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Temperature extreme records: World Meteorological Organization metrological and meteorological evaluation of the 54.0°C observations in Mitribah, Kuwait and Turbat,

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**World Meteorological Organization Evaluation and  
Calibration Testing of 2016/17 temperatures of 54.0 °C  
recorded in Mitribah, Kuwait and Turbat, Pakistan as Record  
Temperature Extremes**

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1 **World Meteorological Organization Evaluation and Calibration Testing of 2016/17**  
 2 **temperatures of 54.0 °C recorded in Mitribah, Kuwait and Turbat, Pakistan as Record**  
 3 **Temperature Extremes**

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**40 Abstract:**

41 A World Meteorological Organization (WMO) committee officially evaluated temperature record  
42 extremes of 54.0 °C at two locations, one in Mitribah, Kuwait on 21 July 2016 and a second in Turbat,  
43 Pakistan on 28 May 2017. The committee agreed that quantity and quality of documentation of both  
44 observations were excellent. Additional metrological testing of the equipment focused on three  
45 aspects: the calibration of both thermometers, an effort to estimate the factors influencing the  
46 measurements and a direct comparison of the two thermometers when exposed simultaneously to 54  
47 °C. The metrological analysis's conclusion for the Mitribah value is a temperature estimated to be 53.87  
48 °C with an expanded uncertainty of  $\pm 0.08$  °C. Correspondingly, for the Turbat value the temperature is  
49 estimated to be 53.72 °C with an expanded uncertainty of  $\pm 0.40$  °C. Following that analysis, the  
50 committee recommended acceptance of the calibrated observations to the first decimal digit such that  
51 the Mitribah observation is accepted as 53.9 °C  $\pm 0.1$  °C and the Turbat as 53.7 °C  $\pm 0.4$  °C. The  
52 Mitribah, Kuwait temperature is now accepted by the WMO as the highest temperature ever recorded  
53 for Asia (WMO RA II) and the two observations are the third (tied within uncertainty limits) and fourth  
54 highest WMO-recognized temperature extremes and, significantly, they are the highest, officially-  
55 recognized temperatures recorded in the last 76 years. This evaluation has involved the most extensive  
56 temperature extremes analysis ever been undertaken by an international evaluation committee of the  
57 WMO CCI Archive of Weather and Climate Extremes.

58 Key words: **Temperature Extreme, Middle East, Metrology, Calibration, Uncertainty**

**59 1. Introduction**

60 The World Meteorological Organization (WMO)'s Commission for Climatology (CCI) has created an  
61 online archive of officially recognized weather and climate extremes (e.g., highest recorded global  
62 temperature, strongest wind speed, most deadly tropical cyclone). That WMO Archive of Weather and  
63 Climate Extremes (<https://wmo.asu.edu/>) currently recognizes the 56.7 °C temperature recorded at a  
64 location in Death Valley, USA in 1913 as the hottest temperature for the globe, for the Western  
65 Hemisphere and for Northern Hemisphere. The organization also recognizes 55.0 °C temperature  
66 recorded in Kebili, Tunisia in 1931 as the hottest temperature recorded in Africa and 54.0°C  $\pm 0.5$ °C  
67 temperature recorded in Tirat Tsvi (Tirat Zevi), present-day Israel in 1942. Two locations, one in Kuwait  
68 in 21 July 2016 and another in Pakistan in 28 May 2017, recorded temperatures of 54.0 °C. If verified,  
69 those temperatures would be recognized as the highest temperatures recorded for Asia (WMO RA  
70 region II) and the two observations would be the third highest WMO-recognized high temperature  
71 extremes and, significantly, the highest, officially-recognized temperatures recorded on the planet in the  
72 last 76 years.

73 Consequently, an international panel of atmospheric scientists was tasked with an analysis and  
74 verification of the 54.0 °C temperatures recorded in Kuwait and Pakistan in 2016. As this very detailed

75 and comprehensive evaluation sets a new and very high standard for acceptance of new temperature  
76 extremes, the evaluation's specifics contain important information for the scientific community, and for  
77 the public and media at large. In particular, detailed discussion of the temperature sensor calibration  
78 testing is given for use in future extreme temperature assessment.

## 79 **2. Metadata for Mitribah, Kuwait and Turbat, Pakistan**

80 Starting in late 2016, a WMO committee was tasked with evaluation of two purported occurrences of a  
81 temperature of 54 °C, specifically on 21 July 2016 at Mitribah, Kuwait and on 28 May 2017 at Turbat  
82 Pakistan. Background information of each station's observation was collected.

83 The Mitribah, Kuwait (WMO#40551) station is located at 29°49'N, 47°21'E (Figure 1). The station is  
84 automated and began operation in 2006. Temperature measurements are based on the uses of a  
85 HMP155 from Vaisala mounting a resistive platinum sensing element (Pt100). The sensor is covered by  
86 a naturally ventilated Vaisala DTR13 shield. Data are recorded at a one-minute interval by means of an  
87 Almos datalogger. Detailed equipment history logs were obtained along with photocopies of the actual  
88 observation log. Maps of the installation site as well as photographs of the station site were shared with  
89 the WMO evaluation committee.

90 The Turbat, Pakistan (WMO#41738) station is located at 25°59'N, 63°04' E (Figure 1). The station began  
91 operation in 1997 and with measurements manually recorded. Air temperature is measured with a  
92 mercury in glass thermometer, DDE 7461 manufactured by G.H Zeal, England, which is kept in a  
93 Stevenson screen located 2 m above ground. Detailed equipment history logs were given to the  
94 committee along with photocopies of the actual observation logs, photographs of the station sites, and  
95 maps of the installation site. Calibration history of the thermometer was given to the committee.

96 The national meteorological units of Kuwait and Pakistan shared with the WMO committee extensive  
97 weather data of their respective stations prior to and proceeding from the time of the record  
98 observations (Supplemental materials). This allowed evaluation committee members to ascertain the  
99 degree to which the extreme observation is in context with observations at the same location prior to  
100 and following the extreme occurrence. Contextual temporal consistency in observations, for example,  
101 was not evident in an earlier WMO committee's evaluation of a 1912 observation of 58 °C in El Azizia  
102 Libya and led, in part, to a refutation of that extreme (El Fadli et al. 2013).

103 Additionally, both Kuwait and Pakistan supplied the evaluation committee with detailed weather data  
104 for surrounding stations to Mitribah and Turbat respectively. This allowed the evaluation committee to  
105 assess the geographic consistency existing across the entire region at the time of the purported  
106 extreme. Geographical consistency in observations, for example, was also not evident in the El Azizia's  
107 1922 observation.

108 Unanimously, the committee was quite impressed with the degree and quality of documentation  
109 associated with both observations. Data from both locations show good temporal consistency (e.g., the  
110 record observation was not a "spike" that failed to closely replicate data earlier or later at that location)  
111 and good geographic consistency (e.g., the surrounding stations, while obviously not exceeding the  
112 record observations, demonstrated a good degree of agreement in temperature change and magnitude  
113 with the extreme-recording station). The committee's analysis of the synoptic weather situation for  
114 both high temperature extremes indicated the presence of a large upper air ridge capping a strong  
115 surface high pressure system consistent with producing high surface air temperatures.

116 However, at this point in the discussion, the committee balked on recommending acceptance. They  
117 urged that both sensors be independently calibrated and possibly compared to ensure that the data  
118 were as accurately obtained as possible. This additional request has never before been made in a WMO  
119 evaluation committee of a record weather observation. It sets a new and higher standard than any  
120 previously accepted extreme.

