

Seasonal land-Sea Difference of Arctic Amplification Strength: Insights From Reanalysis Datasets

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Abstract. Quantitative and contrastive understanding of the seasonal land-sea difference in Arctic amplification (AA) strength is important but it still has not been well characterized. This research studied this issue using five reanalysis datasets and compared AA strength with exiting knowledges on AA variations. Results showed that the seasonal AA over Arctic land maintains a relatively stable magnitude (i.e., on the order of 2) and spatial coverage in different seasons; there is no AA effect in summer and the AA magnitudes fluctuate with a relatively large range in different seasons over the Arctic sea. The AA effect over the Arctic sea is more pronounced than that of the Arctic land in terms of magnitude and spatial coverage except in the summer. Results also implied that the AA strength over the sea reported by previous studies is lower than that derived from reanalysis datasets, while the AA strength over the land reported by previous studies is roughly consistent with that of this study. These findings enrich the existing knowledges about the seasonal land-sea difference of the AA and are beneficial to exploring the driving mechanisms of seasonal AA variations.

Keywords: Arctic amplification; Land-sea difference; Reanalysis datasets.

1. Introduction

The Arctic is warming at a faster rate than the global average, which is a phenomenon known as the Arctic amplification (AA) effect. The AA effect has been found in historical observation, climate simulation and paleoclimatic proxies [1, 2, 3, 4, 5, 6]. The AA strength (e.g., its magnitude and spatial coverage) is a direct measure of the relationship between temperature variability over the Arctic and the globe. Studying seasonal land-sea differences in the AA strength helps identify the seasonal driving mechanisms of the AA variations contributions from the land and sea. However, the contribution of Arctic land and sea to seasonal AA magnitudes and spatial patterns remains unclear because previous studies mainly focused on the variations in the AA effect either over the entire Arctic [1, 7, 8] or some local regions of the Arctic [9, 10]. Hence, quantitative and contrastive study on the seasonal differences of the AA between the Arctic land and the Arctic sea still is an ongoing work. This study aims to investigate the seasonal land-sea difference of the AA in terms of magnitudes and spatial patterns during the past decades.

Analyzing the seasonal land-sea difference of the AA strength depends on high-quality and spatiotemporally continuous near-surface air temperature (SAT) data covering the entire Arctic. Although both observational data and model simulations have been used in previous AA studies, these data have shortcomings for studying the land-sea difference of the AA, e.g., observations have a large portion of missing values over the ocean and the Arctic [11, 12]. Model simulations can output spatially continuous data, but a free-running model simulation often contains “climate drift” [13] and does not match the temporal evolution of atmospheric states in the real world [14], which are difficult to recognize or eliminate. Global reanalysis datasets are produced by combining model simulations with multi-source observations (e.g., ground observations, satellite observations and buoy observations) within data assimilation (DA) systems [15]. Thus, to some extent, reanalysis datasets may overcome the problems of poor temporal resolutions associated with remote sensing, insufficient spatial coverage reflected by station-based observations and large biases contained in

model simulations [16, 17]. In this case, reanalysis datasets play a promising role in studying the land-sea difference of the AA since (1) reanalysis data contains both the physical laws and dynamic mechanisms of atmospheric systems represented by atmospheric models and actual atmospheric states observed by sensors and (2) its spatiotemporal continuity enables researchers to carry out studies on the AA contrasting the two areas. Thus, five widely-used SAT reanalysis datasets were adopted in this study, including the Twentieth Century Global Reanalysis Version 2c (20CR-V2c) [15], the Japanese 55-year Reanalysis (JRA-55) [18], ECMWF Re-Analysis Interim (ERA-Interim) [19], Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA-2) [20] and NCEP Climate Forecast System Reanalysis (CFSR) [21]. Owing to the differences in the time spans covered by the five datasets, only the data with overlapping time periods (i.e., from Jan. 1980 to Dec. 2013) were used in this study. The spatiotemporal differences on AA effects of Arctic land and sea are studied based on the seasonal AA indices derived from these five reanalysis datasets.

