Discrepancies between NCEP/NCAR and ERA-40 reanalysis products

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Abstract

This study compares global, atmospheric data from the NCEP/NCAR and ERA-40 reanalyses (presently the most comprehensive reanalysis data sets) with each other and with observations. Especially in the early reanalysis period, large sea level pressure and 500 hPa geopotential height discrepancies between the two reanalyses are present year round over North Africa, the Middle East and Asia, and other discrepancies exist particularly over the Southern Ocean and Antarctica. Low surface air temperature correlation values between the two reanalyses are found over the tropical and subtropical land areas of South America, Africa and southern Asia, even in the period when satellite data were available. Moreover, there is worse agreement between the two reanalyses in upper tropospheric temperature variability over the entire tropical band in the satellite era than there was before.

1. Introduction

Atmospheric reanalyses are one way to investigate the historical atmospheric state. In particular, a dynamically consistent picture of the atmosphere can be obtained from the analyses used for historical weather forecasts with numerical weather prediction (NWP) models. However, these analyses are very inhomogenous since the NWP models and the assimilation systems have undergone big improvements in recent years. Reanalysis projects aim to keep the model and assimilation technique constant and thereby reduce the systematic errors in the data products. Nevertheless, errors occur for various reasons. Flaws in the NWP model and the assimilation technique lead to systematic biases. Moreover, the quantity and quality of the observational data used for the reanalysis are crucial. A quality control of the observational data prior to the assimilation reduces some errors. However, in regions where observations are sparse, different reanalyses often disagree with each other, indicating uncertainties in the reanalysis products.

Among the several reanalyses those of the National Centers for Environmental Prediction / National Center for Atmospheric Research (NCEP/NCAR, Kalnay et al. 1996) and the European Centre for Medium-Range Weather Forecast 40-yrs reanalysis (ERA-40, Uppala et al. 2005) are the most comprehensive and are therefore chosen in this study for comparison with each other and with observed data. No other reanalyses are considered in this study. Known problems in the NCEP/NCAR reanalysis data sets are published online (http://www.cdc.noaa.gov/cdc/reanalysis/problems.shtml) and a description of the ERA-40 project including the verification of various aspects of the reanalysis is available from the ERA-40 project report series (http://www.ecmwf.int/research/era).

Greatbatch and Rong (2006, hereafter GR06) note discrepancies in sea level pressure (SLP), 500 hPa height (Z500), and air temperature between the two reanalyses for Northern Hemisphere summer. Here we show that these discrepancies are not restricted only to the summer season, but rather exist year round, and that other discrepancies are present particularly on the Southern Hemisphere. An indication that discrepancies are also present in winter is given in Yang et al. (2002), who note a discrepancy over eastern Asia between the NCEP/NCAR reanalysis and the Trenberth SLP data set (Trenberth and Paolini 1980) in the early reanalysis period prior to the late 1960's. This issue has been explored further by Inoue and Matsumoto (2004), who point to SLP discrepancies over Asia in summer between NCEP/NCAR and ERA-40 reanalyses. GR06 show that the problem over Asia is connected with a similar problem over North Africa in summer. However, the discrepancies between the NCEP/NCAR reanalysis and data from other sources over Asia and North Africa coincide with strong transitions in the global climate system. The Sahel region in North Africa underwent a prolonged drought from the late 1960's to the 1990's (e.g., Ward et al. 1998). Hurrell and Folland (2002) note a change in the summer atmospheric circulation over the North Atlantic that took also place in the late 1960's and they speculate that this regime shift may be connected with the Sahel drought. Also in the late 1960's the winter rainfall of southwest Australia decreased considerably (IOCI 2002), and Baines (2005) attributes the long-term decrease of winter rainfall over Australia to the African monsoon. These examples show the need to distinguish between real trends and artificial transitions in the reanalysis products.

In addition to the problem in the late 1960's, GR06 point out considerable differences between the NCEP/NCAR and ERA-40 reanalysis in upper tropospheric temperature in the late 1970's. The upper tropospheric temperature over the tropics in summer has a marked offset in the NCEP/NCAR compared to the ERA-40 reanalysis. This is almost certainly associated with the introduction of satellite data into the reanalysis systems (Sturaro 2003), which has, for example, also an effect on the trends computed from the reanalyses for global mean surface temperature (Simmons et al. 2004), global mean lower tropospheric temperature, globally integrated water vapor, and global kinetic energy (Bengtsson et al. 2004), Southern Hemisphere SLP, Z500, sea surface temperature (SST), and latent heat flux (Sterl 2004). Hines et al. (2000) note artificial trends in the SLP and geopotential height fields over the Southern Ocean and Antarctica in the NCEP/NCAR reanalysis due to strong biases that decrease with time. Marshall and Harangozo (2000) also note the large SLP trend over the South Pacific in the NCEP/NCAR reanalysis and attribute it to a lack of surface observations entering the reanalysis model prior to the availability of Global Telecommunication System-based data in 1967. Marshall (2002) notes that the NCEP/NCAR reanalysis does not capture the stratospheric cooling trend over Antarctica associated with the seasonal ozone loss. He gives evidence that the different trends are principally caused by errors in the NCEP/NCAR reanalysis prior to the assimilation of satellite sounder data, which coincides with significant jumps in upper-air temperatures in the NCEP/NCAR reanalysis. Thompson and Solomon (2002) argue that trends in the Southern Hemisphere tropospheric circulation can be interpreted as a bias toward the high index phase of the Southern Annular Mode (SAM). Marshall (2003) points, however, to erroneous trends in the SAM derived from the NCEP/NCAR reanalysis data. He argues that the ERA-40 reanalysis provides an improved representation of the high latitude Southern Hemisphere atmospheric circulation variability which can be used with high confidence at least as far back as 1973. Bromwich and Fogt (2004) find also that the ERA-40 reanalysis follows more closely observations over the high and midlatitude Southern Hemisphere than the NCEP/NCAR reanalysis, but they find also many shortcomings to be present in the ERA-40 reanalysis. Specifically, Bromwich and Fogt (2004) warn against the usage of reanalysis data over the high southern latitudes during non-summer months prior to the assimilation of satellite sounding data.

The analysis method used in GR06 is extended here to the Southern Hemisphere and to the winter season to identify discrepancies between the different atmospheric data products. The remainder of this paper is organized as follows: The data used in this study are introduced in Section 2. The discrepancies between the different data sets in some basic variables like SLP, Z500 and air temperature are presented in Section 3. Section 4 concludes this paper with a summary and discussion of the results.

2. Data

The data used here are from three different main sources: the NCEP/NCAR reanalysis (http://www.cdc.noaa.gov), the ERA-40 reanalysis (http://data.ecmwf.int/data), and gridded observational data from the Hadley Centre (http://www.hadobs.org) of the Met Office in combination with data from the Climatic Research Unit (http://www.cru.uea.ac.uk) of the University of East Anglia, UK. The NCEP/NCAR reanalysis (Kalnay et al. 1996, Kistler et al. 2001) covers the period 1948-2005 with a monthly update. It is based on a NWP model with T62 spectral resolution and 28 sigma levels in the vertical. The ERA-40 reanalysis (Uppala et al. 2005) covers the period September 1957-August 2002. The ERA-40 model uses a T159 spherical harmonic resolution and 60 levels in the vertical. These two reanalyses are compared with each other and with the HadSLP1 and the HadCRUT2v observational data sets. The HadSLP1 data set is an update of the GMSLP2 data set (Basnett and Parker 1997); it is an unique combination of monthly globally-complete fields of air pressure observations on a 5° by 5° latitude-longitude grid from 1871-1998. The HadCRUT2v data set (Jones and Moberg 2003, Rayner et al. 2003) is a combined land and marine air temperature data set on a regular 5° by 5° latitude-longitude grid for the period 1870-2005 with a monthly update. To avoid problems with direct air temperature measurements over the ocean, night marine sea surface temperatures are used instead. The global HadCRUT2v data set is interpolated on a regular grid, however, some of the grid cells of the data set still contain missing values. In this study seasonal means from the HadCRUT2v data set are calculated only when the data set holds no missing values in each single month over the whole analysis period. The data from the different sources are compared with each other over the period for which the data from all data sets overlap (1958-1998) for the boreal summer (June, July, August, JJA) and winter (December, January, and February, DJF) seasons.

