Weather whiplash: Trends in rapid temperature changes in a warming climate

Cameron C. Lee

Department of Geography, Environmental Science and Design Research Institute, Kent State University, Kent, Ohio, USA

Correspondence
Cameron C. Lee, Department of Geography, Environmental Science and Design Research Institute, Kent State University, Kent, OH 44240, USA.
Email: cclee@kent.edu

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Abstract
Both research and media attention has shown an increasing interest in rapidly changing weather, colloquially termed “weather whiplash” events. This research examines the spatial and seasonal variability of trends in seasonally standardized short-term temperature ranges across the globe. Trends are calculated for three different “range windows”: 7-day ranges, 1-day departure, and diurnal (24-hr) temperature ranges. Results show that globally, over the 70-year period of record 7- and 1-day ranges are increasing substantially in all seasons, while diurnal trends are only changing (decreasing) significantly in boreal autumn. Since 1985, however, ranges at all three time windows have increased significantly. The most widespread changes are occurring as significant increases in these ranges in the Southern Ocean, Africa, and South America and in regions of coastal upwelling. Significant decreases in these ranges are noted mostly at the Arctic Ocean confluence with the Pacific and Atlantic Oceans, especially in the Greenland, Iceland, and Norwegian Seas, and more recently, in northeastern Canada. Oceanic trends appear driven by changes in wind speeds, especially in the Southern Hemisphere where increasing open-ocean winds are nearly ubiquitous. Trends in temperature variability over land are largely inverse of the long-term changes in cloud cover. This research adds to a growing body of climate change literature examining temperature variability trends, and it represents the first examination of full 70-year trends of many variables contained in the recently released ERA5 reanalysis.

KEYWORDS
climate change, diurnal temperature range, temperature variability, weather whiplash

1 | BACKGROUND AND INTRODUCTION

While rapidly changing weather is a common feature of the extra-tropical climate system, such extreme changes have nonetheless garnered increased public and media attention as of late. In particular, in the United States, some recent media reports of cold-season weather shifts have labelled the phenomenon “winter whiplash” or “weather whiplash” (Cohen, 2016; Casson et al., 2019; Harvey, 2019; CBS, 2020; Ma and Zhu, 2021). While most of the attention on climate change focuses on trends in...
climatological means, recent research highlights the need to expand the breadth of impacts research to include more detailed analyses of other statistical parameters (Lee et al., 2021). Moreover, with increasing public attention to the issue of global climate change (Marlon et al., 2020), the question of whether climate change is impacting the frequency or severity of these whiplash events has been posed to the author of this research more than once.

With the impetus stemming from this backdrop, the simple goal of the research herein is to explore the long-term changes in shorter-term climate variability. Specifically, this research will aim to investigate four broad questions: (a) is short-term temperature variability changing over time; (b) where do we see the greatest changes in variability; (c) within what time windows (e.g., diurnal ranges, 1-day departure [1DD], weekly variability) is variability changing; and (d) do such trends differ by season? In an effort to figure out why temperature variability is changing, trends in multiple other (non-temperature) near-surface meteorological variables from one of the latest reanalysis products (ERA5) are also documented and discussed.

2 Data and Methods

The main analysis was undertaken using hourly 2-m temperature data retrieved from the European Center for Medium Range Weather Forecasting’s ERA5 reanalysis dataset (Hersbach et al., 2020) for the years 1950–2019 (note that the 1950–1978 portion of the reanalysis was considered “preliminary” at the time of retrieval). While the original spatial resolution was 0.25° × 0.25°, temperature data were resampled to an equal-spaced grid of 10,242 points across the globe, so as to correct for latitude in all space-based calculations (to prevent oversampling the poles relative to the rest of the globe).

