

Report on estimates of observational uncertainty in surface humidity and free-atmosphere temperature and humidity data

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Key outcomes/non technical summary

- **From a combined analysis of satellite, radiosonde, and surface humidity data we cannot reject the hypothesis that global and northern hemisphere mean relative humidity has remained constant, in other words specific humidity has increased in response to surface warming close to the rate predicted by Clausius-Clapeyron.**
- **Discrepancies between different humidity and surface temperature data sets over the global oceans, coupled with a short period of satellite observations results in a range of estimate for trends in relative humidity 1987-2004 from -0.7%/decade to +0.5%/decade.**
- **Over northern hemisphere land both synoptic surface data and radiosondes suggest little or no change in relative humidity since 1973.**
- **We have shown that following homogenisation the radiosonde record across the northern hemisphere is of sufficient quality for the analysis of inter-annual variability and trends.**

Associated publications

None at this time

Press interest

None at this time

Report on estimates of observational uncertainty in surface humidity and free-atmosphere temperature and humidity data

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Summary

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- **Discrepancies between different humidity and surface temperature data sets over the global oceans, coupled with a short period of satellite observations results in a range of estimate for trends in relative humidity 1987-2004 from -0.7%/decade to +0.5%/decade.**
- **Over northern hemisphere land both synoptic surface data and radiosondes suggest little or no change in relative humidity since 1973.**
- **We have shown that following homogenisation the radiosonde record across the northern hemisphere is of sufficient quality for the analysis of inter-annual variability and trends.**

1) Introduction

The importance of water vapour in the atmosphere cannot be overstated. Water vapour through latent heat exchanges is the principal method of energy transport through the global atmosphere and is a dominant greenhouse gas (e.g. Held and Soden, 2000). Therefore it is critical to fully understand how water vapour changes as concentrations of other greenhouse gases increase, and the accurate representation of water in all its forms is vital if we are to have faith in predictions of future climate change.

If relative humidity remains constant under climate change, as predicted by climate models (IPCC, 2001), then the net climate feedback is insensitive to the magnitude of the temperature lapse rate and water vapour feedbacks (Allan et al. 2002, Colman 2003). However most of the troposphere is highly under-saturated, so that there is scope for water vapour feedbacks either stronger or weaker than predicted by constant relative humidity. At the surface societal and environmental considerations also require accurate knowledge of past changes in near-surface relative and specific humidity.

In this report we diagnose uncertainty in estimates of observed trends in specific and relative humidity from a number of observation platforms sensitive to water vapour variations at the surface and in the free troposphere. Relative humidity represents the ratio of vapour pressure to saturation vapour pressure, and is therefore a measure of how far from saturation air is. Fractional change in relative humidity can be related to changes in

vapour pressure (dewpoint) and saturation vapour pressure (temperature) through equation 1 below.

$$\frac{\partial RH}{RH} = \frac{\partial e(T_d, p)}{e(T_d, p)} - \frac{\partial e_s(T, p)}{e_s(T, p)} \quad (1)$$

RH represents relative humidity, $e(T_d, p)$ is vapour pressure as a function of dewpoint temperature and pressure, and $e_s(T, p)$ is the saturation vapour pressure as a function of temperature and pressure. Uncertainty in relative humidity therefore can be determined from the root of the sum of squared error in vapour pressure and saturated vapour pressure. The dependence upon air pressure is very weak, so we can make the reasonable assumption that surface air pressure is constant in our analysis of vapour pressure (Buck 1980). We also assume that the scale height of water vapour is constant (Stephens, 1990), meaning that we can use changes in total column water vapour as a proxy for changes at the surface. These assumptions mean we can make approximations to specific humidity (q) and total column water vapour (w) as follows:

$$\frac{\partial e(T_d, p)}{e(T_d, p)} \approx \frac{\partial q}{q} \approx \frac{\partial w}{w} \quad (2)$$

A combination of satellite, surface, and radiosonde observations are used in this report, monitoring different parts of the atmosphere, with different sampling and data availability. For this reason, observations over ocean and land are presented separately and the analysed units, and reference periods for trends and climatologies change through the report. Where they are presented, trends and their confidence limits have been calculated using the method of median of pairwise slopes (Lanzante 1996)

2) Surface and Lower Troposphere – Oceans

2.1 – Data

Total Column Water Vapour

The Special Sensor Microwave Imager (SSM/I) has flown on the US Defense Meteorological Satellite Program (DMSP) since July 1987. The SSM/I is a passive microwave radiometer that measures microwave emission from the surface and atmosphere at four frequencies with an Earth footprint of approximately 56km. Brightness temperatures at these frequencies are sensitive to, amongst other things, total column water vapour (TCWV), near-surface wind-speed, cloud liquid water, and precipitation. The microwave emission is also dependent upon surface type. In order to reduce the complexity of the retrieval they are limited to ocean scenes only, that are free of sea-ice and free from heavy precipitation.

A variety of statistical and physical algorithms to retrieve TCWV are available, and their discrepancies are discussed in detail in Sohn and Smith (2003). In this report we use a dataset generated by Remote Sensing Systems (RSS, Wentz, 1997) whose retrieval method was selected as an optimal performer by Sohn and Smith (2003).

