ERA-40 Project Report Series

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ERA-40 Project Report Series No. 18

Comparison of trends and variability in CRU, ERA-40 and NCEP/NCAR analyses of monthly-mean surface air temperature

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Abstract

Monthly-mean anomalies in surface air temperature from the ERA-40 and NCEP/NCAR reanalyses are compared with corresponding values from the CRUTEM2v dataset, which is derived directly from monthly station data. There is mostly very good agreement as regards short-term variability, particularly between ERA-40 and CRUTEM2v. Least-square linear trends are significantly lower for the two reanalyses when computed over the full period studied, from 1958 to 2001, but ERA-40 trends are within 10% of CRUTEM2v values for the northern hemisphere when computed over the period from 1979 onwards. A small number of erroneous station values that entered the CRUTEM2v analysis and an even smaller number of highly suspect values in the reanalyses have been identified by the three-way comparison. Gaps in the availability of synoptic surface data contribute to relatively poor performance of ERA-40 prior to 1967.

Trends and variability are quite similar in the ERA-40 background and analysis fields, although the increments made to the background by ERA-40's analysis of synoptic screen-level temperature observations bring closer agreement with CRUTEM2v. The increments reduce a warm model bias prevalent at middle and high latitudes and a cold bias at low latitudes. Trends and variability in ERA-40 temperature analyses throughout the boundary layer are generally similar to those at the surface from the late 1970s onwards. Evidence points to a cold bias early in the period at 500hPa over the data-sparse southern extratropics and at the surface over Antarctica. One indicator of this comes from comparing the ERA-40 analyses with a simulation produced using the same model and same distributions of sea-surface temperature and sea-ice as used in the ERA-40 data assimilation. The simulation itself reproduces quite well the trends in surface air temperature over land seen in CRUTEM2v, and captures some of the variability.

1 Introduction

Comprehensive reanalyses derived by processing multi-decadal sequences of past meteorological observations using modern data assimilation techniques developed for numerical weather prediction (NWP) have found widespread application in many branches of meteorological and climatological research. Their utility for helping to document and understand climatic trends and low-frequency variations is nevertheless a matter of some debate. Problems arise partly because the atmospheric models that carry the assimilated observational information forward in time have biases. If observations are abundant and unbiased, they can correct the bias of a background model when assimilated. In reality, however, observational coverage varies over time, some types of observation are themselves prone to bias, and observational biases vary over time. This introduces trends and low-frequency variations in analyses that are mixed with the true climatic signals. Progress in the longer term depends on identifying and correcting model biases, accumulating as complete a set of historic observations as possible, and developing improved methods of detection and correction of observational biases. In the shorter term, awareness of how these factors influence a particular reanalysis can help in the interpretation of its results.

The temperature trend of most direct public interest is that at the surface. Kalnay and Cai (2003) examined trends and variability in surface air temperature over the USA, comparing results from the NCEP/NCAR reanalysis (Kalnay *et al.*, 1996) with corresponding data for 1950 to 1999 from stations below 500m elevation. They reported a quite good degree of agreement as regards interannual variability, but found that the reanalysis gave significantly less net warming over time than seen in the station data. They noted that synoptic station measurements of surface air temperature had not been used in the production of the NCEP/NCAR reanalyses; the surface air temperature product was derived instead from analysed atmospheric values that were constrained primarily by observations of upper-air variables and surface pressure. They argued that warming in the surface station data caused by urbanization and land-use change could be a significant factor in explaining the difference between the trends in reanalysis and station values. Their study attracted criticism (Trenberth, 2004, and Vose *et al.*, 2004) to which Cai and Kalnay (2004) responded.

The present study is a new comparison of processed station values of monthly-mean surface air temperature with values from two reanalyses, ERA-40 and NCEP/NCAR. A global view is taken and upper-air data from ERA-40 and a corresponding simulation are used as part of the evaluation.

ERA-40 is the most recent comprehensive reanalysis to be completed, and the first to provide an alternative to the NCEP/NCAR reanalysis for the years before 1979. Observations from September 1957 to August 2002 were analysed using a version of the ECMWF data assimilation system. A general account of ERA-40 is currently being prepared; in the meantime, considerable information can be found on the project's web pages (http://www.ecmwf.int/research/era) and in other project reports (http://www.ecmwf.int/publications).

One of the products of ERA-40 is a set of analyses of temperature at a height of two metres, for the observing times 00, 06, 12 and 18UTC. These analyses were produced as part of the ERA-40 data assimilation, but not directly from the primary three-dimensional variational analysis of atmospheric fields. Instead, a separate analysis of measurements of dry-bulb temperature was made using optimal interpolation. The background field for this analysis was derived from the background forecast of the main data assimilation, by interpolating between the lowest model level (at a height of about 10m) and the surface. The interpolation made use of Monin-Obukhov similarity profiles consistent with the assimilating model's parametrization of the surface-layer part of the planetary boundary layer (Beljaars and Viterbo, 1999). Details of the optimal interpolation analysis are given in an appendix to this report.

The two-metre temperature analysis and a corresponding analysis of two-metre humidity were developed primarily to provide input to an analysis of soil temperature and moisture (Douville *et al.*, 2000). This surface analysis assumes that error in model background values of surface air temperature and humidity are indicative of error in model background values of soil temperature and humidity. The two-metre temperature analysis was not used to modify the model-level atmospheric fields from which the background forecast for the next analysis in the data assimilation sequence was initiated. It nevertheless influenced this background forecast through the adjustments made to the model's soil temperature and moisture fields by the surface analysis.

The monthly-mean ERA-40 and NCEP/NCAR analyses of two-metre temperature have been compared with the CRUTEM2v dataset of surface air temperature anomalies of Jones and Moberg (2003), referred to in subsequent paragraphs simply as CRU data. CRUTEM2v uses all available monthly station averages of mean temperature from land regions of the world. Full details of the sources used are given in Jones and Moberg (2003). In order to cope with stations that are at different elevations and sometimes calculate monthly averages in different ways, station averages are used only if there are sufficient data to derive monthly climatic normals for the station for the period 1961-90. CRUTEM2v additionally adjusts individual grid-box series for changes in station numbers in each 5º by 5º square (Jones *et al*., 1997; Jones *et al*., 2001). Another dataset (HadCRUT2v) is available from the Climatic Research Unit web site (http://www.cru.uea.ac.uk). It includes estimates of sea surface temperature (SST) anomalies over marine regions, using SST data derived from Rayner *et al*. (2003). As the same SST analyses were used in ERA-40 up to November 1981, and similar though not identical analyses from NCEP (Reynolds *et al.*, 2002) were used thereafter (Fiorino, 2004), comparisons in this report are restricted to the predominantly terrestrial regions covered by the CRUTEM2v dataset.

Some computational details are given in the following section. Section 3 presents the main comparisons of surface air temperature between the CRU, ERA-40 and NCEP/NCAR analyses. Time series are presented for different geographical regions, maps of the linear trends computed over the periods 1958-2001 and 1979-2001 are discussed, and data values that are particularly suspect in either of the reanalyses or in the CRU dataset are identified. Some further results for the ERA-40 reanalysis are presented in sections 4 and 5. The consistency between the two-metre temperature analyses, corresponding background values and analysed boundary-layer temperatures is discussed in section 4. Section 5 provides further insight through comparison with results from an atmospheric simulation of the ERA-40 period produced by the model used for the ERA-40 data assimilation, forced by the sea-surface temperatures and sea-ice distributions likewise used for the ERA-40 assimilation. Conclusions are presented in section 6.

2 Some computational details

The CRU data are values for a set of 5^ox5^o grid boxes. Corresponding 5^ox5^o values of the reanalyses were needed to make comparisons. For ERA-40, linear interpolation was used to transform analysis and background values of two-metre temperature from the native computational grid of the assimilating model, an irregular grid with approximately uniform spacing of about 125km (Hortal and Simmons, 1991; Courtier and Naughton, 1994), to a finer 0.5^o regular latitude/longitude grid. The basic T159-truncated spherical harmonic representation of atmospheric model fields was used directly to evaluate model-level values on this 0.5^o grid. All comparisons presented here used 5^ox5^o ERA-40 values derived by calculating area averages of the 0.5^o values. Several of the comparisons were repeated using 5^ox5^o ERA-40 values based on the simpler approach of direct linear interpolation from the ERA-40 to the CRU grid. Little difference was seen.

To enable comparisons to be made with the NCEP/NCAR reanalysis (Kalnay *et al.*, 1996), monthly-mean surface air temperatures on a 2.5^o grid from this reanalysis were downloaded from the NOAA-CIRES Climate Diagnostics Center (http://www.cdc.noaa.gov). Values were averaged onto the 5^ox5^o CRU grid and otherwise processed exactly as for the 5^ox5^o ERA-40 data.

The model-based reanalyses produce complete representations of fields in space and time, for their given spatial and temporal resolutions. In contrast, for any particular month, the CRU dataset contains values only for grid boxes for which there was at least one station reporting in the box. The monthly-mean reanalysis values are based on averages over all four times of day for which analyses were produced. Except where stated below, means over groups of grid boxes and linear trends for individual grid boxes have been computed by selecting only those reanalysis values for which there is a corresponding CRU value for the month in question. No account has been taken of the model land-sea distributions in producing reanalysis values on the CRU grid. Thus for some grid boxes, the CRU values are derived from island stations whereas the reanalysis values are derived primarily or totally from model sea points. For coastal grid boxes the CRU data are based only on observations from land or offshore island stations whereas the reanalysis values are derived from a mixture of model land and sea points. Air temperatures measured aboard the fixed-position Ocean Weather Ships operated from the 1950s to the late 1990s are included in the CRU analysis.

The CRU data are analyses of anomalies for each station with respect to the monthly normals for that station, computed for the period 1961-1990. This is the best reference period as station coverage falls off during the 1990s. The reanalyses examined here have accordingly been expressed as anomalies with respect to their own monthly climatic means for 1961-1990. Anomalies of the ERA-40 background forecasts and model simulation have been computed with respect to the climate of the ERA-40 analyses. Working with anomalies rather than absolute values avoids the need to make adjustments for differences between station heights and the terrain heights of the assimilating reanalysis models.

For display of time series, each set of analysed monthly anomalies has been adjusted by subtracting its 180-month mean value for the period 1987-2001. The mean value for the ERA-40 analysis was subtracted in the case of the ERA-40 background and simulation. The period 1987-2001 was chosen as a reference so as to present the time series in what is arguably the fairest light. Observational coverage (apart from radiosondes) and quality are generally best for the most recent years, the data assimilation and forecast statistics for ERA-40 indicate best performance of this reanalysis then, and (as will be seen later) the consistency of temporal variations between surface and upper levels in ERA-40 and between the reanalyses and CRU data is best then. Evidence will be presented of biases in ERA-40 that are relatively large prior to 1967, and still quite significant over the southern hemisphere until the 1980s. Without the adjustment, comparison of the time series of monthly anomalies with respect to 1961-1990 would show a misleading mean discrepancy between the CRU and ERA-40 time series for the most recent years.

3 Comparison of analyses of surface air temperature

3.1 Time series of area-averages from the CRU and ERA-40 analyses

Figs. 1 and 2 show time series of monthly ERA-40 and CRU values for the period 1958-2001. Corresponding twelve-month running means are also plotted. Fig. 1 presents values averaged over all CRU grid boxes for which data are available, and over all boxes in the northern and southern hemispheres respectively. Fig. 2 shows averages for Europe, North America and Australia, based on selecting all CRU grid-boxes within the domains (35^o-80^oN, 10^oW-40^oE), (20^o-80^oN, 170^o-50^oW) and (50^o-10^oS, 110^o-160^oE) respectively. Averages were made with area weighting by the cosine of the central latitude of each grid box. By construction the means of the ERA-40 and CRU anomalies over the period 1987-2001 are both zero.

It can be seen from Figs. 1 and 2 that the overall warming trends are smaller for ERA-40 than for CRU. Much of this comes from differences in the first half of the period; it is difficult in these plots to distinguish between the ERA-40 and CRU curves beyond the mid 1970s for the northern hemisphere. Table 1 shows linear least-square trends derived from the monthly-mean data for the full period 1958-2001, and for 1979-2001. Over the northern hemisphere, and for Europe and North America separately, the ERA-40 trend is about 30% smaller than the CRU trend for the full period, but within 10% of the CRU trend for 1979 to 2001. Agreement is less good for the southern hemisphere. For Australia, ERA-40 cools over the period as a whole, whereas CRU warms, albeit at a lower rate than for other regions (see also Jones and Moberg, 2003).

Table 1: Linear trends (^{o}C/decade) for the CRU, ERA-40 and NCEP/NCAR analyses, and for the ERA-40 background and simulation

		Global	N Hem	S Hem	Europe	N America	Australia
1958 to 2001	**CRU**	0.16	0.19	0.13	0.17	0.21	0.14
	ERA-40	0.10	0.13	0.04	0.11	0.14	-0.10
	NCEP/NCAR	0.10	0.14	0.03	0.16	0.11	-0.08
	Background	0.07	0.09	0.03	0.06	0.14	-0.09
	Simulation	0.14	0.14	0.14	0.14	0.14	0.22
1979 to 2001	**CRU**	0.24	0.30	0.11	0.46	0.30	0.01
	ERA-40	0.20	0.27	0.04	0.42	0.28	-0.10
	NCEP/NCAR	0.11	0.19	-0.06	0.31	0.25	-0.12
	Background	0.17	0.23	0.04	0.37	0.30	-0.07
	Simulation	0.22	0.27	0.10	0.38	0.32	0.19

The discrepancy between the ERA-40 and CRU curves in Figs. 1 and 2 is particularly marked before 1967. This appears to be related to limited availability of surface air temperature observations for ERA-40 combined with a net warm bias in the model background forecasts of two-metre temperature over this period. Most of the observations prior to 1979 assimilated in ERA-40 were supplied by NCAR, with Antarctic observations supplied also by the British Antarctic Survey[1] and the Australian Bureau of Meteorology. At the time of data supply, NCAR's holdings for the early years of ERA-40 had some serious deficiencies, with very few synoptic reports from Australia and several European countries, for example. Coverage in fact declines over the period from 1958 to 1966. Data from many countries can be seen to be missing in the data coverage for the 12UTC analysis for 1 July 1966 shown in the upper panel of Fig. 3. This example is typical of coverage for the years 1965 and 1966. Many more observations were supplied from 1967 onwards[2], both filling national gaps and increasing the density of coverage generally. The number of observations jumps on 1 January 1967 and increases during subsequent months; the number of land stations providing data for the 12UTC analysis is 2602 for 1 July 1966, 2529 for 31 December 1966, 4739 for 1 January 1967 and 6684 for 1 July 1967. The coverage for the latter date is shown in the lower panel of Fig. 3. A complete set of data coverage maps showing observation frequencies month by month for each observation type can be viewed on the project web site (http://www.ecmwf.int/research/era/) under the section on monitoring[3].

The quality of the ERA-40 analysis of two-metre temperature depends not only directly on the availability of the assimilated synoptic observations, but also on the quality of the background forecasts. Background-forecast accuracy for two-metre temperature is likely to have improved over the course of ERA-40 due partly to general improvement over time of the atmospheric observing system, but also due to improvement over time in the initial soil-moisture and snow-cover conditions used in the background forecasts. As noted earlier, the soil-moisture analysis uses the two-metre temperature analysis and a corresponding humidity analysis as input, and thus is likely to be more reliable for later years when there is a better coverage of screen measurements. The snow analysis uses observations of snow depth. These were limited to Canada for the early years of ERA-40. Data for the former Soviet Union were available from 1966 onwards, but data for other countries could be used only from 1976 onwards.

Notwithstanding the differences in long-term trends, Figs. 1 and 2 show very similar shorter-term variability in the ERA-40 and CRU analyses throughout the period. Table 2 shows correlations and root-mean-square differences between the ERA-40 and CRU time series of monthly anomalies, after removal of mean differences and linear trends. Results are presented both for the full period, 1958-2001, and for 1979-2001. Over the full period there is much better agreement between ERA-40 and CRU for the northern than for the southern hemisphere, with a correlation as high as 99.6% for Europe and a correlation of 92.5% for Australia. Agreement is distinctly better for the southern hemisphere when the comparison is restricted to 1979-2001; the correlation for Australia increases substantially to 97.3%. The root-mean-square difference for Australia reduces from 0.22^{o}C for the full period to 0.13^{o}C for 1979-2001.