Each of the steps described below were completed separately for each of these 10,242 individual locations. First, multiple windows were analysed: diurnal temperature range (DTR; using the 24 hourly values for each UTC-based day), the absolute 1-day temperature departure (the absolute value of the difference between two consecutive days’ mean temperatures), and the 7-day temperature range (using a centred moving range of the daily mean temperatures). For the sake of clarity below, these three windows of analysis will collectively be referred to as range/departure stats, or RDS. These RDS were then transformed into deseasonalized standardized anomalies in range (DSARs) separately for each RSD. Similar to methods used by Lee (2020a, 2020b), standardized deseasonalization is completed by first calculating the monthly mean value of each RDS and the monthly SD of each RDS across the time series. Then, a piecewise cubic spline is used to smooth the means of RDS and SDs of RDS each into a seasonal curve. These seasonal curves – one for means of RDS, and one for SDs of RDS – were then used in the traditional z-score transformation in the numerator and denominator, respectively. That is:

\[
\text{DSAR}_d = \frac{\text{RDS}_d - \bar{\text{X}}_d}{\sigma_d}
\]

where DSAR_d is the deseasonalized standardized anomaly in range on day d; RDS_d is the value of one of the range/departure statistics on day d; \(\bar{\text{X}}_d\) is the value of the smoothed mean on day d, and \(\sigma_d\) is the value of the smoothed SD on day d. It should be noted, that in addition to using ranges of 24-hr, 2 days (or, alternatively, 1DD), and 7 days, more traditional SDs were also examined (e.g., SD of temperatures within a day instead of ranges within a day), with virtually identical results to those presented below.

Two types of variability change were examined: changes in the magnitude of the DSARs, and changes in the frequency of extreme temperature range events (XTREs). These XTREs were defined individually for each of the 10,242 locations and time windows, based upon the DSAR being greater than or equal to the 95th percentile of all DSARs for that location. Season-by-season averages of DSARs and season-by-season sums of XTREs were computed for the 280 seasons (4 seasons × 70 years) in the study period. Then, for each season and for each year as a whole, Theil–Sen slope estimations were computed on the \(n = 70\) annual mean values (of DSARs or XTREs), using the nonparametric Mann–Kendall trend test for statistical significance (with \(\alpha = .05\)). A second trend analysis was completed for 1985–2019 \((n = 35)\), to examine whether recent trends are differing from those in the overall temporal domain.

In order to account for the spatial correlation of 10,242 separate significance tests being compared, Wilks’ method for controlling for the false detection ratio was employed (Wilks, 2016), essentially requiring a lower local \(p\)-value to achieve field significance.

In order to examine causes for the main results, monthly averaged, 2 m dew point temperature, 10 m zonal and meridional wind components, sea-level pressure, and total column cloud cover data were also retrieved from ERA5 for the 1950–2019 period, resampled to correct for latitude, and subjected to Theil-Sen slope estimation. While other meteorological variables may also play a role, these five additional variables were chosen both because they provide a holistic examination of the near-surface variables most likely to
contribute to changes in temperature variability, and due to trends of these variables noted in prior research by the author (Lee, 2020b). In order to sub-set the results spatially, regional boundaries were hand-drawn around areas of the globe that showed the largest changes in the global maps displayed below (Figure 1).

The ERA5 reanalysis data were chosen as the primary dataset in order to get a continuous global picture (and visualize spatial patterns) of changes over a multi-decadal time period. While no validation on station-based observations was undertaken specifically for the research described herein, prior research has shown reanalysis temperature data to associate well with observed station-based data. For example, Lee et al. (2021) found that temperature trends in the North American Regional Reanalysis – an older-generation reanalysis than ERA5 – were only significantly different in ~2% of locations examined. And, Sheridan et al. (2020) found that extreme temperature days from ERA-5 data matched observations 80% of the time over the United States and Canada – with some areas exhibiting >98% accuracy – better than any of the other reanalyses examined. Nonetheless, the results described below are still based upon the output of a reanalysis model rather than actual surface observations, and should be interpreted with caution in more remote areas of the planet with sparse weather station networks, especially in the earlier decades of the period of study.

