Potential predictability of Eurasian spring snow water equivalent in IAP AGCM4 hindcasts

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ABSTRACT
The potential predictability and skill of Eurasian spring snow water equivalent (SWE) are explored by using a suite of ensemble hindcast experiments with the fourth-generation IAP AGCM (IAP AGCM4) and observations for the period 1982–2012. IAP AGCM4 is generally capable of reproducing the spatial distribution of Eurasian spring SWE; nevertheless, the model overestimates the SWE over Eurasia, possibly because of positive precipitation biases in wintertime. IAP AGCM4 can successfully capture the long-term trend and leading pattern of Eurasian spring SWE. Additionally, the spring SWE anomalies are generally predictable in many regions over Eurasia, especially at high latitudes; moreover, IAP AGCM4 exhibits a remarkable prediction skill for spring SWE anomalies over Eurasia in many years during 1982 to 2012. In order to reveal the relative impacts of SST anomalies and atmospheric initial conditions on the seasonal predictability of Eurasian spring SWE, two additional sets of experiments are carried out. Overall, atmospheric initial anomalies have a dominant role, though the impact of SSTs is not negligible. This study highlights the importance of atmospheric initialization in seasonal climate forecasts of spring SWE anomalies, especially at high latitudes.

KEYWORDS
Potential predictability; Eurasian spring SWE; IAP AGCM4

1. Introduction
Snow is an important component of the global climate system. With its high albedo and low conductivity, snow can directly impact the local surface energy balance and thus modulate climate anomalies (Dewey 1977). Furthermore, snowmelt can serve as an important source of freshwater recharge, which can influence soil moisture and groundwater. Previous studies have been devoted to understanding the important influence of the Eurasian snow condition on climate anomalies over East Asia by diagnosing observational datasets and numerical simulation (e.g. Liu and Luo 1990; Wu and Qian 2003; Zhao, Zhou, and Liu 2007; Li, Wu, and Zhu 2009). For example, Wu, Yang, and Zhang (2009) reported that increasing Eurasian spring (seasonal mean of March–April–May) snow water equivalent (SWE) is significantly associated with reducing precipitation in southeastern China. Mu and Zhou (2010) found that the winter snow cover over northern Eurasia has remarkable negative correlations with summer rainfall in the region to the south of the Yangtze River. Wu and Kirtman (2007) also revealed the important impact of spring SWE over Eurasia on the spring and summer rainfall in China.

The importance of Eurasian snow on climate anomalies over East Asia implies that a reasonable representation of the snow condition in climate models is required. As such, evaluation of the potential predictability of Eurasian snow conditions may be helpful for further upgrading climate models and improving the predictability of snow variables. IAP AGCM4 is the fourth-generation AGCM developed at the Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences (Zhang, Lin, and Zeng 2009). It performs well in simulating the basic features of the global climate (Zhang, Zhang, and Zeng 2013; Dong et al. 2012; Sun,
Zhou, and Zeng 2012); however, the seasonal prediction capability of IAP AGCM4 for snow properties has not yet been evaluated. In view of the importance of Eurasian spring SWE to the climate prediction of summer rainfall over East Asia, in this study, we examine the potential predictability of the Eurasian spring SWE using IAP AGCM4.

The remainder of the paper is organized as follows: Section 2 describes the model experiment, the observational data and methods for evaluation. In section 3, we investigate the potential predictability of the Eurasian spring SWE in terms of climatology and interannual variation, and explore the sources of predictability. Conclusions and discussion are provided in section 4.

2. Model experiments, observational data, and methods

Dynamical seasonal predictions (DSPs) are generated by IAP AGCM4 in this study. The dynamical framework of IAP AGCM4 is inherited from the former generations of IAP AGCMs but with some newly introduced techniques or schemes, such as flexible but permissible substitutions, a flexible leaping-point scheme at high latitudes, a time-splitting method and semi-Lagrangian vapor transport scheme (Zhang, Lin, and Zeng 2009). The model has a horizontal resolution of 1.4° × 1.4° and 26 levels in the vertical direction, with the top level at 2.2 hPa. The physical processes in IAP AGCM4 are introduced from the Community Atmospheric Model, version 3.1, of the National Center for Atmospheric Research.