1. These data were used by Jones and Moberg (2003) in producing the CRUTEM2v dataset; see also Turner *et al.* (2004). Due to a technical problem, not all were assimilated in ERA-40.
2. The better coverage of surface observations came from NCAR's copy of US Air Force archives for the period 1967-1976, and subsequently from NCEP's and ECMWF's operational archives.
3. The web-site plots of synoptic data coverage, unlike those in Fig. 3, include stations reporting only snow depth.

Table 2: Correlation (%) and rms difference (^oC) between the monthly CRU analyses and the ERA-40 analyses, the NCEP/NCAR analyses, the ERA-40 background and the ERA-40 simulation, with mean and linear trend removed

		Global	N Hem	S Hem	Europe	N America	Australia
Correla-tion 1958-2001	**ERA-40**	97.8	98.3	92.6	99.6	98.7	92.5
	NCEP/NCAR	93.1	93.4	87.6	98.1	96.7	94.1
	Background	95.5	96.0	88.9	99.1	97.2	90.4
	Simulation	49.7	40.0	54.0	14.0	25.7	13.8
Correla-tion 1979-2001	**ERA-40**	98.8	98.8	96.3	99.6	99.1	97.3
	NCEP/NCAR	95.1	95.2	88.0	98.8	97.1	94.0
	Background	97.4	97.7	91.9	99.3	98.0	95.4
Difference 1958-2001	**ERA-40**	0.06	0.06	0.09	0.09	0.12	0.22
	NCEP/NCAR	0.10	0.12	0.11	0.18	0.19	0.19
	Background	0.08	0.10	0.11	0.14	0.18	0.24
	Simulation	0.26	0.36	0.24	1.07	0.85	0.73
Difference 1979-2001	**ERA-40**	0.04	0.05	0.06	0.08	0.11	0.13
	NCEP/NCAR	0.08	0.10	0.11	0.15	0.20	0.20
	Background	0.06	0.07	0.09	0.13	0.17	0.17

Betts and Beljaars (2003) document a subset of near-surface ERA-40 data for the period 1986-1995 produced in support of the second International Land-Surface Climatology Project (ISLSCP-II). They briefly discuss the agreement between the two-metre temperature analyses included in the dataset and a gridded ISLSCP-II dataset of monthly-mean surface temperatures derived from an earlier Climatic Research Unit dataset (New *et al.*, 1999 and 2000). Although absolute seasonal-mean values show some differences, particularly in regions of high terrain, close agreement is seen in the sample maps of anomalies presented by Betts and Beljaars.

3.2 Comparison with the NCEP/NCAR reanalysis

Fig. 4 shows times series of the twelve-month running means of the ERA-40, CRU and NCEP/NCAR temperature anomalies averaged over all CRU grid boxes for the northern and southern hemispheres. Although all three time series are in broad agreement, it is ERA-40 of the two reanalyses that is generally in closer agreement with CRU from 1967 onwards. Examining the results for NCEP/NCAR included in Table 1 it can be seen that whilst there is little to choose between the two reanalyses as regards trends over the whole period, the trends for 1979-2001 from ERA-40 are in closer agreement with CRU than are the corresponding trends from NCEP/NCAR. Table 2 shows substantially higher correlations and smaller root-mean-square differences between ERA-40 and CRU than between NCEP/NCAR and CRU, except for Australia when calculated over the full period.

Fig. 5 presents time series of monthly differences between the ERA-40 and CRU values and between the NCEP/NCAR and CRU values. They are for averages over the northern and southern hemispheres, and for averages restricted to Europe and North America. These plots show again that ERA-40 is generally the closer of the two reanalyses to the CRU values from 1967 onwards, and that the NCEP/NCAR reanalysis exhibits a more pronounced trend relative to the CRU analyses from the mid to late 1970s onwards. The NCEP/NCAR plots also show generally larger intra-annual variations than the ERA-40 plots. As the mean annual cycle computed for the period 1961-1990 is subtracted from each dataset, this indicates a greater variability over the period in the annual cycle in the NCEP/NCAR reanalysis than in either the ERA-40 reanalysis or the CRU dataset. Part of the reason ERA-40 performs better than NCEP/NCAR in this regard is its use of observations of surface air temperature. Intra-annual variability in differences from the CRU dataset is more pronounced for the background temperatures from the ERA-40 assimilation than for the analyses, though not as large as for the NCEP/NCAR analyses. Such variability may arise from biases in the annual cycle of two-metre temperature in the assimilating reanalysis models, either because control of these biases in the analysis process varies due to a varying observing system or because the biases themselves vary due to natural inter-annual variations of the atmospheric circulation.

3.3 Geographical distribution of trends

Maps showing the least-squares linear trends for each CRU grid box are presented for the CRU, ERA-40 and NCEP/NCAR analyses in Fig. 6. Trends are shown for the periods 1958-2001 and 1979-2001. Values are plotted only for grid boxes for which there is a quite complete temporal record in the CRU dataset. They are shown for all grid boxes for which data from no more than 48 months were missing from the 44 years in the case of the 1958-2001 trend, and for which no more than 24 months of data were missing for the 1979-2001 trend. As such linear trend calculations can be particularly sensitive to data values close to the end points of time series, examination has also been made of the differences between eleven-year means for 1958-1968, 1969-1979, 1980-1990 and 1991-2001. This confirmed the findings reported below for linear trends.

There is reasonable agreement between ERA-40, NCEP/NCAR and CRU for many features of the linear trends for 1958 to 2001 shown in Fig. 6. All datasets exhibit predominant warming over Europe, northern Asia and northern America. ERA-40 shows a pronounced (and almost certainly erroneous) cooling over much of Australia. There is also strong cooling in ERA-40 for grid boxes in tropical South America east of the Andes where, as for Australia, there were few surface observations available for assimilation in ERA-40 prior to 1967 (see Fig. 3). NCEP/NCAR is closer than ERA-40 to CRU full-period trends for Australia and tropical South America. Both ERA-40 and NCEP/NCAR show more warming than CRU at several of the small number of Antarctic grid boxes.

ERA-40 does not show the warming over the United Kingdom, Norway and Sweden that is seen in the CRU data for the 1958-2001 period. Here too there was relatively poor or nonexistent coverage of synoptic observations prior to 1967 in the data sets supplied for assimilation in ERA-40 (see again Fig. 3). The same behaviour is, however, seen also for the NCEP/NCAR reanalysis, which did not use surface air temperature measurements at any time.

Fig. 6 shows a distinctly closer agreement between ERA-40 and CRU trends for 1979-2001, as has already been discussed for the regional means. This is the case in particular for northwestern Europe, tropical South America and Antarctica. The disagreement over Australia is less marked, but ERA-40 still has many more Australian grid boxes with cooling than CRU, as does NCEP/NCAR. The CRU trends for 1979-2001 are matched more closely by ERA-40 than by NCEP/NCAR in several regions: around the Mediterranean and over Chile and Argentina, for example. Overall, of the two reanalyses ERA-40 is the one that is closer to CRU at 64% of the CRU grid boxes for the 1979-2001 trend. The figure is 55% for the 1958-2001 trend.

Corresponding figures are 68% and 57% for trends derived respectively from differences between the 1991-2001 and 1980-1990 means and from differences between the 1991-2001 and 1958-1968 means.

The reanalysis data assimilation systems provide a complete global representation of two-metre temperature. The upper three panels of Fig. 7 show the twelve-month running means of the anomalies of ERA-40 temperature averaged over all land points, and averaged over all northern and southern hemisphere land points. Also shown for comparison are the corresponding ERA-40 values limited to the CRU grid boxes and the CRU values themselves, as presented in Fig. 1. The ERA-40 temperature averaged over all land points matches the CRU temperature well throughout the period, but this is fortuitous. In the early years, ERA-40 values for all northern hemisphere land points are warmer than the northern hemisphere CRU values, but this is balanced by much colder ERA-40 values for the southern hemisphere.

The individual monthly values for ERA-40 over all southern hemisphere land points are shown in the bottom panel of Fig. 7. A distinct warming of about 0.5^{o}C occurs at the beginning of 1980. The overall observing system for the southern hemisphere was dramatically improved around the end of 1978, with better satellite temperature and humidity sounding, new winds deduced from geostationary satellite imagery, new surface observations from drifting buoys and increased data from commercial aircraft. Characteristics of the ERA-40 data assimilation and the accuracy of medium-range forecasts initiated from the ERA-40 analyses are much improved from 1979 onwards (e.g. Simmons, 2003). Others have noted improved agreement between ERA-40 and extratropical southern hemispheric station data (Bromwich and Fogt, 2004) and improved agreement between ERA-40 and NCEP/NCAR (Sterl, 2004) from 1979 onwards. In the light of this, the shift in the southern hemisphere two-metre temperature analysis at the beginning of 1980 may not reflect a change in the observing system (or data collection) at that time, but rather a fundamental shift that would have been seen one year earlier had it not been masked by interannual variability, which the bottom panel of Fig. 7 shows can be of the order of 0.5^{o}C.

The upper panels of Fig. 8 show maps of the complete global trends of the ERA-40 two-metre temperature analysis for the periods 1958-2001 and 1979-2001. The reanalysis shows a spatially coherent warming at northern latitudes, encompassing both land and sea-ice points where there are missing values in the CRUTEM2v dataset. It also shows a pronounced warming over Antarctica, particularly for the full 1958-2001 period. The warming over this region and over southern Africa contributes to the larger warming seen when averages are taken over all land points rather than just the CRU points. It has already been noted that ERA-40 shows more warming than CRU over 1958-2001 at several of the few Antarctic grid boxes for which comparison can be made. Other results that cast doubt on the ERA-40 trend over Antarctica are presented later.

The trends in the ERA-40 two-metre temperature analyses over the oceans are not surprisingly very similar to the trends in the externally-produced sea-surface temperature analyses used by the ERA-40 data assimilation (Reynolds *et al.*, 2002; Rayner *et al.*, 2003; Fiorino, 2004). Maps of the trends in SST are presented in the lower panels of Fig. 8. The regions of warming and cooling over the oceans for 1979-2001 match quite well the regions of warming and cooling seen both in measured layer-average tropospheric temperatures from channel-2 of the satellite-borne Microwave Sounding Unit and in equivalents derived from the ERA-40 analyses (Santer *et al.*, 2004). Cooling earlier in the period south of Greenland is consistent with temporal shifts in the analysed flow patterns (not shown) over the northwestern Atlantic.

Over the Indian and tropical western Pacific Oceans the two-metre temperature analysis shows a weaker warming trend than the SST analysis. An intermediate trend is found for the background field, indicating that the surface air temperature observations assimilated in ERA-40 tend to counteract some of the trend imposed by the SST analysis in this region. Examination of analysis increments indicates a strong daytime warming of the background field due to assimilation of air temperature measurements from ships, which probably arises due to an uncorrected effect of solar heating (Tett, personal communication). As there are changes over time in both ship size and the number of analysed observations from buoys, differences in trend between the ERA-40 two-metre temperature analyses over sea and the SST analyses cannot be regarded as reliable.

3.4 Identification of suspect values

The three-way comparison of the CRU, ERA-40 and NCEP/NCAR analyses has identified a relatively small number of highly suspect values in these datasets. For example, the difference between ERA-40 and CRU temperatures for Europe plotted in Fig. 5 is atypically large for November 1981. The same is true for the difference between NCEP/NCAR and CRU; this cannot be seen in Fig. 5 as the dip in the NCEP/NCAR plot is masked by the dip in the ERA-40 plot. The cause of the difference has been identified as erroneous values from several Turkish stations entering the CRU analysis. To illustrate this, Table 3 shows the data points and data values for the ten points (out of a total of 38297) from the European area for which both the ERA-40 and the NCEP/NCAR anomalies differ from the CRU anomaly by more than 5^{o}C. Three of the entries, including the two for which differences are largest, are from grid boxes within Turkey for November 1981, and it is the CRU anomalies rather than the anomalies from the two reanalyses that are unusually large. This problem with the Turkish data for 1981 is not confined to the CRU dataset. The same wrong data are also evident in the WMO publications *Monthly Climatic Data for the World* and *World Weather Records*.

Table 4 shows a set of North American data points that exhibit extreme values. The ten points and data values for which the NCEP/NCAR anomaly differs from the CRU anomaly by more than 10^{o}C are tabulated. All are high-latitude points in winter or spring, suggesting problems with snow or sea-ice fields as a likely cause. The points clearly divide into two groups of five. The first is characterised by highly anomalous CRU values, and ERA-40 values that are similar to NCEP/NCAR values, suggestive of erroneous (or highly unrepresentative) CRU values. The second is characterised by highly anomalous NCEP/NCAR values, and ERA-40 values that are similar to CRU values. This suggests a problem in the NCEP/NCAR reanalyses for these five data points. Three refer to a single grid box for the winter months of 2000/2001. Two refer to neighbouring grid boxes for December 1980. There is no North American data point other than the first five shown in Table 4 at which the ERA-40 anomaly differs from the CRU anomaly by more than 10^{o}C.

Overall, there are fourteen points in whole dataset where the ERA-40 anomaly differs from the NCEP/NCAR anomaly by more than 10^{o}C. Ten are over North America, and for each one it the ERA-40 anomaly that is closer to the CRU anomaly. Four are over Antarctica, and for three of these it is the NCEP/NCAR anomaly that is closer to the CRU anomaly. There are 35 points in the whole dataset where the ERA-40 anomaly differs from the CRU anomaly by more than 10^{o}C. For all but four (all of which are over Antarctica) it is the CRU anomaly that is the larger of the two. The total number of data points is 388315. Several errors in station values entering the CRU analyses other than those from Turkey for November 1981 have been identified from this three-way comparison of CRU, ERA-40 and NCEP/NCAR values. The Climatic Research Unit is currently working to correct values that are clearly in error and to revise station normals, and is collaborating with the Hadley Centre of the Met Office to produce a new HADCRUT3 dataset which is scheduled to be completed by the end of 2004.

Table 3: European grid boxes for which the differences between ERA-40 and CRU anomalies and between NCEP/NCAR and CRU anomalies both exceed 5°C in magnitude. Entries are ordered by the magnitude of difference between ERA-40 and CRU. Values of the CRU anomaly and its difference from ERA-40 and NCEP/NCAR values are given in °C for each grid box.

Month	Latitude	Longitude	CRU	ERA-40 - CRU	NCEP - CRU
Nov 1981	40N-45N	30E-35E	7.7	-9.1	-8.9
Nov 1981	35N-40N	30E-35E	6.8	-8.5	-9.5
Feb 1976	40N-45N	20E-25E	5.8	-7.4	-8.1
Feb 1966	75N-80N	15E-20E	-2.1	-6.7	-7.3
Feb 1991	50N-55N	20E-25E	4.9	-6.6	-5.8
Nov 1981	35N-40N	35E-40E	4.3	-5.9	-7.0
Feb 1963	70N-75N	15E-20E	-9.8	5.8	5.6
Dec 1967	70N-75N	10W-5W	-0.3	-5.7	-5.6
Apr 1993	50N-55N	15E-20E	-3.7	5.3	5.2
Mar 1976	40N-45N	20E-25E	3.7	-5.3	-6.1

Table 4: North American grid boxes for which the difference between NCEP/NCAR and CRU anomalies exceeds 10oC in magnitude. Entries are ordered by the magnitude of these differences. Values of the CRU anomaly and its difference from ERA-40 and NCEP/NCAR values are given in oC for each grid box.

Month	Latitude	Longitude	CRU	ERA-40 - CRU	NCEP - CRU
Jan 1963	75N-80N	70W-65W	24.9	-19.6	-20.2
Feb 1964	75N-80N	70W-65W	-13.8	17.8	18.5
May 1961	75N-80N	70W-65W	14.3	-16.1	-16.7
May 1973	55N-60N	55W-50W	16.5	-16.1	-16.2
Jan 1995	55N-60N	160W-155W	12.5	-11.3	-12.2
Jan 2001	70N-75N	80W-75W	-3.0	1.0	12.2
Feb 2001	70N-75N	80W-75W	-1.7	0.8	12.0
Dec 1980	70N-75N	125W-120W	-2.8	1.3	10.7
Dec 1980	70N-75N	130W-125W	-2.1	0.1	10.2
Dec 2000	70N-75N	80W-75W	0.0	2.4	10.2

4 Comparisons of ERA-40 background and analysed near-surface temperatures

The significance of the agreement between the ERA-40 and CRU analyses would be limited if it resulted overwhelmingly from ERA-40's explicit analysis of observations of surface air temperature. If it did, there would be little significance to the differences in behaviour of the two-metre temperatures from the ERA-40 and NCEP/NCAR reanalyses, as the latter did not utilize such observations. In particular, results from ERA-

40 could not be used to comment on Kalnay and Cai’s (2003) use of the discrepancy between station measurements and the NCEP/NCAR reanalysis to estimate the effect of urbanization and land-use change on surface warming over the USA. It is thus important to establish whether or not a significant component of the agreement between ERA-40 and CRU comes from information brought forward in the background forecasts of the ERA-40 data assimilation, and whether or not the variations and trends in the ERA-40 two-metre temperature analyses are matched by the variations and trends of temperatures analysed higher in and above the planetary boundary layer. The latter are not affected directly by the separately analysed observations of surface air temperature, although some influence of these observations may be felt via their contribution to the analysis of soil moisture and temperature.

