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1 Reassessing changes in Diurnal Temperature Range: A new dataset and
2 characterization of data biases.

3

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25 **Key points**

- 26 • Breakpoints are found to be more prevalent in DTR than other elements
- 27 • DTR has decreased since the early 20th Century but decrease is not linear
- 28 • Effects of homogenization change many details of global and regional DTR

29 **Abstract**

30 It is almost a decade since changes in Diurnal Temperature Range (DTR) globally
31 have been explicitly assessed in a stand-alone data analysis. The present study takes
32 advantage of substantively improved basic data holdings arising from the
33 International Surface Temperature Initiative's databank effort and applies the
34 National Climatic Data Center's automated pairwise homogeneity assessment
35 algorithm to reassess global and regional DTR records. It is found that breakpoints
36 are more prevalent in DTR series than other temperature elements and that the
37 resulting adjustments have a broader distribution. This strongly implies that there
38 is an over-arching tendency across the global meteorological networks for non-
39 climatic artifacts to impart either random or anti-correlated rather than correlated
40 biases in maximum and minimum temperature series. Future homogenization
41 efforts would likely benefit from a consideration of DTR, maximum and minimum, in
42 addition to average temperatures. Estimates of change in DTR are relatively
43 insensitive to whether adjustments are calculated directly or inferred from
44 adjustments returned for the maximum and minimum temperature series. The
45 homogenized series exhibit a reduction in DTR since the early 20th Century globally.
46 Adjustments serve to roughly half the magnitude of the long-term global reduction
47 in DTR in the basic 'raw' data. Most of the estimated reduction in globally-averaged
48 DTR occurred over 1960-1980. In several regions DTR has apparently increased
49 since the 1990s, whilst globally it has exhibited very little change. Estimated
50 changes in DTR are an order of magnitude smaller than in maximum and minimum
51 temperatures, which have both been increasing rapidly on multi-decadal timescales.

52 **1. Introduction**

53

54 Diurnal Temperature Range (DTR) is defined as the daily maximum (T_x) minus the
55 daily minimum (T_n) temperature. Herein consideration of DTR is restricted to land
56 regions where DTR is far more dynamic than over the oceans. Over land areas DTR
57 varies enormously both seasonally and geographically [Wang and Dillon, 2014]. The
58 nature of DTR variability is important from a theoretical perspective for myriad
59 reasons including in understanding microclimate impacts and the nature of changes
60 within the deeper boundary layer [e.g. Christy et al., 2009, Pielke and Matsui, 2005,
61 Zhou and Ren, 2011, Parker, 2006, Steenveld et al., 2011, McNider et al., 2012], and
62 potentially as a determinant between forcings that have different Short Wave and
63 Long Wave radiative fingerprints but may otherwise be similar [e.g. Jackson and
64 Forster, 2013; Wang and Dickinson, 2013]. Trends and variability in DTR also have
65 important practical implications for human health [Paaijmans et al., 2010], ecology
66 [Peng et al., 2013, Vasseur et al., 2014], and agriculture [Battisti et al., 2009]
67 amongst others.

68

69 Meteorological records have been undertaken at observing stations that extend back
70 to the late 18th Century regionally and to the late 19th Century quasi-globally
71 [Rennie et al., 2014]. Efforts have been made for at least three quarters of a Century
72 [Callendar, 1938, Hawkins and Jones, 2013] to collate these data, apply homogeneity
73 assessments and ascertain the nature of changes in Land Surface Air Temperatures
74 (LSAT) over the globe. Today, there exist several such datasets globally [Lawrimore

75 et al., 2011 (see also Williams et al., 2012a,b, 2013), Jones et al., 2012, Rohde et al.,
76 2013] and regionally [e.g. Bohm et al., 2010; Tietavainen et al., 2010, Li et al., 2010,
77 Jain and Kumar, 2012, Trewin, 2012, Vincent et al., 2012, Falvey and Garreaud,
78 2009, Christy et al., 2009; Van der Schrier et al., 2013]. Many of these analyses have
79 been limited to a consideration of changes in average temperatures (T_m), in part
80 because records for average temperatures are more complete (Figure 1).
81 Proportionately the effect becomes substantial prior to about 1950 and critical prior
82 to 1895 (Figure 1 lower panel). Most US series post-1895 have been digitized to
83 include T_x and T_n elements as part of the Climate Database Modernization Program.
84 Elsewhere the situation is substantially more mixed and depends upon the data
85 source.

86

87 Although DTR has been discussed as part of more general analyses globally [Rohde
88 et al., 2012, Donat et al., 2013] and regionally [e.g. Makowski et al., 2008, Sen Roy
89 and Balling, 2005, Christy et al., 2009, Zhou and Ren, 2011], it is almost a decade
90 since the last stand-alone comprehensive analysis of global DTR data and its
91 homogeneity was produced [Vose et al., 2005] and over twenty years since the first
92 such assessment [Karl et al., 1993]. The IPCC in the most recent working group 1
93 assessment [Hartmann et al., 2013] noted that there was only '*medium confidence*'
94 (see Mastandrea et al. [2010] for an interpretation of the specific meaning of this
95 term in an IPCC context) in available records of observed changes in DTR due to the
96 presence of a number of unresolved issues raised in the literature [Fall et al., 2011,

97 Williams et al., 2012c, Christy et al., 2009] and the lack of recent studies and
98 analyses.

99

100 In the last decade substantial progress has been made in:

- 101 • Creating better more complete records of daily data holdings of T_x and T_n
102 with better provenance and quality control [Menne et al., 2012];
- 103 • In combining disparate global holdings of monthly records with the
104 improved daily holdings to provide a more robust data basis from which to
105 undertake analyses of long-term LSAT changes [Rennie et al., 2014]; and
- 106 • The creation of automated monthly climatic timeseries homogeneity
107 assessment methods and their performance benchmarking and assessment
108 [Venema et al., 2012, Williams et al., 2012c, Menne and Williams, 2009].