Near-surface humidity – HadCRUH marine

Hourly observations of dry-bulb, wet-bulb, and dewpoint temperatures from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) supplemented with marine data from the Global Telecommunications System (GTS) archived at the National Center for Environmental Prediction (NCEP) have been converted to instantaneous measurements of vapour pressure, specific and relative humidity at locations across the global oceans (Worley et al., 2005). For most of the record the data are from ships and small number of marine platforms, and typical annual coverage is presented in Fig. 1. For the most recent years (since 2000) the contribution of observations from buoys has increased.

The individual reports are quality controlled, checking not only the physical consistency of the observations, but also rejecting outliers with reference to local climatology and neighbour checks. The data are then aggregated into monthly means on a 5° latitude-longitude grid. These data will be referred to as SFC (q) and SFC (RH).

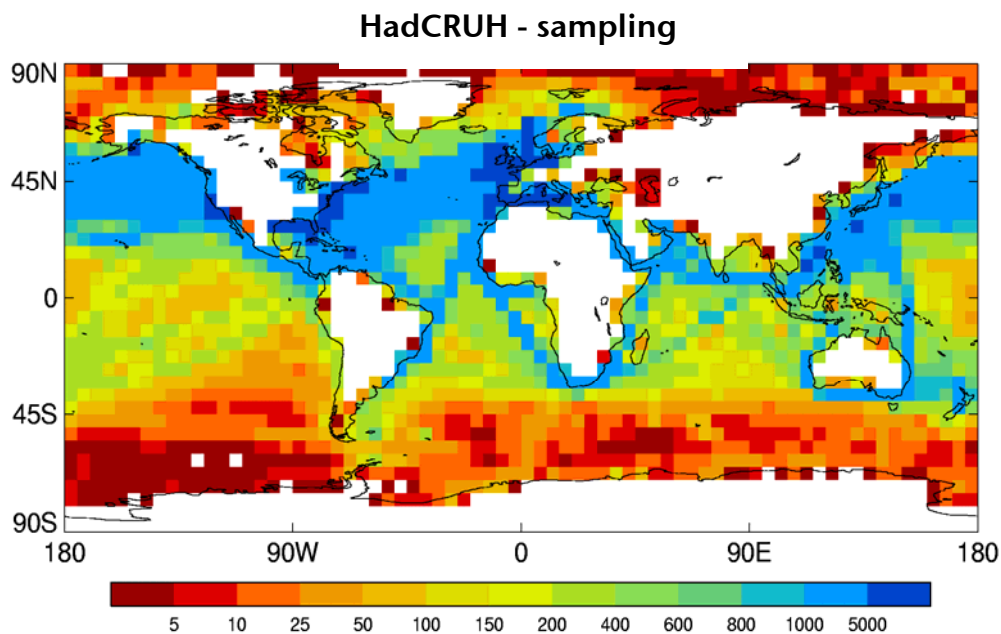


Figure 1: Average number of observations per year within each grid box of the surface marine humidity data set HadCRUH.

Surface Temperature

We have compared the above humidity observations with four different Hadley Centre surface temperature datasets: the new un-interpolated sea surface temperature analysis HadSST2 (Rayner et al. 2006); the optimally interpolated blend of in-situ and satellite sea surface temperature and sea-ice analysis HadISST (Rayner et al., 2003); the interpolated night marine air temperature data set HadNAT2 (Rayner and Hill, 2006), and the un-interpolated night marine air temperature data set MOHMAT (Parker et al., 1995).

In each case the monthly gridded surface temperature actuals were converted to an estimate of monthly mean saturation vapour pressure using the formulation of Buck (1981) assuming a constant surface pressure of 1000hPa:

$$e_s = 6.1375 \times EXP \left[\frac{\left(18.729 - \frac{T}{227.3} \right) T}{T + 257.87} \right] \quad (3)$$

where e_s is the saturation vapour pressure in hPa, and T is temperature in $^{\circ}\text{C}$

The non-linear relation between temperature and vapour pressure means that an error will be introduced when calculating vapour pressure from monthly gridded means. In order to determine the magnitude of this bias we also calculated vapour pressure from point SST observations and then passed them through the HadSST2 processing algorithm. These data are referred to as HadSST2(point) in the subsequent analysis.

2.2 – Trends

Dai (2006) analyzed synoptic surface data for 1976 to 2005 from ships and buoys identifying increases in specific humidity close to that expected from constant relative humidity, although small negative trends in relative humidity were also identified. Trenberth et al. (2005) showed trends in SSM/I TCWV of 1.3%/decade 1988-2003 were well explained by patterns SST change over the same period, and was close to that expected from constant relative humidity.

We build upon these analyses by providing a more comprehensive assessment of the sources of uncertainty in trends in relative humidity. Moisture parameters derived from the datasets listed in section 2.1 were converted to percentage anomalies with respect to a 1987-2005 climatology, thereby providing the right-hand side of equation 1. In this case the climatology period was selected for consistency with the short-period of satellite observations.