Examination is first made of values of two-metre temperature derived from the data assimilation’s six-hour forecasts, which provide the background fields for the OI analyses of two-metre temperature. Twelve-month running means are plotted in Figs. 9 and 10 together with corresponding values for the ERA-40 and CRU analyses. The background values are plotted as anomalies with respect to mean analysed values to show the sign of the “analysis increments”, the differences between the analysed and background values, or equivalently the direct impact of the analysed observations. The results shown in Fig. 9 are averages over all northern hemispheric grid boxes at which there are CRU data, and over European and North American subsets. Fig. 10 shows results for the southern hemisphere and for Australian and Antarctic subsets.

Background values are warmer than analysed ERA-40 values in the early part of the period for each of the northern regions shown in Fig. 9, and for Australia. Here the screen-level ERA-40 analysis brings about a smaller discrepancy with the CRU analysis than would otherwise have been the case. Quite pronounced cooling analysis increments persist throughout the period in the mean over North America, and smaller net cooling increments occur throughout for Australia. Conversely, the increment shifts from cooling early in the period to warming at the end of the period for the northern hemisphere as a whole, and for Europe in particular. Antarctica differs from other regions in that the ERA-40 analysis is substantially colder (relative to its 1987-2001 mean) than the CRU analysis (relative to its own 1987-2001 mean) prior to the late 1970s. Here analysis increments warm the ERA-40 background values systematically in the period from 1973 to 1980.

Linear trends for 1958-2001 and 1979-2001 in the ERA-40 background temperatures are included in Table 1, and correlations and root-mean-square differences between background and CRU values for the same two periods are included in Table 2. The background trends are generally weaker than the trends in the ERA-40 analyses, although North America is an exception. The CRU trends over the period 1979-2001 are nevertheless matched more closely by the ERA-40 background trends than by the trends in the NCEP/NCAR analyses. Month-to-month variations are quite well captured in the ERA-40 background. The correlations with CRU values are for the most part higher for the ERA-40 background than for the NCEP/NCAR analysis, and root-mean-square differences are correspondingly mostly smaller. The better fit that ERA-40 provides to the CRU data is not entirely a direct consequence of ERA-40’s analysis of surface observations; the information carried in the background forecasts is a factor also.

Fig. 11 presents maps of annual-mean analysis increments in temperature at two metres, at the lowest model level (level 60), which is located at a height of about 10 metres, and at level 49, which is the model level closest to 850hPa for a surface pressure close to 1000hPa. Results for 1958 and 2001 are shown. The figure illustrates how the separate OI analysis of surface observations produces much larger local mean increments in two-metre temperature than are produced by the main variational analysis either at the lowest model level or close to the top of the boundary layer. The increased availability of surface observations results in mean two-metre temperature increments over Australia, Antarctica and Brazil that are more widespread in 2001 than in 1958. The warming over the oceans from analysis of shipboard air temperature measurements, discussed earlier, can also be seen.

The greater availability of observations over the northern hemisphere is reflected in widespread mean increments in two-metre temperature in 1958 as well as 2001, and more widespread increments away from the surface also. The increments from the variational analysis at level 60 are largely consistent in sign with those from the OI surface analysis for 2001. This is seen also over North America in 1958, but over Russia in 1958 there is a large mean cooling increment at two metres but mostly a (weaker) warming at level 60. The general pattern of cooling increments at two metres over the USA, Canada and northern Eurasia and warming further south is characteristic of other years examined. Over Eurasia there is a decrease over time in the extent and intensity of the cooling increment and an increase in the warming increment. This results in the shift over time of the net increment from cooling to warming in the averages for Europe and the northern hemisphere shown in Fig. 10.

The increase over time in the warming increment over southern Europe occurs primarily in summer daytime analyses whereas that over southern Asia occurs primarily in winter night-time analyses. A shift in bias of the background forecasts could in part, following Kalnay and Cai (2003), be associated with unmodelled changes in land-use and urbanization, but as Trenberth (2004) has pointed out there are other reasons why such a shift might occur. In particular, ERA-40 exhibits a marked upward trend in water vapour at low latitudes and an increasingly excessive tropical rainfall, associated with assimilation of increasing volumes of satellite data (Andersson *et al.*, 2004). Changes in water vapour, cloud and circulation are all candidates for changing biases in background temperature. Further investigation is, however, beyond the scope of this study.

The low-latitude warming increments extend throughout the tropics. As analysis increments do not fully compensate for bias in background temperatures, the pattern of increments implies an overall warm bias in the ERA-40 analyses at high latitudes and an overall cold bias at low latitudes. Just such a pattern is seen in differences in mean temperatures for 1986-1995 between the ISLSCP-II datasets from ERA-40 and New *et al*. (1999, 2000), as illustrated by Betts and Beljaars (2003). An exception to the picture of high-latitude warm bias occurs around Greenland, where annual-mean ERA-40 increment maps such as presented in Fig. 11 show warming increments and the ISLCP-II comparisons show the ERA-40 analyses to be colder than those of New *et al*. in wintertime.

Fig. 12 shows times series of ERA-40 temperature anomalies at two metres, level 60 and level 49, averaged over CRU grid boxes for comparison with plots shown earlier. Results are presented for the northern and southern hemispheres, and for North America and Australia. From the mid 1970s onwards trends and low frequency variations in the two-metre temperature analyses are generally matched very closely by trends and low frequency variations throughout the planetary boundary layer. Agreement is close throughout the period for North America. Both level-60 and level-49 temperatures are however relatively warm early in the period for the northern hemisphere as a whole. Background temperatures at two metres have been seen to be similarly warmer than the analysed values early in the period. Two-metre and level-60 temperatures vary similarly throughout the period for the southern hemisphere, and for Australia in particular, but differences in temperature between level 49 and the surface are larger earlier in the period than later. Two-metre temperatures from ERA-40 have been shown to be biased warm compared with CRU values for the early years; the implication is that the ERA-40 biases are quite small near the top of the boundary layer for the southern hemisphere.

Kalnay and Cai (2003) attributed the underestimation of surface warming over the continental USA in the NCEP/NCAR reanalysis to an un-modelled and un-analysed effect of urbanization and land-use change. Such changes are also not modelled in ERA-40, but their effect may be felt through ERA-40's analysis of surface air temperature measurements. If significant net warming were to have been caused by changes in surface character, it would be expected that over the course of the ERA-40 reanalysis period there would be a warming trend in the analysis increment, as the observations force in a warming that would otherwise have been underestimated by the assimilation system. This is not the case over North America, where the trend in the 6h background forecast is very similar to that in the analysis. Moreover, if a significant component of the surface warming were to be due to urbanization and land-use change the warming would not be expected to be as strong throughout the planetary boundary layer. Kalnay and Cai (2003) themselves noted that weaker warming measured at upper levels could be partially explained by a predominance of land-use effects over greenhouse warming near the surface. It has, however, been shown for ERA-40 that the temperature changes at a model level close to the top of the boundary layer are very similar to those at the surface over North America.

It has been checked whether these results from ERA-40 hold also for the means over CRU grid boxes covering the eastern USA from 100W to 70W and 25N to 45N, a region that contains most of the US stations below 500m examined by Kalnay and Cai (2003). Following these authors, temperature differences between the two twenty-year periods 1980-1999 and 1960-1979 have been computed. The resulting values are 0.44^{o}C for the CRU analysis, 0.34^{o}C for the ERA-40 analysis and 0.20^{o}C for the NCEP/NCAR analysis. For ERA-40, corresponding differences are 0.38^{o}C for the background forecasts, 0.40^{o}C for the analysis at model level 49 and 0.37^{o}C for the 500hPa analysis. The larger warming found aloft and in background forecasts for ERA-40 makes it difficult to ascribe much of the discrepancy between the CRU and ERA-40 surface warmings to unmodelled urbanization and land-surface change. Some such effect cannot be ruled out, but the results presented here do not provide confidence in the estimate made by Kalnay and Cai. The increase in 500hPa temperature in the NCEP/NCAR reanalysis is in fact higher still, 0.54^{o}C. This is larger than for ERA-40 because of a shift of about 0.2^{o}C in the difference between ERA-40 and NCEP/NCAR temperatures around 1979, when there was a substantial change to the observing system.

5 Comparisons of analysed and simulated ERA-40 temperatures

It is instructive to compare the ERA-40 analyses with a simulation of the atmosphere for the ERA-40 period that has been carried out using the same model and the same analyses of SST and sea-ice cover as employed for the ERA-40 data assimilation. This provides evidence of shifts in the analyses that can be related to changes in the observing system or in the treatment of observational biases, and evidence of the extent to which variability and trends in the analyses can be regarded as forced either by the variability and trends in the SST/sea-ice analyses or by the trends in specified, radiatively active gases that were included in the ERA-40 model. The latter were based on values given in the 1995 scientific assessment of the International Panel on Climate Change (Houghton *et al.*, 1996). The model did not include any aerosol trend or variability due to volcanic eruptions, and there was no interaction between the model's radiation scheme and variable ozone fields. Instead, a fixed geographical distribution of aerosol and a climatological ozone distribution were used in the radiation calculation. There was also no variation over time in the model's vegetative characteristics.

Figs. 13 and 14 compare time series of two-metre temperature from the simulation and from the ERA-40 and CRU analyses. The simulation is presented as an anomaly relative to mean analysed ERA-40 values. Results are presented in Fig. 13 for the mean over all CRU grid boxes in the northern hemisphere, and for Europe and

North America separately, and in Fig. 14 for the southern hemisphere as a whole and for Australia and Antarctica separately.

In the hemispheric means the simulation is generally quite close to the CRU values, rarely deviating by more than 0.5^{o}C in the twelve-month running means. Some larger differences are seen regionally, of the order of 1^{o}C for Europe and Antarctica. The differences between the simulation and the ERA-40 analyses over Europe are quite similar throughout the period. In contrast, over Antarctica the ERA-40 “analysis” is very close to the simulation (and not to the CRU analysis) for the data-sparse years up to 1979, whereas beyond this time the ERA-40 and CRU analyses are in close agreement and the simulation is significantly colder than both. A different behaviour occurs for Australia. Here, the simulation is colder than the ERA-40 analysis for the early years and closer to the CRU analysis. The warm bias of the early ERA-40 analyses over Australia thus cannot be ascribed simply to an inherent bias in the climate of the assimilating model, and must be related to a characteristic of the data assimilation, albeit possibly model-related. Radiosonde data over Australia (unlike surface data) were available for assimilation in ERA-40 for the early years, and presumably countered the model’s cold mid-tropospheric bias (illustrated below). If the model’s vertical structure is such as to have a warm bias in surface temperature relative to the mid-tropospheric temperature, it is possible for the surface temperature to be biased cold in a simulation in which the mid troposphere drifts colder still, but to be biased warm in an assimilation in which the free tropospheric temperature (but not the surface temperature) is controlled by radiosonde data.

The linear trends in the simulation (included in Table 1) are substantially larger for Australia than in the CRU data, opposite to what is seen for the ERA-40 analysis. Generally, Table 1 shows that the linear trends in the simulation for the period 1958-2001 are in closer agreement with the CRU trends than are the trends in the ERA-40 analysis. The trends for 1979-2001 from the simulation and ERA-40 show similar levels of agreement with the CRU trends.

There is, not surprisingly, much poorer agreement between the simulation and CRU than between ERA-40 and CRU as regards the shorter-term variability of monthly means. This can be seen by examining the results for the simulation included in Table 2. There is, nevertheless, a quite substantial degree of correlation between the times series of twelve-month running means from the simulation and the CRU data, 76% and 82% respectively for the northern and southern hemispheric averages, and 51% for the European average, with the time-mean and linear trend removed. This almost certainly reflects a significant net influence of SST anomalies on anomalies of surface air temperature over land for sufficiently large space and time averages. If so, the agreement between the simulation and the CRU data provides partial validation of the variability of the SST analyses used in ERA-40 (see also Folland *et al*., 2001).

Maps of the linear trend from the simulation for the periods 1958-2001 and 1979-2001 are presented in Fig. 15. The simulation reproduces the predominant signal of strong warming over the northern hemisphere land masses seen in the CRU and ERA-40 analyses (Figs. 6 and 8), including the larger values seen at higher latitudes and for the 1979-2001 period. Moreover, consistent with Fig. 14, the maps from the simulation show neither the strong cooling over Australia (and tropical South America, for 1958-2001) nor the strong warming over Antarctica seen in the ERA-40 analyses. The simulation shows a slightly stronger warming trend than in the SST analyses (Fig. 8) over the Indian and tropical western Pacific Oceans, in contrast to the ERA-40 analyses which show a generally weaker trend than the SST analyses for these regions.

Fig. 16 shows twelve-month running means of the difference in temperature between two-metre height and model level 49 for the ERA-40 analysis and for the simulation. Results are shown for the average over all

CRU boxes in the northern and southern hemispheres respectively. The analysis and simulation are in quite close agreement throughout for the northern hemisphere. Both exhibit little variation over time for much of the period and a distinct increase in the temperature difference across the boundary layer towards the end of the period. In contrast, the analysed and simulated temperature differences are similar only initially in the southern hemispheric average. They start to diverge in the late 1960s and evolve in parallel from about 1980 onwards, both showing a decreasing temperature difference and similar shorter-term variations. The agreement between analysis and simulation early in the period for the southern hemisphere appears to be fortuitous. Taking the CRU analysis (and the ERA-40 analysis later in the period) to be close to the truth, the southern hemispheric analysis is biased warm at two metres in the early period, and the simulation is generally biased cold near the top of the boundary layer.

The simulation exhibits a larger cold bias at 500hPa, and the model deficiency responsible for this appears similarly to cause a cold bias at this level in the ERA-40 analyses for the southern hemisphere in the data-sparse years up to the mid 1970s. The early-period southern hemispheric bias in ERA-40 thus shifts in the vertical from predominantly warm at the (land) surface to cold at 500hPa.

This cold mid-tropospheric model bias is illustrated in Fig. 17, which presents time series of twelve-month running means of 500hPa temperature anomalies from the simulation and the ERA-40 analyses. Again, the anomalies for the simulation are defined with respect to mean analysed values. Here results are averages over the whole northern and southern hemispheres. The simulation can be seen to be colder than the analysis at 500hPa for almost all months and both hemispheres.

The ERA-40 analysis shows almost no temperature trend at 500hPa for the northern hemisphere, whereas the simulation warms at a rate of a little over 0.1^{o}C/decade, the two curves becoming close towards the end of the period. As for two-metre and boundary-layer temperature over land, much of the variability in the twelve-month running mean analysis is captured by the simulation. Results for the southern hemisphere differ in that although the simulation exhibits only a slightly larger warming trend than in the northern hemisphere, the analysis warms much more. The extent of the warming in the analysis is almost certainly exaggerated by improvement of the observing system for the southern hemisphere. Radiosonde coverage in the early years appears insufficient to counter the cold bias of the assimilating model over the hemisphere as a whole, resulting in analyses that are biased cold[1]; the advent of satellite data and other enhancements to the observing system then result in a warming of analyses during the 1970s.

The warming due to assimilation of the early satellite data appears in fact to have been too strong in ERA-40 for a number of years from 1975 onwards. Error in the bias correction of VTPR sounding data from the NOAA-4[2] satellite during 1975 and the first half of 1976 accounts for the sharp divergence between simulation and analysis that is seen over 1975 in the twelve-month running mean shown in Fig. 17. The period of highly erroneous bias correction (which produced very anomalous temperatures at higher levels) is marked by a period of particularly large monthly-mean differences between analysis and simulation at 500hPa, as can be seen in the time series of these differences that is presented for the southern hemisphere in the middle panel of Fig. 18. Differences between analysis and simulation continue to be relatively large for many months until they stabilize around 1985. This comes mostly from the tropics, for which monthly differences are shown in

1. A reduced cold anomaly at 500hPa is seen for southern hemispheric analyses early in the period when the average is restricted to CRU grid boxes; this is to be expected as radiosonde ascents are generally made from stations that also provide surface air temperature data that are used in the CRU analysis.

