CLIMATE OBSERVATIONS - THE INSTRUMENTAL RECORD

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Abstract. A survey is given of the available instrumental data for monitoring and analysis of climatic variations. We focus on temperature measurements, both over land and ocean, at the surface and aloft.

Over land, the older observations were subject to exposure changes which may not have been fully compensated. The effects of urbanization have been largely avoided in studies of climatic change over the last 150 years. There are few records for pre-1850 outside Europe and eastern North America, and the global network shows a recent decline. Over the ocean, sea surface temperature (SST) has been measured using buckets, engine intakes, hull sensors, buoys, and satellites. Many of these data have been effectively homogenized, but new challenges arise as observing systems evolve. Available SST and marine air temperature datasets begin in the 1850s. The data are concentrated in shipping lanes especially before 1900, and very sparse during the world wars, but additional historical data are being digitized.

The radiosonde record is short ($\sim$40 years) and has major gaps over the oceans, tropics and Southern Hemisphere. Instrumental heterogeneities are beginning to be assessed and removed using physical and statistical techniques. The MSU record is complete but only began in 1979, and is not highly resolved in the vertical: major biases, mainly affecting the lower-tropospheric retrieval, have been reduced as a result of recent analyses.

Advanced interpolation or data-assimilation techniques are being applied to these data, but the results must be interpreted with care.

1. Introduction

The signals being sought in many climate variability and change detection studies are small. So it is important that the observational data be homogeneous, i.e. that changes of climate are not misrepresented as a result of changes in instrumentation, observing practice, or the local environment. Because of natural inderdecadal variability, it is important that the records used for climate change detection be long; because of spatial variations in climate anomalies, global coverage is needed. So here we review some aspects of the homogeneity, length and geographical coverage of the instrumental record of temperature. We include both land and marine surface temperatures, and temperatures in the troposphere and lower stratosphere. We also present a recently-developed interpolation technique which can be used to alleviate some of the difficulties caused by poor spatial coverage and provide an estimate of the uncertainty in areal averages of incomplete fields.

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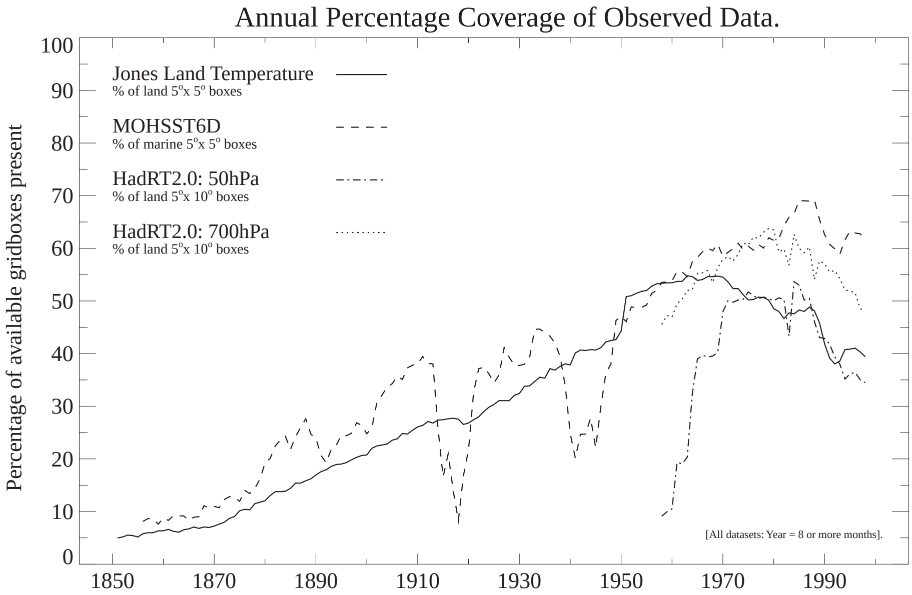

Figure 1. Annual coverage (%) of observed data. Data sources: Land air temperature, Jones *et al.* (1999); Met. Office Historical sea surface temperatures (MOHSST6), Parker *et al.* (1995); Radiosonde temperatures (HadRT), Parker *et al.* (1997).

