

Quality of Reanalyses in the Tropics

KEVIN E. TRENBERTH, DAVID P. STEPANIAK, AND JAMES W. HURRELL

National Center for Atmospheric Research, Boulder, Colorado*

MICHAEL FIORINO

Lawrence Livermore National Laboratory, University of California, Livermore, California

(Manuscript received 4 February 2000, in final form 12 May 2000)

ABSTRACT

Broad vertical layer-averaged temperatures from the microwave sounder unit (MSU) are used as a quasi-independent validation of temperature fields from the U.S. National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) and the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalyses. While the MSU and NCEP–NCAR temperatures show fairly good agreement overall, large discrepancies with ECMWF temperatures indicate that changes in the satellite observing system may have adversely affected the ECMWF reanalyses, especially in the Tropics. Two spurious discontinuities are present in tropical temperatures with jumps to warmer values throughout the Tropics below 500 mb in late 1986 and early 1989, and further spurious interannual variability is also present. These features are also reflected in the specific humidity fields. The temperature discrepancies have a complex vertical structure with height that is not fully understood, although it seems that the problems partly arise from positive reinforcement of biases in satellite radiances with those of the assimilating model first guess. Changes in the observing system provide a limit to the usefulness of the reanalyses in some climate studies.

1. Introduction

Global analyses produced by the operational centers, National Centers for Environmental Prediction (NCEP) and the European Center for Medium-Range Forecasts (ECMWF), for weather forecasting purposes contain many discontinuous changes in the analyses arising from improvements in the system used to produce them (Trenberth and Olson 1988). Unfortunately, these introduce artificial changes in the apparent climate record as seen through the analyses. “Reanalysis” of the historical data by several centers using a state-of-the-art system that is held constant for the entire record is designed to address these discontinuities. The only sources of spurious change then are the changes in the observing system, including those arising from the distribution, types and quality of observing platforms such as radiosondes and satellites (e.g., Uppala 1997). Here the focus is on the reanalyses from NCEP–NCAR (Kalnay et al.

1996) and from ECMWF (Gibson et al. 1997). In particular, we show how some of the changes in the observing system appear to have adversely affected the ECMWF reanalyses of the temperature and moisture fields in the Tropics. Those influences are seen in other fields as well, thereby potentially limiting the usefulness of the reanalyses in addressing climate variability.

Comprehensive evaluation of the moisture budget from NCEP–NCAR reanalysis was given by Trenberth and Guillemot (1998) who concluded that there is a negative bias in tropical precipitation, which is probably an indication that the divergent circulation is too weak. A comparison of the reanalyses moisture budgets by Stendel and Arpe (1997) concluded that the ECMWF precipitation fields were superior in the extratropics to those of other reanalyses when compared with Global Precipitation Climatology Project (GPCP) observational data. Annamalai et al. (1999) found the ECMWF reanalyses to be better in describing the summer Asian monsoon. Engelen et al. (1998) confirmed the superior ECMWF reanalysis of water vapor fields in the lower and upper troposphere. A further evaluation by Newman et al. (2000) of the NCEP, National Aeronautics and Space Administration (NASA), and ECMWF reanalyses, which focused especially on the warm pool area of the Pacific from the standpoint of outgoing longwave radiation, precipitation and 200-mb divergence, found

* The National Center for Atmospheric Research is sponsored by the National Science Foundation.

Corresponding author address: Kevin E. Trenberth, NCAR, P.O. Box 3000, Boulder, CO 80307-3000.
E-mail: trenbert@ucar.edu

substantial problems with all reanalyses, although ECMWF reanalyses gave the best estimates of the 200-mb divergence.

Therefore several evaluations have indicated superior performance by ECMWF on some facets of the reanalyses. However, as we show here, the ECMWF reanalyses also have some problems that are quite severe for some climate studies. Continuity problems are present in the ECMWF reanalyses that can be traced to the bias correction of satellite radiances in the temperature and moisture retrieval process. These very likely contribute to the substantial problems regionally in the hydrological cycle, especially over Africa (Stendel and Arpe 1997). Over South America the problems discussed here become confused with those in western Amazonia associated with how the semidiurnal tide interacted with the soil moisture relaxation and assimilation method for humidity (Kållberg 1997). This was discovered while analyzing 1986, and so a fix of removing surface synop surface pressure observations from the analysis was included from January 1987 onward. The tropical temperature time series of the NCEP–NCAR reanalyses appear to be relatively more consistent beginning in 1979. However, they too are adversely influenced by observing system changes (Basist and Chelliah 1997).

Often, it is difficult to decide which of two analyses are correct as there is no independent truth. In the case of temperatures, there is a somewhat independent product based on satellite data from the microwave sounder unit (MSU) of Christy et al. (1998; 2000). A preliminary comparison of broad layer temperatures from MSU data with the reanalyses was given by Hurrell and Trenberth (1998); see also Santer et al. (1999). This report is an update to make use of a later improved version of the MSU data (Christy et al. 2000) and to focus on the implications for the ECMWF reanalyses, in particular.

Section 2 discusses the reanalysis data, the MSU data and the background that led to this report. Section 3 presents the main results, and conclusions are given in section 4.

2. Data and the issues

a. Reanalyses

The period examined is that of the common reanalysis data from 1979 to 1993. The global analyses are produced on model (sigma or hybrid) surfaces. We use the postprocessed values on standard pressure levels produced from 6-h data averaged into monthly means.

The NCEP system is based on a numerical weather prediction model with T62 spectral resolution and 28 sigma levels in the vertical. Fields are not initialized. Trenberth and Guillemot (1998) provided a comprehensive evaluation of the NCEP–NCAR reanalyses focused on the hydrological cycle. For convenience we refer to these as the NCEP reanalyses.

The ECMWF reanalyses, known as ERA-15, are at T106 resolution and 31 levels in the vertical with a hybrid coordinate that transitions to a pressure coordinate above about 100 mb. Of note is that a diabatic, nonlinear normal mode initialization was applied. Evaluations of performance of the system are given by Uppala (1997) and Kållberg (1997), and by Stendel and Arpe (1997) for the hydrological cycle for both reanalyses.

Of particular relevance here is a prominent difference in the two reanalyses in the way satellite data were assimilated. NCEP used temperature profiles retrieved by National Environmental Satellite, Data and Information Service (NESDIS). In ERA-15, the TOVS cloud cleared radiances were assimilated indirectly through a one-dimensional variational (1DVAR) scheme that calculates a temperature (thickness) and moisture (precipitable water) profile based on the first guess (6-h forecast) from the assimilating model (Eyre et al. 1993). As part of this process, the first-guess information is translated to top-of-atmosphere radiances by a radiative transfer model for comparison with the observed radiances. Hence, the 1DVAR scheme calculates a correction to the retrieval taken from first guess. Thus, the 1DVAR retrieval, which is identical in structure to the NESDIS retrieval and was treated as an independent observation in the ERA-15 OI analysis, is strongly linked to the assimilating model. Bias in the model can only be removed in the correction step, and experience has shown (Fiorino 1999) that the reanalyzed temperature responds rapidly (~ 10 days) to changes in the bias-corrected radiances as seen in the “radgrams” (not shown), which are used to monitor observations, first-guess and analysis performance.

