Appendix B:
Climate Overview of the Oak Ridge Area

Appendix
B. Climate Overview of the Oak Ridge Area

B.1 Regional Climate

The climate of the Oak Ridge area and its surroundings may be broadly classified as humid subtropical. The term “humid” indicates that the region receives an overall surplus of precipitation compared to the level of evaporation and transpiration that is normally experienced throughout the year. The “subtropical” designation indicates that the region experiences a wide range of seasonal temperatures. Such areas are typified by significant differences in temperature between summer and winter.

Oak Ridge winters are characterized by synoptic weather systems that produce significant precipitation events every 3 to 5 days. These wet periods are occasionally followed by arctic air outbreaks. Although snow and ice are not associated with many of these systems, occasional snowfall does result. Winter cloud cover tends to be enhanced by the regional terrain (due to cold air wedging and moisture trapping).

Severe thunderstorms, which can occur at any time of the year, occur most frequently during spring and rarely during winter. The Cumberland Mountains and Cumberland Plateau often inhibit the intensity of severe systems that traverse the region, particularly those moving from west to east, due to the downward momentum created as the storms move off higher terrain into the Great Valley. Summers are characterized by very warm, humid conditions. Occasional frontal systems may produce organized lines of thunderstorms (and rare damaging tornados). More frequently, however, summer precipitation results from “air mass” thundershowers that form as a consequence of daytime heating, rising humid air, and local terrain features. Although adequate precipitation usually occurs during the fall, the months of August through October often represent the driest period of the year. The occurrence of precipitation during the fall tends to be less cyclical than for other seasons but is occasionally enhanced by decaying tropical cyclones moving north from the Gulf of Mexico. During November, winter-type cyclones again begin to dominate the weather and may continue to do so until April or May.

Decadal-scale climate change has recently affected the East Tennessee region. Most of these changes appear to be related to the hemispheric effects caused by the frequency and phase of the El Niño–Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the Atlantic Multidecadal Oscillation (AMO). The ENSO and PDO patterns, with cycles of 3 to 7 years and about 40 years, respectively, affect Pacific Ocean sea surface temperatures. The AMO, with a cycle of 30 to 70 years, affects Atlantic sea surface temperature. All of these patterns collectively modulate long-term regional temperature and precipitation trends in eastern Tennessee. The AMO shifted from a cold to a warm sea surface temperature phase (mid-1990s) and could continue in its present state for another decade or so. The PDO entered an either cool or transitional sea surface temperature state around 2000. Also, the ENSO pattern had frequently brought about warmer Eastern Pacific sea surface temperatures during the 1990s, but this phenomenon had subsided somewhat in the 2000s. A very strong El Niño occurred in 2015–2016, leading to above-normal temperatures, both locally and in much of the globe by 2016. Additionally, some evidence exists that human-induced climate change may be producing some effects (via an assembly of first-order influences such as well-mixed greenhouse gases, land cover change, carbon soot, aerosols, and other effects). Solar influences on the jet stream, via changes to the stratospheric temperature gradient with respect to the 11-year solar cycle, also play a role in inter-annual climate variability (Ineson et al. 2011). Perhaps partly due to the effects of the AMO and ENSO, the Oak Ridge climate warmed about 1.1°C from the 1980s to the 1990s but has stabilized just above the 1990s values during the 2000s (a further warming of 0.2°C was observed). The recent warming appears to have lengthened the growing season [i.e., the period with temperatures above 0°C (32°F)] by about 2 to 3 weeks over the last 30 years. This warming has primarily affected minimum temperature over the last 30 years, the effect being presumably related to changes in the interaction of the surface boundary layer with greenhouse gases and/or aerosol concentration changes. The effects of greenhouse gases on the nocturnal inversion layer (and thus on minimum temperatures) represent a redistribution of heat in the lower portion of the surface atmospheric layer. Temperature averages for individual years can vary significantly, as noted by the recent contrast of greater than 1°C between 2014 (14.8°C average) and 2015 (16.0°C average), largely the result of the recent strong El Niño. In 2017, the annual average temperature at ORNL returned almost to the 2014 level (14.9°C).

B.2 Winds

Five major terrain-related wind regimes regularly affect the Great Valley of eastern Tennessee:

- pressure-driven channeling,
- downward-momentum transport or vertically coupled flow,
- forced channeling,
- along-valley and mountain-valley thermal circulations, and
- down sloping.