109

110 This paper aims to take advantage of these methodological and data innovations to
111 create a new estimate of long-term changes in DTR globally and regionally. A
112 subsequent companion paper compares these results to a broad range of other
113 observationally based estimates [Thorne et al. submitted]. These subsequent
114 analyses permit an assessment of sensitivity to both structural and parametric
115 uncertainties [Thorne et al., 2005] in DTR estimation. A holistic assessment of DTR
116 and its changes is stayed to the companion piece. This paper focuses instead upon
117 the effects of the Pairwise Homogenization Algorithm (PHA) technique upon the
118 data and a characterization of the resulting series and a consideration of
119 implications for trends in T_x and T_n .

120

121 The remainder of the paper is structured as follows. In section 2 the data and
122 homogenization methods employed in this study are briefly introduced. Section 3
123 summarizes the impacts of running the PHA algorithm on the data and discusses
124 potential implications for the nature of non-climatic artifacts in the record. Section 4
125 describes the spatial and temporal evolution of the homogenized series for the
126 spatially incomplete global mean and a subset of regions for which data are
127 complete enough to analyze back to 1901 (Europe, N. America and Australia).
128 Section 5 provides a brief discussion. Section 6 contains details on the dataset
129 availability and Section 7 concludes.

130

131 **2. Data and homogeneity assessment method**

132

133 **2.1 Source data**

134

135 The present analysis is exclusively based upon the version 1 ‘recommended merge’
136 release of the Global Land Surface Databank [Rennie et al., 2014] at monthly data
137 resolution. This databank release is a result of efforts by many international
138 collaborators under the auspices of the International Surface Temperature Initiative
139 [Thorne et al., 2011]. It has combined holdings from over 50 constituent sources
140 ranging from single stations to holdings of many thousand stations. These sources
141 have been merged hierarchically with merge decisions based upon both metadata
142 and data similarity metrics. Sources with T_x and T_n and better provenance and

143 believed to be closer to the original recorded 'raw' basic data have been prioritized.
144 The merge creates a single unique version per station that is as long as possible
145 while minimizing potential discontinuities through false imputation of short period
146 data. In total this version consists of just over 32,000 stations, most of which have
147 T_x and T_n series for at least part of their records and many of which extend over at
148 least 100 years (although not necessarily continuously).

149

150 The processing of the databank series merged T_x and T_n series stations first and
151 only then went back to look for record segments for which solely T_m records exist.
152 Despite this deliberate effort to maximize the amount of T_x and T_n data pull-
153 through, availability for these elements is always lower than for T_m (Figure 1). It is
154 all but certain that T_x and T_n data, or at least observations at intervals over the day,
155 were associated with the original records for which in the digital archives now only
156 T_m data exist in most cases. These data have either been lost or more likely were
157 never digitized. This attests to the real importance of data rescue efforts, even for
158 those stations which nominally already have records but for which the records are
159 incomplete in important aspects such as availability of daily summaries which serve
160 to inhibit understanding [e.g. Allan et al., 2011].

161

162 To facilitate the analysis herein a fourth field – T_{dtr} – the difference between T_x and
163 T_n has also been calculated and analyzed. In addition, for those analyzes of
164 homogenization performance (Section 3) which include recourse to results for T_m
165 these consider solely T_m values derived directly from the T_x and T_n elements as

166 their average. This avoids conflation of data completeness and data characteristics
167 in the analysis, which would otherwise ensue from use of the more temporally
168 complete merged T_m series (Figure 1). In many cases for remaining T_m reports the
169 archived T_m may not result simply from averaging T_x and T_n . For example in at
170 least Australia (and perhaps many other regions) in recent years the monthly
171 average reported in CLIMAT messages is the average of hourly reports. Regardless,
172 given that PHA is a neighbor-based procedure it is important to have the same
173 networks for each element to perform a fair comparison and evaluation.

174

175 Both the DTR and the T_m fields result from direct calculation from the monthly
176 mean T_x and T_n series. So, the basic data used herein are internally consistent in
177 that in the data presented to the homogenization algorithm DTR will always be the
178 difference between T_x and T_n , T_m will always be their average, and these elements
179 are only ever calculated when both T_x and T_n are present. However, for months
180 where either T_x and / or T_n have missing daily values this is not going to be
181 equivalent to the average of the calculable daily DTRs (or T_m 's) within the month.
182 While a more restrictive criteria of calculation of these values from the dailies could
183 be applied to the subset of the databank arising from daily sources [Rennie et al.,
184 2014] it would result in considerably fewer candidate station records, particularly
185 prior to the 1950s. This comes at a potential cost regarding the monthly statistical
186 mean and / or standard deviation characteristics for those stations where data is
187 patchy on an intra-month basis due either to frequent missing days or frequent
188 quality control flagging on the daily reports.

189

190 2.2 Pairwise Homogeneity Assessment

191

192 The data are presented to the exact same processing suite as those for Global
193 Historical Climatology Network Monthly (GHCN, currently GHCN-Mv3.2.0)
194 [Lawrimore et al., 2011, Williams et al. 2012a,b, 2013]. This consists of a set of
195 quality control checks followed by application of a Pairwise Homogeneity
196 Assessment (PHA) breakpoint identification and adjustment procedure [Menne and
197 Williams, 2009]. The interested reader is directed to these papers for a fuller
198 exposition of the methodology than is possible here if technical details are required.

