



Low-frequency variations in surface atmospheric humidity, temperature, and precipitation: Inferences from reanalyses and monthly gridded observational data sets

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[1] Evidence is presented of a reduction in relative humidity over low-latitude and midlatitude land areas over a period of about 10 years leading up to 2008, based on monthly anomalies in surface air temperature and humidity from comprehensive European Centre for Medium-Range Weather Forecasts reanalyses (ERA-40 and ERA-Interim) and from Climatic Research Unit and Hadley Centre analyses of monthly station temperature data (CRUTEM3) and synoptic humidity observations (HadCRUH). The data sets agree well for both temperature and humidity variations for periods and places of overlap, although the average warming over land is larger for the fully sampled ERA data than for the spatially and temporally incomplete CRUTEM3 data. Near-surface specific humidity varies similarly over land and sea, suggesting that the recent reduction in relative humidity over land may be due to limited moisture supply from the oceans, where evaporation has been limited by sea surface temperatures that have not risen in concert with temperatures over land. Continental precipitation from the reanalyses is compared with a new gauge-based Global Precipitation Climatology Centre (GPCC) data set, with the combined gauge and satellite products of the Global Precipitation Climatology Project (GPCP) and the Climate Prediction Center (CPC), Merged Analysis of Precipitation (CMAP), and with CPC's independent gauge analysis of precipitation over land (PREC/L). The reanalyses agree best with the new GPCC and latest GPCP data sets, with ERA-Interim significantly better than ERA-40 at capturing monthly variability. Shifts over time in the differences among the precipitation data sets make it difficult to assess their longer-term variations and any link with longer-term variations in humidity.

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1. Introduction

[2] Comprehensive observations and analyses of the hydrological cycle are crucial for improved understanding, modeling and prediction of climate. Water vapor is the most significant of the gases responsible for the natural greenhouse warmth of the atmosphere and release of latent heat when water vapor condenses is a significant driving factor in atmospheric circulation systems. Feedback from change in the hydrological cycle is thus a potentially important part of the net response to the radiative forcing from anthropogenic greenhouse gases and aerosols. Moreover, many of the societal concerns about climate change relate to the hydrological cycle, whether they be over potential impacts of increased intensity or frequency of heavy rainfall events,

stresses from reduced availability of water in marginal regions, or health impacts of changes in humidity.

[3] The distribution of water vapor near the surface of the Earth is one of the components of the hydrological cycle that is most amenable to study. Over land it has long been observed from the network of synoptic stations. Over sea it is measured directly from ships, buoys and other platforms, and is linked physically to the underlying water surface whose temperature is reasonably well known from in situ and space-based measurement. Taking account of a number of regional studies and a study by Dai [2006] of a near-global collection of observations, the latest Intergovernmental Panel on Climate Change (IPCC) assessment of atmospheric observations [Trenberth *et al.*, 2007] reported an increase in near-surface specific humidity after 1976 in close association with higher temperatures over both land and ocean. Observations of trends in relative humidity were viewed as uncertain, but suggested that relative humidity had remained largely the same overall near the surface, though with a modest reduction as temperature increased, as expected in water-limited regions. These conclusions were confirmed by Willett *et al.* [2008], based on analysis of a newly constructed near-global

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$5^{\circ} \times 5^{\circ}$ data set (HadCRUH) of monthly mean surface humidity anomalies over land and sea from 1973 to 2003. *Willett et al.* [2007] attributed the rise in specific humidity in HadCRUH primarily to anthropogenic climate forcing, with high confidence.

[4] Significant progress has also been made recently in the analysis of humidity observations through data assimilation [*Andersson et al.*, 2007]. This paves the way for improved products relating to the hydrological cycle from atmospheric reanalysis, and addresses in particular some severe deficiencies reported earlier for the ERA-40 reanalysis [*Andersson et al.*, 2005; *Trenberth et al.*, 2005; *Uppala et al.*, 2005]. Improved humidity analyses are accordingly expected from ERA-Interim, a new European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis for recent decades. ERA-Interim also improves on ERA-40 due to the use of four-dimensional variational data assimilation (4D-Var) rather than three-dimensional variational data assimilation (3D-Var), higher horizontal resolution, and variational bias correction of satellite radiance data [*Dee*, 2005; *Dee and Uppala*, 2009]. These and other changes less relevant to the present study are tabulated and discussed by *Simmons et al.* [2007]. ERA-Interim overlaps with ERA-40 from 1989 to 2001, has reached the present day and will be continued until superseded by a next-generation ECMWF reanalysis.

[5] The study reported here started with comparison of the near-surface specific and relative humidity values from HadCRUH with the corresponding values from ERA-40 and ERA-Interim. The aim was to investigate whether the quite different ways of processing the synoptic data record had provided gridded values sufficiently similar to give confidence in their suitability for climate studies, and whether there were any differences that shed light on deficiencies in one or other of the data analyses. In the event, having shown mostly very good agreement between the ERA reanalyses and the 31 year long HadCRUH record, it was found that the ERA-Interim analyses for the most recent years showed a marked drop in relative humidity over low-latitude and midlatitude land areas, with averages over all land values well outside the range of variability seen in HadCRUH. Having found no problem in the diagnostics of ERA-Interim production, the HadCRUH data set was augmented by a “quick-look” extension to cover the years 2004 to 2007. This confirmed the relative drying detected in ERA-Interim.

[6] A secondary aim of this study was to document the extent to which ERA-Interim can be used to extend the near-surface temperature record of ERA-40. The latter was shown by *Simmons et al.* [2004] to agree well with the CRUTEM2v analysis of monthly station data [*Jones and Moberg*, 2003] over the period since the major 1978/1979 upgrade of the global observing system, and longer for some regions. The results presented here are for comparisons of the ERA-40 and ERA-Interim temperature records with the updated CRUTEM3 temperature record [*Brohan et al.*, 2006]. Study of these temperature records, supplemented by records of sea surface temperature, has also provided a possible interpretation of the recent fall in relative humidity over much of the land surface.

[7] In addition, various data sets for precipitation were examined to see whether their variations over time could be linked with the variations in near-surface humidity. Although

shifts over time in the differences between these data sets made it difficult to assess their longer-term variations, several results concerning the relative quality of the data sets emerged and are presented in this paper. The main comparison is between monthly precipitation rates derived from accumulating 12 hourly totals from twice-daily forecasts run from the ERA-40 and ERA-Interim analyses and monthly rates from a new gridded analysis of gauge data from Global Precipitation Climatology Centre GPCP [*Schneider et al.*, 2008]. Further comparison is made with the established combined gauge and satellite products from Global Precipitation Climatology Project (GPCP) [*Adler et al.*, 2003] and Climate Prediction Center Merged Analysis of Precipitation (CMAP) [*Xie and Arkin*, 1997], and the gauge-based PREC/L data set [*Chen et al.*, 2002].

[8] Several features of the analysis methods used to produce the data sets examined in this paper are presented in section 2, and some computational details of the present study are given in section 3. Although the main focus of this paper is on the humidity analyses, some pertinent results for temperature are presented first in section 4 to set the scene. Results for humidity are discussed in section 5. Both specific and relative humidity are considered, as working with monthly and a real averages of anomalies masks the relationship between these two humidity variables and temperature, and because the variable of interest changes depending on context. The comparisons of the precipitation analyses are reported in section 6, which is followed by a concluding discussion.

2. Analyses of Surface Air Temperature, Humidity, and Precipitation

2.1. ERA-40 and ERA-Interim

[9] The two ERA product sets include analyses of temperature and dew point at a height of 2 m. These analyses are produced six hourly as part of the data assimilation, but are not provided directly by the primary variational analysis of atmospheric fields. Instead, separate analyses of near-surface temperature and relative humidity are made using optimal interpolation (OI) of data from screen-level measurements. In a first step, reported values of temperature and dew point from the synoptic network are converted into values of relative humidity. The corresponding background values are provided by the background forecasts of the full variational data assimilation, which employed 6 hourly cycling in ERA-40 and uses 12 hourly cycling in ERA-Interim. The optimal interpolation analysis for near-surface temperature is described by *Simmons et al.* [2004], and the scheme for relative humidity is generally similar. The background and observation errors are set at 5% and 10%, respectively, for relative humidity, and observations are used only if the derived relative humidity is in the range from 2 to 100%. The resulting relative-humidity analysis is likewise bounded between 2 and 100%, and values are converted to dew point temperature for archiving.

[10] The 2 m temperature and humidity analyses are not used to modify the model-level atmospheric fields from which the background forecast for the next analysis in the data assimilation sequence is initiated. They are, however, used as input to an analysis of soil moisture and temperature

[*Douville et al.*, 2000]. They thus influence the background forecast through the resulting adjustments to the model's initial soil moisture and soil temperature fields.

[11] Screen-level observations of temperature are used only in the analysis of 2 m temperature, and not directly in the variational analysis of temperature higher in the boundary layer. In contrast, the screen-level observations of humidity are used also in the variational analysis of specific humidity at higher levels. The ERA-40 3D-Var used the screen-level humidities at all times of the day, whereas the ERA-Interim 4D-Var uses them only in daytime, to avoid an inappropriate upward spreading of information above shallow nocturnal boundary layers. The variational boundary layer humidity analysis over land is also influenced significantly by humidity measurements from radiosondes [*Andersson et al.*, 2007]. This use of surface and radiosonde measurements in the variational analysis influences the background fields at 2 m height used in the separate OI analysis of screen-level humidity measurements.

[12] The sea surface temperature (SST) analysis for ERA-40 was based on the monthly HadISST1 data set [*Rayner et al.*, 2003] up to November 1981, and the weekly U.S. National Centers for Environmental Prediction (NCEP) two-dimensional variational data assimilation (2D-Var) data set [*Reynolds et al.*, 2002] thereafter until June 2001. Interpolation was used to produce daily values from each data set. Daily operational NCEP products were used after June 2001. ERA-Interim used the same SSTs as ERA-40 in the period of overlap, and continued to use the daily operational NCEP data stream over the additional period from 2002 to 2008 considered in this paper.

[13] Further information on the ECMWF data assimilation system can be found in the online documentation available from <http://www.ecmwf.int>. The analyses themselves are also available from this website: they can be downloaded directly with resolutions of 2.5° for ERA-40 and 1.5° for ERA-Interim.

2.2. CRUTEM3, HadCRUT3, and HadCRUH

[14] CRUTEM3 [*Brohan et al.*, 2006] is based on temperature anomalies computed for all stations that provide sufficient data to derive monthly climatic normals for the period 1961–1990. Station values are aggregated over $5^\circ \times 5^\circ$ grid boxes. Compared with the earlier CRUTEM2 version [*Jones and Moberg*, 2003], there are improvements in quality control, definition of station normals and gridding, and use of some additional observations. A data set in similar format, HadCRUT3 [*Brohan et al.*, 2006], has been formed by blending CRUTEM3 with anomalies in sea surface temperature derived from the HadSST2 analysis described by *Rayner et al.* [2006].

[15] *Simmons et al.* [2004] compared ERA-40 with CRUTEM2v, a variance-adjusted version of CRUTEM2. The comparisons reported below for CRUTEM3 have also been made for the corresponding variance-adjusted version CRUTEM3v [*Brohan et al.*, 2006]. Results differ very little, and are presented here for CRUTEM3 rather than CRUTEM3v because a problem in implementing the adjustment to CRUTEM3 has resulted in slightly reduced data coverage for the variance-adjusted version, principally in regions of the southern hemisphere that are already data-sparse.

[16] HadCRUH is a data set of anomalies in specific and relative humidity over land and sea, in a $5^\circ \times 5^\circ$ format similar to that of the temperature data sets [*Willett et al.*, 2008]. The land component is a station-based data set where each station must report sufficiently to create station climatologies for the 30 year period 1974–2003. The data over land are taken from the Integrated Surface Data set (ISD, formerly ISH) [*Lott et al.*, 2001] provided by the U.S. National Climatic Data Center (NCDC) from 1973 to 2003. Simultaneously observed temperature and dew point are converted to specific and relative humidity, and data are put through a series of quality checks for internal consistency, outliers, and humidity-specific measurement problems. Spatial comparisons are made with neighbor composites to detect inhomogeneities within the record for each station, and time series are adjusted where necessary. The data are then converted to a set of monthly anomalies by subtracting the climatology (separately for specific and relative humidity) and averaging over each $5^\circ \times 5^\circ$ grid box and month.

[17] The marine component of HadCRUH is based on specific and relative humidity derived from in situ measurements of temperature and dew point from ships, marine platforms, and drifting buoys. The data are taken from the International Comprehensive Ocean-Atmosphere Data Set, from 1973 to 1997 [*Worley et al.*, 2005], updated with data for 1998 to 2003 accumulated by NCEP. Observations undergo quality checks for internal consistency, spatial consistency, and outliers and the remaining values are converted to anomalies by subtracting 1974–2003 climatological means. Values are then averaged to form monthly anomalies on the $5^\circ \times 5^\circ$ grid, and blended with the land values with weighting according to the proportional spatial presence of land or ocean in each grid box, imposing a minimum weighting of 25% for each component for boxes containing both land and marine data.

[18] A new gridded data set of specific and relative humidities over land, HadCRUHext, has been constructed for the purpose of this paper. It runs from 1994 to 2007, and is based on a newer version of the ISD than used for HadCRUH. The time period was chosen to provide a 10 year overlap with HadCRUH and four further years of overlap with ERA-Interim. Data for 2008 were not available from the ISD when HadCRUHext was constructed. Although the period of overlap with HadCRUH reveals some discrepancies, especially over North America, the extension serves to demonstrate agreement with ERA-Interim's depiction of recent changes in near-surface humidity. Further detail and discussion of the construction and quality of HadCRUHext are provided in Appendix A.