3. Results

a) Biases

Figure 1 shows the SLP, surface air temperature and Z500 differences between mean values from the NCEP/NCAR and ERA-40 reanalysis over the period 1958-1998 for the summer and winter seasons, respectively. The largest SLP differences, with values of more than 25 hPa, exist over the Antarctic continent in the austral winter (Fig. 1a). In boreal winter, differences of more than 5 hPa over the Antarctic continent are of the same order of magnitude as differences over Greenland and parts of Asia (Fig. 1b). These are also the regions where the main differences are present on the Northern Hemisphere in boreal summer. The largest surface air temperature differences, with values of more than 5 K, are present over the sea ice covered Southern Ocean and the Antarctic continent in austral winter (Fig. 1c). The NCEP/NCAR reanalysis has used a constant sea ice thickness of 3 m for the Southern Ocean, which is more correct in the Arctic and which causes negative temperature biases in winter. Moreover, a 100% sea ice cover is assumed which is known to artificially reduce sea-air heat fluxes and thereby to introduce a negative temperature bias over sea-ice covered regions (Connolley and Harangozo 2001). In austral summer, large differences remain over the Antarctic continent. In this season (DJF) large differences also exist over northeast Asia, Greenland, the Arctic, North Africa and South America (Fig. 1d). In Z500, the two reanalyses differ by more than 30 gpm over the Southern Ocean and Antarctic continent in both seasons, summer and winter (Fig. 1e,f).

b) Sea level pressure and geopotential height

Figure 2 shows the linear trend in SLP in the NCEP/NCAR, ERA-40 and HadSLP1 data sets for the period 1958-1998 in boreal summer and winter. Instead of Trenberth's Northern Hemisphere SLP data set (Trenberth and Paolino 1980), used in GR06, the observational data set HadSLP1 with a global coverage is chosen here for comparison. In the NCEP/NCAR reanalysis large negative trends are present in the JJA season (Fig. 2a) over the Southern Ocean and Antarctic continent while large positive trends are present over Asia, the Middle East, and North Africa. These trends are much weaker or missing in the ERA-40 reanalysis (Fig. 2c) and the HadSLP1 data set (Fig. 2e) in this season. The comparison with the results from GR06 shows that the absence of any positive trends in the HadSLP1 data set in boreal summer is in agreement with Trenberth's SLP data set over North Africa, but not over the Middle Eastern and Asian regions. In the boreal winter, the main feature in all three data sets is a positive trend of the North Atlantic Oscillation (NAO), which is stronger in the NCEP/NCAR and ERA-40 reanalyses than in the HadSLP1 data set (Fig. 2b,d,f). The winter NAO is a sea-saw in SLP, with centers of action over the Azores and Iceland, and is the leading mode of climate variability in the North Atlantic region (Greatbatch 2000, Hurrell et al. 2003). The time series associated with the NAO will be presented later (see Fig. 4). Differences in SLP trends between the NCEP/NCAR and both the ERA-40 and HadSLP1 data sets exist, as for the boreal summer, over the Southern Ocean and Antarctic continent, North Africa, the Middle East and Asia.

The temporal evolution of the SLP trends between the three data sets will now be analyzed in detail in regions where the three data sets most strongly disagree. Figure 3 shows the area mean SLP differences between the three data sets averaged within the boxes shown in Fig. 2. These boxes are North Africa (10-30°N, 10°W-30°E), the Middle East (35-45°N, 30-50°W), Asia (35-55°N, 70-120°E) and the Southern Ocean/Antarctic region (south of 60°S). In the boreal summer season, large SLP differences exist between the NCEP/NCAR and both the ERA-40 and HadSLP1 data set over the North African, Middle Eastern and Asian regions prior to the late 1960's (Fig. 3a,c,e). The largest biases exist, however, over the Antarctic region during austral winter with a SLP difference of 15 hPa between NCEP/NCAR and HadSLP1, 10 hPa between NCEP/NCAR and ERA-40 and 6 hPa between ERA-40 and HadSLP1 on average over the period 1958-1998 (Fig. 3g). Especially the bias of the NCEP/NCAR reanalysis decreases with time, causing a large artificial trend (Hines et al. 2000). In the boreal winter season large SLP differences exist also, similar to the boreal summer season, between the NCEP/NCAR and both the ERA-40 and HadSLP1 data set over North Africa prior to the late 1960's (Fig. 3b). Over the Middle East the SLP differences in boreal winter between the NCEP/NCAR and both the ERA-40 and HadSLP1 data persist into the 1970's, even longer than in the summer season (Fig. 3d). Over Asia the differences between the SLP data sets are more complicated in winter (Fig. 3f) than in summer, with a large offset in the NCEP/NCAR data between the late 1960's and the late 1970's. While the SLP from the NCEP/NCAR data set is higher than that of the HadSLP1 data set until the late 1960's, it is lower in the period between the late 1960's and the late 1970's while, at the same time, the SLP of the ERA-40 data set is higher than that of the HadSLP1 data set. The result is two strong transitions between the NCEP/NCAR and the ERA-40 data sets occurring in the late 1960's and late 1970's. In the austral summer season almost no SLP bias exists between the NCEP/NCAR and ERA-40 data over the Antarctic continent, but a bias of approximately 3 hPa exists between the two reanalyses and the HadSLP1 data set over the period 1958-1998 (Fig. 3h).

The analysis of the SLP trends has shown that the largest trends on the Northern Hemisphere in winter reflect a pattern which is associated with the NAO (see the discussion of Fig. 2). Figure 4 shows the wintertime NAO indices derived from the NCEP/NCAR, ERA-40 and HadSLP1 data sets, respectively. The NAO index is defined here as the normalized SLP difference between the Azores (40°N, 30°W) and Iceland (65°N, 22.5°W), as in Hurrell (1995). These positions are marked in Fig. 2b,d,f with a cross. The variability of the NAO indices derived from the different atmospheric data sets are very similar. GR06 have previously shown the robustness of the summer NAO in the NCEP/NCAR and ERA-40 reanalyses and Trenberth's data set.

Figure 5 shows correlation maps of seasonal mean SLP between the different data sets and conveniently summarizes where the main discrepancies are found. The resulting patterns are remarkably similar in all cases, with a region of discrepancy between all three of the data sets, extending from Africa to Asia. Other common regions of discrepancy are found over the Southern Ocean and Antarctica, and over the Rocky Mountains in North America and large parts of South America. Similar maps produced for each month of the year show the same basic pattern.

Figure 6 shows the linear trends of the 500 hPa height in the NCEP/NCAR and ERA-40 reanalysis and the correlation values between the undetrended fields from the two reanalyses for the period 1958-1998 in boreal summer and winter. The Z500 trends show similar features as the SLP trends. In the boreal winter season the main feature of the Z500 trend in both reanalyses is, as for the SLP, a positive NAO trend (Fig. 6b,d). In boreal summer, on the other hand, a positive Z500 trend is present over Asia in the NCEP/NCAR reanalysis which is almost absent in the ERA-40 reanalysis (Fig. 6a,c). Other differences of Z500 trends between the NCEP/NCAR and ERA-40 reanalysis exist, for example, over the Southern Ocean and Antarctica in both seasons. The correlation maps show low correlation values over the North African, Middle Eastern and Asian regions in boreal summer pointing again to problems over these regions (Fig. 6e), as noted by GR06. In boreal winter the correlation values of the Z500 fields from the NCEP/NCAR and ERA-40 reanalyses are everywhere relatively high (Fig. 6f).

c) Surface air temperature

Figure 7 shows the linear trends of the surface air temperature in the NCEP/NCAR, ERA-40 and HadCRUT2v data sets for the period 1958-1998 in boreal summer and winter. In the JJA season (Fig. 7a,c), the temperature trends in the two reanalyses disagree mainly over South America and Asia. Over South America, a cooling is present in the ERA-40 but not in the NCEP/NCAR reanalysis. Over Asia, the slight warming in the ERA-40 reanalysis agrees better with the trend in the HadCRUT2v data set than the relatively strong warming in the NCEP/NCAR reanalysis in this season. In the DJF season (Fig. 7b,d), the temperature trends in the two reanalyses disagree mainly over the Antarctic continent, the Irminger Sea, North Africa and South America. Over the Antarctic continent the temperature is decreasing in the NCEP/NCAR reanalysis and increasing in the ERA-40 reanalysis. Over the Irminger Sea and adjacent regions the moderate cooling in the ERA-40 reanalysis agrees better with the trend in the HadCRUT2v data set than the relatively strong cooling in the the NCEP/NCAR reanalysis in this season. Over North Africa, a cooling is present in the NCEP/NCAR but not in the ERA-40 reanalysis in the winter season. Over South America a cooling is present in the ERA-40 reanalysis which is missing in the NCEP/NCAR reanalysis. The introduction of Brazilian surface synoptic data in the ERA-40 reanalysis after January 1967 caused a marked shift from a warm to cold bias in the 2 m temperature over South America (Betts et al. 2004).