199

200 The data are submitted separately for each of the four data streams considered (T_x ,
201 T_n , T_m and DTR). No attempt is made herein to consider these data jointly to ensure
202 consistency in returned adjustments across the elements when assessing
203 homogeneity of the series, although such an approach is being actively developed
204 for new versions of GHCNM. This is likely to yield inconsistencies at the station level
205 between elements herein, which may occasionally be substantial (Section 3). The
206 PHA algorithm analyzes timeseries of pairwise differences between nearby stations.
207 It uses a Standardized Normal Homogeneity Test (SNHT) test statistic
208 [Alexandersson, 1986] which is a t-test class of test, to identify potential
209 discontinuities in each station pair. After doing so for all identified neighbor
210 combinations the very large matrix of potential breakpoints is decomposed such
211 that breakpoints are assigned iteratively to those stations in which they arise

212 concurrently across multiple inter-comparisons with the resulting counts reduced
213 accordingly until no further plausible breakpoint candidates exist. Then
214 adjustments are inferred for the resulting population of identified candidate real
215 breakpoints through comparisons to apparently homogeneous neighbor segments
216 and applied if the distribution of returned adjustment estimates is substantively
217 non-zero. The process is run solely once and the resulting set of applied and rejected
218 adjustments are returned. The stations have been adjusted based upon the
219 adjustment estimates and quality control decisions returned by the PHA in its
220 operational version settings. The ensemble analysis of Williams et al. [2012c]
221 highlights potential impacts from giving different, plausible, parameter settings to a
222 number of the uncertain parameters within the PHA algorithm. For the present
223 analysis consideration of such ensembles is deemed beyond scope.

224

225 2.3 Station gridding

226

227 For subsequent analysis only stations and months with sufficient data to create a
228 1971-2000 climatology under a Climate Anomaly Method have been retained in the
229 gridded fields. As is discussed in the accompanying paper [Thorne et al., submitted]
230 this is one of several possible approaches to gridding. For each station and calendar
231 month, the minimum data requirement for calculating a climatology is 2/3 of data in
232 the 30 year period taken as a whole and at least 1/2 in each decade (1971-1980,
233 1981-1990 and 1991-2000). This implies that a climatology may have been
234 computed for some, but not all, calendar months at a particular station. For example,

235 if the station's operator always took a vacation in July, then an insufficient amount
236 of data may have been available for July while data for the other months of the year
237 were sufficiently complete. In practice stations tend to be either substantively
238 complete over the climatology period or have a marked data paucity that precludes
239 their inclusion, meaning this affect is relatively minor in the retained station set.
240 Stations for which a climatology can be calculated for any month tend to have
241 climatologies for all twelve calendar months.

242

243 The climatology value has only been calculated with a trimmed mean based upon
244 solely months within 3 standard deviations (σ) of the climatology period data mean
245 for the given calendar month. An additional simple 5σ anomaly QC check has then
246 been applied to the resulting anomaly series on a calendar month basis to remove
247 gross outliers. Data between 3 and 5 standard deviations are retained but do not
248 inform the climatological estimate. In stations with a strong secular trend this
249 quality control step may remove real points far away in time from the climatology
250 period. A high critical threshold of 5σ was chosen to mitigate this risk while still
251 ensuring grossly questionable data did not get gridded. The check removes solely a
252 handful of grossly questionable data points.

253

254 Resulting anomalies have simply been gridded, without any further weighting, into
255 bins of 5 degrees latitude by 5 degrees longitude. Data have been gridded for all T_x ,
256 T_n and DTR for both the raw and adjusted series. Gridded T_m series are not
257 considered herein but will be documented in forthcoming GHCNM analyses instead.

258

259 For DTR it is possible to estimate the adjustments and resulting gridded series both
260 directly from applying PHA to the timeseries and indirectly, through applying the
261 net effect of the returned adjustments to T_x and T_n . The latter approach will yield a
262 set of physically consistent estimates by construction, but at a potential cost if it
263 misses breaks more amenable to identification and / or adjustment in DTR.
264 Regardless, differences arising between ‘directly adjusted’ and ‘indirectly adjusted’
265 series provide some indication of likely uncertainties / sensitivities of the resulting
266 analyses using the PHA method. However, these are very much an incomplete
267 indicator of the likely true uncertainties. Comparisons to other estimates,
268 constructed using distinct methods for all processing choices including quality
269 control, adjustment, climatology calculation and gridding, will likely give a more
270 realistic assessment of the true magnitude of the uncertainties in DTR estimates and
271 are discussed further in the accompanying paper [Thorne et al., submitted].

272

273 **3. Analysis of homogeneity adjustments**

274

275 3.1 A consideration of the potential structure and magnitude of breakpoints

276

277 The four sets of series submitted to PHA consist of the two primary elements (T_x
278 and T_n), their average (T_m), and their difference (DTR). To ascertain the possible
279 effects of the different data artifact characteristics on breakpoint magnitudes and
280 distributions all possible combinations of T_x and T_n breakpoints between -5 and 5 K

281 have been considered in Figure 2. By construction breakpoints in T_m are always
282 smaller than the break in either T_x or T_n except in the special case where the breaks
283 in both elements are identical in sign and magnitude (perfectly correlated). Because
284 DTR is the difference between the two elements there is no such cancellation in
285 breakpoints of DTR and absolute breakpoint magnitudes reach 10K at $[-5K, 5K]$ and
286 $[5K, -5K]$. Hence DTR has twice as large a potential breakpoint magnitude for
287 combinations explored as any of the other elements. By construction breakpoint
288 magnitudes in DTR and T_m are orthogonal. In the limit of perfectly correlated
289 breakpoints in T_x and T_n (T_x break = T_n break) there will be no breakpoints in DTR.
290 Similarly for perfectly anti-correlated breakpoints (T_x break = $-T_n$ break) there will
291 be no breakpoints in T_m .

292

293 In cases where the breakpoints in T_x and T_n are correlated (both of the same sign)
294 one or other of the breakpoints in T_x and T_n will always be the largest breakpoint.
295 Where the breakpoints in T_x and T_n are anti-correlated (one positive, one negative)
296 the largest breakpoint will always be in DTR. Restricting to a consideration of solely
297 T_m and DTR, the breakpoint in DTR will be largest both when the breakpoints in T_x
298 and T_n are anti-correlated, and when they are only weakly correlated (same sign
299 but substantially distinct magnitude whereby the difference is greater than their
300 mean).