2. Bias correction coefficients computed for the NOAA-3 satellite were inadvertently applied in adjusting data from NOAA-4.

the bottom panel of Fig. 18. The predominant signal for the northern hemisphere (top panel) is an annual cycle. Simulated 500hPa winter temperatures are on average colder than analysed temperatures, whereas summer temperatures are similar for the first half of the period, and warmer in the simulation after 1981.

Fig. 19 shows corresponding differences between the ERA-40 and NCEP/NCAR reanalyses. They are relatively small in the northern hemisphere, where the analyses are quite well controlled throughout by radiosonde data. A low-frequency component to the northern hemispheric differences is evident however, ERA-40 being a few tenths of a degree warmer in the 1970s and a few tenths of a degree colder in the years around 1990. An upward trend in the southern hemispheric differences is partly because the NCEP/NCAR analyses do not exhibit as pronounced a cold bias in the early years as ERA-40. The ERA-40 analyses are warm relative to NCEP/NCAR from 1976 to 1985, as they are relative to the simulation, providing further evidence of a bias in the ERA-40 analyses for this period. Conversely, the larger differences for the southern hemisphere and tropics seen for the final years of the period appear to be due to a shift in the NCEP/NCAR analyses, as the ERA-40 analyses do not shift relative to the simulation.

The most likely explanation for the relatively warm 500hPa temperatures in ERA-40 from late 1976 to about 1985 is that the bias correction of satellite data, though not grossly in error, was poorer for these years than later in the reanalysis period. It does not appear to result in a strong signal in the time series of near-surface temperature, but plots presented earlier do show relatively large differences between southern hemispheric ERA-40 and CRU temperatures in 1975 and the first half of 1976, suggesting that the highly erroneous bias adjustment of NOAA-4 VTPR data had some detrimental impact right down to the surface.

6 Conclusions

It has been shown that there is a good measure of agreement between the CRUTEM2v dataset of surface air temperature anomalies derived from monthly mean station data and corresponding results from the comprehensive ERA-40 reanalysis. Linear trends computed over the full period of the comparison, 1958-2001, are generally lower in ERA-40, but there is agreement to within about 10% in the rate of warming of the terrestrial northern hemisphere since the late 1970s. Variability on shorter time scales is similar in the two datasets throughout the period examined, but agreement is better in the second half of the period than the first, especially for the southern hemisphere.

ERA-40 suffers from significant gaps in the coverage of synoptic screen-level data available for assimilation prior to 1967. Improved retrieval of pre-1967 data from national or other collections would clearly be of benefit to future reanalyses. Analysis of the southern hemisphere is likely however to remain a challenge for the data-sparse years before the introduction of comprehensive satellite, buoy and aircraft observations, as would also be analysis of the northern hemisphere for the first half of the twentieth century or earlier. Progress in this may require specific developments in data assimilation, either alternative approaches (see, for example, Whitaker *et al.*, 2004) or at least retuning of error statistics and quality control, as direct application of systems developed to work effectively in the comparatively data-rich present may well not be the best approach when data coverage is poor. Nevertheless, more than twenty-five years have now passed since the global observing system was very significantly upgraded by the additional types of observation that are an enduring legacy of the work in the 1970s of the Global Atmospheric Research Programme. For these years and into the future there is already a clear role for comprehensive NWP-style reanalysis to play alongside specific analyses of station data and other individual datasets in the monitoring of variations in climate.

Capability to produce better NWP-style analyses of the global atmosphere arises from improvements in the observing system, from improvements in the technique of data assimilation and from improvements in the realism of the assimilating model. Improvements in recent years have been substantial (Simmons and Hollingsworth, 2002), and ERA-40 has benefited from many of them. Particularly important in the present context has been work by Viterbo *et al.* (1999) to address the substantial cold bias in winter temperatures that was evident in ECMWF's earlier ERA-15 analysis (Kållberg, 1997). Comparing the ERA-40 reanalysis with the earlier NCEP/NCAR reanalysis, it is ERA-40 that is the closer to the CRU analysis for all but the earliest years. The value of having three diverse analyses available, albeit not of equal overall quality, has been demonstrated nevertheless by the way they have been used here to identify both a relatively small number of erroneous station values that entered the CRUTEM2v analysis and an even smaller number of highly suspect values in the NCEP/NCAR and (to a lesser extent) the ERA-40 reanalyses.

The two-metre temperature analysis from ERA-40 was derived by analysing surface synoptic observations; that from the NCEP/NCAR reanalysis was not. This contributed to some degree towards the better agreement between ERA-40 and the CRU analysis, although it also exposed ERA-40 to spurious trends associated with changes in synoptic data coverage. The match with the CRU analysis benefits also from the general quality of the observing and data assimilation systems used by ERA-40. Although the observation-driven analysis increments in two-metre temperature can reach annual-mean values in excess of 1^oC locally, the continental-scale trends and variability of background and analysed temperatures are quite similar, although trends are lower in the background for many regions. After the 1970s upgrade of the observing system there is overall consistency in trends and variability between the analyses of temperature at two-metre height and the analyses of temperature at model levels throughout the planetary boundary layer. Results for North America cast doubt on Kalnay and Cai's (2003) estimate of the effect of urbanization and land-use change on surface warming over the USA.

There are insufficient upper-air data earlier in the reanalysis period to prevent contamination of the southern hemispheric analysis by a cold model bias, and there are problems also with the bias correction of early satellite data. A cold bias early in the period is seen also in near-surface temperatures over Antarctica, where analysed ERA-40 values increase substantially by some 1.5^oC in the second half of the 1970s, behaviour not seen in the CRU data. Temperatures appear generally to be biased cold around Greenland, although elsewhere the ISLSCP-II comparison and patterns of analysis increments indicate a warm low-level ERA-40 bias over land at high latitudes, and a cold bias at low latitudes.

The simulation of the atmosphere over the ERA-40 period produced using the same model, sea-surface temperatures and sea-ice cover as used in the ERA-40 data assimilation has provided extra insight into the differences between the ERA-40 and CRU analyses. The simulation is of intrinsic interest in that it captures many features of the variations and trends in the CRU data. The simulation has also helped to identify problems in the ERA-40 assimilation. It was carried out for this purpose after production of the ERA-40 analyses had been completed. In future it would be advantageous to carry out such a simulation prior to a new reanalysis, as a preliminary check of both the model and the ocean boundary conditions, and to provide a baseline for use in monitoring the subsequent production of the reanalysis.

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Appendix: The ERA-40 analysis of screen-level temperature

The method of two-dimensional univariate statistical interpolation was used for the analysis of screen-level temperature in ERA-40. In a first step, the background field derived from the six-hour forecast of the data assimilation cycle was interpolated horizontally to the observation locations using bilinear interpolation, and "background increments" (the deviation between the observation and the background value) ΔX_i^b were calculated at each observation location i.

The "analysis increments" ΔX_k^a that were added to the background field at each model grid-point j to form the analysis were then derived by linearly combining the background increments at N observation points:

$$\Delta X_k^a = \sum_{i=1}^{N} W_{ki} \times \Delta X_i^b$$

The weights W_{ki} were computed by solving a matrix equation for each grid-point k:

$$(\mathbf{B} + \mathbf{O})\mathbf{W}_k = \mathbf{b}_k \qquad \text{(A.1)}$$

where the column vector $\mathbf{b}_k$ (of dimension N) represents the error covariances between background values at the observation points i and the model grid-point k and the $N \times N$ matrix $\mathbf{B}$ describes the error covariances of background values at pairs of observation points i and j. The horizontal correlation coefficients (structure functions) of background error were specified to have the form:

$$\mu_{il} = \exp\left(-\frac{1}{2}\left[\frac{r_{il}}{d}\right]^2\right)$$

where r_{il} is the horizontal separation between observation point i and point l, which is either an observation point j in the case of $\mathbf{B}$ or the model grid-point k in the case of $\mathbf{b}_k$. The horizontal scale d was set to the value 300 km. $\mathbf{B}$ and $\mathbf{b}_k$ were thus given by:

$$B_{ij} = \sigma_b^2 \mu_{ij} \text{ and } b_{ki} = \sigma_b^2 \mu_{ki}$$

where σ_b is the assumed fixed standard deviation of background errors.

The covariance matrix of observation errors $\mathbf{O}$ was set to $\sigma_o^2 \times \mathbf{I}$ where σ_o is the assumed fixed standard deviation of observation errors and $\mathbf{I}$ the identity matrix. σ_o has to take account both of measurement error and of how representative a point measurement is of the grid-square-mean estimate provided by the background model.

σ_b and σ_o were set respectively to 1.5°C and 2°C. The maximum number of observations N used to solve (A.1) was 50. The observations located nearest to the model grid-point in question were chosen, provided they lay within a radius of 1000km. The analysis was performed over land and ocean, but only land (ocean) observations were used for model land (ocean) grid points.

Gross quality checks were applied to the observations. Observations taken within a six-hour period centred on the analysis time were considered, and in the case of multiple reports from a station, only the report closest to the analysis time was used. Observations from stations whose heights differed by more than 300m from the background model orography were rejected. Any observation that differed sufficiently from the background value was also rejected, using the criterion

$$\left|\Delta X_i^b\right| > 3\sqrt{\sigma_o^2 + \sigma_b^2}$$

No bias correction was applied to the observations.

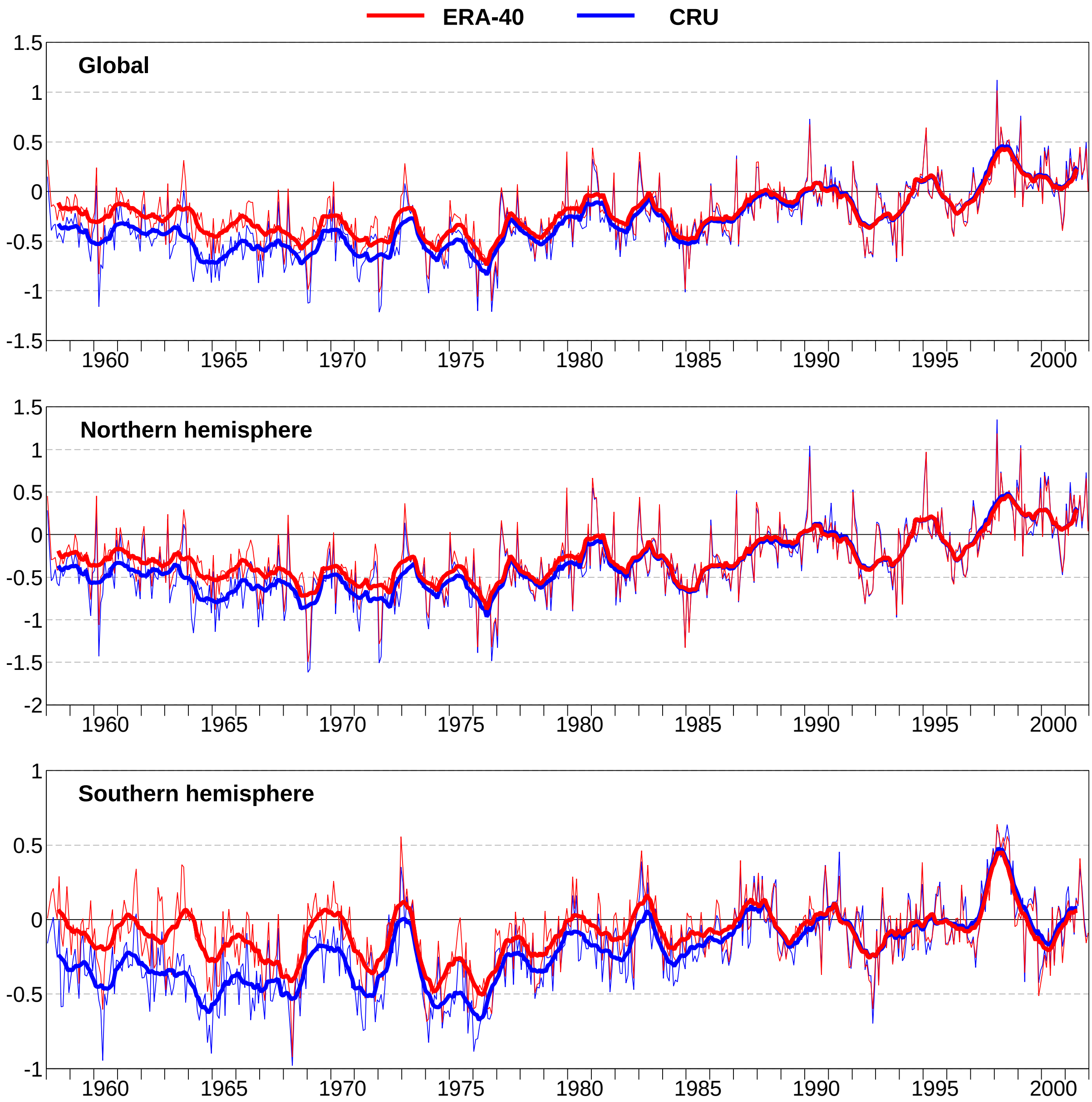


Figure 1 Time series of monthly two-metre temperature anomalies and twelve-monthly running means from the ERA-40 (red) and CRU (blue) analyses, averaged over all CRU grid boxes (top) and over all grid boxes in the northern (middle) and southern (bottom) hemispheres. Anomalies are defined with respect to monthly climate normals for the reference period 1961-1990. Values are adjusted further to have zero mean over the period 1987-2001.

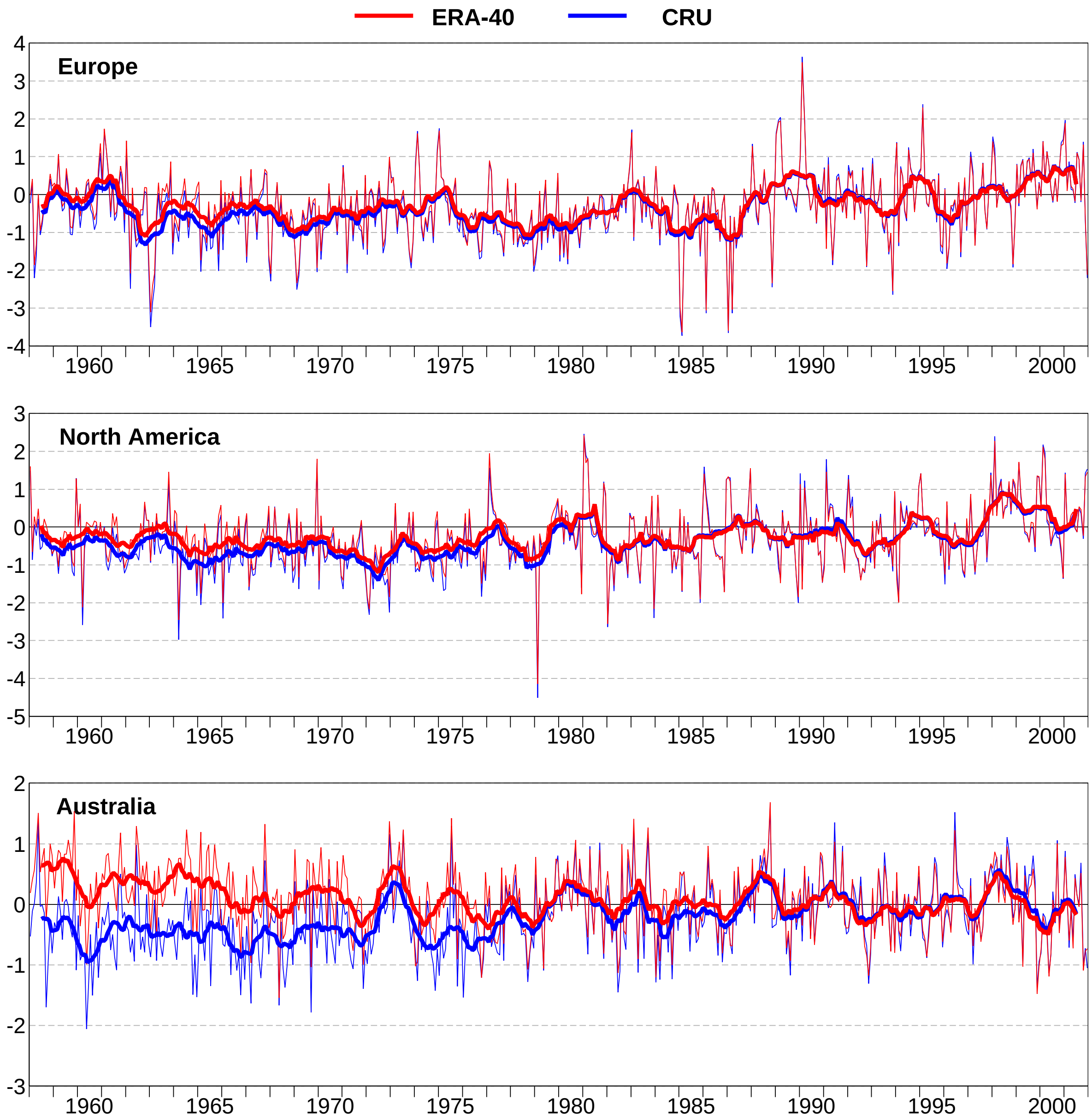
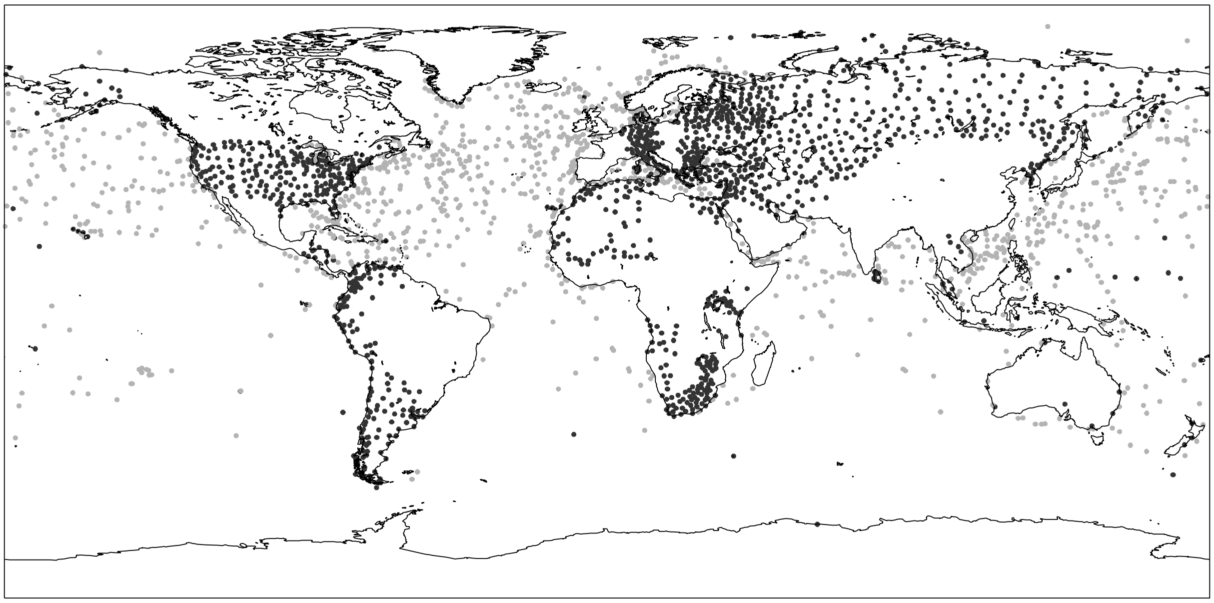


