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September Sea-Ice Extent Predicted by June Reflected Solar Radiation

Yizhe Zhan\textsuperscript{1, a)} and Roger Davies\textsuperscript{1, b)}

\textsuperscript{1}Department of Physics, University of Auckland, Auckland, New Zealand.

\textsuperscript{a)}Corresponding author: y.zhan@auckland.ac.nz
\textsuperscript{b)}r.davies@auckland.ac.nz

Abstract. A significant three-month lag correlation between June top-of-atmosphere reflected solar radiation (RSR) and the subsequent September sea-ice extent (SIE) is found within the Arctic, and the predictability of September SIE is examined by both satellite observations and reanalysis datasets. The correlation coefficient between de-trended June RSR and September SIE reaches up to 0.88 for MISR, and the forecast skill of 0.36 using MERRA-2 reanalysis dataset is similar to or better than complex prediction models. Results confirm the particular importance of the early summer surface energy budget and help to explain the abrupt declines of September SIE in the past decade (2007, 2012, 2015).

INTRODUCTION

The Arctic has undergone a rapid decline of its sea-ice extent (SIE) for all months, and is on a trajectory to a mainly seasonal ice cover state [1]. The September SIE (also known as the annual minimum) has dropped 35% since 1979, with much thinner ice thickness [2]. Although the dramatic change has been extensively studied, the wide range of 3-month ice forecasts implies a lack of knowledge of conducting a successful prediction [3].

Thus, a number of recent studies tried to find the key component that can be used to achieve an acceptable prediction. From a thermodynamic perspective, for example, Kapsch et al. [4] found a correlation of 0.5 between predicted and observed September sea-ice concentration (SIC) based on springtime downwelling longwave radiation. Schröder et al. [5], on the other hand, achieved a skillful September SIE forecast by using May-June pond fraction. More recently, Choi et al. [6] argued that late summer SIC is significantly related to the solar radiation absorbed in the early summer. In general, they all emphasized a crucial role of the atmospheric/surface condition of the early melt season in determining the annual minimum SIE.

In this study, we showed a robust 3-month lag correlation between June top-of-atmosphere (TOA) reflected solar radiation (RSR) and the subsequent September SIE, as well as its ability of carrying out a seasonal ice prediction. In order to do this we used both satellite observations and reanalysis datasets, and used the Rapid Radiative Transfer Model (RRTM) to investigate the relationship between June TOA RSR and surface net flux.

DATA AND METHODS

The monthly datasets from both satellite observations and reanalysis were area-weighted and averaged over the Arctic, poleward of 70°. SIE, defined as the summed area of all pixels that are each at least 15% covered by sea ice with a spatial resolution of 25 km, is provided by the National Snow and Ice Data Centre [7]. Monthly gridded RSR data come from both satellite observations (CERES-EBAF, MISR-CGAL, 2000-2015, excluding 2001, and ERBE-Scanner, 1985-1988) and reanalysis datasets (ERA-Interim, NCEP/NCAR Reanalysis 1 (NRA), and MERRA-2, 1980-2015). While we have confidence in the latest satellite-retrieved RSR products, the reanalysis dataset provides a much longer time period to test the relationship and establish the forecast model.
To quantify the lag correlation between June RSR and September SIE, all data were de-trended to place emphasis on the inter-annual variability. A linear and a 2nd-order polynomial trend with fits over 2000-2015 and 1980-2015, were subtracted from the satellite and reanalysis datasets, respectively. Meanwhile, RRTM was used to explain the relationship between RSR and surface net flux. To assess the predictability of this relationship, both hindcast and forecast experiments have been carried out. In order to make a direct comparison with recent studies [4, 5], we also evaluated our forecast model by calculating the forecast skill (S),

\[ S = 1 - \frac{\sigma_{\text{ref}}^2}{\sigma_{\text{ref}}^2} \]

where \( \sigma_{\text{ref}} \) and \( \sigma_{\text{frr}} \) are the standard deviation of de-trended observed ice extent and of forecast error, respectively. To thoroughly examine S, we applied a Monte-Carlo method, which randomizes the selection of 50% of the data (fitting period) and used the regression line to test the remaining 50% data (forecasting period). This procedure was repeated for 1000 times to obtain stable results. \( \sigma_{\text{ref}}, \sigma_{\text{frr}} \) and the anomaly correlation coefficient (ACC) were averaged over all iterations.

