1. Introduction

Temperature inversions have long been recognized as a pervasive feature of the Arctic low-level atmosphere, especially in autumn and winter (Serreze et al. 1992; Curry et al. 1996; Zhang et al. 2011). Arctic inversion is a crucial factor affecting the atmospheric stability of polar regions, regulating the formation and development of regional clouds and fog (Sedlar and Tjernström 2009; Gilson et al. 2018; Wang et al. 2020) and the diffusion and transport of high-concentration pollutants near the top of the inversion layer (Bridgman et al. 1989). The inversion strength and depth substantially affect physical processes central to the Arctic climate, including the development of the atmospheric mixed layer and vertical transport of moisture and heat from leads and polynyas over sea ice regions (Andreas and Murphy 1986). Moreover, Arctic inversions influence the extent of temperature and sea ice changes in the Arctic by controlling the negative longwave radiation feedback mechanisms (Boé et al. 2009). In most applications, a realistic description of temperature inversions is essential for accurate simulations of snow and ice melt and glacier mass balance (Mernild and Liston 2010). Bintanja et al. (2011) pointed out that the predominant surface temperature inversion inhibited infrared cooling by generating additional radiation in winter, which can thus intensify Arctic amplification. Several studies have examined the inversion trends in the Arctic based on satellite observations (Liu and Key 2003; Pavelsky et al. 2011) and radiosonde observations from sparse stations at or near the coast (Bradley et al. 1992; Kahl et al. 1992; Zhang et al. 2011; Malingowski et al. 2014). Inversions in winter are ubiquitous and stronger than those in spring and summer (Devasthale et al. 2010; Zhang et al. 2011). In winter, both increasing and decreasing trends in inversion strength are found in different areas, which are strongly coupled with trends in surface temperature (Bradley et al. 1992; Liu et al. 2006; Zhang et al. 2011). In some areas, changes in inversion strength may result from advection aloft (Liu et al. 2006).

However, observations have restricted and discontinuous temporal scopes and limited coverage (Serreze et al. 1992). Many reanalysis datasets and models have been applied to evaluate the temporal-spatial variations in temperature inversion in the Arctic (Pavelsky et al. 2011; Zhang et al. 2011). Most climate models generally overestimate the inversion strength in the Arctic (Boé et al. 2009; Pithan et al. 2014). Boé et al. (2009) indicated that most of the models in phase 3 of the Coupled Model Intercomparison Project (CMIP3) were likely to largely overestimate inversion strength, which thus may lead to excessive negative longwave feedback and generally underestimate Arctic climate change in the future. This overestimation of inversion strength in CMIP3 is also shown in phase 5 of the Coupled Model Intercomparison Project (CMIP5) (Pithan et al. 2014). Pithan et al. (2014) explained that the overestimation of the inversion strength was associated with inadequate mixed-phase cloud microphysics. In addition, Kilpeläinen et al. (2012) found that the strength and depth of temperature inversion in Svalbard during early spring were notably underestimated in the mesoscale Weather Research and Forecasting (WRF) Model, which was likely caused by excessive mixing in the atmospheric boundary layer. However, few studies have focused on the...
projections of temperature inversion variations in the Arctic, leading to poor knowledge of the variations in inversion in the future.

The Community Earth System Model (CESM) is a state-of-the-art community-wide project that makes substantial efforts to understand and predict climate change on Earth (Hurrell et al. 2013). Previous studies demonstrated that the CESM was able to accurately simulate sea surface temperature (SST) and clouds relative to observations (Hurrell et al. 2013; Small et al. 2014). The surface climate over the Greenland ice sheet and the surface mass balance are realistically simulated in the CESM, which has been regarded as a promising modeling tool (Vizcaino et al. 2013, 2014). The CESM also works well with regard to performing Arctic simulations and realistically reproduces the interannual cycle and internal variability in the sea ice concentration (Barnhart et al. 2015; Labe et al. 2018).

In this study, the outputs from CESM Large Ensemble (CESM-LE) simulations are used to project the inversion depth trends in the Arctic in autumn and winter. We first evaluate the temporal–spatial variabilities of the present-day (1979–2005) inversion depth in the Arctic based on several reanalysis datasets and then validate the model results based on one of the reanalysis datasets with good performance in the simulation of Arctic low-tropospheric air temperature. Finally, the depth of inversions in autumn and winter in the mid-twenty-first century (2031–50) are projected using the validated model, and the reasons leading to the variations in inversions in different regions of the Arctic are discussed.