[19] The ERA analyses are not fully independent of the CRUTEM3 and HadCRUH data sets. CRUTEM3 uses monthly average (World Meteorological Organization CLIMAT message) data provided by stations for which there is a sufficient data record to derive monthly climatological values, and thus anomalies. The averaging was carried out by the original data providers from individual temperature measurements. Many messages were formed from daily averages of maximum and minimum temperatures, which are not assimilated in the ERA analyses, but where they were formed from the daily average of synoptic measurements it is likely that the same measurements would have been assimilated in the ERA analyses, which used all readily available synoptic observations, most

of which were transmitted originally as World Meteorological Organization SYNOP messages. Although both ERA and HadCRUH near-surface humidity analyses are based on surface synoptic measurements, ERA assimilates observations from many more stations, again because it can exploit data from all stations from which messages are received. Moreover, the basic temperature and humidity measurements are processed very differently in ERA, CRUTEM3, and HadCRUH. Although a common influence of a change over time in measurement biases cannot be entirely ruled out, it would be expected that any significant impact would manifest itself in a shift over time in the fit of the ERA background forecasts to the measurements. This is discussed later in this paper for humidity; discussion for temperature is given by *Simmons et al.* [2004].

[20] The CRUTEM3, CRUTEM3v, HadCRUT3, and HadCRUH data sets can be downloaded from <http://hadobs.metoffice.com>. These data sets are referred to generically below as the HadCRU data sets.

2.3. GPCC, GPCP, CMAP, and PREC/L

[21] The principal precipitation data set against which the ERA products are compared over continental areas is the 2.5° resolution full data product version 4 provided by the GPCC [*Schneider et al.*, 2008] (downloaded from <http://gpcc.dwd.de> after the data set was updated on 25 September 2008). This data set was formed by gridding monthly precipitation anomalies using the complete set of gauge measurements held at the time in the GPCC station database. The data available from 1973 to 2007 are utilized in this study. As noted on the GPCC website, variations over time in the number of stations providing gauge data for each month are such that caution has to be applied when using the full data product for climate variability and trend analysis, especially in data sparse areas. The GPCC's recommended product adjusted to support such analysis is its 50 year Variability Analysis of Surface Climate Observations data set, but this was not used as it was available only to the year 2000 at the time this study was carried out. The GPCC products are fully independent of those from ERA, which did not assimilate any gauge data.

[22] Comparison is also made with two data sets that combine a different GPCC analysis (the so-called Monitoring Product available from 1986 onward) with other gauge-based data and estimates of precipitation from satellite measurements. The GPCC Monitoring Product is based on significantly fewer gauge measurements than the Full Data Product for all but the most recent years (as will be illustrated later), and until recently was based on gridding the full gauge values rather than anomalies. The combined data sets are Version 2 of the Global Precipitation Climatology Project product (GPCP) [*Adler et al.*, 2003] (downloaded from <http://precip.gsfc.nasa.gov>) and the Climate Prediction Center Merged Analysis of Precipitation (CMAP) [*Xie and Arkin*, 1997] (standard version, without use of NCEP reanalysis values, downloaded from <http://www.cdc.noaa.gov/data/gridded/data.cmap.html>). Both data sets begin in 1979 and comparisons are made for the period up to the end of 2007. The gauge-based data sets used to form the GPCP product are adjusted for estimated systematic errors of gauge measurement [*Adler et al.*, 2003]. The merged products are not strictly independent of the ERA analyses as each are to some degree

dependent on data from the same satellite instruments, but again the data processing is very different and the merged products are largely determined in any case by the independent GPCC data over land.

[23] A further gauge-based data set of monthly precipitation over land (PREC/L) [*Chen et al.*, 2002] (downloaded from http://www.cpc.ncep.noaa.gov/products/global_precip/html/wpage.50yrrec.html) is included in the comparison. PREC/L is based on different collections of gauge data than used for the GPCC Monitoring Product, with a larger number of stations until the 1990s, but fewer since. It is constructed using optimal interpolation with the background provided by long-term observational means.

[24] A new version of the GPCP data set was released while this paper was at an advanced stage of the review/revision process. This version, numbered 2.1, is based over land on the GPCC full data product version 4 up to the end of 2007, and thereafter on a revised GPCC monitoring product that uses gridding of monthly anomalies. Version 2.1 has also been downloaded from <http://precip.gsfc.nasa.gov>, and apart from time-invariant differences of 0.1–0.4 mm/d in continental averages that stem from the gauge-bias correction, it gives results over land that are very similar to those presented here for the GPCC full data product version 4. Thus most of what is presented below in section 6 for the differences between GPCC and GPCP can be regarded as applying equally to the differences between versions 2.1 and 2 of GPCP.

3. Some Computational Details

[25] Monthly values of the reanalyses for $5^\circ \times 5^\circ$ and $2.5^\circ \times 2.5^\circ$ grid boxes are needed for comparison with the various data sets gridded directly from observations. First, linear interpolation is used to transform archived 2 m temperature, 2 m dew point, model-level specific humidity and precipitation fields from the irregular computational grid of the assimilating model (which has approximately 125 km resolution for ERA-40 and 80 km for ERA-Interim) to a finer $0.25^\circ \times 0.25^\circ$ regular latitude/longitude grid. Archived surface pressure and pressure-level relative humidity are evaluated directly on the 0.25° grid from the T159 (ERA-40) and T255 (ERA-Interim) spherical harmonic representations in which these fields are stored. The dew points, temperatures, and surface pressures are used to compute 2 m specific and relative humidities. Monthly means for temperature and humidity are computed by averaging over the set of daily analyzed values for 0000, 0600, 1200, and 1800 UTC. Monthly precipitation values are formed by summing 12 h accumulations from forecasts carried out daily from 0000 and 1200 UTC, using either the 0–12 h or the 12–24 h forecast range as discussed in section 6. The monthly $5^\circ \times 5^\circ$ (temperature and humidity) and $2.5^\circ \times 2.5^\circ$ (precipitation) values are then formed by area-weighted averaging of the various fields over the 0.25° subgrid. All-land and all-sea averages from the reanalyses are evaluated directly from the 0.25° grid values.

[26] The HadCRU data sets do not provide complete spatial and temporal coverage. Except where stated otherwise, the comparisons presented here use only those reanalysis values for which there is a corresponding HadCRU value for the month and grid box in question. Each value is weighted

by the area of its grid box in forming averages over a collection of grid boxes. No account has been taken of model land-sea distributions in producing averages for the CRUTEM3 grid boxes. The CRUTEM3 values are mostly for continental landmasses, but for some grid boxes they are derived from island stations and for these one or both of the reanalysis values may be derived from model sea points. For coastal grid boxes the CRUTEM3 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.

[27] A different approach has to be used when comparing ERA with the other HadCRU and precipitation data sets, which mostly contain values over sea as well as land. In this case averages over either land or sea are formed by multiplying values for each $5^\circ \times 5^\circ$ or $2.5^\circ \times 2.5^\circ$ grid box by a fractional land-sea mask derived from that used in the ERA-Interim model, using the procedure for deriving grid box values described in the preceding paragraph.

[28] The HadCRU data are anomalies with respect to 30 year station normals, based on the periods 1961–1990 for temperature and 1974–2003 for humidity. For ERA-40, which runs from 1958 to 2001, temperature data are accordingly expressed as anomalies with respect to their own monthly climatic means for 1961–1990. Humidity data are expressed as anomalies relative to the 28 year period 1974–2001. For ERA-Interim, which begins only in 1989, the normal for a particular month of the year is derived from the corresponding ERA-40 normal by adding the mean difference for the month between ERA-Interim and ERA-40 computed for the overlap period 1989–2001. The generally good agreement between the ERA and HadCRU data sets presented below shows that these unavoidable inconsistencies in the computation of anomalies do not have significant effect.

[29] In most cases, each set of monthly anomalies has been further adjusted by subtracting the mean value (averaging over all months of the year) for the period 1989–1998. This is partly for convenience of presentation, enabling the zero line to be centered in all plots of time series, and 10 year mean differences to be displayed in maps covering 1979–1988 and 1999–2008. Moreover, data assimilation and forecast statistics for ERA-40 indicate best performance in more recent decades, particularly from 1979 onward, following the very significant and subsequently sustained upgrade to the global observing system originating from work in the 1970s under the Global Atmospheric Research Programme in preparation for the Global Weather Experiment [Uppala *et al.*, 2005]. Without adjustment, time series of monthly anomalies with respect to 1961–1990 for temperature would have shown a misleading mean discrepancy between CRUTEM3 and the reanalyses for recent years, even if the ERA and CRUTEM3 analyses were to have been perfect from 1979 onward. The point has been discussed further by Simmons *et al.* [2004], who chose to adjust to zero anomaly for the period 1987–2001 when comparing CRUTEM2v and ERA-40.

4. Comparison of Surface Air Temperature Analyses

4.1. Time Series of Continental Averages

[30] Figure 1 presents 12 month running means of the CRUTEM3 temperature anomalies, and the monthly

differences between the ERA and CRUTEM3 anomalies. The ERA values are taken from ERA-40 from 1973 to 1988, and ERA-Interim from 1989 to 2008. Results are shown for averages over all grid boxes with CRUTEM3 values that lie in domains representative of Europe, Asia, North America, Africa, Australia and South America. The latitude and longitude limits that define each domain are specified in Table 1. Results are not presented for Antarctica in this paper as coverage in the HadCRU data sets is generally sparse, and in some months nonexistent for humidity. Where there are CRUTEM3 values over Antarctica they are reproduced by the ERA reanalyses from 1979 onward to a reasonable degree of accuracy, similar to that shown by Simmons *et al.* [2004] for the comparison of ERA-40 and CRUTEM2v.

[31] Figure 1 shows CRUTEM3's depiction of the much discussed near-surface warming of the atmosphere since the mid 1970s. Warming occurs over each continent, although its magnitude varies from region to region. Differences between the monthly ERA values and CRUTEM3 are generally small for Europe and Asia. They show a small drift over time, which is such as to make the least squares fit linear warming trend some 10% lower in the reanalysis values (sampled as CRUTEM3) than in CRUTEM3 for these regions (see Table 2). Differences are mostly small also for North America, but are larger and biased warm in ERA-40 relative to CRUTEM3 until the early 1980s. The linear warming trend from reanalysis accordingly shifts from about 5% below that of CRUTEM3 to about 5% above when the period over which the trend is calculated is changed from 1973–2008 to 1979–2008. These differences in trend are, however, small compared with the uncertainties due to the incomplete spatial and temporal sampling of the CRUTEM3 data set, as discussed in section 4.2.

[32] Differences are somewhat larger and more variable over time for the other continents. They nevertheless mostly cluster around the zero line, indicating that the low-frequency variability in CRUTEM3 is largely reproduced by the reanalyses. ERA-40 results for Australia are poor in the mid 1970s, as discussed by Simmons *et al.* [2004], and this causes relatively large differences in the 1973–2008 linear trends in Table 2. ERA-Interim shifts relative to CRUTEM3 by around 0.15K from its first to its second decade over Africa and South America, moving to relatively cooler values for Africa and warmer values for South America.

[33] Table 1 includes correlations between the time series of continental mean monthly anomalies from ERA-40, ERA-Interim, and CRUTEM3, calculated over their 1989–2001 period of overlap. Both reanalyses correlate well with CRUTEM3, especially for Europe, North America and Asia, where values exceed 99%. Agreement is least good for Africa, more so for ERA-Interim than ERA-40. The latter is a consequence of differences in the background forecasts from the two reanalyses, as ERA-Interim uses the same OI analysis scheme and observations of 2 m temperature as ERA-40, but the underlying reason for this difference in data-assimilation performance has yet to be determined. Correlations between ERA-Interim and ERA-40 are especially high; such discrepancy as there is between the two reflects differences in surface observational coverage, with best agreement for Europe and poorest agreement for Africa.

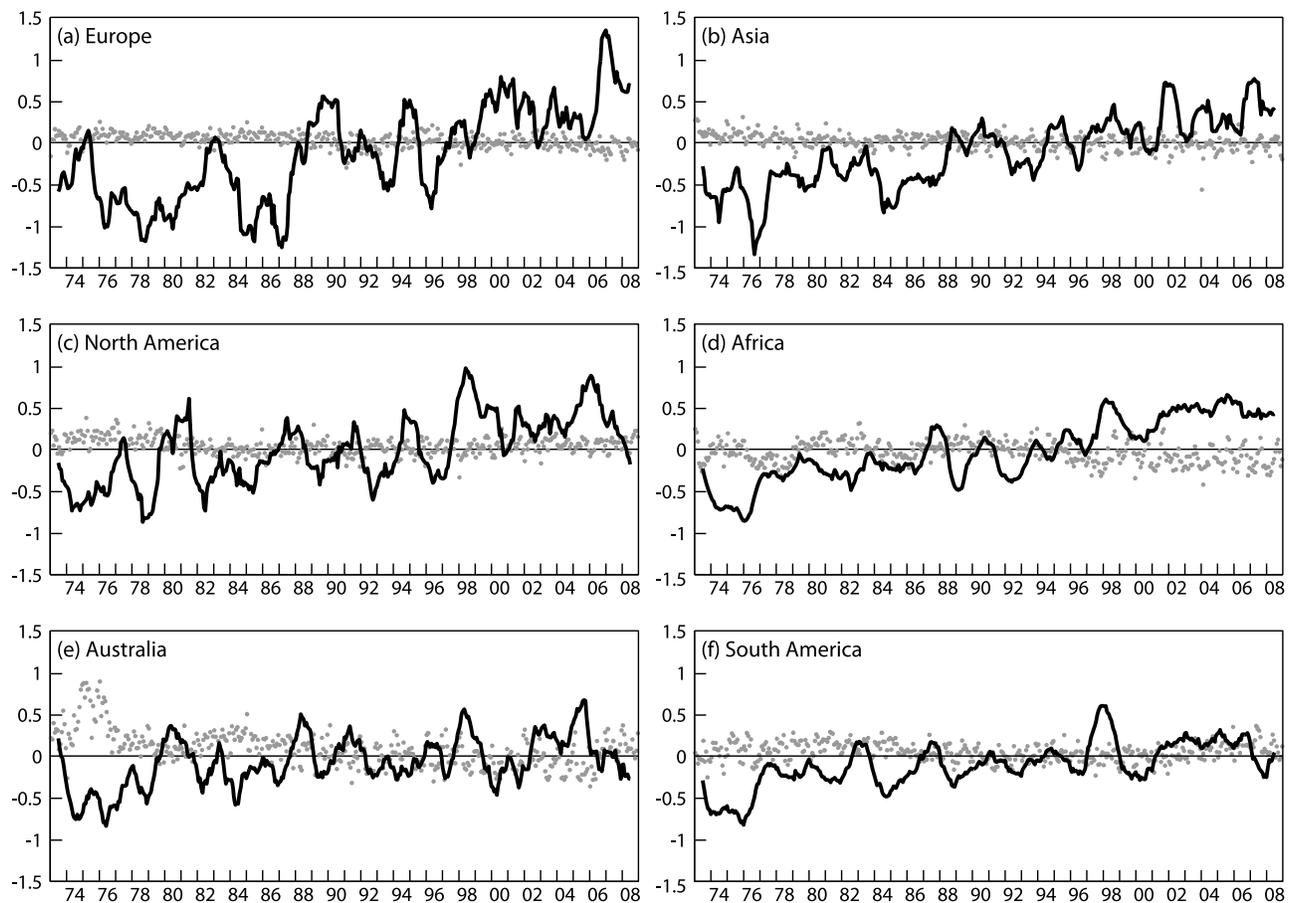


Figure 1. Black solid curve is 12 month running means of 2 m temperature anomalies (K) from the CRUTEM3 analysis of monthly station data from 1973 to 2008. Grey dots are differences (ERA-CRUTEM3) between monthly reanalysis and CRUTEM3 values, with reanalysis values taken from ERA-40 for 1973–1988 and ERA-Interim for 1989–2008. Reanalyses are sampled with the same spatial and temporal coverage as CRUTEM3. Results are shown for averages over the continental domains defined in Table 1.