**LAG RELATIONSHIP ANALYSIS**

Previous studies have shown that it is difficult to conduct a prediction of de-trended September SIE with lead times of three months and longer [8], and even harder in the large anomaly years [9]. Figure 1 shows the original values of September SIE along with June RSR from various datasets. While September SIE remained high in the 1980s and decreased rapidly since 2000, satellite retrievals (ERBE) also showed large June RSR that dropped significantly during the recent decade (CERES, MISR). However, this dramatic change was not fully captured by reanalysis datasets, especially NRA. Moreover, although ERA-Interim is one of the best datasets representing the Arctic climate and has been extensively used in the previous studies [4, 9], it shows the least consistency of RSR with CERES observations. The correlation coefficient of 0.44 is much lower than that of 0.88 for MERRA-2. As a result, we treated MERRA-2 as the ‘best’ reanalysis dataset in representing the RSR in the following study.

**FIGURE 1.** Time series of September sea-ice extent and June reflected solar radiation from various datasets.

To quantify the relationship between June RSR and September SIE, Figure 2 shows their de-trended anomalies. It is clear that the two quantities follow the similar pattern. Except for three years (2005, 2008, and 2014), June RSR and September SIE anomalies correspond rather well, with the same sign and similar relative magnitude. For years with particularly low September SIE (2007, 2012, 2015), there are correspondingly large negative anomalies of June RSR. The overall anomaly correlation coefficients are 0.85 and 0.88 for CERES and MISR, and 0.69 for MERRA-2, which is much higher than previous studies using other variables from the reanalysis dataset [9]. It should be noted that the three linear fitting lines are almost identical, indicating the stability of the relationship during the past several decades.

Why is there such a strong lag correlation? Based on RRTM simulations, we found that the surface net flux (SW+LW) is very closely related to the TOA-RSR in June. Both of them are dominated by changes in surface albedo under the clear-sky condition. As solar radiation is the main energy source during the Arctic summer, the
cloud shielding effect over the ocean would significantly reduce the surface net flux, at the same time significantly increasing TOA-RSR. This is also the case when the underlying surface is sea-ice, but is much less in magnitude. Thus, the June RSR anomaly is well represented by its surface net flux anomaly. This also can be seen from the CERES EBAF dataset, which shows a similar relationship between surface net flux and TOA-RSR for both clear-sky and all-sky conditions (not shown). Since the late summer SIE is found to be related to the early summer surface energy budget [6, 10], June RSR is expected to show a significant correlation with the subsequent September SIE.

![FIGURE 2](image_url) Relationship between de-trended June satellite-retrieved reflected solar radiation and September sea-ice extent anomalies (a) and corresponding scatter plot (b) with additional MERRA-2 reanalysis dataset. Linear regression lines have been fit to the data (dashed lines).

**PREDICTIVE SKILL ANALYSIS**

To assess the potential of using June RSR for Arctic September sea-ice prediction, both hindcast and forecast models were tested. For the hindcast, we used all available datasets from MERRA-2, CERES and MISR. Figure 3 shows the comparison between predicted and observed September SIE for both the anomalies (a) and absolute values (b). The prediction errors show subtle differences among datasets, ranging from 0.28 million km² for MISR to 0.37 million km² for MERRA, which is comparable to the 0.33 million km² of Schröder et al. [5]. MERRA-2 data are also considered for establishing a forecast model, because the durations of the CERES and MISR datasets are too short to achieve a stable model. By using the aforementioned Monte-Carlo method, our model errors (σ_err) are 0.35 and 0.4 million km² for the fitting and forecasting period, respectively. Taking into account the mean variance of de-trended observed ice extent (σ_ref) of 0.5 million km², our forecast skill value (S) is 0.36. Although this is slightly smaller than the result of Schröder et al. [5] (S=0.41), our anomaly correlation coefficient (ACC=0.68) of the forecasting period is better than the recent studies [4, 5].

![FIGURE 3](image_url) The observed (NSIDC) and predicted September sea-ice extent anomaly from the trend line (a) and absolute values (b) by hindcasts from MERRA, CERES, and MISR. σ_err is the prediction error in million km².
SUMMARY

We found a significant 3-month lag correlation between June RSR and September SIE. This relationship is evident for both satellite observations and reanalysis datasets, and agrees with the recent study of [6]. This may be because the surface net flux (SW+LW), which is crucial in shaping the late summer sea-ice, is very closely related to the TOA-RSR in June. Since it is difficult to directly measure the surface net flux within the Arctic, satellite retrievals ensure the stability of using June RSR as an indicator for September sea-ice prediction. We found the predictive skill of June RSR is encouraging. The forecast skill of 0.36 and ACC of 0.68 are comparable or even better than other prediction models. Therefore, we can achieve a forecast of September sea-ice extent with an accuracy of 0.4 million km² by the end of June. For September 2015 we forecast a sea-ice extent of 4.5 ± 0.4 million km² based on MERRA-2 dataset, which is very close to the observed value of 4.63 million km². In comparison, the median value of the 35 predictions presented on the Arctic Sea Ice Outlook webpage [11] in July is 4.99 million km², and the estimations of two recent studies [4, 5] are 4.1 and 5.1 million km², respectively.

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