2. Land Surface Air Temperatures

Major efforts have been made by several groups to create long, homogeneous worldwide data bases of land surface air temperature (Hansen *et al.*, 1999; Jones *et al.*, 1999; Peterson *et al.*, 1998b). A wide range of statistical methods of improving the homogeneity of station temperature and other records has been developed (Peterson *et al.*, 1998a). The impact of urban warming on global and large regional temperature trends has been shown to be minimal (Peterson *et al.*, 1999). The different techniques used for estimating global and hemispheric temperature changes yield very similar results, though the Hansen *et al.* (1999) method gives smoother fields and reduced interannual variance of the global and hemispheric anomalies (Peterson *et al.*, 1998b). Nevertheless, some biases remain. The instrumental exposures in the nineteenth century often resulted in overheating by day and excessive cooling at night. In some tropical countries the thermometers were suspended under thatched sheds, where temperatures were typically 0.2 to 0.7°C higher than in Stevenson screens. A review of these and other early exposures and their effects is given by Parker (1994). Caution is also needed when using more recent data: for example, Quayle *et al.* (1991) reported artificial warming of 0.3°C by night and cooling of 0.4°C by day when liquid in glass thermometers in wooden shelters were replaced by thermistor-based instruments in plastic shelters in the USA. The longest instrumental record is that of Central England Temper-

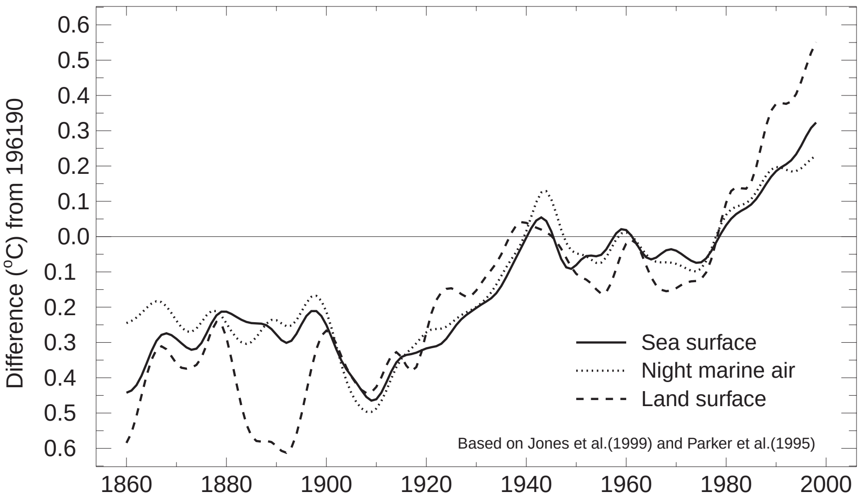

Figure 2. Smoothed annual global temperatures, 1861-1998 relative to 1961-1990 climatology. Land: Jones *et al.* (1999); sea surface temperature and night marine air temperature: Parker *et al.* (1995).

ature (CET): monthly since 1659 (Manley, 1974) and daily since 1772 (Parker *et al.*, 1992). However, the coverage of available land surface air temperature data before the mid nineteenth century is largely restricted to Europe and eastern North America. By 1910, the gaps had shrunk to the Arctic and Antarctic and the interiors of the tropical continents (Parker et al., 1994) and by the 1950s coverage was good except over Antarctica. Since then, observations have been made in Antarctica, but coverage has declined in some other areas, especially in the tropics, resulting in an overall reduction (Figure 1). The Global Climate Observing System (GCOS) Surface Network (GSN) (Peterson *et al.*, 1997) has been set up to ensure the maintenance of a network of homogeneous data for monitoring and researching into global climate, and to ensure the wide availability of the data. Key findings from the land network are that the warming since the 1970s has been greater than over the oceans (Figure 2), and night-time warming has exceeded that by day in most continental areas in the last several decades (Easterling *et al.*, 1997).

3. Sea Surface and Marine Air Temperatures and Comparison with Land

Sea surface temperatures (SSTs) and marine air temperatures (MATs) require major adjustments to ensure homogeneity. The older SSTs were adjusted by Folland and Parker (1995) to compensate for the use of uninsulated or partly-insulated buckets to sample the water. Corrections approached 1°C over the Gulf Stream and Kuroshio in winter, and 0.5°C in most of the tropics, if canvas buckets were used. However, modern SSTs measured from ships may also need adjustments

(Kent *et al.*, 1993). Careful adjustment is also required when blending satellite-based SSTs with *in situ* data (Reynolds and Smith, 1994), because the former are measures of skin rather than bulk temperature, and may be biased by atmospheric aerosol or cloud. MATs are also biased, principally by historically varying on-deck heating, so that only night-time data should be used. Adjustments are also required for changing deck-elevations. Guided by SSTs, MATs were also adjusted for non-standard observing practices in the nineteenth century and during the second world war (Parker *et al.*, 1995; Peterson *et al.*, 1998a).

Coverage of marine temperature data is limited to the main shipping lanes in the mid nineteenth century, with a steady expansion until 1910 (Parker *et al.*, 1994). There were major reductions during both world wars (Parker *et al.*, 1995 and Figure 1) followed by an expansion to most areas except the Southern Ocean and the ice-covered Arctic. These areas are now analysed with the aid of satellite data and advanced interpolation schemes (Reynolds and Smith, 1994; Rayner *et al.*, 1996; Section 5). Historical coverage is now being improved by the digitization of several million observations from ships (Parker *et al.*, 1995), including SST, MAT, pressure and wind.