4.2. Geographical Coverage

[34] Figure 2 displays temperature-change information in map form. Combining ERA-40 and ERA-Interim provides 30 years of reanalysis data covering the period since the upgrade of the observing system for the Global Weather Experiment in 1978/9. Accordingly, 10 year mean temperature differences are presented in Figure 2, showing differences between the periods 1979–1988 and 1989–1998 for CRUTEM3 and ERA-40, and between 1999–2008 and 1989–1998 for CRUTEM3 and ERA-Interim. The predominance of blue shades in the 1979–1988 maps and red shades

in the 1999–2008 maps is indicative of a progressive overall warming over the three decades.

[35] Figure 2 shows generally good agreement between CRUTEM3 and the reanalyses, as regards both large-scale patterns and magnitudes. ERA-40 has greater spatial coherence than CRUTEM3 for 1979–1988, as it does not have isolated grid boxes with values of opposite sign to their neighbors such as occur over Asia for CRUTEM3. There are otherwise few areas of discrepancy; the southern part of South America is one such.

[36] A striking feature of Figure 2 is the difference in coverage in CRUTEM3 between 1979–1988 and 1999–2008.

Table 1. Correlations Between the CRUTEM3, ERA-40, and ERA-Interim Time Series of Continental Mean Monthly Temperature Anomalies Over the Period 1989–2001

	Latitude Range	Longitude Range	Correlation (%)		
			ERA-40 With CRUTEM3	ERA-Interim With CRUTEM3	ERA-Interim With ERA-40
Europe	35°N–80°N	20°W–40°E	99.7	99.7	99.99
Asia	0°N–85°N	60°E–180°E	99.0	99.1	99.91
North America	15°N–85°N	170°W–50°W	99.2	99.3	99.90
Africa	40°S–35°N	25°W–55°E	95.4	94.6	99.2
Australia	50°S–10°S	110°E–160°E	96.6	96.5	99.8
South America	65°S–15°N	90°W–25°W	96.7	96.7	99.6

Table 2. Linear Trends Computed by a Least Squares Fit to Continental Mean Monthly Anomalies Over the Period 1973–2008^a

	Europe	Asia	North America	Africa	Australia	South America
CRUTEM3	0.39	0.32	0.24	0.31	0.12	0.17
ERA, sampled as CRUTEM3	0.36	0.29	0.23	0.28	0.01	0.16
ERA, full coverage	0.41	0.37	0.34	0.30	0.02	0.23

^aTrends given in K/decade. Results are shown for CRUTEM3, for ERA sampled as CRUTEM3, and for ERA with full coverage. The ERA values are from ERA-40 for 1973–1988 and ERA-Interim for 1989–2008.

Grid boxes are shown here for CRUTEM3 only if values are missing for no more than six months in the 10 year period, but the numbers of grid boxes for which CRUTEM3 provides values shift substantially over the course of the 30 years, and the poor recent coverage is far more than a question of a few missing months. For North America, the number of grid boxes with data falls from the order of 150–160 in the years up to 1990 to under 110 from 2005 onward. For Asia, the number drops from around 190–200 before 1990 to a minimum of around 150 in 2003 before rising to about 170. Africa drops from about 120 to 80 and Australia from 40 to 30. Coverage over Europe and South America falls least, by about 10%. It should be noted that this decline in coverage is due mainly to lack of availability of recent monthly station data in the form used by CRUTEM3, and is not indicative of a substantial reduction in the number of observing stations. There is scope to improve coverage in future CRUTEM versions, in particular by accounting for some known changes in station identifiers and by extracting additional data from new volumes when published in the next of the World Meteorological Organisation's decadal series of World Weather Records, which will cover 2001–2010.

[37] Much of the drop in North American and Asian coverage in CRUTEM3 seen in Figure 2 is at high latitudes, where the ERA reanalyses and data from the remaining grid boxes in CRUTEM3 both indicate strong recent warming, in accord with other evidence (particularly cryospheric) and expectations, as reviewed by *Intergovernmental Panel on Climate Change (IPCC)* [2007] for example. A reduction in

coverage over southwestern Asia also occurs in a region that ERA-Interim indicates was much warmer over the past 10 years than the previous 10. As a consequence, temperature trends computed over North America and Asia from the ERA reanalyses using complete spatial and temporal coverage show distinctly larger warming than the trends computed either from the CRUTEM3 data or from the ERA data sampled only where CRUTEM3 provides coverage. This is quantified for least squares fit linear trends in Table 2.

[38] It should be noted that the ERA reanalyses typically assimilate near-surface air temperature data from some 8000 stations, substantially more than utilized in constructing CRUTEM3, which is based on data from around 2000 stations for recent years. The ERA analyses are also constrained by the many in situ and space-based observations that are assimilated in the variational analyses that provide background fields. Maps showing data coverage month by month for ERA-40 can be found in the monitoring plots displayed at <http://www.ecmwf.int/research/era/do/get/era-40>, and current data coverage maps indicative of the situation for the later years of ERA-Interim can be viewed at <http://www.ecmwf.int/products/forecasts/d/charts/monitoring/coverage>. It is nevertheless to be expected that the accuracy of the reanalysis temperatures is higher for grid boxes where CRUTEM3 provides values than for grid boxes where it does not, because the density of assimilated near-surface observations will be lower for most if not all of the boxes without CRUTEM3 values. Also, the background temperatures for the reanalyses are likely to be less accurate at high

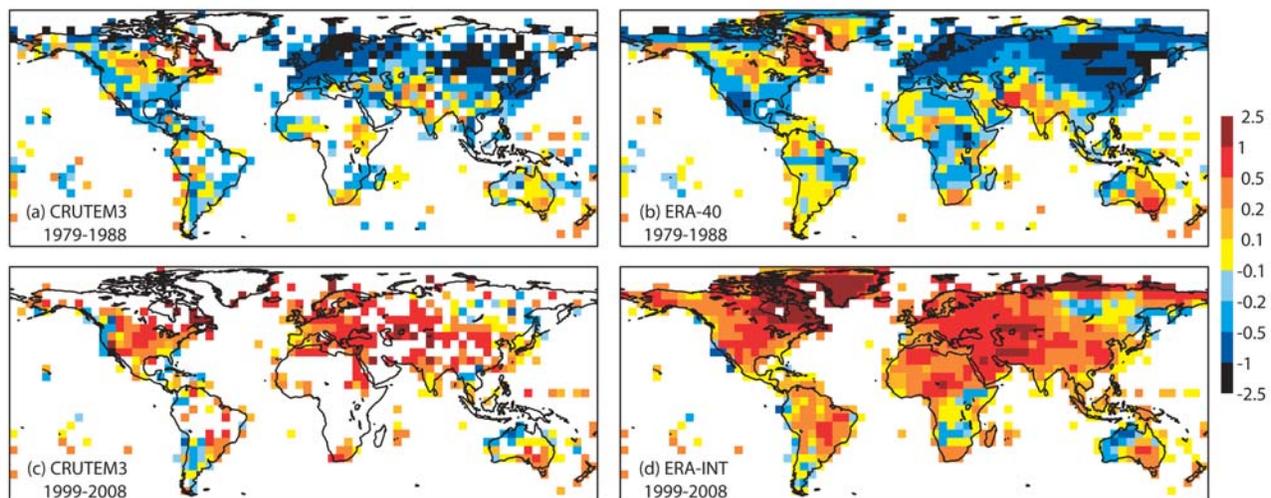


Figure 2. Ten year mean anomalies in 2 m temperature (K) relative to the 1989–1998 mean for (a) CRUTEM3 for 1979–1988, (b) ERA-40 for 1979–1988, (c) CRUTEM3 for 1999–2008, and (d) ERA-Interim for 1999–2008. Reanalysis values are plotted for all 5° grid squares for which there are CRUTEM3 data and for all other grid squares with more than 10% land.

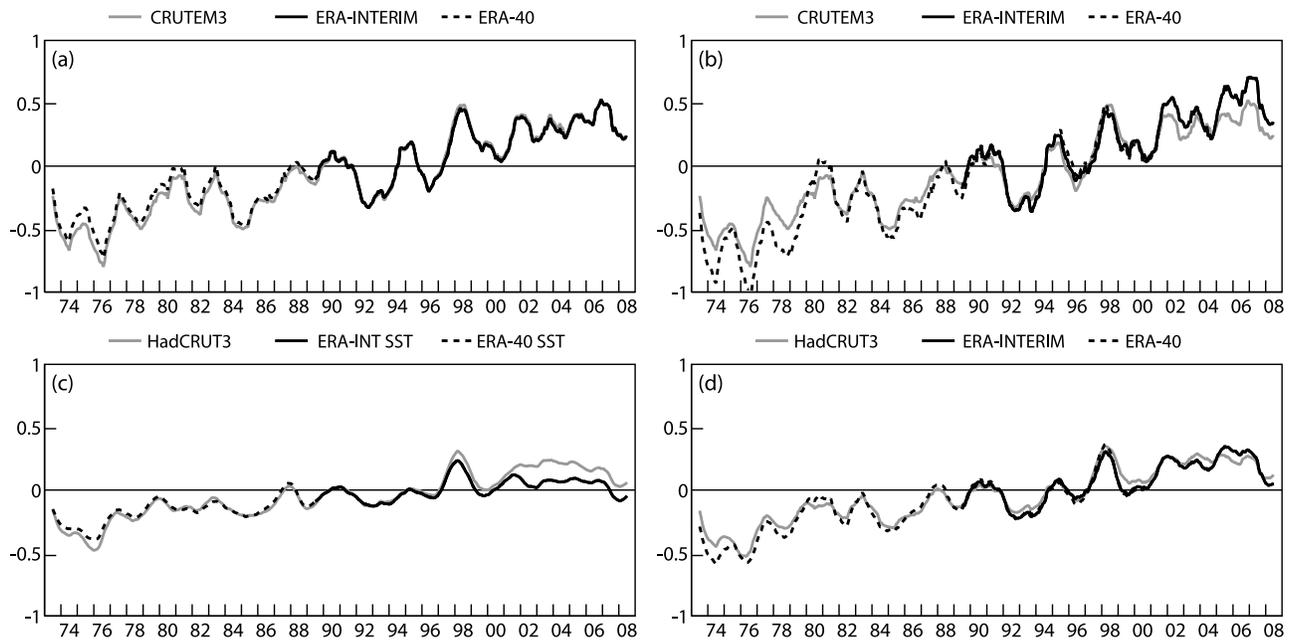


Figure 3. Twelve month running means of temperature anomalies (K) from the ERA-40 (dotted curve) and ERA-Interim (black solid curve) reanalyses and from the CRUTEM3 and HadCRUT3 data sets (gray solid), averaged globally, from 1973 to 2008. (a) Comparison of 2 m temperatures over land from CRUTEM3 and the reanalyses, with the reanalyses sampled with the same spatial and temporal coverage as CRUTEM3. (b) Same as Figure 3a but with reanalyses averaged over all land values. (c) Comparison over sea areas of HadCRUT3 with reanalysis values of sea surface temperatures, with the reanalyses sampled with the same spatial and temporal coverage as HadCRUT3. (d) ERA 2 m temperatures averaged over whole globe compared with average over all HadCRUT3 values. Time series are adjusted to have zero mean from 1989 to 1998, with the exception of the ERA SSTs, which are adjusted by the same amount as HadCRUT3.

latitudes than elsewhere, due to the difficulty of modeling near-surface temperature over snow-covered surfaces.

4.3. Global Averages Over Land and Sea

[39] A set of 12 month running means of global temperature averages is presented in Figure 3. Figures 3a and 3b show averages over all land values from ERA-40, ERA-Interim, and CRUTEM3, with the reanalyses sampled as CRUTEM3 in Figure 3a and averaged over all land areas in Figure 3b. CRUTEM3 values from fixed marine platforms and islands that are not resolved by ERA-Interim are not taken into account in the latter averaging. The closeness of fit of the reanalyses to CRUTEM3 is evident in Figure 3a, in which it is difficult to detect the ERA-40 and CRUTEM3 values where they are overlain by the ERA-Interim values from 1989 onward. Differences between ERA and CRUTEM3 are much more obvious in Figure 3b, in which the stronger warming trend in the all-land reanalysis averages can be clearly seen, consistent with the continental trend values shown in Table 2.

