Analysis of moisture variability in the European Centre for Medium-Range Weather Forecasts 15-year reanalysis over the tropical oceans

Richard P. Allan and A. Slingo[1]
Hadley Centre, Met Office, Bracknell, UK

V. Ramaswamy
Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey, USA

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[1] We compare European Centre for Medium-Range Weather Forecasts 15-year reanalysis (ERA-15) moisture over the tropical oceans with satellite observations and the U.S. National Centers for Environmental Prediction (NCEP) National Center for Atmospheric Research 40-year reanalysis. When systematic differences in moisture between the observational and reanalysis data sets are removed, the NCEP data show excellent agreement with the observations while the ERA-15 variability exhibits remarkable differences. By forcing agreement between ERA-15 column water vapor and the observations, where available, by scaling the entire moisture column accordingly, the height-dependent moisture variability remains unchanged for all but the 550–850 hPa layer, where the moisture variability reduces significantly. Thus the excess variation of column moisture in ERA-15 appears to originate in this layer. The moisture variability provided by ERA-15 is not deemed of sufficient quality for use in the validation of climate models. *INDEX TERMS:* 1655 Global Change: Water cycles (1836); 1610 Global Change: Atmosphere (0315, 0325); 1836 Hydrology: Hydrologic budget (1655); 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); *KEYWORDS:* water vapor, reanalyses, interannual variability

1. Introduction

[2] Because water vapor is the most significant greenhouse gas and it exhibits a strong theoretical dependence on temperature via the Clausius Clapeyron equation, its potential importance in providing a strong, positive feedback to global warming is well recognized [e.g., *Houghton et al.*, 1990]. Indeed, column-integrated water vapor (CWV) measured by satellites over the ocean is observed to increase with surface temperature over an interannual timescale [*Wentz and Schabel*, 2000], and its tropical variability is well captured by climate model simulations when forced by observed sea surface temperatures [*Soden*, 2000].

[3] While oceanic moisture in the tropical boundary layer, which strongly determines the CWV, is strongly coupled to surface temperature, the dependence of atmospheric moisture in the free troposphere on the surface temperature is not well understood [e.g., *Lindzen*, 1990]. Further, it is unclear whether climate models adequately account for processes that determine the distribution of upper tropospheric water vapor and its variability. There has been limited observational evidence suggesting that climate models overestimate correlations between atmospheric moisture and the temperature [*Sun and Held*, 1996] although it is not yet clear whether some of this discrepancy may be an artifact of inconsistent spatiotemporal sampling.

[4] The paucity of atmospheric moisture measurements therefore limit our ability to evaluate climate models and improve our depiction of the hydrological cycle. Such limitations may potentially be overcome by using reanalyses which constitute a model continually forced by an array of conventional and satellite observations via a self consistent assimilation system. For example, *Slingo et al.* [2000] used the 15-year reanalysis from the European Centre for Medium-Range Weather Forecasts (ERA-15; *Gibson* [1997]) to evaluate the depiction of water vapor feedback in versions of the Hadley Centre climate model, HadAM3 [*Pope et al.*, 2000]. Use of ERA-15 data and output from the U.S. National Centers for Environmental Prediction–National Center for Atmospheric Research 40-year reanalysis (NCEP; *Kalnay et al.* [1996]) were further used to assess the vertical correlations of water vapor with the near surface values in the tropics [*Sun et al.*, 2001].

[5] While reanalyses provide global output throughout the troposphere, the changing density and quality of observations may potentially introduce artificial variability into the simulated climate [e.g., *Kållberg*, 1998]. Thus, before such products can be utilized in the evaluation of climate models, they must themselves be thoroughly checked against the available observational record. In the present study we concentrate on the CWV variability depicted by

[1] Now at Environmental Systems Science Centre, University of Reading, Reading, UK.