The temporal evolution of the surface air temperature trends between the NCEP/NCAR and ERA-40 reanalyses will now be analyzed in detail in regions where the data sets most strongly disagree. Figure 8 shows the area mean surface air temperature time series from the two reanalyses averaged within the boxes shown in Fig. 7. These boxes are North Africa (10-30°N, 10°W-30°E), South America (0-20°S, 40-70°W) and the Southern Ocean/Antarctic region (south of 60°S). Here are shown absolute values rather than the differences between the time series, as was done for the SLP (see discussion of Fig. 3) (it should be noted that the HadCRUT2v contains missing data for the problematic regions and cannot be considered for the comparison). The comparison between the time series is done here by calculating the running cross-correlation coefficients for windows of 11-years width. All time series (Fig. 8a-e) show offsets, with a tendency for these offsets to reduce, although problems persist over the Antarctic region and over South America in DJF. The jumps in the time series occurring in the late 1960's cause low correlation values between the two time series in the early period.

Figure 9a-b show the correlation values between the undetrended surface air temperature fields from the NCEP/NCAR and ERA-40 reanalyses for the period 1958-1998 in boreal summer and winter, respectively. Low correlation values exist over the polar regions, especially in the summer season, and also over the tropical and subtropical land areas extending almost entirely over South America, Africa and large parts of south Asia, with an extension further into subtropical regions in the respective summer hemisphere. Figure 9c-f show the correlation maps after splitting the full period into two segments of 20 years length (1958-1977 and 1979-1998) for each of the seasons. In the later period, when satellite observations became available, improvements are obvious, especially over the Southern Ocean, due to the incorporation of sea surface temperature observations from satellite microwave sounders into the reanalysis systems. Although the correlation values improve in the tropical and subtropical land areas, the problem of low correlation values over these regions persists in the satellite era.

d) Upper tropospheric temperature

Figure 10a-b show the correlation values between the undetrended 100 hPa air temperature fields from the NCEP/NCAR and ERA-40 reanalyses for the period 1958-1998 in boreal summer and winter, respectively. Low correlation values exist mainly in a band encompassing the whole tropical/subtropical region. Similar to the analysis of the surface air temperature, Figure 10c-f show the correlation maps for the separation of the full period into two segments of 20 years length (1958-1977 and 1979-1998). Overall the correlation values are even lower in the later than in the earlier period, especially in the tropical/subtropical band, although some improvements are present in the recent period, for example over the Southern Ocean.

Figure 11 shows a time series of differences in monthly mean 100 hPa temperatures between the NCEP/NCAR and ERA-40 reanalyses averaged over the tropical band between 17.5°N and 17.5°S. After the late 1970's, a strong discrepancy of 4 to 5 K is present between the two reanalyses, decreasing with time but still persisting at the end of the ERA-40 reanalysis in the early 2000's. Sturaro (2003) attributes this problem to the introduction of satellite data. These results show that the problem in 100 hPa temperature noted by GR06 is not restricted to the summer season, but is, in fact, found in all months of the year. Furthermore, the correlations shown in Figure 10c-f argue that there is worse agreement between the reanalysis products in the satellite era than there was before.

4. Conclusions

This study documents some discrepancies between the NCEP/NCAR and the ERA-40 reanalysis in the period 1958-1998 affecting the SLP, 500 hPa height, and surface and 100 hPa air temperature globally for both the summer and winter season. The discrepancies can be summarized as follows:

- The 100 hPa temperature from the NCEP/NCAR and ERA-40 reanalysis correlate poorly over the tropics and subtropics in both seasons, summer and winter, with worse agreement in the satellite era (1979-1998) than in the pre-satellite era (1958-1977) that must somehow be due to the introduction of satellite data into the reanalysis systems (Sturaro 2003).

- Large SLP, surface air temperature and Z500 biases between the two reanalyses exist over the Southern Ocean and the Antarctic region over the period 1958-1998 in both seasons, winter and summer. The SLP and Z500 biases decrease with time causing large spurious trends, particularly in the NCEP/NCAR reanalysis in the austral winter season (Hines et al. 2000).

- GR06 found large SLP and Z500 discrepancies over North Africa, the Middle East and Asia in the boreal summer season. Large discrepancies exist in these regions also in the boreal winter season. A negative SLP offset, similar to that detected for the summer season, exists in the NCEP/NCAR reanalysis over North Africa prior to the late 1960's also in winter. The SLP offset in the NCEP/NCAR reanalysis over the Middle East lasts longer in winter, until the late 1970's, than in summer. The problem over Asia in winter is more complex than in summer since offsets are present in both reanalyses.

- The wintertime NAO trend is a robust feature of the two reanalyses and the HadSLP1 data set.

- The positive surface air temperature trend over Asia in summer and the negative one over the Irminger Sea in winter are overestimated in the NCEP/NCAR reanalysis. A negative surface air temperature trend is present over North Africa in winter in the NCEP/NCAR but not in the ERA-40 reanalysis and a negative surface air temperature trend is present over South America in the ERA-40 but not in the NCEP/NCAR reanalysis in summer and winter. The introduction of Brazilian surface synoptic data in the ERA-40 reanalysis in 1967 possibly cause the artificial temperature trends over South America (Betts et al. 2004).

- Low correlation values of surface air temperatures between the two reanalyses exist over the Southern Ocean/Antarctic region and tropical and subtropical land areas extending over almost the entire South American, African and large parts of the south Asian land masses in both seasons. This problem extends into the respective summer hemisphere. Although the correlation between the two reanalyses is higher in the satellite era (1979-1998) compared with the pre-satellite era (1958-1977), the problem of low correlation values over these regions persists in the recent period.

The causes for the discrepancies between the NCEP/NCAR and ERA-40 reanalysis specified in this study are various and it is not in all circumstances possible to attribute a single cause to only one effect. Some problems are listed here:

- The problem of the assimilation of Australian pseudo-observations (PAOBS): In the NCEP/NCAR reanalysis pseudo-observations were shifted longitudinal by 180° between 1979 and 1992 (Marshall and Harangozo 2000, Kistler et al. 2001). Unlike conventional data, pseudo-observations are the product of human analysts, and are estimated (in this case SLP) based on satellite data, conventional data, and time continuity. The Australian Bureau of Meteorology generated these data for the NCEP/NCAR reanalysis, but they were wrongly read when used for the reanalysis. The surface climate south of 40°S over the ocean is mostly affected by this error, strongest in the austral winter season. Details can be found at http://www.cpc.ncep.noaa.gov/products/wesley/paobs/paobs.html

- The problem with pressure at the surface (PSFC): In the NCEP/NCAR reanalysis surface pressure observations were incorrectly encoded between 1948 and 1967. With this problem it appears that ~5% of observations (all less than 1000 hPa) were given values 100 hPa too great and were subsequently rejected by the assimilation quality control scheme: thus the problem is one of omission (Marshall and Harangozo 2000). Details can be found at http://wwwt.emc.ncep.noaa.gov/gmb/bkistler/psfc/pscf.html

- An error in the complex quality control (CQC) module exists in the NCEP/NCAR reanalysis. Apparently the conversion of temperature to virtual temperature was never done during the Tropical Ocean Global Atmosphere - Coupled Ocean Atmosphere Response Experiment (TOGA-COARE) period (1992-1993). The consequence of this error is that the model's tropical oceanic boundary layer is too warm relative to the SST. Details can be found at http://www.cpc.ncep.noaa.gov/products/wesley/toga/toga.html

- In the NCEP/NCAR reanalysis, the snow cover of the year 1973 is erroneously used for the period 1974-1994 (Kistler et al. 2001). Details can be found at http://www.cpc.ncep.noaa.gov/products/wesley/ek.snow.html

- The NCEP/NCAR reanalysis has used a constant sea ice thickness of 3 m for the Southern Ocean, which is more correct in the Arctic, and which causes negative temperature biases in winter. Moreover, a 100% sea ice cover is assumed which is known to artificially reduce sea-air heat fluxes and thereby to introduce a negative temperature bias over sea ice covered regions (Connolley and Harangozo 2001).

