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warming structure in  
the Arctic

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# Evaluation of the warming structure in the Arctic

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## Abstract

There has been growing interest in the vertical structure of the recent Arctic warming. We investigated temperatures at the surface, 925, 700, 500 and 300 hPa levels in the Arctic (north of 70° N) using observations and four reanalyses: ERA-Interim, CFSR, MERRA and NCEP II. For the period 1979–2011, the layers at 500 hPa and below show a warming trend in all seasons in all the chosen reanalyses and observations. Restricting the analysis to the 1998–2011 period, however, all the reanalyses show a cooling trend in the Arctic-mean 500 hPa temperature in autumn, and this also applies to both observations and the reanalyses when restricting the analysis to the locations with available IGRA radiosoundings. During this period, the surface observations mainly representing land areas surrounding the Arctic Ocean reveal no summer-time trend, in contrast with the reanalyses whether restricted to the locations of the available surface observations or not.

In evaluating the reanalyses with observations, we find that the reanalyses agree better with each other at the available IGRA sounding locations than for the Arctic average, perhaps because the sounding observations were assimilated into reanalyses. Conversely, using the reanalysis data only from locations matching available surface (air) temperature observations does not improve the agreement between the reanalyses. At 925 hPa, CFSR deviates from the other three reanalyses especially in summer after 2000, and it also deviates more from the IGRA radiosoundings than the other reanalyses do. The CFSR error in summer  $T_{925}$  is due mainly to underestimations in the Canadian-Atlantic sector between 120° W and 0°. The other reanalyses also have negative biases in this longitude band.

## 1 Introduction

The surface warming in the Arctic is observed to be at least twice as large as the global average warming in the recent decades (Hassol, 2004; Bekryaev et al., 2010).

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Causes for the so-called Arctic amplification of the warming have been proposed to be the snow and ice feedbacks (Manabe, 1983; Hall, 2004), and the poleward energy transport from lower latitudes (Alexeev et al., 2005) among many proposed causes. Graversen et al. (2008) and Screen and Simmonds (2010) used the vertical structure of Arctic temperature trends in reanalyses to gain insights into this issue. They argue that if the maximum warming occurs much above the surface, the poleward energy transport would be the primary mechanism for the warming amplification. Graversen et al. (2008) found the maximum warming well above the surface, whereas Screen and Simmonds (2010) showed the warming to be largest in the lowest layers. Graversen et al. (2008) and Screen and Simmonds (2010) used different reanalyses and different periods for their analyses.

Chung and Räisänen (2011), on the other hand, addressed the origin of Arctic warming rather than the Arctic amplification. They hypothesize, based on idealized climate model experiments, that if the *summer-time* warming is largest well above the surface, the poleward energy transport would be mainly responsible for the Arctic warming irrespective of the warming structure in winter. Taken together, the vertical profile of Arctic warming has emerged as one of the top climate issues.

Here, we use sounding and surface observations, and reanalyses collectively to investigate the recent warming and its vertical structure in the Arctic. In doing so, we also evaluate the reanalyses in Arctic warming. Reanalysis evaluation is important, because reanalyses are so broadly applied in climate research including Arctic research. Reanalyses are not observation but commonly treated as observation in the literature. For example, the atmospheric forcing for ocean, sea ice, glacier, and hydrological models are often taken from reanalyses. Reanalyses are also employed in the studies of climate variability and trends as well as occurrence of extreme events. Reanalyses are, however, not free of errors (Lüpkes et al., 2010; Bromwich et al., 2011; Jakobson et al., 2012).

Reanalysis is a system where observations are assimilated into a global model in order to provide the atmospheric state continuous in space and time (Saha et al., 2010;

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Dee et al., 2011; Rienecker et al., 2011). Reanalyses differ from each other due to several reasons. First, the usage of observations varies between reanalyses. While all the reanalyses assimilate radiosonde sounding data, there are differences in the assimilation of satellite data. Also, the assimilation method varies. ERA-Interim applies a method based on four-dimensional data assimilation (4-D-VAR), where exact time of observations is taken into account by sophisticated means, whereas other reanalyses apply simpler methods. Second, there are large differences in the horizontal and vertical resolutions of the models applied. Third, the physical parameterization schemes for radiative transfer, turbulent mixing, cloud physics, and surface processes vary between the models.

Over the Arctic, where there are very few in-situ observations, the quality of reanalyses is particularly questioned. Recent studies (e.g., Screen et al., 2012) tend to utilize multiple reanalyses to establish the robustness of the vertical warming structure in the Arctic. In this study, we examine 2 m air temperature, temperature ( $T$ ) at 925, 700, 500 and 300 hPa, and the temperature difference between 925 and 500 hPa levels in the latest reanalyses, so as to estimate the accuracy of each reanalysis product in Arctic warming. Recently, Alexeev et al. (2012) used sounding observations to evaluate the warming structures in the older NCEP/NCAR and ERA-40 reanalyses. Here, we consider the most recent reanalyses and focus on Arctic-averaged temperatures.

## 2 Surface (air) temperature

We analyze monthly-mean 2 m air temperature fields from three latest-generation atmospheric reanalyses: ECMWF ERA-Interim reanalysis (ERA-I) (Dee et al., 2011), NASA Modern-Era Retrospective analysis for Research and Applications (MERRA) (Rienecker et al., 2011) and the NCEP Climate Forecast System Reanalysis (CFSR) (Saha et al., 2010). The 2 m air temperature will be referred to as the surface air temperature for the remainder of the paper. The CFSR surface air temperature analysis is available at two resolutions; here we use the T62 Gaussian grid version. We also

analyze NCEP's earlier-generation reanalysis product, the so-called NCEP II reanalysis (Kanamitsu et al., 2002). The period of analysis is from 1979 to 2011. Due to data availability, CFSR is only analyzed until the year 2009.

The reanalyses agree on the large-scale features in surface air temperature climatology (see Fig. 1 for the summer season). Furthermore, for all four reanalyses considered, the domain-average air surface temperature for the 70°–90° N region shows a clear warming trend, both for annual and seasonal means (Fig. 2a–e). There are, however, also disagreements between the reanalyses, which will be discussed further below.

To evaluate the surface air temperature in the reanalyses, we use the Goddard Institute for Space Studies (GISS) analysis of global surface temperature change (Hansen et al., 2010), referred to as “GISTEMP” here. GISTEMP integrates in-situ surface air temperature measurements over land and ship-based and satellite-derived sea surface temperature (SST) measurements. The SST measurements are, however, only used over year-round ice-free areas. The latter is because GISTEMP data were produced for comparison with the surface air temperature in climate models and only in year-round ice-free areas SST anomaly is a good approximation to surface air temperature anomaly (Hansen et al., 2010). The GISTEMP version we use here is a gridded monthly-mean dataset with a 250 km smoothing. The use of a smoothing distance of 250 km instead of 1200 km (the default of GISTEMP) avoids the uncertainty related to the extrapolation of temperature measurements made at Arctic observation sites to large distances over the open ocean or sea ice, thereby providing a more robust point of comparison for the reanalyses. On the other hand, a consequence of the 250 km smoothing distance is that it leaves a large amount of data gaps. The GISTEMP data we use is defined only for a fraction of the Arctic area (on the average, 27% from 1979 to 2011), mainly limited to the vicinity of the observation sites on the land and permanently ice-free parts of the Barents Sea and Greenland Sea (see Fig. 10). The GISTEMP algorithm and its application to the Arctic are discussed in more detail in Hansen et al. (2010).