2. Method

In this study, an AA index is defined to directly measure the magnitude of the AA effect. Previous studies defined the AA index as the ratio of changes in Arctic temperature to a corresponding change in global mean temperature [1, 3]. However, using this ratio as a measure of AA may result in some shortcomings, e.g., the extreme value always occurs when the denominator is close to zero [8, 22], and the use of the ratio may also lead to unrealistic estimates of AA [9]. Hence, we employed a more stable and rational measure of the AA index [9] to better characterize the AA and avoid extreme values. The AA can be statistically linked to global anomalies via a regression relationship:

$$T_{Arctic} = a_0 + a_1 * T_{Global} + \varepsilon \quad (1)$$

Where: T_{Arctic} represents the temperature anomalies over the Arctic; T_{Global} represents the temperature anomalies over the global during the corresponding period like T_{Arctic} ; a_1 in Equation (1) is a slope defining the AA index. The ordinary linear least squares solution is used to determine parameters a_0 , a_1 , and ε . The regression interval was set to 1980-2013. According to the ordinary linear regression, the regression coefficient $a_1 > 1$ indicates the existence of the AA effect; $0 < a_1 < 1$ indicates there is no AA effect. The AA index values are computed at seasonal time scales over the Arctic land and sea, respectively.

3. Results

3.1 Magnitude of the AA Strength

Fig. 1a shows that the seasonal AA magnitude over the Arctic land is highest in autumn ($mean = 2.56$), followed by spring ($mean = 2.44$), winter ($mean = 2.36$) and summer ($mean = 1.95$). All of the five reanalysis datasets can capture the AA effect over the Arctic land in all seasons. The seasonal AA amplitudes over the Arctic land range from 1.95 to 2.56, suggesting the AA effect over Arctic land is relatively stable ($mean = 2.33$; $var = 0.07$) and the warming rates over Arctic land are about twice as fast as the global mean in the four seasons. Additionally, proxy records (i.e., ice cores) covering the past 20,000 years sampled from Greenland [4], observations for the period 1875-2008 [9], climate simulations during the last glacial maximum [23] and future climate projections [24] commonly indicate that the AA factor is on the order of 2.0. These evidences have led to accept that the AA amplitude fluctuations are on the order of 2.0. That is, the AA magnitudes over Arctic land derived from the five SAT reanalysis datasets are consistent with those of previous studies. This agreement is partly due to the fact that recent observations mainly cover Arctic land and a large portion of missing values over the Arctic sea, and climatic proxies (e.g., tree rings, ice cores) used to reconstruct Arctic temperature are mainly distributed over the Arctic land [25]. Therefore, the AA magnitudes derived from observational datasets and paleoclimatic proxies reflect largely the Arctic land. Moreover, although the AA magnitudes of the Arctic land derived from

SAT reanalysis datasets are also very close to those derived from climate model simulations, which can cover both the Arctic land and the Arctic sea, most general circulation models (GCMs) have large cold biases in reproducing Arctic temperature compared to the observational data [17], possibly, leading to an underestimation of the AA magnitudes using GCMs' outputs.