In this study, the conventional hindcasts have an initial date of 15 February and are run for seven months. Ensembles of seven integrations are performed for the period 1982–2012 (hereafter, this experiment is referred to as the ‘DSP’ experiment). The initial atmospheric conditions of the IAP AGCM4 hindcasts are from National Centers for Environmental Prediction global reanalysis data (Kalnay et al. 1996). Monthly-observed SSTs of the Hadley Center (Rayner et al. 2003) are used as the major sources of anomalous boundary forcing. All initial land surface states are derived from the climatology based on the outputs of multi-year simulations of IAP AGCM4 forced with the climatological SST. Thus, the hindcasts from IAP AGCM4 incorporate both the influence of observed initial atmospheric conditions and of observed SST conditions. The result analyzed for this study is expressed as the ensemble mean of the seven integrations with the same weights.

Previous studies have revealed that short-term climate prediction based on a climate dynamical model heavily depends on external forcing and initial atmospheric conditions (Wang, Matsuno, and Kurihara 2000; Zhao and Guo 2000). In order to identify the sources of predictability for Eurasian spring SWE, another two experiments are carried out. For one experiment, a framework similar to that of the DSP experiment is used. The only difference between them is the SST conditions. The climatological SST is used instead of observed monthly SST, so only the impact of atmospheric initial conditions (ICs) is taken into account in this experiment (ICs experiment). The other experiment is an Atmospheric Model Intercomparison Project (AMIP)–type experiment, in which ICs are irrelevant. The model is continuously integrated from 1979 to 2012 using the monthly observed SST. Thus, the source of the predictability in the AMIP simulations is the observed SST alone. In this paper, the relative contribution of SST and ICs on the potential predictability of Eurasian spring SWE is preliminary revealed by comparing the outputs of these three experiments.

The GlobSnow-2 monthly SWE product taken from the European Space Agency is introduced as a verification dataset. The GlobSnow dataset is currently the best global SWE product in comparison with the NSIDC SWE (Hancock et al. 2013). It is a prior selection for model evaluation. However, it should be noted that the GlobSnow dataset is only available between the latitudes of 35°N and 85°N.

The statistical methods used in this paper include the temporal correlation coefficient (TCC), pattern correlation coefficient (PCC), linear trend, and empirical orthogonal function (EOF).

3. Results

3.1. Climatology

We investigate the capability of IAP AGCM4 to hindcast the climatological Eurasian spring SWE. Figure 1(a) illustrates that the spring SWE is mainly concentrated in northern Eurasia, with high values in western Siberia, the Scandinavian Peninsula and eastern Siberia (maximum larger than 120 mm). IAP AGCM4 can capture the observed basic features of the climatological Eurasian spring SWE and the maximum SWE over western Siberia, the Scandinavian Peninsula and eastern Siberia with a positive bias (Figure 1(b)). The PCC over (40°–80°N, 0°–180°E) of the climatology between the observation and hindcasts is 0.60, illustrating that IAP AGCM4 has certain capability to predict the climatological Eurasian spring SWE. Although the basic features and maximum regions are predicted by IAP AGCM4, the SWE value is larger than that observed. As shown in Figure 1(c), IAP AGCM4 overestimates the Eurasian spring SWE, especially in regions near Okhotsk and the Bering Sea. Figure 2 describes the averaged climatological SWE...
over Eurasia (40°–80°N, 0°–180°E) in February and the SWE change in March, April and May relative to the previous month for IAP AGCM4 and observation. IAP AGCM4 overestimates the Eurasian SWE in February. For the SWE change in each month during springtime, the SWE increases in March and decreases in April and May both in the observation and IAP AGCM4. The total change in the three months of spring is −47.7 mm for IAP AGCM4 and −49.6 mm for observation. Therefore, the excessive spring SWE over Eurasia in the model might be attributable to the excessive simulated SWE in February. Snow through time accumulates and the snowpack depth increases in most regions of Eurasia during the stable snow accumulation period, from December to February. Precipitation is the dominant resource in the process of snow accumulation, so the SWE in February is considered to be related to total precipitation in wintertime. Correlation analysis also shows that the SWE in February has remarkable positive correlations with winter precipitation in the mid–high latitudes of Eurasia (figure now shown). Further analysis shows that winter precipitation is overestimated in IAP AGCM4 (figure not shown), which can lead to the excessive simulated SWE in February. Therefore, positive precipitation bias in wintertime is probably the prominent cause for the excessive predicted spring SWE over Eurasia for IAP AGCM4.