b. MSU and radiance data

The MSU measures a brightness temperature of the vertically averaged atmospheric thermal emission by molecular oxygen at different spectral intervals (channels). The weighting functions encompass very broad layers of the atmosphere (see Hurrell and Trenberth 1998); for instance MSU Channel 2 (53.74 GHz) extends from the surface into the lower stratosphere. Therefore, Spencer and Christy (1992) proposed a retrieval technique in which the off-nadir Channel 2 data, which have a somewhat different vertical weighting function, are used to remove the stratospheric influence and thus provide an adjusted, narrower vertical weighting function (MSU-2LT), which peaks lower in the troposphere but is more sensitive to surface effects. The Spencer–Christy MSU product is constructed to give reliable monthly mean but not synoptic or even daily temperatures. A difficulty in creating a continuous, consistent climate record from satellite observations alone is that satellites and instruments have a finite lifetime of a few years and have to be replaced, and their orbits differ and are not stable. A key point with regard to the

current comparison is that bias corrections resulting from offsets in different MSU instruments on different satellites are removed in quite different ways in the Spencer–Christy product than for NESDIS or ECMWF. While the latter in principle use collocated radiosondes, the continuity of the MSU record is based on intersatellite comparisons.

For the Spencer–Christy product, nine satellites comprise the current operational MSU record, and the methods of merging the data from these different satellites are complex (Christy et al. 1998). Essentially, after removing an annual cycle, biases of measurements from one satellite relative to another are determined as the average difference between temperatures of the MSUs at each latitude during overlap periods, and these biases are removed. A disadvantage of this approach is that any systematic influence on both satellites, such as orbital decay, becomes built into the record. Earlier comparisons of MSU with reanalyzed temperatures (Hurrell and Trenberth 1998) used MSU data version “b,” which has been updated and improved in several ways to give versions “c” (Christy et al. 1998) and “d” (Christy et al. 2000). In particular, version d has been modified to take into account changes in viewing geometry due to decay in the satellite orbits (Wentz and Schabel 1998), which contributed to a spurious cooling in previous MSU-2LT data of roughly $0.1^{\circ}\text{C decade}^{-1}$ but with little impact on MSU-2. In addition, Christy et al. (2000) describe two other sources of error adjusted in version d: variations in the instrument body temperature on each of the satellites (a consequence of orbit drift), and erroneous calibration coefficients for the *NOAA-12* satellite.

In interpreting the comparisons, it should be noted that the reanalyses are not independent of the MSU brightness temperatures. While the radiance data are not incorporated into the analysis system at NCEP, as they are indirectly at ECMWF, the NESDIS temperature satellite retrievals do include MSU data in clear, partly cloudy, and cloudy retrievals. In cloudy regions the retrievals depend entirely on MSU data. However, in ERA-15 there is no dependence on cloudy or partly cloudy data in the Tropics from 30°S to 30°N , and then they are used only below 100 mb. As a result, there is probably a greater influence of MSU data on the NESDIS retrievals and thus the NCEP reanalyses than there is for ERA-15, because the latter come under a larger influence of High-resolution Infrared Radiation Sounder (HIRS) soundings.

Procedures to obtain NESDIS retrievals were changed in September 1988 from a statistical to a physical method by making use of a search through a library of atmospheric radiosonde temperature profiles and associated radiances. The entries with closest observed radiances are averaged to form the initial profiles of temperatures for the inversion process. The final temperature and humidity profile is obtained by minimizing variance. Andersson et al. (1991) and Kelly et

al. (1991) identified large errors and biases in the operational NESDIS retrievals used at NCEP. The retrieval algorithms are very sensitive to the initial atmospheric state used in the schemes and often force the retrieved profiles to contain inaccurate a priori information. Moreover, NCEP temperatures appear to have been adversely affected by a major change in the cloudy algorithms in the NESDIS retrievals over oceans in April 1992 (Basist and Chelliah 1997).

To avoid problems with the NESDIS retrievals, ERA-15 used the model first guess and a radiative model to obtain profiles from the cloud-cleared radiances. Although generally very successful and believed to be responsible for the superior water vapor fields (Engelen et al. 1998), this turns out to be the likely source of the substantial problems in the ERA-15 reanalyses. The 1DVAR bias correction is based on a linear regression of the MSU data against biases near radiosonde stations. Biases are present for many reasons: some related to the instrument and its calibration, some to changes from satellite to satellite and with orbital drift, and some from the radiative transfer model and the assimilating model.

Since the bias correction is a function of the MSU channels, a change in any channel will influence the retrieval at all levels. For instance, an uncompensated cold bias in one channel, such as MSU-3 (which has a peak weighting function about 200 mb) would imply cold temperatures in the upper troposphere, which is also sensed in part by MSU-2 (which peaks near 500 mb). Thus, to reproduce the correct MSU-2 radiance, warmer temperatures would be inferred for the lower troposphere. Similarly MSU-3 overlaps with MSU-4 whose peak weighting function is about 70 mb. This makes the tracing of sources of problems rather difficult.

To retrieve an equivalent channel 2 or 2LT brightness temperature from the reanalyses, simple vertical weighting functions equal to the MSU weighting functions were applied to the reanalysis multilevel temperatures, as given in Hurrell and Trenberth (1998). Santer et al. (1999) showed that equivalent MSU anomalies generated using both global mean weighting functions and a radiative transfer code gave very similar results.

c. Previous results

Hurrell and Trenberth (1998) show that averaged over 20°N – 20°S the NCEP-2LT anomalies are highly correlated with the MSU-2LT (version b) measurements over the 17 yr, 1979–96 ($r = 0.95$), but with some systematic biases. The agreement was better overall with MSU-2 data, but a large stepwise relative difference appeared after mid-1991, with the NCEP analyses much colder than the satellite data, as also found by Basist and Chelliah (1997). A contributing factor is the change in NESDIS retrievals mentioned earlier. The ECMWF data from 1979 to 1993 exhibited poor agreement with both the NCEP and MSU anomalies. The correlation coefficient between monthly ECMWF and MSU-2LT

(NCEP-2LT) anomalies was 0.71 (0.74) over the 15 yr. The largest differences relative to MSU-2LT and MSU-2 temperatures occur after 1987 when the ECMWF data were much warmer.

Fiorino (1999) first identified the nature of some of the apparent problems with the ERA-15 reanalyses. He also noted an apparent low-level warming around late 1986 in the Tropics that was not as evident over land or near island radiosonde observations, suggesting a problem with the satellite data. On tracing the ERA-15 logs and a detailed analysis of the fit of the model first guess to the MSU radiances, Fiorino (1999) found that the warming resulted from a combination of factors: (i) erroneous bias-corrected satellite data were assimilated, altering the analysis and the subsequent first guess; (ii) the 1DVAR retrievals are made relative to the departures from the first guess; and therefore, (iii) a bias could be perpetuated unless compensated through a link to unbiased observations. This is apparently exactly what happened when there was only one satellite present during 1986–87 and a jump occurred in NOAA-9 MSU-3 values in early November 1986.