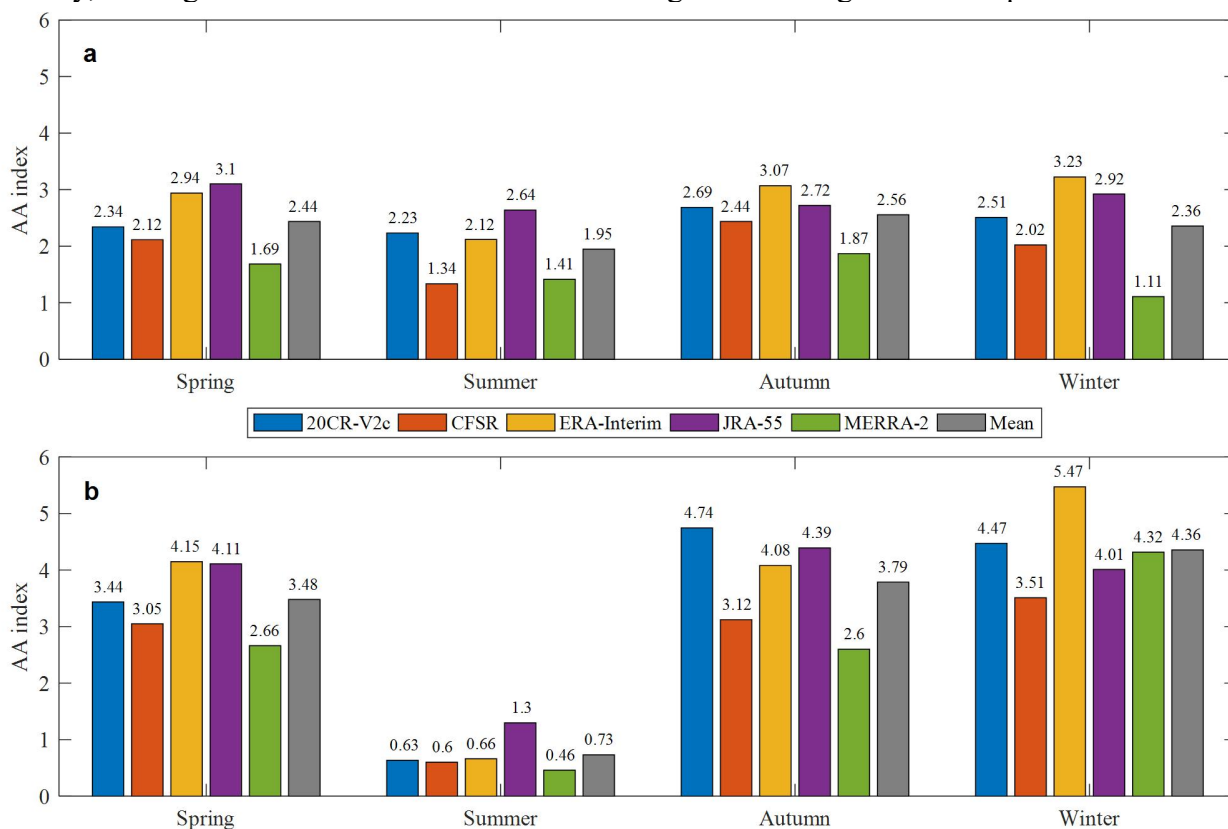


Fig. 1 Seasonal AA index values derived from the five reanalysis during the period of 1980-2013. (a) Arctic land. (b) Arctic sea. Spring: March-April-May; Summer: June-July-August; Autumn: September-October-November; Winter: December-January-February.

Fig. 1b demonstrates that the seasonal AA magnitude over the Arctic sea is greatest in winter ($mean = 4.36$), followed, in order, by autumn ($mean = 3.79$) and spring ($mean = 3.48$). Four of the five reanalysis datasets do not reflect the AA effect over the Arctic sea in summer. The AA magnitude derived from JRA-55 is only 1.30, reflecting a very weak AA effect. From the mean (i.e., 0.73) of the AA magnitudes over the Arctic sea in summer, accordingly, it can be concluded that there is no AA effect over the Arctic sea in summer. In addition, although both GCMs outputs and reanalysis datasets completely cover the Arctic land and sea, most of the AA index values over the Arctic sea in spring, autumn and winter presented in Fig. 1b are much larger than those reported in previous studies using GCMs [23, 24]. Therefore, this result indicates that the AA magnitudes may have been underestimated by previous studies using GCMs if we compared them to the AA strength derived by this study using reanalysis datasets. This underestimation is possibly due to the large cold biases associated with the GCMs in reproducing Arctic temperature [17] and the GCMs' inability of capturing the observed dominant SAT mode variability over the Arctic ocean [26]. However, in the Arctic, there are barely any direct observations that can get assimilated in the reanalysis project and the dynamical, thermodynamical, and radiative processes that govern the SAT development over the Arctic ocean (especially in the central Arctic ocean) are crudely parameterized in the atmospheric models. Consequently, these two factors lead to uncertainties in both the reanalysis data and model simulations in the Arctic ocean as well. For example, recent studies also have found that reanalysis datasets show warm biases in these areas [27, 28]. Therefore, the AA strength in the Arctic ocean remains highly uncertain and needs to be further comparatively studied based on multi-source data such as remote sensing datasets.

3.2 Spatial Pattern of AA Effect

This study calculated the percentages of spatial coverages of the AA effect over the Arctic land and sea (see Fig. 2a). For Arctic land, on average, the percentage of spatial coverage of the AA effect is largest in autumn (92.74%), followed by spring (84.15%). Winter and summer have an equal percentage of spatial coverage of the AA effect (~76.70%). In addition, Fig. 2b shows that the percentage of spatial coverage of the AA effect over the Arctic sea also is largest in autumn (92.68%), while the spatial coverages of the AA effect in winter and spring are found to be similar (e.g., one is 89.25%, the other is 88.08%). The lowest spatial coverage ratio of the AA effect is found in summer (i.e., only 28.00%), indicating that there is probably no AA effect over the Arctic sea in summer.