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Figure 2f–j compare the 70–90° N average surface air temperature anomalies in the reanalyses with those of the GISTEMP data. Unlike in Fig. 2a–e, for the reanalyses, after linear interpolation onto the GISTEMP grids, only those months and grid cells corresponding to valid GISTEMP data are used in Fig. 2f–j. In generating Fig. 2f–j, the area averaging is done for each month, and then seasonal or annual means are computed. The temperature anomalies are defined with respect to the climatology of years 1979–2009. For GISTEMP, which provides temperature anomalies with respect to the 1951–1980 climatology, anomalies with respect to the 1979–2009 climatology were formed by subtracting the 1979–2009 annual or seasonal mean of Arctic-average temperatures. In summer, the spread between the reanalyses (Fig. 2h) tends to decrease slightly from that in Fig. 2c. However, in winter, the spread rather seems to increase. Thus, overall, restricting the analysis to the regions with GISSTEMP data does not improve the mutual agreement between the reanalyses. This might actually not be surprising because in the Arctic region GISSTEMP is mainly based on in-situ surface air temperatures from land, and among the reanalyses considered in this study, these data are only assimilated in ERA-Interim. This is done through a separate surface analysis, which is based on Optimal Interpolation, in contrast to 4dVAR in the main atmospheric analysis (Dee et al., 2011). MERRA assimilates in-situ surface air temperatures only over oceans (from ships and buyos; Rienecker et al., 2011), while CFSR and NCEP II do not explicitly assimilate surface air temperature observations (Wang et al., 2011).

### 3 Upper-air temperatures

As for upper-air temperatures from the reanalyses, we again use ERA-Interim reanalysis, MERRA, CFSR and NCEP II reanalysis. The CFSR upper-air temperature product is available at two resolutions; here we use the 2.5° × 2.5° version. We first discuss the 500 hPa and 925 hPa levels, because the temperature trend difference between these two levels is a good measure of the vertical warming structure. The left panels in Figs. 3–6 show the 70–90° N average temperature from the four reanalyses consid-

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ered. In case of 500 hPa summer-time temperature (Fig. 4a), the differences between the reanalyses are small, mostly within 0.5 K. However, in fall and winter, MERRA displays lower 500 hPa temperatures than the other reanalyses (Figs. 5a and 6a). Furthermore, NCEP II is systematically colder than the other reanalyses at 925 hPa in winter (Fig. 6b). The most unexpected and striking feature of the left panels in Figs. 3–6 is that at the 925 hPa level in summer, CFSR deviates substantially from the remaining three reanalyses, by  $-0.5$  to  $-1.7$  K, since around the year 2000 (Fig. 4b). As a result, the difference between  $T_{925}$  and  $T_{500}$ , as shown in Fig. 4c, clearly separates CFSR from the other three reanalyses. In CFSR the temperature difference is less than in the other reanalyses by more than 1 K in the mid 2000's (Fig. 4c). This outlier behavior of CFSR is surprising because CFSR is an updated product from NCEP II. Another notable feature in Fig. 4c is that for ERA-Interim, the summertime temperature difference between 925 and 500 hPa increases substantially (by almost 2 K) from late 1990's to early 2000's. This feature is not reproduced by the other reanalyses, and it is mainly linked to a larger increase in 925 hPa temperature in ERA-Interim as compared with MERRA, CFRS and NCEP II (Fig. 4b).

To evaluate the reanalyses, we use the Integrated Global Radiosonde Archive (IGRA) data (Elliott and Gaffen, 1991). IGRA consists of quality-assured soundings over the globe, and has 34 radiosonde stations north of  $70^{\circ}$  N. IGRA provides monthly and 4 times daily products, and we only use the latter (hereafter referred to as daily IGRA data) for comparing the reanalyses with IGRA data (the IGRA monthly means are not particularly reliable in the Arctic, because they are averaged from the available observations, in many cases with less than 30 days of data). Moreover, in comparison with the 00Z values of the reanalyses, IGRA soundings within two hours of 00Z are used. Similarly, the 10Z–14Z IGRA soundings are used to evaluate the 12Z reanalysis values. Soundings near 06Z and 18Z are only available from a fraction of the stations and are therefore not included in the analysis below. Naturally, the use of only two observations per day implies that the diurnal cycle is not fully represented. For example, if there are problems specific to a certain part of the diurnal cycle in a reanalysis (such







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It is further noted from Fig. 7a–d that all the reanalyses have a cold bias at 925 hPa. Also, MERRA has a cold bias at all the 4 levels and 4 seasons. The reasons for this cold bias tendency might be related to free-running climate models having a cold bias in the Arctic. Note that our evaluation of the reanalyses is limited to the use of the IGRA data, which must have been largely incorporated into each reanalysis product. Using sounding observations that are not assimilated over the Arctic, Jakobson et al. (2012) also found the CFSR to perform the worst at 925 hPa (roughly 600 m). However, they found CFSR to be the best reanalysis for temperature in the lowermost 100 m layer, indicating that the performance of each reanalysis depends strongly on altitude.

It is surprising that the old NCEP II reanalysis is superior to the new CFSR in summer at 925 hPa. We show in Fig. 8 the difference between the reanalysis summer-time  $T_{925}$  and the IGRA value for each station. The most conspicuous feature of Fig. 8 is that all the reanalyses have negative (cold) biases in the Canadian-Atlantic sector between 120° W and 0°, and less negative or slightly positive biases in the other longitudes. We found that this bias is not directly related to interpolation of data below the Earth surface, since the surface altitudes of the IGRA stations and those of the nearby reanalysis grid cells are safely below the 925 hPa level. Out of the four reanalyses, the CFSR and NCEP II have particularly negative biases over the 120° W–0° band compared to the bias over the other longitudes (Fig. 8). While the negative bias over the 120° W–0° band is largely cancelled out by the positive bias over the other longitudes in the NCEP II, the bias is still negative outside of the 120° W–0° band in the CFSR. In this regard, the better performance of NCEP II for the Arctic mean values is fortuitous.

## 4 Temperature trends

In this section, we quantify temperature trends at selected levels. Considering first the surface level, the reanalyses and GISTEMP both show clear warming trends from 1979 to 2011 (Fig. 2), and Table 3 quantify them. For the recent period, however, the warming trends in GISTEMP agree very well with those in the reanalyses, except in summer

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(Fig. 2f–j). In summer (Fig. 2h), GISTEMP shows no clear trend since 1998, while all the reanalyses show a warming trend. Hence, we have a closer look at the period 1998–2011. The trends of the time series of Fig. 2–6 are computed for the 1998–2011 period in Table 4, and Figs. 9–10. Reverting back to surface temperature trend, the summer-time warming trends in the reanalyses appear for the true Arctic averages as well as when only those data corresponding to the available GISTEMP data are sampled, while GISTEMP does not show a warming trend (Table 4). On the contrary, in spring, autumn and winter, the reanalyses and GISTEMP all show significant warming trends. When annual mean trends are analyzed, all the reanalyses agree with the GISTEMP trend of about 1.6 K/14 yr, except for ERA-Interim (about 2.1 K/14 yr). We also note that both GISTEMP and the reanalyses show a large increase ( $\sim 1.5$  K) in summertime temperature from 1996 to 1998, indicating that the trends are sensitive to the choice of the period considered.