Figure 2 Time series of monthly two-metre temperature anomalies and twelve-monthly running means from the ERA-40 (red) and CRU (blue) analyses, averaged over all CRU boxes in domains covering Europe (top), North America (middle) and Australia (bottom). Values are adjusted to have zero mean over the period 1987-2001.

12UTC 1 July 1966



12UTC 1 July 1967

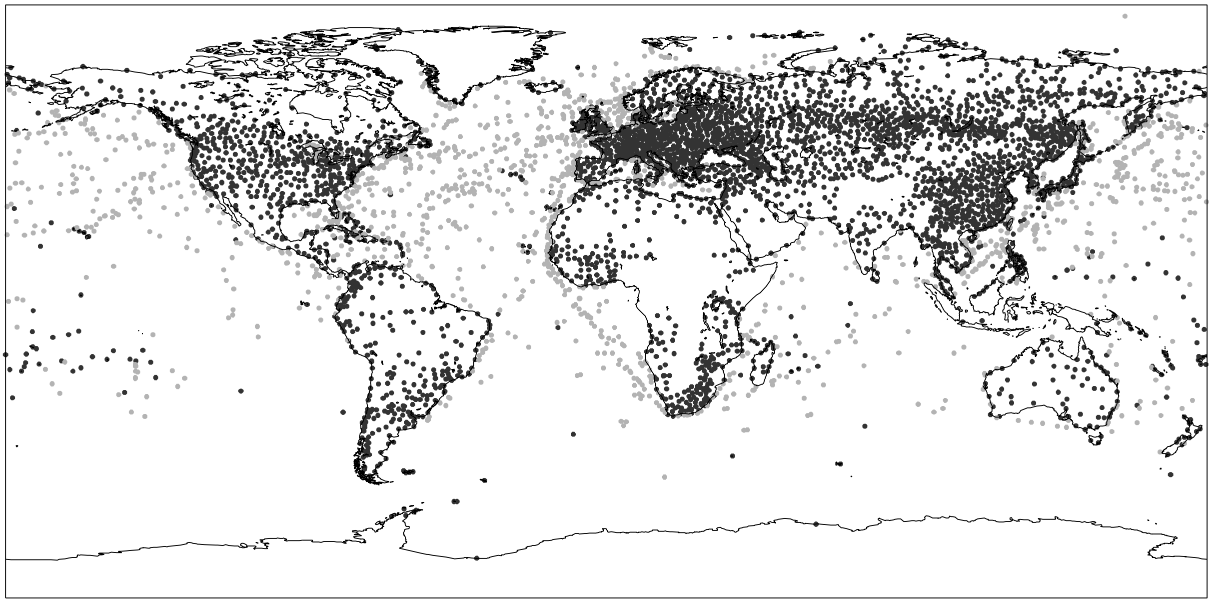


Figure 3 Coverage of surface synoptic observations from land stations (black) and ships (grey) supplied to ERA-40 for 12UTC 1 July 1966 (upper) and 12UTC 1 July 1967 (lower).

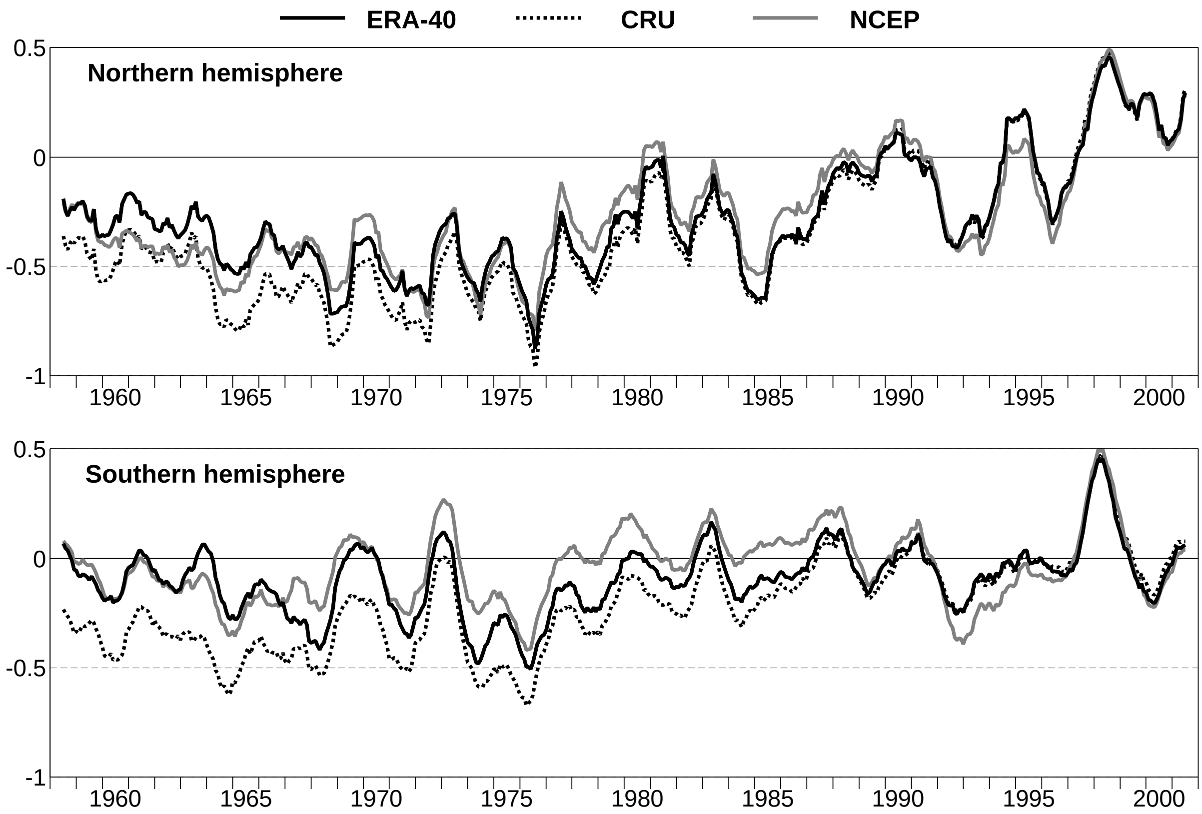


Figure 4 Twelve-monthly running means of two-metre temperature anomalies from the ERA-40 (black solid), CRU (black dotted) and NCEP/NCAR (grey) analyses, averaged over all CRU grid boxes in the northern (upper) and southern (lower) hemispheres. Values are adjusted to have zero mean over the period 1987-2001.

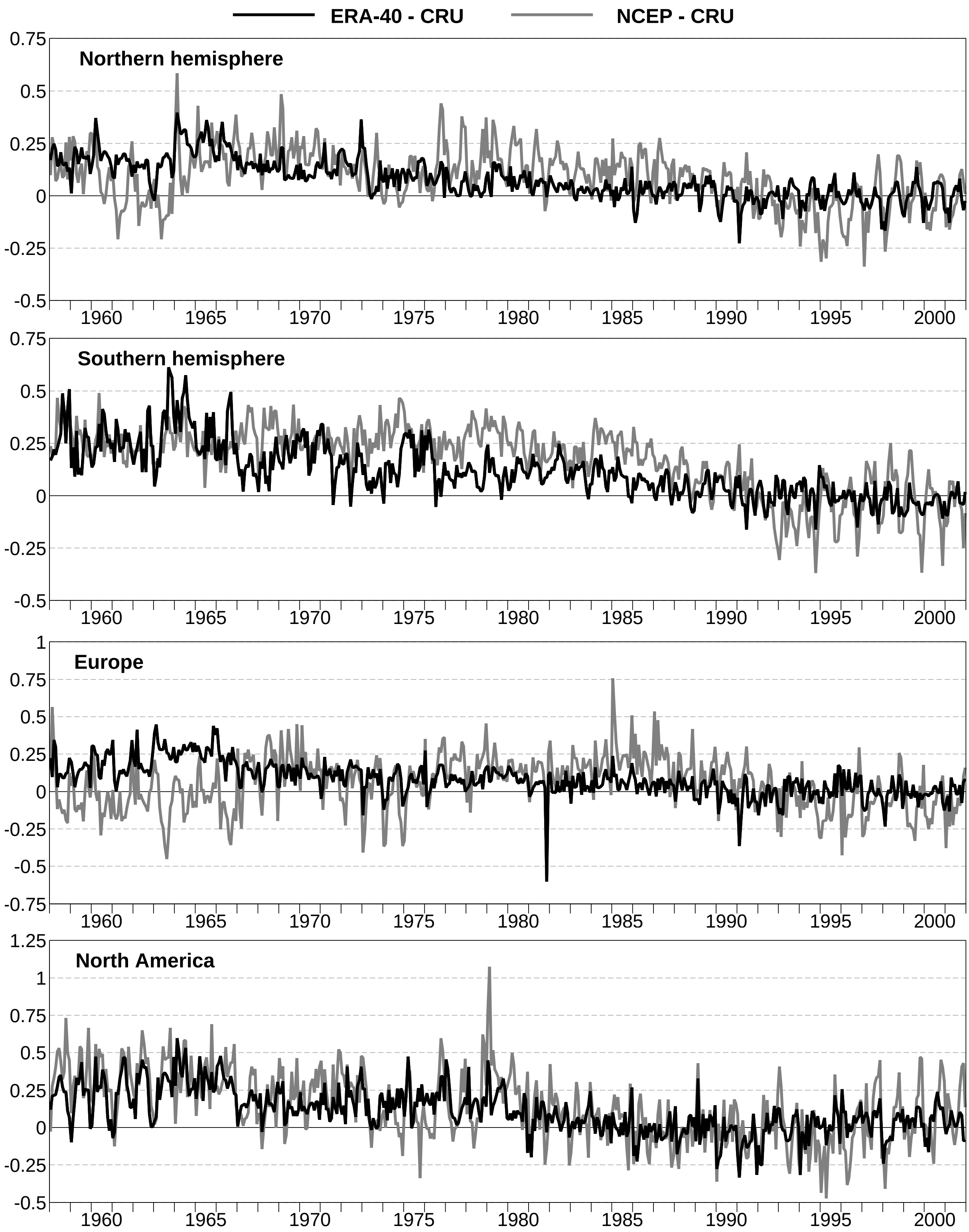


Figure 5 Time series of the monthly differences in two-metre temperature anomalies between ERA-40 and CRU analyses (black) and between NCEP/NCAR and CRU analyses (grey), averaged over all CRU grid boxes in the northern (top) and southern (upper middle) hemispheres and over European (middle) and North American (bottom) grid boxes. Values are adjusted to have zero mean over the period 1987-2001.

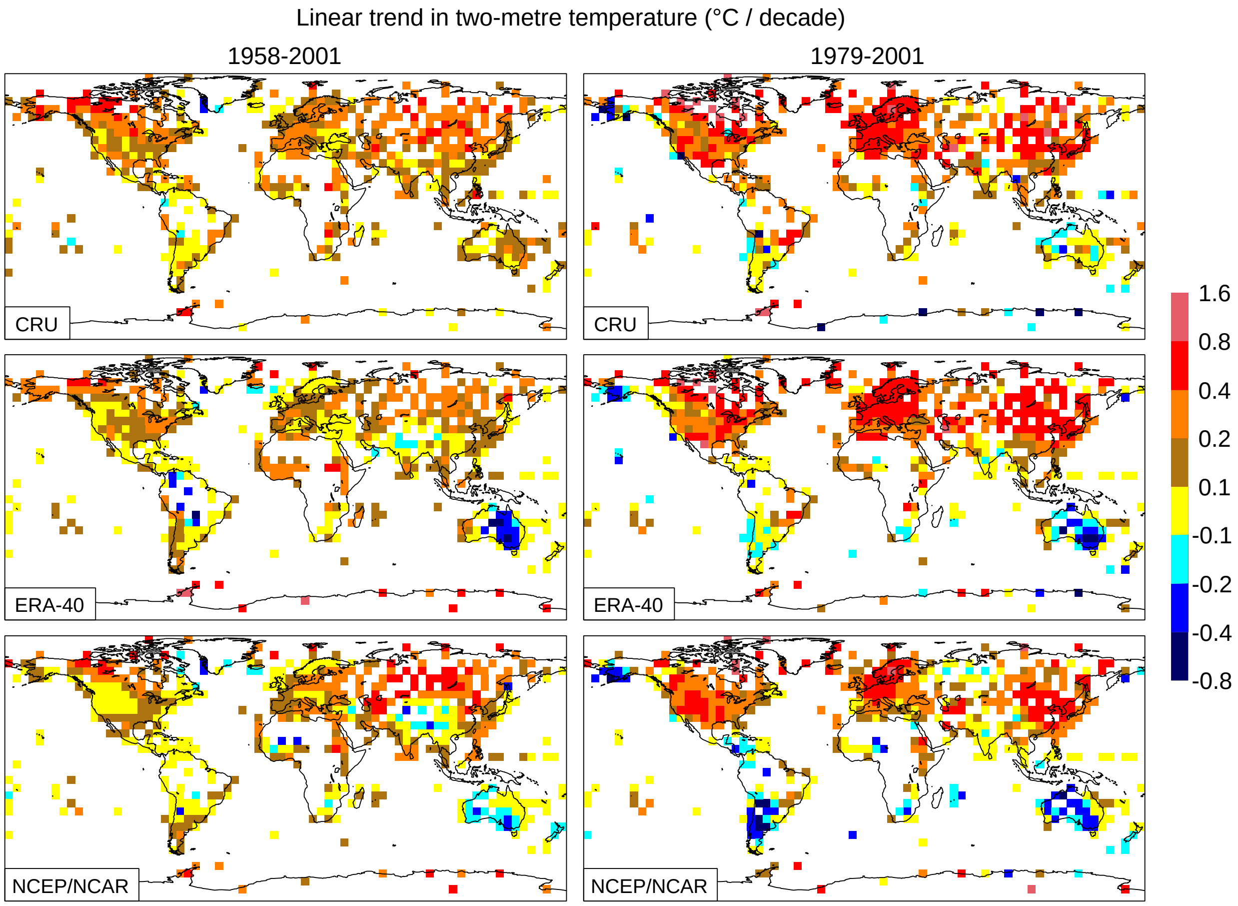


Figure 6 Linear trend over the periods 1958-2001 (left) and 1979-2001 (right) in two-metre temperature computed using all available CRU data (top), and equivalents from the ERA-40 (middle) and NCEP/NCAR (bottom) reanalyses.