In Fig. 2 we present time-series of near-global average (70°N to 70°S) of the components of equation 1 estimated from the satellite, and in-situ observations over the oceans. There is close agreement in the inter-annual variability between the water vapour and surface temperature data sets which is dominated by ENSO events and volcanic activity. A correlation coefficient of between 0.7 and 0.8 is found between temperature and water vapour depending upon the combination of data sets compared. The correlation between the SSM/I TCWV and SFC(q) time series is 0.76. The derived relative humidity time-series will contain errors due to different spatio-temporal sampling of the water vapour and temperature data sets, but it is clear that much (but not all) of the variance on timescales greater than one year is removed, supporting an approximately constant relative humidity. A discontinuity in SFC(RH) is apparent in 1982. This shift likely results from a change in the reporting practise for dewpoint observations. Prior to this date dewpoint temperatures were consistently rounded to the nearest whole $^{\circ}\text{C}$, further investigation is being done to ascertain whether this accounts for the apparent jump in relative humidity at this time.

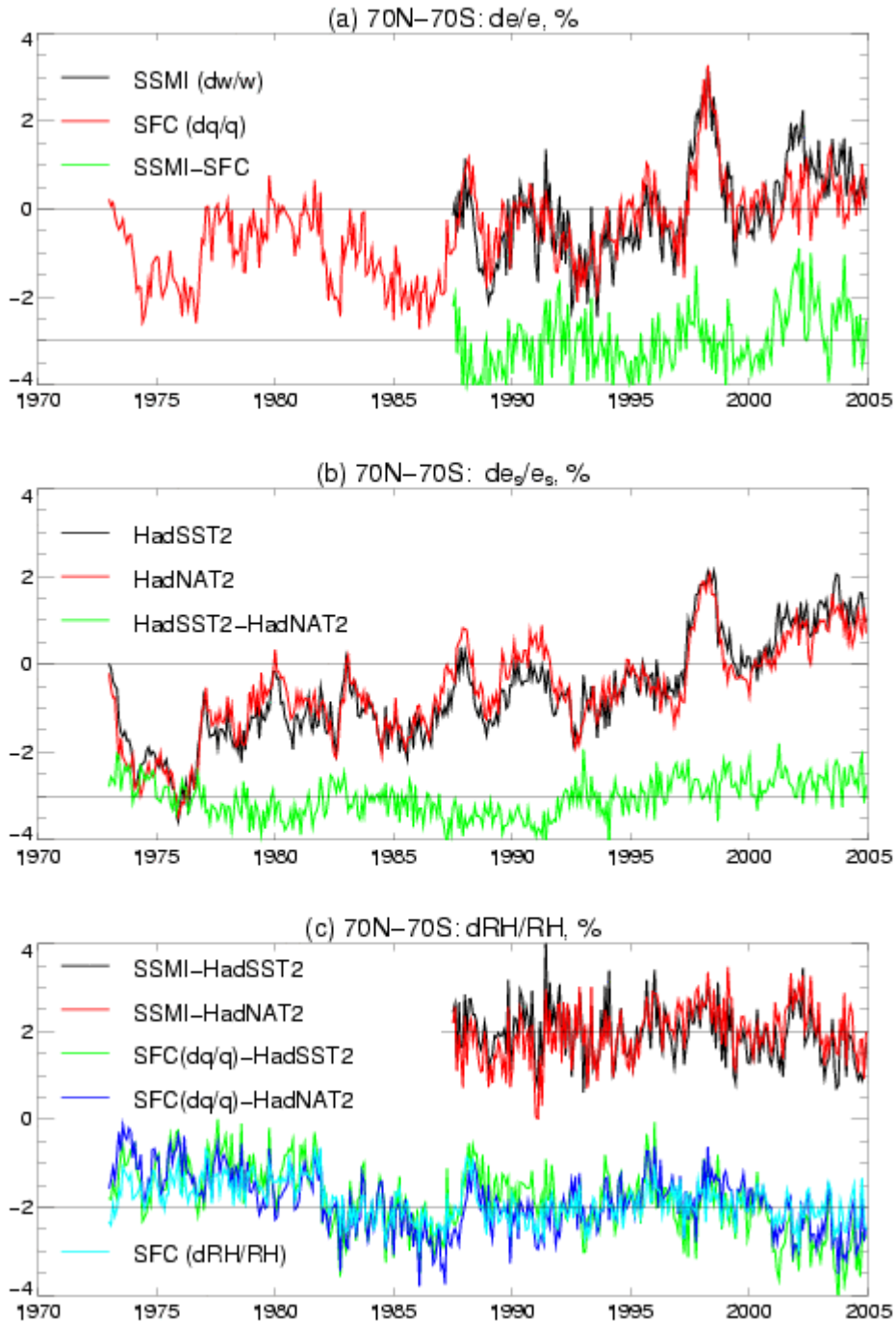


Figure 2: (a) Time series of $100*dw/w$ from SSMI observations, and $100*dq/q$ from surface in-situ observations and their difference, averaged over the oceans between $70^{\circ}N$ and $70^{\circ}S$. (b) As (a) for $100*de_s/e_s$ derived from sea surface (HadSST2) and marine air temperature (HadNAT2). (c) $100*dRH/RH$ estimated from the differences between (a) and (b). The SSMI and surface data are offset by ± 2 respectively. The cyan curve is the equivalent dRH/RH estimated directly from the coincident surface dry and wet bulb temperatures. In all figures the reference climatology period is taken as 1987-2004 for consistency with the satellite data. Where time-series have been offset from zero for clarity, the reference zero line is also shown.