301

302 Assuming that the inter-station noise arising from random effects and real physical
303 effects is similar across the elements such that Signal-to-Noise Ratios (SNRs) are

304 similar in all resulting pairwise comparisons for breakpoint detection (Section 2.2)
305 there is therefore a set of *a priori* expectations that can be made:

- 306 1. If the breakpoints in T_x and T_n are entirely randomly distributed and not
307 conditionally dependent such that the break in T_x has no *a priori*
308 distributional basis given a break in T_n , then it would be expected that there
309 would be more and larger breaks in DTR than in T_x or T_n and fewest in T_m .
- 310 2. If the breaks in T_x and T_n are conditionally dependent such that if the break
311 in T_n is positive it is more likely that T_x is also positive and vice-versa then
312 most and larger breakpoints would be expected to be found in T_x and T_n
313 with fewest in DTR or T_m (depending upon whether the conditioning was
314 weak (T_m) or strong (DTR))
- 315 3. If the breaks in T_x and T_n are conditionally independent such that a negative
316 break in T_n has a tendency to lead to a positive break in T_x and vice-versa
317 then it would be expected that most breaks would be found in DTR and they
318 would be substantially larger than in T_x and T_n with fewer, much smaller
319 breaks in T_m

320

321 3.2. Analysis of returned breakpoint adjustments from the PHA algorithm

322

323 The PHA algorithm (Section 2.2) was run on the subset of stations which had
324 sufficiently long records and for which sufficient neighbor estimates existed. The
325 data masks are exactly equivalent for T_m and DTR as they require T_x and T_n to both
326 be available (Section 2.1). For T_x and T_n some additional data exists for some

327 stations. However, to a first approximation the number of stations and record length
328 are equivalent for all four elements presented to PHA. Despite this similarity in
329 input data availability there exist marked differences in the estimated frequency,
330 magnitude and distribution of adjustments returned across the 4 elements (Figure
331 3). There are more adjustments returned for DTR (66,572) than for T_n (62,013), for
332 which there are more again than for both T_x (51,777) and T_m (50,378). The
333 standard deviation of the returned adjustment estimates is largest for DTR (1.24K),
334 roughly equivalent for T_x (0.98K) and T_n (1.00K), and smallest for T_m (0.75K).
335 There is no obvious substantial departure for any element from Gaussian
336 distributional assumptions. In all cases there is a 'missing middle' of undetectable /
337 unadjustable real-world breakpoints that must in reality exist.

338

339 Following from Section 3.1 if there is no difference in effective power of PHA to
340 detect and adjust for breaks between elements then the implication is that the
341 breakpoints in T_x and T_n are either entirely random or conditionally independent.
342 However, there are also reasons why DTR may be expected to exhibit lower noise as
343 it is the difference between two variables, T_x and T_n , which tend to co-vary on
344 monthly timescales. If the noise in the pairwise station comparators, which form the
345 basis for the breakpoint statistical assessment, was lower then it may simply be that
346 PHA can more efficiently detect smaller breakpoints from the 'missing middle'
347 clearly evident in all panels of Figure 3. It is obvious given the broader distribution
348 of DTR adjustments from Figure 3 that the increased number of breakpoints found

349 and adjusted in DTR results from larger discontinuities rather than any difference in
350 efficacy of breakpoint identification.

351

352 The breakpoint behavior can be further investigated by consideration of directly
353 inferred and indirectly inferred adjustment estimates for DTR and T_m (Figures 4
354 and 5). Breaks in the derived variables would be expected to be coincident in timing
355 and resulting magnitude with those estimated from the T_x and T_n analyses.

356 Comparing direct and indirect adjustment estimates therefore provides a check on
357 internal consistency of results. The direct and indirect adjustment estimates should
358 be correlated and show no overall offset from one another. Scatter would be
359 expected to arise due to variations in breakpoint date assignments and neighbor
360 segments used to adjust. The degree of scatter provides some indication of the
361 probable uncertainty in the resulting station series estimates.

362

363 For DTR these comparisons exhibit substantial scatter, even when a collocation
364 error of 12 months in the breakpoint locations found is allowed for (Figure 4 left
365 hand panel). There are many cases where either a DTR adjustment is made without
366 a corresponding adjustment to either T_x or T_n and vice-versa (points along either
367 $y=0$ $x \neq 0$ or $x=0$ $y \neq 0$ respectively). In numerous cases the adjustments differ in sign
368 (top left and lower right quadrants). Overall, however, there is a tendency to
369 broadly agree with the cloud of points scattered around the 1:1 line rather than
370 entirely randomly. The histogram of adjustment comparators (Figure 4 right hand
371 panel) is zero mean and broadly Gaussian, albeit with a large sigma such that almost

372 23% of differences exceed 1K in magnitude. A similar analysis of T_m (Figure 5)
373 exhibits far less scatter between directly and indirectly inferred adjustments (left
374 hand panel, points lie much closer to the 1:1 line) with only just under 5% of
375 differences exceeding 1K in magnitude (right hand panel).

376

377 Both direct and indirect adjustments to DTR act to reduce the apparent spread in
378 individual station linear trend fit estimates over 1901-2012 and 1951-2012 (Figure
379 6). This is consistent with what would be expected if reasonable adjustments were
380 being applied to data containing inhomogeneities. Individual station series in the
381 basic data contain systematic data errors. Such systematic effects are equivalent to
382 adding units of red noise to the time-series, causing artificial dispersion in the
383 distribution of long-term station series behavior. Figure 6 suggests that many such
384 systematic biases are being effectively removed in a reasonable manner by the PHA
385 algorithm.