Figure 9 shows the observed trends in surface (air) temperature ( $T_s$ ), 925 hPa  $T$  and 500 hPa  $T$ . In summer, the  $T_s$  trend is near zero while upper-air temperature trends are positive. Also, the warming at 925 hPa is almost equal to that at 500 hPa. In the other 3 seasons, on the other hand, the warming tendency is larger at lower altitude. Fall is particularly interesting, since the surface shows a very large warming when there has been a statistically significant cooling trend at 500 hPa. The reanalyses agree on the cooling trend at 500 hPa in fall, with the trends of  $-0.74$  K to  $-0.03$  K/14 yr for true Arctic  $70$ – $90^\circ$  N mean values, and with the trends of  $-1.25$  K to  $-0.91$  K/14 yr when sampled according to the availability of IGRA data (Table 4). On the other hand, analyzing the entire 1979–2011 period reveals that the trend is not necessarily negative in fall and the warming tendency does not necessarily become larger at lower altitude (Table 3). This raises a hypothesis that the recent warming is associated with different mechanisms than the earlier warming.

The spatial distribution of recent summertime temperature trends for GISTEMP and the reanalyses is shown in Fig. 10. The near-zero summertime trend in GISTEMP is related to a negative temperature trend in the Eurasian sector between  $20^\circ$  and

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110° E. This cooling trend is not well reproduced in the reanalyses. Also over the ocean, the reanalyses noticeably differ from GISTEMP (Fig. 10), but we have to bear in mind that, using the 250 km smoothing, there are very few GISTEMP values in the central Arctic. In the sea areas that are open only in summer and autumn (e.g. parts of the Barents, Kara, Laptev, East-Siberian, Chukchi, and Beaufort Seas), the GISTEMP data are probably less reliable than the reanalyses in these seasons. This is because (a) reanalyses effectively assimilate satellite SST observations from the seasonally ice-free seas, whereas GISTEMP applies SST observations only from permanently ice-free areas, and (b) the GISTEMP values seen in these sea areas are based on the extrapolation of land observations.

With regard to the differences between GISTEMP and reanalyses over the central Arctic (the area where GISTEMP has very few data), one might simply think that reanalyses are more accurate because they assimilate satellite radiances or satellite-based upper-air temperatures, and those should affect the surface air temperatures. However, satellite retrievals have a coarse vertical resolution, and cannot well represent the fine structure of temperature in the shallow atmospheric boundary layer in the Arctic. Due to the close coupling of the open ocean and near-surface air, we believe that the surface air temperature in reanalyses is more affected by the assimilation of satellite data on SST than upper-air temperatures.

In addition to differences in satellite data usage, another potential reason for the detected discrepancies (Figs. 2h and 10) is that in GISTEMP  $T_s$  refers to a combination of SST and surface air temperature, whereas in reanalyses  $T_s$  refers to surface air temperature (SAT). Even though SST observations are assimilated in reanalyses, SAT and SST are not perfectly correlated, and so their trends are not necessarily equal.

## 5 Discussion

As noted in the introduction, various factors can cause differences between temperature fields in different reanalyses. These include differences in the usage of obser-

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5 vations, differences in the atmospheric model used in producing the reanalysis, and the methodology used for data assimilation. In general, it is difficult to pinpoint the exact causes for the differences between different reanalysis temperatures and their trends. However, some general comments can be made. First, as noted in Sect. 3, the spread between reanalysis upper-air temperatures is generally smaller over those regions where IGRA radiosounding data are available. This is expected because most or all of the radiosounding data must have been assimilated in the reanalyses, thereby constraining them. Over the central Arctic regions lacking sounding data, the reanalysis systems have more freedom to form their own climate, and thus biases.

10 In contrast, for surface air temperature, restricting the analysis to the locations with available GISTEMP data did not reduce the spread between the different reanalysis. As pointed out in Sect. 2, this might be explained by the fact that among the reanalyses considered, only ERA-Interim assimilates surface air temperatures from land stations.

15 While all the reanalyses agree that the Arctic is, in general, warming, they show substantial differences in the details, such as the vertical structure of summertime warming (as characterized by the time series of the temperature difference between 925 and 500 hPa in Fig. 4c). There are two general causes that can explain time-varying differences between the reanalyses. First, the reanalysis systems may respond differently to real changes in the Arctic environment, such as diminishing Arctic sea ice. For instance, the performance of the atmospheric models used in producing the reanalyses may depend on the surface status. Surface status can also vary among the reanalyses despite the assimilation of satellite-based sea ice extent data. The differences may originate from the remote sensing algorithm applied (Valkonen et al., 2008) and because out of the reanalyses included in this study only in CFSR the atmospheric model is coupled with an ocean model and a dynamic-thermodynamic sea ice model (Saha et al., 2010). Second, while the models used for reanalyses are “frozen”, the availability of observations has changed during the reanalysis period, in particular, due to the increasing amounts of satellite data. Changes in the observation systems may cause artificial trends and shifts in the reanalyses, such as those demonstrated for ERA-40



## References

- Alexeev, V. A., Langen, P. L., and Bates, J. R.: Polar amplification of surface warming on an aquaplanet in “ghost forcing” experiments without sea ice feedbacks, *Clim. Dynam.*, 24, 655–666, doi:10.1007/s00382-005-0018-3, 2005.
- 5 Alexeev, V. A., Esau, I., Polyakov, I. V., Byam, S. J., and Sorokina, S.: Vertical structure of recent arctic warming from observed data and reanalysis products, *Clim. Change*, 111, 215–239, 2012.
- Bekryaev, R. V., Polyakov, I. V., and Alexeev, V. A.: Role of polar amplification in long-term surface air temperature variations and modern arctic warming, *J. Climate*, 23, 3888–3906, doi:10.1175/2010JCLI3297.1, 2010.
- 10 Bromwich, D. H., Nicolas, J. P., and Monaghan, A. J.: An Assessment of precipitation changes over antarctica and the southern ocean since 1989 in contemporary global reanalyses, *J. Climate*, 24, 4189–4209, 2011.
- Chung, C. E. and Räisänen, P.: Origin of the Arctic warming in climate models, *Geophys. Res. Lett.*, 38, L21704, doi:10.1029/2011GL049816, 2011.
- 15 Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J. J., Park, B. K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J. N., and Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, *Q. J. Roy. Meteor. Soc.*, 137, 553–597, 2011.
- 20 Elliott, W. P. and Gaffen, D. J.: On the utility of radiosonde humidity archives for climate studies, *Bull. Am. Meteorol. Soc.*, 72, 1507–1520, 1991.
- 25 Graversen, R. G., Mauritsen, T., Tjernstrom, M., Kallen, E., and Svensson, G.: Vertical structure of recent Arctic warming, *Nature*, 451, 53–56, doi:10.1038/nature06502, 2008.
- Hall, A.: The role of surface albedo feedback in climate, *J. Climate*, 17, 1550–1568, doi:10.1175/1520-0442(2004)017<1550:trosaf>2.0.CO;2, 2004.
- Hansen, J., Ruedy, R., Sato, M., and Lo, K.: Global surface temperature change, *Rev. Geophys.*, 48, RG4004, doi:10.1029/2010RG000345, 2010.
- 30 Hassol, S. J.: Impacts of a Warming Climate – Arctic Climate Impact Assessment, Cambridge University Press, New York, 144 pp., 2004.