Support for both marine and land surface air temperature records comes from the agreement of their global trends (Figure 2). Comparison of collocated SSTs with air temperatures from islands and coasts (Parker *et al.*, 1995) suggests that the nineteenth century biases were small on a global average and that the difference in global anomalies in 1880-1895 (Figure 2) arose from atmospheric circulation anomalies and/or sparse sampling. The relative warmth on land in 1900-1930 is likely to have been at least partly the result of the exposures used in the tropics (Section 2). Enhanced westerly winds at midlatitudes in the northern winter may also have raised air temperatures on windward coasts more than collocated SST. The relative warmth over land since 1980 comes from the high latitude northern continents where winters have been anomalously warm owing to an increase in westerly wind flow (Wallace *et al.*, 1996) and springs have been warmed through a positive feedback through reduction in snow cover (Groisman *et al.*, 1994).

Figure 3 compares seasonal anomalies (relative to 1961-1990 climatology) of SST and night MAT for four ocean regions: the North Atlantic north of 35°N, the tropical east Pacific (20°N−20°S, east of 170°W), the Indian Ocean north of 50°S, and the South Pacific north of 50°S. Series for the latter two regions are shown in Figure 4.1 of Folland *et al.* (1999) who also address patterns of oceanic temperature variability. Here, however, the SSTs are from a new analysis, MOHSST7, in which random and sampling errors are reduced by reducing the deviations from an initial reduced-space optimum interpolation (RSOI, Kaplan *et al.*, 1998; Folland *et al.*, 2000) of the available SST data. The reductions are greater where data are sparse. In addition, the night MATs are from a new analysis, MOHMAT5, based on RSOI. In the extratropical North Atlantic, differing trends of SST and MAT may be a result of atmospheric circulation changes, with relatively lower MAT in more westerly epochs such as 1900-1930. In the east tropical Pacific and the Indian

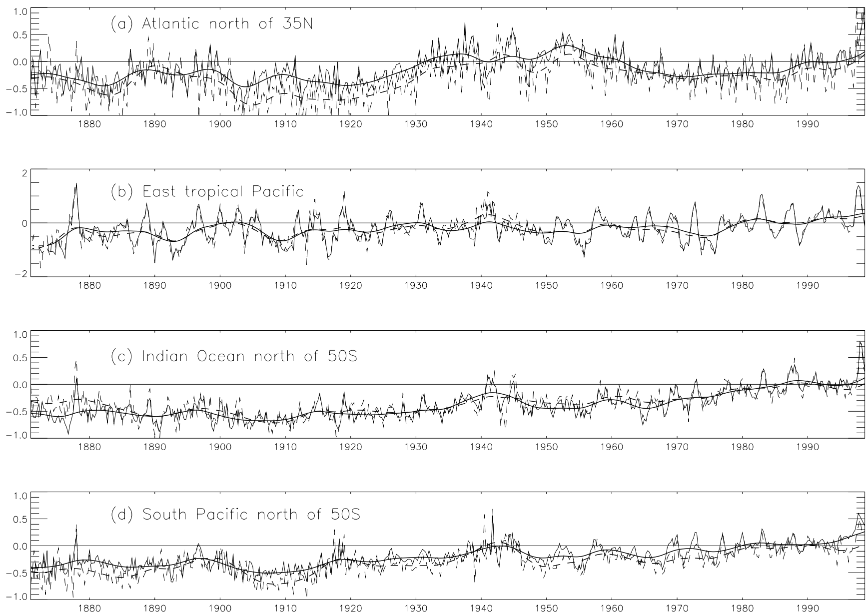

Figure 3. Seasonal anomalies (relative to 1961-1990 climatology) of SST (MOHSST7, solid) and night MAT (MOHMAT5, dashed) for four ocean regions: the North Atlantic north of 35°N, the tropical east Pacific (20°N−20°S, east of 170°W), the Indian Ocean north of 50°S, and the South Pacific north of 50°S. Data are not collocated, i.e. the coverage of SST and night MAT may differ.

Ocean, SST and MAT trends are very similar. In the South Pacific, MAT has not followed SST in showing strong warming in the 1990s. The reasons for this are still under investigation and may include atmospheric and/or oceanic circulation changes, sampling errors owing to data sparsity, and biases in the measurement of SST and/or MAT from the heterogeneous network of *in situ* measuremant platforms (Kent *et al.*, 1993). Figure 3 shows that the SST and MAT data are able to distinguish different climatic variations in different ocean basins: for example, the warming since the beginning of the 20th Century has been steady in the Indian Ocean, whereas there was a marked mid-20th Century warm peak, and a subsequent cool period, in the extratropical North Atlantic.