386

387 3.3 Synthesis of adjustments analysis

388

389 Breakpoints are more easily discoverable using PHA in DTR than they are in T_x or
390 T_n which in turn are somewhat more discoverable than in T_m . Earlier analyses over
391 the European domain [Wijngaard et al., 2003] and globally using HadISD [Dunn et
392 al., 2014] found similarly that breakpoints in DTR were somewhat more amenable
393 to detection. Not only were more breakpoints found in DTR but they were on
394 average larger and had a broader standard deviation than other elements. When

395 calculated directly from DTR or indirectly from T_x and T_n adjustments, individual
396 adjustment estimates show similar behavior but with substantial dispersion.
397 Therefore care should be taken in interpretation of individual adjusted station DTR
398 series. However, the overall distribution of station trend estimates is less dispersive
399 following application of adjustments with many obviously questionably large
400 station trends removed. Taken as a whole this analysis provides confidence in the
401 efficacy of PHA when applied to DTR series at least at regional or global scales.

402

403 Overall, results from PHA strongly imply that breakpoints in T_x and T_n are either
404 randomly distributed or conditionally independent. Strong conditional dependence
405 whereby T_x and T_n breakpoints are almost always of the same sign and similar
406 magnitude can be ruled out by the present analysis. Reasons and implications are
407 returned to in the discussion (Section 5).

408

409 **4. Analysis of gridded fields and regional averages**

410

411 4.1 Data completeness

412

413 As with most preceding analyses of DTR [e.g. Vose et al., 2005] data is globally
414 incomplete and the data density in those areas sampled varies over at least two
415 orders of magnitude. Figure 7 shows gridbox DTR station data counts for the month
416 when data density is globally maximal (October 1987). Sampling is dense over
417 much of Australia, China and Japan, Europe and in particular North America.

418 Sampling is particularly poor (or even non-existent) over much of Africa, SE Asia,
419 the Arabian Peninsula, the Amazon basin and the ice sheets of Antarctica and
420 Greenland. Sampling varies substantively through time both globally and regionally
421 in those regions with records that extend back to the early 20th Century (Figure 8).
422 Outside North America there exists a step-change in availability in 1960 with far
423 fewer stations prior to this. As a result trends and variability in DTR for analyses
424 across 1960 may be an artifact of coverage changes rather than true changes. As
425 discussed further in Section 2.1 there likely exist records which if rescued digitized
426 and shared could mitigate this issue.

427

428 4.2 Diurnal Temperature Range

429

430 Herein analysis is made of changes in DTR from the original 'raw' data records and
431 following adjustments calculated directly and indirectly from applying the
432 adjustments returned to T_x and T_n and then calculating DTR from these series as
433 outlined in Section 2.3. The analysis starts with spatial patterns of trends over
434 increasingly shorter periods to present. Recourse is then made to regionally
435 averaged timeseries behavior and linear trend estimates.

436

437 4.2.1 Spatial trends

438

439 Trends calculated since the beginning of the 20th Century greatly reduce coverage if
440 a data completeness mask is applied to ensure early and late period data availability

441 in addition to total timeseries completeness (Figure 9 c.f. Figure 7). Data remain
442 only for N. America, Europe, parts of Australia, E. China and Japan and a handful of
443 dispersed additional locations. The spatial domains sampled in Figure 9 govern the
444 designation of sub-domains considered in subsequent regional analyses and
445 denoted henceforth by geographic shorthand as: N. America (45W-135W, 25-60N);
446 Europe (10W-60E, 25-60N); and Australia (110E-155E, 10S-45S). The cluster over
447 Japan and E. China is deemed too small to calculate a reasonable regional average.
448

449 Century timescale trends in DTR (Figure 9) are of the order 0.1K/decade at most
450 across the sampled gridboxes in the raw data and in the two adjusted products.
451 Trends are significant at the gridbox level in many of the gridboxes sampled in the
452 input data, but this decreases substantially following application of adjustments
453 either using the direct or the indirect approach. In the input data most gridboxes
454 exhibit a reduction in DTR over time. Although a majority of gridboxes still indicate
455 a reduction in DTR following the application of adjustments, the magnitude of the
456 DTR reduction is far less significant. Adjustments change the sign of the DTR trends
457 in much of the South Western / Western United States from negative to positive and
458 reduce the negative trends elsewhere in N. America. This change is more marked
459 when adjustments are calculated indirectly than when they are calculated directly.
460 There are less spatially consistent changes in remaining regions with many
461 gridboxes experiencing large changes including changing the sign of the DTR trend.
462

463 Starting in 1951 as expected from Figure 8, spatial sampling is much more complete
464 although Africa, the Indian sub-continent and S. America remain substantively
465 incompletely sampled in addition to Greenland and Antarctica (Figure 10). Over this
466 62 year period in the input data records the vast majority of gridboxes exhibit
467 substantial reductions in DTR that are particularly marked over much of Asia and N.
468 America. Application of adjustments substantively changes the trend behavior over
469 N. America where trends are reduced with a sign change in many gridboxes west of
470 the Rockies to an increasing DTR and very few gridbox series remain significant. In
471 Southern Europe adjustments indicate small increases in DTR. Overall, adjusted
472 series are visually somewhat more spatially homogeneous than the input data
473 trends lending some support to the findings detailed in Section 3 regarding the
474 efficacy of the PHA when applied either directly or indirectly to DTR records.

475

476 The last period for which geographical trends are considered is from 1979, a start
477 date typically used in climate studies because it is the advent of regular polar-
478 orbiter satellite measurements. Although the current analysis is in-situ only it is still
479 potentially informative to other studies to document changes over this period
480 (Figure 11). Over this period sampling is more complete again, particularly so over
481 South America although large areas remain data void. Since 1979 trends are
482 substantively larger in magnitude and of more mixed sign. That trends over shorter
483 periods are larger, more spatially heterogeneous, and of mixed sign is to be
484 expected as shorter periods increasingly reflect decadal-scale regional variability
485 [Santer et al., 2011]. Over this shorter period, the application of adjustments leads

486 to large changes in apparent sign and magnitude of DTR trends in many regions.
487 This is particularly marked in the United States, in parts of Europe and over much of
488 China and SE Asia.

