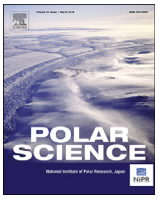
Polar Science xxx (2016) 1–11

Contents lists available at ScienceDirect

Polar Science

journal homepage: http://ees.elsevier.com/polar/



Relationship between the Arctic oscillation and surface air temperature in multi-decadal time-scale

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ARTICLE INFO

Article history:
Received 2 November 2015
Received in revised form
14 February 2016
Accepted 6 March 2016
Available online xxx

Keywords:
Arctic oscillation
Arctic amplification
Energy balance model
Planetary albedo
Multi-decadal variability

ABSTRACT

In this study, a simple energy balance model (EBM) was integrated in time, considering a hypothetical long-term variability in ice-albedo feedback mimicking the observed multi-decadal temperature variability. A natural variability was superimposed on a linear warming trend due to the increasing radiative forcing of CO_2. The result demonstrates that the superposition of the natural variability and the background linear trend can offset with each other to show the warming hiatus for some period. It is also stressed that the rapid warming during 1970–2000 can be explained by the superposition of the natural variability and the background linear trend at least within the simple model.

The key process of the fluctuating planetary albedo in multi-decadal time scale is investigated using the JRA-55 reanalysis data. It is found that the planetary albedo increased for 1958–1970, decreased for 1970–2000, and increased for 2000–2012, as expected by the simple EBM experiments. The multi-decadal variability in the planetary albedo is compared with the time series of the AO mode and Barents Sea mode of surface air temperature. It is shown that the recent AO negative pattern showing warm Arctic and cold mid-latitudes is in good agreement with planetary albedo change indicating negative anomaly in high latitudes and positive anomaly in mid-latitudes. Moreover, the Barents Sea mode with the warm Barents Sea and cold mid-latitudes shows long-term variability similar to planetary albedo change. Although further studies are needed, the natural variabilities of both the AO mode and Barents Sea mode indicate some possible link to the planetary albedo as suggested by the simple EBM to cause the warming hiatus in recent years.

1. Introduction

Recent global warming is characterized by an Arctic amplification as was predicted by pioneer studies by Manabe and Wetherald (1975) and Manabe and Stouffer (1980). The Arctic amplification is a response to the anthropogenic radiative forcing by increasing greenhouse gases such as CO_2. When the radiative forcing acts as uniform warming of the atmosphere, the Arctic warms more than the global average. For example, when the global mean temperature warms 2.0 °C, the Arctic tends to warm 5.0 °C, which is 2.5 times larger than the global mean. Likewise, when the radiative forcing acts uniform cooling of the atmosphere, the Arctic cools more than the global average. The arctic amplification is an enhanced response of the Arctic to both warming and cooling. When the response is argued not only for the Arctic but also for the Antarctic, the naming of polar amplification is used for a general case (Langen and Alexeev, 2007).

The mechanism of the Arctic amplification was explained mostly by the ice-albedo feedback occurring in the cryosphere in high latitudes. The short wave radiation is reflected back to the space by the surface high albedo over the cryosphere, which cools the climate system more to expand the cryosphere in high latitudes. This strong feedback operates at the subarctic where the sun shine can reach in winter season. According to the comprehensive diagnostic analysis of the climate system models (Yoshimori et al., 2009, 2014), the Arctic amplification is induced not only by the ice-albedo feedback but also by many other processes, including the enhanced meridional heat transport by the atmosphere and ocean, changes of long-wave radiation by cloud amount or moisture in the atmosphere, changes of lapse rate and vertical temperature profile with strong inversion, and

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http://dx.doi.org/10.1016/j.polar.2016.03.002
1873-9652/© 2016 Published by Elsevier B.V. and NIPR.

Please cite this article in press as: Tanaka, H.L., Tamura, M., Relationship between the Arctic oscillation and surface air temperature in multi-decadal time-scale, Polar Science (2016), http://dx.doi.org/10.1016/j.polar.2016.03.002

radiation changes by black carbon aerosol or life activity in snow at microscopic scales. Those processes are mutually related in a complex way to cause the robust Arctic amplification. However, we aware that the ice-albedo feedback is the most important process among those according to the quantitative comparison of each process by the variational method in response to the prescribed radiative forcing due to the increasing greenhouse gases (Yoshimori et al., 2009, 2014).

The anthropogenic Arctic warming is superimposed by natural (or internal) variability, such as the Arctic oscillation (AO) in the atmosphere, or Pacific decadal-oscillation (PDO) and Atlantic multidecadal oscillation (AMO) in the ocean (Trenberth and Fasullo, 2013; Wallace and Thompson, 2002). The AO is defined by the first empirical orthogonal function (EOF) of the sea level pressure (SLP) having low pressure anomaly in the Arctic and high pressure anomaly in mid-latitudes with the node at 60° N for the positive AO index (Thompson and Wallace, 1998). The polar jet stream is enhanced by the large meridional pressure gradient. The corresponding regression map for surface air temperature (SAT) shows cold anomaly in the Arctic and Greenland and warm anomaly in mid-latitudes especially over northern Siberia for the positive AO index. Those patterns in pressure, wind, and temperature reverse for the negative AO index.