4. Temperatures in the Troposphere and Lower Stratosphere

The radiosonde network became worldwide in 1958 for the International Geophysical Year. However, coverage of the Southern Hemisphere remained sparse, and the oceans and parts of the tropical continents have remained poorly represented. Stratospheric coverage is sparser than that in the troposphere, and there has been a recent decline in overall coverage (Figure 1). So the GCOS Upper Air Network (GUAN) is being established, to ensure the maintenance of key stations and availability of their data (Folland *et al.*, 2000). A major task of the Comprehensive

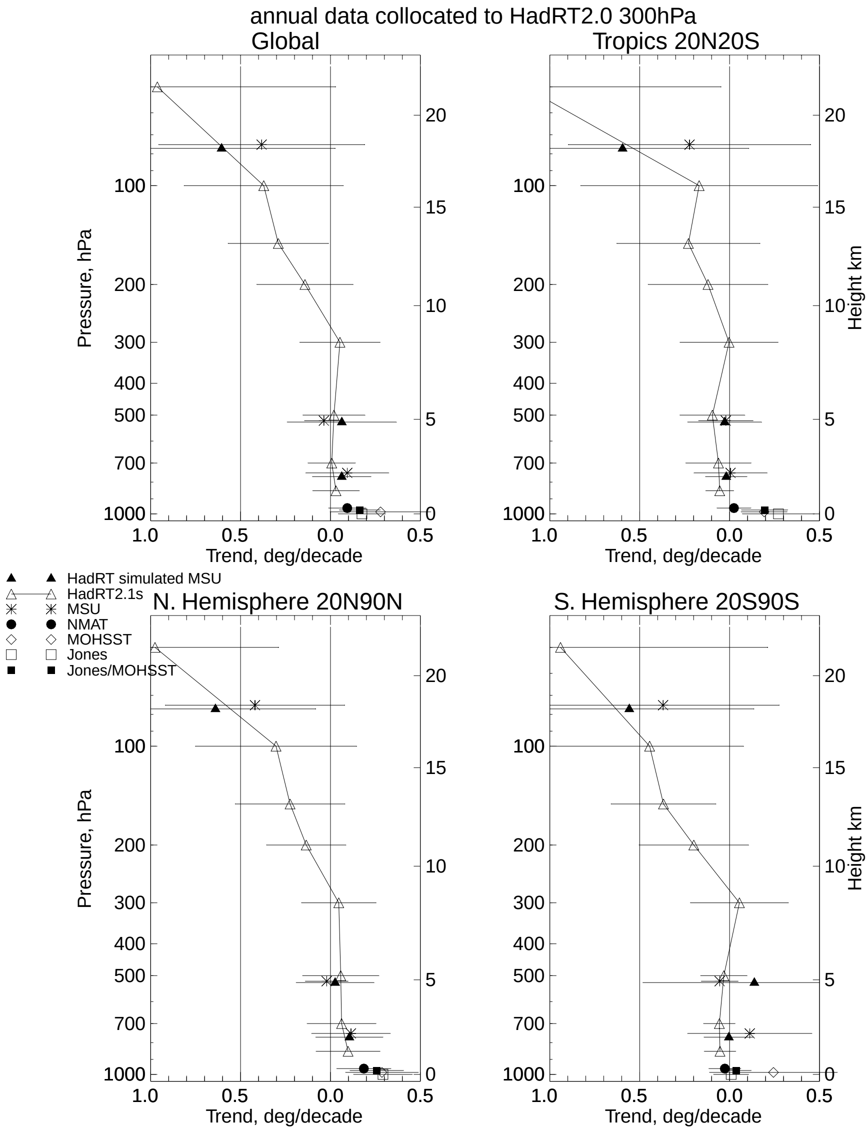

Figure 4. Profiles of temperature trends for 1979-1998: Globe, Tropics 20°N−20°S, N. Hemisphere 20° − 90°N, S. Hemisphere 20° − 90°S. Trends and their 2σ-error bars are estimated by restricted maximum likelihood (Diggle *et al.*, 1994) allowing for first order autoregression. Data sources: land surface air temperature: Jones *et al.* (1999); SST and night MAT: Parker *et al.* (1995); tropospheric temperature: HadRT2.0 (update of Parker *et al.* (1997), India omitted; no bias-adjustments), MSU2 and MSU2LT; stratospheric temperature: HadRT2.1 (India omitted: bias adjustments if stations had metadata, using MSU4 as a reference) and MSU4. All surface records are collocated to HadRT2.0 coverage at 300 hPa.

Aerological Reference Data Set (CARDS) project (Eskridge *et al.*, 1995) is the homogenization, archiving, and provision of data from GUAN and other stations.