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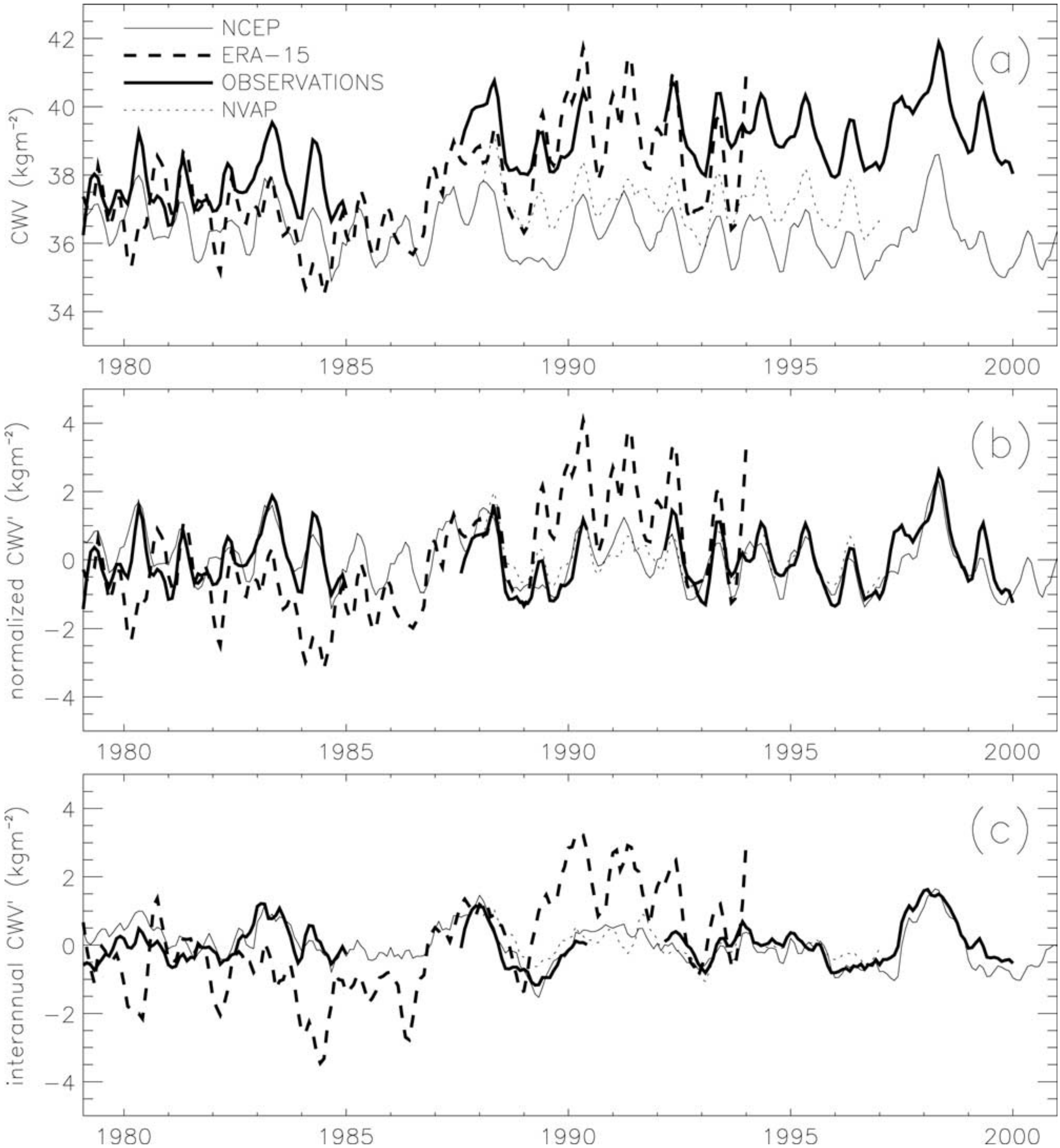

Figure 1. (a) Time series from 1979 through 1999 of monthly mean column water vapor (kg m^{-2}) over the tropical oceans (30°S to 30°N) for satellite observations, ERA, NCEP and NVAP. The same time series are shown normalized by (b) removing the mean value and (c) removing the mean seasonal cycle from each data set. A three-month running mean was applied.

the ERA-15 and NCEP reanalyses and observations from the Scanning Multichannel Microwave Radiometer (SMMR; *Wentz and Francis* [1992]), the Special Sensor Microwave Imager (SSM/I; *Colton and Poe* [1999]), and the NASA Water Vapor Project Data Set (NVAP; *Randel* [1996]) which combines a blend of conventional radiosonde measurements with satellite data (including SSM/I). In agreement with the recent analysis from *Trenberth et al.* [2001] we find that the moisture variability displayed by ERA-15 appears to be of insufficient quality for use in the evaluation of interannual variability in climate models.