Figure 1. Climatology of spring SWE from 1982 to 2012 in (a) GlobSnow observations and (b) DSP hindcasts. (c) Climatological bias of spring SWE between model and observation. Units: mm.
3.2 Predictability of spring SWE anomalies

Figure 3 illustrates the observed and hindcast linear trend distribution of Eurasian spring SWE during 1982–2012. The observed trend seems to show a negative–positive–negative distribution from north to south over Eurasia during 1982–2012 (Figure 3(a)). A more significant decreasing trend can be found in Siberia, with a minimum of less than −1.0 mm yr\(^{-1}\). A regional increasing trend is evident in areas such as Northeast Asia and Mongolia, with trend values larger than 0.6 mm yr\(^{-1}\). IAP AGCM4 captures the trend pattern well, such as the decreasing trend in western Siberia and increasing trend in the regions between the latitudes of 50°N and 60°N. However, the model fails to reproduce the downward trend over central Siberia and southern Europe; moreover, the trend amplitude of the hindcast Eurasian spring SWE is slightly less than that of observation, and this might be attributed to the weak interannual variability of the IAP AGCM4 hindcast. Weaker-than-observed variation of SWE is a common phenomenon in most climate models.

Figure 4 illustrates the leading EOF pattern of Eurasian spring SWE anomalies for observation and prediction. The prominent feature of the observed first EOF (EOF1) pattern exhibits positive anomalies over western and central Siberia and weak negative anomalies over Northeast Asia, western Europe and eastern Siberia. IAP AGCM4 follows the key features of the observed first leading pattern of Eurasian spring SWE well. It is worth noting that the negative anomalies over western Europe...
and eastern Siberia in the model are stronger compared to those in the observation, which may be related to overestimated climatology in these two regions. The PCC over (40°–80°N, 0°–180°E) of the EOF1 pattern from the observation and IAP AGCM4 is 0.65, at confidence levels greater than 99%. The first principal component (PC1) shows linearly decreasing trends, suggesting that the spring SWE is decreasing in western and central Siberia, which is consistent with the conclusion from Figure 3. The TCC between the corresponding PC1 of the observation and IAP AGCM4 ensemble mean is 0.49, confirming the strong simulation capability of the

Figure 4. First leading EOF mode of spring SWE anomalies in (a) observation and (b) the DSP hindcast. (c) The first PC (solid line) and its trend (dashed line) in the observation (red line) and hindcast (green line).
model in the interannual variations of the leading pattern of Eurasian spring SWE anomalies.

Figure 5(a) shows the point-wise TCC of the Eurasian spring SWE anomaly for the DSP hindcasts. Clearly, the results show an overall positive level of skill over Eurasia. High predictability can be found over some regions, such as western Siberia, central Siberia, western Europe, some regions of Mongolia, and northern China, with TCC values exceeding the 90% confidence level. The Siberian spring SWE, which exhibits intensive variability, is closely associated with summer rainfall over China (Zuo et al. 2014), so the high potential predictability of the spring SWE anomaly over Siberia is beneficial for the accuracy of seasonal forecasts of summer rainfall over China. Moreover, we calculate the PCC over (40°–80°N, 0°–180°E) of the spring SWE anomaly from the observation and DSP hindcast. Figure 5(d) illustrates that, for most years, the PCCs are positive, with high values greater than 0.3 for several years. In heavy SWE anomaly years, such as 1993, 1997, 1998, 2008, 2010 and 2011 (shown in Figure 4(c)), PCC values are all greater than 0.2. For almost 24 years in the hindcast period, the PCC values exceed the 95% confidence level (PCC greater than 0.05), illustrating the high potential predictability of IAP AGCM4 for the Eurasian spring SWE anomalies. Overall, the results using TCC and PCC scores show a reasonable skill of Eurasian spring SWE anomalies in DSP hindcasts.

### 3.3 Possible causes of the predictability

In this section, we attempt to investigate the relative impacts of SST anomalies and ICs on the predictability of Eurasian spring SWE.