Pressure-driven channeling and vertically coupled flow affect winds on scales comparable to those of the Great Valley (hundreds of kilometers). Forced channeling occurs on similar scales but is also quite important at small spatial scales, such as those characterizing the ridge-and-valley terrain on the Oak Ridge Reservation (ORR) (Birdwell 2011). Along-valley and mountain-valley circulations are thermally driven and occur within a large range of spatial scales. Thermally driven flows are more prevalent under conditions of clear skies and low humidity, favoring summer and fall months. Down sloping frequently is responsible for a slight temperature elevation when the Cumberland Mountains are on the windward side of ORR. Such windward flow also favors reduced wind speeds.

Forced channeling is defined as the direct deflection of wind by terrain. This form of channeling necessitates some degree of vertical motion transfer, implying that the mechanism is less pronounced during strong temperature-inversion conditions. Although forced channeling may result from interactions between large valleys and mountain ranges (such as the Great Valley and the surrounding mountains), the mechanism is especially important in narrow, small valleys such as those on ORR (Kossman and Sturman 2002).

Forced channeling within the Central Great Valley represents the dominant large-scale wind mechanism, influencing 50 to 60 percent of all winds observed in the area. For up-valley flow cases, these winds are frequently associated with large wind shifts when they initiate or terminate (45°–90°). At small scales, ridge-and-valley terrain usually produces forced-channeled local flow (more than 90 percent of cases). Most forced-channeled winds prefer weak to moderate synoptic pressure gradients of less than 0.010 mb/km (Birdwell 2011).

Large-scale forced channeling occurs regularly within the Great Valley when northwest to north winds (perpendicular to the axis of the central Great Valley) coincide with vertically coupled flow. The phenomenon sometimes results in a split-flow pattern (winds southwest of Knoxville moving down-valley and those east of Knoxville moving up-valley). The causes of such a flow pattern may include the shape characteristics of the Great Valley (Kossman and Sturman 2002) but also may be associated with the specific location of the Cumberland and Smoky Mountains relative to upper-level wind flow (Eckman 1998). The convex shape of the Great Valley with respect to a northwest wind flow may lead to a divergent wind flow pattern in the Knoxville area. This results in downward air motion. Additionally, horizontal flow is reduced by the windward mountain range (Cumberland Mountains), which increases buoyancy and Coriolis effects (also known as Froude and Rossby ratios). Consequently, the leeward mountain range (Smoky Mountains) becomes more effective at blocking or redirecting the winds.

Vertically coupled winds tend to occur when the atmosphere is unstably or neutrally buoyant. When a strong horizontal wind component is present, as in conditions behind a winter cold front or during strong cold air advection, winds tend to override the terrain, flowing roughly in the same direction as the winds aloft. This phenomenon is a consequence of the horizontal transport and momentum aloft being transferred to the surface. However, Coriolis effects may turn the winds by up to 40° to the left (Birdwell 1996).

In the Central Valley, vertically coupled winds dominate about 25 to 35 percent of the time; however, most such winds are turned toward an up-valley or down-valley direction when small-scale ridge-and-valley terrain is present. Wintertime vertically coupled flow is typically dominated by strong, large-scale pressure forces, whereas the summertime cases tend to be associated with a deep mixing depth (greater than 500 m). Most vertically coupled flows are associated with major wind shifts (90°–135°) when they begin or terminate (Birdwell 2011).

Pressure-driven channeling, in essence, is the redirection of synoptically induced wind flow through a valley channel. The direction of wind flow through the valley is determined by the axis of the pressure gradient superimposed on a valley axis (Whiteman 2000). The process is affected by Coriolis forces, a leftward deflection of winds in the Northern Hemisphere. Eckman (1998) suggested that pressure-driven channeling plays a significant role in the Great Valley. Winds driven purely by such a process shift from up-valley to down-valley flow or conversely as large-scale pressure systems induce flow shifts across the axis of the Great Valley. Since the processes involved in pressure-driven flow primarily affect the horizontal motion of air, the presence of a temperature inversion enhances this pattern significantly. Weak vertical air motion and momentum associated with such inversions allow different layers of air to slide over each other (Monti et al. 2002).

Within the Central Great Valley, and especially ORR, winds dominated by down-valley pressure-driven channeling range in frequency from 2 to 10 percent, with the lowest values in summer and the highest in winter. Up-valley pressure-driven channeling usually does not dominate winds in the Central Great Valley but co-occurs with forced-channeled winds 50 percent of the time. Winds dominated by pressure-driven channeling often result in large wind shifts (90°–180°) before and after the occurrence of the wind pattern. These wind shifts occur about twice as frequently within and near ORR when compared with wind shifts that take place in other parts of the Great Valley (Birdwell 2011). Most pressure-driven channeled winds occur in association with moderate (0.006–0.016 mb/km) synoptic pressure gradients.