- Brazilian surface synoptic data is not included in the ERA-40 reanalysis before January 1967, and with its introduction there is a marked shift from a warm to cold bias in the 2 m temperature over South America (Betts et al. 2004).

A caveat of both reanalyses is the poor representation of surface land climate variability over regions with sparse observations, not only in the early reanalyses period but persisting also in the satellite era. We give the recommendation to incorporate satellite land surface observations in forthcoming reanalysis projects. For example, Jin (2004) discusses the potential for land surface temperature derivations from Advanced Very High Resolution Radiometer measurements available from the National Oceanic and Atmospheric Administration polar orbiting satellites (1981-1998). Some other land surface observations from space like the vegetation type, leaf area index, or land use may also be of advantage if a vegetation model is included into the reanalysis model.

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Figure Captions:

Fig. 1: Differences between mean values, NCEP/NCAR minus ERA-40, over the period 1958-1998 for (a,b) SLP (hPa), (c,d) surface air temperature (K), and (e,f) 500 hPa height (gpm) in boreal summer (JJA, left column) and winter (DJF, right column), respectively. Positive values are contoured with a full line and negative values with a dashed line.

Fig. 2: Linear trend of SLP (hPa/yr) over the period 1958-1998 in the (a,b) NCEP/NCAR reanalysis, (c,d) ERA-40 reanalysis, and (e,f) HadSLP1 data set in boreal summer (JJA, left column) and winter (DJF, right column), respectively. Positive values are contoured with a full line and negative values with a dashed line.

Fig. 3: Time series of area mean SLP differences, NCEP/NCAR minus ERA-40 (full), NCEP/NCAR minus HadSLP1 (dotted), and ERA-40 minus HadSLP1 (dashed), over (a,b) North Africa, (c,d) the Middle East, (e,f) Asia, and (g,h) Southern Ocean/Antarctica within the enframed regions in Fig. 2. The left column shows time series for the boreal summer (JJA) and the right column for the boreal winter (DJF) season, respectively.

Fig. 4: Time series of the wintertime NAO indices and corresponding linear trends derived from the NCEP/NCAR (dotted), ERA-40 (dashed) and HadSLP1 (full) data sets, respectively.

Fig. 5: Correlation maps of undetrended, seasonal mean SLP between the (a,b) NCEP/NCAR and ERA-40, (c,d) NCEP/NCAR and HadSLP1 and (e,f) ERA-40 and HadSLP1 data sets over the

period 1958-1998 in boreal summer (JJA, left column) and winter (DJF, right column), respectively.

Fig. 6: (a-d) Same as Fig. 2, but for the 500 hPa height (gpm/yr) and the (a,b) NCEP/NCAR, and (c,d) ERA-40 reanalyses only. (e-f) same as Fig. 5 but for undetrended, seasonal mean 500 hPa height and between the NCEP/NCAR and ERA-40 reanalysis only.

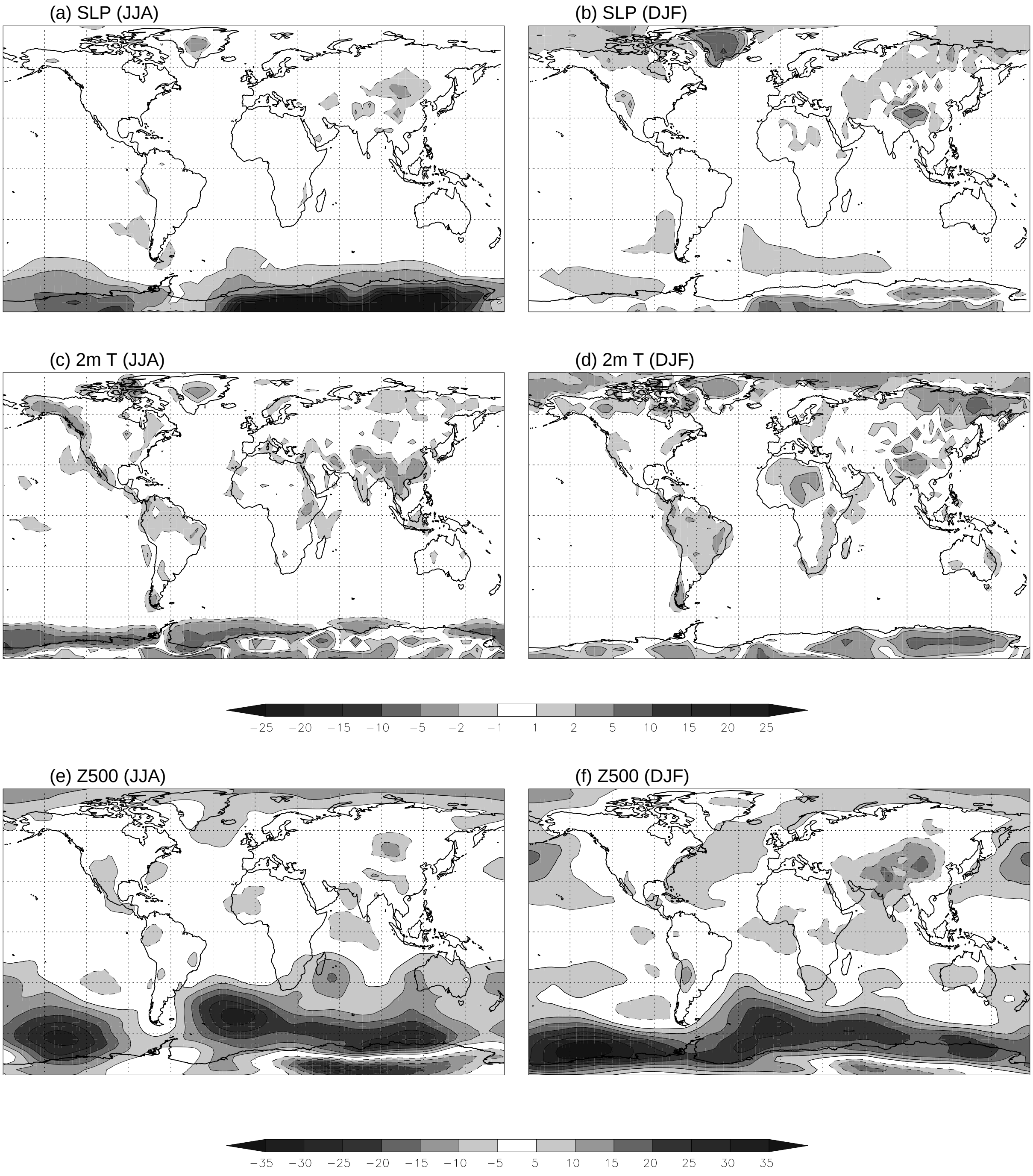
Fig. 7: Same as Fig. 2, but for the trend of the surface air temperature (K/yr) in the (a,b) NCEP/NCAR reanalysis, (c,d) ERA-40 reanalysis, and (e,f) HadCRUT2v data sets. In (e) and (f) grid cells with negative values are marked with a '-' symbol and those with missing vales with diagonal lines.

Fig. 8: Time series of area mean surface air temperature in the NCEP/NCAR (dotted) and ERA-40 (dashed) reanalyses over (a,b) North Africa, (c,d) South America, and (e,f) Southern Ocean/Antarctica within the enframed regions in Fig. 7 in boreal summer (JJA, left column) and winter (DJF, right column), respectively. The full line represents the running cross-correlation coefficient (11-yrs window width) between the time series from the two reanalyses with the value (given on the right axes) plotted at the center of the window for periods when the two reanalyses overlap. The correlation coefficient between the undetrended time series from the two reanalyses over the period 1958-1998 is given in the lower right corner. A threshold of 0.6/0.3 indicates a correlation significantly different from zero at the 5% level for the 11-yrs/1958-1998 period, respectively.