The magnitude of trends in TCWV, SFC(q), and SFC(RH) are given in Table 1. Trends in SFC(q) are approximately half that observed by SSM/I, and the differences are much greater than the 95% confidence ranges from the statistical fit of each trend. Relatively large uncertainty in the magnitude of these trends may result from the relatively short period of satellite observations coupled with the large magnitude of inter-annual variations, and indeed much of the trend discrepancy appears to arise from differences in the two water vapour time-series during 2001-2005.

	SSMI	SFC (q)	SFC (RH)
1987-2004	$+1.15 \pm 0.25$	$+0.57 \pm 0.20$	0.00 ± 0.10
1973-2004	N/A	$+0.53 \pm 0.10$	-0.18 ± 0.05

Table 1: Trends in 70°N to 70°S mean water vapour (dq/q or dRH/RH) over oceans, given as %/decade. The 90% confidence range for each trend estimate is also given.

Trends in saturation vapour pressure (Fig. 2b) and absolute temperature are shown in Table 2, which shows decreasing trends as you move from the left to right-hand column. MOHMAT and HadISST have less warming than the newer analyses of HadNAT2 and HadSST2. Much of the discrepancy appears to relate to a discontinuity around 1997 (not shown), coincident with a change from ICOADS to NCEP/GTS data, and a change in the relative contribution of ship and buoy measurements. Therefore much of the trend discrepancy may result from the treatment of ship and buoy biases over this period (John Kennedy, personal communication). An unexplained discontinuity in the early 1990s (Fig. 2b) appears to explain much of the trend discrepancy between HadSST2 and HadNAT2. It is beyond the scope of this report to comment further on these discrepancies in surface temperature trends, but these differences translate to much larger uncertainties in saturation vapour pressure, and consequently relative humidity.

The calculation of saturation vapour pressure from monthly mean values results in an underestimate of trends in saturation vapour pressure of 0.24%/decade, which is shown in Table 2 by comparing HadSST2(point) with HadSST2(monthly). This error is significantly reduced over the longer period back to 1973, again suggesting that the short period of satellite observations is a limitation in accurate trend detection.

	HadSST2 (point)	HadSST2 (monthly)	HadNAT2	HadISST	MOHMAT
1987-2004 e_s (%/decade)	$+1.41 \pm 0.17$	$+1.17 \pm 0.17$	$+0.84 \pm 0.21$	$+0.59 \pm 0.13$	$+0.45 \pm 0.19$
1987-2004 T (K/decade)	$+0.18 \pm 0.03$	$+0.18 \pm 0.03$	$+0.13 \pm 0.03$	$+0.10 \pm 0.02$	$+0.07 \pm 0.03$
1973-2004 e_s (%/decade)	$+1.00 \pm 0.08$	$+0.94 \pm 0.07$	$+0.87 \pm 0.08$	$+0.70 \pm 0.06$	$+0.73 \pm 0.08$
1973-2004 T (K/decade)	$+0.15$ (0.01)	$+0.15$ (0.01)	$+0.14$ (0.01)	$+0.11$ (0.01)	$+0.12$ (0.01)

Table 2: As Table 1 for trends in saturation vapour pressure as %/decade and for absolute temperature in K/decade.

Trends in dRH/RH (Fig. 3c and equation 1) are shown in Table 3 for all combinations of humidity and surface temperature data sets, thus giving an estimate of the range of uncertainty in relative humidity trends resulting from structural uncertainty in both specific humidity and temperature observations. There is a clear distinction between trends estimated using HadSST2 compared with the earlier data sets HadISST and MOHMAT, with HadNAT2 being intermediate. These differences are significant for both the satellite period since 1987, and the longer period since 1973, although they are reduced over the longer period. Accounting for the monthly sampling bias over the 1987-2004 period yields close agreement between SFC(RH) trends in Table 1 compared with those estimated from SFC(q) and MOHMAT.

	HadSST2 (point)	HadSST2 (monthly)	HadNAT2	HadISST	MOHMAT
SSMI (1987-2004)	-0.25 ± 0.17	-0.02 ± 0.16	$+0.37 \pm 0.18$	$+0.58 \pm 0.17$	$+0.71 \pm 0.17$
SFC (q, 1987-2004)	-0.78 ± 0.16	-0.54 ± 0.16	-0.12 ± 0.16	$+0.02 \pm 0.16$	$+0.19 \pm 0.17$
SFC (q, 1973-2004)	-0.45 ± 0.07	-0.39 ± 0.07	-0.32 ± 0.07	-0.16 ± 0.07	-0.21 ± 0.08

Table 3: Trends with 90% confidence limits, in dRH/RH in %/decade as estimated from equation 1 (see text) with different combinations of water vapour and surface temperature data. HadSST2(point) refers to saturation vapour pressure calculated from point SST measurements. For all other data the vapour pressure was calculated from gridded monthly mean data.