Other hints of the problems are found in Uppala (1997), in particular in his Fig. 48, which showed the height-time sections of tropical (20°N–20°S) time evolution of temperature bias as given by (i) the first-guess minus radiosonde and (ii) analysis minus radiosonde. Although a change is evident in late 1986, a bigger change is evident in early 1989 after which time the analysis and first guess were warmer by several tenths C for the area mean in the analyses and as much as 1°C for the first guess for the region below 500 mb. From 300 to 500 mb the same region was colder than the radiosondes. Apparently the few tropical radiosondes were not able to bring the bias under control and obtain reliable results.

3. The tropical reanalysis temperatures

a. Time series

Several diagnostic analyses were attempted to determine the nature of the problems in the reanalyses and how they were manifested. Singular value decomposition of the temperature variability in the two reanalyses and the MSU data helped to isolate the problems and suggested a focus on the Tropics. However, the problems are most readily revealed by fairly simple analyses.

Figure 1 shows the standard deviations of the monthly anomalies over the 15 yr, 1979–93 for the 2LT temperatures. These reveal considerably higher variance in the ERA-15 reanalyses over the radiosonde sparse tropical Pacific east of 150°W than either MSU or NCEP temperatures, which are relatively similar. In fact, the ERA-15 variance tends to be higher throughout the Tropics.

We can highlight some problems by focusing on the area-mean temperatures from 20°N to 20°S (Fig. 2). The

correlations reveal the good agreement between the MSU and NCEP 2LT products (0.96) whereas they are only 0.70 (0.74) for ERA-15 with MSU (NCEP). Also, the overall variance is much higher in the ERA-15 (standard deviation 0.34°C) versus MSU and NCEP (both 0.26°C). Root-mean-square differences are 0.25 and 0.23°C of ERA-15 with NCEP and MSU, respectively, but only 0.07°C between NCEP and MSU.

Because of the very different methods of dealing with the multiple satellite radiance information in the NESDIS retrievals and the MSU-2LT series of Christy et al. (2000), these results support the view that the MSU and NCEP temperatures are somewhat close to the truth or at least their biases are similar, while the ERA-15 values are substantially different. Therefore, the differences in the ERA-15 plots in Figs. 1 and 2 may provide direct indications of the problems. Figure 3 shows the difference in the ERA-15 and MSU 2LT temperatures. It highlights several characteristics worth noting. First, there are two distinct discontinuities present, one near the end of 1986 and the other in early 1989. Note also the extra fluctuations in the ERA-15 temperatures, in particular the relatively cold values in late 1979–80 and again in late 1985–86, which are also not present in the NCEP reanalyses. Other fluctuations unique to ERA-15 are evident after 1989.

To isolate the first discontinuity, we matched the records of ERA-15 to MSU for various dividing points in late 1986 to early 1987, and found that the maximum offset occurs between October and November 1986 for the Tropics. This timing coincides with the evidence compiled by Fiorino (1999), who narrows the jump to 2 November 1986 based on a 1.5°C jump to lower values in the global averaged MSU-3 observation-model first-guess statistics (the so-called radgrams).

We similarly identified the second discontinuity as between March and April 1989. Overall the offsets (ERA-15 – MSU) are: 0.163°C in November 1986 and a further 0.302°C in April 1989, so that ERA-15 temperatures after the latter jump average 0.465°C higher than before October 1986. We therefore break the record up into three superperiods: subperiod 1 from January 1979 to October 1986, subperiod 2 from November 1986 to March 1989, and subperiod 3 from April 1989 to December 1993.

These results highlight what appears to be two spurious jumps to warmer temperatures throughout the lower troposphere Tropics in ERA-15. In early November 1986, NESDIS reported several problems, especially with NOAA-9 MSU-3 radiances (believed to be due to a solar flare). This did cause a spike in the analyzed ERA-15 upper-tropospheric temperatures (e.g., at 200 mb) toward colder values but these quickly recovered. However, as discussed in section 2, this can have effects throughout the column and of opposite sign in the lower troposphere. Consequently, the derived correction may not be appropriate. It resulted in a model first-guess warm bias in the lower troposphere that was evidently

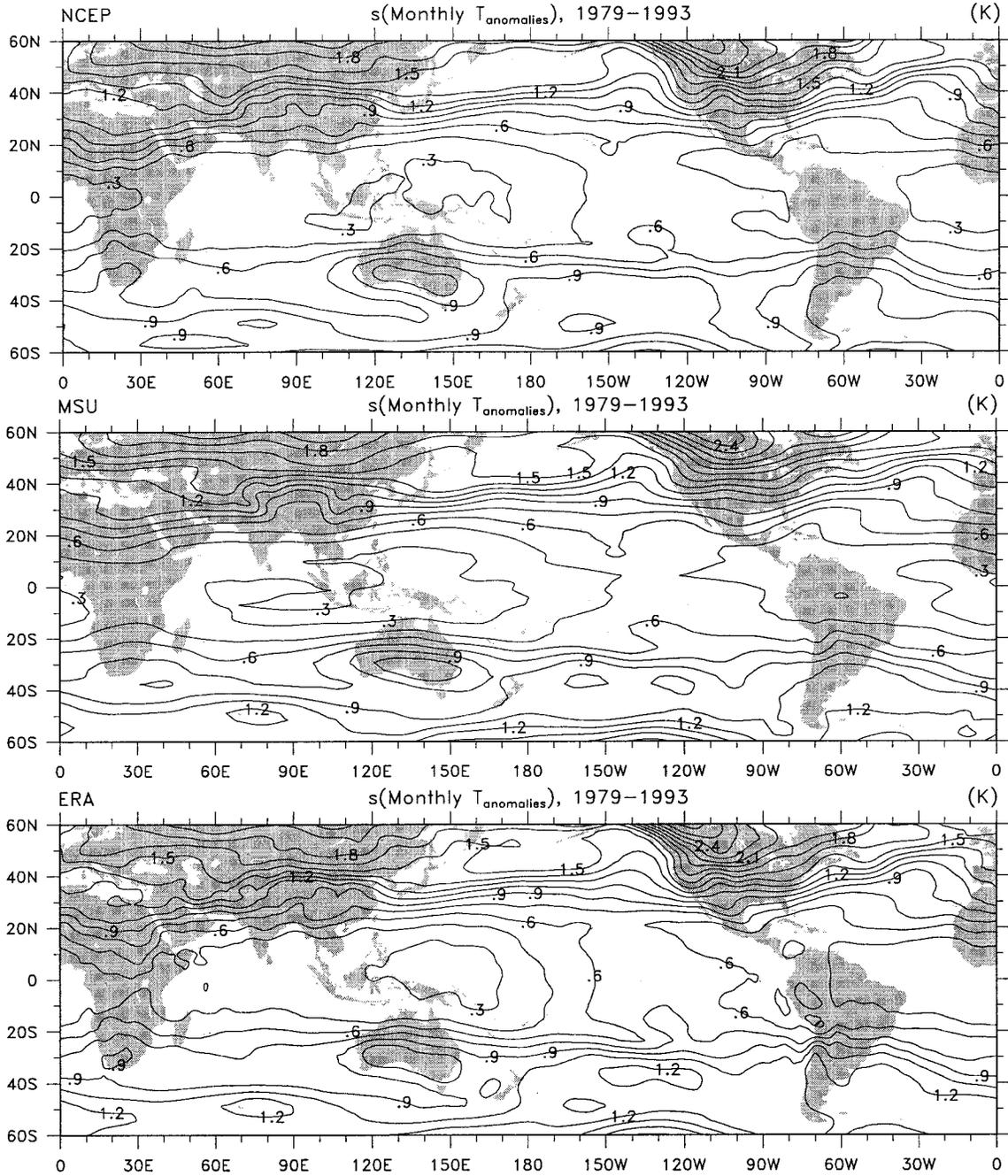


FIG. 1. Standard deviation of the monthly 2LT temperature anomalies from NCEP, MSU, and ECMWF. The plot is from 60°N to 60°S and the contour interval is 0.15°C.

perpetuated and which overwhelmed other influences in the analyses. It appears that the system is more vulnerable to such things whenever there is only one satellite present. This was the case from 1 July 1985 to 1 February 1989 when only *NOAA-9* was used in the re-analyses (Uppala 1997). Note also the spurious cooling in late 1985 during this interval before the blip in November toward warmer values.