121 The committee suggested that detailed investigation could achieve a quite reliable estimation of  
122 uncertainty associated to a recorded air temperature value, specifically instruments calibration  
123 uncertainty and measurement condition associated uncertainty. Moreover, the unique situation of  
124 having the same measured temperature values of 54.0 °C in both records makes the comparison of the  
125 sensors, when exposed to 54 °C, an unparalleled aspect to the study. Italian National Institute of  
126 Metrology (INRiM) staff was requested to join the evaluation committee. Recent work at INRiM included  
127 research activities and scientific production of direct interest for the present study: development of  
128 specific calibration systems and procedures (Musacchio et al. 2016), also for application in extreme  
129 environmental conditions (Musacchio et al. 2015), inclusion of changes in temperature standards for  
130 temperature series and extremes (Pavlasek et al. 2013), and specifically with the coordination of the  
131 large European project "MeteoMet – Metrology for Meteorology (Merlone et al. 2015, Merlone et al  
132 2017).. Both the Mitribah and Turbat stations were asked to send the thermometers that recorded the

133 top temperature values to INRiM, where staff was made available for this specific study that requested  
134 specific calibration and comparison procedures. The Kuwait sensor was sent to INRiM in May 2017,  
135 while the Pakistan sensor arrived in January 2018. Details of the metrology analysis are given in Section  
136 3 for the Mitribah sensor and in Section 4 for the Turbat sensor. Section 5 details a direct comparison  
137 test of the two sensors. The analysis was made following the definitions and prescriptions of the Guide  
138 to the expression of uncertainty in measurement “the GUM” [JCGM 100:2008]

### 139 **3. Metrology Analysis (Mitribah, Kuwait sensor)**

#### 140 **3.1 Instrument Calibration**

141 The Kuwait HMP155D was calibrated at INRiM on 12 to 16 June 2017 using the procedure for calibration  
142 of thermometers PT-T.3.3-01 Rev2, associated to the Institute’s Calibration and Measurement Capability  
143 (CMC) as contained in the appendix C of the Mutual recognition Arrangement (MRA) of the CIPM, the  
144 International Committee for weights and measures (Comité International des Poids et Mesures). The  
145 CIPM MRA was signed also by WMO on 1 April 2010. The calibration results were reported in the  
146 calibration certificate n. 17-0496-01 issued on 2017-06-22. The calibration was made by comparison  
147 against a reference traceable to the ITS-90 fixed points in a comparator block inside the reference  
148 humidity generator. The sensor was positioned at 45° facing downward to avoid the embedded  
149 electronics warming the sensing element. The calibration was performed in air flowing at 0.04 m/s and  
150 with 50 %rh. The calibration uncertainty accounts for 0.06 °C and takes into account all contributions  
151 including the reference sensors, the calibration mean, the sensor's stability during calibration and its  
152 resolution.

153 The calibration demonstrated a deviation of the thermometer’s reading in line with the instrument  
154 specification and declared uncertainty. The thermometer’s sensing element is a Pt100 resistance  
155 thermometer, a platinum wire with nominal resistance of 100 Ω at 0 °C. The instrument output was  
156 recorded in resistance  $R$  and the temperature conversion  $T_{\text{calc}}$  was obtained applying the curve used by  
157 the Almos datalogger for the conversion, at the Mitribah station using equation (1).

$$158 \quad T_{\text{calc}} = [(R-100.0)/0.39082] + (5.802/39082.0) * [(R-100.0)/0.39082]^2 \quad (1)$$

159 The calibration points and results are reported in Table 1.

160 Consequently, the calibration correction at 54 °C was -0.12 °C with a calibration uncertainty of 0.06 °C  
161 ( $k=2$ ), being  $k$  the numerical factor used as a multiplier of the combined standard uncertainty in order to  
162 obtain an expanded uncertainty to cover 95 % of the distribution.

### 163 **3.2 Evaluation of measurement uncertainty components**

164 Full evaluation of measurement uncertainty for near-surface air temperature records using contact  
165 thermometer is not a trivial issue due to the numerous quantities of influence and non-perfect  
166 knowledge of the amplitude of their effects on different typologies of instruments and under different  
167 conditions. Moreover, evaluating an uncertainty budget “back in time” presents some difficulties. As  
168 reported above, the Kuwait Mitribah station measured and kept record of the main atmospheric  
169 variables: this is of fundamental help in this validation process. The main effects requiring qualitative  
170 and quantitative analysis are: wind speed at the time of the record, solar shield aging in terms of  
171 increased heat transferred to the sensor, datalogger contribution, sensors self-heating, sensor stability  
172 or drift in years.

### 173 **3.3 Solar shield aging**

174 Previous work [Lopardo et al. 2014] evaluated the effect of aging of solar shields in atmospheric  
175 thermometers. That analysis considered that exposure to meteorological conditions over time reduces  
176 the shield’s white-painting reflectivity, thus slowly introducing a temperature increase to the sensor  
177 reading. In this work three Vaisala screens were involved, a brand new one, a three-years old screen and  
178 a five-year old screen, equipped with the same sensors, calibrated in a climatic chamber were compared  
179 using identical thermometers. The results of this study are therefore interesting for this record  
180 validation, since the screen used at the Mitribah station is also in this case a Vaisala one and is three  
181 years old.

182 Experiments carried out on the five-year old and three-year old screens confirm the existence of shield  
183 ageing effect due to the degradation of the protective paint, in both cases. However, as expected, this  
184 effect is more evident when comparing shields with longer time of field use. The work also took into  
185 account the effect of wind on the magnitude of the aging contribution to temperature deviations. The  
186 differences between one-year and three-year old screens were distributed around 0 °C with a *thermal*  
187 *noise* of about 0.06 °C in presence of wind between 3.5 m/s and 5 m/s (as the case of Kuwait).

188 To evaluate the uncertainty associated to the aging, we therefore considered the max-min difference =  
189  $0.06\text{ }^{\circ}\text{C}$  as a rectangular distribution (uniform-shape probability function) with associated standard  
190 uncertainty equals to  $0.06 / (12)^2$ . This makes the contribution to the standard uncertainty due to the  
191 aging of about  $\pm 0.02\text{ }^{\circ}\text{C}$  (thus  $\pm 0.04\text{ }^{\circ}\text{C}$  with  $k=2$ ). Consequently, the solar shield aging correction was 0  
192  $^{\circ}\text{C}$  with a solar shield aging uncertainty:  $\pm 0.04\text{ }^{\circ}\text{C}$  ( $k=2$ ).

### 193 **3.4 Datalogger contribution**

194 Any electronics interface contributes to the uncertainty of an associated measurement. The magnitude  
195 of the uncertainty for the sensor with its electronic interface needs to be determined if a combined  
196 uncertainty for the measurement network is to be gauged. The data process and collection unit used at  
197 the Mitribah station is an ALMOS datalogger. Among the numerous activities on performance tests of  
198 Automatic Weather Station (AWS), WMO delivered a report made by Bruce Forgan [WMO 1999] on  
199 ALMOS AWS MSI2 - Sensor Interface Card Testing. This work evaluated the effect of the datalogger in  
200 the output of the different sensors potentially associated to the AWS, including the temperature value  
201 as translated from a resistance measurement. The board was also tested for effects of ambient  
202 temperature on the temperature measurements, in particular, on the electronics used for temperature  
203 measurement. The system was placed in a climatic chamber and exposed to temperatures up to  $55\text{ }^{\circ}\text{C}$ ,  
204 thus in line with the present work. Decade box resistors were used to input the resistance in  
205 temperature channels. The 95% uncertainty in the average of the measurement of the entire  
206 temperature range was no greater than  $0.0007\text{ }^{\circ}\text{C}$ , which represents the repeatability of the system. This  
207 value is a negligible contribution in the present study. On the contrary, at a resistance close to the one  
208 read by the HMP155 at  $54\text{ }^{\circ}\text{C}$ , the Almos logger showed a deviation from the input resistance equivalent  
209 to  $-0.01\text{ }^{\circ}\text{C}$  with an uncertainty of  $\pm 0.02\text{ }^{\circ}\text{C}$  ( $k=2$ ). In any case, the accuracy over the range of  $-10\text{ }^{\circ}\text{C}$  to  
210  $+55\text{ }^{\circ}\text{C}$  met the specification as laid out in Equipment Specification A2672 of  $\pm 0.05\text{ }^{\circ}\text{C}$ . For this  
211 investigation, the value measured in the report are considered to avoid over-estimation of uncertainty  
212 for the single  $54\text{ }^{\circ}\text{C}$  point. Consequently, the datalogger correction was  $-0.01\text{ }^{\circ}\text{C}$  with associated  
213 uncertainty of  $\pm 0.02\text{ }^{\circ}\text{C}$  ( $k=2$ ) and with datalogger repeatability considered to be negligible.

### 214 **3.5 Self-heating**

215 The HMP 155 is a platinum resistance thermometer. The measurement of temperatures with this type  
216 of thermometer necessarily requires the pass of an electrical current through the thermometer's  
217 sensing element. The resistance of the thermometer is then calculated by observing the generated

218 voltage and using the Ohm's law. This electrical current heats the thermometer element, by the Joule  
219 effect, causing a difference between the temperature of the sensor and the temperature to be  
220 measured. This effect is known as the self-heating. The sensor self-heating is usually determined in  
221 calibration laboratories under fixed conditions of temperature and wind speed but these conditions are  
222 highly variable when the thermometer performs air temperature measurements under real  
223 environmental conditions.