3 | RESULTS

On average, temperature ranges are increasing for the 1DD and 7-day ranges (7DR; Table 1). Interestingly, DTR show virtually no 70-year trend when averaged across the globe, but do show significant increases over the last 35 years. The changes in 7-day temperature ranges (\(z = +0.013\) to \(z = +0.023\); \(p < .05\) for all) are more substantial than those for 1DD (\(z = +0.007\) to \(z = +0.009\); \(p < .05\) for all), though this difference has lessened in recent decades. Seasonally, the greatest changes are happening in boreal spring (April–June) and summer (July–September), though winter (January–March) is also seeing fairly substantial changes. Boreal autumn (October–December) is the only season with significant globally-averaged changes (decrease) in DTRs (\(z = -0.003\); \(p < .05\)). Moreover, even though both 1DD (\(z = +0.007\)) and 7DR (\(z = +0.013\)) are significantly increasing in autumn (\(p < .05\)) over the 70-year period of study, the magnitude of this increase is a bit lower than it is in most other seasons, and is non-significant in the last 35 years. While changes in XTREs were also examined, the results are nearly identical to those found with

| TABLE 1 | Globally-averaged decadal change (slope × 10) in DSARs over the a) entire 70-year period of study, and b) the 1985–2019 subset. Bold and italic values indicate statistical significance (\(p < .05\)). Units are standardized scores (z-scores) |
|-----------|-------------------------------------------------|
| a)        | DSARs (1950–2019) — Decadal change              |
|           | JFM  | AMJ | JAS | OND | YR              |
| Diurnal   | -0.0002 | 0.0021 | 0.0003 | -0.0026 | -0.0001         |
| 1-Day     | **0.0069** | **0.0111** | **0.0101** | **0.0070** | **0.0086**      |
| 7-Day     | **0.0157** | **0.0234** | **0.0226** | **0.0127** | **0.0191**      |
| b)        | DSARs (1985–2019) — Decadal change              |
|           | JFM  | AMJ | JAS | OND | YR              |
| Diurnal   | **0.0096** | **0.0151** | **0.0133** | **0.0091** | **0.0120**      |
| 1-Day     | **0.0106** | **0.0150** | **0.0111** | **0.0058** | **0.0104**      |
| 7-Day     | **0.0126** | **0.0164** | **0.0148** | **0.0065** | **0.0138**      |
DSARs, and thus, the latter will form the basis for all further discussion below.

While the linear trend in temperature range is the metric quantified herein, smoothed year-over-year time series plots (Figure 2) reveal that many locations (and indeed the world on the whole) have experienced nonlinearities in their temperature ranges over the course of the 70-year period of study, which inspired a more-focused analysis on the recent trends. Most of these fluctuations do appear fairly consistent across the four seasons. However, they differ based upon the range-window of analysis. For example, globally, for DTRs, the 1960s experienced an increase in DTR, followed by a steady decrease in the 1970s and 1980s; a slow multi-decadal rise in temperature ranges from 1990 to 2015, followed by a sharp decline since. For the other two windows, however, the peak in rising temperature ranges in the late 1960s – which was very steep for 7DR – plateaued over the following decade before rising much more gradually through the 1980s, 1990s, and early 2000s. Not until the early-to mid-2010s is there any notable decrease in these temperature ranges. Although, as mentioned above, despite this very recent decrease, over the entire 70-year period of study, there is still a statistically significant increase in the 1DD and 7DR, both annually and in each season, and a significant increase in DTRs over the last 35 years.

There is substantial spatial variability in all of these results, with the largest changes occurring in the Southern Hemisphere (Figure 3). Indeed, the single largest area of change is over the Southern Ocean, where all RSDs (DTR, 1DD, and 7DR) show marked increasing trends. In the eastern basin of the Southern Atlantic and Pacific Oceans – off the west coasts of South America and Africa – increased 7DR and 1-day temperature departures are noted, though the trend flattens over the last few decades. Adjacently, both South America and Africa are experiencing significant increases in most of these ranges as well (Table 2). Australia is experiencing large increases in the ranges of all three temporal windows examined, especially in the northern and eastern portions of the continent. And, Antarctica is showing increased ranges in all three temporal windows examined.

In the Northern Hemisphere, the largest area of change is exhibited in the Greenland, Iceland, and Norwegian (GIN) seas, where a marked decrease in 1DD, 7DR, and DTR is observed in all seasons except summer. North America exhibits a north-south split in ranges; in Canada, there is a significant increase in temperature ranges in all seasons except autumn (Figure 4); however, in the United States, decreases in DTR are quite evident in the eastern half of the country in Spring and Summer.