2. Data and methods

a. Reanalysis datasets

Observations in the Arctic with short time series and sparse data cannot satisfy the temporal and spatial scales required in this paper. Hence, it is necessary to use reanalysis datasets that have high spatiotemporal resolution and have been widely adopted in Arctic research. For this purpose, we apply three reanalysis datasets to study the spatial and interannual variations in temperature inversions, and the most reasonable dataset will be chosen to verify the simulation of the model. These reanalysis datasets include the European Centre for Medium-Range Weather Forecasts interim reanalysis (ERA-Interim) (Dee et al. 2011), the Japanese 55-year Reanalysis Project (JRA-55) (Ebita et al. 2011), and the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis (hereafter, simply NCEP–NCAR) (Kalnay et al. 1996). In the analyses, we use 6-hourly data of air temperature on 1.5° × 1.5° (1.25° × 1.25°) grids at 37 pressure levels in autumn from September to November, hereinafter denoted SON, and winter from December to February, hereinafter denoted DJF, during 1979–2005 from ERA-Interim (JRA-55). The sea ice concentration data in ERA-Interim are taken from NCEP two-dimension variational SST data assimilation during January 1989–June 2001. The NCEP real-time global daily SST is used in the sea ice concentration data during January 2002–January 2009 (Dee et al. 2011). In JRA-55, the sea ice cover product is from microwave imager retrievals (Ishii et al. 2005). For NCEP–NCAR, monthly mean air temperature data with 2.5° × 2.5° grids and 17 pressure levels are also applied during the same period. The regions north of the Arctic Circle (north of 66.5°N) are selected as the scope of the Arctic in this study.

b. Model

We use a global coupled model based on 30 ensemble members of the CESM-LE Project (Kay et al. 2014). These members, which differ only in their initial atmospheric conditions, are all generated from the same model, a single CMIP5 coupled climate model: the Community Earth System Model version 1 with the Community Atmosphere Model version 5 [CESM1 (CAM5); Hurrell et al. 2013]. The CESM-LE, with approximately 1° horizontal resolution and 30 vertical levels, is fully coupled, including atmosphere, ocean, land, and sea ice components. The specified external forcing used here consists of historical forcing from 1920 to 2005 (Lamarque et al. 2010) and representative concentration pathway 8.5 (RCP8.5) forcing (Meinshausen et al. 2011; Lamarque et al. 2014) from 2006 to 2100. The CESM-LE provides a range of possible climate trajectories and enables researchers to separate forced climate change from internal variability, which has never been achieved in ensembles with the scope and amount of community input afforded by the CESM-LE (Kay et al. 2014; Lehner et al. 2016). The notable improvements in the sea ice component in the model play an important role in the climate simulations at high latitudes (Hurrell et al. 2013). The ability of this model to simulate climate change is shown in the first section. A more detailed description of CESM-LE and its performance is provided in Kay et al. (2014).

c. The definition of inversion depth

Many studies have defined inversion depth as the pressure difference between two altitudes (Serreze et al. 1992; Liu et al. 2006; Medeiros et al. 2011; Pavelsky et al. 2011). Here, the inversion bottom is identified as the lowest pressure level at which the temperature starts to rise. The inversion top is chosen as the level below 600 hPa showing decreasing temperature with height. The inversion depth is scaled using the pressure difference between the top and bottom of the inversion layer. Because of the limited vertical resolution, some shallow inversions may be missed with these criteria.

3. Differences in inversion depths among various reanalysis products

Present-day monthly mean inversion depths and standard deviations among three reanalyses in autumn and winter are shown in Figs. 1 and 2. In autumn, the results in different reanalysis datasets consistently indicate that the inversion gradually deepens from September to November. The spatial distribution of the inversion depth in ERA-Interim is basically consistent with that in JRA-55, but the overall inversion depth in JRA-55 is deeper than that in ERA-Interim. There are significant differences between NCEP–NCAR and the other reanalyses, and the largest difference is the nonexistence of inversion in the Atlantic sector from NCEP–NCAR. In addition, there is no obvious difference between ocean and land in ERA-Interim. In JRA-55, the inversion in the Arctic Ocean is significantly deeper than that over land, especially in September and October. However, the inversion depth of NCEP–NCAR over land is greater than that over the ocean. The differences among three reanalyses are small in the central Arctic but are large in the Pacific.
sector of the Arctic Ocean and eastern Eurasia. The standard deviations are also large in the Atlantic sector in November.