Fig. 9: Same as Fig. 5, but for the surface air temperature between the NCEP/NCAR and ERA-40 reanalysis over the periods (a,b) 1958-1998, (c,d) 1958-1977, and (e,f) 1979-1998, respectively.

Fig. 10: Same as Fig. 9 but for the 100 hPa temperature.

Fig. 11: Time series of area mean 100 hPa temperature differences, NCEP/NCAR minus ERA-40, averaged over the entire tropical band between 17.5°N and 17.5°S based on monthly means.



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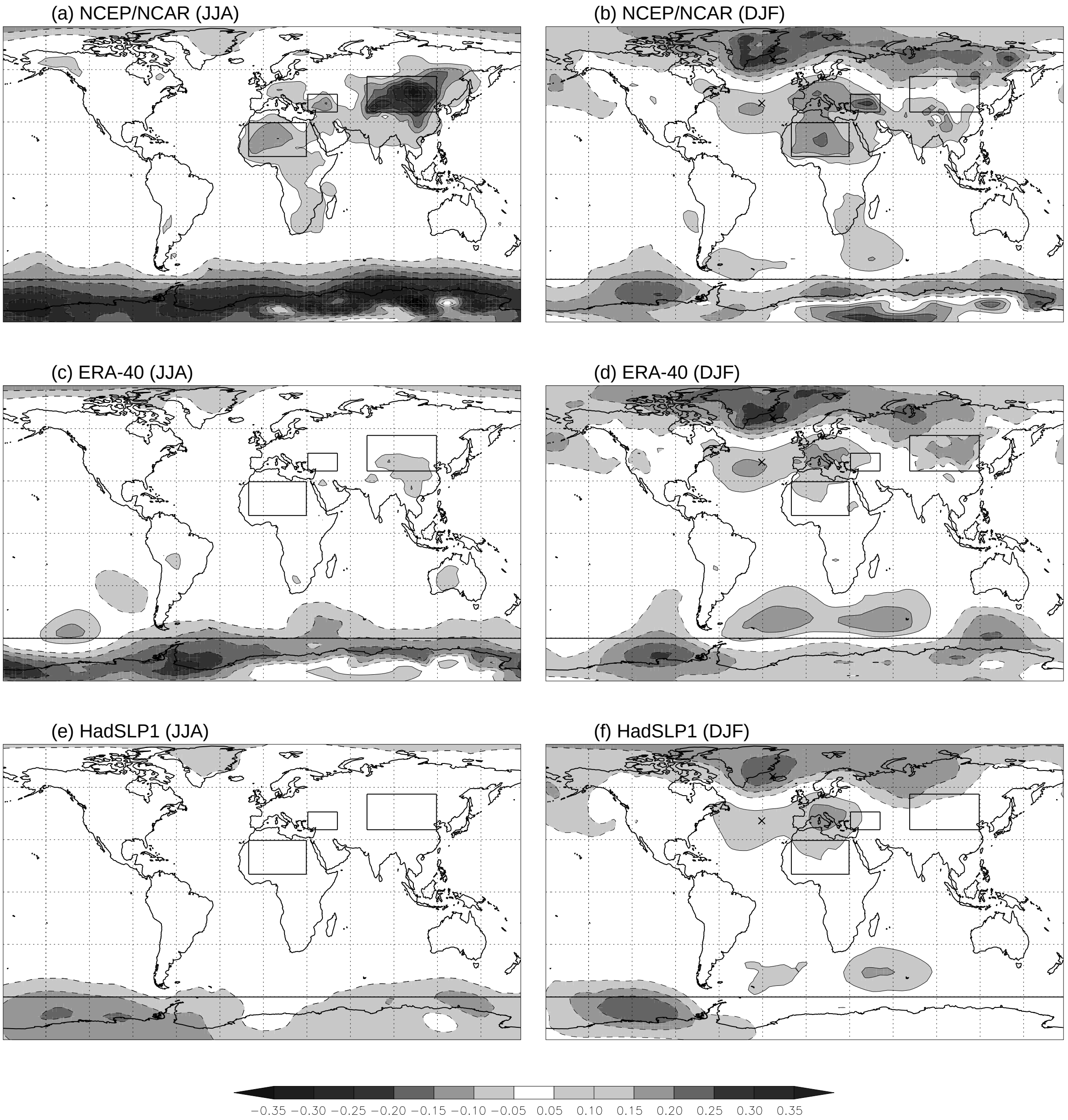

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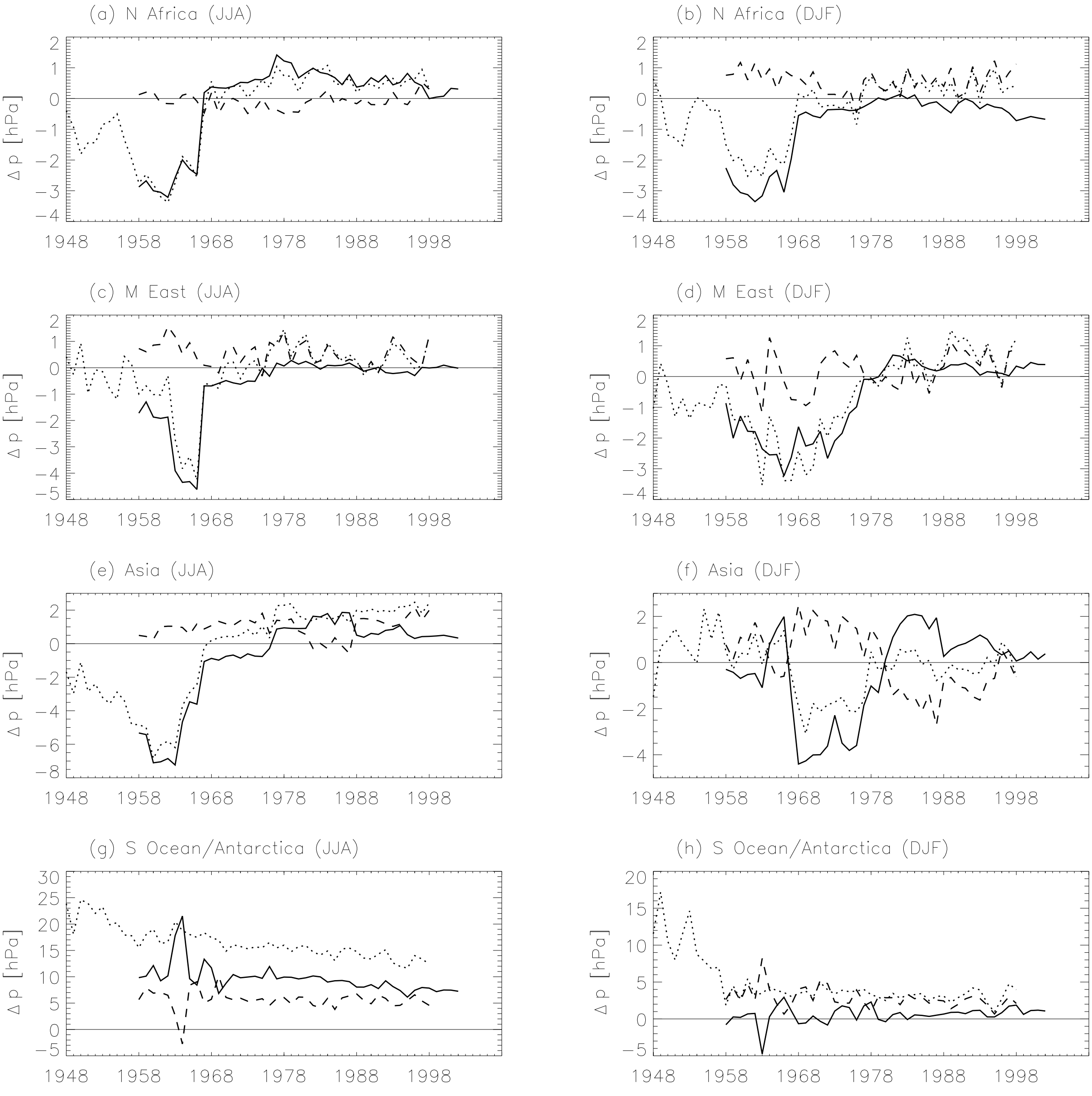

