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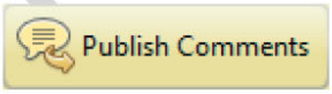

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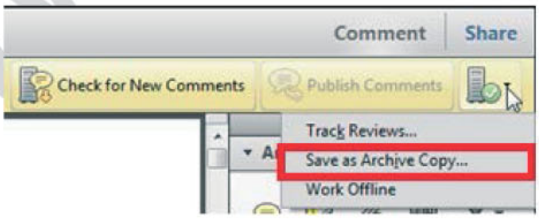

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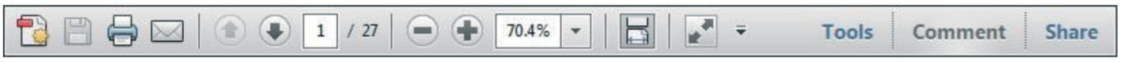

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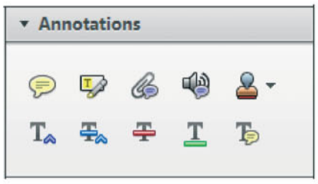

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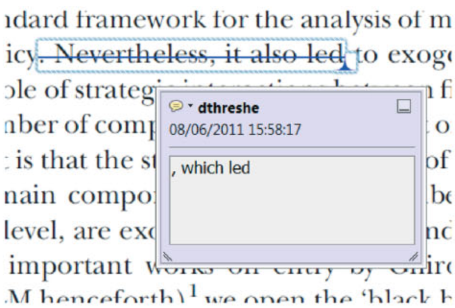

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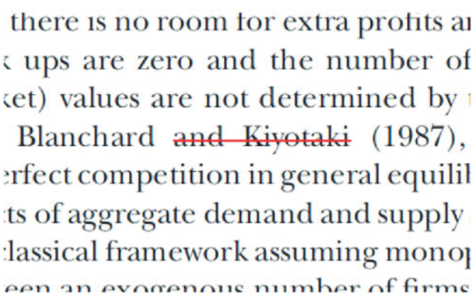

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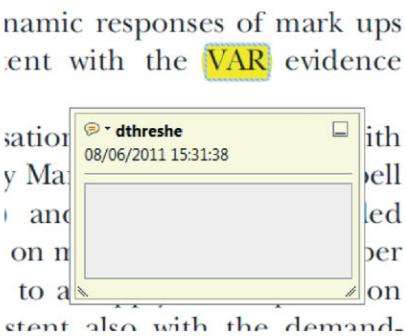

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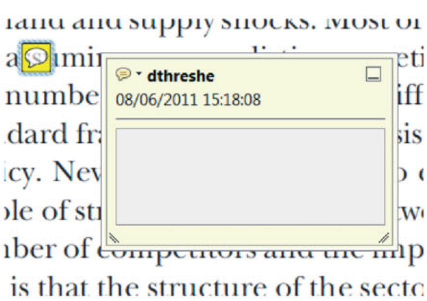

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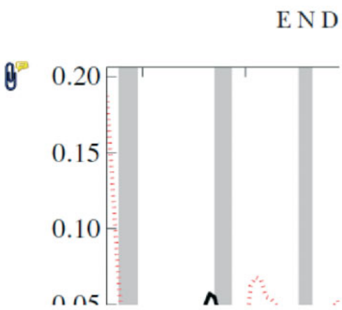

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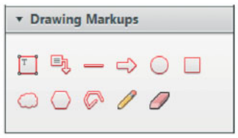

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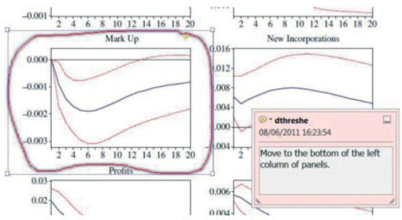

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The Tosontengel Mongolia world record sea-level pressure extreme: spatial analysis of elevation bias in adjustment-to-sea-level pressures

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ABSTRACT: A World Meteorological Organization (WMO) committee evaluated the record sea-level pressure (SLP) measurement of 1089.4 hPa on 30 December 2004 in Tosontsengel, Mongolia (1724.6 m). Although instrumentation and data collection procedures were properly followed according to the assessment of the committee, concern was raised regarding the reliability of SLP adjustment from such a high-elevation station. This paper addresses this concern with a number of analyses that look at relationships between SLP extremes and corresponding station elevation and temperature. First, we selected data from stations extracted from the Integrated Surface Database (ISD-Lite) of NOAA's National Climate Data Center. A spatial analysis indicates that elevation shows little to no association (R^2 values essentially zero) to extreme SLP. However, a second analysis between extreme SLP and air temperature indicates that high regionalism exists in spatial correlations (local R^2) between those two variables. This relationship to temperature is likely the result of differences in SLP adjustment formulae used around the world. Based on this analysis, on the need to differentiate the SLP values adjusted using extremely cold temperatures (and generally high elevation), and following past WMO SLP guidelines, the WMO Rapporteurs for Climate and Weather Extremes therefore have created two distinct SLP records: (a) highest adjusted SLP (below 750 m), currently 1083.3 hPa recorded on 31 December 1968 at Agata, Evenhiyskiy, Russia; and (b) highest adjusted SLP (above 750 m), currently 1089.4 hPa (by Russian method; 1089.1 hPa by WMO formula) on 30 December 2004 in Tosontsengel, Mongolia. Future WMO guidance regarding SLP adjustment may lead to re-evaluation of this and other SLP records.

KEY WORDS sea-level pressure; computation; Mongolia; extreme

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1. Extreme value of sea-level pressure at Tosontsengel, Mongolia

Beginning in 2006, the World Meteorological Organization (WMO) Commission of Climatology (CCl) has established and maintained a Global Archive of Weather and Climate Extremes (Cerveny *et al.*, 2007a). Since that time, the WMO CCl has empanelled a number of individual evaluations of specific weather extremes (Cerveny *et al.*, 2007b; Quetelard *et al.*, 2009; Courtney *et al.*, 2012; El Fadli *et al.*, 2013). Starting in 2011, the WMO CCl, through an *ad hoc* evaluation committee, assessed a record sea-level pressure (SLP) measurement of 1089.4 hPa on 30 December 2004 in Tosontsengel, Mongolia, at 8 am local time (00 UTC). The committee consisted of meteorologists from around the world, including a regional expert, as well as scientists specializing in the type of phenomenon being investigated and meteorologists currently linked to the WMO.