The historical radiosonde record is affected by many changes of instrumentation and operating practices including observing time. Basic quality controls such as hydrostatic checks (Eskridge *et al.*, 1995; Parker and Cox, 1995) can remove random errors incurred during measurement, transcription or telecommunication, but systematic biases remain. Essential for the estimation and removal of these are accurate metadata describing the exact nature and timing of the instrumental and procedural changes (Gaffen, 1994; Gaffen, 1996; Parker and Cox, 1995; Parker *et al.*, 1997; Gaffen *et al.*, 1999). The remit of the CARDS Project includes the improvement of the metadata base.

Radiosonde data may be adjusted using an independent record for reference. This was done by Parker *et al.* (1997) using the retrievals made since 1979 from Microwave Sounding Units (MSU). The stratospheric "MSU4" (Spencer and Christy, 1993) and the low-mid tropospheric "MSU2R" (now known as "T2LT") retrievals (Spencer and Christy, 1992) were used to adjust monthly radiosonde temperatures since 1979. Adjustments were only applied in cases of known instrumental or procedural change at a station. Some changes in instrumentation had resulted in spurious cooling of up to 3°C in the lower stratosphere. Biases were much smaller in the troposphere. However, tropospheric MSU temperatures were shown by Wentz and Schabel (1998) to have been biased by orbital decay of the satellites. In addition, the MSU record has been affected by orbit time changes, variations in the temperature of the instruments, and the brevity of some of the overlaps between successive instruments. Improvements have now been made (J. Christy, pers. comm., 1999), but detailed validation is required. Furthermore, MSU cannot be used to adjust radiosonde data older than 1979, and although MSU has global coverage, it samples the atmosphere with much coarser vertical resolution than radiosondes (Spencer and Christy, 1992, 1993).

Radiosonde temperatures can also be adjusted using heat transfer models of the instruments, and the results verified using day-night differences (Luers and Eskridge, 1998). These models have now been developed for the majority of radiosonde types used since 1960. In some cases erroneous radiation corrections need to be removed before application of the model-based adjustments. Within the CARDS project, the models are being applied to the daily radiosonde data. As a result, a basic network of homogeneous radiosonde temperature data should soon be available for climate change detection.

Radiosonde data may also be used with other sources of data in model-based reanalyses (Section 5). However, if the data supplied to a reanalysis have biases, the output is also likely to be biased. A review of the impacts of the choice of reanalysis or radiosonde dataset and processing technique on estimates of temperature trends aloft is given by Santer *et al.* (1999). These authors conclude that biases in the National Centers for Environmental Prediction reanalysis (Kalnay *et al.*, 1996) diminish its usefulness for climate change detection studies.

Comparisons of surface, radiosonde and MSU data have shown an apparent decrease in global and tropical lower-tropospheric lapse rate during the last 20 years. Figure 4 shows profiles of temperature trends for 1979-1998 for the globe, Northern Hemisphere $20° - 90°$N, Southern Hemisphere $20° - 90°$S and the tropics $20°$N$-20°$S. Reasons for a real change in lapse rate include weakening of high-latitude winter surface inversions by strengthening atmospheric circulation (Hurrell and Trenberth, 1996), and thermal forcing by stratospheric ozone loss (Hansen *et al.*, 1995). Spurious changes in lapse rate may result from biases in any of the data sets, or from the sampling errors of the sparse radiosonde network. However, longer term surface and tropospheric trends (not shown) are in closer agreement, in accord with Nicholls *et al.* (1996).

5. Advances in Interpolation Techniques

Reanalyses (e.g. Kalnay *et al.*, 1996) use all available historical data, along with a fixed state-of-the-art dynamical model's data assimilation scheme, to create a homogeneous set of analyses of the past state of the atmosphere (or ocean). Within the assimilation scheme, errant data are amended or excluded on the basis of comparisons with neighbours and a first-guess analysis. The latter is based on a previous analysis and the model's dynamics and physics. Thus, the quality control of the data incorporates real physical constraints. However, biases affecting large regions, e.g. when radiosondes are changed simultaneously in a country, may not be detected by such schemes, because the initial analyses will be biased. Furthermore, in areas with few *in situ* data the reanalysis may be affected by, for example, inadequate model physics or biased satellite data: when data quality and/or quantity improve, these biases are reduced but the overall result is a non-climatic change in the reanalysis (Santer *et al.*, 1999).