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- 5 Kanamitsu, M., Ebisuzaki, W., Woollen, J., Yang, S. K., Hnilo, J. J., Fiorino, M., and Potter, G. L.: NCEP-DOE AMIP-II reanalysis (R-2), *B. Am. Meteorol. Soc.*, 83, 1631–1643+1559, 2002.
- Lüpkes, C., Vihma, T., Jakobson, E., König-Langlo, G., and Tetzlaff, A.: Meteorological observations from ship cruises during summer to the central Arctic: a comparison with reanalysis data, *Geophys. Res. Lett.*, 37, L09810, doi:10.1029/2010gl042724, 2010.
- 10 Manabe, S.: Carbon dioxide and climatic change, in: *Advances in Geophysics*, edited by: Barry, S., Elsevier, Cambridge, MA, 39–82, 1983.
- Rienecker, M. M., Suarez, M. J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich, M. G., Schubert, S. D., Takacs, L., Kim, G. K., Bloom, S., Chen, J., Collins, D., Conaty, A., Da Silva, A., Gu, W., Joiner, J., Koster, R. D., Lucchesi, R., Molod, A., Owens, T., Pawson, S., Pegion, P., Redder, C. R., Reichle, R., Robertson, F. R., Ruddick, A. G., Sienkiewicz, M., and Woollen, J.: MERRA: NASA's modern-era retrospective analysis for research and applications, *J. Climate*, 24, 3624–3648, 2011.
- 15 Saha, S., Moorthi, S., Pan, H. L., Wu, X., Wang, J., Nadiga, S., Tripp, P., Kistler, R., Woollen, J., Behringer, D., Liu, H., Stokes, D., Grumbine, R., Gayno, G., Hou, Y. T., Chuang, H. Y., Juang, H. M. H., Sela, J., Iredell, M., Treadon, R., Kleist, D., Van Delst, P., Keyser, D., Derber, J., Ek, M., Meng, J., Wei, H., Yang, R., Lord, S., Van Den Dool, H., Kumar, A., Wang, W., Long, C., Chelliah, M., Xue, Y., Huang, B., Schemm, J. K., Ebisuzaki, W., Lin, R., Xie, P., Chen, M., Zhou, S., Higgins, W., Zou, C. Z., Liu, Q., Chen, Y., Han, Y., Cucurull, L., Reynolds, R. W., Rutledge, G., and Goldberg, M.: The NCEP climate forecast system reanalysis, *B. Am. Meteorol. Soc.*, 91, 1015–1057, 2010.
- 20 Screen, J. A. and Simmonds, I.: The central role of diminishing sea ice in recent Arctic temperature amplification, *Nature*, 464, 1334–1337, doi:10.1038/nature09051, 2010.
- Screen, J. A. and Simmonds, I.: Erroneous Arctic temperature trends in the ERA-40 reanalysis: a closer look, *J. Climate*, 24, 2620–2627, doi:10.1175/2010jcli4054.1, 2011.
- Screen, J. A., Deser, C., and Simmonds, I.: Local and remote controls on observed Arctic warming, *Geophys. Res. Lett.*, 39, L10709, doi:10.1029/2012GL051598, 2012.
- 30 Valkonen, T., Vihma, T., and Doble, M.: Mesoscale modeling of the atmosphere over Antarctic sea ice: a late-autumn case study, *Mon. Weather Rev.*, 136, 1457–1474, 2008.



Wang, W., Xie, P., Yoo, S. H., Xue, Y., Kumar, A., and Wu, X.: An assessment of the surface climate in the NCEP climate forecast system reanalysis, *Clim. Dynam.*, 37, 1601–1620, 2011.

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**Table 1.** r.m.s. error of seasonal and 70-90 N average temperature in the reanalyses in units of K. There are four values separated by a blank, and these four values represent ERAICFSRIMERRAINCEP II. The r.m.s. error here is between each reanalysis and the IGRA data. To compute the error, we use the reanalysis data that correspond to the available IGRA observations. 00Z and 12Z daily data are used, instead of monthly means.

	MAM				JJA				SON				DJF			
	E	C	M	N	E	C	M	N	E	C	M	N	E	C	M	N
300 hPa	0.49	0.28	0.37	0.26	0.49	0.20	0.37	0.63	0.34	0.13	0.27	0.59	0.32	0.28	0.31	0.18
500 hPa	0.10	0.12	0.21	0.12	0.09	0.12	0.22	0.16	0.19	0.14	0.15	0.06	0.21	0.23	0.16	0.07
700 hPa	0.12	0.08	0.22	0.15	0.13	0.10	0.12	0.13	0.12	0.14	0.11	0.07	0.12	0.29	0.14	0.07
925 hPa	0.27	0.26	0.33	0.30	0.34	0.48	0.28	0.22	0.22	0.33	0.22	0.35	0.26	0.76	0.25	0.58

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**Table 2.** Same as Table 1, except for mean bias of seasonal and 70–90° N average temperature of each reanalysis product, relative to the IGRA data, in units of K.

	MAM				JJA				SON				DJF			
	E	C	M	N	E	C	M	N	E	C	M	N	E	C	M	N
300 hPa	-0.38	-0.23	-0.16	+0.20	-0.37	-0.13	-0.14	+0.61	-0.20	-0.04	-0.03	+0.55	-0.20	-0.19	-0.18	+0.14
500 hPa	+0.02	+0.01	-0.19	-0.11	+0.04	-0.03	-0.19	-0.14	+0.16	+0.09	-0.13	+0.02	+0.18	+0.15	-0.12	+0.06
700 hPa	-0.06	-0.04	-0.21	-0.13	-0.08	-0.06	-0.10	-0.10	+0.02	+0.11	-0.01	-0.01	+0.03	+0.16	-0.06	-0.04
925 hPa	-0.21	-0.20	-0.29	-0.17	-0.29	-0.30	-0.14	-0.06	-0.17	-0.24	-0.18	-0.28	-0.05	-0.06	-0.18	-0.48

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**Table 3.** 70–90° N average temperature trend from 1979 to 2011 in units of temperature change (in K) over the 33 yr. In case of CFSR, the trend is from 1979 to 2009 in units of temperature change over the 31 yr. There are five values separated by a blank, and these five values represent Observation|ERA|CFSR|MERRA|NCEP II. Observation here refers to either GISTEMP or IGR data. In the rows with observation (i.e., five values separated by a blank), the 70–90° N average is made with the reanalysis data corresponding to the available observation, whereas in the rows without observation (i.e., four values separated by a blank), true 70–90° N average values are used. The standard error of each trend is shown with ± in each row.