The second discontinuity in 1989 occurred shortly after the introduction of *NOAA-11* data to the system, but it did not seem to coincide with the February start time. Instead NESDIS reported some teething problems, and on 5 April 1989 the attenuation coefficients on 4 channels were changed on *NOAA-11* while two *NOAA-10* orbits gave bad data. Whether these events were factors is not known; however, a new bias tuning had

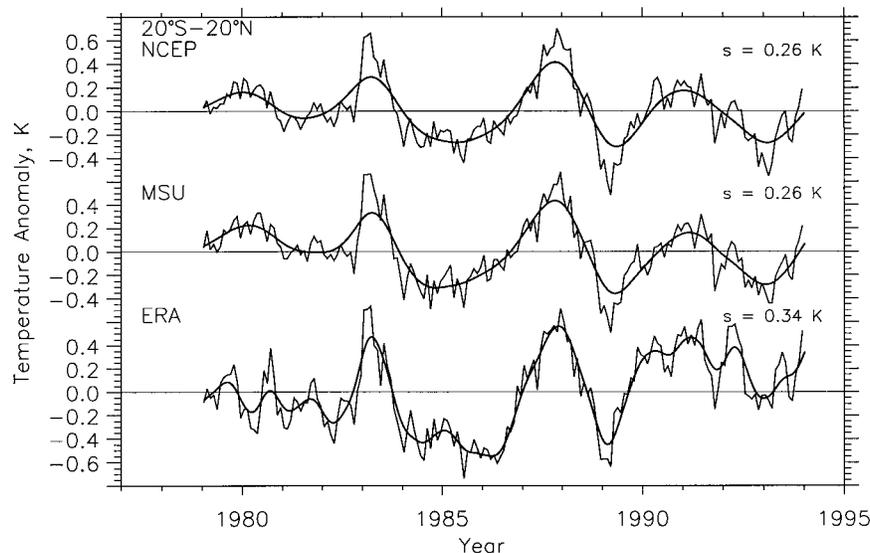


FIG. 2. Time series of the monthly mean tropical (20°N to 20°S) 2LT temperatures from NCEP, MSU, and ERA-15. The standard deviation of each is given in the insets. A low-pass smoothing spline has been fitted to the data to show the decadal variations.

to be implemented in ERA-15 to deal with the new satellite. Moreover, this was a time when the number of radiosondes from 50°W to 160°W , 20°N to 20°S dropped somewhat (Uppala 1997, his Fig. 10). Consequently the opportunity was present for further problems to be perpetuated in regions where inadequate radiosonde data existed.

b. Regional analysis

To further explore how universal the problems were, we separately analyzed each of the four 90° sectors of the Tropics. The same discontinuities were present in all sectors, and the extraneous variability was also common to each sector showing that this was not a local problem. However, by far the largest variance of the temperature from the four sectors (44% of the zonal mean) comes from 180° to 90°W and is mostly associated

with the El Niño–Southern Oscillation phenomenon while the smallest variance (14%) is from the Pacific Warm Pool region from 90°E to 180° .

To explore regionally where these discontinuities were manifested most, we regressed the difference in Fig. 3 with the values at each grid point for the ECMWF 2LT values. The correlation is shown in Fig. 4. If two uncorrelated series with the same variance are differenced and the result is correlated with the original series, then the expected correlation would be 0.72. However, as the two series are positively correlated, the expected correlation with the differenced series should approach zero. Given that the difference time series in Fig. 3 has an ECMWF component, positive correlations are expected, but Fig. 4 reveals that very high correlations (often exceeding 0.8) are present throughout the Tropics. Over Mexico, values are negative, as might be expected where there are adequate radiosonde data. However,

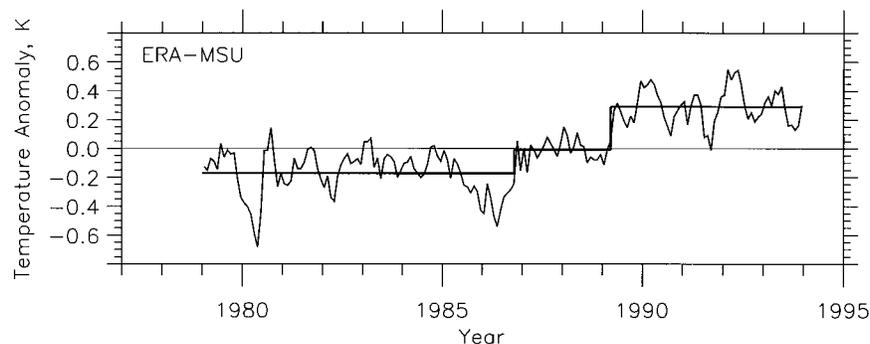


FIG. 3. Difference in time series of the monthly mean tropical (20°N to 20°S) 2LT temperatures from MSU and ERA-15, as ERA–MSU. A straight line fit has been added to the series to show the two discontinuities.

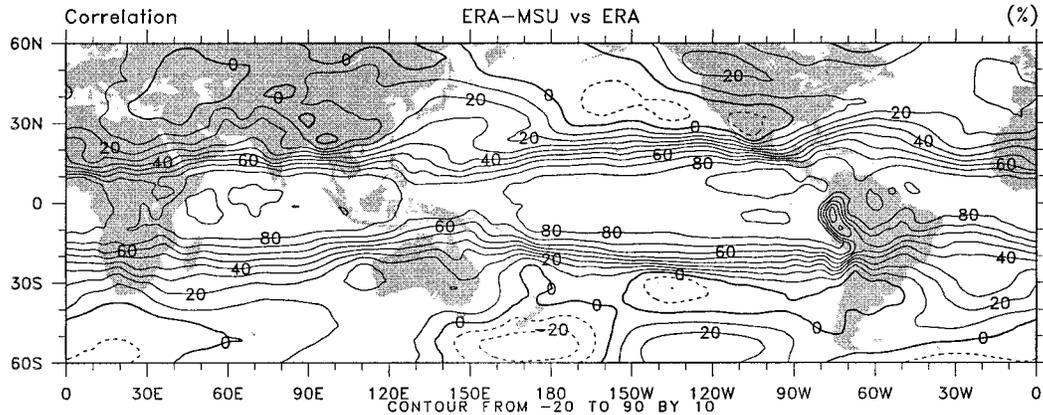


FIG. 4. Correlation of the time series in Fig. 3 with ECMWF 2LT temperatures (%).

large positive values are present even over northern Australia where there should be adequate radiosonde coverage. A factor there may be that Australian radiosondes changed brand (from Phillips to Vaisala) in 1987 and tropospheric temperatures jumped by about 0.4°C to higher values (Hurrell and Trenberth 1998). Because regression coefficients are correlations weighted by the standard deviation (Fig. 1), the tropical Pacific east of 180° is the dominant contributor to the discrepancy in the time series in Fig. 3 in terms of magnitude.