The skill of the ICs and AMIP simulations in reproducing the observed spring SWE anomalies over Eurasia is summarized in Figure 5(b–d). The AMIP simulation exhibits poor skill compared with the DSP experiment. In most parts of the high latitudes of Eurasia, the simulated spring SWE anomalies bear much less correspondence to the observed anomalies (Figure 5(b)). From Figure 5(d), the PCC skill is found to be relatively low, with negative values in almost half of the simulated years in the AMIP simulation. The ENSO cycle is the largest known source of year-to-year climate variability. However, there is no apparent ENSO pattern of correlation for the observation between SST and Eurasian spring SWE (figure not shown). Relatively low skill can also be found in some strong ENSO years, such as 1983, 1989 and 1998, in the AMIP simulation (Figure 5(d)). Thus, the weak relationship between ENSO and spring Eurasian SWE might be one factor contributing to the lower potential predictability of spring SWE in the AMIP simulation. In contrast to the AMIP simulation, from Figure 5(c) it can be seen that the ICs simulation shows high predictive skill over many parts of Eurasia, such as eastern Europe, central Siberia, Lake Baikal, and some regions of eastern Siberia, with TCC values at the 90% significant level. Also, for the PCCs, the results clearly show an overall positive level of skill, and skill scores become much greater after the mid-1990s. In short, the atmospheric initialization of IAP AGCM4 hindcasts plays an important role for skillful predictions of Eurasian spring SWE. The initialization could improve the model predictive skill by minimizing the impact of systematic atmospheric biases. Zhao and Guo (2000) revealed that the influence of ICs on general circulation motion in the mid- and high-latitude regions is more important than that of SST anomalies. In general, the above investigation indicates that the atmospheric initial anomalies have a dominant effect on the forecasting of Eurasian spring SWE anomalies, as compared to the SST anomalies.

### 4. Conclusion and discussion

In this study, the potential predictability for Eurasian spring SWE and its sources are explored using IAP AGCM4 hindcasts and observations. Generally, IAP AGCM4 hindcasts have predictive capability for the Eurasian spring SWE. IAP AGCM4 is able to reproduce the observed climatological distribution of Eurasian spring SWE, with high centers located in western Siberia, the Scandinavian Peninsula and eastern Siberia; nevertheless, the model overestimates the SWE over Eurasia, which is most likely because of positive precipitation biases in wintertime. IAP AGCM4 can successfully represent the observed long-term trend of Eurasian spring SWE; however, the trend amplitude of the hindcast is slightly less than that of observation, and this is probably related to the weak interannual variability of the IAP AGCM4 hindcast. In addition, IAP AGCM4 realistically captures the key features of the observed first leading pattern of Eurasian spring SWE anomalies.

The spring SWE anomalies are generally skillful in many regions over Eurasia, especially at high latitudes. Meanwhile, IAP AGCM4 exhibits a reasonable prediction skill in many years during 1982 to 2012, especially in heavy SWE anomaly years, which is beneficial for the accuracy of seasonal forecasts of summer rainfall over China. Further analysis shows that the potential predictability of Eurasian spring SWE anomalies cannot be solely related to SST anomalies; successful forecasts of IAP AGCM4 depend heavily on the atmospheric ICs. According to the findings in this paper, the influence of ICs prevails over that of SSTs. This
study emphasizes the importance of atmospheric initialization in seasonal climate forecasts, especially in extratropical regions. The actual mechanism underpinning the high skill of Eurasian spring SWE in the DSP hindcasts is beyond the scope of this study.

In this study, the atmospheric initial anomalies are found to have a dominant effect on the forecasting of Eurasian spring SWE, as compared to the SST anomalies. Nevertheless, the role of atmospheric ICs could be weakened beyond a certain lead-time, and therefore the model...
predictability would be decreased with an increase in lead time. Furthermore, previous studies suggest that realistic treatments of land initialization could contribute appreciably to the skill of dynamical subseasonal and seasonal forecasts (Jeong et al. 2013; Chen 2014). However, in this study, the impact of land ICs on the model predictability is not considered. Thus, it is necessary to further improve the initialization system of IAP AGCM4 for better simulation.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

**Funding**

This work was jointly supported by the Strategic Priority Research Program of the Chinese Academy of Sciences [grant number XDA19030403] and the National Natural Science Foundation of China [grant number 41575080].

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