Trends in DTR diverge from those of 1DD and 7DR in a few places. For example, much of Northern Africa and the Middle East and India are exhibiting significant declines in DTR, with very little change in 1DD and 7DR ranges. Most of Europe is displaying large increases in DTR,

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**FIGURE 2** Smoothed regionally-averaged time series of annual DSARs for diurnal ranges (red), 1-day departures (blue) and 7-day ranges (green). Vertical axis units are standardized scores (z-scores), and differ for each graph [Colour figure can be viewed at wileyonlinelibrary.com]
especially in spring and summer, again with virtually no significant areas of change in 1DD and 7DR ranges.

Examining the more recent period (1985–2019) more closely, a few differences stand out (Table 1b and right-most columns in Table 2). Globally, while 7DRs are still significantly increasing nearly every season, that trend has waned over the last 35 years. DTRs, on the other hand, have all shown steepening positive trends since 1985, and are statistically significantly increasing in every season. Regionally, perhaps the biggest difference is in northeastern Canada, where annual 7DR is significantly increasing when examined over the last 70 years, but is significantly decreasing in the last half of the study period. This is in line with what would be expected with the well-documented recent decreases in sea ice in the adjacent waters (Screen and Simmonds, 2010), leading the land to take on a more maritime/moderate character. And, nearby in the GIN seas, the decreasing trend in all three DSARs has accelerated over the last 3+ decades.

Another noteworthy difference is the large change of the DTR trend in Western Australia, where there is a non-significant decreasing trend in DTRs from 1950 onwards, but a significant increasing trend in DTRs since 1985 – becoming more in-line with what is happening with 1DD and 7DR in the same region. Finally, on the global scale, while the only significant trend in 70-year DTRs was a decrease in boreal autumn, since 1985, DTRs are significantly increasing in every season, and annually.

### 4 | DISCUSSION

The Southern Ocean is one of the few places on Earth that is bucking the long-term trend upwards in mean temperature, showing non-significant increases in temperature (and in some places there are decreases in temperature (e.g., decreased SST in Bulgin et al., 2020)) and non-significant changes in humidity (Figure 5). The
Southern Ocean is also undergoing decreases in SLP ($\Delta -3\text{mb to } -4\text{mb in many places over the 70-year period of study}$), and increased winds, especially westerly winds – a change that has also been noted in prior research (e.g., Young and Ribal, 2019). From an examination of Figure 5, these increased wind speeds are due not

**TABLE 2** Regionally-averaged decadal change (slope $\times 10$) in DSARs over the 1950–2019 (left) and 1985–2019 period (right). Bold and italic values indicate statistical significance ($p < .05$). Units are standardized scores (z-scores)

| Region                  | 1950–2019  | 1985–2019 |
|-------------------------|------------|-----------|
|                         | 1-Day      | 7-Day     | Diurnal   | 1-Day      | 7-Day     | Diurnal   |
| E. South Pacific        | 0.024      | 0.046     | 0.002     | 0.042      | 0.055     | 0.042     |
| South America           | 0.036      | 0.061     | 0.047     | 0.038      | 0.066     | 0.074     |
| Southern Ocean          | 0.021      | 0.049     | 0.021     | 0.016      | 0.017     | 0.032     |
| E. South Atlantic       | 0.024      | 0.049     | 0.016     | 0.012      | 0.006     | $-0.006$  |
| Indian Ocean and Indonesia | 0.020    | 0.049     | 0.001     | 0.045      | 0.082     | 0.020     |
| W. Australia            | 0.024      | 0.041     | $-0.022$  | 0.012      | 0.023     | 0.048     |
| E. Australia            | 0.026      | 0.048     | 0.080     | 0.023      | 0.041     | 0.116     |
| GIN Seas                | $-0.033$   | $-0.061$  | $-0.047$  | $-0.057$   | $-0.114$  | $-0.064$  |
| Africa                  | 0.031      | 0.055     | 0.012     | 0.034      | 0.059     | 0.035     |
| Central Pacific         | $-0.003$   | 0.002     | $-0.031$  | $-0.004$   | $-0.021$  | $-0.041$  |
| Great Lakes             | $-0.009$   | $-0.018$  | $-0.020$  | $-0.013$   | $-0.032$  | $-0.013$  |
| NE Canada               | 0.012      | 0.017     | 0.035     | $-0.019$   | $-0.053$  | 0.017     |
| Alaska and Bering Sea   | $-0.015$   | $-0.026$  | $-0.026$  | $-0.024$   | $-0.051$  | $-0.023$  |
| N. Africa               | 0.008      | 0.011     | $-0.022$  | 0.009      | 0.011     | $-0.014$  |
| Europe                  | 0.000      | 0.001     | 0.033     | $-0.003$   | $-0.001$  | 0.061     |
| World                   | 0.009      | 0.019     | 0.000     | 0.010      | 0.014     | 0.012     |