Model-independent interpolation schemes are therefore being developed. Optimum interpolation (Reynolds and Smith, 1994) uses the spatial covariance structure of the data, along with estimated random and spatially-coherent data-errors, to yield complete fields of both the parameter being analysed and the error of estimate. Optimum averaging (Kagan, 1979) uses the same theory to provide the average value of the parameter over the field, along with error bars. In reduced-space optimum interpolation (Kaplan *et al.*, 1998) and averaging, the covariance matrix is truncated to remove those eigenvectors which are regarded as noise. Reduced-space optimum smoothing (Kaplan *et al.*, 1998) incorporates a temporal dependence, e.g. Markov red noise, into the interpolation algorithm. All these techniques assume that the covariance statistics, which must be derived for some well-sampled period, remain valid throughout the period analysed. It is essential to detrend the data before applying optimum interpolation and related techniques; otherwise, there will be a bias towards climatology in data-sparse areas. It is also necessary to remove biases, e.g. by applying bucket-corrections to SST (Folland

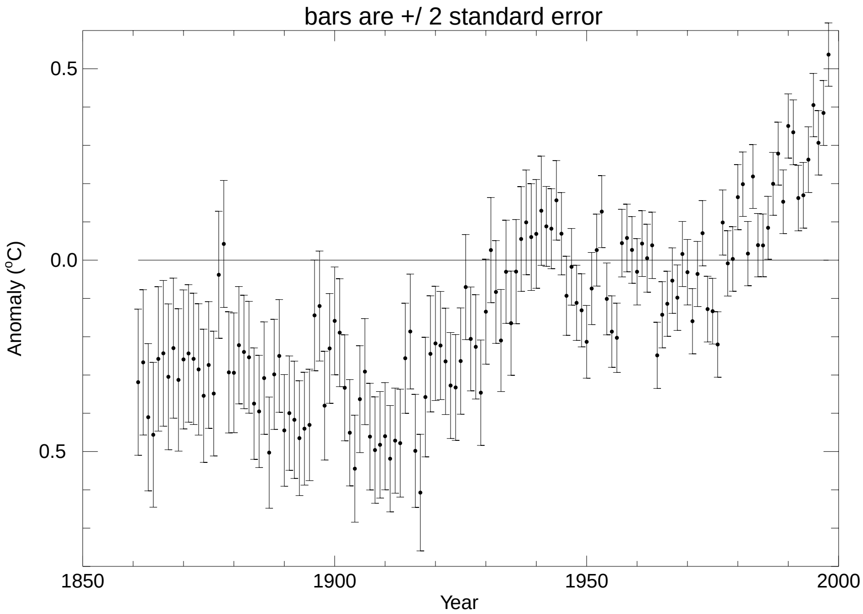

Figure 5. Annual combined land surface air temperature and SST anomalies, relative to 1961-1990 climatology, for the globe, 1861-1998. The averages and associated 2σ-error bars were calculated using reduced space optimum interpolation including an estimate of the uncertainties in the bucket-corrections to SST.

and Parker, 1995) or by adjusting satellite SSTs for their biases (Reynolds *et al.*, 1989; Reynolds, 1993; Reynolds and Smith, 1994.

In Figure 5 we show annual combined land surface air temperature and SST anomalies, relative to 1961-1990 climatology, for the globe for 1861-1998. The averages and associated $2\,\sigma$-error bars were calculated using reduced space optimum averaging. Note the steady reduction in the width of the error bars from the nineteenth century to the late twentieth century, with temporary widenings during the two world wars when data were sparser. Recently digitized data for 1911-1920 are expected to reduce the errors of estimate in future analyses for that period. There has not been a significant recent increase in the estimated errors, despite the decline in data availability over land (Figure 1) because the marine data coverage has been maintained. The error bars are similar to those obtained by Jones *et al.* (1997, 1999) who used analytic spatial correlation fits to estimate the standard errors of gridbox data and the number of independent gridbox data in the globe. Global temperature anomalies calculated by area-weighted averaging of gridbox values (as shown e.g. in Nicholls *et al.* (1996) generally lie well within the error bars in Figure 5.

6. Conclusions

The instrumental surface temperature record is marginally adequate for monitoring variations on multidecadal to century time scales. Although some biases may remain, the land-based and marine records offer mutual support, especially since the 1890s. In addition, the SST and night MAT records offer very good evidence for the diverse behaviour of different ocean basins.

With care it should be possible to remove many radiosonde temperature biases and allow a realistic assessment of interdecadal tropospheric and lower stratospheric temperature changes since the 1960s. The MSU record, though only available since 1979, is geographically complete; its lower stratospheric data are likely to be less affected by biases than its lower tropospheric retrievals.

Advanced interpolation techniques, such as model-based Reanalyses and reduced space optimum interpolation, show promise, but the results must be interpreted with care. In particular, these methods cannot remove biases from the data to which they are applied.

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References

Diggle, P. J., Liang, K.-Y., and Zeger, S. L.: 1994, 'Analysis of Longitudinal Data', Clarendon Press, Oxford, Chap. 4, p. 64.