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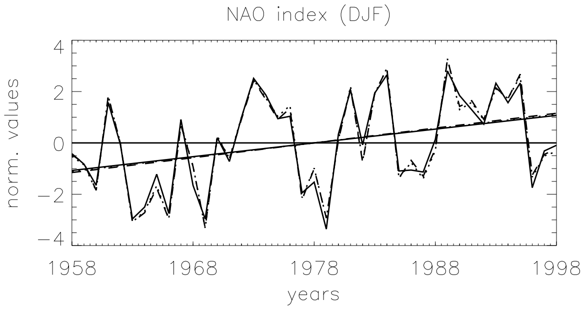

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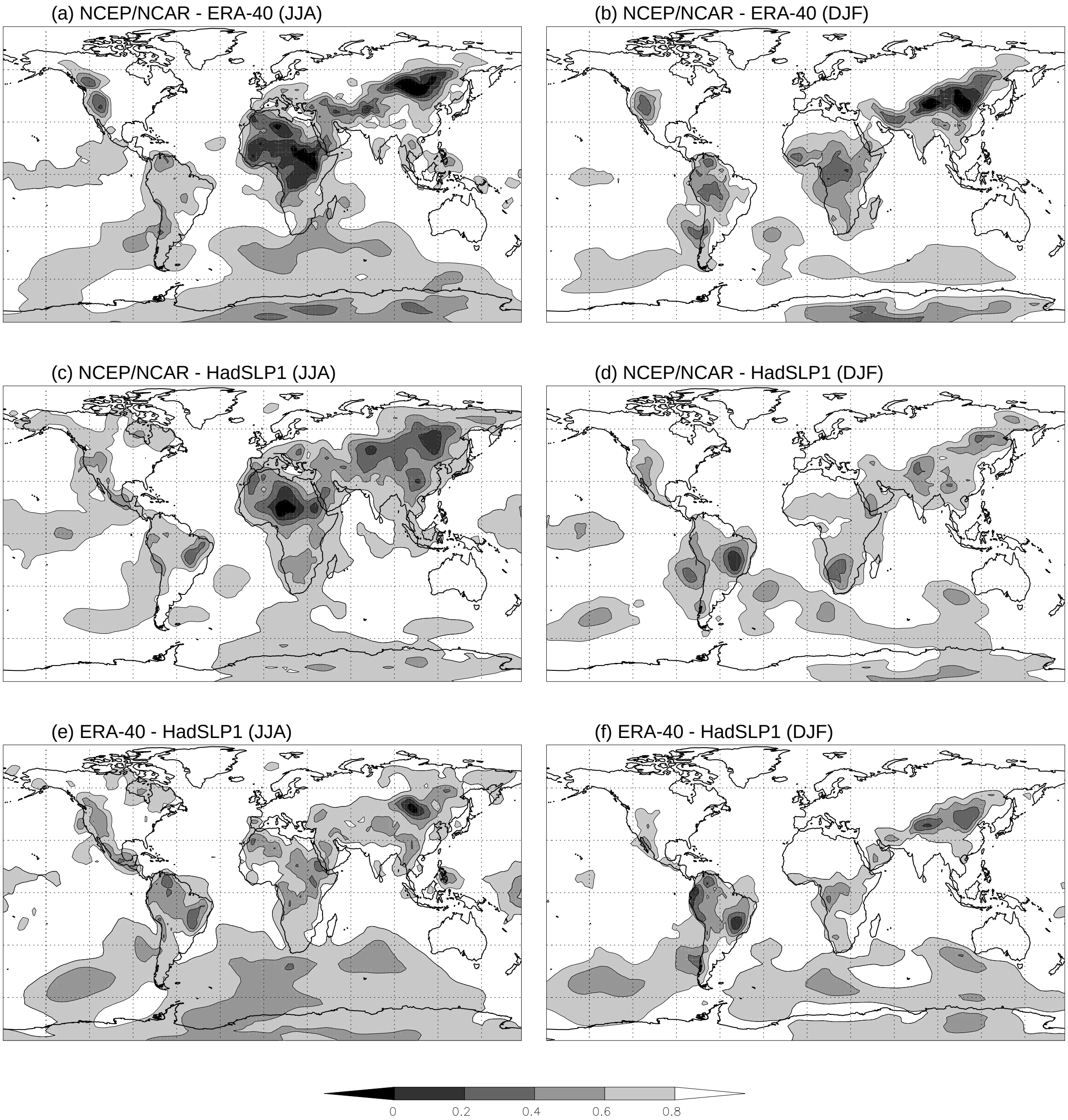

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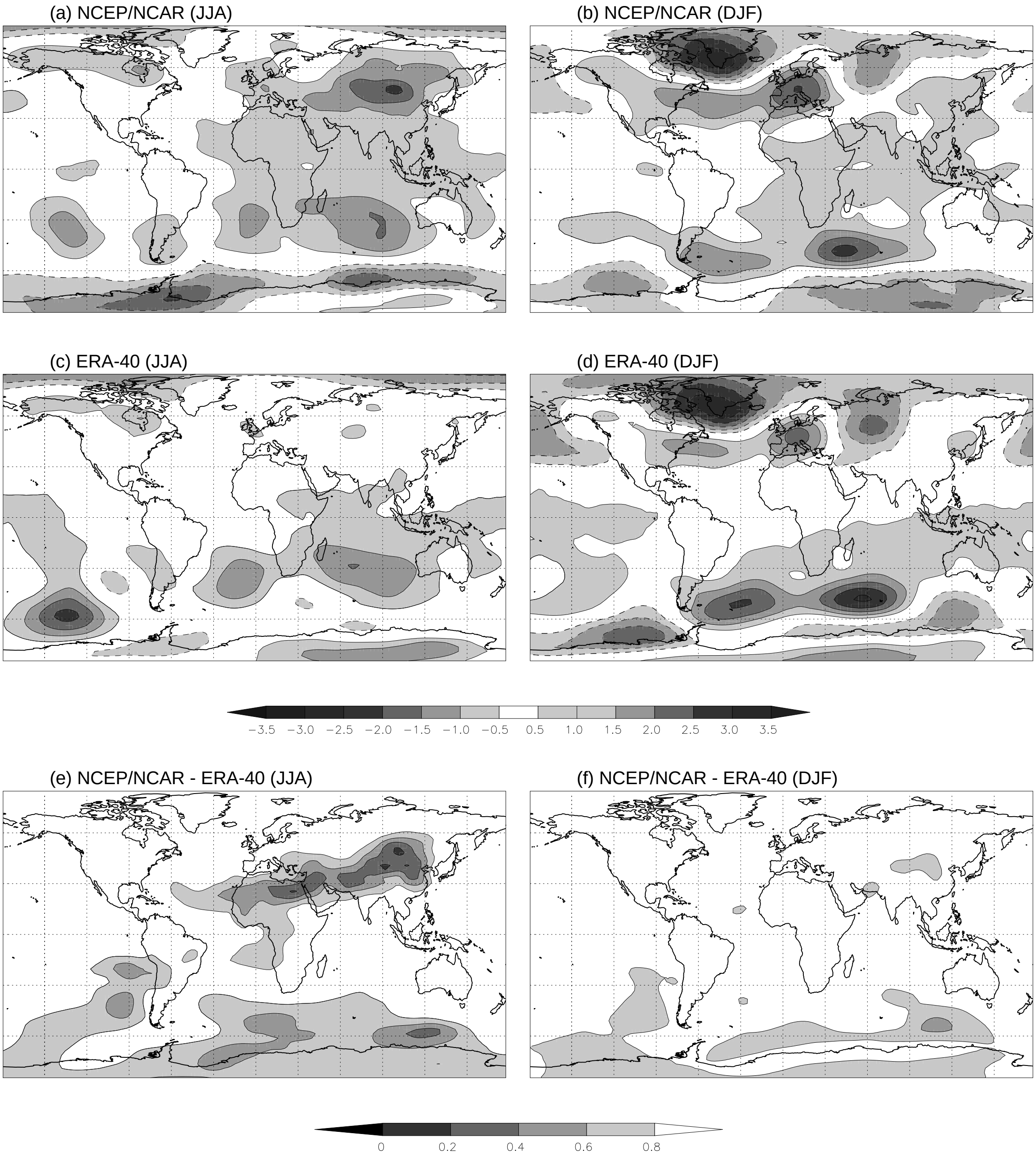