We also correlated the idealized linear fit (the straight lines containing the two discontinuities) shown in Fig. 3 to the regional temperatures, and the patterns were quite similar to those in Fig. 4, although correlations were lower and peaked at 0.6 at 180° on the equator. These results strongly suggest that the discontinuities in Fig. 3 are present throughout the Tropics and that the region was dominated by satellite data, even in some areas where there ought to be adequate radiosonde coverage to control spurious drifts. The northern Andes region stands out in Fig. 4 and was the western Amazonia area discussed by Kållberg (1997) for which a fix was implemented in January 1987.

c. Cross sections

While the analysis has focused on the lower-tropospheric temperatures, we noted earlier how these might arise from biases in the upper troposphere, where some of the problems may have originated. The vertical structure of the subperiods are most clearly shown by latitude–height cross sections of the two later superperiods relative to the first and relative to the NCEP reanalyses.

We computed the two differences (i) November 1986–March 1989 and (ii) April 1989–December 1993 of the temperature anomalies from the mean anomalies for January 1979 to October 1986. We first compared the two subperiods of the ERA-15 reanalyses and, because the subperiods do not fit nicely onto the calendar, the annual cycle was removed and anomalies used. However, these results not only include possible spu-

rious changes but also real changes such as those associated with ENSO variations that are quite apparent in the tropical time series of Fig. 2. The El Niños of 1982–83 and 1986–87 are clearly evident and the latter falls entirely in the second interval, dominating the anomalies found. The weaker El Niño in 1991 continuing throughout 1993 is less apparent, although it may be partially masked by the effects of the Mt. Pinatubo volcanic eruption in June 1991. Therefore, it is difficult to interpret these results directly and they are not presented.

Another way to determine the vertical structure of the discrepancies is to directly compare total temperatures rather than anomalies in the two reanalyses. Therefore, we formed means for each of the three subperiods from ERA-15 and NCEP, and computed their differences. The somewhat surprising result was how similar all three looked, and it was apparent that there are substantial systematic differences between the two reanalyses that continue throughout the 15 yr. Figure 5 presents the meridional cross section of zonal mean total temperature differences for January 1979 to October 1986. All features on this figure are present in all three subperiods to some degree. This bias presumably arises from different analysis procedures, the differences in the assimilating model, and factors such as the extra level at 775 mb included in the ERA-15 reanalyses. Thus the ERA-15 tropical tropopause is systematically colder by over 2°C than NCEP and the higher latitude tropopause (near 300 mb) is also colder in both hemispheres by about 1.5°C . Note that the average ERA-15 analysis minus radiosonde differences in standard-layer mean temperatures vary only between -0.4 and 0.2 K in the tropical troposphere and lower stratosphere (Uppala 1997, Fig. 55) and are a better fit to the radiosonde observations than NCEP, particularly at 100 mb in the Tropics (Pawson and Fiorino 1998). ECMWF reanalyses are warmer throughout in the equatorial lower troposphere but colder at 850 mb at 30°N and 20° to 50°S . This bias is removed from subsequent plots.

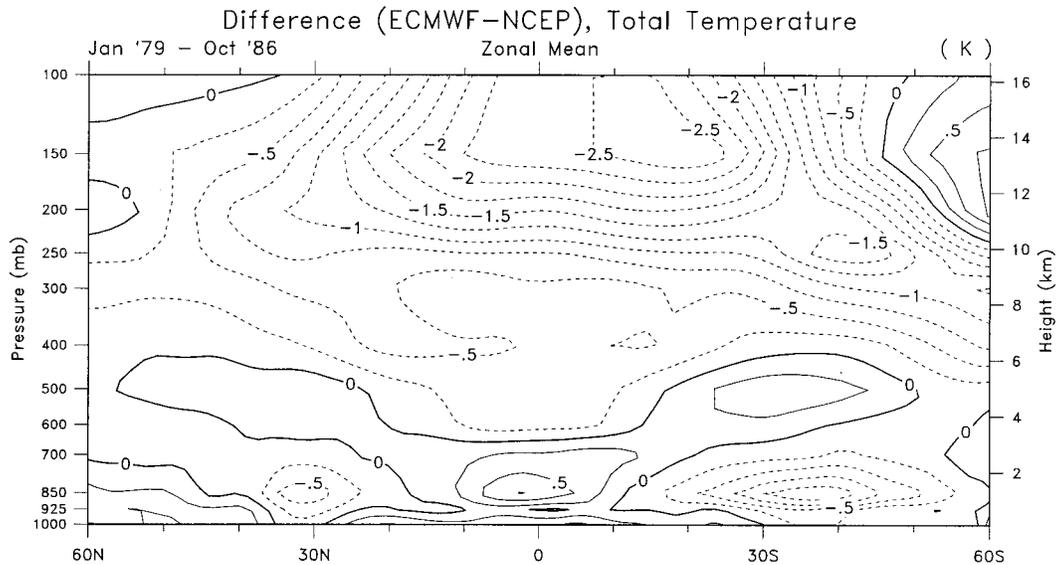


FIG. 5. Differences for Jan 1979 to Oct 1986 of the total temperatures ECMWF–NCEP. The contour interval is 0.25°C .

Figure 6 shows the differences for the last two subperiods of ERA-15 with NCEP reanalyses, but with the bias from subperiod 1 (Fig. 5) removed. For November 1986 to March 1989 (subperiod 2) ERA-15 temperatures are warmer below 500 mb from 50°S to 50°N , with biggest differences near 30°S . Temperatures are slightly lower from 500 to 300 mb in the Tropics and much warmer above 250 mb. From April 1989 to December 1993 (subperiod 3) ERA-15 temperatures are much warmer below 600 mb in the Tropics by over 0.5°C at 850 mb relative to subperiod 2 (not shown) and $>0.6^{\circ}\text{C}$ relative to subperiod 1 (Fig. 6). Colder values exist from 500 and 400 mb, warmer values are centered near 200 mb, and values are again colder by $>0.5^{\circ}\text{C}$ near 100 mb at the tropical tropopause.

The relative warmth in the lower troposphere in these two panels of Fig. 6 is consistent with that shown in Fig. 3 for the 2LT layer, but the figure reveals a complicated vertical structure and, especially for subperiod 2, that the discrepancy is not confined to the Tropics. Further illumination is provided by Fig. 7, which shows a height-time series of the differences for the Tropics (20°N to 20°S). Slight smoothing (1–3–4–3–1)/12 has been performed to make the plot more readable. Again the bias for subperiod 1 has been removed throughout. This figure shows the fluctuating differences prior to October 1986 below 400 mb and reveals the cold ERA-15 fluctuations in early 1980 and from late 1985 into 1986. Much larger discrepancies are evident in the upper troposphere, however.