224 In the framework of European project MeteoMet [Merlone et al. 2015, Merlone et al. 2017] the self-  
225 heating of HMP 155 sensors was evaluated both in climatic chamber and in wind tunnel [Izquierdo et al.  
226 2018]. Results of this study showed a significant contribution to temperature records due to self-  
227 heating. Moreover, the study showed differences of the same magnitude of the effect itself depending  
228 on whether the thermometer is calibrated in bath or in air. Considering that in the majority of the  
229 meteorological and climate applications the air temperature is the quantity to be measured, if the  
230 thermometers have been previously characterized in stirred liquid baths, the error due to self-heating  
231 can be under-estimated when on site temperatures are being performed. For this reason, the study  
232 mentioned and the present evaluation of the record both focused on tests in air. The temperature  
233 increase was evaluated to range up to more than 0.5 °C in case of currents of 3 mA in climatic chamber  
234 with 0.3 m/s of air flow. The uncertainty was evaluated to be 0.015 °C ( $k=2$ ). At increasing airflow, the  
235 heat added by the passing current is removed by convection. The investigation continued in wind tunnel  
236 to evaluate the self-heating change when sensors are exposed to winds up to 5 m/s. As expected, higher  
237 wind speeds caused the heat brought by the current to the sensor to be removed by increasing  
238 convection. At wind speed of 5 m/s, close to the air velocity recorded at the time of the record, the self-  
239 heating was evaluated to be 0.027 °C.

240 For this record evaluation, the HMP 155 was calibrated, tested and measured in climatic chamber and  
241 any investigation in liquid was avoided. In the climatic chamber, airflow is approximately around  
242 0.04 m/s. The calibration is so made with the sensor in heat equilibrium with the convection and self-  
243 heating at such wind speed. The calibration curve therefore already keeps into account the self-heating,  
244 which cannot be reduced to zero, as in standard thermometry, where measurements at multiple  
245 currents are made. For this reason, the value recorded in Mitribah at 2 pm of 2016-07-21 under a wind  
246 speed of 5.5 m/s does not require a correction with respect to the calibration value, due to self-heating  
247 which is already included in the calibration procedure that is made at lower air velocity. No correction is

248 then applied for the self heating effect in field, with respect to the calibration correction, while a self  
249 heating uncertainty contribution of  $\pm 0.015$  °C ( $k=2$ ) is included.

### 250 **3.6 Sensor drift**

251 Platinum resistance thermometers are quite stable sensors. Their drift is normally very low and allows  
252 calibrations to be scheduled at more than one-year intervals. One-year recalibration is recommended  
253 for reference climate observations. Such sensors are moreover also quite stable at temperature changes  
254 in the range  $-40$ ° C to  $+60$  °C and do not present significant hysteresis, as also studied in MeteoMet.  
255 Despite such advantage and due to the importance of the measurement here investigated, since the  
256 HMP 155 involved in this investigation arrived at INRiM for calibration about one year after having made  
257 the record measurement, it is important to make an evaluation of the drift of the sensor, if any, and the  
258 associated uncertainty. For this purpose, three different and independent analysis contributed to  
259 evaluate the drift and associated uncertainty: a) Vaisala study, b) Field exposure effect on drift made  
260 during MeteoMet (2013-2015) and c) Specific laboratory analysis carried on at INRiM for this study.

#### 261 **3.6.1 Vaisala study.**

262 Due to its ongoing active collaboration within the MeteoMet consortium, Vaisala has direct links with  
263 the metrology community. For this specific record investigation, Vaisala provided relevant information  
264 about a drift analysis for 21 HMP155D probes that have been calibrated at  $40$  °C at least twice within  
265 twelve months during three years (2014-2017). Most of the analyzed sensors have operated in Vantaa,  
266 Finland where temperature typically varies between  $-15$  °C and  $+25$  °C; all calibrations reached  $40$  °C.  
267 Ideally, it would have been better to do drift analysis for sensors that have operated in similar conditions  
268 to the sensor in Kuwait, but there is not enough calibration data available in order to do statistically  
269 significant analysis for such sensors. However, the drift analysis should represent well also the sensor in  
270 Kuwait. Weather conditions in Kuwait, where temperature do not reach such low values, cause less  
271 stress to the platinum sensor than in Finland, so annual drift is hardly more than in Finland. Results of 40  
272 repeated calibrations are reported in the following graph where difference of calibrations curves one  
273 with respect to the previous one are plotted. Using Figure 2, it is possible to evaluate that long-term  
274 drift is centered to  $0$  °C with an uncertainty (rectangular) mainly within  $\pm 0.02$  °C, with exception of an  
275 outlier compensated immediately after.

276 In addition to this drift analysis, the sensor manufacturer was asked about long-term stability of the  
277 platinum sensor used in HMP155D. They test sensors according to DIN EN 60751:2009. In practice, this

278 means 1000 hours at highest temperature. They also answered that they have never observed any drift  
279 at temperatures between 0 - 200 °C.

### 280 **3.6.2 Field exposure effect on drift made during MeteoMet (2013-2015)**

281 During the MeteoMet project, an effect of environmental conditions on characteristics of temperature  
282 sensors used by meteorological services was studied by three Polish institutions: Central Office of  
283 Measures, the Polish National Institute of Metrology, Institute of Low Temperature and Structure  
284 Research acting as Designated Institute in charge of maintaining the national temperature standard in  
285 Poland and University of Wrocław. The aim of this study, carried out over a two years period, was to  
286 investigate the factors affecting meteorological air temperature thermometers during normal  
287 operational work, which have an influence on sensor characteristic variability and uncertainty. Several  
288 series of calibration were performed just after an exposition of the thermometer to different  
289 atmospheric factors such as high humidity, high and low temperatures and rapid temperature changes.  
290 This study surpassed the values of exposure met by the sensor in Kuwait, but contains important  
291 information for this validation process. The repeated calibration after having exposed the sensor to  
292 conditions met in Kuwait, were made up to 50 °C thus giving significant contribution to this study. This  
293 allows to include a further aspect on the sensor stability from the time the record was measured and the  
294 time the instrument was calibrated.

295 The uncertainty on this evaluation ranged up to  $\pm 0.09$  °C ( $k=2$ ) with exposure of the thermometer down  
296 to temperatures well below those met in Kuwait and at constant 100 % relative humidity for months  
297 (Table 2). This uncertainty limit is in any case of the same order of magnitude as the one here evaluated.  
298 Such major value of course arises from the more extreme and accelerated changes.

299 Figure 3 shows the calibration curves obtained according to the treatment sequence of exposure as  
300 given in Table 2. It is of interest for this investigation that the second and third cycles were more similar  
301 to the conditions in Kuwait and consequently the differences between calibrations number 3 and  
302 number 4. Moreover, before and after both second and third cycles the thermometer was calibrated up  
303 to 50 °C thus forcing also under calibration a temperature range similar to the one here of interest.

304 Considering the plots of calibration 3 and 4 in Figure 3, temperatures around 50 °C demonstrate a  
305 repeatability of about 0.03 °C. This value differs from the one declared by Vaisala, since it is based on an  
306 used thermometer, already exposed to a number of conditions such as quick changes as well as forced

307 and amplified thermal shocks. Additionally, the Vaisala calibration was limited to 40 °C, according to a  
308 general use in Finland, while the Polish test raised up to 50 °C.

309 The calibration uncertainties associated to the repeatability contribution evaluated both by Vaisala and  
310 in the MeteoMet study are respectively  $\pm 0.07$  °C and  $\pm 0.09$  °C: these values do not have to be added as  
311 source of uncertainty in the record investigation, since it has already been included as composition of  
312 the contributions of the calibration performed for the purpose at INRiM. This repeatability becomes  
313 then a source of uncertainty itself.

### 314 **3.6.3 Specific laboratory analysis for this study**

315 The Kuwait sensor was tested at INRiM for its repeatability when exposed to different temperatures.  
316 Four cycles of temperature changes were performed between 15 °C and 55 °C from September 2017 to  
317 March 2018. Due to this specific research, values were measured in terms of maximum change of  
318 readings at 54 °C, after thermal cycles, evaluated as differences with respect to reference thermometers  
319 in climatic chamber. Relative humidity was controlled during the cycles and ranged from 50 % to short  
320 exposure to 85 %.

321 The result of this repeatability test resulted for the Kuwait HMP 155 in line with the previous reported  
322 investigations, with a drift of no more than 0.04 °C all over the test duration and period. Considering this  
323 contribution having a rectangular distribution, centered symmetrically around 0 °C, the corresponding  
324 uncertainty is  $\pm 0.023$  °C ( $k=2$ ) with drift correction 0 °C.

### 325 **3.7 Measurement value and uncertainty for the Kuwait record**

326 The total uncertainty budget on the measured value of 54 °C for the Kuwait sensor is reported in Table  
327 4, together with the associated corrections. All contributions are reported as expanded uncertainties in  
328  $k=2$  Therefore, the fundamental results of the metrology test for the Mitribah Kuwait thermometer  
329 reading of 54 °C is that the calibrated temperature is  $53.87$  °C  $\pm$   $0.08$  °C.