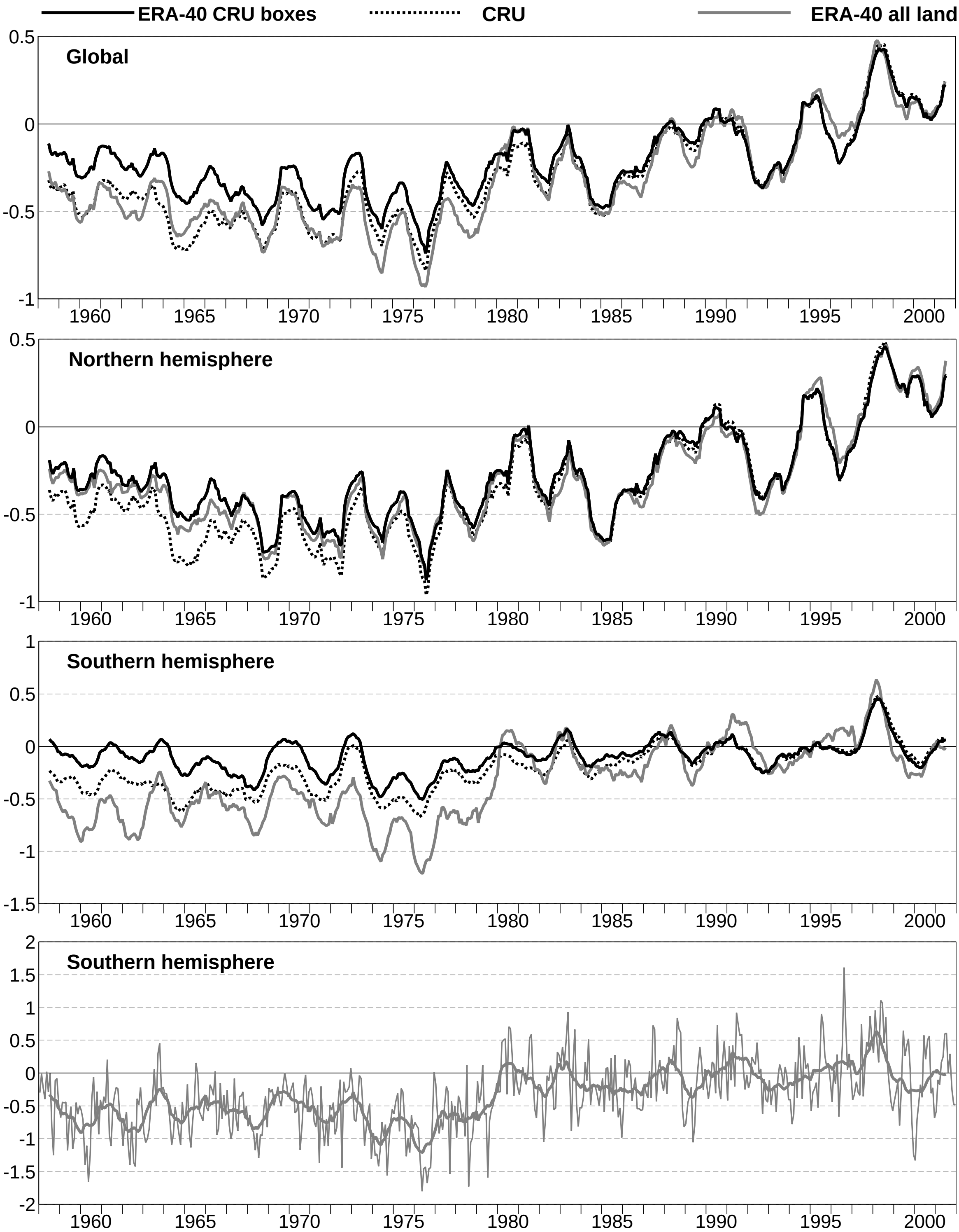


Figure 7 Twelve-monthly running means of two-metre temperature anomalies from the CRU analysis (black dotted), the ERA-40 equivalent (black solid, based on values only where and when there are corresponding CRU data), and corresponding ERA-40 values for all land grid boxes (grey). Values are averaged over all grid boxes (top) and over all grid boxes in the northern (upper middle) and southern (lower middle) hemispheres, and adjusted to have zero mean over the period 1987-2001. The bottom panel repeats the southern-hemisphere series for all ERA-40 land boxes and shows also corresponding individual monthly values.

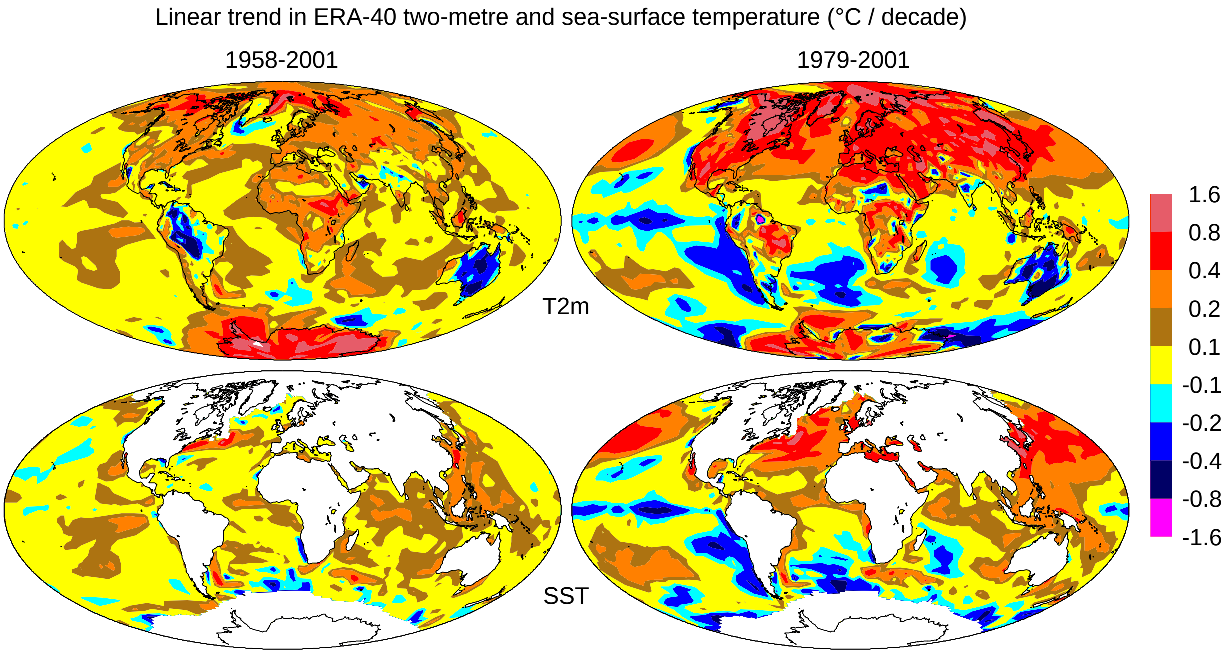


Figure 8 Linear trends over the periods 1958-2001 (left) and 1979-2001 (right) in the ERA-40 two-metre temperature analyses (upper) and in the sea-surface temperature analyses used by ERA-40 (lower). The trends in sea-surface temperature are shown only for points that are free of ice for every month in each period.

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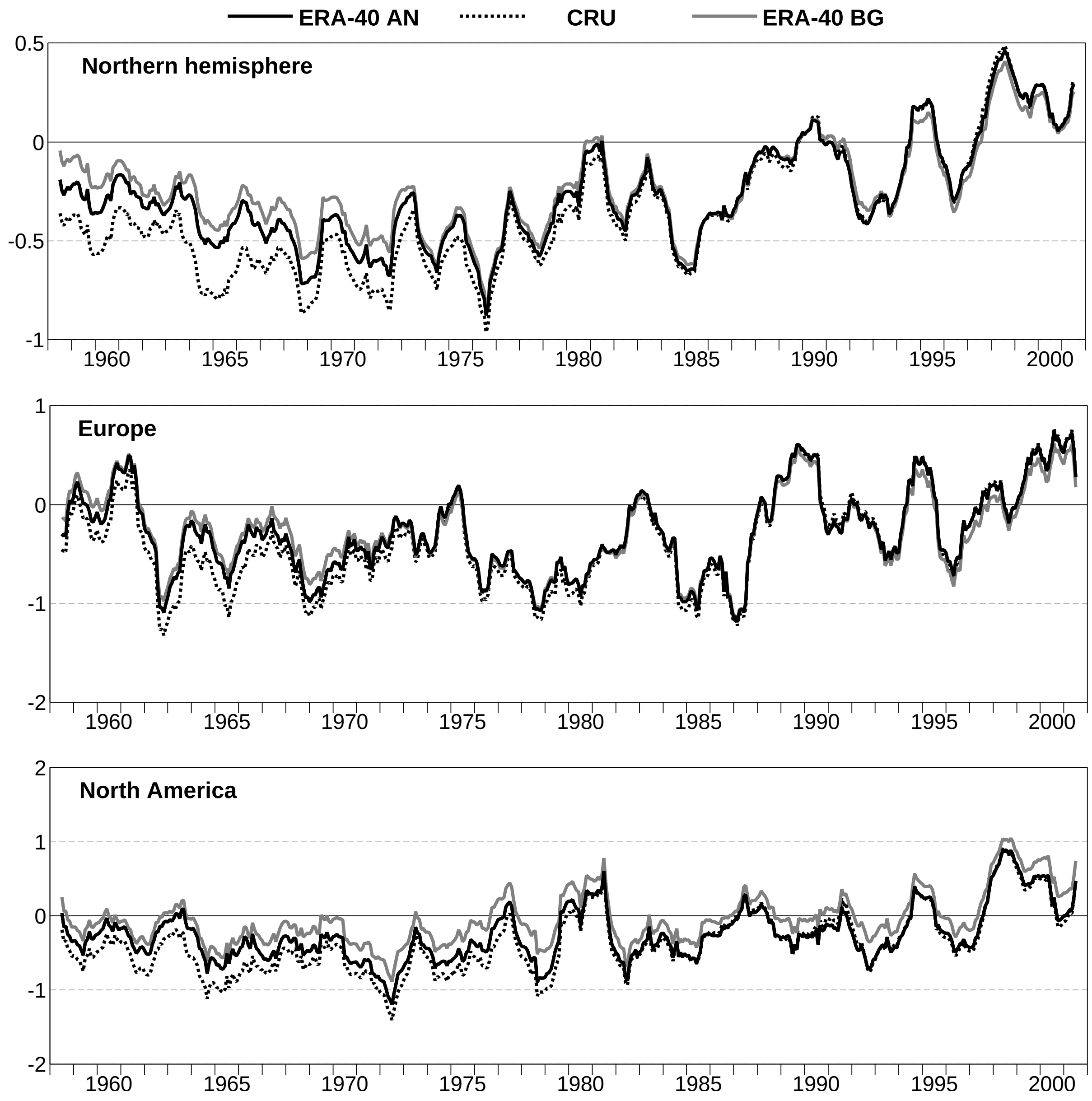

Figure 9 Twelve-monthly running means of two-metre temperature anomalies from the ERA-40 (black solid) and CRU (black dotted) analyses and from the ERA-40 background forecasts (grey), averaged over all CRU grid boxes in the northern hemisphere (top) and for European (middle) and North American (bottom) grid boxes. The two time series based on analyses are adjusted as before to have zero mean for the period 1987-2001. The ERA-40 background anomalies are computed with respect to the monthly climate derived from the ERA-40 analyses for the reference period 1961-1990, and then adjusted by the same single amount applied to adjust the ERA-40 analysis time series to zero mean value for 1987-2001.

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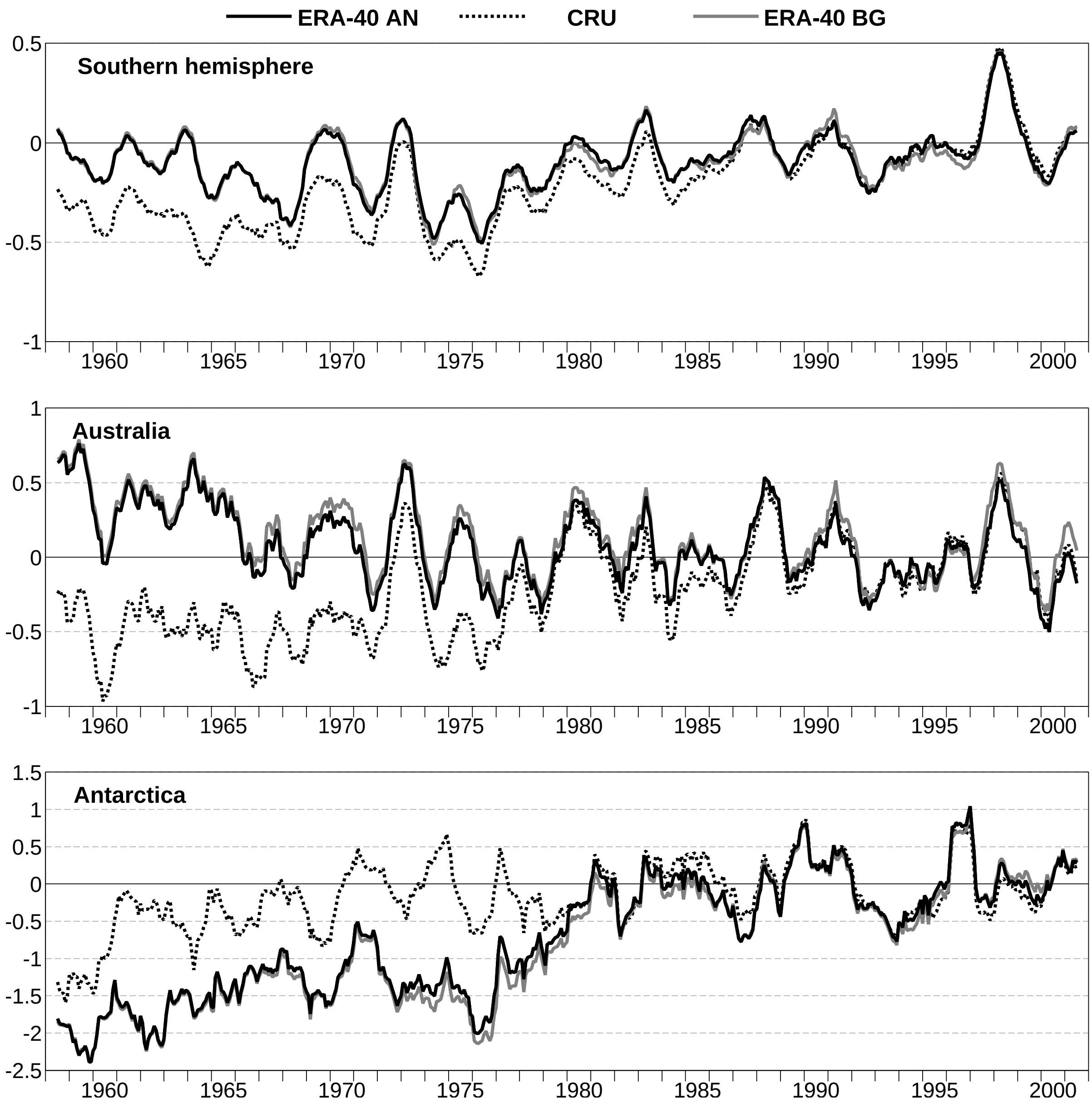

Figure 10 Twelve-monthly running means of two-metre temperature anomalies from the ERA-40 (black solid) and CRU (black dotted) analyses and from the ERA-40 background forecasts (grey), as in Figure 9, but averaged over all CRU grid boxes in the southern hemisphere (top) and for Australian (middle) and Antarctic (bottom) grid boxes.