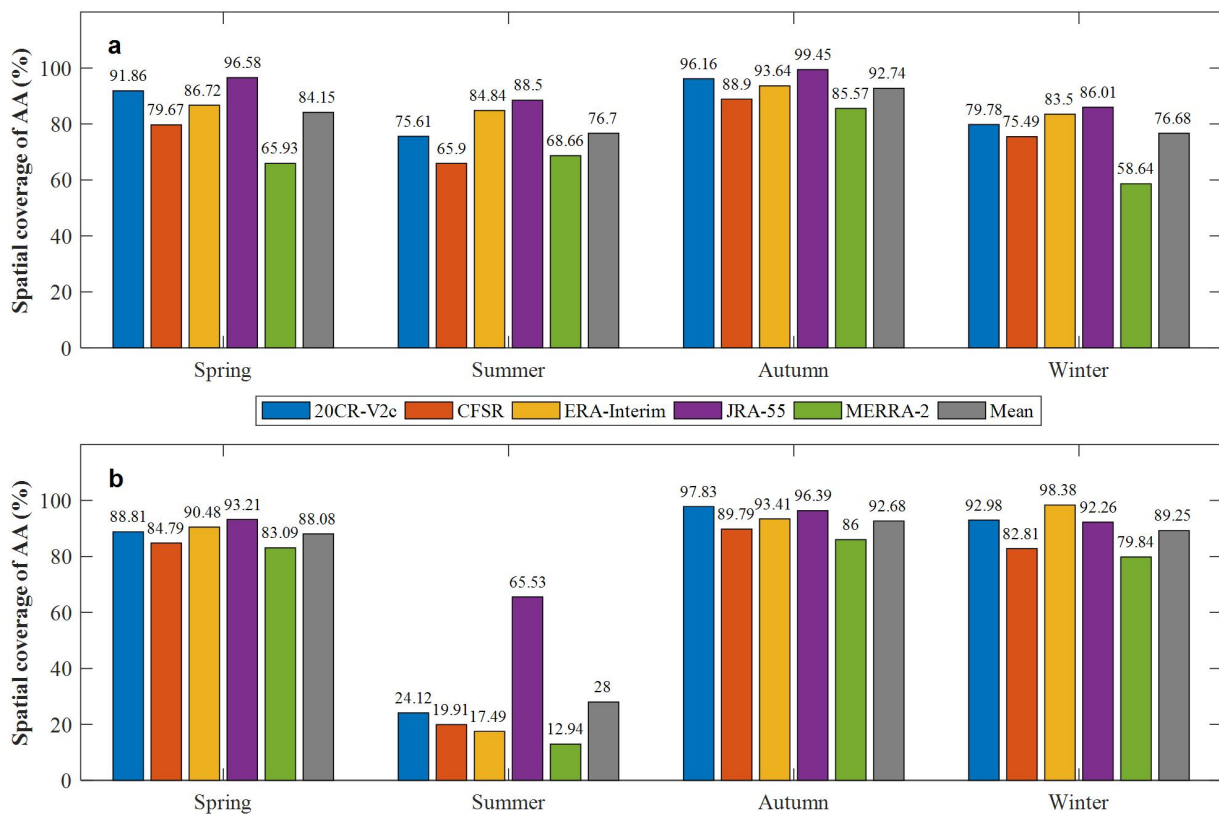


Fig. 2 Percentages of spatial coverage of the AA effect over (a) the Arctic land and (b) the Arctic sea in different seasons derived from the five SAT reanalysis datasets.

Finally, the seasonal spatial patterns of the AA derived from the five reanalysis datasets are presented in Fig. 3. In spring, the Arctic exhibits an apparent AA effect except in the North Atlantic. In summer, almost all of the five reanalysis datasets clearly indicate that there is no or very weak AA effect over the Arctic sea. Previous findings [29] regarding (1) seasonal variations of Arctic sea ice extent and thickness and (2) seasonal differences of energy budgets between the Arctic sea and near-surface air may be used to explain this phenomenon. In autumn, almost the entire Arctic shows a significant AA effect except for parts of the North Atlantic and parts of Northwest North America over which there are weak to no AA effects. The spatial patterns of the AA effect in winter are a little more complicated than those of spring, summer, and autumn, but most areas of the Arctic present the AA effect, especially over the mid- and high-latitudes of the Arctic. The low-latitudes of the Arctic do not show the AA effect.

4. Conclusions

This study investigated the seasonal land-sea difference of the AA strength using five SAT reanalysis datasets. Results revealed the seasonal land-sea differences of the AA effect in terms of

magnitude and spatial pattern. Main findings include: (1) the strongest AA effect is found over the Arctic sea in winter; (2) the AA effect over the Arctic land maintains a relatively stable state fluctuating on the order of 2.0, while the AA effect over the Arctic sea can not be clearly found in summer and the AA magnitudes over the Arctic sea fluctuate with a relatively large range in different seasons; (3) the AA amplitudes over the Arctic sea are greater than those of over the Arctic land in corresponding seasons (except in summer), indicating that the AA effect is more pronounced over the Arctic sea. To some extent, this study enriches the existing knowledges about the land-sea difference of the AA during the last decades and helps advancing researches on identifying the driving mechanisms of the AA over the Arctic land and sea. However, we should be aware that the AA strength in the Arctic is still uncertain due to the biases in model simulations and reanalysis datasets and the scarcity of observed data in the Arctic, therefore, further comparative study based on multi-source data is expected to a good way to solve this problem in future.