	Annual mean					JJA					DJF				
	O	E	C	M	N	O	E	C	M	N	O	E	C	M	N
Ts	2.09	2.52	1.75	1.84	2.71	1.05	0.86	0.76	1.01	1.09	2.22	3.03	1.91	1.63	3.16
	±0.29	±0.31	±0.29	±0.26	±0.28	±0.23	±0.18	±0.21	±0.17	±0.19	±0.62	±0.71	±0.71	±0.63	±0.67
	2.43	1.78	1.73	2.83		0.71	0.51	0.89	1.18		2.86	2.05	1.55	3.01	
	±0.34	±0.32	±0.27	±0.31		±0.17	±0.20	±0.15	±0.18		±0.73	±0.72	±0.64	±0.71	
925hPa T	2.77	2.61	0.83	2.63	3.10	1.78	1.84	0.93	1.56	1.53	3.83	3.30	0.80	3.37	4.43
	±0.31	±0.32	±0.35	±0.32	±0.33	±0.42	±0.43	±0.50	±0.40	±0.41	±0.66	±0.63	±0.83	±0.65	±0.63
	2.10	1.50	2.12	2.21		2.06	0.53	1.49	1.60		1.95	1.99	2.26	2.05	
	±0.32	±0.27	±0.28	±0.31		±0.44	±0.34	±0.34	±0.31		±0.57	±0.60	±0.58	±0.64	
500hPa T	1.36	1.34	0.48	1.42	1.29	0.57	0.61	1.28	0.81	0.43	1.75	1.74	0.77	1.64	1.72
	±0.21	±0.20	±0.25	±0.22	±0.21	±0.36	±0.35	±0.51	±0.35	±0.38	±0.37	±0.36	±0.52	±0.39	±0.37
	0.90	0.33	0.98	0.84		1.01	1.04	1.22	0.71		0.97	0.08	0.88	0.94	
	±0.17	±0.23	±0.19	±0.18		±0.32	±0.35	±0.32	±0.35		±0.29	±0.38	±0.37	±0.31	

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**Table 3.** (continued).

	O	E	MAM			O	E	SON		
			C	M	N			C	M	N
Ts	2.21	3.00	1.94	2.19	2.72	2.87	3.17	2.40	2.52	3.85
	±0.47	±0.46	±0.43	±0.36	±0.40	±0.39	±0.43	±0.41	±0.35	±0.45
		2.97	2.12	1.76	3.02		3.19	2.43	2.73	4.11
		±0.50	±0.50	±0.39	±0.47		±0.45	±0.44	±0.37	±0.46
925 hPa T	2.42	2.37	1.45	2.48	2.94	3.07	2.94	0.12	3.11	3.49
	±0.40	±0.40	±0.53	±0.42	±0.40	±0.71	±0.71	±0.55	±0.72	±0.70
		2.28	1.30	2.13	2.47		2.12	2.20	2.62	2.74
		±0.46	±0.43	±0.49	±0.47		±0.41	±0.40	±0.42	±0.43
500 hPa T	1.65	1.58	0.83	1.68	1.61	1.47	1.42	−0.96	1.57	1.39
	±0.30	±0.30	±0.46	±0.30	±0.29	±0.42	±0.42	±0.60	±0.43	±0.41
		0.94	0.87	0.97	0.98		0.67	0.87	0.88	0.75
		±0.32	±0.31	±0.32	±0.28		±0.31	±0.36	±0.32	±0.32

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**Table 4.** 70–90° N average temperature trend from 1998 to 2011 in units of temperature change (in K) over the 14 yr. In case of CFSR, the trend is from 1998 to 2009 in units of temperature change over the 12 yr.

	Annual mean					JJA					DJF				
	O	E	C	M	N	O	E	C	M	N	O	E	C	M	N
Ts	1.57	2.06	1.55	1.36	1.59	0.09	0.42	0.45	0.43	0.74	2.35	3.13	2.70	1.72	1.93
	±0.34	±0.37	±0.41	±0.34	±0.32	±0.22	±0.20	±0.26	±0.18	±0.16	±0.85	±1.1	±1.1	±1.0	±1.0
925 hPa T	2.25	1.60	1.52	1.89		0.49	0.45	0.49	0.80		3.57	3.00	2.32	2.58	
	±0.37	±0.44	±0.34	±0.32		±0.18	±0.26	±0.17	±0.19		±1.0	±1.1	±0.98	±1.0	
500 hPa T	1.07	1.06	0.83	1.33	1.35	1.23	1.55	0.93	1.39	1.54	0.94	0.72	0.80	1.27	1.01
	±0.34	±0.36	±0.35	±0.33	±0.33	±0.45	±0.47	±0.50	±0.47	±0.45	±0.82	±0.83	±0.83	±0.83	±0.77
925 hPa T	1.61	0.79	1.59	1.90		1.70	0.09	0.85	0.81		1.62	1.74	2.00	2.46	
	±0.41	±0.35	±0.34	±0.32		±0.56	±0.47	±0.48	±0.38		±0.83	±0.85	±0.81	±0.83	
500 hPa T	0.41	0.14	0.48	0.40	0.44	1.36	1.17	1.28	1.26	1.34	0.50	0.17	0.77	0.59	0.56
	±0.31	±0.30	±0.33	±0.30	±0.30	±0.49	±0.49	±0.51	±0.48	±0.49	±0.51	±0.52	±0.52	±0.54	±0.49
500 hPa T	0.14	0.38	0.74	0.48		0.41	0.50	0.71	0.61		0.63	1.14	1.44	1.13	
	±0.26	±0.28	±0.27	±0.24		±0.44	±0.47	±0.44	±0.45		±0.43	±0.47	±0.47	±0.39	

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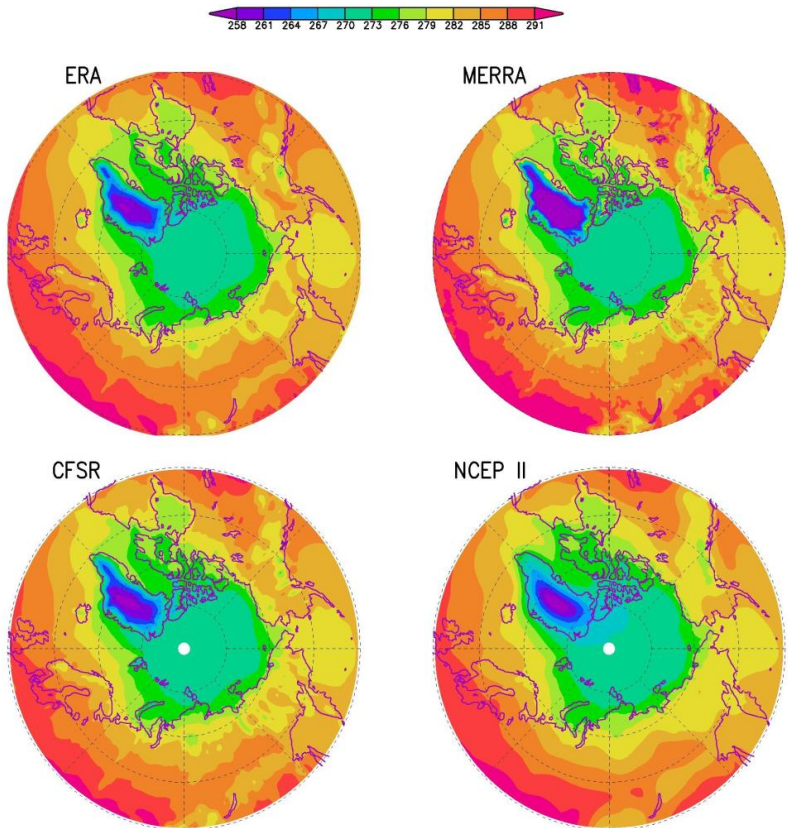
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**Table 4.** (continued).