Tosontengel, Mongolia, is located in the northwest portion of Mongolia and is a *sum* (second-level administrative

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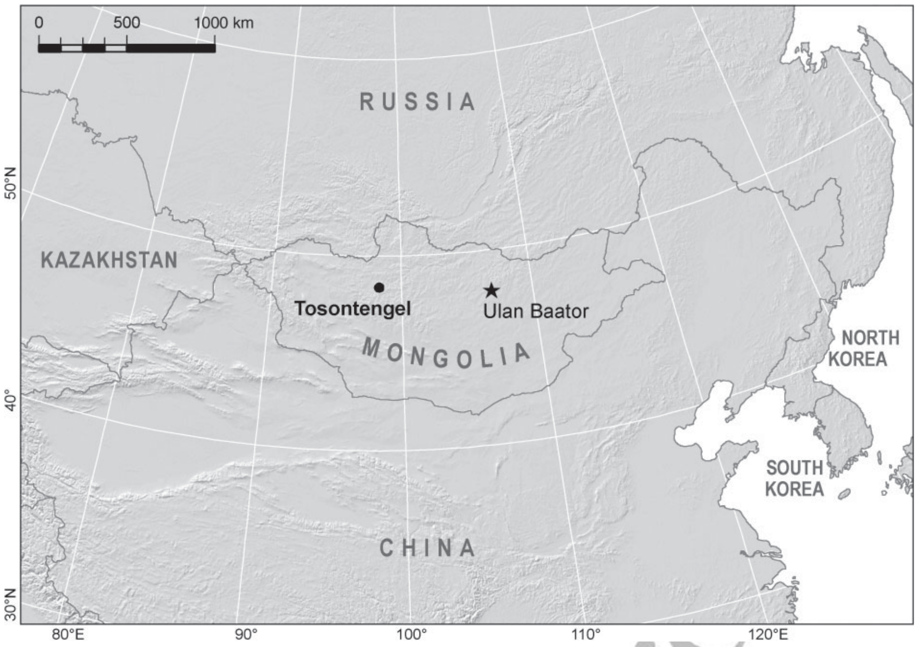


Figure 1. Map showing location of Tosontengel, Mongolia, in relation to Mongolia's capital and surrounding countries.

subdivision) of Zavkhan Province in north-central Mongolia (Figure 1). The spatial coordinates of Tosontengel are 48°44′N, 98°16′E. The station is located 1724.6 m above mean sea level (amsl) (1725.8 geopotential metres, gpm). The station was established in 1963 and has operated continuously until the present. The characteristics of the area are such that Tosontengel is located within a large valley surrounded by mountains. The equipment used to make the barometric reading was a mercury barometer, which was made in Russia (former USSR) under the brand name SRA-A(B) [in Russian, СРА-А(Б)] (Figure 2). A coinciding barograph pressure trend measurement is in general agreement with the actual barometric record although the barograph is simply used to identify trends of pressure within the last 3 h and is not the source of the actual absolute values. The mercury barometer accuracy is assessed as ±0.5 hPa. Note that the precision of all observational instruments (barometers, temperature) is critical to high-quality readings (Hubbard *et al.*, 2005). Operational procedures involve the observer taking a manual measurement every 3 h by visual reading using the scaling on the barometer. Note that the barometer was located inside to prevent the mercury from freezing (Figure 3) but used ambient outdoor temperature in sea-level calculations. Station ambient temperature was measured by a TM3-type mercury thermometer, and minimum temperature was measured by TM2 spirit thermometer (Raipher *et al.*, 1971). This difference between use of ambient and indoor temperatures is a critical point as temperature influences these calculations in two distinct ways. First, temperature at the barometer is critical in adjusting the actual (station) barometric pressure to account for effects of variations in the expansion/contraction of the instrument's materials (prior to adjustment-to-sea-level calculations) (WMO, • 2008). Second, ambient outdoor temperature is used in the formulae for adjustment to sea level (WMO, 2010, 2012). The focus of the following sections of this paper concerns the importance of ambient temperature to SLP calculations.

Figure 2. Photograph of Tosontengel meteorological station's SPA-A(B) mercury barometer.

Starting around the year 2000, the Tosontsengel station barometer was compared with a reference barometer for Mongolian measurements roughly every 3 years. For each comparison, the reference barometer was from the central laboratory inspection office for meteorological instruments. In the period from 2000 to 2012, that central laboratory gave the reference barometer to the central meteorological office for Zavkhan Province where station personnel conducted calibration comparisons of station barometers every 1.5 years. Because of the normal occurrence of extremely high pressures (roughly one or two above 1050 hPa every winter), while the inspection personnel usually did comparisons, they did not keep specific calibration measurement values during those extreme events.