489

490 Over the United States the adjustments in the post-1979 era lead to a change from a
491 slight reduction in DTR to a larger increase in many gridboxes. The adjusted DTR
492 increases are significant in several gridboxes in the South Western states. This
493 adjustment is consistent with understanding of the transition from Cotton Region
494 Shelters (CRS, termed Stevenson Screens elsewhere) to electronic Maximum
495 Minimum Temperature Sensor (MMTS) starting in the 1980s and substantively
496 completed by the late 1990s. In this change both the instrument and its shielding
497 were changed substantively, often associated with a change in measurement
498 location. This change affected roughly 70% of the COOP network, which is the
499 backbone of the US records. Field based studies and statistical analyses have
500 variously concluded that the CRS to MMTS transition led to a positive bias in T_n and
501 a negative bias in T_x artificially reducing DTR in the raw data [Fall et al., 2011,
502 Williams et al., 2012c and references therein]. Assuming that the PHA algorithm is
503 adequate the effect of this change is larger than the underlying real-world DTR
504 signal over much of the United States. The size of the effect found and adjusted for
505 here is consistent in magnitude with understanding from various side-by-side
506 comparisons under the assumption that c.70% of the network experienced the
507 change.

508

509 In Europe adjustments lend support to the propensity for increased DTR in recent
510 years [Vautard et al., 2009]. In China and SE Asia, although gridbox trends remain
511 significant the reductions in DTR are generally less following adjustment than is
512 implied by the raw data.

513

514 4.2.2 Regional and global timeseries and trends

515

516 As is visually obvious from Figures 9-11 linear trend estimates do not describe all
517 facets of the timeseries behavior globally or regionally. Timeseries for global (Figure
518 12) and regional (Figure 13) DTR averages serve to highlight the presence of
519 substantial interannual to multi-decadal variability in DTR even globally. In all cases
520 these timeseries have been derived from averaging all available gridded data at each
521 timestep using $\cos(\text{lat})$ area weighting. As noted earlier, given the varying station
522 count and gridbox availability care should be taken in interpretation in particular of
523 pre-1960 data. The effects of different completeness inclusion criteria for this step
524 are further discussed and analyzed in the accompanying paper [Thorne et al.,
525 submitted].

526

527 Following adjustments it is estimated that globally averaged DTR was elevated
528 relative to present day until the late 1950s, declined by of the order 0.2C by the
529 early 1980s and has then been relatively steady since according to both adjusted
530 series considered. There are substantial differences between directly and indirectly
531 adjusted series estimates prior to around 1950. Overall the adjusted series are more

532 similar to each other than they are to the input data both in terms of the long-term
533 trend and also decadal timescale variability. Globally adjustments have a substantial
534 impact in the most recent period since 2000 when (semi-)automation has been
535 prevalent across the global network as a whole (although some regions experienced
536 this change 10-20 years earlier), and prior to the 1970s.

537

538 Global and regional average trends are substantively impacted by the PHA
539 homogenization procedures. Adjusting either directly or indirectly the net effect is
540 to reduce the magnitude of the apparent long-term trends in global DTR (Table 1).
541 Nonetheless, trends towards globally reduced DTR are statistically significant over
542 the period 1901 to 2012 and the shorter sub-period 1951 to 2012 for the 'raw'
543 series and remain so for the adjusted series. Over the period 1979 to 2012 the
544 global mean trend reverses from a significant reduction in the 'raw' data, to a slight
545 increase in both of the adjusted series neither of which are statistically significant
546 (c.f. Figure 11 and associated discussion).

547

548 In North America the adjustments reduce DTR prior to 1950 and increase DTR since
549 the 1980s yielding a large reduction in the apparent narrowing of DTR implied by
550 the basic 'raw' data (Figure 13, top panel). As discussed previously post-1980
551 changes are consistent with understanding of the effects of transition from CRS to
552 MMTS across roughly 70% of the US observing network. Earlier period adjustments
553 may relate either to the effects of changes in time of observation [Karl et al., 1986]
554 or a propensity to relocate from city to airport locations. Trends over 1901-2012 are

555 significantly negative in the basic 'raw' data and both adjusted series, but are halved
556 in magnitude following adjustments. Over the two shorter periods considered
557 neither adjusted series exhibits significant trend behavior. Estimates are slightly
558 negative over 1951-2012 and slightly positive over 1979-2012 (Table 1). The two
559 adjusted series are very similar to each other and very distinct from the basic 'raw'
560 data behavior.

561

562 Over the European domain adjustments act to increase DTR both since the 1980s
563 and prior to the 1950s (Figure 13, middle panel). This yields a marked change in
564 multi-decadal variability in this region removing an apparent trend of increasing
565 DTR in the first half of the twentieth Century in the basic 'raw' data. On the longest
566 timescales this leads to an increased negative trend in DTR following adjustments,
567 which is significant in both adjusted estimates but not the basic data (Table 1). Over
568 1951-2012 again all estimates are significantly negative. Since 1979 both adjusted
569 series imply positive trends in DTR over the European domain taken as a whole but
570 these are not statistically significant. As is the case globally and over N. America the
571 adjusted series are much more similar to each other than they are to the basic 'raw'
572 data.

573

574 Australian DTR series exhibit far greater variability than those over Europe and
575 America (Figure 13, lower panel). Variability appears to be highly correlated with
576 continental scale aridity / rainfall (and by extension ENSO). For example the very
577 wet year of 2010/11 is associated with a marked negative DTR anomaly, consistent

578 with basic theoretical understanding of partitioning of fluxes [Peterson et al., 2011].
579 The effect of the adjustments is more muted for this region with slight increases in
580 DTR in the mid-20th Century and reductions in the early 20th Century. Trends are
581 generally not significant in the adjusted series with the exception of indirectly
582 adjusted series for 1901-2012 (Table 1) and confidence intervals are larger than for
583 other regions considered reflecting the much greater year to year variability in the
584 series. Over this region there is less obvious concordance between the adjusted
585 series.