2. Results

[6] We initially compare the variability of column-integrated water vapor with the available observations. Figure 1a

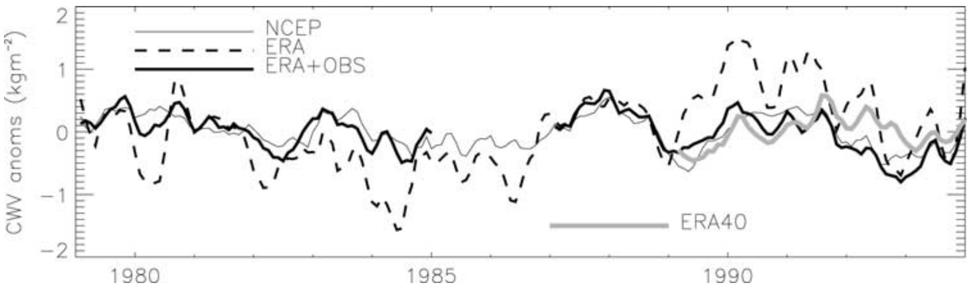

Figure 2. Anomalies of global-mean column water vapor (kg m^{-2}) with the mean seasonal cycle removed for ERA constrained by SMMR and NVAP observations over the tropical oceans (ERA + OBS) and for the ERA and NCEP reanalyses. For comparison, corresponding values from the new 40-year ECMWF reanalysis (ERA40) are plotted from 1989 to 1993. A three-month running mean was applied to all time series.

shows the monthly mean time series of column water vapor for ERA-15, NCEP, NVAP and the satellite observations over the tropical oceans from 30°S to 30°N. The observations constitute SMMR data for 1979–1984 and SSM/I data from 1987 to 1999 (SSM/I data between 1990 and 1992 were discarded due to instrument unreliability). These data are presented normalized with respect to the mean CWV for each data set in Figure 1b while the mean seasonal cycle from each data set is removed in Figure 1c to emphasize the interannual monthly anomalies. A three-month running mean is applied to these data to improve clarity of the figure. Removing this high frequency variability does not affect the conclusions of the study.

[7] While SSM/I data were used in the NVAP data set, there is a difference of about 2 kg m^{-2} between these products. Given that mean NVAP values are in reasonable agreement with SMMR, it is possible that SSM/I retrievals exhibit a moist bias (an alternative version of the SSM/I data from *Wentz* [1997] does not display a significant moist bias). Nevertheless, the observed seasonal variability is consistent with column water vapor maxima generally during April. The NCEP reanalysis generally contains less CWV than the observations for the entire period. However, when the systematic difference between each data set is removed there is excellent agreement for the seasonal variability between the observations and NCEP (Figure 1b). Further, NCEP reproduces the observed interannual monthly anomalies, displayed in Figure 1c, which are dominated by the El Niño Southern Oscillation (ENSO) with peaks coinciding with the warm events of 1982/1983, 1987/1988 and 1997/1998.

[8] The variability of ERA-15 column water vapor is clearly greater than the observational record, including a systematic increase in moisture from 1986 to 1990. This is particularly evident in Figures 1b and 1c. While ERA appears to simulate the decrease in column water vapor following the 1986/1987 warm event, the remainder of the comparison period shows little similarity. Some of this difference is related to an apparent change in the seasonal cycle of ERA column water vapor from 1988 which is aliased in the interannual anomalies. This may be related to the spurious shift in the African ITCZ during 1987 [*Stendel and Arpe*, 1999]. The disagreement between ERA and observations raises questions as to the validity of using ERA for analyzing interannual moisture fluctuations and water vapor feedback. This conclusion is backed up by evidence from previous studies [*Stendel and Arpe*, 1999; *Trenberth et al.*, 2001].