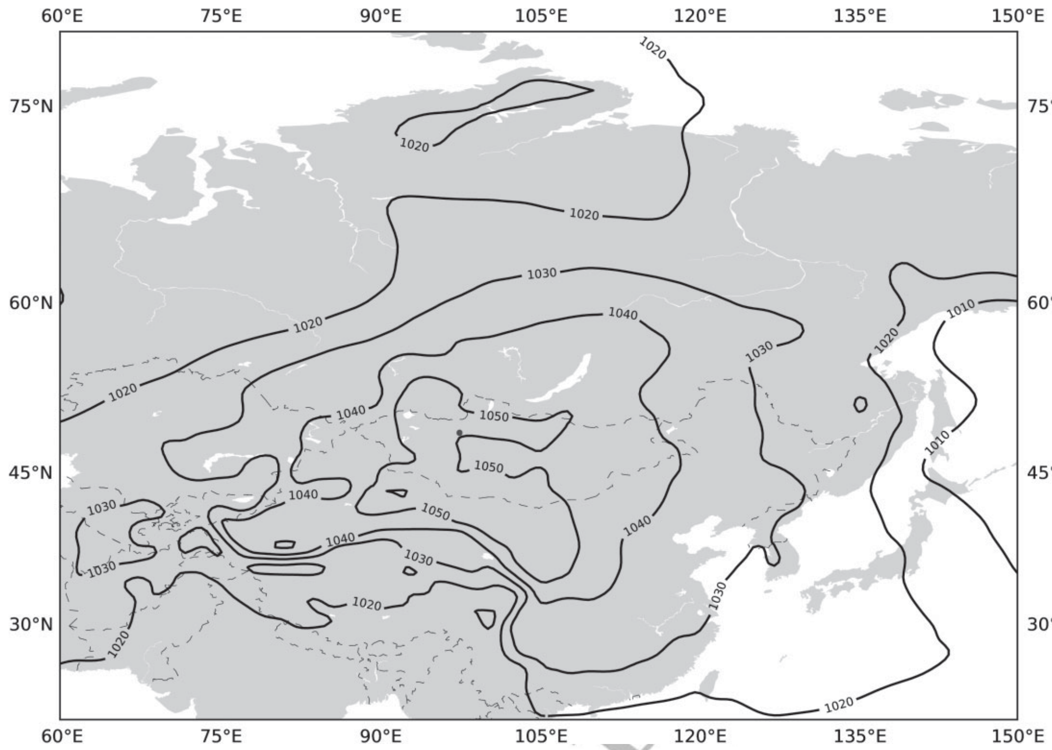


Figure 3. ERA-Interim reanalysis mean SLPs (hPa) for the central Asian region containing Mongolia for 00 UTC 30 December 2004 with the location of Tosontengel, Mongolia, identified by a dot.

Since September 2012, an AWS has been installed at Tosontsengel. Station personnel recorded that immediately after installation they conducted a 15-day simultaneous set of observations between the mercury barometer and the AWS simultaneously in order to quantify differences between them, with average differences during that comparison period on the order of 0.2 hPa. Consistent and proper instrument calibration, specifically with regard to observations of meteorological extremes, is critical to extremes verification. Specifics on WMO guidance on instrument procedures and calibration standards can be obtained from WMO (2010; specifically Chapters 2 and 3), WMO (2013) and fundamentally WMO (1988; specifically Chapter B).

To adjust a station pressure value to SLP, station personnel use a special table, whose entries are calculated from a barometer formula provided in 1968 (used in a Russian method provided by the Mongolian Institute of Meteorology and Hydrology and given below) and updated in 1980. This complex adjustment formula is given as follows (with specific values used given in square brackets):

$$P_{\mathrm{o}} = P \exp\left(\left[10/\left\{R\left(T + 0.377\frac{e\,(T-273)}{P} + \frac{H}{2}\left(\gamma + \alpha\left[0.377\frac{e\,(T-273)}{P}\right]\right)\right)\right\}\right]\phi \log e\right) \quad (1)$$

where P is station pressure (hPa) (846.5 hPa), T is station air temperature (K) (−44.8 °C), H is the height of the station above sea level (m) (1724.6 m), ϕ is geopotential height of the station above sea level (gpm) (1725.8 gpm), α is a constant based on long-term temperature (°C) (4.4), γ is a constant (5.0), e (5.1 hPa) and P (840.6 hPa) are constants based on long-term pressure (hPa), and R is the gas constant for dry air (287 J kg^{-1} K^{-1}). This equation gives the record SLP adjusted value of 1089.4 hPa for the measured station pressure of 846.5 hPa and measured temperature of −44.8 °C (measured at 8 am local time on 30 December 2004).

Nearby stations also experienced very high adjusted SLPs at the time of the Tosontengel extreme pressure observation. A spatially complete data set, such as the ERA-Interim Reanalysis archive, developed by the European Centre for Medium-Range Weather Forecasts, is particularly useful for demonstrating the regional consistency of this extreme event in that it has detailed horizontal and vertical resolution and includes advanced cloud, radiation, and boundary layer parameterizations (Dee *et al.*, 2011). Reanalysis SLP data reveal a large region of high pressure in place over central Asia concentrated over the Mongolian area (Figure 3), indicating a large-scale synoptic feature consistent with the Tosontegel measurement. The highest SLP value determined in the Reanalysis, however, was only 1057.9 hPa, far below the actual extreme SLP value of 1089.4 hPa computed for Tosontengel Mongolia.

2. Differences in the raw observations *versus* reanalysis products

The reasons behind these differences between the ERA-Interim Reanalysis SLP values and the raw SLP calculations for Tosontengel Mongolia are important to discuss in detail. Fundamentally, we believe that there are three reasons for the difference and address these below.

The first rationale for the marked difference is that the reanalysis data are not the raw pressure observations themselves, but rather are the result of millions of raw observations from satellites, weather balloons, aircraft, other stations, and many other observing systems being objectively combined with a numerical forecast model field. This data assimilation procedure represents a compromise among the various available observations weighted by their errors.

A second factor contributing to the difference is that the ERA-Interim Reanalysis algorithm assimilates observed surface pressures rather than adjusted SLP values (Dee *et al.*, 2012, 556) and the digital terrain model of the ERA-Interim Reanalysis may produce slightly different elevations at grid-point locations than the actual location.

A third factor involves the intense high-elevation, winter-time low-level inversions common in this region and the associated impact on assumptions in the SLP adjustment equation, such as (1). This was a critical point to which the WMO evaluation committee in evaluating the record was particularly concerned. Specifically, the adjustment of high-elevation station pressure measurements to SLP can be problematic due to assumptions associated with the standard lapse rate used between the surface and sea level in a particular procedure.