586

587 4.3 Maximum and minimum temperatures

588

589 For T_x and T_n only direct adjustments exist so analysis is limited to the raw and
590 directly adjusted series. Trends over 1951-2012 for T_x (Figure 14) and T_n (Figure
591 15) both exhibit strong warming in the vast majority of the gridboxes that are
592 sampled. Adjustments remove an apparent cooling in T_x in the eastern United States
593 consistent with the United States Historical Climatology Network (USHCN) [Menne
594 et al., 2010] and our understanding of US biases arising from the CRS to MMTS
595 transition. Cooling in T_x in Southern China is also reduced and several obviously
596 erroneous gridbox series look more similar to surrounding series after
597 homogenization. Adjustments to T_n adjust several obviously erroneous gridbox
598 trends and increase slightly the apparent warming in eastern North America but
599 otherwise have little obvious effect at the gridbox scale.

600

601 Global average timeseries of T_x and T_n are strongly positive (Figure 16), particularly
602 since the early 1970s. Adjustments serve to narrow the difference in trends (which
603 is consistent with a reduction in the estimated rate of decrease in DTR in the
604 preceding subsection). The overall effect of PHA adjustments is to increase the long-
605 term trend in both T_x and T_n with the effect being larger for T_x (although the T_x
606 trend is still smaller than that for T_n , Table 2). Trends in T_x and T_n are highly
607 significant over all three periods considered in the present analysis and, in the
608 adjusted series, roughly an order of magnitude larger than DTR trends. Trends in T_x
609 and T_n are consistent with GHCNv3.2.0 trends for T_m even though the station basis
610 set differs substantially.

611

612 **5. Discussion**

613

614 The adjustments returned by the PHA algorithm strongly imply that breakpoints in
615 T_x and T_n are either random or conditionally independent. Random breaks would
616 mean that the break size and magnitude in T_n on average had no influence upon the
617 resulting break size and magnitude in T_x . Conditionally independent would imply an
618 overall tendency for T_x and T_n breakpoints to be of opposite sign such that they
619 partially or completely cancel in the mean. This raises two interesting questions:
620 first whether there are more optimal approaches to homogenization than analyzing
621 T_m as is commonly the case for global centennial timescale LSAT reconstructions to
622 date; and second why, metrologically, the over-arching tendency may be so.

623

624 5.1 Future homogenization efforts considerations

625

626 Homogenization of surface meteorological station records is inherently a signal-to-
627 noise problem. Small, relative to meteorological and climatological variability,
628 breakpoints arising for myriad reasons must be found and then accurately
629 quantified. Therefore it is important to search in an optimal direction. State of the
630 art algorithms like PHA perform pairwise comparisons that act to remove common
631 real-world variations between candidate nearby stations and leave a difference
632 series that in the absence of any biases in the two comparators should behave as iid
633 white noise arising from random measurement errors and real inter-site variability.
634 The white noise places a hard lower limit on signal detectability. No break will be
635 discoverable that is of comparable magnitude to the standard deviation of the
636 series. Yet, small breaks arguably matter substantively because they are systematic
637 effects that do not cancel, so methods should try to optimize breakpoint
638 detectability and adjustments whilst simultaneously minimizing false alarm rates.
639 All breakpoint algorithms return bivariate distributions (cf. Figure 3) that in reality
640 are the two wings of the true Gaussian distribution of real-world breaks with breaks
641 around zero not being found and / or adjusted for.

642

643 If the breakpoints in T_x and T_n were strongly conditionally dependent (similar sign
644 and magnitude) then searching for breakpoints in T_m would be quasi-optimal. The
645 further towards conditional independence of T_x and T_n breakpoints the less optimal
646 use of T_m series to locate and adjust for breakpoints will become as the dominant

647 direction of breaks becomes increasingly orthogonal to T_m (Figure 3). Section 3
648 strongly implies breakpoints are at best random, if not conditionally independent. If
649 the breakpoints are random then a search should be made in all four elements. If the
650 breakpoints are mainly conditionally independent then consideration could be
651 limited to DTR, T_x and T_n . Thus in future, homogenization procedures that search
652 for breakpoints in T_m , T_x , T_n and DTR simultaneously will very likely yield a more
653 accurate and optimal set of breakpoint locations.

654

655 Finding the breakpoints is just the first part of the problem. The resulting
656 adjustment estimates then need to be reconciled. Here, no such effort has been
657 made and instead the difference between direct DTR and indirect DTR adjustments
658 has been used to illustrate potential sensitivities. In future, efforts could be made
659 given a set of 4 adjustment estimates (or better still conditional density functions of
660 the adjustments) and a closure condition that the adjustments to T_x and T_n must
661 average to the adjustment of T_m and difference to the adjustment to DTR to form a
662 combined set of adjustments. Such an approach is being pursued to develop future
663 versions of GHCNM.

664

665 All of the above considerations are moot if the station series are only available as
666 T_m , as is the case for many of the stations in the current databank (Figure 1, lower
667 panel). Therefore to optimize future analyses of surface temperature changes over
668 land efforts should be made to recover T_x and T_n records for stations and periods of
669 record for which currently only T_m records exist in addition to rescuing that data

670 for new stations to improve both coverage and station periods of record [Allan et al.,
671 2011].

672

673 5.2 Why metrologically may breakpoints in T_x and T_n be random or conditionally
674 independent?