After October 1986 all of the differences in Fig. 7 in the lower troposphere are positive and especially so after early 1989 (the discontinuity is blurred by the smoothing). This figure reveals an annual cycle to the differences with peak values early in the calendar year close

to 1°C at 850 mb. Synchronous cool patches are present at 400–500 mb and 100–150 mb with the same annual cycle. These differences have some resemblance to those of Uppala (1997) in his Fig. 48, which shows the analysis and first guess minus the radiosonde in the same region for ERA-15. This correspondence suggests that the NCEP reanalyses may be more closely following the low-frequency variability implied by the radiosondes throughout the Tropics.

The existence of an annual cycle to the discrepancies seen in Fig. 7 suggests some subtleties to the nature of the problems. Large annual cycles are present in differences between version c and version d of MSU-2LT after about 1991 (Hurrell et al. 2000) and arise because of corrections for instrument body temperatures on the satellite and erroneous calibration coefficients for NOAA-12 in version c (Christy et al. 2000). Such effects are present in the radiances used in the ERA-15 assimilation and may not have been tuned out.

d. Moisture

Until now we have focused on temperatures. We have found manifestations of these problems in other diagnostics, notably the energy cycle, which will be reported on elsewhere. Here we focus only on one other variable, that of specific humidity. The moisture fields in ERA-15 are influenced strongly by 1DVAR as three HIRS moisture channels are included. NCEP does not use any information from water vapor channels in their assimilation. As the analysis moisture variable is relative humidity, temperature analyses also affect the specific humidity.

Indeed, we find remarkably similar changes in the specific humidity to those in temperature. Figure 8 is

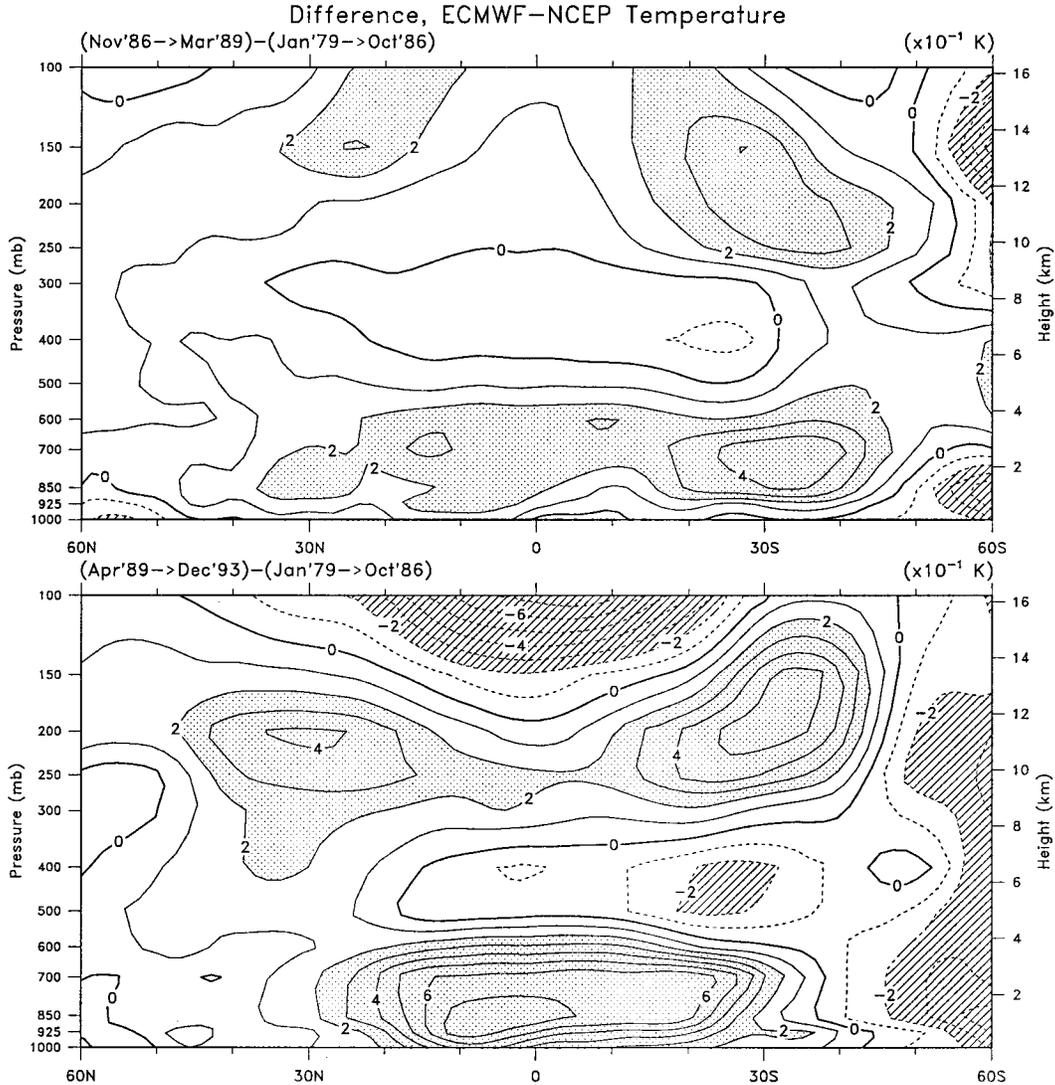


FIG. 6. Differences between ERA-15 and NCEP reanalyses for (i) Nov 1986–Mar 1989 and (ii) Apr 1989–Dec 1993 of the temperatures with the bias for Jan 1979 to Oct 1986 subtracted. The contour interval is 0.2°C . Values greater than 0.2°C are stippled.

the equivalent of Fig. 6 and presents the differences of subperiods two and three with subperiod one for the specific humidity field. Figure 9 shows the time series of the tropical averages of the ERA-15–NCEP specific humidity with the bias for the January 1979 to October 1986 removed, as in Fig. 7. Figures 7 and 9 are remarkably similar below 500 mb. The two discontinuities in October–November 1986 and March–April 1989 are present and several, but not all, of the other variations match up. The cooling (Fig. 7) in early 1980 corresponds to a drying (Fig. 9) but the patterns do not correspond as well in 1984 and 1985. This may be partially because of the problems over western Amazonia and the fix that was implemented there (Källberg (1997)). Therefore the differences in the subperiods (Fig. 8) depict the effects of the discontinuities on the moisture field. For Novem-

ber 1986 to March 1989 (subperiod 2) the moistening was mainly from 0° – 30°S , while it was distributed throughout the Tropics in the third subperiod. The warming and the concomitant moistening no doubt contributed to the spurious shift in the Inter-Tropical Convergence Zone over Africa, and other related changes (Stendel and Arpe 1997).