[40] A distinction between the ERA-40 and ERA-Interim values within their 1989–2001 period of overlap can also be discerned in Figure 3b. The correlation between the monthly ERA-40 and ERA-Interim values for the overlap period is 99.9% when the reanalyses are sampled as CRUTEM3 and 98.2% when the average is over all land surfaces. This too points to lower accuracy of the reanalyses in grid boxes where CRUTEM3 values are missing. Differences between the plotted 12 month running mean all-land averages from ERA-40 and ERA-Interim are nevertheless small.

[41] Figure 3c shows averages over sea of HadCRUT3 (essentially the average of HadSST2 values) and the ERA SSTs. For this comparison the HadCRUT3 time series were adjusted to have zero mean for 1989–1998, as for the other time series, and the ERA SSTs were then adjusted by the same amount, rather than adjusted also to have zero mean for 1989–1998. This is considered to give the fairest comparison between the HadCRUT3 and ERA SST data, as the HadISST1 data set used by ERA-40 up to late 1981 has a similar provenance to HadSST2, and the NCEP 2D-Var used after then matches HadSST2 closely over the remainder of the 1961–1990 period used for calculating monthly anomalies.

[42] Two points emerge from Figure 3 that will be returned to in later discussion. The first is that the recent warming over land has not been matched by a recent rise in SST, which has shown little net change over the past 10 years. The second is that there is nevertheless an evident degree of uncertainty in the recent SST analyses, as the ERA SST shifts to distinctly cooler values relative to HadSST2, starting with the 1997/8 El Niño and increasing in 2001, which is when ERA moves to use the operational products from NCEP. Maps show the differences to be widespread geographically. It is beyond the scope of the present paper to investigate this further, but it will be important to reconcile the differences prior to the next ERA reanalysis of the period. A consequence is that relative to HadCRUT3, ERA exhibits a smaller recent warming trend over sea which compensates the larger trend over land. Thus if global averages are taken over both land and sea, the ERA

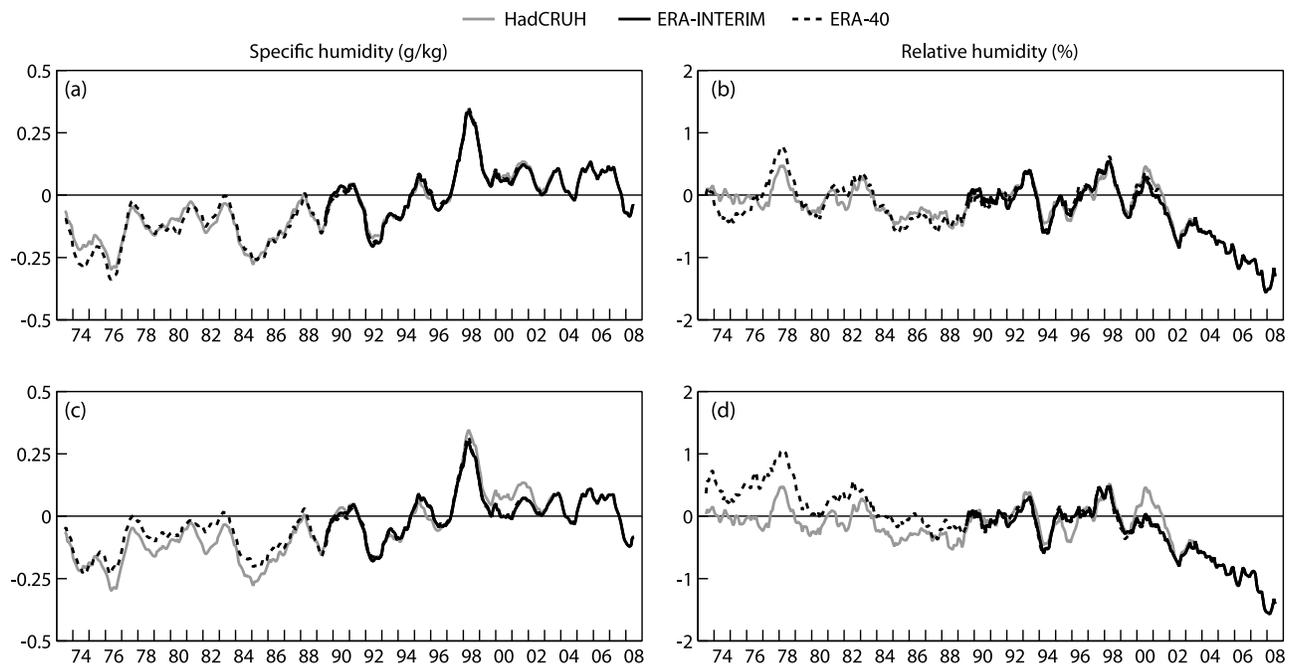


Figure 4. Twelve month running means of anomalies in (a and c) specific humidity (g/kg) and (b and d) relative humidity (%) at 2 m height from the ERA-40 (dotted curve) and ERA-Interim (black solid curve) reanalyses and from the HadCRUH monthly analyses of synoptic observations (gray solid curve) for data from 1973 to 2008 averaged over land areas. Time series are adjusted to have zero mean from 1989 to 1998. Figures 4a and 4c reanalyses are sampled with the same spatial and temporal coverage as HadCRUH. Figures 4b and 4d reanalyses are averaged over all land values.

near-surface air temperature and HadCRUT3 time series exhibit similar warming, as can be seen in Figure 3d. The ERA values used over sea in this calculation were the 2 m background temperatures, as the analyzed values of air temperature over sea are problematic, as discussed by *Simmons et al.* [2004].

5. Comparison of Specific and Relative Humidity Analyses

5.1. Global Averages Over Land

[43] Twelve month running means of the global averages over land of the specific and relative humidities from ERA and HadCRUH are presented in Figure 4. In Figures 4a and 4b the reanalyses are sampled only where there are HadCRUH values, using the HadCRUH distribution of values for December 2003 to select ERA-Interim values from 2004 onward. Figures 4c and 4d show reanalysis values averaged over all land areas. There is generally very good agreement between ERA and HadCRUH results when sampling is similar, especially for specific humidity. This is confirmed by Table 3, which shows the correlations between the time series of monthly values computed for each continent over the period of overlap of all three data sets. Correlations for specific humidity are for the most part lower than those for temperature, but are in almost all cases higher than those for relative humidity. For Australia the correlations between ERA and HadCRU for both specific and relative humidity are higher than those for temperature, and there is little to choose between the temperature and humidity correlations for Africa.

[44] Comparing Figures 4a and 4b to Figures 4c and 4d, little difference is seen in the specific humidity curves. Low values of specific humidity in the ERA-Interim analyses for high-latitude grid boxes where HadCRUH values are absent are likely to contribute little to the global averages, but adding ERA values where HadCRUH lacks coverage over South America and Africa also does not change the picture for specific humidity. More difference is seen for relative humidity, with more of a decline over time in the all-land averages from the reanalyses over the period covered by HadCRUH.

[45] The data from ERA-Interim go 5 years beyond those of HadCRUH, and the addition of values for the latest 5 years has a quite radical impact on the appearance of the time series plotted in Figure 4. HadCRUH and ERA both show specific humidity increasing over land from the mid 1970s, rising to a sharp peak that coincides with the strong 1997/8 El Niño event. Specific humidity subsequently shows no increase in time, and even drops in 2008 to a value not seen since the mid 1990s. In contrast, temperature declines for only a short period following the El Niño before increasing again over land (Figure 3). The relative humidity plots presented in Figure 4 accordingly show a steep decline in values over the current decade. Thus although the ERA results largely confirm the previous results of *Dai* [2006] and *Willett et al.* [2008], adding ERA-Interim data for the most recent years changes the previous picture of increasing specific humidity and at most gently decreasing relative humidity over land. Evidence that supports the realism of this finding from ERA-Interim is discussed in the remainder of this section.

Table 3. Correlations Between the HadCRUH, ERA-40, and ERA-Interim Time Series of Continental Mean Monthly Specific and Relative Humidity Anomalies Over the Period 1989–2001

	Specific Humidity Correlations (%)			Relative Humidity Correlations (%)		
	ERA-40 With HadCRUH	ERA-Interim With HadCRUH	ERA-Interim With ERA-40	ERA-40 With HadCRUH	ERA-Interim With HadCRUH	ERA-Interim With ERA-40
Europe	98.8	98.8	99.97	96.1	95.9	99.8
Asia	98.0	98.4	99.7	95.2	95.9	99.0
North America	96.6	96.6	99.8	95.0	94.6	99.4
Africa	94.5	94.9	98.7	93.4	94.3	98.2
Australia	97.8	97.8	99.6	97.6	97.9	99.5
South America	94.5	94.1	98.6	82.2	83.3	96.2

5.2. Geographic Variations

[46] The changes over time in humidity have a coherent geographical pattern. Figure 5 shows maps of 5 year mean differences from 1989–1998 means, for the 1999–2003 mean from HadCRUH and for the 1999–2003 and 2004–2008 means from ERA-Interim. For 1999–2003 there is good overall agreement between HadCRUH and ERA-Interim, although a systematic difference can be seen over Canada, where the reanalysis shows more moistening relative to 1989–1998 than HadCRUH. The largest data void in HadCRUH occurs over Africa where ERA-Interim exhibits its strongest drying.

[47] Figure 5 shows increases in specific humidity over many regions for the latest 10 years (1999–2008), but net drying over the western United States, South America, north central Africa, eastern Australia and eastern China, in terms of both specific and relative humidity. It must be kept in mind

that this drying is relative to 10 year mean values for a period that includes the strong 1997/1998 El Niño. Figure 4 has shown an imprint of this event on the time series of specific humidity over all land, and corresponding peaks occur in specific-humidity time series at the time of the El Niño for each of the continents except Europe. This is not shown explicitly here, but can be inferred as the time series of continental mean temperatures shown in Figure 1 mostly exhibit peaks at the time of the El Niño whereas the corresponding relative humidity time series (presented later in Figure 7) do not. What is made clear nevertheless by Figure 5 is that the predominant recent change in relative humidity is one of widespread reduction in tropical and middle latitudes, with a general small increase at high latitudes.

[48] Figure 6 shows that the changes are coherent in the vertical across the planetary boundary layer. It presents maps of the differences between means for 1999–2008 and

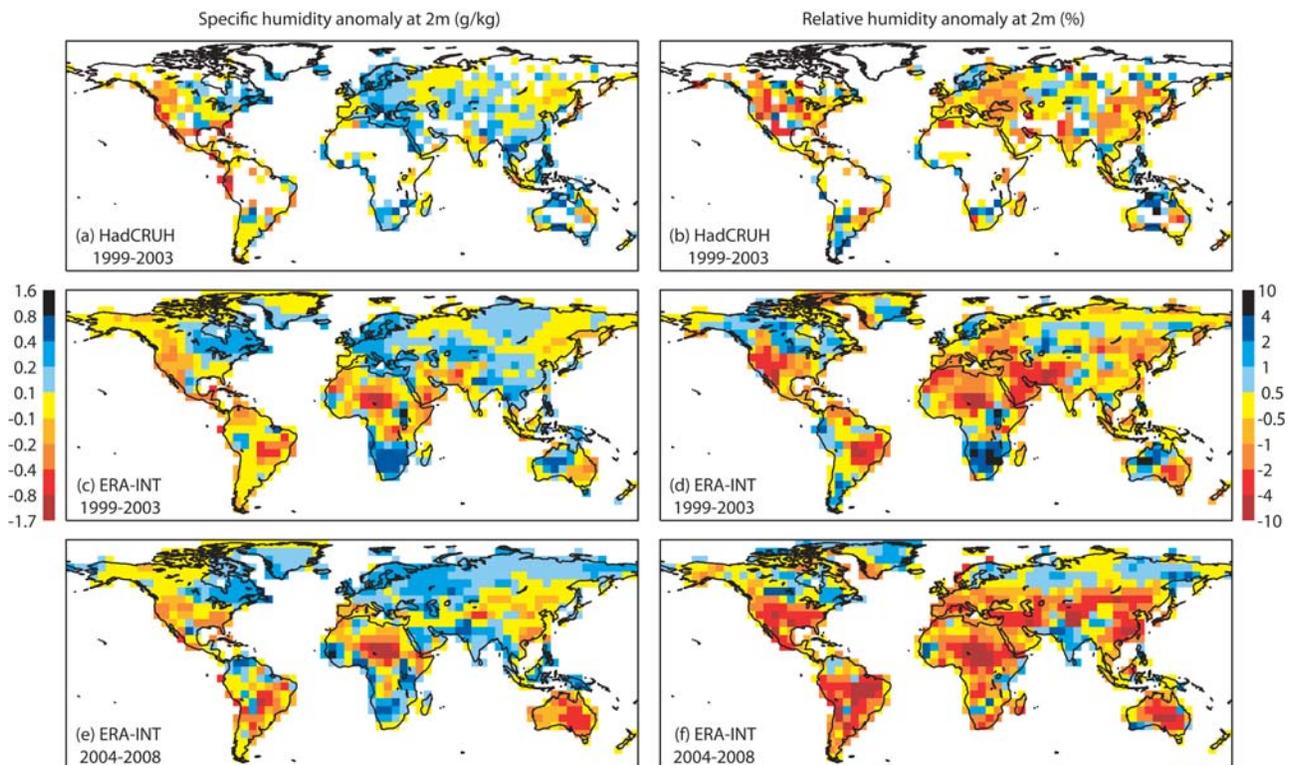


Figure 5. Five year mean anomalies relative to the 1989–1998 mean in 2 m (left) specific humidity (g/kg) and (right) relative humidity (%) for 1999–2003 from (a and b) HadCRUH and (c and d) ERA-Interim, and for 2004–2008 from (e and f) ERA-Interim. Values are plotted for all grid squares with more than 10% land for which data are available.