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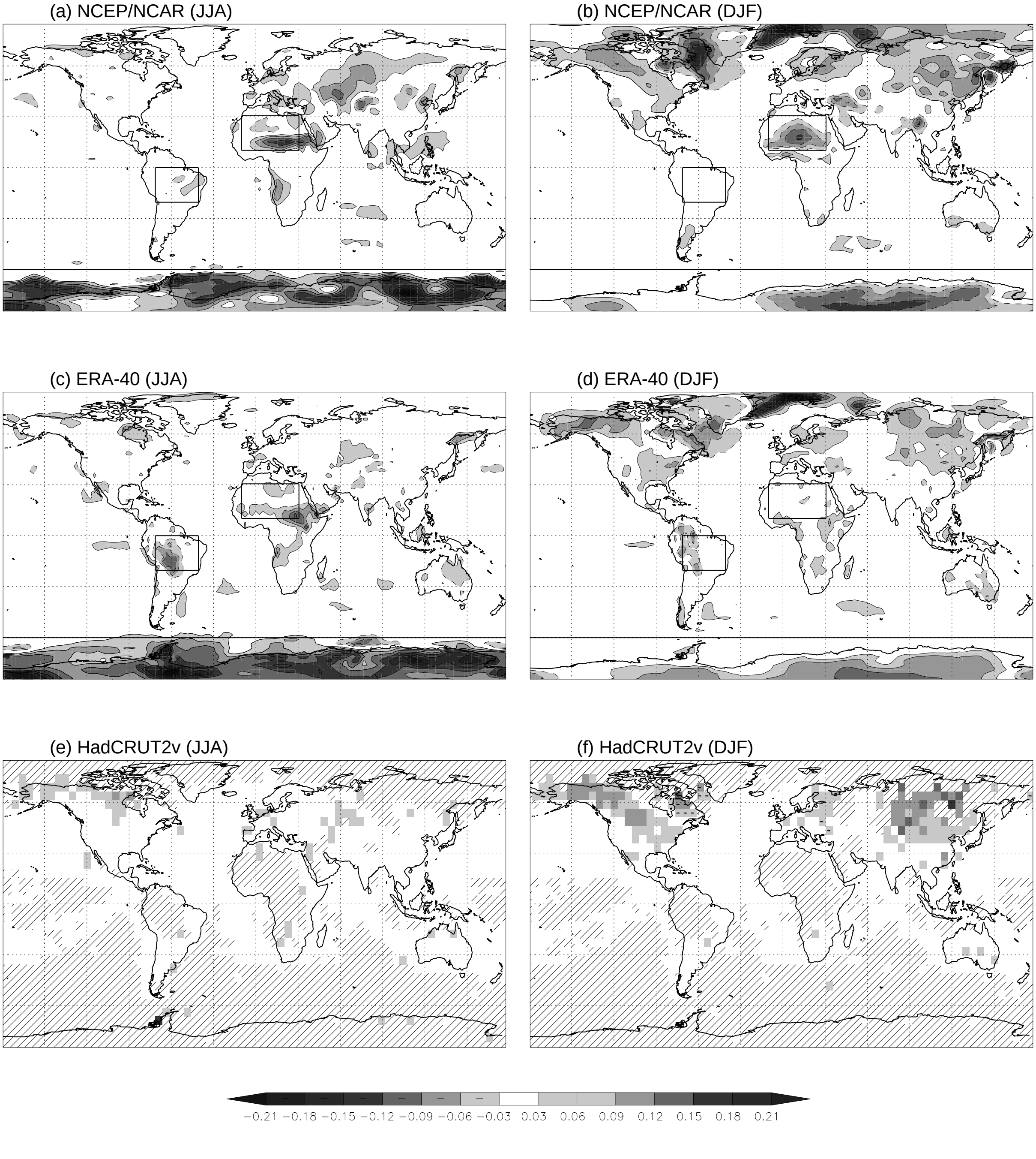

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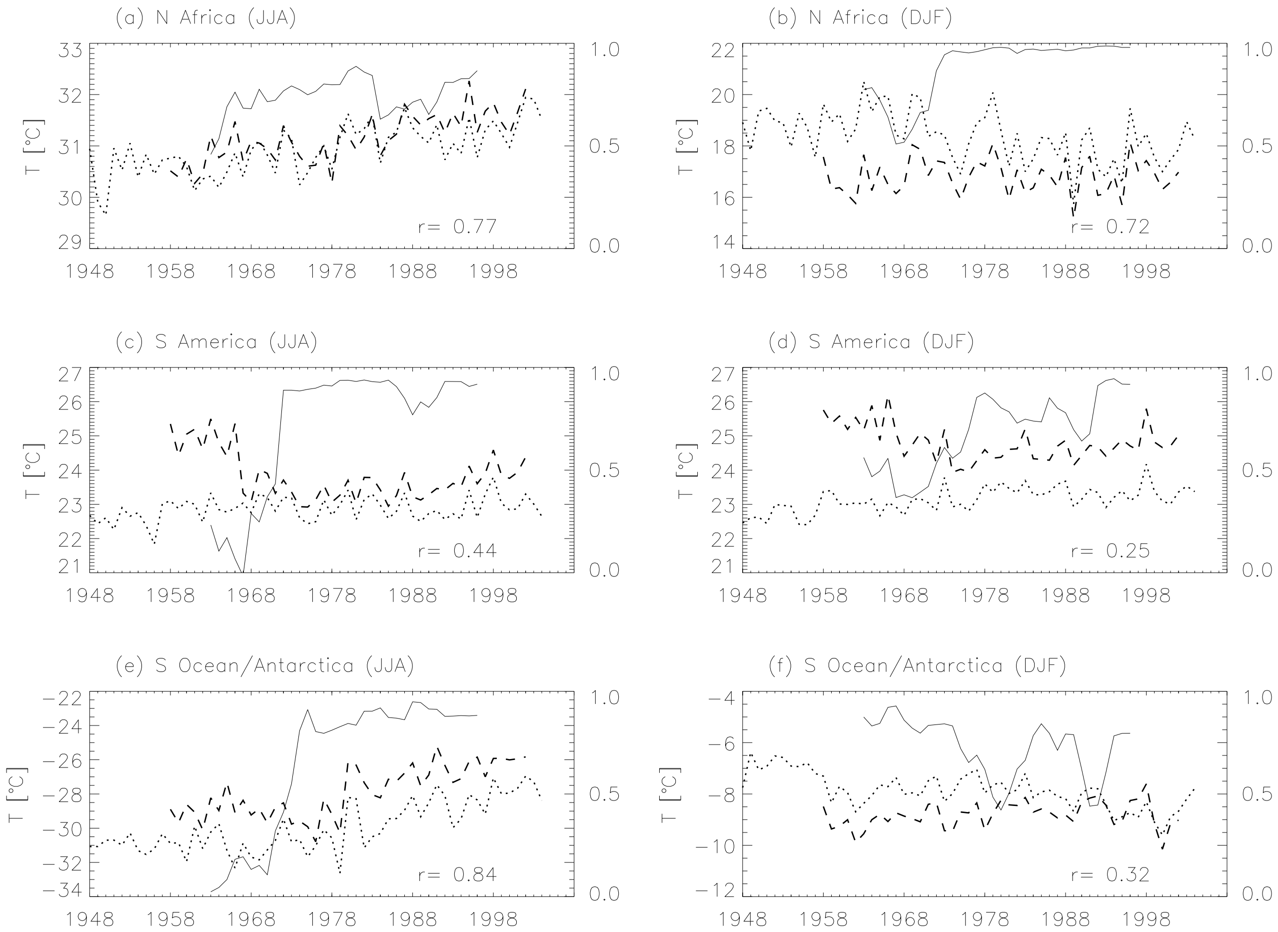