## 330 **4. Calibration Analysis (Turbat Pakistan)**

331 The sensor used at the Turbat station in Pakistan is a mercury in glass thermometer made in England by  
332 G.H.Zeal number DDE7461 range -10 °C to 65 °C. No calibration report is present nor is a recent  
333 calibration certificate available and therefore, as in the case of the Kuwait sensor, the validation process  
334 requires the calibration of the thermometer. Normally such sensors are calibrated in liquid bath at

335 stable temperature and in adiabatic condition with the calibration mean, to have their readings  
336 associated to a reference thermometer also inserted in the same bath. Due to the specific purpose of  
337 this investigation, it was considered more significant to perform a calibration in air, to better represent  
338 the measurement conditions with the calibration process. No internationally recognized and accepted  
339 standard guidelines are at present available for the calibration of thermometers in air, and this is still an  
340 open issue under discussion both within the international metrology community as well as by WMO.  
341 Internal procedures are adopted, but a defined standard is not available. A project will start on this topic  
342 in 2018 by the European metrology organization, EURAMET.

343 A specific procedure was therefore adopted for the calibration of this thermometer in air. The  
344 thermometer was placed in a climatic chamber together with three INRiM Pt 100 thermometers coded  
345 GS01, GS02, NS02, NS05. The three Pt 100 are secondary thermometers directly traceable to the  
346 primary standards through a calibration by comparison against primary ones calibrated at ITS-90 fixed  
347 points. They were positioned close to the bulb of the Turbat thermometer, in a volume of a few cubic  
348 centimeters, to constantly evaluate the components due to the uniformity and stability, reported in the  
349 uncertainty table. The chamber used and the method is the one presented at the 2016 world  
350 meteorology exposition with the WMO TECO and called 'Meteocal.' It is based on a Kambic climatic  
351 chamber, a Fluke 1586A Super DAQ Precision temperature scanner equipped with m2588 STAQ  
352 Multiplexer unit. According to the temperature range occurring in Turbat, the calibration was made  
353 between 0 °C and 60 °C at the following points: 0 °C, 20 °C, 40 °C, 54 °C and 60 °C. The calibration  
354 showed a linear response of the thermometer and originated a calibration curve.

355 A general problem of the mercury-in-glass thermometer is that an air bubble can form in the liquid  
356 mercury column, thus introducing systematic errors in the readings and affecting the reproducibility. It is  
357 assumed that the thermometer was in correct operating condition at the time of the record; during tests  
358 and calibration at INRiM at the occurrence of the bubble formation, due mainly to handling and thermal  
359 cycles, the bubble was removed by slightly shaking the thermometer to allow mercury column to re-  
360 compact. The Pakistan thermometer was calibrated in vertical position and checked at 54 °C both in  
361 vertical and horizontal position showing no changes in the 54 °C indication.

362 The resulting calibration curve is close to linear with a constant term of -0.33 °C and is the following:

363 
$$T_{\text{cal}} = T_{\text{read}}^2 * a + T_{\text{read}} * b + c \quad (2)$$

364 where  $a = -9.181 \times 10^{-5} \text{ }^\circ\text{C}^{-1}$ ,  $b = 1.006$ ,  $c = -0.333 \text{ }^\circ\text{C}$ ,  $T_{\text{cal}}$  is the temperature value corrected by the  
365 calibration curve, and  $T_{\text{read}}$  is the temperature marked on the sensor.

366 The residuals of this curve were accounted to determine the fitting uncertainty and originated a value of  
367  $\pm 0.03 \text{ }^\circ\text{C}$  all over the range. The uncertainty components for such calibration are reported in the  
368 following table under the "calibration" group. The analog resolution of the thermometer plays the major  
369 role, being it  $0.5 \text{ }^\circ\text{C}$ , but since this is a uniformly distributed uncertainty (rectangular distribution) its  
370 value is  $0.15 \text{ }^\circ\text{C}$  which at the same time is very close to the human sensibility. A good operator, correctly  
371 positioned in front at the thermometer, can detect changes in the mercury column of about  $0.15 \text{ }^\circ\text{C}$ . This  
372 was confirmed by ten people at INRiM, independently requested to read a temperature value. The  
373 resulting uncertainty was of the same order.

374 To achieve a better knowledge on the uncertainty associated with the measurement recorded on the  
375 27<sup>th</sup> of May 2017 in Turbat, a couple of additional components are required. This being a mechanical  
376 system, there is no contribution from any datalogger. The ageing of the Stevenson screen is unknown  
377 and its effect in any case would introduce a zero to positive error in temperature reading. Therefore, the  
378 aim is intended at validating the maximum reliable air temperature at the time of the record, based on  
379 the available information. No self-heating is present in the case of mercury in glass thermometers.

380 The two main components on the measurement uncertainty to be added to the calibration uncertainty  
381 are therefore the thermometer repeatability or drift and the reading resolution as reported in the  
382 record table and accounted for  $0.5 \text{ }^\circ\text{C}$  with rectangular distribution (i.e., the data indicate that  
383 measurements were taken to the nearest  $0.5 \text{ }^\circ\text{C}$ ). As reported for the Kuwait sensor, a series of thermal  
384 cycles were made also to the Pakistan sensor, by exposing it to temperatures between  $0 \text{ }^\circ\text{C}$  and  $60 \text{ }^\circ\text{C}$   
385 and the reproducibility at  $54 \text{ }^\circ\text{C}$  was evaluated. This included asking different people to read in different  
386 days the value of  $54 \text{ }^\circ\text{C}$  restored after keeping the thermometer at room temperature (approximately  $20$   
387  $^\circ\text{C}$ ) and re-warming it. The test, corresponding to evaluating the reproducibility of the readings, did not  
388 showed a significant correction to be applied. After a statistical analysis on the standard deviation, the  
389 thermal cycles analysis originated a distribution of values of  $0.052 \text{ }^\circ\text{C}$  around  $54 \text{ }^\circ\text{C}$ , that corresponds to a  
390 rectangular distribution originating a value of about  $\pm 0.015 \text{ }^\circ\text{C}$ .

391 A further data analysis regarded the repetition of the points at  $54 \text{ }^\circ\text{C}$ . A fitting curve was calculated,  
392 together with its residuals as check in the points around  $54 \text{ }^\circ\text{C}$ . This curve confirmed the deviation of  
393 about  $0.3 \text{ }^\circ\text{C}$  as calculated by the calibration curve over the  $0 \text{ }^\circ\text{C}$  to  $60 \text{ }^\circ\text{C}$  temperature interval. Values

394 recorded by the Pakistan sensor and associated uncertainties are given in Table 4. Therefore, the  
395 fundamental results of the metrology test for the Turbat Pakistan thermometer reading of 54 °C is the  
396 calibrated temperature is 53.7 °C ± 0.42 °C.

### 397 **5. Comparison of the Mitribah and Turbat Thermometers**

398 This specific case allowed the unique opportunity directly to compare the two thermometers response  
399 when exposed to the same temperature at the same time. The fact that both measurements recorded  
400 equal values of 54 °C makes the comparison of the instrument reading at that temperature more  
401 significant. For this reason, despite the fact that calibration and characterization of the Kuwait HMP155  
402 sensor was completed, its shipping back was delayed, to wait for the Pakistan thermometer to be  
403 received at INRiM. In early 2018, a test comparison was made by keeping both sensors at the same time  
404 in the climatic chamber (Figure 4). The sensing element of the HMP 155 and the bulb of the G.H.Zeal  
405 were kept in close vicinity to reduce thermal differences due to the inner gradient in the chamber; the  
406 HMP155 body and element were positioned in a way to avoid possible heat generated by the inner  
407 electronic to affect the G.H.Zeal readings (Figure 5).

408 Four calibrated INRiM PRTs were positioned in the surrounding volume to check for stability, gradient  
409 and accurate temperature value. The temperature was set to constantly 54 °C at 50 % of Relative  
410 Humidity and its reference value was evaluated as mean of the three PRTs closer to the two  
411 thermometers under test.

412 Four repeated comparisons were conducted in different days and bringing back the thermometers to  
413 room temperature between each measurement. Measurement values were recorded when the  
414 temperature of the chamber was stable within a few millikelvin and for at least 20 minutes, after hours  
415 of stabilization at 54 °C, to be sure any dynamic effect was concluded by both thermometers. Results are  
416 reported in Table 5.