**FIGURE 4** Seasonally-averaged changes ($\Delta$) over the 70-year period of study (slope $\times 70$) for 1-day departure (top row), 7-day range (middle row), and diurnal (bottom row) temperature range intensity. Statistical significance ($p < .05$) is indicated with black plus-symbols. Units are standardized scores (z-scores). Note the different colour bar for each row [Colour figure can be viewed at wileyonlinelibrary.com]
only to the increased westerly winds in the Southern Ocean, but are also forced by expanding subtropical high pressures further north (especially in the southern Indian Ocean) which are increasing the pressure gradient around 50°S latitude – all of which has strengthened counterclockwise flow of the near-surface Southern Hemisphere subtropical atmosphere. This stronger (zonal) flow could be perceived analogously as decreasing persistence, with synoptic systems moving more quickly west-to-east across this latitudinal belt than if the atmosphere were more meridional, and thus, ushering in more variable weather and increasing temperature ranges at synoptic time scales. This said, the positive trend in 7DR over the Southern Ocean has largely flattened out over the last half of the study period, and just misses the threshold for statistical significance ($p = .062$).

In the eastern basin of the Southern Atlantic and Pacific Oceans, increased 7DR and 1-day temperature departures coincide with increases in cloud cover and increasingly strong meridional (southerly) winds off the west coasts of Africa and South America, strengthening the eastern boundary currents flowing northwards from the Southern Ocean. In the Northern Hemisphere, strengthening northerly flow along the coast of California, Mexico, and northern Africa are also observed, suggesting stronger ocean currents in these areas too. These trends, noted in prior literature (e.g., Sydeman et al., 2014), are also likely leading to enhanced coastal upwelling of cold water, increasing coastal fog, and thus, cloud cover trends in these regions. Despite this rise in cloud cover, the maritime environment below largely negates the moderating influence of cloud cover (comparatively to the moderating influence of cloud cover over land), and instead, the increased wind speeds are more likely the key forcing agent leading to increased variability and corresponding changes in 1DD and 7DR in these areas.

Australia is one of the few places that are getting both hotter and drier, leading to increases most DSARs examined, especially in Eastern Australia. Further, while most of the globe is seeing significant increases in both diurnal minimums and maximums, Australia is also the only place that has opposite trends in diurnal minimums and maximums (Figure 5). For example, in Austral autumn (AMJ) and winter (JAS), northern and eastern Australia are seeing very large changes in DTR due to both decreasing daily minimums and increasing daily maximums (Figure 5). And, positive trends in DTRs here have only steepened since the mid-1980s, especially in Western Australia where the pre-1980 trend was actually negative.
In the GIN seas, a large decrease in 1DD, 7DR and DTR is prominent in all seasons except summer. The well-documented slowing of meridional overturning circulation and the oft-noted “warming hole” on the southern end of the area (Bryden et al., 2005; Liu et al., 2020; Caesar et al., 2021) is leading to cooler water temperatures. Further, in this high latitude ocean, feedbacks between Arctic amplification and dramatic long-term declines in sea ice (Kumar et al., 2010; Screen and Simmonds, 2010) are likely playing a large role in moderating the temperatures along the fringes of the Arctic ocean, decreasing the temperature ranges in the region. Similar phenomena are now occurring in the extreme coastal ocean surrounding Antarctic sea ice over the last decade, leading to decreased ranges here as well. In addition, prior research shows a poleward shift of the storm track over time (e.g., Kidston and Gerber, 2010; Shaw et al., 2016), which in turn brings more precipitation and further moderation of the temperatures, both in the Arctic and Antarctic.