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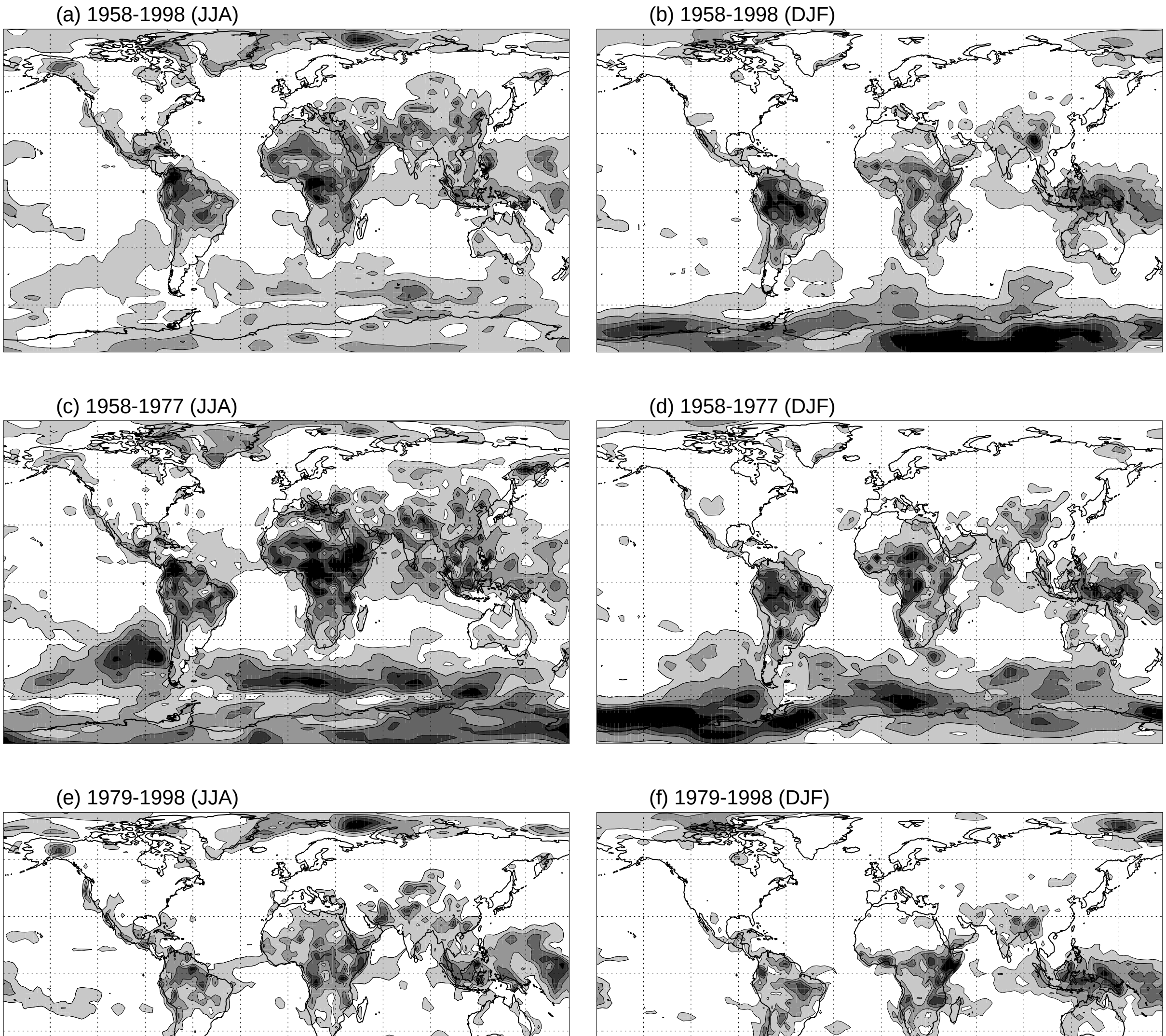

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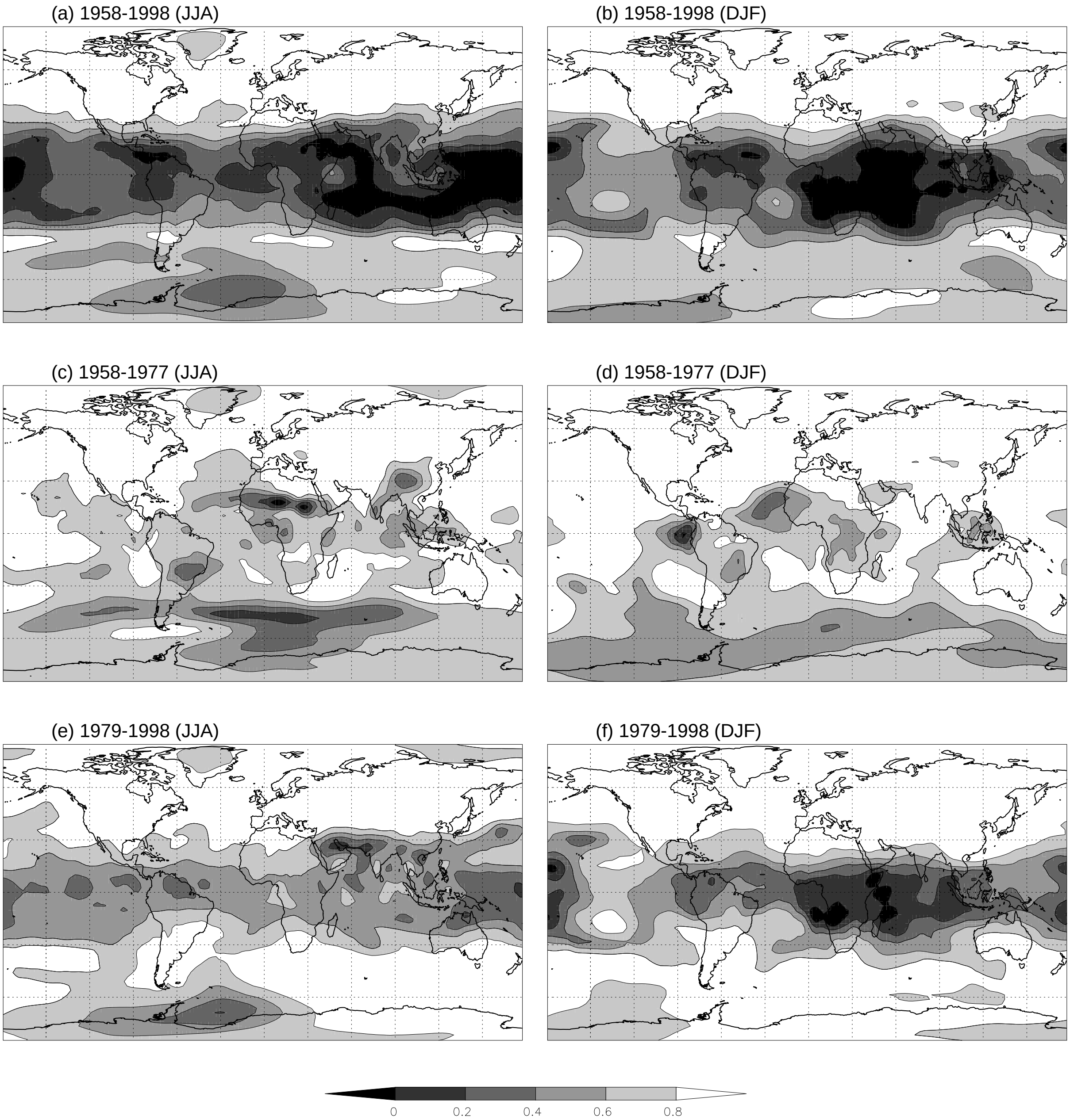

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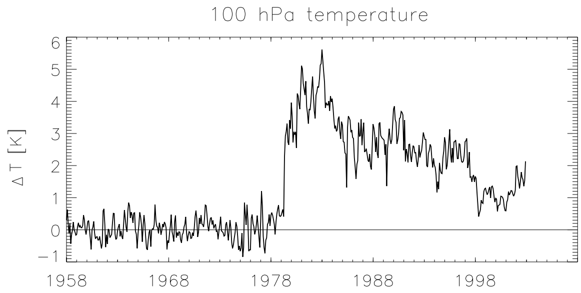

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