Thermally driven winds are common in areas of significant complex terrain. These winds occur as a result of pressure and temperature differences caused by varied surface-air energy exchange at similar altitudes along a valley's axis, sidewalls, or slopes. Thermal flows operate most effectively when synoptic winds are light and when thermal differences are exacerbated by clear skies and low humidity (Whiteman 2000). Ridge-and-valley terrain may be responsible for enhancing or inhibiting such flow, depending on ambient weather conditions. Large-scale thermally driven wind frequency varies from 2 percent to 20 percent with respect to season in the Central Great Valley. Frequencies are highest during summer and fall, when intense surface heating and/or low humidity help drive flow patterns (Birdwell 2011).

Annual wind roses have been compiled for 2017 for each of the 10 DOE-managed ORR meteorological towers (towers MT2, MT3, MT4, MT6, MT7, MT9, MT10, MT11, MT12, and MT13). These, along with other annual wind rose data may be viewed online **here**. The wind roses represent large-scale trends and should be used with caution for estimates involving short-term variations.

A wind rose depicts the typical distribution of wind speed and direction for a given location. The winds are represented in terms of the direction from which they originate. The rays emanating from the center correspond to points of the compass. The length of each ray is related to the frequency at which winds blow from the given direction. The concentric circles represent increasing frequencies from the center outward, given in percentages. Precipitation wind roses display similar information except that wind speed frequencies are replaced with data associated with the rate of hourly precipitation. Likewise, wind direction stability and wind direction mixing height roses replace wind speeds with data on stability class and mixing height, respectively. Wind direction peak gust roses reflect the frequency of peak 1 to 10 s wind gusts for various wind directions.

B.3 Temperature and Precipitation

Temperature and precipitation normals (1981–2010) and extremes (1948–2017) and their durations for the city of Oak Ridge and ORNL are summarized in Table B.1. Decadal temperature and precipitation averages for the four decades of the 1970s to 2000s, as well as the partial decade of the 2010s, are provided in Table B.2. Hourly freeze data (1985–March 2018) are given in Table B.3. Overall, at ORNL, 2017 was 0.2°C above normal with regard to temperatures compared to the 1981–2010 Oak Ridge base period, and precipitation was about 10 percent above normal compared to the 1981–2010 mean. ORNL became the official reporting site for climate purposes in 2015 instead of the Oak Ridge townsite. This change was made in response to the implementation of climate-data-quality measurements initiated at ORNL in 2014 and in response to siting problems at the Oak Ridge townsite (KOQT).

B.3.1 Recent Climate Change with Respect to Temperature and Precipitation

Table B.2 presents a decadal analysis of temperature patterns for the decades of the 1970s to the 2010s (to 2017). In general, temperatures in the Oak Ridge area rose until the 1990s but with a much slower rise since the 1990s. Based on these average decadal temperatures, temperatures have risen 1.4°C between the decades of the 1970s and the 2000s from 13.8°C to 15.2°C (56.8°F to 59.3°F). More detailed analysis reveals that these temperature increases have been neither linear nor equal throughout the months or seasons.

For the 1970s to the 2000s, January and February average temperatures have seen increases of 2.1°C and 1.9°C, respectively. This significant increase is probably dominated by the effects of the AMO, though this climate response may include both natural and anthropogenic effects. The Arctic has seen the largest increase in temperatures of anywhere in the Northern Hemisphere over the last 30 years, although the increase could also be associated with a variety of causes.

During the months of January and February, much of the air entering eastern Tennessee comes from the Arctic. As a result, Oak Ridge temperatures have warmed more dramatically during those months from the 1970s and 1980s to the 2000s. However, this trend has noticeably stalled during the 2010s, with winter temperature averages remaining roughly steady or even slightly declining. From the 1980s to the 2010s, spring (March–May) temperatures rose by about 2°C. Summer and fall temperatures underwent lesser temperature rises, about 0.6°C, since the 1980s. Overall, temperatures remained approximately steady during the 2000s and 2010s. The only significant increases occurred in April and December. Most of the overall warming that has occurred over the last several decades has been driven by increases in minimum daily temperatures, a change likely resulting from the redistribution of heat in the boundary layer resulting from the increased presence of greenhouse gases and aerosols near the surface. An increase in greenhouse gases and aerosols acts to weaken the strength of nighttime surface temperature inversions. Specifically, overall annual minimum temperatures seem to have increased more dramatically (2.0°C from the 1980s to the 2010s) than maximum temperatures (0.9°C from the 1980s to the 2010s).