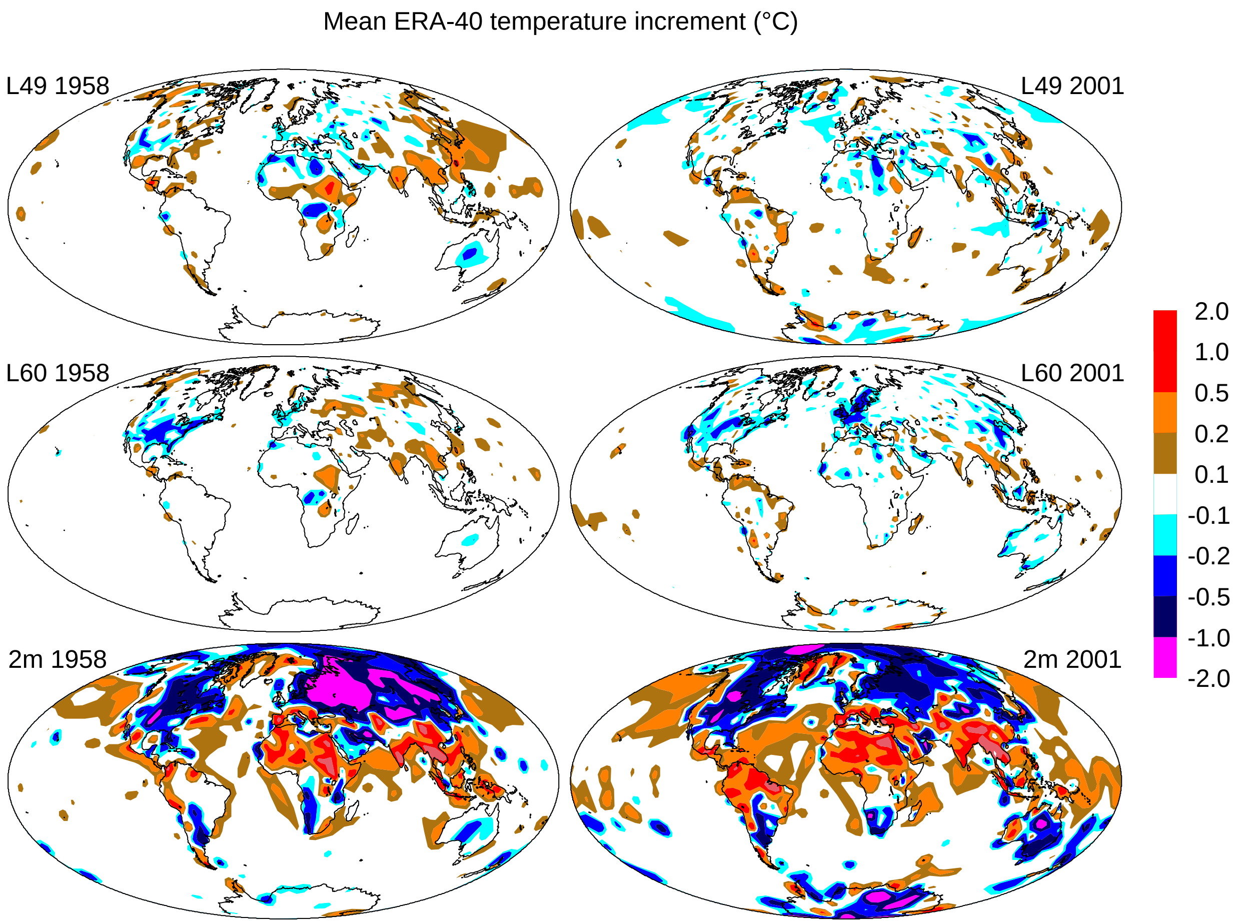

Figure 11 Annual-mean ERA-40 analysis increments (analysis minus background values) for 1958 (left) and 2001 (right), at model level 49 (top; level located close to 850hPa for a surface pressure of 1000hPa) at model level 60 (middle; level located at a height close to ten metres) and at a height of two metres (bottom).

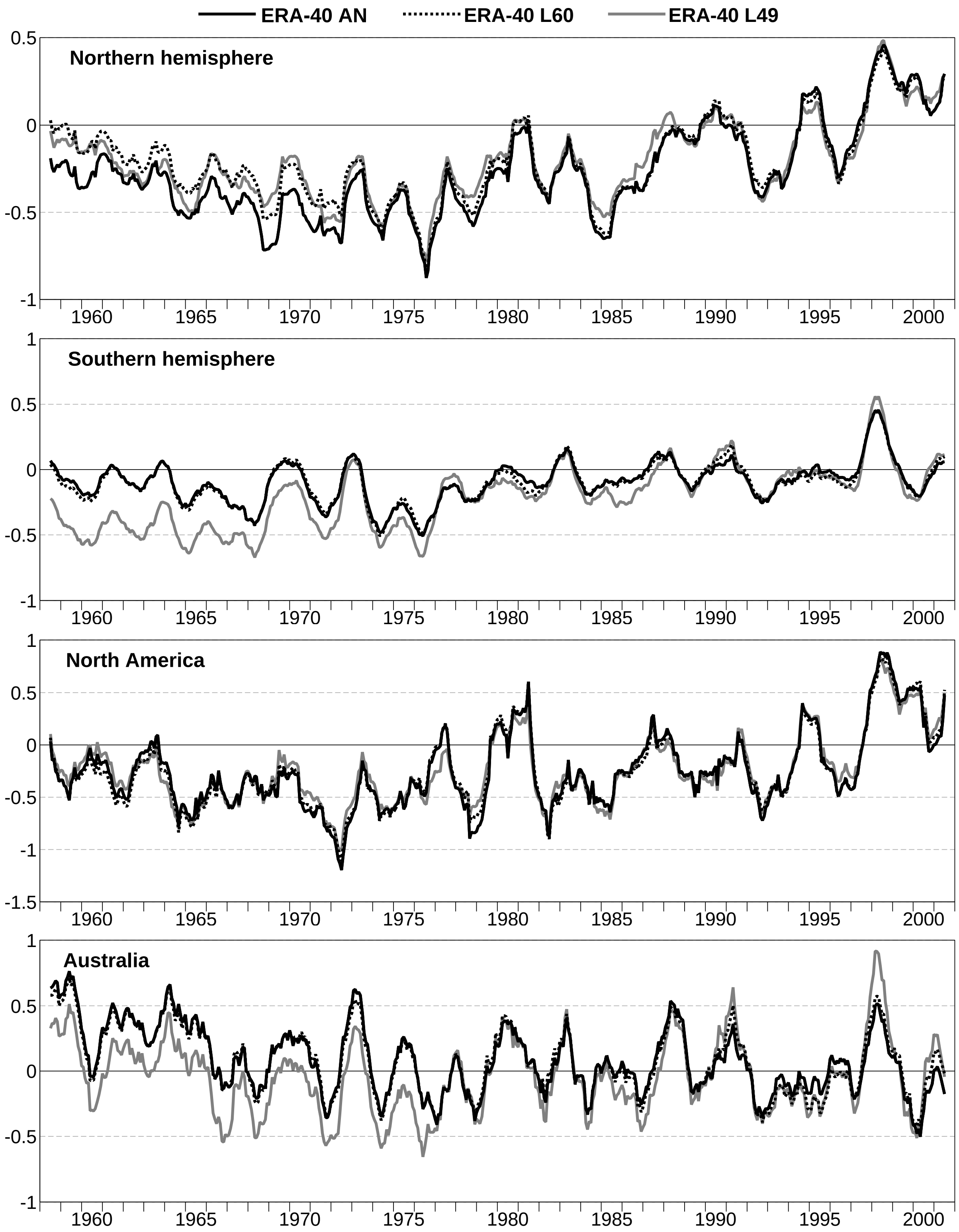

Figure 12 Twelve-monthly running means of temperature anomalies from the ERA-40 analyses at two-metre height (black solid) and at model levels 60 (black dotted) and 49 (grey). Values are averaged over all CRU grid boxes in the northern (top) and southern (upper middle) hemispheres, and for North America (lower middle) and Australia (bottom). Values for each level are adjusted to give zero mean value over the period 1987-2001.

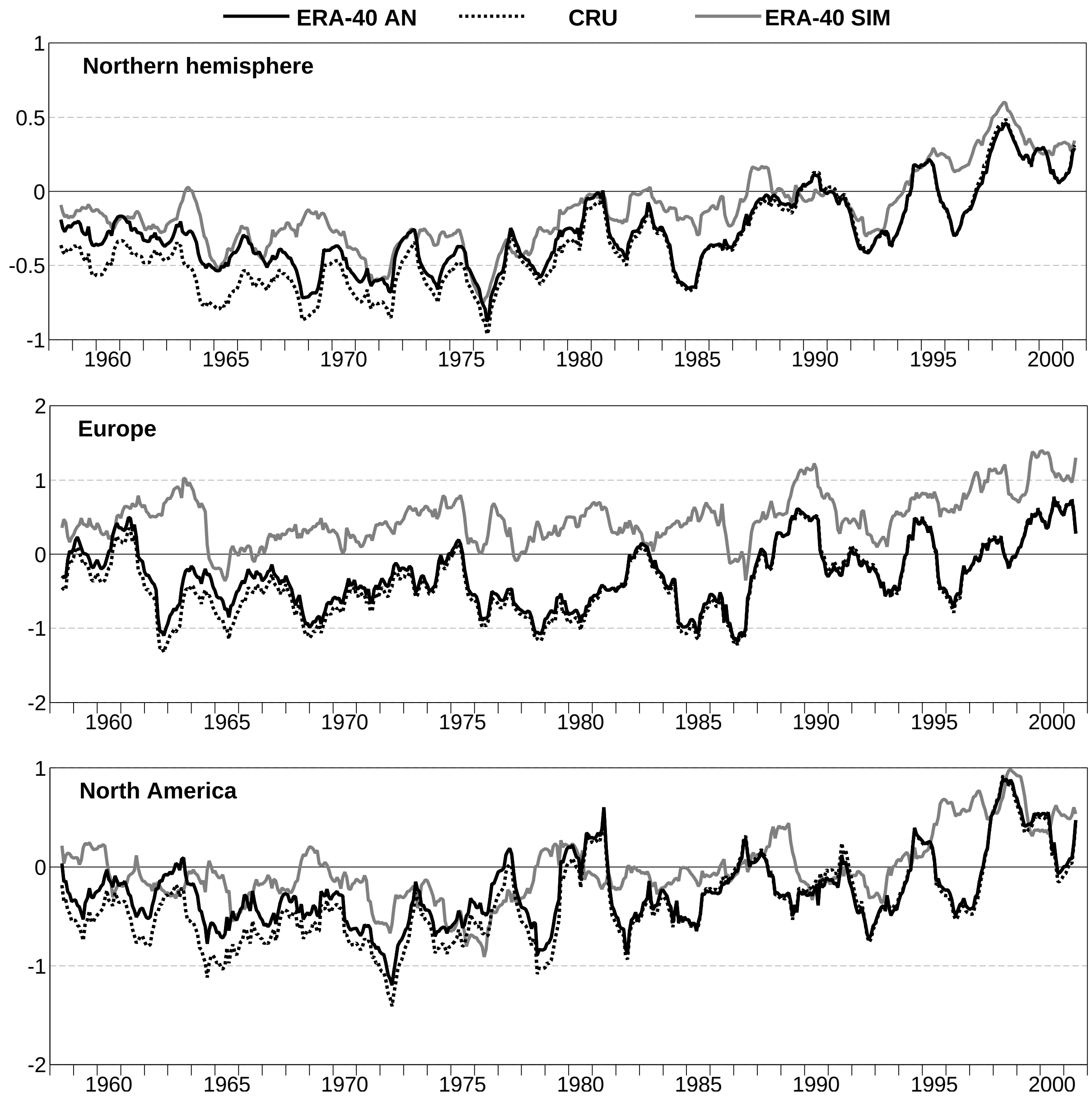

Figure 13 Twelve-monthly running means of two-metre temperature anomalies from the ERA-40 (black solid) and CRU (black dotted) analyses and from the simulation using the ERA-40 model (grey), averaged over all CRU grid boxes in the northern hemisphere (top) and for European (middle) and North American (bottom) grid boxes. The two time series based on analyses are adjusted as before to have zero mean for the period 1987-2001. The simulated anomalies are computed with respect to the monthly climate derived from the ERA-40 analyses for the reference period 1961-1990, and then adjusted by the same single amount applied to adjust the ERA-40 analysis time series to zero mean value for 1987-2001.

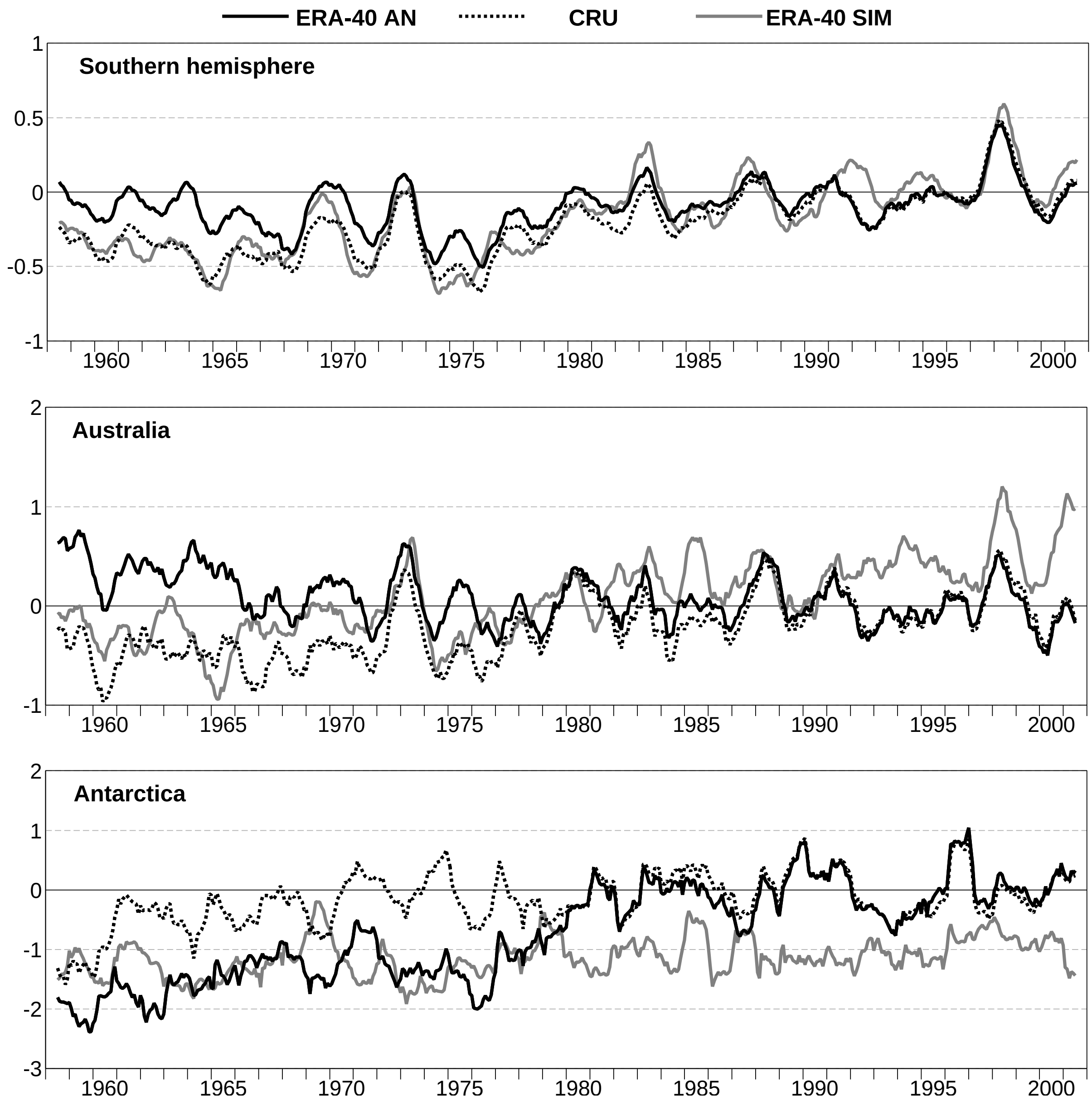

Figure 14 Twelve-monthly running means of two-metre temperature anomalies from the ERA-40 (black solid) and CRU (black dotted) analyses and from the simulation using the ERA-40 model (grey), as in Figure 13, but averaged over all CRU grid boxes in the southern hemisphere (top) and for Australian (middle) and Antarctic (bottom) grid boxes.