	O		MAM			O		SON		
	O	E	C	M	N	O	E	C	M	N
Ts	1.96	2.33	1.10	1.39	1.50	1.87	2.37	1.94	1.90	2.20
	±0.66	±0.66	±0.59	±0.48	±0.57	±0.30	±0.27	±0.36	±0.28	±0.25
		2.59	1.14	1.53	1.84		2.35	1.81	1.74	2.33
		±0.70	±0.70	±0.52	±0.66		±0.37	±0.51	±0.40	±0.37
925 hPa T	1.84	1.86	1.45	2.13	2.16	0.29	0.13	0.12	1.51	0.71
	±0.53	±0.55	±0.53	±0.54	±0.54	±0.50	±0.50	±0.55	±0.50	±0.50
		1.86	0.19	1.92	2.11		1.28	1.15	1.60	2.20
		±0.72	±0.56	±0.70	±0.72		±0.36	±0.39	±0.44	±0.41
500 hPa T	0.70	0.49	0.83	0.71	0.77	-0.93	-1.25	-0.96	-0.94	-0.91
	±0.47	±0.45	±0.46	±0.44	±0.44	±0.57	±0.55	±0.60	±0.58	±0.55
		0.25	0.18	0.83	0.70		-0.74	-0.29	-0.03	-0.51
		±0.50	±0.48	±0.50	±0.46		±0.40	±0.48	±0.44	±0.41



**Fig. 1.** June–August average surface air temperature climatology for the period 1979–2011 in units of K. In case of CFSR, the climatology is for 1979–2009.

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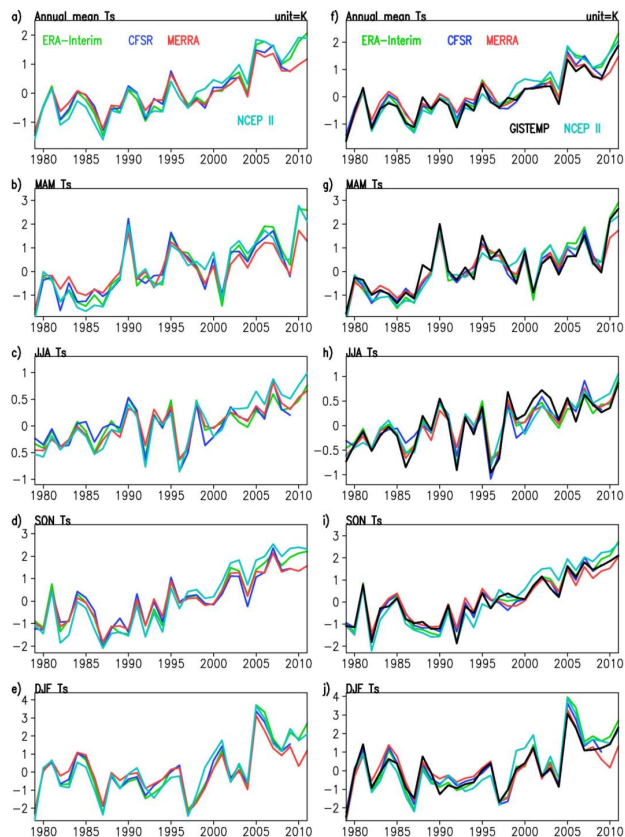
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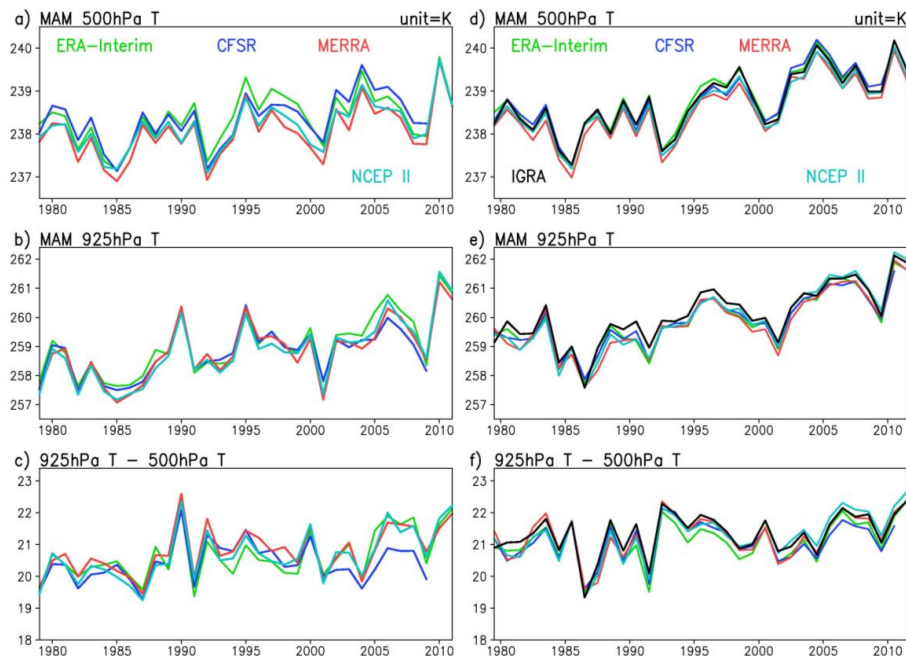


**Fig. 2.** 70–90° N average  $T_s$  anomalies relative to 1979–2009 climatology from four reanalyses and GISTEMP. On the left, the true 70–90° N average is shown. On the right, the average is calculated using only those reanalysis data that correspond to the available GISTEMP data in location and time. Note that  $T_s$  refers to surface air temperature (SAT) for the reanalyses, and to a combination of SAT over land and SST over ocean for GISTEMP.