However, the WMO has not yet recommended a single particular adjustment method, except in the case of low-level stations (WMO, 2010). For those stations, if its elevation is at or below 750 m amsl, the WMO recommends the following reduction formula (WMO, 1964, 2010);

$$\log_{10}\frac{P_o}{P} = \frac{K_p \cdot H_p}{T_{mv}} = \frac{K_p \cdot H_p}{T_S + \left(a \cdot H_p/2\right) + e_S \cdot C_h} \qquad (2)$$

where, in the first equality of this equation, P_o is the SLP in hPa; P is station pressure in hPa; K_p is a constant (0.0148 275 K gpm^{-1}); H_p is the station elevation in gpm; and T_{mv} is the mean virtual temperature in K. The second equality of Equation (2) defines T_{mv} where T_S is the station (outdoor) temperature in K; a is the assumed lapse rate in the imaginary air column extending from sea level to the level of the station elevation level (0.0065 K gpm^{-1}); e_S is the saturated vapour pressure at the station in hPa; C_h is a coefficient, which is equal to 0.12 K hPa^{-1} (WMO, 2012). Using the Tosontsengel, Mongolia, station pressure of 846.5 hPa, a geopotential height of 1725.8 m, and the observed ambient (outdoor) air temperature of −44.8 °C for 30 December 2004, this WMO method produces an SLP value of 1089.1 hPa, only slightly lower than the 1089.4 hPa value produced by the Russian method of Equation (1).

A noted climatologist external to the WMO committee raised the question that the '*a*' term of Equation (2), the assumed lapse rate in the imaginary air column extending from sea level to the level of the station elevation level (0.0065 K gpm^{-1}), coupled with a pronounced low-level inversion can create a layer temperature that is unrepresentative of the free atmosphere. For example, as that climatologist discussed, and subsequent analysis by the committee confirmed, the station at Muren (1283 m elevation), observations at a location close to Tosontengel in Mongolia led to a computed SLP of 1053.3 hPa – markedly different than that for Tosontegel – for 30 December 2004 observation because of the differences associated with elevation and the strength of the near-surface inversion.

The WMO committee appreciated these concerns. However, if the WMO committee interprets that point correctly – that SLP should not be calculated when there is a strong surface inversion, then the process of assessing a world-record SLP extreme becomes untenable. Strong surface inversions can and do occur across the world, regardless of elevation, temperature, or location. This raises the existential issue of whether the existence of such inversions invalidates all SLP measurements. Furthermore, if inversions are critical to SLP adjustment, under what inversion criteria should SLP adjustments be made?

This WMO SLP extremes evaluation committee, in conjunction with discussions with the members of the WMO Commission for Instruments and Methods of Observation (CIMO) (WMO, 2012), has decided to evaluate the quality and validity of this specific observation extreme and future SLP records, regardless of the existence of strong inversions. We address this point more fully in Section 6; however, the influence of contributing meteorological variables to extreme SLP observations in relation to existing SLP reduction formulae and WMO criteria (e.g. use of formulae above/below specific elevation limits) is a related point which the committee addressed and analysed in more detail.

In most SLP reduction formulae, the two primary additional station variables needed for computation are the station elevation and the station temperature (WMO, 1966). Consequently, to make a global categorization of SLP extremes, a critical issue must be investigated: the relative importance of station elevation and station temperatures on reported SLP values. In this study and in the WMO record extreme evaluation, the sensitivity of SLP values to station elevation and station temperature is examined using a global data set.

3. Extreme SLP data

One of the more comprehensive raw-data compilations of SLP data was conducted by the UK Met Office Hadley Centre to develop their monthly mean sea-level pressure (MSLP) gridded data set, HadSLP2 (Allan and Ansell, 2006; Haylock *et al.*, 2007), which is based on raw SLPs for the 2458 usable stations. However, potential limitations of monthly data in the analysis of SLP extremes suggested that, in order to assess relationships between station elevation, station temperature, and adjusted SLP, a daily or hourly SLP data set, rather monthly SLP data set, would be more useful.

Such a data set is the relatively new ISD-Lite data set. The ISD-Lite data set is a data product derived from

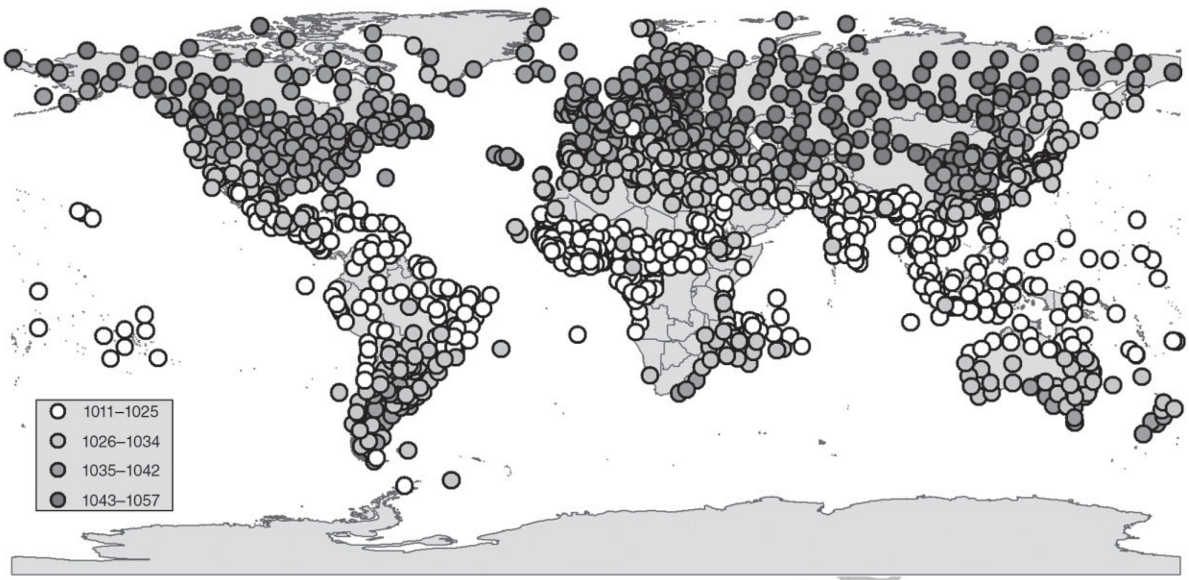


Figure 4. Variations in the extreme SLP value, SLP_{ex} (hPa) for 1537 ISD-Lite stations around the world (see text for details).

