere teleconnection indices. Panels on right include all the predictors on the left with exclusion of temperature. Each PCA for the two sets (i.e. left and right panels) were conducted separately.