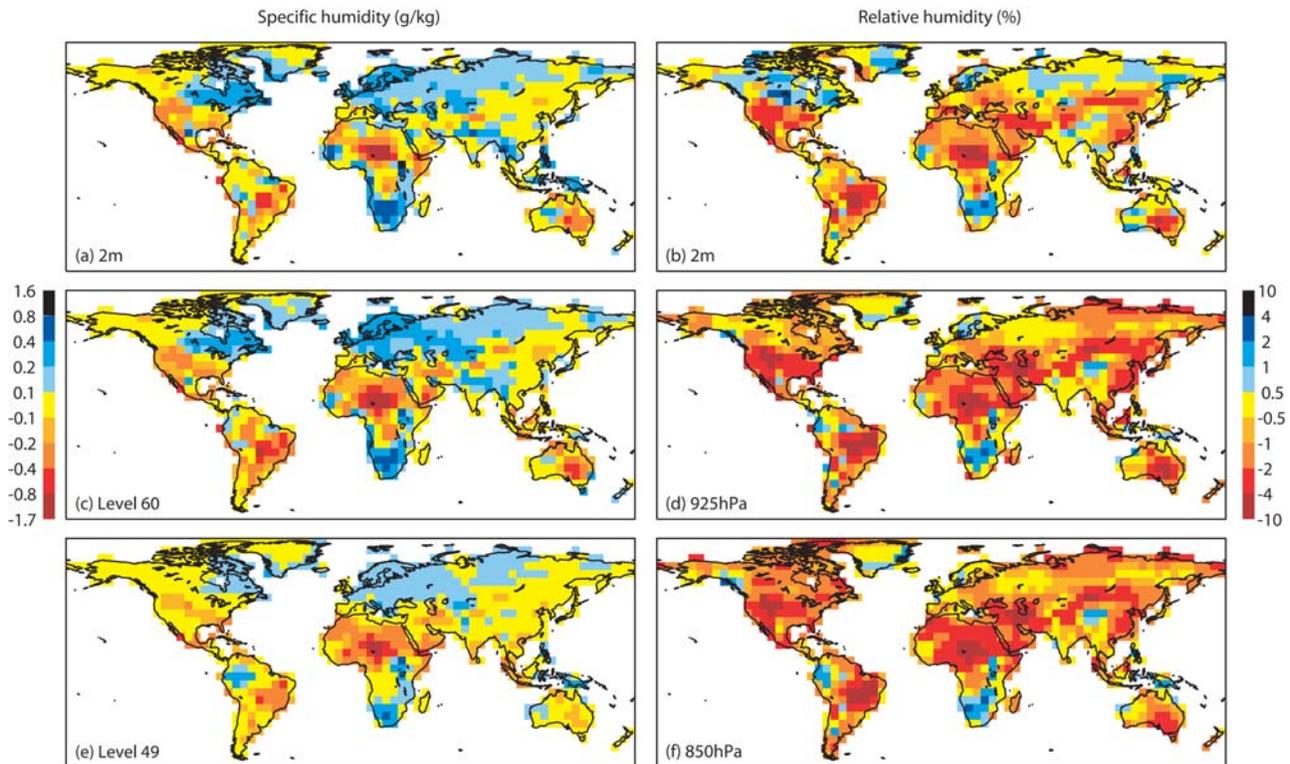


Figure 6. Differences between ERA-Interim means for 1999–2008 and 1989–1998 for all grid squares with more than 10% land, for specific humidity (g/kg) at (a) a height of 2 m, (c) model level 60 (close to 10 m height), and (e) model level 49, and for relative humidity (%) at (b) 2 m, (d) 925 hPa, and (f) 850 hPa.

1989–1998 for specific and relative humidity from ERA-Interim. The maps are for analyses at 2 m (for which the plots show simply the averages of the two 5 year ERA-Interim means presented in Figure 5) and at model levels 60 and 49 for specific humidity (the analyzed model upper air humidity variable). Level 60 is the lowest model level, which is located at a height of around 10 m. Level 49 is the model level closest to 850 hPa for a surface pressure close to 1000 hPa. Relative humidity is shown for the pressure levels of 925 hPa and 850 hPa at which values are routinely derived and archived during the ERA-Interim production process.

[49] The 2 m humidities shown in Figure 6 are from the OI analysis of observations from the surface synoptic network, whereas the values at higher levels are from ERA-Interim’s primary 4D-Var analysis of many types of observation. As noted earlier, the primary observational influence at the levels shown over land comes not only from the surface synoptic network but also from radiosondes. The variational analysis typically makes smaller changes to background fields at low levels than the OI analysis for variables at 2 m height, as illustrated by *Simmons et al.* [2004] in the case of temperature from ERA-40’s 3D-Var. Thus the difference map shown for specific humidity at the lowest model level is very similar to the corresponding map (not shown) for the background specific humidity at 2 m used by the OI analysis. Both are in good general agreement with the map shown for the analysis at 2 m, but show slightly more moistening over eastern Europe, and slightly more drying in the tropics. The difference patterns for specific humidity at level 49 are similar to those much nearer the surface. The amplitudes of

the differences are smaller in absolute terms, but the amplitudes of the fields themselves are also smaller at level 49. The maps for relative humidity have similar patterns and magnitudes at all three levels shown over the tropics and middle latitudes. The increase in relative humidity at high northern latitudes seen at 2 m is largely replaced by a decrease at higher levels.

[50] The general consistency between the humidity fields from the OI analysis for 2 m and the 4D-Var analysis for levels throughout the boundary layer is one piece of evidence that gives confidence in the realism of the recent widespread decrease in relative humidity revealed by ERA-Interim. Further evidence is discussed below.

5.3. Recent Drop in Relative Humidity Over Land

[51] The HadCRUHext data set was prepared especially to investigate whether the recent decrease in relative humidity found in ERA-Interim was reproduced by an independent analysis of the synoptic record. The data set has a 10 year overlap with HadCRUH to provide a measure of reliability, and extends to the end of 2007. Figure 7 presents a set of time series of relative humidity over continental regions, from reanalysis (ERA-40 for 1973–1988 and ERA-Interim for 1989–2008), from HadCRUH (1973–2003) and HadCRUHext (1994–2007). As previously, the ERA and HadCRUH curves are adjusted so each has zero mean value in the average for 1989–1998. The HadCRUHext curves are adjusted by the same amount as HadCRUH.

[52] The ERA and HadCRUH curves are mostly in close agreement from the early to mid 1980s onward, although a

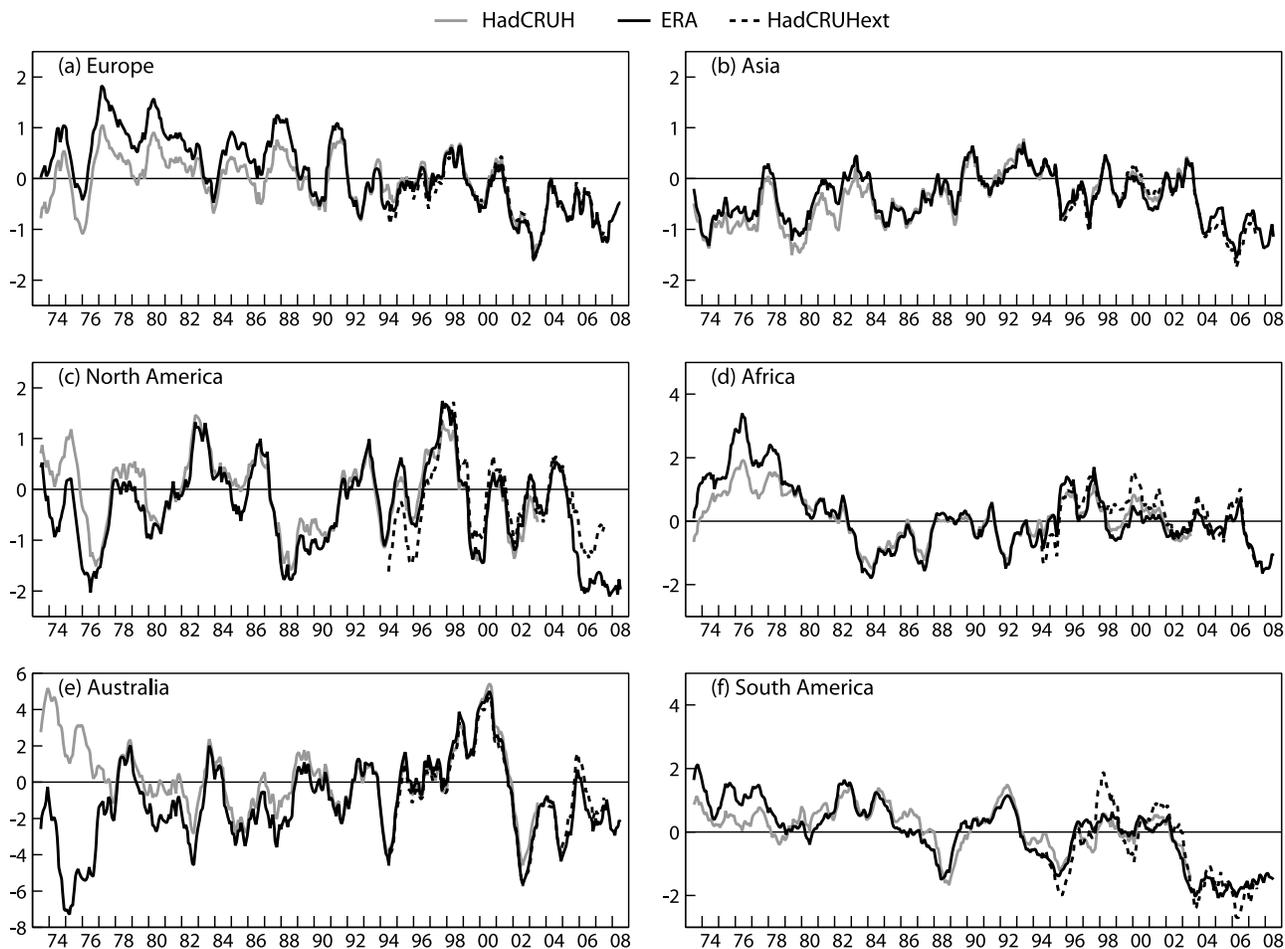


Figure 7. Twelve month running means of 2 m relative-humidity anomalies (%) showing ERA-40 for 1973–1988 and ERA-Interim for 1989–2008 (black solid curve) and HadCRUH for 1973–2003 (gray curve). The “quick-look” extension HadCRUHext is also plotted (black dotted curve), for 1994–2007. Reanalyses are sampled with the same spatial and temporal coverage as HadCRUH. Results are shown for averages over land for the continental domains defined in Table 1.

clear shift between the two time series occurs closer to 1990 for Europe, as discussed further below. HadCRUHext is barely discernible as different from HadCRUH and ERA-Interim for Europe, Asia, and Australia, and although differences for Africa and South America are somewhat larger, HadCRUHext reproduces the decline in relative humidity near the end of the period for each region. Only over North America is there a systematic discrepancy, but here HadCRUHext does not match HadCRUH (or the similar ERA-Interim) in the mid 1990s, so it is difficult to attach much significance to its showing a smaller reduction than ERA-Interim at the end of the period. The issues faced in extending HadCRUH over North America are discussed in Appendix A. HadCRUHext nevertheless provides confirmation of the general decline in relative humidity over the extension period: the mean anomaly for 2007 relative to 1989–1998 is -1.3% for ERA-Interim and -1.1% for HadCRUHext when averaged over all values, and -1.2% for both ERA-Interim and HadCRUHext when values from North America are excluded.

[53] Although comprehensive comparisons have not been made with near-surface humidity fields from other reanal-

yses, the routine monitoring of ERA-Interim includes a monthly updating of plots of time series of anomalies in monthly mean temperature and dew point that compare ERA-Interim with reanalyses undertaken by the Japan Meteorological Agency (JMA). The latter are JRA-25 (1979–2004) [Onogi *et al.*, 2007] and its extension from 2005 onward produced by the JMA Climate Data Assimilation System (JCDAS; data downloaded from <http://jra.kishou.go.jp>). The JRA-25/JCDAS data exhibit the same increase in temperature over land as illustrated for ERA in Figure 3 [see Onogi *et al.*, 2007, Figure 18], while both ERA-Interim and JRA-25/JCDAS show no corresponding overall increase in dew point over land for the past decade. The data from JRA-25/JCDAS thus also indicate a recent general lowering of relative humidity over land. The monitoring time series are produced for several zonal bands; only for the region from 60°N to 90°N is there a systematic recent increase in dew point. This is seen for both ERA-Interim and JRA-25/JCDAS, and is consistent with the relative humidity maps shown in Figure 5, which show increasing relative humidity at high northern latitudes, notwithstanding the decrease almost everywhere else over land.