For the period 1987-2004, the average estimate of dRH/RH (with the exception of HadSST2(point)) is $+0.15\%/decade$. We then account for the bias resulting from using

monthly mean rather than point observations in calculating e_s by subtracting 0.24%/decade from these estimates. Therefore we have a relative humidity trend estimate of $-0.1 \pm 0.6\%$ /decade, where the uncertainty results from a combination of structural uncertainty in the surface temperature observations and between the satellite and in-situ observations of humidity. In order to significantly reduce this uncertainty we must address the following:

1. In order to ensure an uncertainty of less than 0.3%/decade in saturation vapour pressure, and therefore relative humidity we require structural uncertainty in the global mean marine surface temperature trends to be less than 0.03K/decade. Can we reject the older datasets in favour of HadSST2 and HadNAT2? Can we resolve the recent trend discrepancy between SST and marine air temperatures?
2. The SFC(q) and SFC(RH) records are broadly consistent with temperature changes from the MOHMAT and HadISST datasets. Would the application of HadSST2/HadNAT2 processing to the SFC humidity dataset result in increased trends in SFC(q)?
3. Uncertainty in trends also results from the relatively short period of coincident satellite and surface humidity observations, and the fact that inter-annual variations are of a similar magnitude to the trends themselves. Continued monitoring into the future may resolve some of these issues.

3) Surface and Lower Troposphere – Land

3.1 – Data

Radiosondes – HadTH

Ross and Elliott (2001) provided an assessment of trends in unadjusted radiosonde data, but to the best of our knowledge there have been no other published attempts to rigorously remove artificial breakpoints from the radiosonde humidity data, making our own radiosonde humidity dataset, HadTH, a unique product in this regard. In McCarthy et al. (2005) we presented a preliminary version of HadTH generated from an early version of the automated homogenisation system outlined in McCarthy et al. (2006).

A significant drying across much of continental Europe and Russia was reported, however the smaller spatial scales of water vapour make the neighbour-based approach of McCarthy et al. (2006) less robust, and indeed many instances were found where breakpoint adjustments were underestimated due to the presence of similar events in neighbouring stations. Furthermore improvements to the response time of radiosonde hygrometers, and a general improvement in reporting dry conditions results in a spurious drying.

For this analysis two modifications to the homogenisation process have been made:

1. An initial first-guess of breakpoint adjustments due to known radiosonde instrument changes have been made. For all stations with a particular metadata event an adjustment estimate is made from the difference in the median anomaly two years before and after the reported event. The first guess adjustment is then taken as the median of adjustment estimates from all stations with the same metadata event.

2. The homogenisation system is multi-variate, and conducted simultaneously on each of the HadTH variables: temperature; dewpoint; relative humidity; specific humidity, and for each of day, night, and day minus night. Breakpoints are therefore consistent between each of the variables, a failing in the earlier version, although the adjustment magnitudes are still calculated independently.

HadTH provides homogenised temperature, dewpoint, relative humidity, and specific humidity on 6 pressure levels (1000, 850, 700, 500, 400, 300hPa). For this analysis we consider only 850, 700, 500, and 400hPa in the region 20°N to 70°N where there is reasonably good data coverage.

Surface humidity – HadCRUH land

Temperature and dewpoint measurements from over 3000 land surface stations since 1973 (and back to 1901 for a smaller number of stations) have been quality controlled and converted to vapour pressure, specific humidity, and relative humidity. Quality control includes physical consistency checks and removal of outliers. In addition homogenisation and adjustment of the data are conducted using a near neighbour comparison approach similar to that of McCarthy et al. (2006). The quality controlled and homogenised land data are aggregated onto a monthly mean 5° latitude-longitude grid, and will be referred to as SFC(q) and SFC(RH).

Land surface air temperature data have been taken from the HadCRUT3 data set (Brohan et al. 2006). For this analysis we have not generated an equivalent saturation vapour pressure product since we already have relative humidity estimates directly from both the radiosonde and surface data sets.

3.2 – Trends

Both the radiosonde and surface data are presented as anomalies with respect to a 1979-1998 climatology. Fig. 3 shows maps of linear trend estimates for 1973-2003 from HadTH at 850hPa alongside the surface data record. Following homogenisation of the radiosonde data there is a clearly better agreement with both relative and specific humidity at the surface, particularly over Europe and Russia. Discrepancies do still exist, for example HadTH has larger trends in specific humidity over North America, and smaller trends over Russia than the surface data.

Time-series of 20°N to 70°N area-weighted averages are shown in Fig. 4, showing good agreement in inter-annual variability and trends between the surface data and the homogenised radiosondes for temperature and both moisture variables. For the purposes of comparison the specific humidity data have been normalised by their standard deviation in Fig. 4, accounting for the large differences in the absolute quantity of water vapour at different atmospheric levels. The homogenisation of the radiosonde data clearly results in an improvement to the data when compared to the changes at the surface.