[9] To understand how the errors in ERA-15 CWV affect the height-dependent variability and therefore impact previous studies that use such information [e.g., *Allan et al.*, 1999; *Sun et al.*, 2001], a separate analysis of ERA column water vapor (ERA + OBS) was produced that forces agreement with the observations. It was decided to employ the NVAP data rather than the SSM/I-only data because of the discrepancy between annual mean SSM/I and SMMR values. The observations were regridded to the ERA grid and at each grid point the ratio between monthly mean observed and ERA column water vapor was calculated. The specific humidity at each vertical level was subsequently scaled by this ratio such that the grid point column water vapor in ERA agreed with observed values. This ratio was applied at each level apart from the uppermost four levels where specific humidity was fixed in ERA. The adjusted ERA data (ERA + OBS) contain all the original height-dependent specific humidity information but are adjusted such that interannual CWV variability at each grid point is in agreement with observations over the tropical oceans.

[10] Rather than attempting to correct the ERA data for use in model evaluation, this method merely constitutes an experimental strategy, in the absence of data, that seeks to identify diagnostically where the errors may be manifest in the atmospheric column. This constraint was only applied over the tropical oceans (30°S to 30°N) and for the period 1979–1984 and 1988–1993 because of the availability of observational data and also because the errors in moisture variability are thought to be dominated by the tropical oceans [*Stendel and Arpe*, 1999]. Here rather than being interested in producing a corrected ERA product we are instead interested in comparison with the original ERA data such that information may be extracted on where in the atmospheric column the errors are manifest.

[11] The ERA + OBS global column water vapor interannual anomalies show reasonable agreement with the corresponding NCEP values (Figure 2). For comparison, data from the new 40-year ECMWF reanalysis [e.g., *Chevallier et al.*, 2001] are also plotted for the 1989–1993 period. Much of the differences between ERA and NCEP global CWV variability are removed from ERA when the moisture column is scaled to agree with observations over

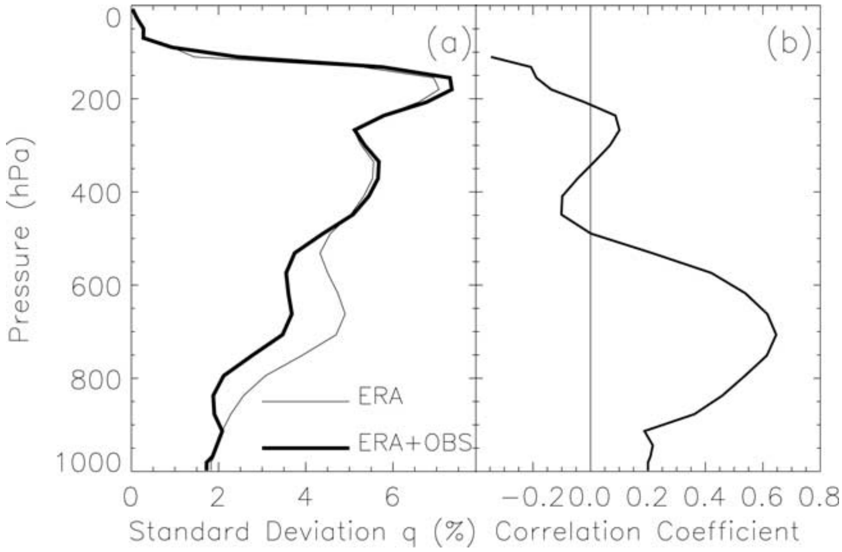

Figure 3. (a) Standard deviation of the height-dependent interannual specific humidity (percent) for ERA and ERA + OBS (ERA constrained by observed column water vapor over the tropical oceans). (b) Vertical correlation of monthly global-mean specific humidity from ERA and the ratio of ERA to ERA + OBS global-mean specific humidity.

the oceans. The regression between global-mean CWV anomalies and surface temperature for ERA + OBS yields a value of 1.5 kg m^{-2} K^{-1}, much less than the ERA correlation of 2.4 kg m^{-2} K^{-1} and in line with the regression for the Hadley Centre climate model [*Slingo et al.*, 2000]. Regionally, the main differences between ERA and observed column moisture are in the dry subtropics after 1988 where ERA overestimates and in the convective regions before 1988 where ERA underestimates. The standard deviation of the time series of differences between ERA and observed CWV are most prominent in the East Pacific and are more pronounced in January than July.