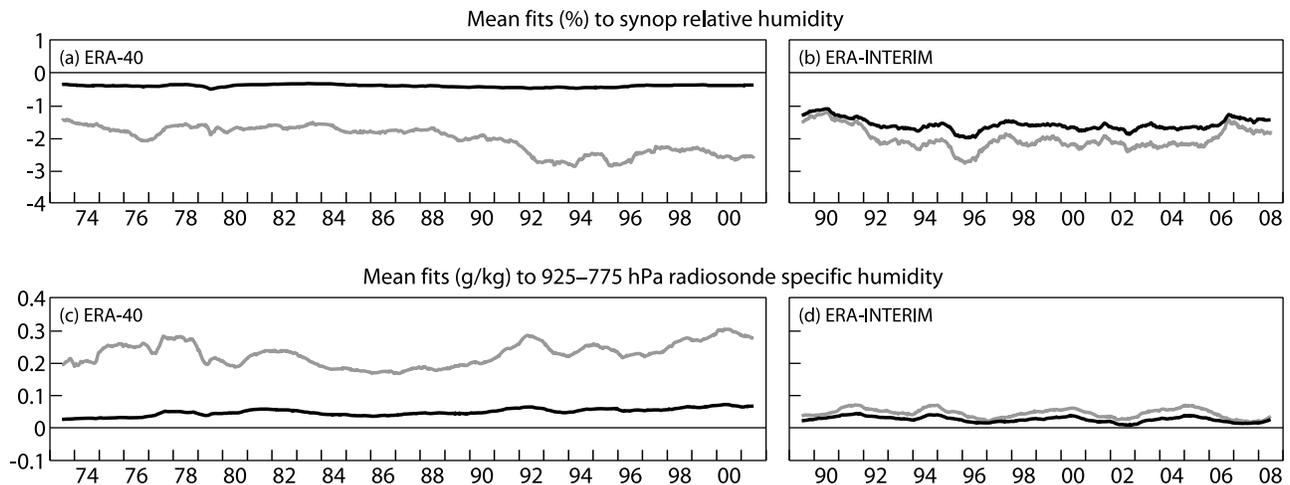


Figure 8. Twelve month running means of analysis (black) and background (gray) differences from assimilated synoptic observations of relative humidity (%) at 2 m for (a) ERA-40 and (b) ERA-Interim and from assimilated radiosonde observations of specific humidity (g/kg) between 925 and 775 hPa for (c) ERA-40 and (d) ERA-Interim averaged over all observation points within the extratropical Northern Hemisphere.

[54] Further confidence in ERA’s depiction of variations over time in low-level humidity is provided by monitoring statistics archived during the running of the ERA data assimilation systems, such as presented in Figure 8. Figures 8a–8d show differences between analyzed and observed values and between background forecast and observed values, accumulated over all assimilated observations located in the extratropical Northern Hemisphere, for surface synoptic observations of relative humidity at a height of 2 m and for specific humidity from radiosondes in the layer from 925 hPa to 775 hPa. This layer is centered on the standard 850 hPa reporting level, but the comparison includes values reported at significant levels within the layer. The data fits were produced by the variational data assimilation, so in this context the analyzed value for relative humidity is not the 2 m value from the OI analysis but rather the value derived at 2 m height from the variational analysis by interpolating specific humidity and temperature between the lowest model level and the surface. These derived values fit the assimilated surface synoptic observations better than the background values, but are generally not expected to fit the observations as well as the OI analysis, partly because they are influenced also by the assimilation of conflicting mean humidity information from radiosondes, and partly because in the case of ERA-Interim the variational analysis assimilates synoptic humidity observations only during daytime.

[55] The averages in Figure 8 are taken without any weighting to introduce uniformity in space or time, and are thus influenced mostly by values from data-dense regions, Europe in particular. For ERA-Interim they are also influenced predominantly by summertime values, due to variations in the length of the day that can mean using surface synoptic humidity observations at 0600, 1200 and 1800 UTC in summer, but only at 1200 UTC in winter over Europe. This is the likely reason why short-term variability is more evident for ERA-Interim in Figure 8.

[56] Notwithstanding such matters of interpretation, Figure 8 shows no substantial shift in values over the second

10 years of ERA-Interim that would indicate that a change over time in measurement bias or other data assimilation problem is responsible for the analyzed decline in relative humidity. Both background and 4D-Var analysis values are biased dry compared with the surface synoptic observations of relative humidity, but values around 850 hPa are relatively close to the radiosonde values. Such change as does occur toward the end of the period for relative humidity is such as to moisten the background field relative to the surface observations. ERA-40’s 3D-Var analysis fits the relative humidity observations much more closely than ERA-Interim, but its background fields are slightly further from these observations, and it is the background values that are used by the 2 m OI analysis whose results form the substance of this paper. The background specific humidities from ERA-40 are substantially further from radiosonde values than is the case for ERA-Interim.

5.4. Changes in Observational Data

[57] It may be questioned whether changes in SYNOP data bias or numbers might contribute to the decline in relative humidity in the analyses examined here. The most substantial measurement change is a gradual shift from manual to automatic measurement, which could introduce a common trend in the analyses if measurement bias changes. However, the change to automatic stations has occurred quite steadily over the past two decades, and thus does not obviously explain a sharp drop in relative humidity that occurs only in the last decade. Moreover, if the effect were to be significant a corresponding drift in analysis increments would be seen, which is not the case, and the homogeneity checks in the HadCRU analyses would be expected to come into operation and limit a spurious trend.

[58] Many more SYNOPs have become available in recent years, but most of the increase has come from more frequent reporting. The ERA OI analysis of near-surface relative humidity is carried out for the main synoptic hours of 0000, 0600, 1200, and 1800 UTC and uses observations

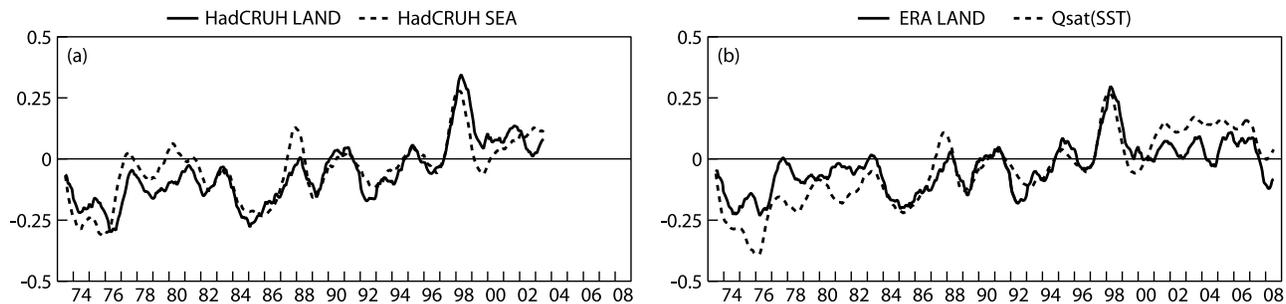


Figure 9. Twelve month running means of specific-humidity anomalies (g/kg) (a) from the HadCRUH monthly analyses averaged over all available land (solid curve) and sea (dotted curve) values and (b) from the ERA-40 (1973–1988) and ERA-Interim (1989–2008) reanalyses, showing analyses at a height of 2 m averaged over all land areas (solid curve) and the saturation specific humidity derived from sea surface temperature and surface pressure analyses, averaged over all sea areas (dotted curve).

outside these times only if the observation for the main hour is missing. Thus the number of data actually used by the OI analysis has increased only a little. There has been a larger increase in the number of data used in the background 4D-Var analysis, but these are likely mainly to have improved the definition of the diurnal cycle. Increasing SYNOP frequency may have caused the problems over North America in HadCRUHext, as discussed in Appendix A, but SYNOP numbers have not changed much in the last 6 years, so changing numbers cannot readily explain the quite steady decline in ERA's land-averaged relative humidity over this period.

[59] A longstanding feature of ECMWF's humidity analysis has been that background and analysis fields are perceived to be biased dry against the surface synoptic observations but biased moist against the low-level data from radiosondes [Andersson *et al.*, 2007]. Figure 8 illustrates this, but also shows a shift in behavior between the 1980s and 1990s. This is most evident for ERA-40, but also happens over the first years of ERA-Interim. Over these years there are increases both in the apparent dry bias in the background field for 2 m relative humidity and in the apparent moist bias against the radiosondes between 925 hPa and 775 hPa. An increase in apparent moist bias is also found for comparison with radiosonde reports at pressures higher than 925 hPa. It is unlikely that a change in the data assimilation system or in other types of assimilated observation could cause drying against the surface observations and moistening against the radiosondes, as the distribution of radiosonde measurements tends to mirror that of the surface measurements, albeit with lower density. The shift is more likely a consequence of increased inconsistency between the surface and radiosonde measurements.

[60] Increased inconsistency may stem from an increase in net dry bias of the radiosonde measurements due to changes in the type of instrument deployed over the years in question. In particular, it is known [e.g., Wang *et al.*, 2002; Turner *et al.*, 2003] that measurements from the Vaisala RS80 instruments exhibit dry biases, especially those from the RS80-H model introduced in 1992. A more widespread use of the RS-80 rather than other makes of radiosonde, and change from the RS80-A to the RS80-H model, could explain the shifts between the 1980s and 1990s seen in Figure 8. This in turn might be why the ERA reanalyses exhibit a larger reduction in relative humidity from the 1980s to the 1990s than

HadCRUH over Europe, as shown in Figure 7. Recent improvements in radiosonde instrumentation that reduce dry biases may in turn explain the recent reduction in bias of ERA-Interim relative to the surface synoptic observations.

[61] Further investigation is beyond the scope of this paper, but would be desirable, though challenging, in the context of developing a scheme for correcting the biases in radiosonde humidity measurements for use in future reanalyses.

5.5. Interpretation of the Reduction in Relative Humidity

[62] There are a number of local factors that may cause long-term change in relative humidity over land, including change in vegetation cover, change in transpiration associated with change in drought, and change in the extent of frozen land and snow cover. However, the recent decline in relative humidity to values not seen in the preceding 30 year data record has been so widespread and quick in its occurrence that a more basic process must be responsible. It is thus natural to turn to the elementary working of the hydrological cycle, whereby the atmosphere receives water vapor over the oceans by an excess of evaporation over precipitation, and transports it over continental regions, where precipitation generally exceeds evaporation. The amount of water vapor over the oceans is linked through evaporation to the sea surface temperature, and variations over sea are likely through transport to be followed by variations in water vapor over land and possibly also by variations in the difference between precipitation and evaporation, although associated circulation changes could be a confounding factor. The response over land would be expected to be delayed by evaporation, which is dependent through soil moisture on earlier precipitation. The average temperature over land has continued to rise in recent years, but the temperature of the sea surface has not (Figure 3). The decline in relative humidity over land may thus be due to lack of the increased supply of water from the ocean that would be needed for relative humidity to be maintained over land as temperature increases.

[63] Figure 9 presents two comparisons of values over land and sea that support the above argument, one based solely on HadCRUH data and one based solely on reanalysis data. Figure 9a shows the variations over time of the averages of specific humidity from HadCRUH taken separately over land and sea. The general similarity between the two time series is clear. Figure 9b shows corresponding variations in the mean

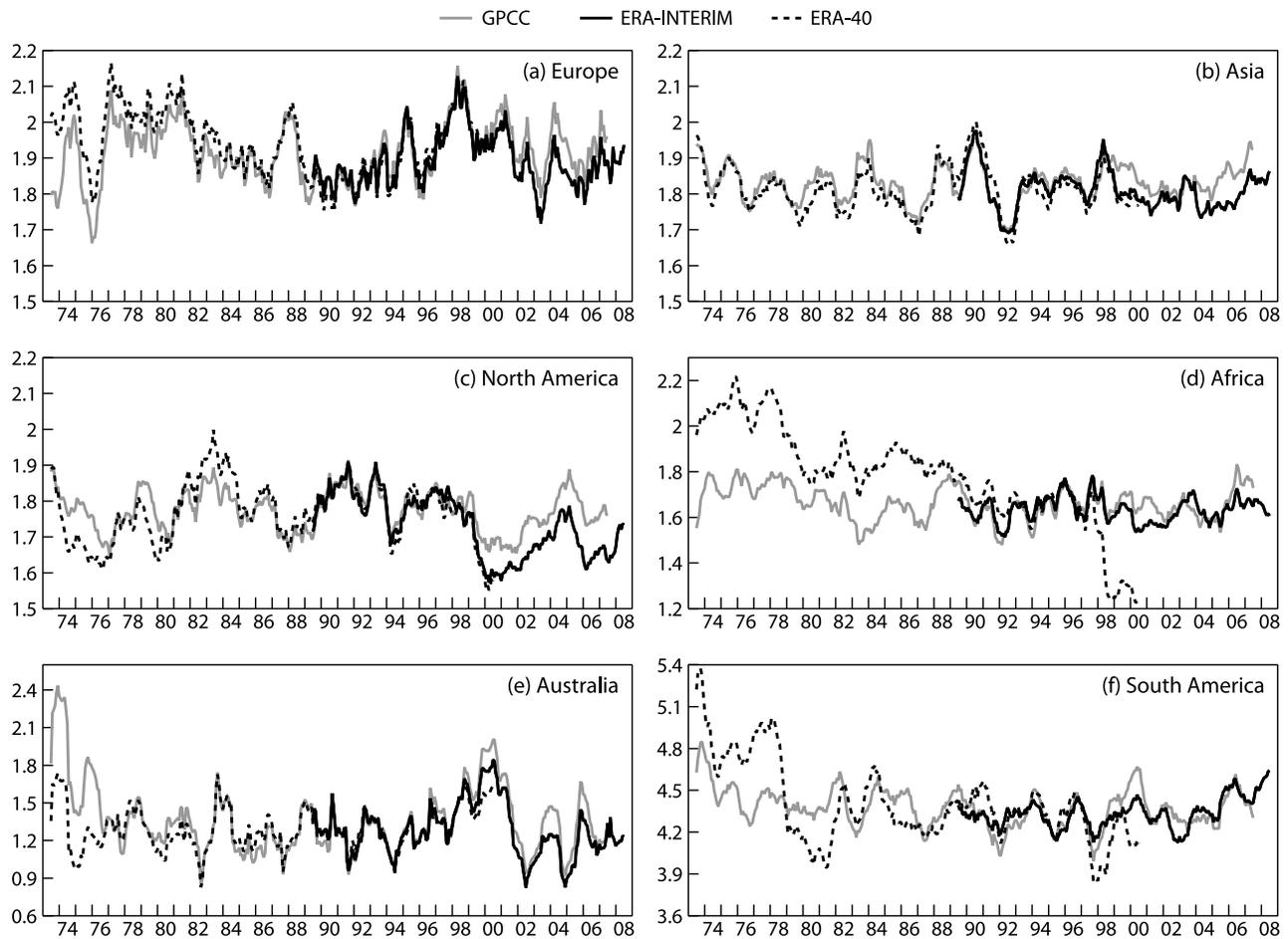


Figure 10. Twelve month running means from 1973 to 2008 of precipitation rate (mm/d) from GPCP (gray solid curve), ERA-Interim (black solid curve), and ERA-40 (black dotted curve). Results are shown for averages over land for the continental domains defined in Table 1. The reanalysis values are accumulated from forecasts for 12 to 24 h ahead initiated from 0000 UTC and 1200 UTC each day, and adjusted to have the same mean as GPCP over the period 1989–1998.

over all ice-free sea areas of the saturation specific humidity computed using the ERA SST and surface pressure analyses, and in the mean specific humidity analyzed over all land areas. Again the similarity between the two time series is clear. The most significant discrepancy in Figure 9 is between the marine values deduced from the ERA SST and the marine values from HadCRUH prior to 1982, which may be linked to a moist bias in the pre-1982 marine component of HadCRUH discussed by *Willett et al.* [2008]. There is good agreement between variations in these marine values and variations in total column water vapor over sea from microwave imagery available from 1988 onward, as presented by *Trenberth et al.* [2005, 2007], who noted the close link with SST. For both ERA and HadCRUH, the changes over land tend to lag the changes over sea, typically by a month or two. Changes in specific humidity over the sea are closely controlled by changes in sea surface temperature, and changes in near-surface specific humidity over land appear to follow in concert.