The linear trends for the period 1973-2003 are summarised in Fig. 5, where the very close agreement between the surface and 850hPa level is apparent. HadTH has a relative cooling trend with altitude, which is at odds with estimates from other radiosonde temperature-only data sets such as HadAT (Thorne et al. 2005). Temperature data are only retained in HadTH if there exists a coincident humidity measurement. Therefore as humidity sensors

have become more reliable the sampling of the radiosondes for humidity has improved. More cold-condition observations were rejected by quality-control procedures earlier in the record than present day, which is the most likely source of a spurious cooling and drying trend that increases with altitude (and also latitude). Therefore we might assume that HadTH is underestimating trends in temperature and specific humidity at upper levels. It is unclear at this stage whether this also affects relative humidity, but the lack of vertical structure in both the unadjusted and adjusted relative humidity trends suggests that this bias probably has little direct impact on relative humidity trends, in other words the bias in temperature and specific humidity compensate each other to leave relative humidity unbiased.

From this analysis our best estimate to-date suggests that relative humidity has remained approximately constant since 1973 from the surface to 400hPa over the northern hemisphere continents. The following problems require further investigation and place some caveats on the results, and will be addressed before HadTH is released to the wider community:

1. Trends in temperature and specific humidity are likely underestimated due to a cold-temperature sampling bias that changes through the record. Adjustments for this effect can be estimated from those stations that are not subject to these biases.
2. Recent known instrument changes (e.g. a switch from the Vaisala RS80 to Vaisala RS90 and RS92 which is expected to result in a moistening bias) have not been directly accounted for due to the metadata archive being incomplete for recent years. Updates to these data, and additional metadata from ECMWF should allow for improved estimates of recent discontinuities.
3. A more comprehensive uncertainty analysis can be obtained through the generation of an ensemble of homogenisations similar to that employed in Titchener et al. 2006, including the additional uncertainty from the first-guess breakpoint adjustment.

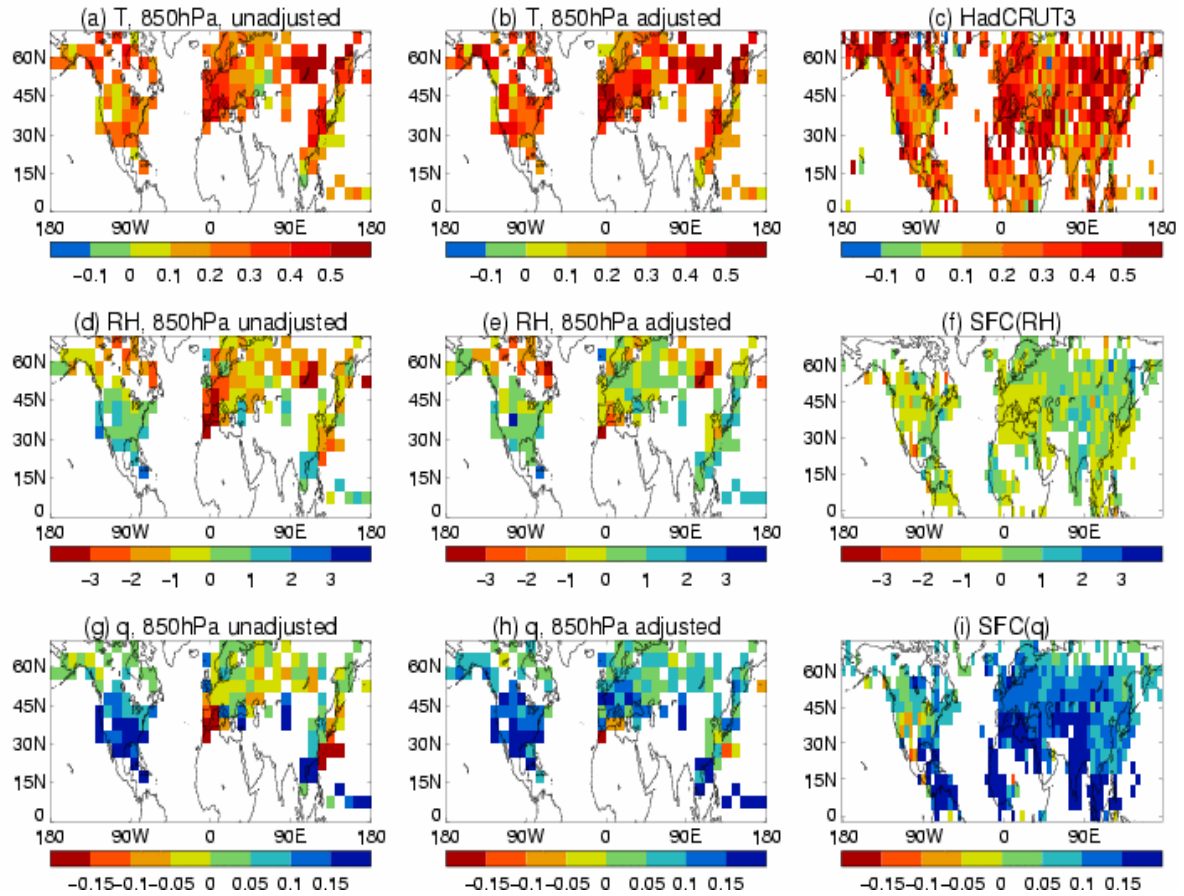


Figure 3: 1973-2003 linear trend estimates for (a) Unadjusted HadTH temperature at 850hPa, (b) Adjusted HadTH at 850hPa, (c) HadCRUT3 surface temperature, (d) Unadjusted HadTH relative humidity at 850hPa, (e) Adjusted HadTH relative humidity at 850hPa, (f) Surface relative humidity, (g) Unadjusted specific humidity at 850hPa, (h) Adjusted specific humidity at 850hPa, (i) Surface specific humidity. Units are K/decade for temperature, %/decade for relative humidity, and g/kg/decade for specific humidity. Warming or drying is shown in yellow and red, cooling or moistening is shown in green and blue.