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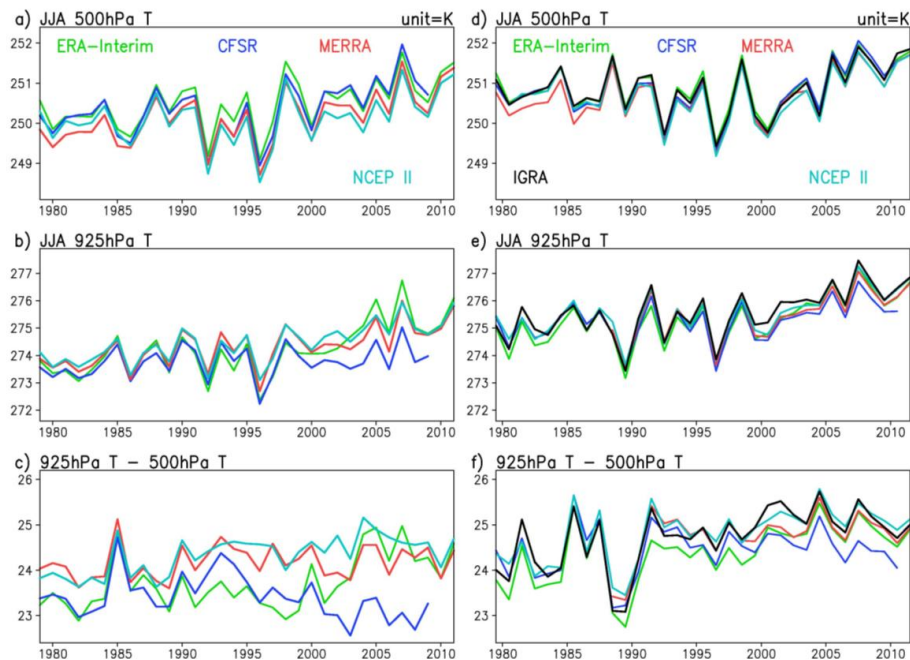


**Fig. 3.** 70–90° N average  $T$  (temperature) from four reanalyses and the IGRA data. On the left, the true 70–90° N average is shown. On the right, the average is calculated using only those reanalysis data that match the available IGRA observations in location and time.

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**Fig. 4.** Same as Fig. 3 except for the JJA (June, July and August) season.

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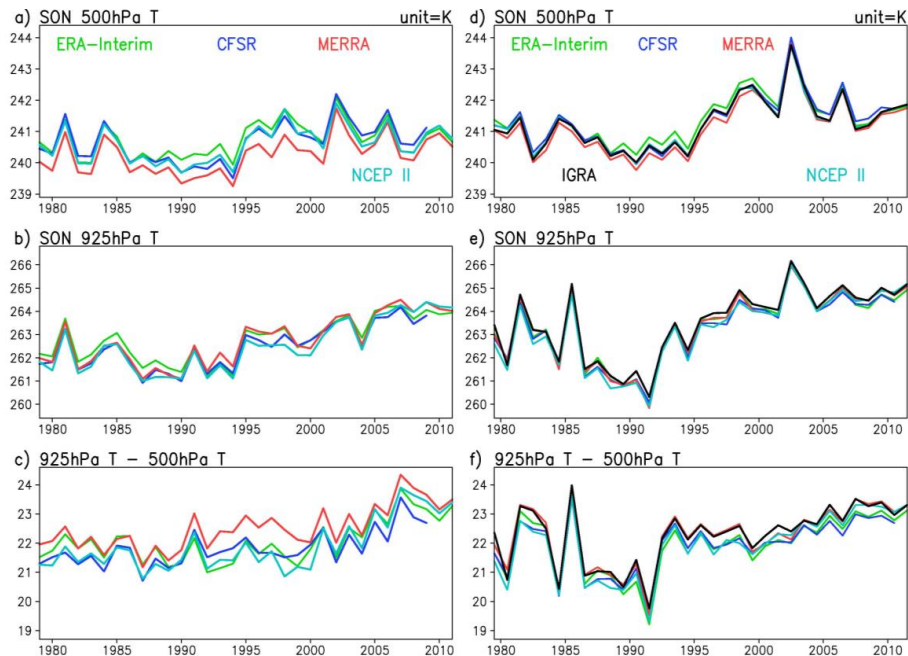


Fig. 5. Same as Fig. 3 except for the SON (September, October and November) season.

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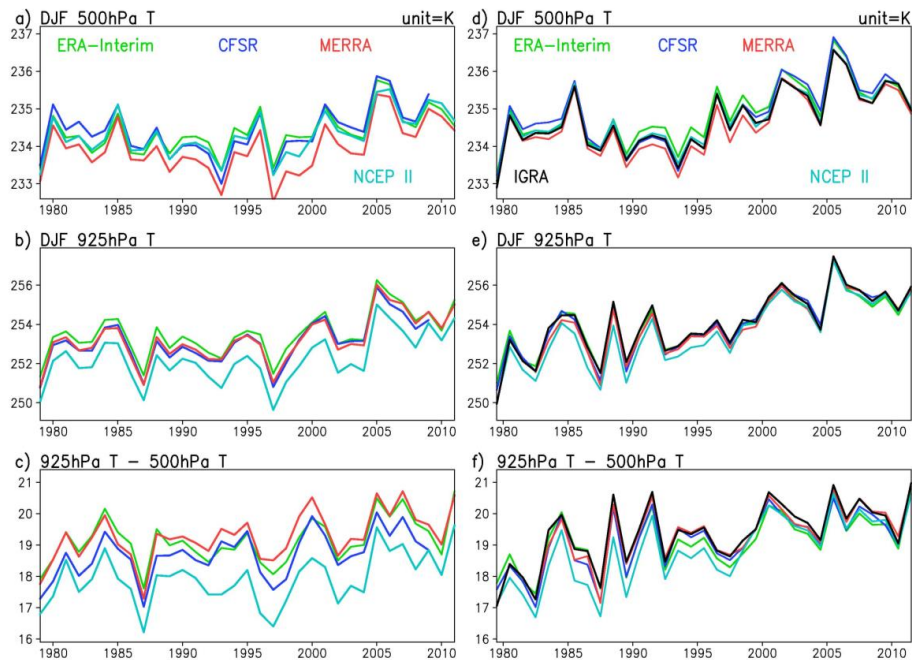
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**Fig. 6.** Same as Fig. 3 except for the DJF (December, January and February) season.

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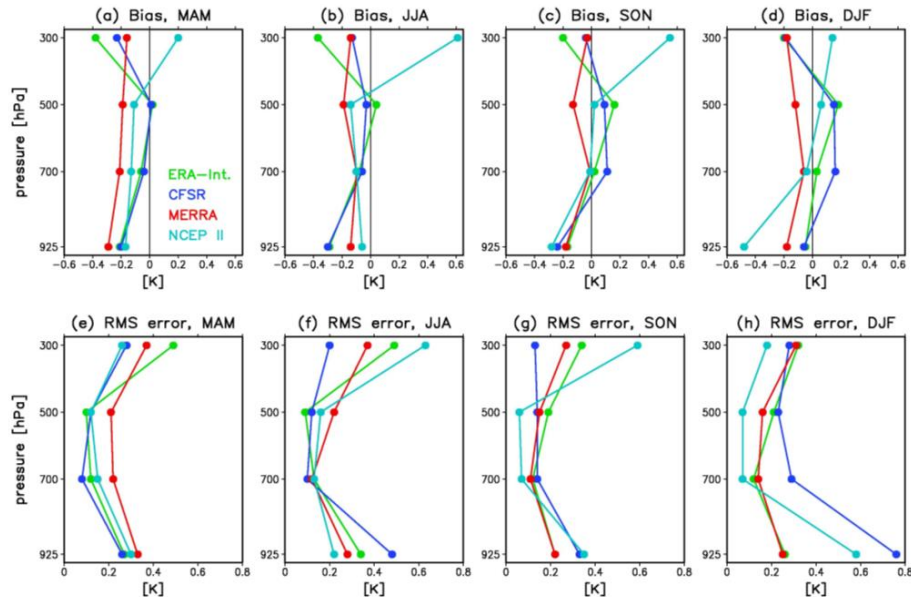
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**Fig. 7.** Mean bias and r.m.s. error of seasonal 70–90° N average temperature in each reanalysis, relative to the IGRA data, in units of K. In the computation, we use the reanalysis data that correspond to the available IGRA observations.