Easterling, D. R., Horton, E. B., Jones, P. D., Peterson, T. C., Karl, T. R., Parker, D. E., Salinger, M. J., Razuvayev, V. N., Plummer, N., Jamason, P., and Folland, C. K.: 1997, 'Maximum and minimum temperature trends for the globe', *Science* **277**, 364–367.

Eskridge, R. E., Alduchov, O. A. Chernykh, I. V., Zhai, P., Polansky A. C. and Doty, S. R.: 1995, 'A Comprehensive Aerological Reference Data Set (CARDS): Rough and systematic errors', *Bull. Amer. Meteorol. Soc.* **76**, 1759–1775.

Folland, C. K. and Parker, D. E.: 1995, 'Correction of instrumental biases in historical sea surface temperature data', *Quart. J. Roy. Meteorol. Soc.* **121**, 319–367.

Folland, C. K., Parker, D. E., Colman, A. W. and Washington, R. 1999: 'Large scale modes of ocean surface temperature since the late nineteenth century', *in* A. Navarra, (Ed.), *Beyond El Niño: Decadal and Interdecadal Climate Variability.*, Springer-Verlag., pp. 73–102.

Folland, C. K., Frich, P., Basnett, T. A., Rayner, N. A., Parker, D. E. and Horton, E. B.: 2000, 'Uncertainties in climate datasets: a challenge for WMO', *WMO Bulletin* **49**, 59–68.

Gaffen, D. J.: 1994, 'Temporal inhomogeneities in radiosonde temperature records', *J. Geophys. Res.* **99**, 3667–3676.

Gaffen, D. J.: 1996, 'A digitized metadata set of global upper-air station histories', NOAA Technical Memorandum ERL-ARL 211, Silver Spring, MD, pp. 38.

Gaffen, D. J., Sargent, M. A., Habermann, R. E. and Lanzante, J. R.: 1999, 'Sensitivity of tropospheric and stratospheric temperature trends to radiosonde data quality', *J. Climate*, in press.

Groisman, P., Ya., Karl, T. R., and Knight, R. W.: 1994, 'Observed impact of snow cover on the heat balance and the rise of continental spring temperatures', *Science* **263**, 198–200.

Hansen, J., Wilson, H., Sato, M., Ruedy, R., Shah, K. and Hansen, E.: 1995, 'Satellite and surface temperature data at odds?', *Climatic Change* **30**, 103–117.

Hansen, J., Ruedy, R., Glascoe, J., and Sato, M.: 1999, 'GISS analysis of surface temperature change', *J. Geophys. Res.* **104**, 30997–31022.

Hurrell, J. W., and Trenberth, K. E.: 1996, 'Satellite versus surface estimates of air temperature since 1979', *J. Climate* **9**, 2222–2232.

Jones, P. D., Osborn, T. J. and Briffa, K. R.: 1997, 'Estimating sampling errors in large-scale temperature averages', *J. Climate* **10**, 2548–2568.

Jones, P. D., New, M., Parker, D. E., Martin, S. and Rigor, I.G.: 1999, 'Surface air temperature and its changes over the past 150 years', *Rev. Geophys.* **37**, 173–199.

Kagan, R. L.: 1979, 'Averaging of meteorological fields', Gidrometeoizdat, Leningrad (now St. Petersburg). Also published in English, L. S. Gandin and T. M. Smith (Eds.), as *Atmospheric and Oceanographic Sciences Library* Vol. **19**, , Kluwer Academic Publishers, Dordrecht/Boston/London, pp. 279.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., and Joseph, D.: 1996, 'The NCEP/NCAR 40-year reanalysis project', *Bull. Amer. Meteorol. Soc.* **77**, 437–471.

Kaplan, A., Cane, M. A., Kushnir, Y., Clement, A. C., Blumenthal, M. B., and Rajagopalan, B.: 1998, 'Analyses of global sea surface temperature 1856-1991', *J. Geophys. Res.* **103**, 18567–18589.

Kent, E. C., Taylor, P. K., Truscott, B. S., and Hopkins, J. S.: 1993, 'The accuracy of voluntary observing ships' meteorological observations - Results of the VSOP-NA', *J. Atmos. Oceanic Tech.* **10**, 591–608.

Luers, J. K. and Eskridge, R. E.: 1998, 'Use of radiosonde temperature data in climate studies', *J. Climate* **11**, 1002–1019.

Manley, G.: 1974, 'Central England Temperatures: monthly means 1659 to 1973', *Quart. J. Roy. Meteorol. Soc.* **100**, 389–405.

Nicholls, N., Gruza, G. V., Jouzel, J., Karl, T. R., Ogallo, L. A. and Parker, D. E.: 1996, 'Observed climate variability and change', *in* J. T. Houghton, L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg and K. Maskell (Eds.), *Climate Change 1995 - The Science of Climate Change'. The second assessment report of the Intergovernmental Panel on Climate Change: Contribution of Working Group I.*, Cambridge University Press, Cambridge, UK, pp. 133–192.