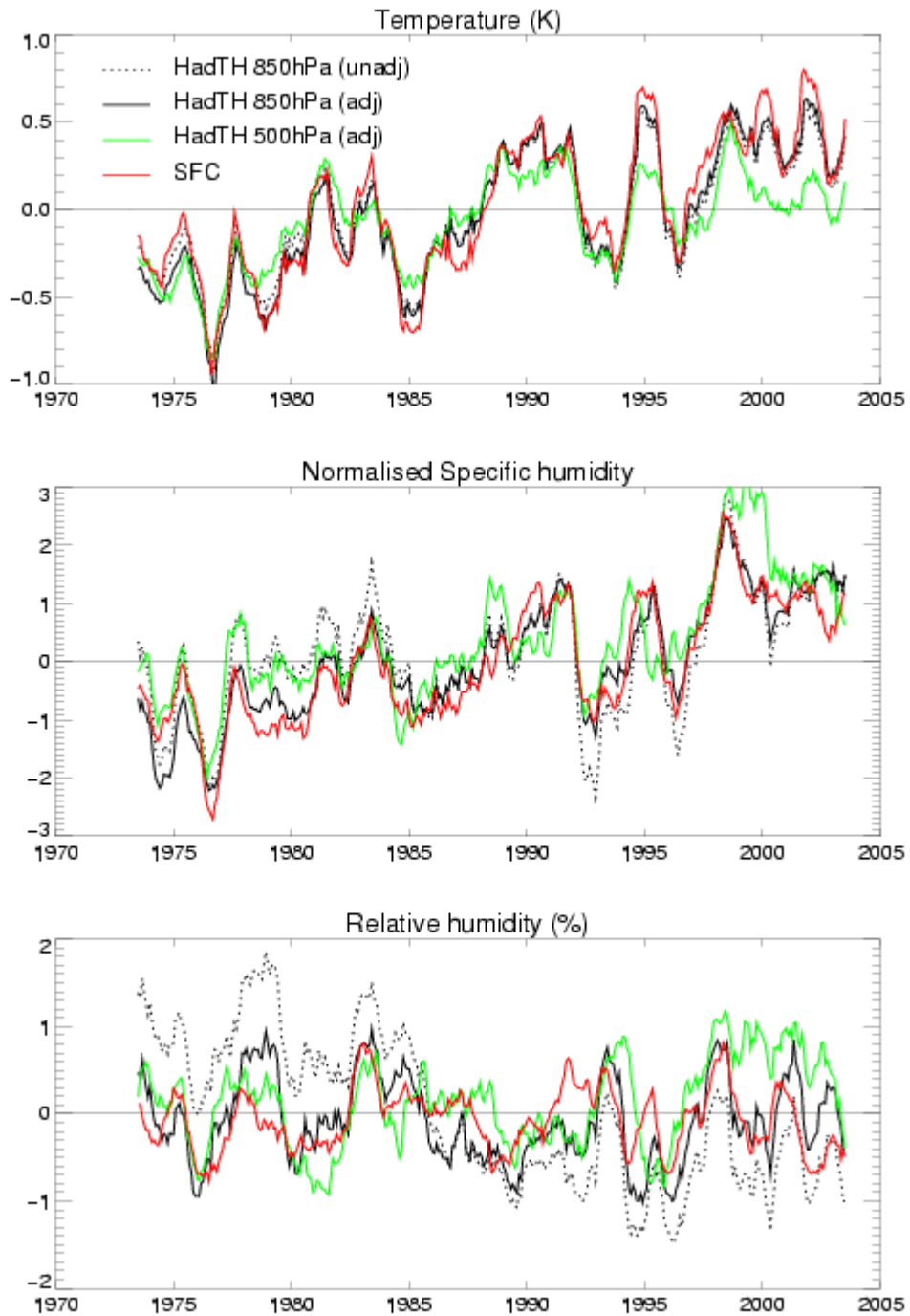


Figure 4: Time series of (top) temperature, (middle) specific humidity (normalised by its standard deviation), and (bottom) relative humidity 1973-2003. Area averaged with HadTH sampling between 20°N and 70°N . The dotted line is HadTH at 850hPa before adjustment, the black solid line the same data after homogeneity adjustment. The green curve is HadTH at 500hPa after adjustment, and the red curve is surface data.