In winter, the monthly mean inversion depth in JRA-55 is significantly greater than that in the other reanalyses. Similar to autumn, NCEP–NCAR has no inversion in the Atlantic sector in winter. The obvious differences among three products are also shown in the Pacific sector, eastern Eurasia, and Atlantic sector (Fig. 2). The largest standard deviation exceeds 60 hPa in eastern Eurasia.

As shown in Fig. 3, the maximum depth of NCEP–NCAR is the largest, and the value of ERA-Interim is the smallest. The maximum inversion depth gradually increases from November to January in ERA-Interim and JRA-55. However, NCEP–NCAR differs in the fact that there is a lower value in December than November and January. The abnormal inversion depth in NCEP–NCAR can be related to the poor vertical resolution with only 17 pressure levels in this dataset.

Previous studies confirmed that the inversion strength and depth are inaccurately shown in ERA-Interim (Palarz et al. 2020). ERA-Interim overestimates the temperature in the atmospheric boundary layer and the base height of the inversion in the Arctic (Lüpkes et al. 2010). This overestimation of the base height may lead to a shallower inversion, which is consistent with Figs. 1 and 2. Cao et al. (2016) indicated that JRA-55 agreed better with the surface albedo in satellite observations than other reanalysis datasets [e.g., ERA-Interim, Modern-Era Retrospective Analysis for Research and Applications (MERRA), and Climate Forecast System Reanalysis (CFSR)] in the Arctic, which may be because the observed sea ice concentration, to which the inversion depth is sensitive, is employed in the parameterization scheme in JRA-55. Therefore, we choose JRA-55 to validate the simulation of CESM-LE.

4. Verification of model results

a. Spatial distribution

Compared with JRA-55, the CESM-LE model could adequately reproduce the overall spatial distributions and seasonal variations in monthly mean inversion depth in autumn and

FIG. 1. Spatial distribution of inversion depth (hPa) derived from ERA-Interim in (a) September, (e) October, and (i) November; JRA-55 in (b) September, (f) October, and (j) November; and NCEP–NCAR in (c) September, (g) October, and (k) November. (right) Also shown are the standard deviations (hPa) among the three reanalyses in (d) September, (h) October, and (l) November. The horizontal and vertical color bars represent inversion depth and standard deviations, respectively.
winter (Fig. 4). In autumn, the CESM-LE model underestimates inversion depth in JRA-55. This underestimation is most pronounced in September and October. The inversion depth simulated by the model is highly consistent with the reanalysis results in late autumn and winter. The inversion depth simulated by CESM-LE is underestimated in the Atlantic sector and the Greenland, but the spatial distribution can be basically reproduced. Therefore, CESM-LE can reasonably simulate the spatial and seasonal variations in the present-day inversion depth in the Arctic.

b. Interannual variations and trends

As shown in Fig. 5, the interannual variations in inversion depth presented by the JRA-55 and CESM-LE simulations were compared during 1979–2005. The yellow rectangle shows the $\mu \pm 2\sigma$ range of JRA-55, in which $\mu$ represents the average value and $\sigma$ represents the standard deviation, indicating an error range. This definition of uncertainty has been used in many studies (e.g., Bintanja and Andry 2017). The model adequately reproduces the increase in inversion depth from September to November. The mean inversion depth given by JRA-55 is underestimated in CESM-LE, and the deviation is less than 11 hPa. In autumn, when the temperature inversion is shallow, the mean inversion depth in CESM-LE is outside the $2\sigma$ uncertainty of JRA-55. However, CESM-LE shows an improved simulation within $2\sigma$ in winter. These differences in simulation between autumn and winter are also present in the spatial distribution as mentioned above (Fig. 4).
The mean inversion depth in JRA-55 peaks in February at 108.06 hPa, but the maximum value of the mean depth simulated by CESM-LE is 102.98 hPa in January (Table 1). Considering that the mean depth in February is 102.76 hPa, which is slightly smaller than that in January, this discrepancy is within a reasonable range. Using the least squares method, regression coefficients (slope) are calculated to obtain the trends of the inversion depth from JRA-55 and CESM-LE during 1979–2005, which are shown in Table 1. The inversion depth shows a significant decreasing trend from 1979 to 2005 in CESM-LE during autumn and winter, which is consistent with the trend in JRA-55. However, the significant trend in JRA-55 is only observed in October. The model simulates a larger and more significant trend in the inversion depth.