417 Even though this procedure does not take into account an estimation of field conditions, it gives an extra  
418 information with reduced uncertainty on the response of both sensors at the same temperature of the  
419 record. As well known in metrology and measurement techniques, a relative process such this one  
420 strongly reduces the uncertainties due to common features. The main source of uncertainties, in this  
421 case are thus limited to:

- 422 a) temperature stability of the chamber, due to the very different dynamics of the two sensors this  
423 is a primary source of uncertainty. It is evaluated as range between the minimum and maximum  
424 values of the means of the closer three out of four reference thermometers, considering the  
425 more stable selected data. It accounts for 0.02 °C as a uniform (Max-Min) PDF;
- 426 b) the temperature gradient evaluated as standard deviation of the difference of the readings of  
427 three out of four of the reference thermometers in the volume around the two devices under  
428 test;
- 429 c) the uncertainty on the reference thermometers;
- 430 d) the uncertainty due to the resistance bridge used to read the reference thermometers
- 431 These components are common to the two sensors and have to be combined with the specific  
432 contributions:
- 433 e) the reading resolutions of the two sensors;
- 434 f) the repeatability, here evaluated as standard deviation on the differences among the reference  
435 value and the reading of respectively the Kuwait and Pakistan sensors over the four cycles.

436 Table 6 reports the uncertainty and the value read by both sensors.

437 The results give a robust confirmation on the independent analysis on the two sensors already showed.  
438 First of all, a direct evaluation at 54 °C confirm the value calculated applying the complete calibration  
439 curve. This means that within the evaluated uncertainty, at 54 °C the Kuwait sensor likely overestimated  
440 the temperature by about 0.16 °C and the Pakistan by about 0.28 °C. These results are reported in Table  
441 7 and Figure 6.

442 The fundamental conclusions of the metrology analysis is, for the Mitribah Kuwait 54 °C thermometer  
443 reading, the calibrated temperature is estimated to be 53.87 °C with an expanded uncertainty of  
444  $\pm 0.08$  °C. Correspondingly, for the Turbat Pakistan 54 °C thermometer reading of 54 °C, the calibrated  
445 temperature is estimated to be 53.72 °C with an expanded uncertainty of  $\pm 0.40$  °C.

## 446 **6. Evaluation, Record Determination and Implications**

### 447 **6.1 Evaluation**

448 Because the establishment of these temperature record extremes has the potential for long-term  
449 significance as the highest temperatures recorded for Asia (WMO RA II), for the Eastern Hemisphere,  
450 and potentially the highest, officially-recognized temperatures recorded on the planet in the last 76  
451 years, this evaluation demanded more extensive analysis and testing of these extremes than has ever  
452 been undertaken by an international evaluation committee of the WMO CCI Archive of Weather &  
453 Climate Extremes.

454 Following standard evaluation of data from both locations demonstrating good temporal consistency  
455 and good geographic consistency, along with analysis of the synoptic weather situation for both high  
456 temperature extremes (Supplemental material), an extensive metrological analysis of the two sensors  
457 was undertaken, including: a) the calibration of both thermometers, b) an effort of understanding and  
458 estimating the factors influencing the measurement and associated uncertainties and, c) a direct  
459 comparison of the two thermometer's readings when exposed simultaneously at 54 °C. The  
460 fundamental conclusions of the metrology analysis for the Mitribah Kuwait is a *calibrated* temperature  
461 estimated to be 53.87 °C with an expanded uncertainty of  $\pm 0.08$  °C ( $k=2$ ). Correspondingly, for the  
462 Turbat Pakistan, the calibrated temperature is estimated to be 53.72 °C with an expanded uncertainty of  
463  $\pm 0.40$  °C ( $k=2$ ).

464 The committee noted that the observed temperatures of the two measurements compared extremely  
465 well with the metrological analysis with the Turbat Pakistan sensor's 54 °C value being well-within the  
466 limits of uncertainty and the Mitribah Kuwait sensor's 54 °C value being only 0.04 °C off the maximum  
467 uncertainty limits of the calibration tests. The critical question next addressed by the committee was  
468 what values to accept officially into the WMO Archive, the observed 54 °C value or the calibrated  
469 values?

470 Discussion by the committee on this point was influenced by the recent decision of another evaluation  
471 committee for the Antarctic region temperature (Laska et al. 2018). That evaluation committee  
472 recommended that a temperature observation atop the Davies Dome glacier be adjusted downward  
473 from its observed value of 17.9 °C to 17.0 °C  $\pm 0.2$  °C (62.6°F  $\pm 0.4$ °F). In essence, this decision set the  
474 precedent of using the calibrated adjusted measurements as the official values in the WMO records.  
475 Therefore, it was the consensus (but not unanimous) decision to recommend acceptance of the  
476 calibrated observations.

477 However, a concern was raised by the committee with regard to the degree of accuracy that should be  
478 reported for the record. The calibrated values were measured (with uncertainties) to the second  
479 decimal place. Panel members noted that the accuracy of most modern meteorological measurements  
480 is to one decimal place (0.1 °C). Therefore, the consensus of the committee was that the Mitribah  
481 Kuwait observation be accepted as 53.9 °C and the Turbat Pakistan observation as 53.7 °C.

## 482 **6.2 Record Determination**

483 Following the precedent for acceptance of calibrated values by the Antarctic temperature evaluation  
484 committee, the official values are recorded as:

485 Mitribah, Kuwait [53.9 °C ± 0.1 °C (129.0°F ± 0.2°F), adjusted by calibration analysis from a reported  
486 observation of 54 °C]

487 Turbat Pakistan [53.7 °C ± 0.4 °C (128.7°F ± 0.7°F), adjusted by calibration analysis from a reported  
488 observation of 54 °C]

489 As such, they are the third and fourth highest WMO-recognized extremes.<sup>1</sup> Significantly, the Mitribah  
490 and Turbat values are the highest, officially-recognized temperatures recorded on the planet in the last  
491 76 years. Therefore, the WMO CCI Archive of Global Weather and Climate Extremes has accepted the  
492 temperature values of 53.9 °C at Mitribah Kuwait in 21 July 2016 and the temperature value of 53.7 °C in  
493 Turbat Pakistan in 28 May 2017 as verified and the Mitribah Kuwait temperature is now accepted as the  
494 highest temperatures recorded for Asia (WMO RA II).

## 495 **6.3 Implications**

496 This calibration analysis marks a major advancement in WMO CCI extreme evaluations. Although  
497 international comparisons of meteorological instruments have been conducted in the past under WMO  
498 guidance, the use of detailed calibration of the instruments producing the global extremes data marks a  
499 new level of assurance that our record of global, hemispheric and regional extremes are, and will  
500 remain, as accurate as possible. The calibration (and indeed the affiliation of this paper's authorship)

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<sup>1</sup>It should be noted that (a) other values of equal or near equal temperatures have not been formally evaluated by the WMO (e.g., 129°F (53.9 °C) value recorded on 30 June 2013 in Death Valley USA) and (b) both the Mitribah and Turbat value are within limits of error with 1942 value 54 °C ± 0.5 °C at Tirat Tsvi (present-day Tirat Zevi Israel) for WMO RA VI (Europe) although the Israeli location is geographically within Asia.

501 demonstrates that a high level of trust and collaboration exists between WMO, national Meteorological  
502 Services, and research institutions around the world.

503 Second, this calibration analysis sets a precedent that may increase the level of difficulty for the World  
504 Meteorological Organization's CCI to approve a new temperature record if the instrument calibrations  
505 and evaluations applied in this analysis are not allowed. At this time, new records are examined with "all  
506 available data" but evaluations do not mandate the use of calibration as a prerequisite to acceptance.  
507 Committee members noted that Regional Instrument Centres can and do assist Regional Members in  
508 calibrating their national meteorological standards and related environmental monitoring instruments  
509 for variables such as temperature, humidity and pressure (CIMO 2014). Indeed, the WMO Commission  
510 for Instruments and Methods of Observation (CIMO) explicitly states (page 64), "All temperature-  
511 measuring instruments should be issued with a certificate confirming compliance with the appropriate  
512 uncertainty or performance specification, or a calibration certificate that gives the corrections that must  
513 be applied to meet the required uncertainty. This initial testing and calibration should be performed by  
514 an accredited calibration laboratory. Temperature-measuring instruments should also be checked  
515 subsequently at regular intervals, the exact apparatus used for this calibration being dependent on the  
516 instrument or sensor to be calibrated." However, as committee members also noted, accurate  
517 assessment of important and critical global extremes often must require a complete re-analysis of the  
518 instruments field performances, station site characteristics, systems ageing and identify quantities of  
519 influence which are normally not included in the calibration. Uncertainty should then be estimated, with  
520 the calibration uncertainty as one of the components and other identified factors to complete the total  
521 expanded uncertainty.