the full ISD data set established by the US NOAA's National Climate Data Center (NCDC) with the goal of making ISD easier to work with for general research and scientific purposes (Smith *et al.*, 2011). ISD-Lite is a subset of the full ISD containing only eight common surface parameters (air temperature, dew point, SLP, wind speed and direction, total cloud cover and 1- and 6-h accumulated precipitation) in a fixed-width format free of duplicate values, sub-hourly data, and complicated flags. Although some ISD-Lite stations are sub-daily, the period of observation (hourly, 3-hourly) varies from station to station. Consequently, in the sensitivity study, we are concerned with the daily (averaged from hourly values) SLP (hectopascals), air temperature (°C), and the metadata (specifically latitude, longitude, and elevation) for each station. In this study, we selected the ISD-Lite data set over the more complete International Surface Pressure Databank version 2 •(Compo *et al.*, 2010) due to computation considerations associated with translation into a Geographic Information System compatible format. However, individual random stations from the ISPDv2 data set were extracted and compared with equivalent ISD-Lite, and similar results were obtained.

To link to previous studies (e.g. Allan and Ansell, 2006; Haylock *et al.*, 2007), we utilized the station locations associated with the monthly MSLP gridded data set, HadSLP2. Consequently, we extracted a daily SLP data set of 1537 locations with at least 10 years of usable observations across the globe from the ISD-Lite database. Unfortunately, Mongolia currently does not have any stations in the ISD-Lite data set meeting these requirements.

For the 1537 stations meeting the criteria, a combined average of 315 days of non-missing data was present for each year of their record. For this analysis, for each station we first extracted the highest SLP daily value for each year ($SLP(i)$) and its corresponding daily temperature ($T_{slp}(i)$). We then computed, for each station's length of record, the overall average of these yearly extreme SLP values (defined for this study as SLP_{ex}) as shown in Equation (3):

$$SLP_{ex} = \frac{\left[\sum_{i=1}^{n} SLP\,(i)\right]}{n} \quad (3)$$

where $SLP(i)$ is the highest SLP value recorded for a specific year and n is the number of years of record at each station. This definition for SLP_{ex} lessens the possibility of any isolated anomalous SLP extreme event at a given station dominating the analysis. A similar procedure was employed to find the corresponding temperature for each highest SLP value in each year. These temperatures were taken exactly at the dates/times that correspond to the annual SLP(i). These temperatures were then averaged to produce T_{slp} in a similar way to Equation (3) for SLP_{ex}.

Of the selected ISD-Lite stations used in this study, the highest station (Zugspitze, Germany 47.42°N 10.98°W) had an elevation of 2960 m and 10 years of usable data. Twenty-two stations had elevations of 0 m (below-zero metre-elevation stations were not included in this analysis because of potential coding problems). The highest SLP_{ex} is 1057.2 hPa for the series from Altay China (47.7°N, 88.08°E, 737 m, 47 years of observations). The lowest SLP_{ex} is 1011.4 hPa, which occurs at Dire Dawa Ethiopia (9.6°N, 41.9 °E, 1260 m, 19 years of observations). These averages of the yearly SLP extremes computed from daily averages for these locations help to put the record 1089.4 hPa instantaneous value at Tosontengel, Mongolia, in context of what is typical for extreme values.

4. Spatial analysis

The spatial representation of the SLP_{ex} values for the extracted stations reveals a pattern with regional coherence (Figure 4). In general, the highest SLP_{ex} values

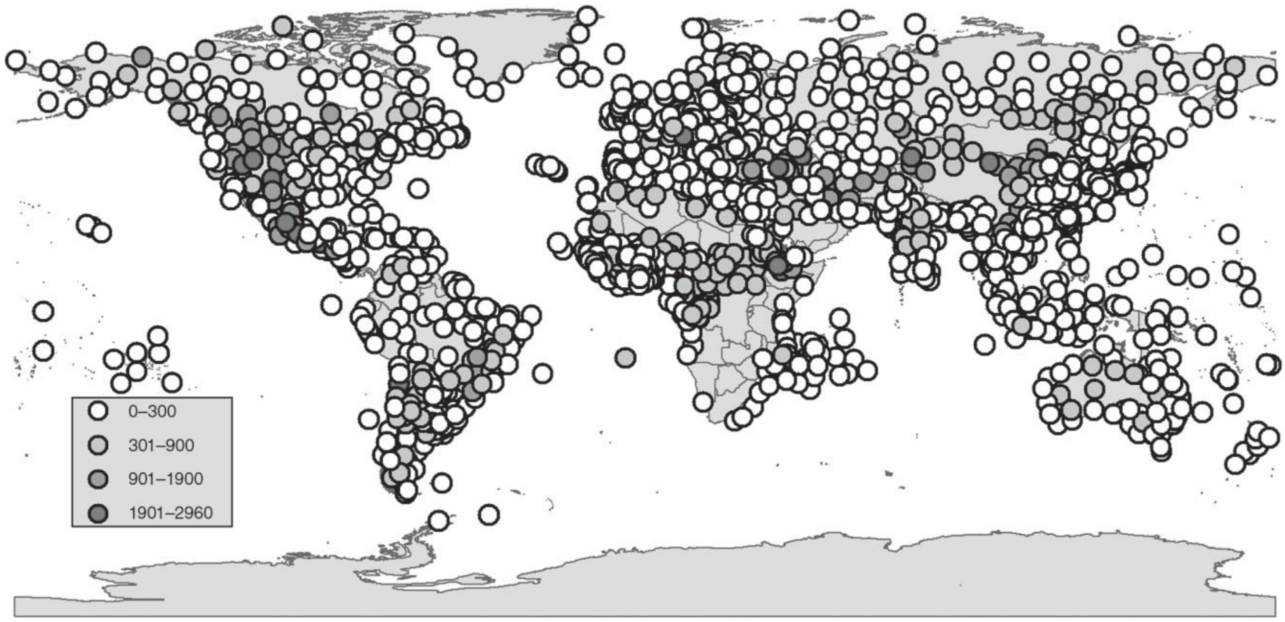


Figure 5. Elevation (m) for the 1537 ISD-Lite stations selected for this study.