675

676 All meteorological temperature measurements are undertaken by a proxy that is
677 correlated with the target measurand be that the expansion of liquid, electrical
678 resistance or some other means. Ideally, the calibration processes for thermometers
679 would be defined by robust and well documented procedures, under highly
680 controlled conditions, leading to a full evaluation and definition of calibration
681 uncertainty components budgets and total values, according to the kind of sensors
682 used and environments experienced.

683

684 Far from being in thermal adiabatic condition, a thermometer used to measure air
685 temperature actually measures the mix of convective, radiative and contact heat
686 transfers. All of these thermodynamic effects are difficult to be corrected with an
687 uncertainty on the correction. Some devices permitting evaluation of the influence
688 of such parameters on the sensors under calibration are being developed, but are
689 still under experimental prototype status [Lopardo et al 2014, Merlone et al. 2014,
690 Musacchio et al. 2014]. Moreover, since the calibration is performed in stable
691 temperature conditions, while the measurement of daily air temperature
692 fluctuations is anything but stable, sensor dynamics can introduce deviations due to

693 the response inertia and delay, not evaluated during calibration. For example, the
694 behavior of two different thermometers calibrated both in a climatic chamber and in
695 a liquid bath, was compared to their performance in a Stevenson Screen (CRS)
696 (Grykalowska, 2014). While both the controlled calibration methods resulted in
697 consistency within uncertainty, when placed in the Stevenson Screen, the readings
698 of the two thermometers differed by substantially more than the sum of their
699 calibration uncertainties, demonstrating that hitherto unaccounted for sensor
700 dynamics effects remained.

701

702 In the atmosphere there are two critical aspects: the response to heat transfer
703 effects; and dynamic behavior in capturing temperature fluctuations. Having long
704 established and recognized the difficulties in estimating the errors induced by these
705 quantities of influence on the sensors there have been the attempts to reduce the
706 effects through e.g. screens protecting from direct radiation on the sensing element,
707 reduced contact surface with the supporting structure, models to minimize the
708 convective effects, and ventilation to reduce extra heating due to stagnant air. The
709 range of measurement, shielding and mounting techniques likely yields differing
710 error characteristics across the meteorological networks, which further are likely to
711 be climatically dependent.

712

713 In principle, three physical co-variates shall influence the temperature
714 measurements: radiation, wind speed and humidity. In days with wind blowing and
715 limited sun radiation these effects are expected to be of low amplitude regardless of

716 instrument configuration whereas in days with sun, absence of wind and larger
717 night-day temperature fluctuations the effects would be maximal. Such conditions
718 amplify the possible differences in DTR recording arising from changes in
719 instrumentation and practices through time.

720

721 There are two broad classes of instrumentation: artificially aspirated and non-
722 aspirated. Artificially aspirated measurements exhibit substantially lower
723 sensitivity to prevailing meteorological conditions so long as adequately screened
724 from direct and indirect radiative effects. They may tend to read slightly high during
725 daytime due to imperfect shielding from radiation or thermal contact and slightly
726 low during nighttime due to cooling effects from condensation of the drawn air.

727 Non-aspirated measures will exhibit substantially greater sensitivity to prevailing
728 meteorological conditions. On average the measures may be warm biased for both
729 T_x and T_n due to a mix of radiative and ventilation effects. The biases will be highly
730 dependent upon configuration and site micro-environment. The change from CRS to
731 MMTS (both non-aspirated but very distinct) had differential effects on T_x and T_n
732 with T_x decreasing and T_n increasing. Changing from non-aspirated to aspirated
733 measurements will tend to yield an apparent and spurious increase in DTR that is
734 larger than any concurrent change in T_m .

735

736 5.3 Caveats pertaining to use of current data products

737

738 For analyses of DTR using the dataset constructed herein, the effects of the changing
739 station availability through time are potentially an insidious effect. The primary
740 effects are two-fold. Firstly changing the neighbor constraint substantively through
741 time will affect the efficacy of any homogenization algorithm and PHA is not
742 immune to this. Secondly, the changing data mask may confound a clean
743 interpretation of global and regional trends even if the data were perfect (which
744 they are not). Care should be taken in interpreting pre-1960 records when the
745 station mix changes substantively both globally and regionally.

746

747 **6. Dataset availability**

748

749 The dataset is made available through [website to be appended here once decided,
750 can we host through NUIM?]. The following series shall be made available:

- 751 • Adjusted station series as CF-compliant netcdf files (one per station)
752 containing several timeseries fields.
- 753 • Gridded raw and adjusted series for T_x , T_n and DTR (including indirectly
754 adjusted) as CF-compliant netcdf files (a total of 7 files)

755 At this time there are no plans to update the series beyond 2012. Dataset users
756 should cite this paper.

757

758 **7. Conclusions**

759

760 The present analysis has re-examined changes in DTR globally and regionally using
761 improved holdings and NCDC's PHA algorithm. Adjustments to the basic 'raw' data
762 have a non-negligible impact upon the resulting series behavior on multi-decadal
763 timescales and are comparable in magnitude to the apparent trend in the basic 'raw'
764 data globally and regionally. DTR is estimated to have decreased globally since the
765 mid-twentieth Century but the adjustments reduce by half the trend compared to
766 that in the basic 'raw' data. Both maximum and minimum temperatures have
767 increased rapidly and changes in these elements are an order of magnitude greater
768 than in DTR globally. Adjustments are more prevalent in DTR than in T_x or T_n ,
769 which in turn are more common than in T_m . This implies that overall the biases in
770 T_x and T_n are either random or conditionally independent and has potentially
771 important implications for future homogenization strategies. It implies that
772 searching for and adjusting breaks in average temperatures is likely to be sub-
773 optimal as the signal to noise ratio will tend to be a minimum in average
774 temperatures. Instead efforts that search in addition for breakpoints in DTR, T_x , and
775 T_n would likely be more efficient at finding and adjusting for non-climatic artifacts
776 in the records.

777

778

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780

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784

785

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