522 Third, it should be noted that this level of calibration potentially accords an unfair advantage to earlier  
523 observations (pre-2000 extremes) where calibration analysis and evaluation simply is not possible  
524 compared to a new temperature-record challenger which undergoes calibration tests. For example,  
525 records from the early 1900s conceivably might have been rejected based on calibration with current  
526 equipment but such reanalysis is not possible given that those equipment/sensors are not available for  
527 modern analysis. However, as committee members note, WMO guidelines to assess the  
528 quality/properties of long time series have been published (WMO, 2009). At this time, the WMO  
529 Archive of Weather and Climate Extremes does not remove historical records without sufficient and  
530 significant cause, e.g., new (ideally physical) evidence of error in the historical record.

531 Lastly, it should be noted that there are limits to the degree that calibration can reveal the true air  
532 temperature. For example, laboratory calibration cannot assess air movement through the shelter on  
533 that day, or other in situ processes that unknown or impossible to replicate in the laboratory. The  
534 potential relative importance of all those other factors may influence the actual observation in the real  
535 world and may be a part of any WMO evaluation and recommendation.

## 536 **7. Acknowledgments**

537

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592 **Figure Captiosn**

593 **Figure 1.** Geographic location of the two extreme temperature stations (Mitribah, Kuwait and Turbat  
594 Pakistan).

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596 **Figure 2.** Drift between calibrations. Calibration is done in a liquid bath. Calibration uncertainty is  $\pm 0.07$   
597  $^{\circ}\text{C}$  ( $k=2$ ).

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599 **Figure 3.** Calibration curves evaluated after exposures to environmental conditions given in Table 2.

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602 **Figure 4.** The Kuwait HMP155 and the Pakistan G.H.Zeal thermometers in the climatic chamber for  
603 comparison.

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605 **Figure 5.** Close up view of the sensing element, mercury bulb and INRiM four Pt 100 reference  
606 thermometer. The four Pt 100 are not in contact with any of the two thermometer to avoid self-heating  
607 to be transferred to the devices under test.

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609 **Figure 6. Summary results.** Values calculated applying calibration curves (A) and from direct comparison  
610 at  $54^{\circ}\text{C}$  (B). Uncertainties of values A include calibration uncertainty and estimation of measurement  
611 uncertainty.

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613 **Table 1. HMP 155 calibration results** where  $T_{ref}$  is the temperature indication of the reference  
 614 thermometer ( °C),  $R$  is the resistance ( $\Omega$ ),  $T_{calc}$  is the temperature conversion through application of the  
 615 curve used by the Almos datalogger,  $\Delta t$  is the temperature difference ( °C) between the readings of the  
 616 HMP155 translated into temperature values using the equation adopted by the station datalogger and  
 617 the reference traceable temperature.  
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$t_{ref}$	$R$	$T_{calc}$	$\Delta t$
20.27	107.9246	20.34	+0.07
39.85	115.5145	39.93	+0.08
54.26	121.0840	54.38	+0.12
59.93	123.2712	60.07	+0.14

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**Table 2. MeteoMet study on HMP15 stability after environmental exposure, using period, factor, place and conditions parameters.**

Calibration		Exposure			
No	Date	Period	Factor	Place	Condition
1	06.2013				
		06.2013 - 03.2014	time	Lab	ambient
		03.2014 - 07.2014	high humidity	cave	$t = 7.5 \text{ °C} \pm 0.5 \text{ °C}$ humidity $\approx 100\%$
		07.2014 - 11.2014	time	Lab	Ambient
2	11.2014				
		12.2014 - 05.2015	mid temperature	Stevenson Screen	$t_{min} = -9 \text{ °C}$ $t_{max} = 26 \text{ °C}$
3	05.2015				
		05.2015 - 09.2015	high temperature	Stevenson Screen	$t_{min} = 11 \text{ °C}$ $t_{max} = 36 \text{ °C}$
4	09.2015				
		09.2015 - 11.2015	time	Lab	ambient
		11.2015 - 12.2015	low temperature	refrigerator	$t = -30 \text{ °C}$
5	12.2015				

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**Table 3. Kuwait sensor - Determining the corrected record temperature and the associated uncertainty.**

Quantity/Contribution	Estimated Value or correction °C	Uncertainty °C	Divisor	Distribution	Uncertainty. (k=1) (°C)
Measured value	54.00				
<i>Calibration</i>					
Calibration (Procedure INRiM PT-T.3.3-01 Rev. 2)	-0.12	0.06	2.00	normal	0.03
<i>Measurement</i>					
Solar shield ageing	0	0.06	3.46	rectangular	0.02
HMP Logging ALMOS	-0.01	0.02	1.00	normal	0.01
Self heating	0	0.015	1.00	normal	0.015
Sensor drift and repeatability (1 year or short term after exposure to whole temperature range)	0	0.02 (Vaisala) 0.04 (MeteoMet) 0.04 (INRiM)	3.46	rectangular	0.01
HMP resolution	0	negligible			0.00
Repeatability during test	0	negligible			0.00
<b>Corrected value</b>	<b>53.87</b>				
Combined uncertainty (k=1)					0.04
<b>Expanded uncertainty (k=2)</b>					<b>0.08</b>

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**Table 4. Pakistan sensor - Determining the corrected record temperature and the associated uncertainty**

Quantity/Contribution	Estimated Value or correction °C	Uncertainty °C	Divisor	Distribution	Uncertainty. (k=1) (°C)
Measured value	54.00				°C
<i>Calibration</i>					
Chamber temperature stability	0	0.02	3.46	rectangular	0.006
Chamber temperature uniformity	0	0.052	3.46	rectangular	0.015
Reference Thermometers calibration	0	0.017	1	normal	0.017
Read-out for reference PRTs	0	0.01	1	normal	0.01
Pakistan Thermometer resolution (includes repeatability and readings from different operators)	0	0.5	3.46	rectangular	0.14
Fitting	0	0.03	1	normal	0.03
<b>Corrected value</b>	<b>53.72</b>				
Combined uncertainty (k=1)					0.15
<b>Calibration uncertainty (k=2)</b>					<b>0.30</b>
<i>Measurement</i>					
Pakistan Thermometer resolution	0	0.5	3.46	uniform	0.14
Reproducibility @ 54 °C	0	0.052	3.46	uniform	0.015
<b>Corrected value</b>	<b>53.72</b>				
Combined uncertainty (k=1)					0.20
<b>Measurement uncertainty (k=2)</b>					<b>0.40</b>

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**Table 5. Results of the comparison at 54 °C between Kuwait and Pakistan sensor.**

Reference Temperature (°C)	Kuwait Sensor Temperature (°C)	Kuwait – Reference Temperature (°C)	Pakistan Sensor Temperature (°C)	Pakistan – Reference Temperature (°C)
54.009	54.168	0.158	54.268	0.259
54.012	54.184	0.171	54.264	0.251
53.832	53.976	0.144	54.125	0.293
53.704	53.887	0.183	54.006	0.303
Mean Difference		0.164		0.276
Repeatability (st. dev.)		0.017		0.025

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**Table 6. Uncertainties on direct comparison of Kuwait and Pakistan thermometers at 54 °C.**

Uncertainty contribution	Value (°C)	Distribution	Uncertainty (k=1) (°C)
<i>Reference system</i>			
Chamber temperature uniformity	0.052	rectangular	0.015
Chamber temperature stability	0.02	rectangular	0.006
Reference Thermometers calibration	0.017	normal	0.017
INRiM Data-logger and resolution	0.01	normal	0.010
<b>Combined uncertainty (k=1)</b>			<b>0.025</b>
<i>Kuwait instrument</i>			
INRiM Data Acquisition for HMP155	0.01	normal	0.010
Repeatability	0.017	normal	0.017
<b>Combined uncertainty (k=1)</b>			<b>0.032</b>
<b>Expanded uncertainty (k=2)</b>			<b>0.064</b>
<i>Pakistan instrument</i>			
G.H.Zeal thermometer resolution	0.5	rectangular	0.14
Repeatability	0.025	normal	0.025
<b>Combined uncertainty (k=1)</b>			<b>0.144</b>
<b>Expanded uncertainty (k=2)</b>			<b>0.29</b>

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**Table 7. Summary results of the metrological analysis.....**

	Corrected Value ( °C)	Uncertainty ( °C)
Kuwait calibration (A)	53.87	±0.080
Kuwait comparison (B)	53.84	±0.064
Pakistan calibration (A)	53.72	±0.40
Pakistan comparison (B)	53.72	±0.29

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681 **Supporting Materials.**

682

683 To establish the synoptic weather conditions for the Mitribah Kuwait 2016 and Turbat Pakistan  
684 2017 events, the ERA Interim Reanalysis (Dee et al. 2011) was queried for specific  
685 meteorological data for those days.