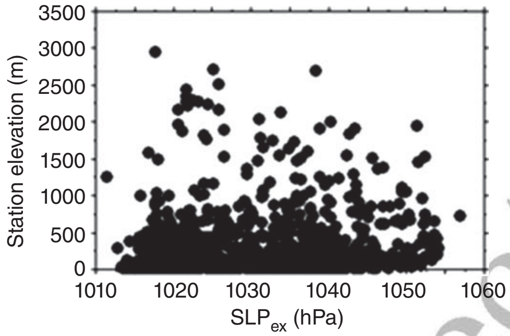


Figure 6. Scatter plot of station elevation (*y*-axis, m) and SLP_{ex} values (*x*-axis, hPa) for 1537 stations from the ISD-Lite data set. The correlation value $R = -0.117$.

are found in northwestern North America and continental Asia. Slightly lower SLP_{ex} values cluster in southern Europe, the rest of North America, Japan, southern South America, southern Africa, and southern Australia. Smallest of these SLP_{ex} values are clustered primarily in the equatorial region.

When the SLP_{ex} pattern (Figure 4) is compared with the station elevations of the selected ISD-Lite stations (Figure 5), there is surprisingly little apparent relationship between the two variables (Figure 6). The highest elevation stations are located in the South American Andes, North American Rockies, Central America, southern Africa, and the Himalayas. The visual lack of agreement is confirmed by an overall statistically insignificant ($R = -0.117$) correlation between the two variables (SLP_{ex} and elevation) over the network of 1537 stations (Figure 6). Not only is there very little relationship, but the correlation is negative indicating that, to the extent that there is a relationship, the larger typical extreme values occur at lower elevations.

While high-elevation (but cold temperature) stations in Siberia do demonstrate high SLP_{ex}, conversely high-elevation stations in southern Africa usually record lower SLP_{ex} due to their relatively warm surface temperatures. Overall, this would suggest that, for the world as a whole, elevation does not play as significant role in determination of SLP_{ex}, despite its presence in the SLP reduction (Equations (1) and (2)).

If elevation is not the critical determining variable resulting in variations of SLP_{ex} values for the ISD-Lite data set, could another variable be more influential in establishing extreme SLP? Equation (2) and WMO guidelines (WMO, 2010) suggest that possible dependence of the SLP_{ex} on the associated station temperature (T_{slp}) may be important.

The spatial distribution displayed by the temperatures associated with SLP_{ex} values for the selected stations of the ISD-Lite data set is not surprising (Figure 7). Highest of these T_{slp} occur in the equatorial regions and southern Africa with lowest T_{slp} values occurring in Asia north of the Himalayas and northern North America.

What is surprising is that a high dependence of SLP_{ex} values on the corresponding temperature (T_{slp}) exists between SLP_{ex} and T_{slp} (Figure 8). Simple regression analysis gives the relationship $SLP_{ex} = 1034.7 - 5.69T_{slp}$, indicating that associated ambient temperature T_{slp} explains more than 80% of the variance in the SLP_{ex} data. Distance-weighted regression between T_{slp} and SLP_{ex} produces a spatial correlation pattern that is surprisingly and markedly regional (Figure 9). The value of the spatial autocorrelation using Moran's *I* from the Local R^2's is 0.602 ($p < 0.001$). Moran's *I* is an accepted measure of spatial autocorrelation with values ranging from −1 (indicating perfect dispersion) to +1 (perfect correlation) (Moran, 1950; Anselin, 1995). The highest explained variances (local $R^2 > 0.81$) are evident in southeast Asia, western

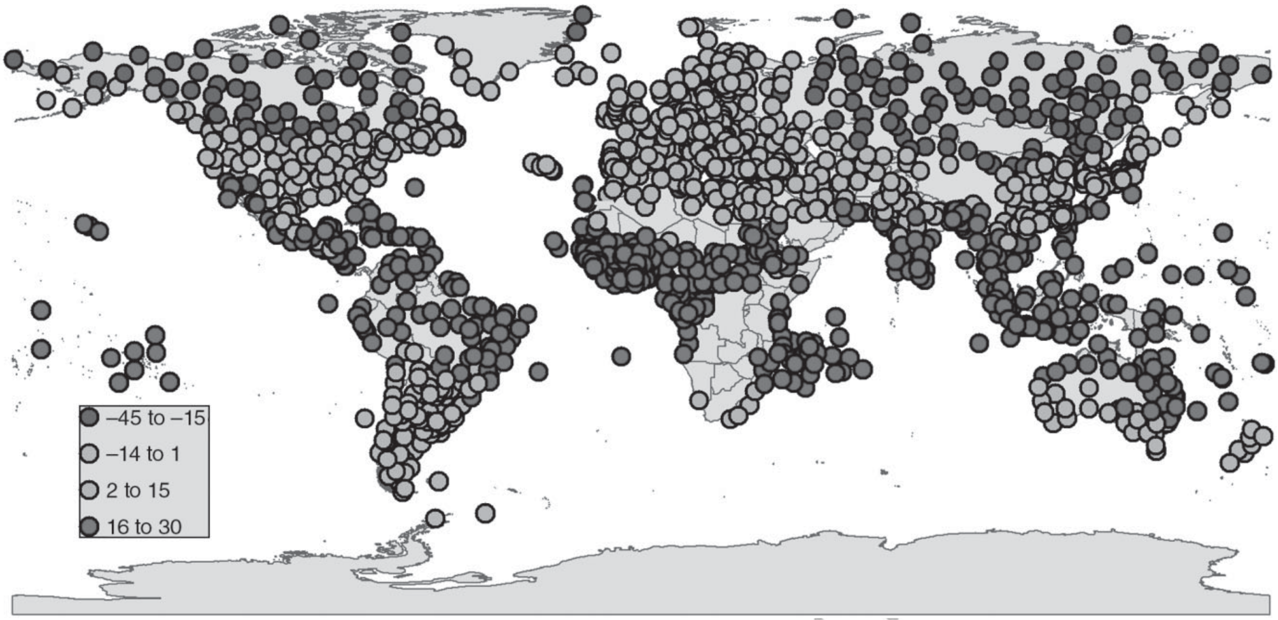
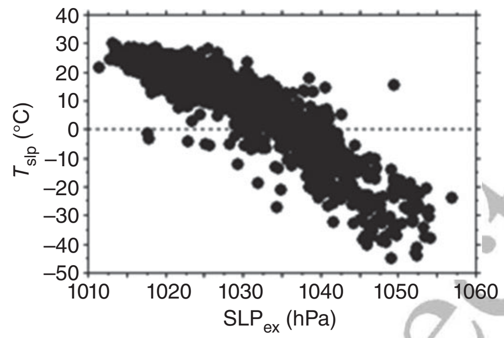


Figure 7. Map of T_{slp} (°C, defined as the average of the temperatures corresponding to annual extreme SLPs) plotted in the quartile ranges from the aggregated station values.