[12] The standard deviation of global-mean interannual monthly anomalies of specific humidity in ERA-15 and ERA + OBS are plotted as a function of vertical pressure level in Figure 3a. There is a significant reduction in the standard deviation, and hence the variability of moisture, in the 550–850 hPa layer when specific humidity is uniformly scaled throughout the troposphere to force agreement of ERA CWV with available observations over the ocean (from ERA to ERA + OBS). Considering Figures 2 and 3, this indicates that the excess variability of ERA CWV compared to the observations and the NCEP data is manifest in the lower troposphere above the boundary layer. Despite the identical scaling factors applied at each vertical level for the ERA tropospheric specific humidity for a given grid point, there is not a significant difference between the humidity standard deviation in ERA and ERA + OBS at other levels. This indicates that the variability away from the 550–850 hPa layer is uncorrelated with the different CWV fluctuations in ERA compared to the observations. Indeed, correlations between the unadjusted ERA specific humidity global-mean time series and the effective scaling factor, calculated here as the ratio between ERA and ERA + OBS global mean specific humidity, are strongest between 550 and 850 hPa (Figure 3b). Therefore it appears that the moisture variation away from this layer is not affected by the factors that caused the CWV variability in ERA to differ from NCEP and observed values. However, it remains unclear as to the accuracy of moisture changes at these other levels.

3. Conclusions

[13] The global-mean column-integrated water vapor in ERA displays a significantly greater temporal variability compared to the NCEP reanalysis. The differences are evident when compared with NCEP values and satellite observations over the tropical oceans. An experimental technique is implemented, using these observations, that provides a diagnostic check on the ERA variations in moisture profiles. Anomalously large humidity variation around 700 hPa in ERA is substantially reduced when humidities are constrained by the SMMR/NVAP observations, suggesting an overestimation in ERA humidity variability in the lower troposphere. While the experimental technique serves the purpose of demonstrating the potential source of the excess variability in the ERA column water vapor data and is used in the absence of robust height-dependent observations, the resulting inference is not to be taken as necessarily pointing to a means of rectifying the ERA-15 height profile of water vapor variability. High temperature variability at about 850 hPa in ERA is also manifest in tropical ocean regions and appears to be correlated with the moisture anomalies at 700 hPa. The causes of this anomalous variability are explained by *Trenberth et al.* [2001] in terms of the assimilation of erroneous satellite data. Using the modified ERA humidity data reduces the sensitivity of global-mean column water vapor to surface temperature from 2.4 kg m^{-2} K^{-1} to 1.5 kg m^{-2} K^{-1} which is in reasonable agreement with the Hadley Centre climate model [*Slingo et al.*, 2000] and further suggests that the strong dependence of ERA specific

humidity on surface temperature in the lower troposphere shown by Slingo et al. is an overestimate.

[14] Humidity variability in the upper troposphere in ERA is insensitive to the introduction of modified humidities, despite identical scaling factors being applied at each model level in the troposphere, suggesting that ERA upper tropospheric humidity variability is unaffected by the mechanisms involved in explaining the spurious interannual trends seen in the lower troposphere. However, the quality of ERA upper tropospheric humidity is at present unknown. While ERA cannot provide reliable information on the height-dependent variability of temperature and moisture, were the assimilation of erroneous observational quantities to be removed in the new 40-year ECMWF reanalysis, these data may be of sufficient quality to provide reliable information on the height-dependent temperature and moisture variability. Indeed, preliminary assessment of these data, shown as a time series from 1979 to 1993 of monthly interannual anomalies in Figure 2, does indicate significant improvment over ERA-15. However, the variability of moisture in ERA-15 is deemed of insufficient quality for use the evaluation of seasonal and interannual variability in climate models.

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R. P. Allan, Hadley Centre, Met Office, London Road, Bracknell, Berkshire, RG12 2SY, UK. (richard.allan@metoffice.com)

A. Slingo, Environmental Systems Science Centre, University of Reading, Harry Pitt Building, 3 Earley Gate, Whiteknights, Reading RG6 6AL, UK. (as@mail.nerc-essc.ac.uk)

V. Ramaswamy, Geophysical Fluid Dynamics Laboratory, P.O. Box 308, Forrestal Campus, Route 1, Princeton, NJ 08452, USA. (vr@gfdl.gov)