4. Concluding remarks

In this analysis we have tended to treat the MSU and NCEP reanalyses of temperature as a standard for comparison, principally because they are somewhat independent and yet show close agreement, suggesting that they may be converging toward the truth. However, there is evidence that the changes in NESDIS retrieval

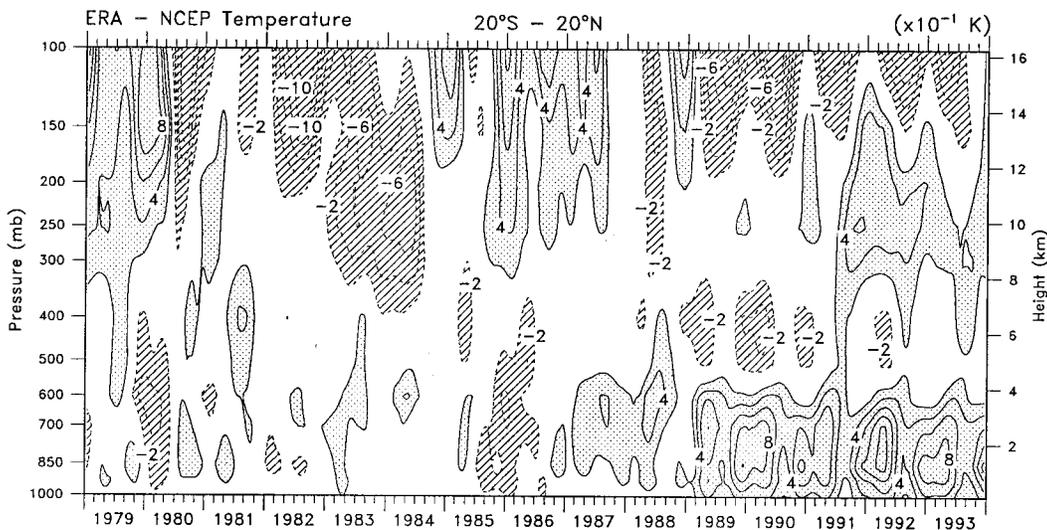


FIG. 7. Tropical (20°N to 20°S) temperature differences between ERA-15 and NCEP (ERA-NCEP) as height-time series, with the subperiod one (Jan 1979–Oct 1986) bias removed. Values have been smoothed with a (1–3–4–3–1)/12 filter. The contour interval is 0.2°C except the zero contour is omitted. Values greater than 0.2°C are stippled and those less than –0.2°C are hatched.

method in 1992 may have caused a spurious cooling of NCEP reanalyses. The myriad of problems with the satellite data also have been confronted and perhaps dealt with by Christy et al. (1998; 2000) in generating the MSU time series, and several recent adjustments have been made, so that it is possible that further biases may still be present, especially associated with how NOAA-9

is treated (Christy et al. 1998). Indeed, Hurrell and Trenberth (1998) concluded that a coincidental cooling was likely present in both NCEP and the earlier version of MSU (version b), and therefore there is no final arbiter of what is the correct answer. Nevertheless, the evidence suggests that problems are present in the ERA-15 reanalyses, and the temperature evidence is bolstered by

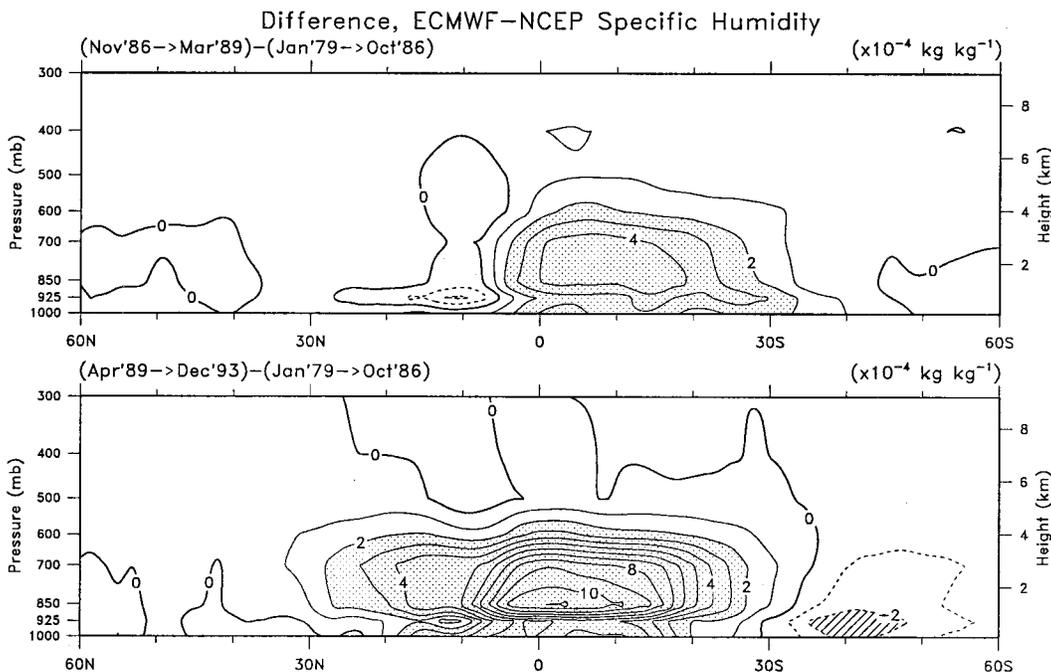


FIG. 8. Differences between ERA-15 and NCEP reanalyses for (i) Nov 1986–Mar 1989 and (ii) Apr 1989–Dec 1993 of the specific humidity with the bias for Jan 1979–Oct 1986 subtracted. The contour interval is $1 \times 10^{-4} \text{ kg kg}^{-1}$. Values greater than 2×10^{-4} are stippled.

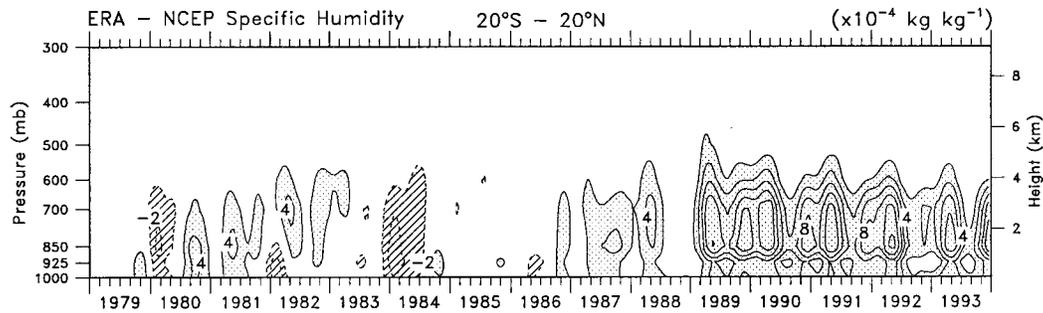


FIG. 9. Tropical (20°N – 20°S) specific humidity differences between ERA-15 and NCEP (ERA–NCEP) as height–time series, with the subperiod one bias removed. Values have been smoothed with a (1–3–4–3–1)/12 filter. The contour interval is 2×10^{-4} except the zero contour is omitted. Values greater than 2 units are stippled and those less than -2 are hatched.

the evidence from the changes in the hydrological cycle documented by Stendel and Arpe (1997).

However, while the two offsets to warmer and moister values in the lower-tropospheric temperatures are the biggest features of note, they are not the only sources of discrepancy as removing them does not bring the ERA-15 reanalyses into agreement with the MSU or NCEP. These results emphasize that there is also evidently spurious variability in ERA-15. These problems apparently arise from changes in satellites and the need to adjust bias corrections as well as miscellaneous other contaminations, such as from inadequate cloud clearing. The latter has been reported by NESDIS at times and seems to be a factor in the cool feature in late 1979 to early 1980, for instance.