Parker, D. E.: 1994, 'Effects of changing exposure of thermometers at land stations', *Internat. J. Climatol.* **14**, 1–31.

Parker, D. E. and Cox, D. I.: 1995, 'Towards a consistent global climatological rawinsonde database', *Internat. J. Climatol.* **15**, 473–496.

Parker, D. E., Legg, T. P., and Folland, C. K.: 1992, 'A new daily Central England Temperature series, 1772-1991', *Internat. J. Climatol.* **12**, 317–342.

Parker, D. E., Jones, P. D., Folland, C. K. and Bevan, A.: 1994, 'Interdecadal changes of surface temperature since the late 19^{th} century', *J. Geophys. Res.* **99**, 14377–14399.

Parker, D. E., Folland, C. K. and Jackson, M.: 1995, 'Marine surface temperature: observed variations and data requirements' *Climatic Change* **31**, 559–600.

Parker, D. E., Gordon, M., Cullum, D. P. N., Sexton, D. M. H., Folland, C. K., and Rayner, N.: 1997, 'A new gridded radiosonde temperature data base and recent temperature trends', *Geophys. Res. Lett.* **24**, 1499–1502.

Peterson, T. C., Daan, H., and Jones, P. D.: 1997, 'Initial selection of a GCOS Surface Network', *Bull. Amer. Meteorol. Soc.* **78**, 2145–2152.

Peterson, T. C., Easterling, D. R., Karl, T. R., Groisman, P., Nicholls, N., Plummer, N., Torok, S., Auer, I., Boehm, R., Gullett, D., Vincent, L., Heino, R., Tuomenvirta, H., Mestre, O., Szentimrey, T., Salinger, M. J., Forland, E. J., Hanssen-Bauer, I., Alexandersson, H., Jones, P. D., and Parker, D. E.: 1998a, 'Homogeneity adjustments of *in situ* atmospheric climate data: A review', *Internat. J. Climatol.* **18**, 1493–1517.

Peterson, T. C., Karl, T. R., Jamason, P. F., Knight, R. and Easterling, D. R.: 1998b, 'First difference method: maximizing station density for the calculation of long-term global temperature change', *J. Geophys. Res.* **103**, 25967–25974.

Peterson, T. C., Gallo, K. P., Lawrimore, J., Owen, T. W., Huang, A., and McKittrick, D. A..: 1999, 'Global rural temperature trends', *Geophys. Res. Lett.* **26**, 329–332.

Quayle, R. G., Easterling, D. R., Karl, T. R., and Hughes, P. Y.: 1991, 'Effects of recent thermometer changes in the Cooperative Station Network', *Bull. Amer. Meteorol. Soc.* **72**, 1718–1723.

Rayner, N. A., Horton, E. B., Parker, D. E., Folland, C. K., and Hackett, R. B.: 1996, 'Version 2.2 of the Global sea-Ice and Sea Surface Temperature data set, 1903-1994', Hadley Centre Climate Research Technical Note CRTN 74. Available from the Hadley Centre, Met. Office, Bracknell, UK.

Reynolds, R. W.,: 1993, 'Impact of Mount Pinatubo aerosols on satellite-derived sea surface temperatures', *J. Climate* **6**, 768–774.

Reynolds, R. W. and Smith, T. M.: 1994, 'Improved global sea surface temperature analyses using optimum interpolation', *J. Climate* **7**, 929–948.

Reynolds, R. W., Folland, C. K. and Parker, D. E.: 1989, 'Biases in satellite-derived sea-surface-temperature data', *Nature* **341**, 728–731.

Santer, B. D., Hnilo, J. J., Wigley, T. M. L., Boyle, J. S., Doutriaux, C., Fiorino, M., Parker, D. E., and Taylor, K. E.: 1999, 'Uncertainties in observationally based estimates of temperature change in the free atmosphere', *J. Geoph. Res.* **104**, 6305–6333.

Spencer, R. W., and Christy, J. R.: 1992, 'Precision and radiosonde validation of satellite gridpoint temperature anomalies. Part II: A tropospheric retrieval and trends during 1979-90', *J. Climate* **5**, 858–866.

Spencer, R. W., and Christy, J. R.: 1993, 'Precision lower stratospheric temperature monitoring with the MSU: technique, validation and results 1979-1991', *J. Climate* **6**, 1194–1204.

Wallace, J. M., Zhang, Y., and Bajuk, L.: 1996, 'Interpretation of interdecadal trends in Northern Hemisphere surface air temperature', *J. Climate* **9**, 249–259.

Wentz, F. J., and Schabel, M.: 1998, 'Effects of orbital decay on satellite-derived lower-tropospheric temperature trends', *Nature* **394**, 661–664.