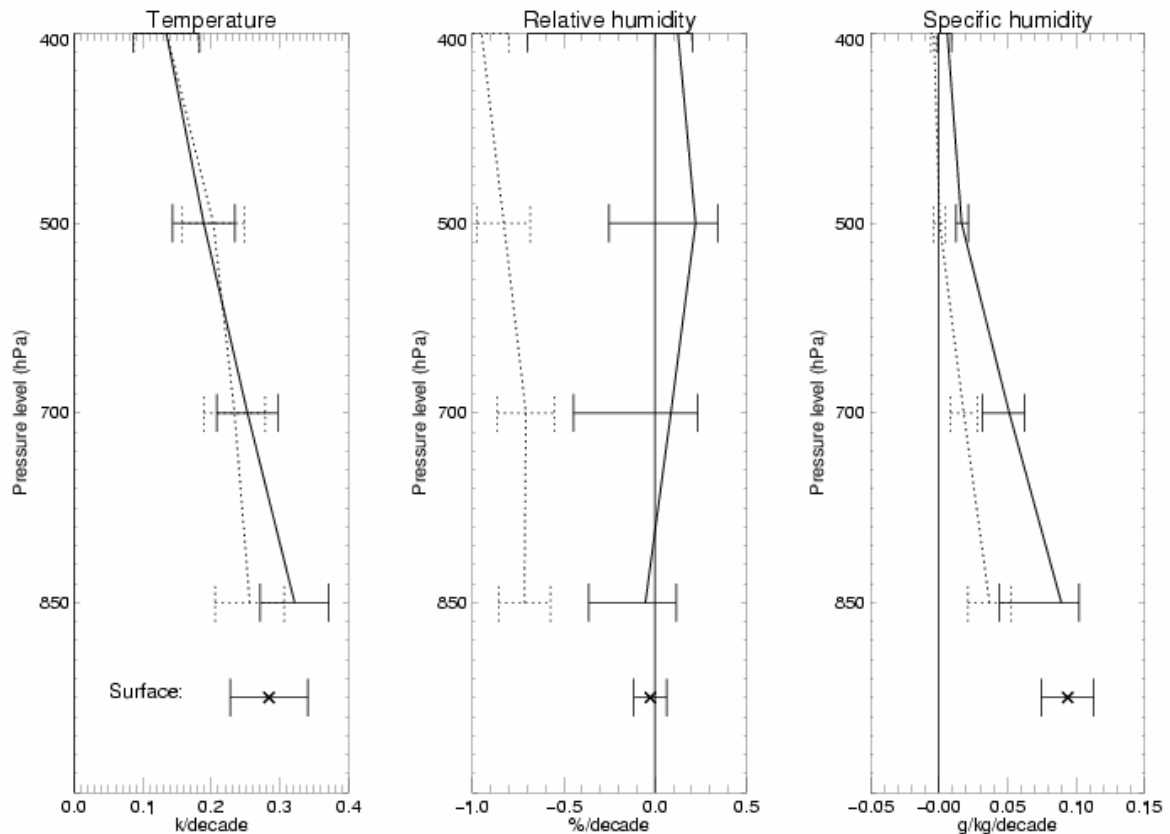


Figure 5: Linear trend estimates for temperature, relative humidity, and specific humidity at pressure levels from HadTH, 1973-2003 for area-averaged data between 20°N and 70°N . Trends in surface data with the same spatial sampling as HadTH are also shown. Dotted lines are the unadjusted radiosonde data, solid lines are the homogeneity adjusted data. Error bars represent the 95% confidence interval from the statistical fit of the linear trend or an estimate of the homogenisation uncertainty (see text), whichever is larger.

4) Concluding remarks

We have presented an analysis of trends in water vapour from satellites, radiosondes, and ground stations. Most of the data sets consistently suggest that in recent decades water vapour near the surface and in the lower-mid troposphere has increased in response to rising surface temperatures in such a way as to maintain relative humidity at a constant value, as predicted by climate models.

Uncertainty in trends remains through a combination of structural uncertainty in the generation of the observational records, including the surface temperature records, the short period of the data record in the presence of large inter-annual variations, and cold-temperature sampling biases in the upper levels of the radiosonde data records. We cannot be certain that we have completely spanned the range of uncertainties in this analysis, and indeed we have outlined a few key areas that require closer inspection, but our current estimation of uncertainty means that we cannot use these data to reject the hypothesis of constant relative humidity. The largest uncertainty is for the satellite period 1987-2005 over oceans where uncertainty in trends in relative humidity stem largely from the surface temperature data sets and suggest that actual trends in global mean relative humidity may lie in the range $-0.7\%/decade$ to $+0.5\%/decade$. This range is large considering that the TCWV and surface specific humidity trends are $+1.15$ and $+0.57\%/decade$ respectively.

Over land both radiosonde and surface data suggest little or no trend in relative humidity with an uncertainty range from individual levels encompassing -0.5%/decade and +0.4%/decade. We have also shown that the homogenisation applied to the radiosonde dataset to generate this version of HadTH brings it into much closer agreement with the independent surface record, providing validation that the homogenisation has improved the radiosonde record. Therefore we conclude that HadTH can be effectively used for analysing inter-annual variations and trends in humidity variables over the well sampled northern hemisphere, although problems may still exist in the mid and upper tropospheric layers, and these problems will be addressed in future work.

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