Generally, the challenge in dealing with satellite data includes the need to

- 1) resolve offsets between MSU radiances from different satellites;
- 2) identify and remove erroneous drifts and jumps over the lifetime of a satellite;
- 3) account for the fact that MSU-2 has a component sensitive to surface emissions and changes in surface emissivity, as well as precipitation.

The ERA-15 assimilation system has a positive feedback link through the first guess from the previous analysis, so if any of these multiple problems get by the checks and balances then they are apt to be perpetuated, as has been warned by Thompson and Tripputi (1994). The in situ radiosonde observations are inadequate in the Tropics and the assimilating model is not able to correct the biases in the implementation in ERA-15.

The fundamental problem exposed here is the effects of changes in the observing system on the reanalyses and thus on the climate record. Although we have highlighted the satellite radiances as the most likely source of problems in the Tropics, other changes occurred in radiosonde types and amounts during the period of interest. Use of the assimilating model first guess as the basis for satellite moisture and temperature retrievals combined with an erroneous bias correction, can and

evidently has perpetuated errors in ERA-15 in the absence of adequate unbiased (e.g., radiosonde) observations. Spurious fluctuations in tropospheric temperatures and moisture on several timescales are present throughout the ERA-15 reanalyses in the Tropics in addition to major discontinuities in late 1986 and early 1989. These features are not present in either the MSU satellite observations or the NCEP reanalyses of temperatures that agree quite well with each other. Accordingly, the two reanalyses exhibit very different and probably false trends, as they are only as good as the input data base. These kinds of problems are likely to be even more acute before 1979 (e.g., Santer et al. 1999). In particular, caution is advised when using the ERA-15 results for studies of low-frequency tropical variability and change.

Acknowledgments. This research was sponsored by NOAA Office of Global Programs Grant NA56GP0247 and the joint NOAA/NASA Grant NA87GP0105. Many thanks to Adrian Simmons and colleagues at ECMWF and J. Eyre for comments.

REFERENCES

- Andersson, E., A. Hollingsworth, G. Kelly, P. Lönnberg, J. Pailleux, and Z. Zhang, 1991: Global observing system experiments on operational statistical retrievals of satellite sounding data. *Mon. Wea. Rev.*, **119**, 1851–1864.
- Annamalai, H., J. M. Slingo, K. R. Sperber, and K. Hodges, 1999: The mean evolution and variability of the Asian summer monsoon: Comparison of ECMWF and NCEP–NCAR reanalyses. *Mon. Wea. Rev.*, **127**, 1157–1186.
- Basist, A. N., and M. Chelliah, 1997: Comparison of tropospheric temperatures derived from the NCEP/NCAR reanalysis, NCEP operational analysis and the Microwave Sounding Unit. *Bull. Amer. Meteor. Soc.*, **78**, 1431–1447.
- Christy, J. R., R. W. Spencer, and E. Lobl, 1998: Analysis of the merging procedure for the MSU daily temperature time series. *J. Climate*, **11**, 2016–2041.
- , —, and W. D. Braswell, 2000: MSU tropospheric temperatures: Dataset construction and radiosonde comparisons. *J. Atmos. Oceanic Technol.*, **17**, 1153–1170.
- Engelen, R. J., I. L. Wittmeyer, and G. L. Stephens, 1998: Assessment of reanalysis hydrology and energy budgets: Water vapour and

- radiative fluxes. *Proc. First Int. WCRP Conf. on Reanalysis*, Silver Springs, MD, WCRP-104, WMO/TD-876, 175–178.
- Eyre, J. R., G. A. Kelly, A. P. McNally, E. Andersson, and A. Persson, 1993: Assimilation of TOVS radiance information through one-dimensional variational analysis. *Quart. J. Roy. Meteor. Soc.*, **119**, 1427–1463.
- Fiorino, M., 1999: The impact of the satellite observing system on low-frequency temperature variability in the ECMWF and NCEP reanalyses. *Proc. Second Int. Conf. on Reanalysis*, Reading, United Kingdom, World Climate Research Programme, 23–27.
- Gibson, J. K., P. Kållberg, S. Uppala, A. Hernandez, A. Nomura, and E. Serrano, 1997: ERA description. ECMWF Reanalysis Project Rep. 1, 72 pp.
- Hurrell, J. W., and K. E. Trenberth, 1998: Difficulties in obtaining reliable temperature trends: Reconciling the surface and satellite MSU 2R trends. *J. Climate*, **11**, 945–967.
- , S. J. Brown, K. E. Trenberth, and J. R. Christy, 2000: Comparison of tropospheric temperatures from radiosondes and satellites: 1979–1998. *Bull. Amer. Meteor. Soc.*, **81**, 2165–2177.
- Kållberg, P., 1997: Aspects of the reanalysed climate. ECMWF Reanalysis Project Rep. 2, 89 pp.
- Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.*, **77**, 437–471.
- Kelly, G., E. Andersson, A. Hollingsworth, P. Lönnberg, J. Pailleux, and Z. Zhang, 1991: Quality control of operational physical retrievals of satellite sounding data. *Mon. Wea. Rev.*, **119**, 1866–1880.
- Newman, M., P. D. Sardeshmukh, and J. W. Bergman, 2000: An assessment of the NCEP, NASA, and ECMWF reanalyses over the tropical west Pacific Warm Pool. *Bull. Amer. Meteor. Soc.*, **81**, 41–48.
- Pawson, S., and M. Fiorino, 1998: A comparison of reanalyses in the tropical stratosphere. Part 1: Thermal structure and the annual cycle. *Climate Dyn.*, **14**, 631–644.
- Santer, B. D., J. J. Hnilo, T. M. L. Wigley, J. S. Boyle, C. Doutriaux, M. Fiorino, D. E. Parker, and K. E. Taylor, 1999: Uncertainties in observationally based estimates of temperature change in the free atmosphere. *J. Geophys. Res.*, **104**, 6305–6333.
- Spencer, R. W., and J. R. Christy, 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.
- Stendel, M., and K. Arpe, 1997: Evaluation of the hydrological cycle in reanalyses and observations. Max-Planck-Institut für Meteorologie Rep. 228, 52 pp. [Available from Max-Planck-Institut für Meteorologie, Bundesstrasse 55, 20147 Hamburg, Germany.]
- Thompson, O. E., and M. T. Tripputi, 1994: NWP-initialized satellite temperature retrievals using statistical regularization and singular value decomposition methods. *Mon. Wea. Rev.*, **122**, 897–926.
- Trenberth, K. E., and J. G. Olson, 1988: An evaluation and intercomparison of global analyses from NMC and ECMWF. *Bull. Amer. Meteor. Soc.*, **69**, 1047–1057.
- , and C. J. Guillemot, 1998: Evaluation of the atmospheric moisture and hydrological cycle in the NCEP/NCAR reanalyses. *Climate Dyn.*, **14**, 213–231.
- Uppala, S., 1997: Observing system performance in ERA. ECMWF Reanalysis Project Rep. 3, 261 pp.
- Wentz, F. J., and M. Schabel, 1998: Effects of satellite orbital decay on MSU lower tropospheric temperature trends. *Nature*, **394**, 661–664.