Previous research has suggested global DTR are significantly decreasing since 1950 (e.g., Sun et al., 2019), due to a variety of possible reasons, including increased aerosols, soil moisture, cloud cover and changes in land-cover (Sun et al., 2019). However, herein, while there is a slight negative slope to DTRs over the 70-year period, there is no statistical significance globally, except for autumn. Further, while Sun et al. (2019) concluded that global DTR had decreased significantly, their study area was limited mostly to land areas with station-based observations – notably excluding much of South America where the research herein finds marked increases in DTR. While remote areas like the South American rainforest, are likely quite data/station-sparse, especially towards the beginning of the 70-year period of study (when the slopes are steepest; Figure 2), these trends hold (and are even stronger) for the more-recent period of analysis (1985–2019; Table 2). Nonetheless, the differences (from prior research using observed data) noted herein should be interpreted with caution.

With regard to 1DD and 7DR, all oceanic areas with statistically significant increases in 1DD and 7DR, are generally exhibiting stronger winds. In the Southern Ocean, it is largely strengthening westerlies; above the eastern boundary currents it is largely strengthening meridional winds (northerlies in the NH, southerlies in the SH), but strengthening zonal (easterly) components as well in the tropics. Essentially, over the ocean especially, increased variability (or decreased persistence) in temperatures appears to mostly be driven by stronger winds. Areas with significant decreases in 1DD and 7DR over the ocean (mostly the Arctic, but also the central Pacific and Atlantic) vary considerably more in their factors. Near the poles, these decreases in 1DD and 7DR are likely due to lower SLP concurrent with a northern migration of the storm track as noted above. However, in the tropical oceans, the factors leading to decreased 1DD and 7DR ranges are difficult to pinpoint. These areas deserve additional attention in future research.

Over land, factors leading to changes in these temperature ranges are more straightforward. For example, South America, Africa, Antarctica and Europe all have large areas of increased temperature ranges coinciding with decreased cloud cover. Since the impacts of cloud cover over land generally moderate temperatures (cooling via reflection of incoming shortwave radiation and warming via absorption of outgoing thermal radiation), decreases in cloud cover would drive increases in temperature ranges. Oppositely, over the Sahara, decreased DTRs are occurring alongside increases in cloud cover.

5 | CONCLUSIONS

This study examined trends in temperature variability at three different time scales: diurnal ranges, 1DD, and 7DR for overlapping 70- and 35-year periods. This research adds to a growing body of literature that is recognizing the importance of examining trends in “other” statistical parameters (besides the mean) of climate change – especially variability – as it is more often the extremes of an atmospheric variable that lead to negative outcomes than it is the statistical mean. It also represents the first examination of full 70-year trends of many variables contained in the recently released ERA5 reanalysis.

Both the 7- and 1-day scales showed globe-wide increases in variability that encompassed all seasons. However, contrary to prior research, DTR are not exhibiting statistically significant decreases when averaged across the globe, with the exception of a slight decrease in boreal autumn. Moreover, over the last 35 years, there has been a significant increase in DTRs during every season, and annually. There is marked geographic variability, with significant changes at all three time scales when examined regionally, especially in the Southern Hemisphere. The largest area of change is an increase in DTR, 7DR, and 1DD for most of the Southern Ocean. Large parts of South America, Africa, and Australia are also exhibiting significant increases in variability, especially for the 1- and 7-day scales, and recently with DTRs. The largest area of decreased temperature variability is noted near the Arctic, and it is especially pronounced for diurnal ranges. Many of the changes noted above have straightforward origins – stronger winds over most marine environments appear to increase variability, while slower winds decrease it. Over land, there is, expectedly, a large inverse relationship between cloud cover trends and these trends in temperature variability. However, the reasons behind temperature range trends in the tropical oceans should be explored further in future research.
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CONFLICT OF INTEREST
The author declares no potential conflict of interest.

AUTHOR CONTRIBUTIONS
Cameron C. Lee: Conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, Software, supervision, validation, visualization.

ORCID
Cameron C. Lee https://orcid.org/0000-0002-5380-6601

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