686 Synoptic weather conditions for both 21 July 2016 at Mitribah, Kuwait and on 28 May 2017 at  
687 Turbat Pakistan show evidence of extensive high pressure over the Middle East at the two  
688 locations and times respectively. Figure A1 indicates that a large 500 hPa ridge was centered of  
689 the northern Arabian (Persian) Gulf in July of 2016 with some of the highest heights located  
690 over Iran and Kuwait (~5830 geopotential meter 500 hPa heights). This was coupled with  
691 surface dew points in the 0 °C range and surface pressures on the order of 1004 hPa over  
692 Kuwait. Nearby surrounding stations recorded markedly high temperatures as well (51.6 °C  
693 Sabriya, 51.1 °C Jal Alyah and 50.8 °C at Al Abraque) with comparable trends to Mitribah.

694 Correspondingly, on 28 May 2017 at Turbat Pakistan, a high pressure ridge is also firmly  
695 entrenched over the Middle East, centered over Iraq (Figure A2). 500 hPa heights over Turbat  
696 Pakistan were on the order of 5820 geopotential meters). With the Mitrihah Kuwait  
697 observation in 2016, the 500 hPa ridge over Turbat was coupled with dry air (wet bulb  
698 temperatures 20 °C) and sealevel pressures at Turbat on the order of 1000 hPa. Nearby  
699 surrounding stations recorded markedly high temperatures as well (46 °C Panjgur, Gwadar 45  
700 °C) with comparable trends to Turbat, noting that Panjgur is at over 900 metres elevation, and  
701 Gwadar is on the coast, so both would normally be expected to be substantially cooler than  
702 Turbat.

703

704 **Reference:**

705 Dee, D. P., and co-author, 2011: The ERA-Interim reanalysis: configuration and performance of  
706 the data assimilation system, *Quarterly Journal of the Royal Meteorological Society* 137(656):  
707 553-597 <https://doi.org/10.1002/qj.828>

### Supporting Material Figure Captions

Figure A1. 500 hPa heights (meters) for 00 UTC, 06 UTC, 12 UTC and 18 UTC for 20-23 July 2016. Dashed red lines indicate 500 hPa air temperature (°C). Black dot indicates location of Mitribah Kuwait. Extreme occurred 12 UTC 21 July 2016.

Figure A2. 500 hPa heights (meters) for 00 UTC, 06 UTC, 12 UTC and 18 UTC for 27-29 July 2017. Dashed red lines indicate 500 hPa air temperature (°C). Black dot indicates location of Turbat Pakistan. Extreme occurred 12 UTC 28 May 2017.

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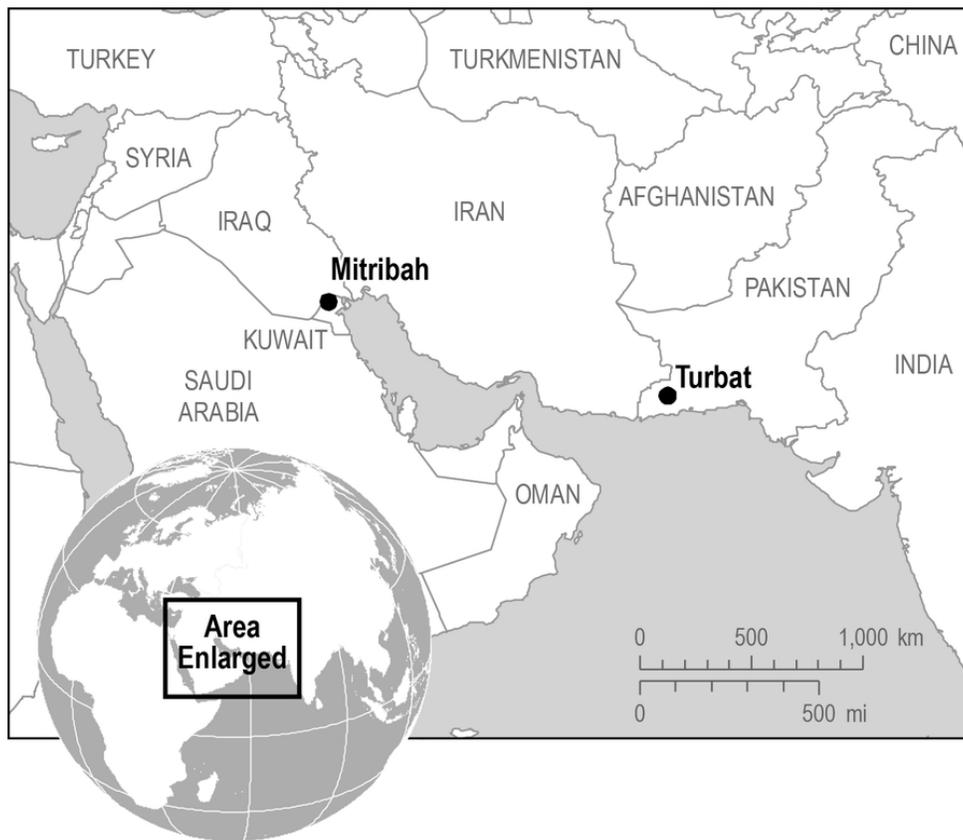


Figure 1. Geographic location of the two extreme temperature stations (Mitribah, Kuwait ad Turbat Pakistan).

78x67mm (300 x 300 DPI)

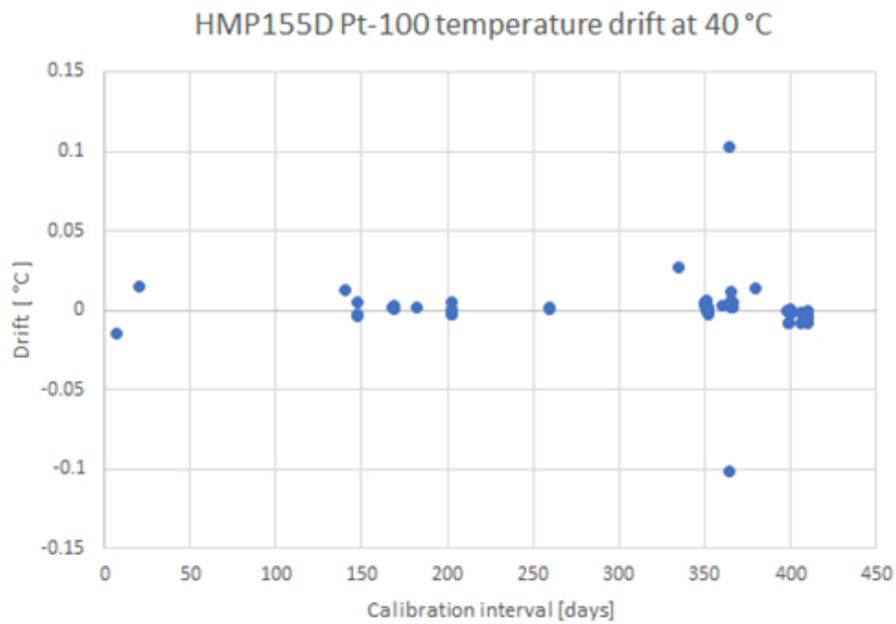


Figure 2. Drift between calibrations. Calibration is done in a liquid bath. Calibration uncertainty is  $\pm 0.07$  °C ( $k=2$ ).

45x30mm (300 x 300 DPI)

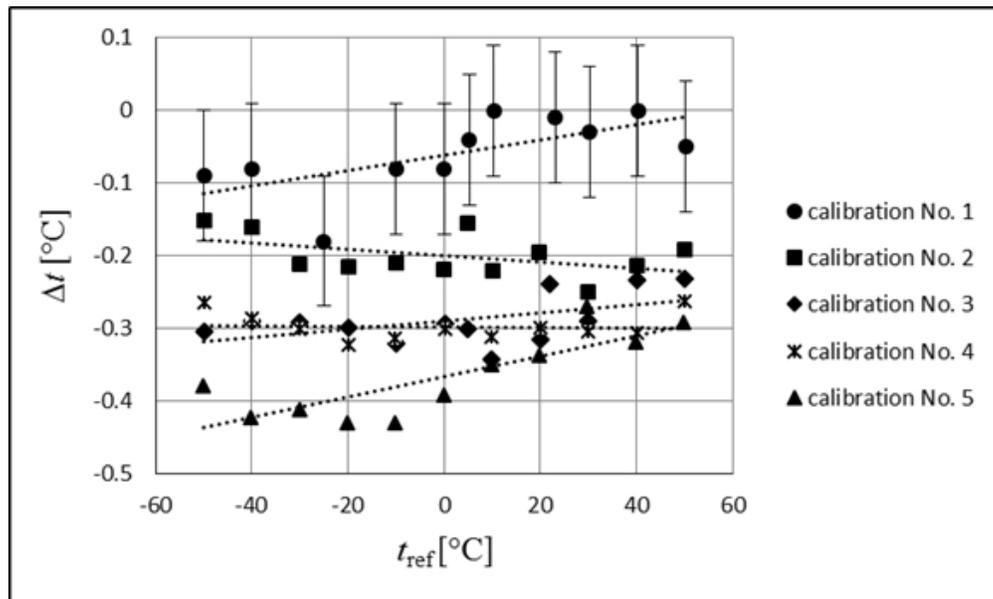


Figure 3. Calibration curves evaluated after exposures to environmental conditions given in Table 2.