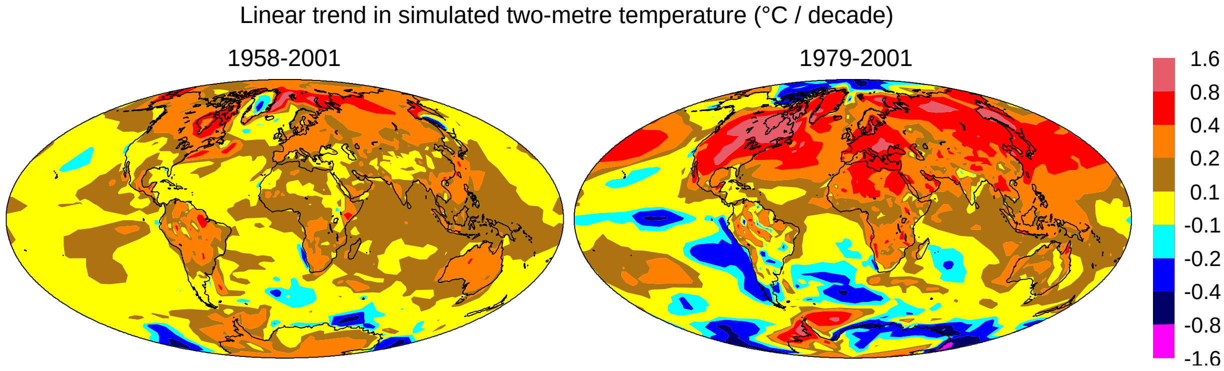

Figure 15 Linear trends over the periods 1958-2001 (left) and 1979-2001 (right) in two-metre temperature from the simulation using the ERA-40 model.

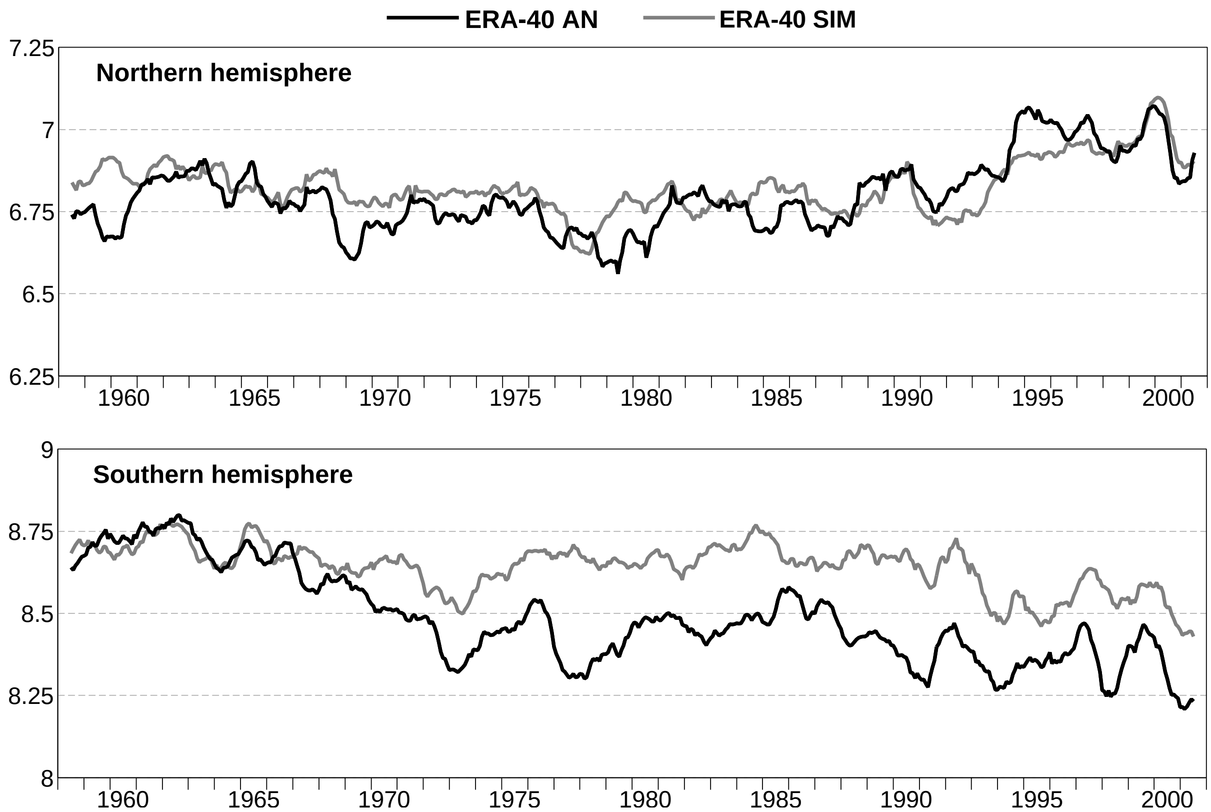

Figure 16 Twelve-monthly running means of differences in temperature between two-metre height and model level 49 for the ERA-40 analysis (black) and the simulation using the ERA-40 model (grey). Values are averaged over all CRU grid boxes in the northern (upper) and southern (lower) hemispheres.

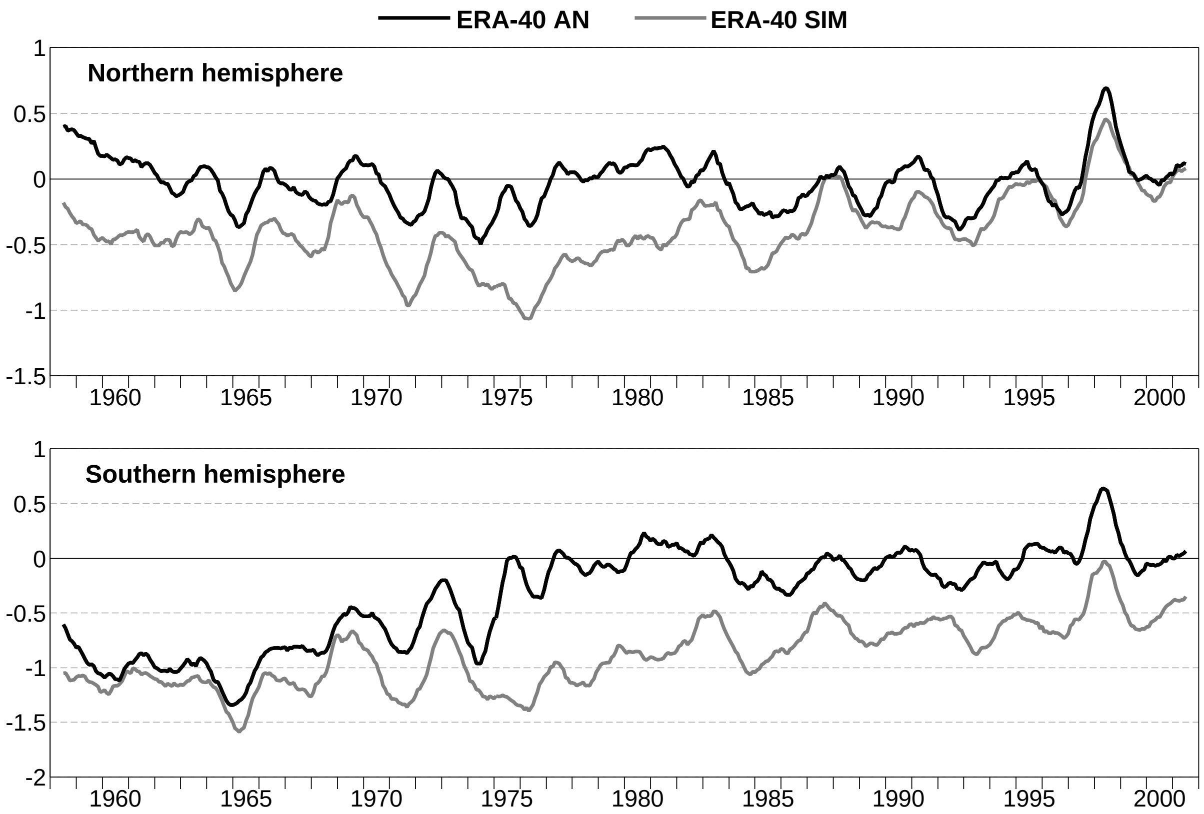

Figure 17 Twelve-monthly running means of 500hPa temperature anomalies from the ERA-40 analyses (black) and from the simulation using the ERA-40 model (grey). Values are averaged over the northern (upper) and southern (lower) hemispheres. Values for the analyses are adjusted as before to give zero mean value over the period 1987-2001. The simulated anomalies are computed with respect to the monthly climate derived from the 500hPa ERA-40 analyses for the reference period 1961-1990, and then adjusted by the same single amount applied to adjust the analyses to zero mean value for 1987-2001.

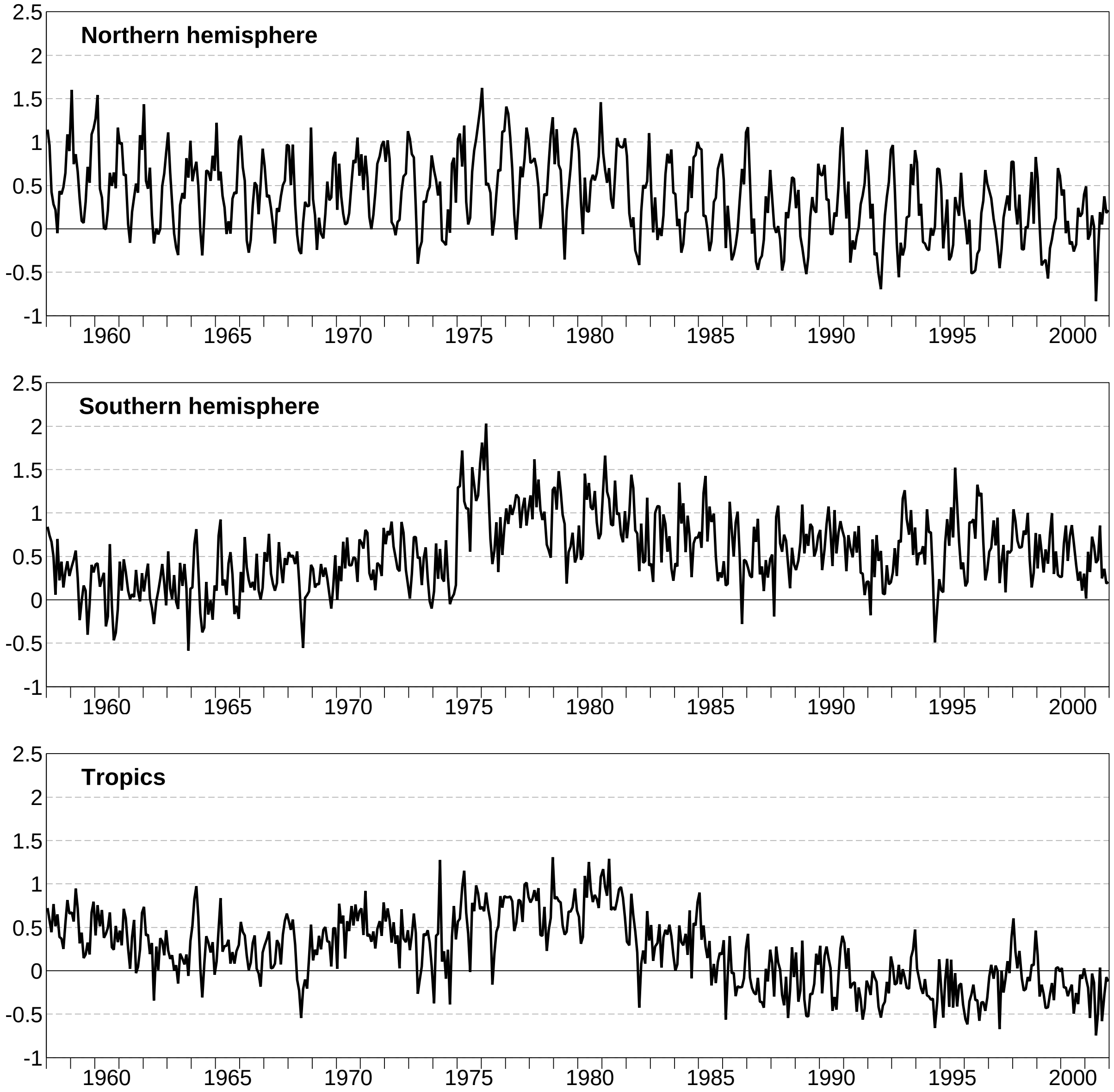

Figure 18 Differences in monthly-mean 500hPa temperatures between the ERA-40 analysis and the simulation using the ERA-40 model, averaged over the northern hemisphere (top), southern hemisphere (middle) and over the tropics from 20N to 20S (bottom).

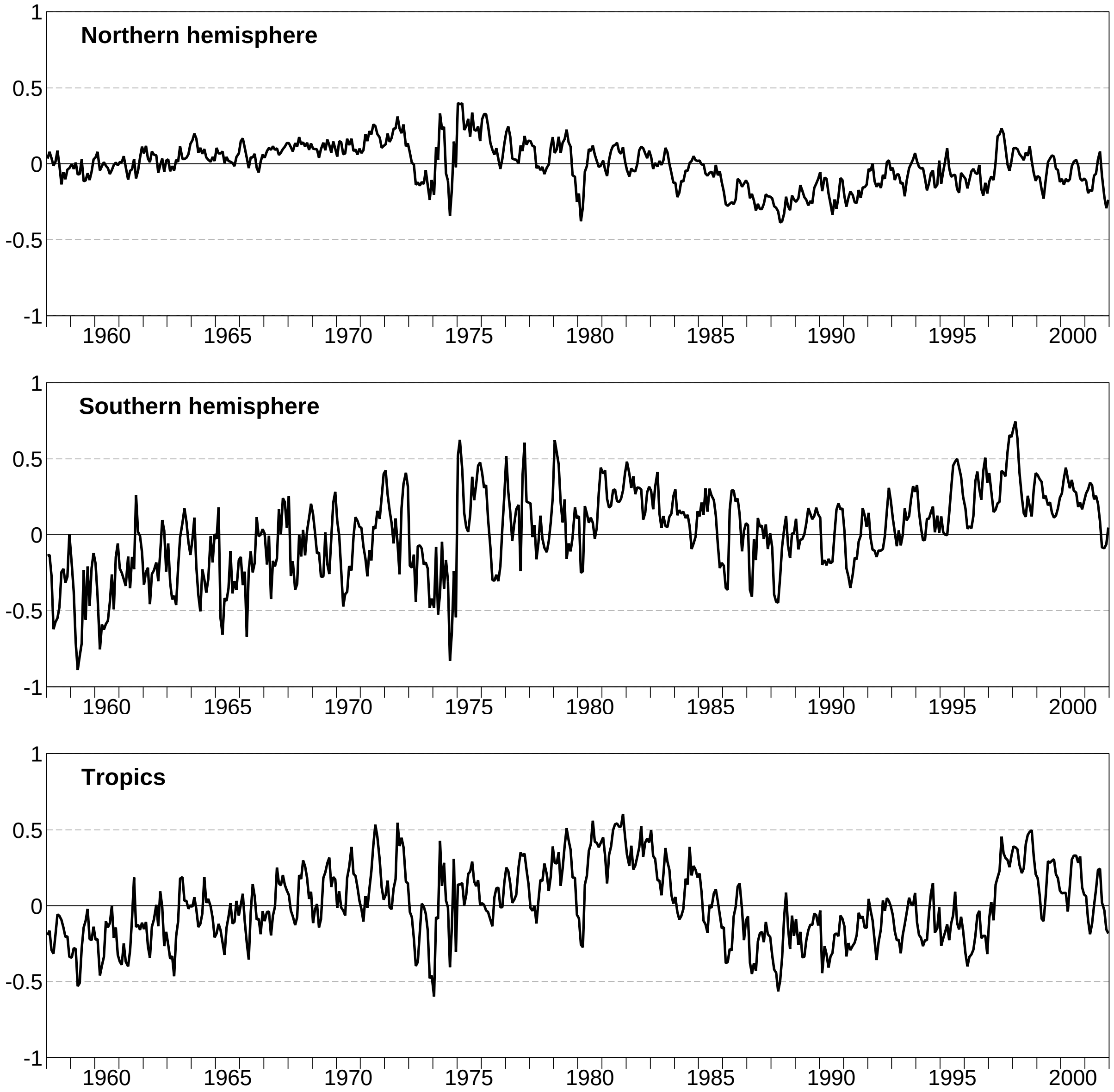

Figure 19 Differences in monthly-mean 500hPa temperatures between the ERA-40 and the NCEP/NCAR reanalyses, averaged over the northern hemisphere (top), southern hemisphere (middle) and over the tropics from 20N to 20S (bottom).