AQ5 Figure 8. •Scatterplot between SLP_{ex} values (*x*-axis, hPa) and T_{slp} (*y*-axis, °C) for the 1537 selected stations of the ISD-Lite data set. Explained variance of a best-fit line is $R^2 = 0.808$.

North America, the Himalayan Plateau region, and parts of Australia, while moderate explained variances (local R^2 between 0.72 and 0.81) are seen across west-central Asia, central India into Northern Africa with an additional concentration evident in eastern North America, Central America, and central South America. Lowest explained variances (local R^2 less than 0.41) between temperature and extreme SLP are found in southern South America, southern Africa, and regions of the North Atlantic.

5. Discussion

Surprisingly, given the dependence of the imaginary lapse rate on elevation computed in reduction-to-sea-level formulae and consequently the elevation dependence of the SLP value, the overall explained variance (R^2) between elevation and the SLP_{ex} values for the 1537 stations of the ISD-Lite data set is essentially zero, and the correlation is, if anything, slightly negative. This indicates that, for extreme SLP values for most of the world, elevation does not significantly influence this variable.

However, beyond elevation, the other key variable in the SLP formulae is temperature at the station (e.g. the corresponding temperature to the station measurement we defined as T_{slp}), which together with humidity data determines the mean virtual temperature. The temperature at the time of the extreme SLP appears to be a strong predictor of the SLP value as suggested by the strong relationship between the typical extreme values, SLP_{ex} and T_{slp}, found here.

The marked regionalism in the relationship of T_{slp} and SLP_{ex} is likely the result of the multitude of different reduction-to-sea-level formulae that exist across the world (WMO, 1966, 1968, 2010). For example, in the western United States and Canada, SLP formulae contain a 'plateau adjustment' to reduce the departure of the actual computed mean SLP at a particular station from the annual mean SLP at the same station (e.g. Pauley, 1998; Mohr, 2004). It is not surprising, given this western North American adjustment to the SLP formula, to see that higher correlations between SLP_{ex} values and associated temperatures T_{slp} exist in western North America than over eastern North America. Other complex and different adjustments such as that noted in Section 1 (the Russian SLP adjustment formula, Equation (1)) are used in other regions of the world. A WMO publication (WMO, 1968) lists more than 15 different methods used around the world in reduction-to-sea-level formulae.

6. Conclusions and recommendations

The problems associated with the regional differences in calculation of SLP have long been noted. Over 50 years ago, Hess (1979, 90) commented that 'it should be clear

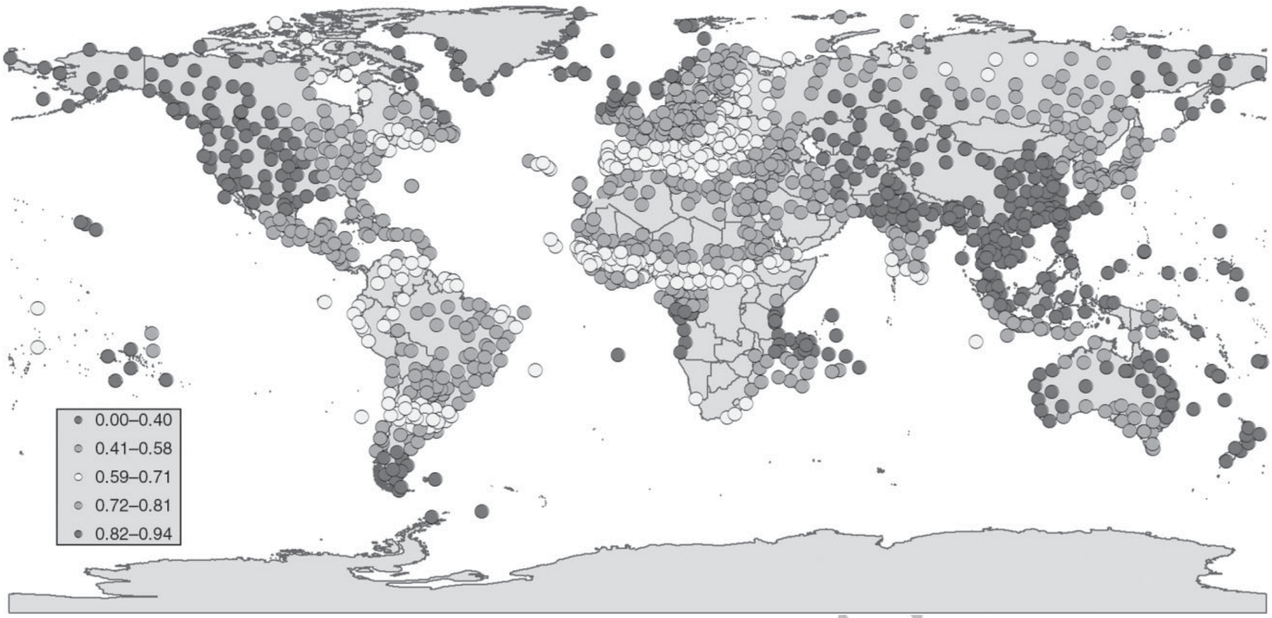


Figure 9. Five-class (classes based on natural-break divisions of the explained SLP_{ex}/T_{slp} variances, local R^2) spatial patterns of explained variance between SLP_{ex} and their corresponding temperatures T_{slp} for 1537 selected stations of the ISD-Lite data set.

that the methods for reduction to sea level are not uniform over the world and are especially complex in the United States. It would be desirable to make the procedure uniform and simple, but because many years of climatological records are based on the current unwieldy system it is unlikely that any revision will be made … All methods of reduction to sea level give unsatisfactory results in certain situations'. These concerns have continued to the recent times to the point where certain countries have developed a multitude of different methods of SLP adjustment (WMO, 2012).