According to the EOF analysis of the monthly mean SAT during winter by Nagato and Tanaka (2012), the AO mode appears as the EOF-1 with 24% of variance, and the Arctic amplification mode appears as the EOF-2 with 15% of variance. The EOF-3 is characterized by warm anomaly over Barents Sea and cold anomaly in mid-latitude, especially over southern Siberia counting 12% of variance. The time series of the EOF-1 for AO is called AO index, showing decreasing trend for 1950–1970, increasing trend for 1970–1990, and decreasing trend for 1990–2010, indicating multi-decadal variability. Since the observed warming pattern in temperature coincides with that of AO for 1970–1990, explaining 40% of variance, AO was considered as one of the causes of the global warming (Shindell et al., 1999). Yet, the AO index started to decrease after 1990 while the mean temperature keeps increasing. The AO thus turns to be excluded from the possible candidate for the cause of global warming.

After the year 1998 of strong El-Niño, global mean temperature halted the increase, despite the monotonic increase of CO_2 concentration (Trenberth and Fasullo, 2013). The discrepancy between the monotonic warming prediction by climate models and the actual observation of halting warming is called as a warming hiatus problem. Since the AO index indicates a decreasing trend during the warming hiatus period, and the temperature anomaly turns to show warm Arctic and cold mid-latitude pattern similar to the AO negative pattern, AO turns to draw more attention again in connection to the global warming hiatus (Overland et al., 2011; Mori et al., 2014). Since the AO is a chaotic internal variability in the atmosphere (Hirata et al., 2011), multi-decadal variability of the AO needs to be investigated in more detail.

The global warming hiatus was partly explained by Kosaka and Xie (2013) and Watanabe et al. (2014) by means of the internal variability associated with the PDO. The SST anomaly is similar to La-Niñ a pattern indicating cold SST anomaly in the tropical eastern Pacific and warm SST anomaly in the northern Pacific. The mean atmospheric temperature associated with the internal variability indicates a warm phase for 1970–2000 and a cold phase for 2000–2012, which is superimposed on the anthropogenic global warming trend. The warming hiatus was explained by the accumulated heat energy in deep ocean by these studies. However, the mechanism of the energy accumulation in ocean deeper than 2000 m without the temperature increase at the ocean surface needs to be clarified.

In this study we attempt to simulate the multi-decadal variability of the mean temperature using a simple energy balance model (EBM) by Alexeev and Jackson (2012). Here the model is constructed by two control volumes of low-latitudes and high-latitudes separated by 30° N. The balance equations for the heat contents are integrated over the entire control volume. Then the total heat content for each box is governed by the cross-boundary flux and the source sink within each the box. Although the EBM is quite simple, it is based on the rigorous physical laws of conservations. It was demonstrated by previous studies that the model is suitable to explain the mechanism of the Arctic amplification induced by the ice-albedo feedback. We attempt in this study to apply this EBM by including the fluctuation of the boundary flux associated with the ice-albedo feedback. Moreover, the relationship between the multi-decadal variability of mean temperature and planetary albedo is investigated using the long-term reanalysis data in reference to the internal variabilities of the atmosphere.

2. Energy balance model

The energy balance model (EBM) used in this study is based on Alexeev and Jackson (2012), where the climate system in the Northern Hemisphere is divided in low-latitude box 1 and high-latitude box 2 separated by the latitude 30° N as seen in Fig. 1. The thermodynamic energy equation is integrated over the control volume of the entire atmosphere and mixed layer of ocean and land surface within the box. The heat capacity of the system is represented by a constant parameter H. Then the balance equation for total heat energy in the control volume is governed by cross boundary fluxes of short wave S and long wave OLR and a meridional heat transport F. The source and sink term within the box ε represents the radiative forcing by doubling CO_2 as a deviation from the present climate. The unique setting of this EBM is a consideration of ice-albedo feedback by the variable ice fraction a over the hemisphere with a constant albedo α in high-latitudes. Refer to Alexeev and Jackson (2012) and Umino (2014) for the detail of the formulation and parameters. Although the governing equations are quite simple, the equation is based on a rigorous fluid mechanics of a balance equation for heat energy of the climate system over the

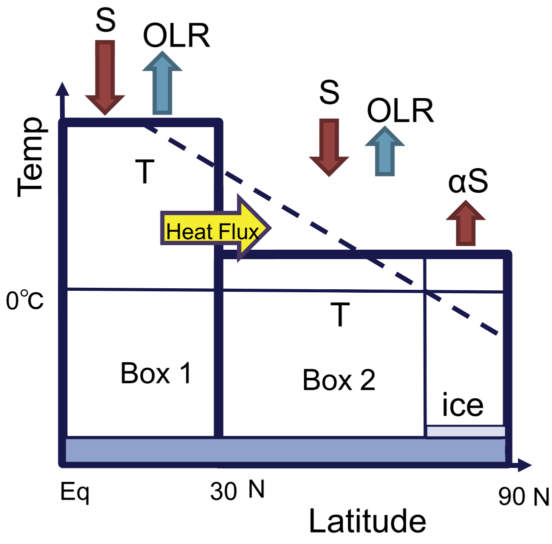

Fig. 1. Schematic picture of the energy balance model (EBM) for Box 1 and Box 2 separated by 30° N. The symbols S and OLR denote short and long wave radiations. A cryosphere (ice) is considered at temperature less than 0° C with higher albedo α.

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