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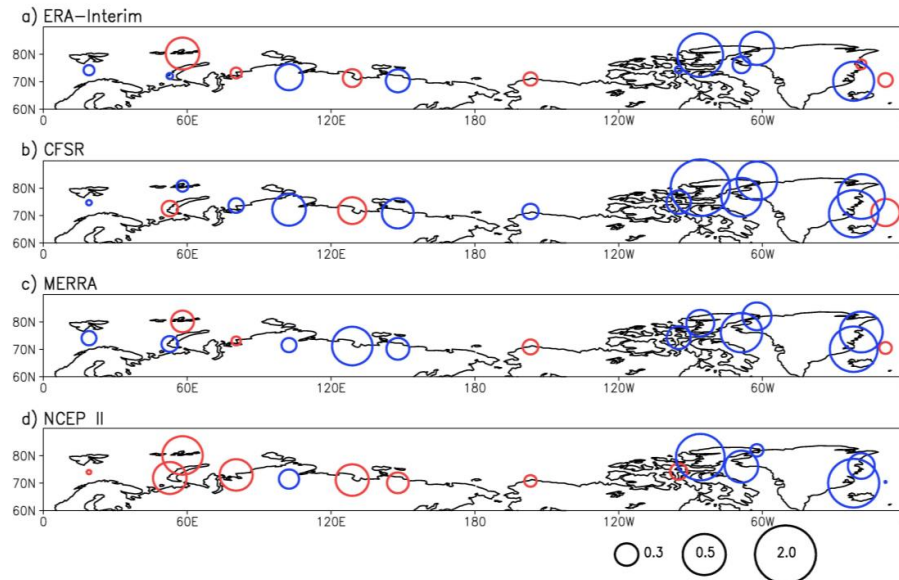
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**Fig. 8.** Evaluation of the reanalyses with the IGRA data in June–August 2000–2009 average 925 hPa  $T$ . The reanalysis data used here match the available IGRA observations in location and time. Shown is reanalysis temperature bias at each IGRA station in units of K, with the circle size indicating the magnitude of the bias. When the bias is positive (negative), the circle is colored red (blue).

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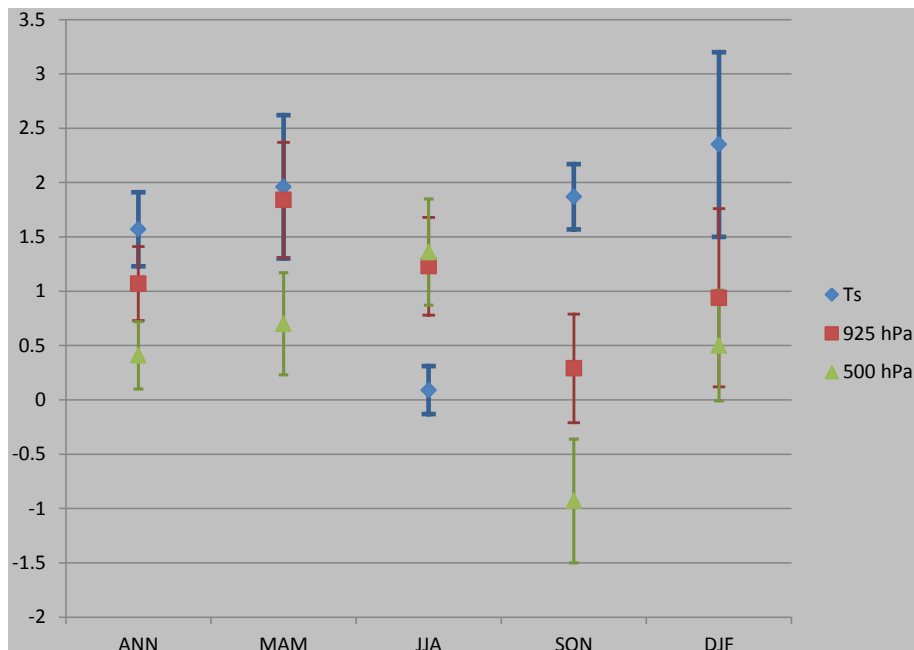
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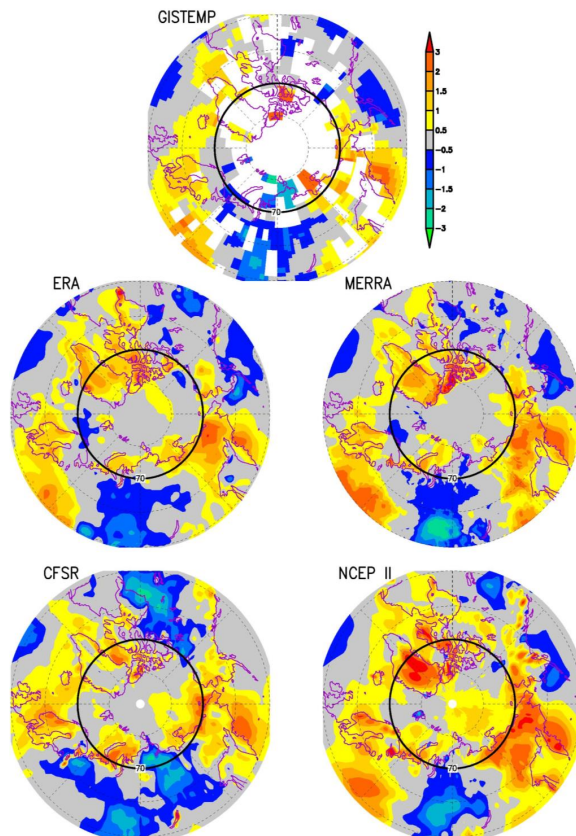
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**Fig. 9.** 70–90° N average temperature trend from 1998 to 2011 in units of change (in K) over the 14 yr, as in Table 4. All the trends here are from pure observations (either GISTEMP or IGRA data) and not from the reanalyses. The error bar represents  $\pm$  standard error of the trend.

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**Fig. 10.** June–August average  $T_s$  trend from 1998 to 2011 in units of change (in K) over the 14 yr for GISTEMP and for the four reanalyses. In case of CFSR, the trend is from 1998 to 2009 in units of change over the 12 yr. White areas in the GISTEMP plot indicate missing data or insufficient data for the trend analysis. Note that  $T_s$  refers to surface air temperature (SAT) for the reanalyses, and to a combination of SAT over land and SST over ocean for GISTEMP. The 70° N circle is thickened in each panel.

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