5. Projected inversion depth in the mid-twenty-first century

The Arctic inversion layer is the strongest in autumn and winter and has a profound impact on the heat flux at the sea ice–air interface and the upward transport of water vapor (Bradley et al. 1992; Devasthale et al. 2010; Pavelsky et al. 2011). Here, we focus on the projected changes in the Arctic temperature inversion during autumn and winter. The CESM-LE model is used to conduct the projections since it can reasonably reproduce the spatiotemporal variabilities in inversion depth during 1979–2005. Compared with the present climate, the projected autumn monthly mean inversion depth significantly decreases over the Arctic Ocean in the mid-twenty-first century (2031–50). However, the decrease in inversion depth is marginal over land (Figs. 6c,g,k). The differences in 95% or more of the inversion depth areas in Figs. 6 and 7 pass the test significance level at $\alpha = 0.05$.

The projected inversion depth is near zero over the Arctic Ocean in September, except for the northern regions of Greenland. It is evident that the decrease in inversion depth in October and November is much stronger in the Arctic Ocean than that in other areas. In November, the inversion depth strongly decreases by over 65 hPa over the marginal seas of the Arctic Ocean (mainly including the Beaufort Sea, the Chukchi Sea, the East Siberian Sea, and the Laptev Sea) (Fig. 6k).

As shown in Fig. 7, there is also a significant decrease of inversion depth in winter in the mid-twenty-first century; however, the decrease is much less than that in autumn. In
general, the greatest decrease is found in the northeast of the Barents Sea, which is more than 45 hPa. However, the decrease is not so great in other regions. The Chukchi Sea exhibits the largest inversion depth decrease in December but exhibits only slight decreases in January and February. The model simulates a greater decrease in inversion depth in December than other winter months.

The differences of monthly mean sea ice concentration simulated by CESM-LE (the sea ice concentration in the future minus that in the present climate) in autumn and winter are presented in Figs. 6 and 7. It is shown that the areas where inversion depth decreases in autumn and winter are consistent with the retreat of Arctic sea ice. The sea ice concentration strongly decreases in the Arctic Ocean in September and October. In November and winter, the greatest retreat of sea ice occurs in the Atlantic sector and Pacific sector, which is consistent with the largest decrease of inversion depth. This finding allows us to easily produce the idea that sea ice may affect the inversion depth by modulating surface heat fluxes. Previous studies suggest that the regions where the inversion depth dramatically decreases also show significant increasing trends of open water. This change is consistent with the obvious changes in sea ice (Barber et al. 2015). Koenigk et al. (2013) suggested that the Arctic mean near-surface temperature reflected an average increase of 12 K during 2006–2100, which is associated with the decrease in sea ice. In particular, it is found that the sea ice in autumn dramatically decreases in the mid-twenty-first century and is almost zero by the late twenty-first century based on CESM-LE (Hyun et al. 2017; Labe et al. 2018). The reduction in sea ice leads to a largely increased extent of open water, resulting in increased upward heat fluxes. As such, weaker

TABLE 1. The average and trend (slope) of inversion depth during 1979–2005 for JRA-55 and CESM-LE. Trends with an asterisk (*) pass the test significance level at $\alpha = 0.05$.