6. Comparison of Precipitation Analyses

[64] Overall, specific humidity over land has increased since 1973, but relative humidity has decreased. Implications

for precipitation are unclear, however. Rising specific humidity means that the atmosphere carries an increasing amount of water that has the potential to fall as precipitation, but lower relative humidity makes it likely that the threshold for condensation is reached less often. Precipitation estimates from ERA have thus been compared with products derived more directly from observations, to explore the quality of some of the available data sets and whether they indicate a reliable link between long-term continental-scale variations in near-surface humidity and precipitation.

[65] Results are presented first for the comparison of the reanalyses with the full data product version 4 GPCP analysis, which is based entirely on gauge data. Figure 10 displays continental averages of 12 month running mean values from GPCP, ERA-40 and ERA-Interim. The raw values from GPCP are plotted, but the ERA values are adjusted to have the same mean value as GPCP for the period 1989–1998. This is to ease comparison of interannual variability and long-term shifts of the reanalyses relative to GPCP. Differences between unadjusted values are discussed later.

[66] Figure 10 shows that GPCP and ERA identify generally similar interannual continental-scale variations in precipitation. Agreement is better for the northern hemisphere

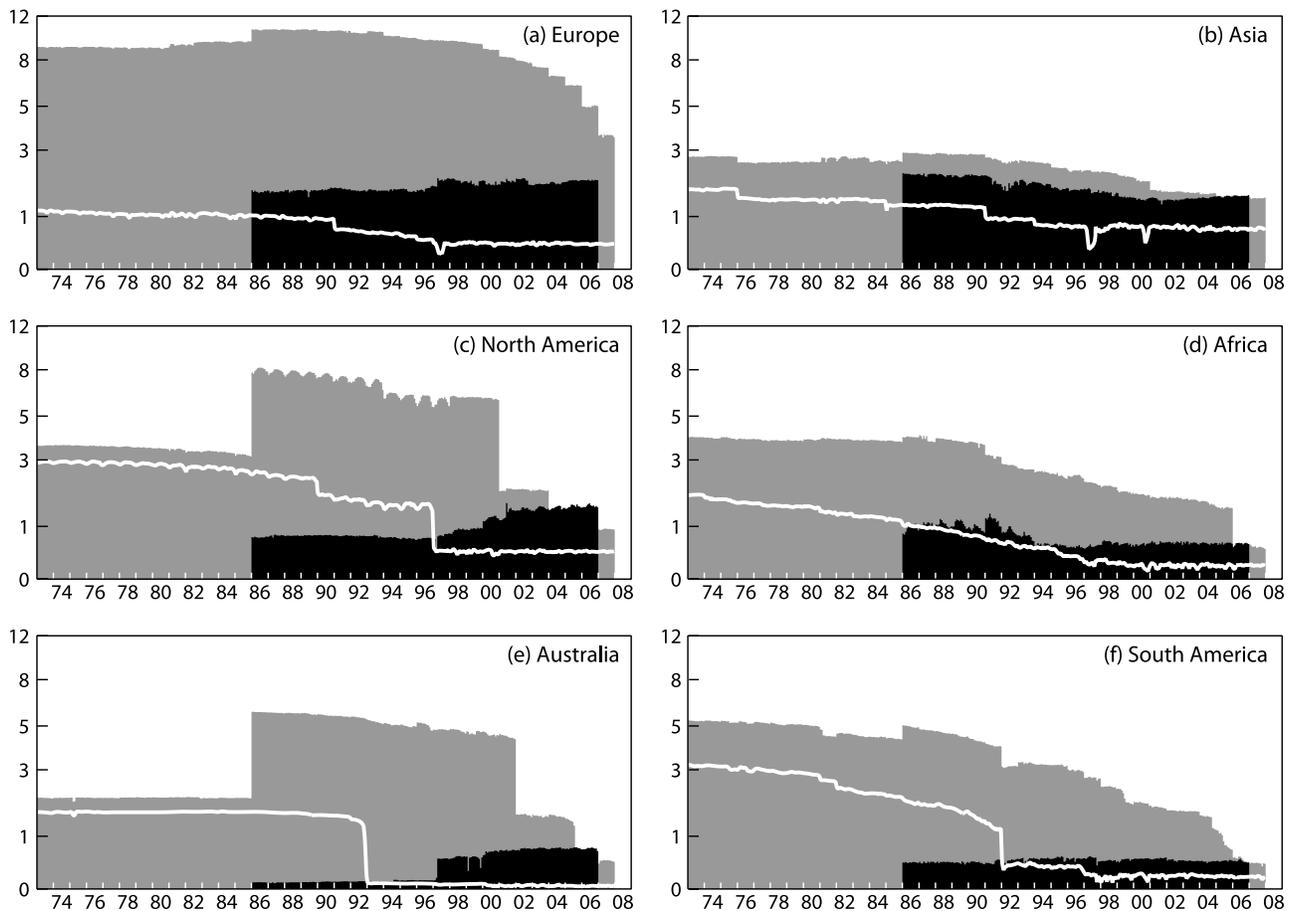


Figure 11. Monthly counts (in thousands) of the number of stations providing data for the full data product version 4 GPCP analysis (gray shading), for the GPCP Monitoring Product (black shading) and for PREC/L (white line) from each of the continental domains defined in Table 1.

continents and Australia than it is for South America and Africa, and better for ERA-Interim than ERA-40. There is, however, a clear shift from the 1990s to the latest decade in the mean difference between ERA-Interim and GPCP. This is largest for North America, but can be seen for all other areas except South America. ERA-Interim shows a general decline in values relative to GPCP for the latest decade.

[67] Two factors have been identified that may contribute to this change in relative values. One is the shift to lower values of SST in ERA relative to HadSST2 illustrated in Figure 3. If it is the ERA values that are too low, then ERA-Interim could suffer from too low evaporation over the oceans and consequently too low precipitation over land in its later years. However, there are also fewer stations in the GPCP archive for recent years. Figure 11 shows the station counts by continent and month for the GPCP full data product version 4, for the GPCP monitoring product used by GPCP and CMAP, and for PREC/L. GPCP's holdings of data for the full data product jump substantially in 1986, but generally decline subsequently, with especially sharp falls at the end of 2000 for North America and the end of 2001 for Australia. This may cause a drift in the gridded GPCP analyses. Changes in assimilated satellite data could also cause a shift in ERA precipitation beginning in the late 1990s, but this would be expected to give a different signal in ERA-Interim than ERA-40, due to several differences in the way

these data were assimilated in the two reanalyses. ERA-40 and ERA-Interim in fact behave similarly over Europe, Asia, and North America in their deviation from GPCP for the years 2000 and 2001.

[68] Table 4 shows mean differences and correlations between the monthly anomalies from GPCP, ERA-Interim and ERA-40, over the period of overlap from 1989 to 2001. Results are shown for both 0–12 h and 12–24 h forecast accumulations for the reanalyses. Although there is little to choose between the two reanalyses as regards mean differences, which vary considerably from region to region and with forecast range, correlations with GPCP are distinctly higher for ERA-Interim than for ERA-40, especially for Africa and South America. Correlations are mainly a little higher for the 12–24 h forecast range than for the 0–12 h range, most likely because some small physical inconsistencies between analyzed temperatures and humidities influence precipitation in the 0–12 h range while the model adjusts to a more consistent state.

[69] Time series of 12 month running mean deviations of ERA-Interim, GPCP, CMAP and PREC/L from GPCP are presented in Figure 12. Apart from Europe, ERA-Interim is the outlier, suggesting that the sign of the bias in the reanalysis is identified even if its magnitude is uncertain because of differences between the other analyses, which can reach around 15% of the corresponding GPCP values shown in

Table 4. Mean Differences and Correlations Between the ERA-40 and ERA-Interim Time Series of Continental Mean Monthly Precipitation Rate, and the Corresponding Time Series From GPCC, Over Land Areas and the Period From 1989 to 2001^a

	Mean Difference (mm/d)				Correlation (%)			
	ERA-40		ERA-Interim		ERA-40		ERA-Interim	
	0–12 h	12–24 h	0–12 h	12–24 h	0–12 h	12–24 h	0–12 h	12–24 h
Europe	−0.44	−0.29	0.03	0.13	87	89	97	98
Asia	0.08	0.25	0.31	0.39	60	64	87	89
North America	−0.15	0.12	0.11	0.27	79	84	89	91
Africa	−0.03	−0.06	0.27	0.23	65	58	81	84
Australia	−0.30	−0.29	−0.13	−0.09	92	92	97	98
South America	0.41	0.36	0.48	0.37	58	57	81	81

^aContinental mean monthly precipitation rate is based on both the 0–12 h and the 12–24 h forecast ranges. The mean annual cycle was removed from each time series prior to calculation of the correlations.

Figure 10. ERA-Interim has higher values than GPCC (which is not corrected for undercatch) for all regions except Australia. GPCP and CMAP exhibit generally similar variations, but GPCP has mostly higher values due to the applied gauge-bias correction [Yin *et al.*, 2004]. PREC/L is in relatively good long-term agreement with GPCC for Africa, Asia, and South America, but shifts occur for Europe, North America and especially Australia, where only around 40 to 50 gauges provide data for PREC/L in the latest decade.

[70] The monthly variability in ERA-Interim precipitation is much closer to that in GPCC Version 4 than it is to that in GPCP, CMAP and PREC/L. This is shown by the correlations of monthly anomalies over the period 1989–2007 presented in Table 5. Agreement is best between ERA-Interim and GPCC for each of the six continents, and agreement between ERA-Interim and either GPCP or CMAP comes close to that between ERA-Interim and GPCC only for Europe and Australia. As ERA-Interim and GPCC are based

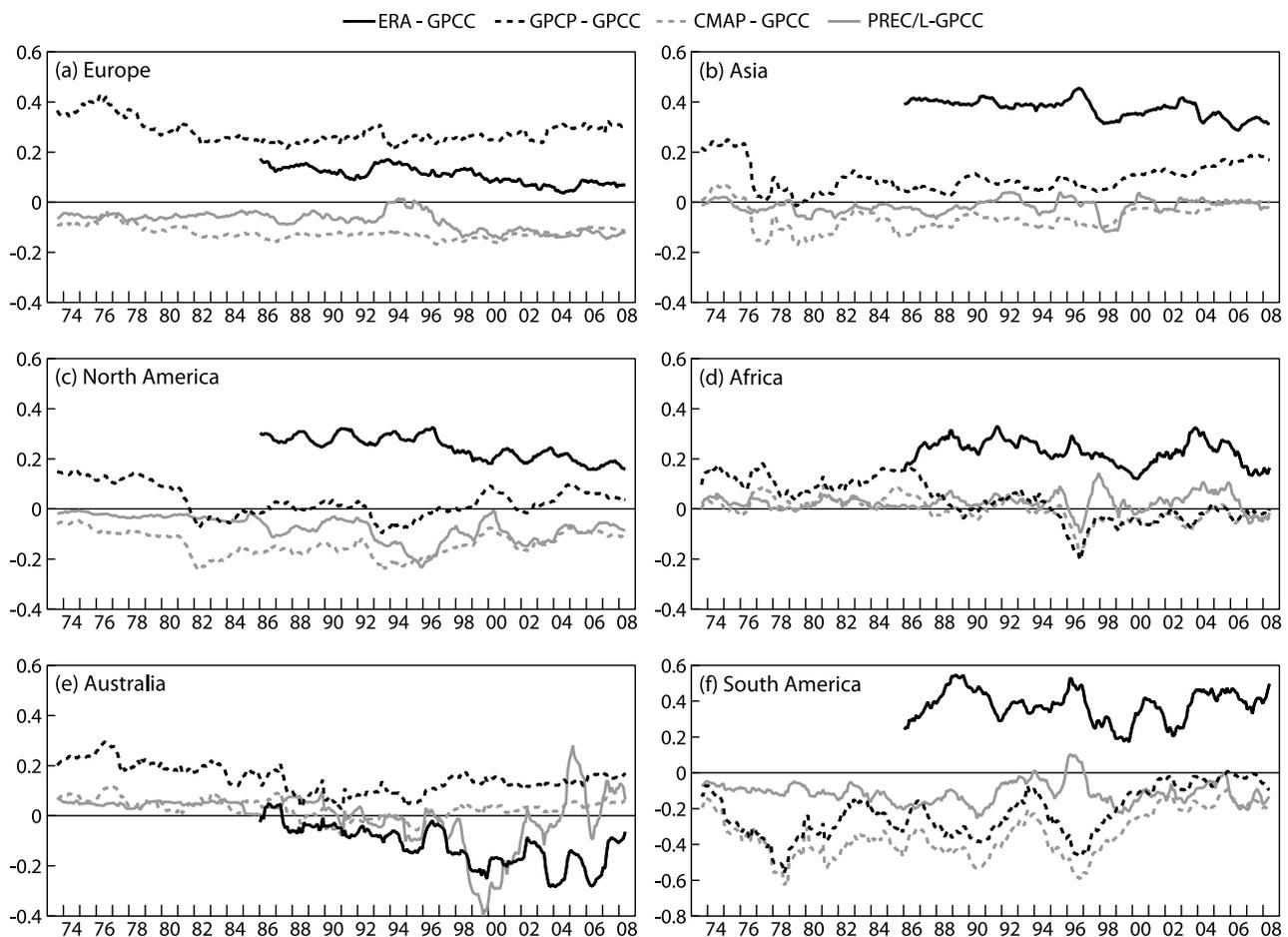


Figure 12. Twelve month running means from 1979 to 2007 of differences in precipitation rate (mm/d) from GPCC for ERA-Interim (black solid curve), GPCP (black dotted curve), CMAP (gray dotted curve), and PREC/L (gray solid curve). Results are shown for averages over land for the continental domains defined in Table 1. The ERA-Interim values are accumulated from forecasts for 12 to 24 h ahead initiated from 0000 UTC and 1200 UTC each day.