49x29mm (300 x 300 DPI)

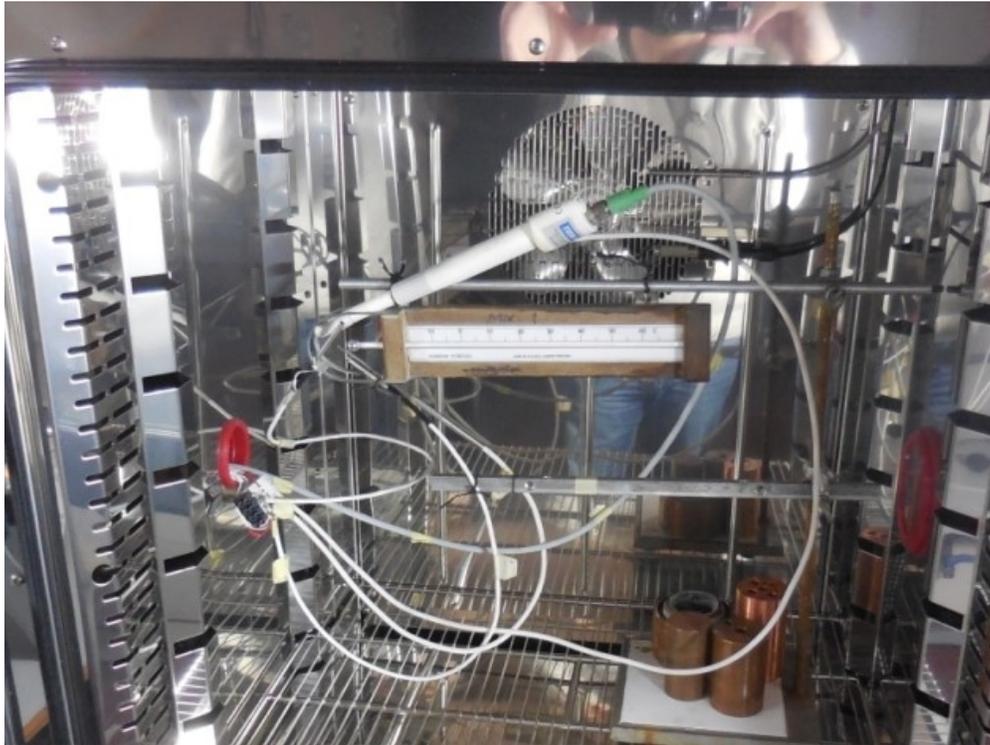


Figure 4. The Kuwait HMP155 and the Pakistan G.H.Zeal thermometers in the climatic chamber for comparison.

53x39mm (300 x 300 DPI)



Figure 5. Close up view of the sensing element, mercury bulb and INRiM four Pt 100 reference thermometer. The four Pt 100 are not in contact with any of the two thermometer to avoid self-heating to be transferred to the devices under test.

102x76mm (220 x 220 DPI)

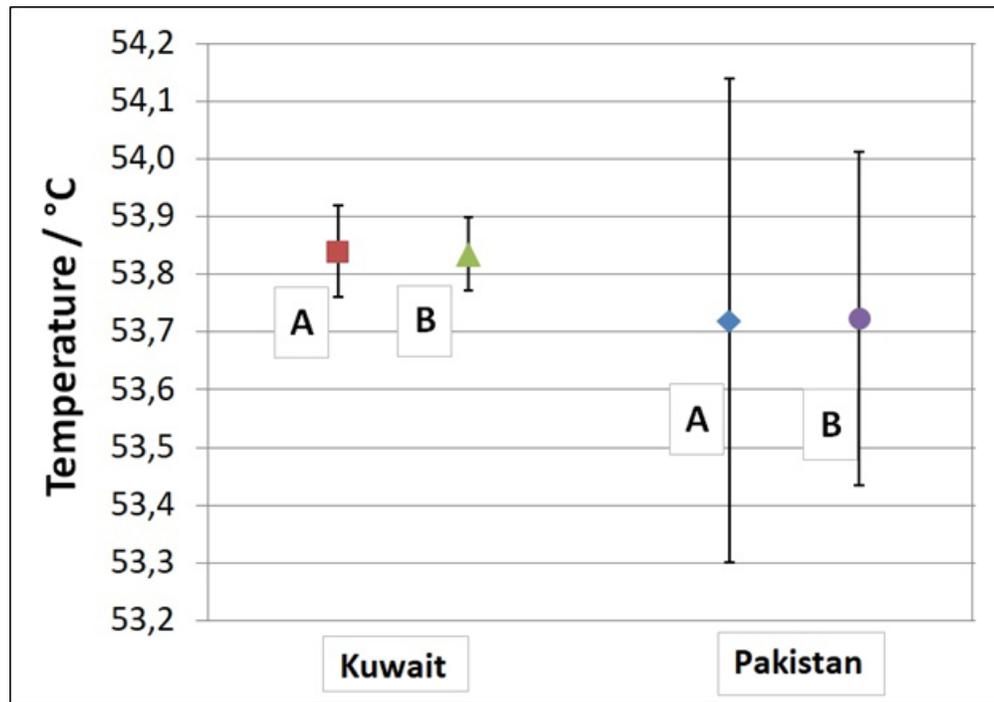


Figure 6. Summary results. Values calculated applying calibration curves (A) and from direct comparison at 54 °C (B). Uncertainties of values A include calibration uncertainty and estimation of measurement uncertainty.

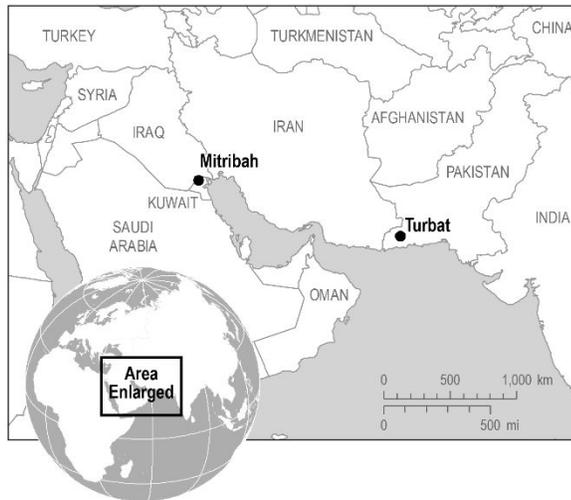
53x37mm (300 x 300 DPI)

## Graphical Table of Contents

**Title:** World Meteorological Organization Evaluation and Calibration Testing of 2016/17 temperatures of 54.0 °C recorded in Mitribah, Kuwait and Turbat, Pakistan as Record Temperature Extremes

**Authors:** Andrea Merlone, Hassan Al-Dashti, Nadeem Faisal, Randall S. Cerveny\*, Said AlSarmi, Pierre Bessemoulin, Manola Brunet, Fatima Driouech, Yelena Khalatyan, Thomas C. Peterson, Fatima Rahimzadeh, Blair Trewin, M.M. Abdel Wahab, Serpil Yagan, Graziano Coppa, Denis Smorgon, Chiara Musacchio, Daniel Krahenbuhl  
(\* corresponding author)

**Caption (80 words or 3 sentences):** A World Meteorological Organization (WMO) committee officially evaluated temperature record extremes of 54.0 °C at two locations, one in Mitribah, Kuwait on 21 July 2016 and a second in Turbat, Pakistan on 28 May 2017. Metrological testing concluded the Mitribah value is a temperature estimated to be 53.87 °C with an expanded uncertainty of  $\pm 0.08$  °C. Correspondingly, for the Turbat value the temperature is estimated to be 53.72 °C with an expanded uncertainty of  $\pm 0.40$  °C.



**Figure:**