This apparent marked difference in the influence of air temperature on extreme SLP makes establishing a single 'world record SLP extreme' difficult and the current plethora of SLP equations prone to potential misinterpretation by non-meteorologists. Ideally, as recommended by Hess over 50 years ago, the selection of a single global SLP adjustment equation would potentially remove some of these regional differences. However, as this issue is currently being addressed by a specific body of the WMO, the WMO Commission for Instruments and Methods of Observation (CIMO) (WMO, 2012), we are faced with establishing working criteria for determining global SLP extremes for the WMO Commission of Climatology's Archive of Weather and Climate Extremes.

Pending a WMO recommendation for global acceptance of a single SLP formula or alternative guidance, the WMO Rapporteurs for Climate and Weather Extremes envisioned three possibilities while trying to maintain and follow current WMO guidance:

(a) Although instrumentation and data collection procedures were properly followed, reject the Tosontengel Mongolia's extreme SLP of 1089.4 hPa (Russian method; 1089.1 hPa WMO formula) as a world record based on the unrepresentative nature of the station's location (e.g. temperature and/or elevation). This possibility can be extended to include the external climatologist's idea of an unrepresentative low-level inversion discussed in Section 2.

(b) Although instrumentation and data collection procedures were properly followed, reject the Tosontengel Mongolia's extreme SLP of 1089.1 hPa as a world record on the basis that use of an SLP reduction formula above 750 m does not follow current WMO policy guidelines (WMO, 2012).

(c) Accept the Tosontengel Mongolia's extreme SLP of 1089.1 hPa as a world record but distinguish it from other SLP extreme observations that do meet current WMO policy guidelines and explicitly state potential caveats associated with its acceptance.

Considerations for rejecting possibilities (a) and (b) were that such an action could potentially bias, infringe, and/or hinder ongoing revision of existing WMO guidance on the use of reduction-to-sea-level formulae as well as confuse the general public (for whom numerous non-official sources, e.g. Wikipedia, cite Mongolian pressure records). For example, if the Tosontengel Mongolia's extreme SLP was rejected on the basis of unrepresentative temperature or elevation, explicit criteria as to the temperature/elevations limits would need to be set (e.g.'what is representative temperature or elevation?') by this or another WMO CCl committee and, consequently, would involve setting policy that WMO CIMO is currently evaluating. In addition, as discussed earlier in this paper, strong surface inversions and extreme cold surface temperatures can occur in many parts of the world. Do those conditions therefore invalidate all SLP calculations under those conditions?

Secondly, as possibility (b) indicates, existing WMO's guidance for reduction of station pressure to a sea-level standard is the recommendation that caution be used in applying sea-level reduction formula above 750 m. If, however, that guidance was strictly followed, vast regions of the globe, specifically including large areas of central Europe, western and central North America, western South America, and central Asia, could not be considered for SLP extremes.

Consequently, it was the unanimous recommendation of the WMO evaluation committee and subsequently accepted by the WMO Rapporteurs for Climate and Weather Extremes that, at this time, the Tosontengel, Mongolia, SLP pressure observation is considered to be a properly conducted observation that can be accepted as a world extreme SLP but with a need for further discrimination against existing record SLP extremes.

Our accompanying analysis has shown that many regions of the earth demonstrate high reliance on abnormally cold air temperature in their SLP adjustment and that these areas are – in general – regions of high elevation (e.g. Tosontengel Mongolia's elevation of 1724.6 m) and that point should be addressed in extremes identification and verification. That relationship indicates that some kind of explicit discrimination of SLP extremes is possible.

Consequently, based on these facts, the WMO Rapporteurs for Climate and Weather Extremes have created two distinct SLP categories for observation extreme measurements using the WMO reduction-to-sea-level formula given in Equation (2), specifically SLPs for stations above and below 750 m. This has the added benefit of linking favourably (but with greater discrimination) to existing non-official record sites (e.g. Wikipedia) where our discrimination rationale is now explicitly stated.

In addition, our evaluation recommends that WMO members requesting verification for a global or continental record pressure extreme should *explicitly* state the specific SLP reduction formulae that they use in their observations of SLP extremes. While the present analysis suggests that actual air temperature associated with the SLP observation may be a better discriminator for extreme SLP, potential confusion and misinterpretation by other science disciplines, as well as the general public, supports the decision to follow existing WMO guidance and to discriminate extreme SLP by elevation.

Therefore, the WMO Archive for Weather and Climate Extremes now lists (a) highest adjusted SLP (below 750 m) with an official observation of 1083.3 hPa recorded on 31 December 1968 at Agata, Evenhiyskiy, Russia (66°53′N, 93°28′E, elevation: 261 m) (Burkova and Dzhordzhio, 1973), and (b) highest adjusted SLP (above 750 m) with an official observation of 1089.1 hPa on 30 December 2004 in Tosontsengel, Mongolia. The WMO evaluation committee unanimously agreed with this decision.

However, the WMO *ad hoc* evaluation committee and Rapporteurs add the following caveat to this decision. In the future, if a single SLP formula is globally accepted (as indicated by WMO, 2012) or if, perhaps, global acceptance of discrimination of SLP based on geographic regions or temperature is made, the WMO CCl Archive for Weather and Climate Extremes, through another *ad hoc* evaluation of international experts, may re-evaluate this and other SLP record extremes. For instance, this WMO committee has noted that, for existing Reanalysis data sets, each employs a single adjustment-to-sea-level formula. We suggest that perhaps the identification and selection of a specific reanalysis adjustment formula by the WMO might provide the means for addressing the problems of SLP adjustment of raw observations.

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