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<tr>
<td>JRA-55</td>
<td>24.45</td>
<td>51.60</td>
<td>80.01</td>
<td>101.65</td>
<td>105.30</td>
<td>108.02</td>
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<tr>
<td>CESM-LE</td>
<td>19.41</td>
<td>40.77</td>
<td>71.03</td>
<td>98.86</td>
<td>102.98</td>
<td>102.76</td>
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<td>Trend (hPa yr$^{-1}$)</td>
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<tr>
<td>JRA-55</td>
<td>$-0.06$</td>
<td>$-0.18^*$</td>
<td>$-0.03$</td>
<td>$-0.02$</td>
<td>$-0.07$</td>
<td>$-0.21$</td>
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<tr>
<td>CESM-LE</td>
<td>$-0.05^*$</td>
<td>$-0.23^*$</td>
<td>$-0.21^*$</td>
<td>$-0.16^*$</td>
<td>$-0.12^*$</td>
<td>$-0.12^*$</td>
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</table>

Fig. 5. Time series of area-weighted inversion depth (hPa) in autumn and winter. Note that different ranges of the vertical axes are shown. The blue lines denote the results from 30 members of CESM-LE, and the black line represents the CESM-LE mean values. The red line shows the time series of inversion depth derived from JRA-55, with the yellow rectangle representing its 2$\sigma$ uncertainty.
mean inversions in the mid-twenty-first century are closely associated with declines in sea ice in the Arctic.

6. Discussion and conclusions

Air temperature inversions are one of the dominant features of the Arctic low-tropospheric atmosphere and play an important role in various physical processes by controlling the transport of heat and moisture fluxes from snow, permafrost, and sea ice. The differences in inversion depths in three reanalyses (i.e., ERA-Interim, JRA-55, and NCEP–NCAR) are shown in the Pacific sector, eastern Eurasia, and the Atlantic sector, and the largest standard deviation is over 60 hPa in eastern Eurasia. NCEP–NCAR reflects poorly on the distributions of inversion depth. The inversion depth in ERA-Interim is shallower than that in the other reanalyses. Considering the overestimation of ERA-Interim in the base height of temperature inversion studied by Lüpkes et al (2010), JRA-55 is applied to verify the simulation of the model. CESM-LE can reasonably reproduce the spatial distribution and seasonal variations in the present-day inversion depth over the Arctic. Although the model underestimates the mean inversion depth in autumn, the model–reanalysis discrepancy is less than 11 hPa, which is thus within a reasonable range. The simulation of CESM-LE in winter is much better than autumn. It is also indicated that the present-day inversion depth simulated by the model has a decreasing trend during 1979–2005, which is consistent with JRA-55. However, the significant trends in JRA-55 are only shown in October, whereas those in CESM-LE are all presented in autumn and winter.

The projections show that the inversion depth decreases significantly in autumn and winter throughout the entire Arctic during the mid-twenty-first century. The decrease is more pronounced over the Arctic Ocean than that over the surrounding land area and is greater in autumn than winter. It is evident that the depth of the inversion layer strongly decreases

![Fig. 6. Spatial distribution of the inversion depth (hPa) simulated by CESM-LE during 1979–2005 in (a) September, (e) October, and (i) November, that during 2031–50 in (b) September, (f) October, and (j) November, and their differences (the inversion depth in the future minus that in the present climate) in (c) September, (g) October, and (k) November. The differences of sea ice concentration (%), the sea ice concentration in the future minus that in the present climate) are shown in (d) September, (h) October, and (l) November. The vertical and horizontal color bars represent inversion depth and sea ice concentration, respectively.](image-url)
over most of the Arctic Ocean in autumn. In contrast, the strongest decrease is found in the Atlantic sector in winter. Spatially, the shallowing temperature inversion is consistent with the retreat of sea ice, indicating that sea ice may regulate the inversion depth by modulating surface heat fluxes.

Considering the important role of Arctic temperature inversion in Arctic boundary layer stability, Arctic amplification, and ice–air interactions during the cold season, the decrease in the inversion depth will have a profound impact on future Arctic climate change. In particular, the thinning of the Arctic inversion layer in the cold season will weaken the Arctic amplification in specific areas, such as the Barents Sea, and its climate effect to a certain extent, since the temperature inversions suppress infrared cooling to space during the cold season. In addition, the thinning of the temperature inversion layer will enhance the moisture and heat exchange between sea ice and the upper atmosphere, which is conducive to the freezing of sea ice in cold periods. Therefore, enough attention should be paid to the temperature inversions in the study of Arctic climate change. This study was conducted based on simulations of large ensembles from a single model CESM.

Considering the potential differences of various models in the simulation of Arctic low-tropospheric temperature changes, we suggest that multiple models should be used for further investigation of Arctic inversions.

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