Table 5. Correlations Between the ERA-Interim Time Series of Continental Mean Monthly Precipitation Rate and the Corresponding Time Series From GPCP, GPCP, CMAP, and PREC/L for Precipitation, and From ERA-Interim for Specific and Relative Humidity, and Over Land Areas and the Period From 1989 to 2007^a

	GPCP Precipitation	GPCP Precipitation	CMAP Precipitation	PREC/L Precipitation	ERA-Interim Specific Humidity	ERA-Interim Relative Humidity
Europe	98	96	97	97	24	54
Asia	86	72	70	74	52	43
North America	88	75	73	78	28	60
Africa	80	69	73	72	66	79
Australia	97	96	96	91	83	83
South America	80	70	70	69	32	41

^aCorrelations are given in percent. Continental mean monthly precipitation rate is based on the 12–24 h forecast range. The mean annual cycle was removed from each time series prior to calculation of the correlations.

on completely independent observational data, it may be concluded that ERA-Interim has sufficient accuracy in its representation of monthly anomalies in continental-scale precipitation to discriminate between the new GPCP full data product and the GPCP and CMAP products. PREC/L is clearly an outlier for Australia, but elsewhere appears to be competitive with GPCP and CMAP despite mostly lower data counts, due presumably to a better analysis method.

[71] Table 5 also presents correlations between time series of continental mean monthly precipitation anomalies and corresponding time series of specific and relative humidity anomalies for ERA-Interim. Correlations are quite moderate, but positive in all cases. For the most part, relative rather than specific humidity correlates more strongly with precipitation amount. Correlations are largest for Australia and Africa, and also exceed 50% for Europe and North America in the case of relative humidity, and for Asia in the case of specific humidity. Positive correlations of precipitation with both specific and relative humidity cannot be expected for overall trends, as specific humidity increases and relative humidity decreases over the period as a whole, but shifts over time in the differences between the data sets make it difficult to assess longer-term variations in precipitation and their link with humidity variations.

7. Conclusions

[72] This paper has provided further evidence of the capability of comprehensive reanalysis of the atmospheric observational data record to describe some important aspects of low-frequency variations in near-surface climate. It has built on the results of *Simmons et al.* [2004] to demonstrate how surface air temperature fields from the new ERA-Interim reanalysis extend the record provided by ERA-40, in continuing good agreement with the gridded record from monthly station data, here represented by the CRUTEM3 data set of *Brohan et al.* [2006]. Time series to the end of 2008 show strong warming at high northern latitudes, and the rise in temperature over land is distinctly larger in averages of the fully sampled ERA data than in averages of the spatially and temporally incomplete CRUTEM3 data. The continuing rise in temperature over land is in contrast with the situation for sea surface temperature, which has shown no appreciable net rise over the decade following the 1997/1998 El Niño.

[73] The general agreement between reanalysis and gridded station data already demonstrated for temperature holds also for near-surface humidity. Agreement for specific humidity is almost as good as for temperature, providing confidence

in the quality not only of the reanalyses but also of the relatively new HadCRUH gridded observational data set of *Willett et al.* [2008] for study of variations over the past 35 years. Agreement is not quite as good for relative humidity, but the main variations appear nevertheless to be well characterized.

[74] A sharp reduction in relative humidity over low-latitude and midlatitude continental areas for the most recent years has been revealed by ERA-Interim, in contrast with the previous 30 or so years over which relative humidity declined only a little as specific humidity increased in line with temperature. The reduction has been confirmed by a “quick-look” extension of the HadCRUH data set, notwithstanding a difficulty in getting a good overlap with HadCRUH over North America. Confirmation has also been provided by comparing monthly 2 m temperature and dew-point anomalies from ERA-Interim with corresponding Japanese reanalysis (JRA-25/JCDAS) products. Variations over time in background and analysis fits to observations do not indicate a drift in observed values that conflicts significantly with the background model, although we have found evidence of a limited effect of changing radiosonde humidity biases on the ERA near-surface humidity analyses. The overall variation in specific humidity over land has been shown to be in close agreement with the variation over sea, and the pronounced recent decline in relative humidity over land is consistent with limited moisture supply from the oceans, the surface temperature of which has not risen in concert with the air temperature over land in recent years. Further investigation of the mechanism is desirable, but beyond the scope of this paper.

[75] These results based on the observational record appear to be at variance with a prevailing modeling view summarized in the IPCC’s Fourth Assessment Report. There, *Randall et al.* [2007] conclude that humidity in the planetary boundary layer is controlled by strong coupling with the surface and describe a broad-scale quasi-unchanged relative humidity response to forcing by increased greenhouse gases as uncontroversial. However, in the same report, *Meehl et al.* [2007] present projections of surface air temperature that show stronger warming over land than sea. An associated decline in relative humidity over land may be expected from the behavior identified here, albeit not as extreme as analyzed for recent years when near-surface warming has continued over land but not sea.

[76] The tendency of models to warm more over land than sea, in a ratio that for each model is fairly steady over time, has been reported by *Lambert and Chiang* [2007] and *Sutton*

et al. [2007]. *Joshi et al.* [2008] present discussion and modeling results pointing to a mechanism that includes a fall in boundary layer relative humidity over land. Lambert and Chiang show that the land/sea warming ratio deduced from annual mean changes in the HadCRUT3 data for 1955–2003 is consistent with the model values, while Sutton *et al.* found a larger observed ratio of land to sea warming using HadCRUT2v data for 1980–2004, ascribing the difference to natural variability. Extending the temperature record to 2008 and using the ERA all-land averages indicates a much more pronounced recent deviation from the concept of a rather steady ratio of land to sea warming. The modern observational record is evidently too short to draw firm conclusions as to the consistency between it and longer-term model projections of land/sea warming and humidity changes, but there is nevertheless scope for model-based investigation of the variations in near-surface humidity over land reported here.

[77] Implications for precipitation of rising specific humidity but falling relative humidity are unclear, and shifts over time in the differences among the various precipitation data sets compared here make it difficult to assess the changes from the previous to the latest decade. Both specific and relative humidity correlate positively with precipitation on the monthly time scale, with correlations stronger for relative than for specific humidity for the most part. The signs of continental biases in the reanalysis products are indicated, but magnitudes are not well determined because of mean differences among the gauge-based products. Nevertheless, it is encouraging as regards month-to-month variability that the reanalyses agree best with the new GPCC data set based on much more gauge data and improved interpolation, and that the newer ERA-Interim reanalysis agrees significantly better with the independent GPCC data set than ERA-40 does.

[78] There remains need and scope for future improvement of reanalysis products. The comparison presented here between the NCEP sea surface temperature data sets used in the ERA reanalyses and the Hadley Centre data set shows a mean difference of 0.1–0.2K over the past 10 years. This widespread difference needs to be understood, and an appropriate choice of SST analysis made, before production of a successor to ERA-40 and ERA-Interim begins. The persistent difference in signal from the radiosonde and surface synoptic measurements of humidity is also disconcerting. Recent improvement in instrumentation has enabled a bias correction scheme to be developed for radiosonde humidities in which observed values are adjusted toward nighttime soundings from the Vaisala RS92 instrument (D. Vasiljevic, personal communication, 2007). This results in a moistening of analyses below 500 hPa by as much as two percentage points in relative humidity depending on area and season, and was introduced into ECMWF's operational forecasting system (though not in ERA-Interim) in November 2007. This offers an improvement for future reanalyses that cover the most recent years, but a robust and general scheme for correcting the biases in older radiosonde measurements of humidity is a continuing requirement.

[79] More generally, this study has illustrated the importance of sustained activities in data collection, reprocessing and reanalysis, with appropriate version control, as called for repeatedly in assessments and plans made under the auspices of the Global Climate Observing System and World Climate Research Programme. It highlights also the need for

sustained data coverage and prompt data exchange and processing in order to meet the increasing needs for reliable monitoring and attribution of the current state of the climate system [Trenberth, 2008]. This is the case for the high-resolution gauge data that are used in analyses such as that from the GPCC, and also for the data sets on which CRUTEM3 and HadCRUH are based.

Appendix A: Extension of HadCRUH to 2007

[80] HadCRUHext covers 1994 to 2007, providing an overlap with HadCRUH for validation and an extension for comparison with ERA-Interim over land. It has been created from a more recent version of the ISD than that used as the source of observational data for HadCRUH. The data comprise ~6000 climate quality stations across the globe providing three hourly or higher-frequency temperature and dew-point observations. They have been subject to an automated and fairly comprehensive quality control (QC) procedure applied by NCDC, involving 57 tests in total, including validity, extreme value, internal, and external consistency checks [Lott *et al.*, 2001]. A series of stricter and humidity-specific tests have also been run to prepare the data for future data set creation. This differs slightly to the QC used for HadCRUH.

[81] Only stations included in HadCRUH proceed into HadCRUHext. Some stations had ceased reporting by the end of the HadCRUH period and so there are fewer stations available for HadCRUHext than HadCRUH (2473 as opposed to 3243).

[82] All hourly observations with simultaneous temperature and dew-point temperature are converted to specific humidity (q) and relative humidity (RH) using the same conventions as HadCRUH [Willett *et al.*, 2008]. All observations within each 5 day period are averaged to pentad means; there are 73 pentads within a year, with 29 February included in the pentad spanning 25 February to 1 March. HadCRUH station pentad climatologies (over 1974 to 2003) are subtracted from the equivalent HadCRUHext station pentad means to create pentad mean anomalies. These are averaged to monthly resolution where each month contains six pentads, except for August, which contains seven.

[83] HadCRUH is an homogenized data set and so for consistency, adjustments made to HadCRUH at pentad mean anomaly resolution over the 1994 to 2003 period are also applied to HadCRUHext stations. HadCRUHext stations are checked for compatibility with their HadCRUH equivalents. They are commonly offset slightly from the HadCRUH counterparts across the overlapping period (1994–2003) due to differences in structural and QC methodology, alterations to ISD by NCDC since the creation of HadCRUH and potential differences in composite station sets (identical stations reporting under more than one identifier). Consequently, HadCRUHext stations are also adjusted by the offset. A t test is run on monthly mean anomaly time series and stations differing from their HadCRUH equivalents significantly (at 5% level) are excluded as are stations with patchy data or less than 8 years of data. As a final check on data quality and given the importance of homogeneity in climate data, each HadCRUHext station time series is compared to a neighbor composite time series and rejected if clear breakpoints are identifiable. Neighbor composites are created

from ten (minimum of three) stations within the candidate station correlation decay distance [Willett *et al.*, 2008] giving the highest correlation score.

[84] This results in 2094 stations going into HadCRUHext. The monthly mean anomalies are then gridded at $5^\circ \times 5^\circ$ resolution by averaging as for HadCRUH. For comparison with HadCRUH, gridded values are also constructed for the inhomogeneous removed stations (ISDBAD) and all stations (ISDALL).

[85] Global, hemispheric, and tropical zonal averages were created for HadCRUHext, HadCRUHextISDBAD and HadCRUHextISDALL to compare with HadCRUH. A close fit between HadCRUH and HadCRUHext was found in both q and RH, especially for the hemispheric and tropical time series. There are some small discrepancies in both q and RH global time series with HadCRUHext not matching the HadCRUH high-resolution variance. However, the low-resolution variability is captured well, and HadCRUHext outperforms HadCRUHextISDBAD and HadCRUHextISDALL regardless. The large-scale features of HadCRUH are matched in HadCRUHext and so it is considered fit for its present purpose.

[86] Despite efforts to ensure homogeneity of the data, the test is manual and subjective and therefore it is plausible that some inhomogeneity remains. Furthermore, it is possible that all stations going into the neighbor composite are from the same country, so that countrywide changes to the observing system will not be picked up as inhomogeneities because they appear in the candidate and neighbor composite time series. This is not thought to be a significant problem for most of the data. However, there appears to be a proportionally larger effect over North America, as indicated in Figure 7c. This may be due to a known issue affecting the U.S. stations. When creating HadCRUH, the ISD data set was missing a large proportion of U.S. stations and the data present came from stations with short records. Efforts were made to composite stations that although reporting under different identifiers were actually the same station. This provided station records long enough to create climatologies. Despite these efforts, the number of U.S. stations within HadCRUH is very small compared to what it should be. This data sparsity, which is far worse for RH than q , means that strong features present in a small number of stations are not dampened by grid box averaging. It is highly likely that data over the United States have been changed in some way since the creation of HadCRUH due to the concentration of NCDC efforts to improve data quality and amount over this region. As such, we can expect differences from HadCRUH, and due to data sparsity, these are conspicuous. Around 1998 to 2000 there is a clear increase in observation frequency for a number of stations in the updated version of the ISD. This improves the representation of the diurnal cycle so it is quite feasible that lower temporal resolution observations focused on the diurnal temperature peak will lead to lower RH values over the period. Higher-resolution observations capturing the nighttime minimum temperature should capture the RH maximum leading to higher RH. Work is ongoing to create a new high-resolution version of HadCRUH fully addressing and correcting this problem with the U.S. stations.

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