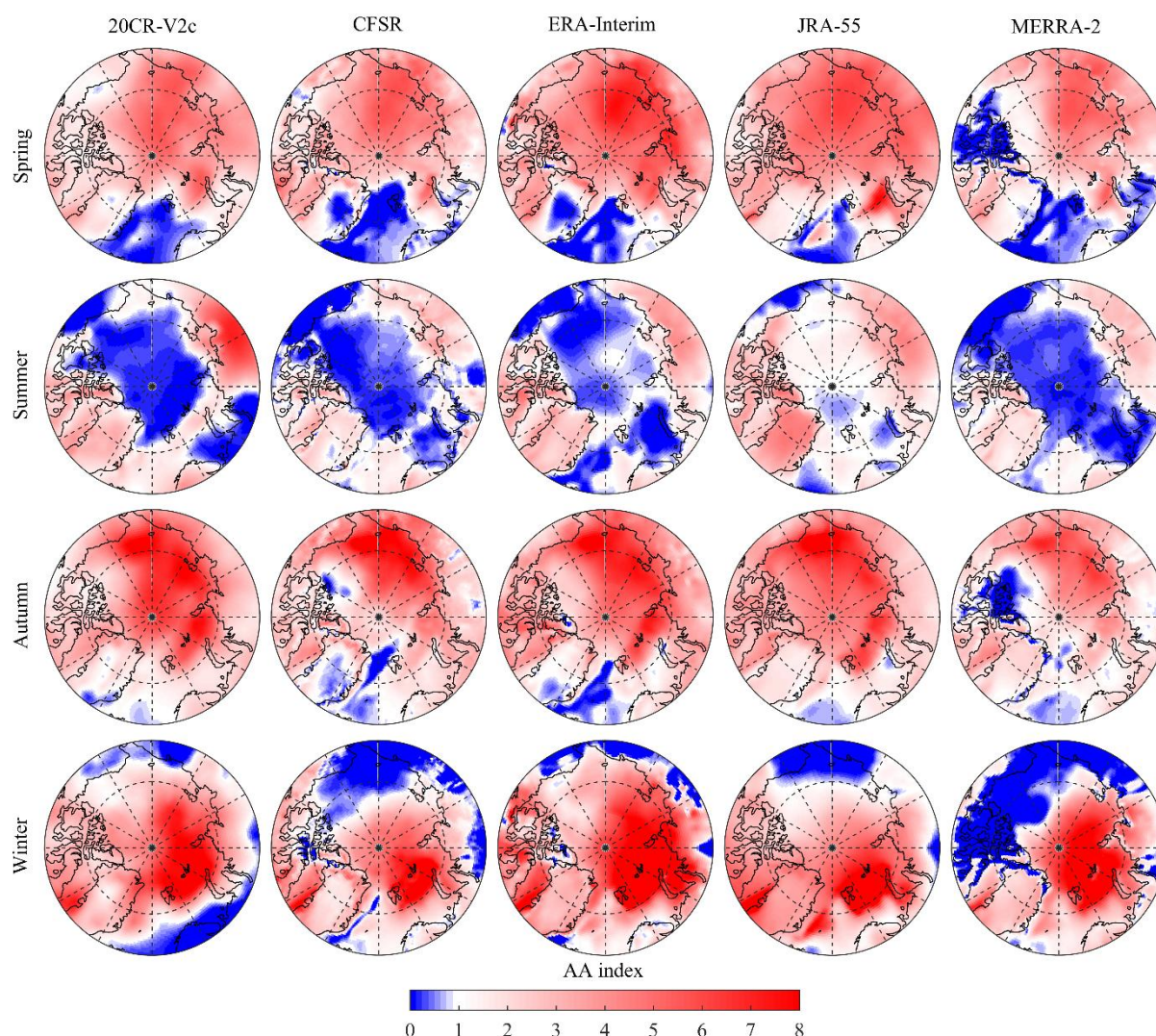


Fig. 3 Spatial patterns of the seasonal AA effect derived from the five reanalysis datasets. The AA index value on each grid is calculated based on the seasonal mean SAT series and the global mean SAT series on the corresponding grid.

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