Table B.1. Climate normals (1981–2010) and extremes (1948–2017) for Oak Ridge National Laboratory, Oak Ridge, Tennessee

Monthly variables	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Temperature, °C (°F)													
30-Year Average Max	8.3 (46.9)	11.2 (52.1)	16.4 (61.6)	21.6 (70.8)	25.9 (78.6)	29.8 (85.7)	31.4 (88.5)	31.2 (88.1)	27.7 (81.9)	22.0 (71.6)	15.7 (60.2)	9.4 (49.0)	20.9 (69.6)
2017 Average Max	12.1 (53.8)	14.9 (58.9)	17.1 (62.8)	24.2 (75.6)	25.0 (77.0)	28.1 (82.6)	30.9 (87.6)	29.2 (84.6)	26.2 (79.1)	22.5 (72.6)	15.9 (60.7)	9.1 (48.4)	21.3 (70.3)
70-Year Record Max	25 (77)	26 (79)	30 (86)	33 (92)	35 (95)	41 (105)	41 (105)	39 (103)	39 (102)	32 (90)	28 (83)	26 (78)	41 (105)
30-Year Average Min	-2.2 (28.0)	-0.6 (30.9)	3.1 (37.5)	7.4 (45.4)	12.6 (54.7)	17.3 (63.1)	19.7 (67.5)	18.9 (66.1)	15.2 (59.3)	8.4 (47.2)	3.1 (37.6)	-0.9 (30.4)	8.5 (47.3)
2017 Average Min	2.9 (37.2)	2.0 (35.6)	3.9 (39.0)	11.1 (52.0)	12.5 (54.6)	16.8 (61.4)	19.6 (67.3)	18.4 (65.2)	14.6 (58.3)	14.6 (58.3)	3.8 (38.7)	-0.4 (31.3)	10.0 (49.9)
70-Year Record Min	-27 (-17)	-25 (-13)	-17 (1)	-7 (20)	-1 (30)	4 (39)	9 (49)	10 (50)	1 (33)	-6 (21)	-16 (3)	-22 (-7)	-27 (-17)
30-Year Average	3.1 (37.5)	5.3 (41.5)	9.8 (49.6)	14.6 (58.3)	19.3 (66.7)	23.6 (74.5)	25.6 (78.1)	25.2 (77.4)	21.5 (70.7)	15.2 (59.4)	9.4 (48.9)	4.3 (39.7)	14.7 (58.5)
2017 Average	7.5 (45.7)	8.5 (47.3)	10.3 (50.7)	17.3 (63.2)	18.6 (65.6)	21.9 (71.2)	24.5 (76.1)	23.0 (73.7)	19.4 (67.0)	14.9 (58.8)	8.6 (47.6)	4.1 (39.5)	14.9 (59.0)
2017 Departure from Average	4.4 (8.2)	3.2 (5.8)	0.5 (1.1)	2.7 (4.9)	-0.7 (-1.1)	-1.7 (-3.3)	-1.1 (-2.0)	-2.2 (-3.7)	-2.1 (-3.7)	-0.3 (-0.6)	-0.8 (-1.3)	-0.1 (-0.2)	0.2 (0.5)
30-year average heating degree days, °C (°F)[a]													
	332 (598)	273 (491)	243 (473)	49(88)	42(75)	0	0	0	14 (25)	107 (192)	224 (403)	428 (770)	1711 (3079)
30-year average cooling degree days, °C (°F)[a]													
	0	0	2 (4)	16 (29)	68 (122)	164 (296)	228 (410)	217 (390)	108 (194)	18 (32)	1 (2)	0	822 (1479)
Precipitation, mm (in.)													
30-Year Average	120.9 (4.76)	124.2 (4.89)	120.9 (4.76)	112.6 (4.43)	116.6 (4.59)	98.3 (3.87)	134.4 (5.29)	82.1 (3.23)	98.1 (3.86)	76.0 (2.99)	122.2 (4.81)	131.1 (5.16)	1337.5 (52.64)
2017 Totals	101.9 (4.01)	67.8 (2.67)	122.5 (4.82)	244.4 (9.62)	114.6 (4.51)	106.5 (4.19)	159.1 (6.26)	140.3 (5.52)	112.3 (4.42)	140.3 (5.52)	77.7 (3.06)	98.6 (3.88)	1485.9 (58.48)
2017 Departure from Average	-20.0 (-0.75)	56.4 (2.22)	1.6 (0.06)	131.8 (5.19)	-2.0 (-0.08)	8.2 (0.32)	24.6 (0.97)	58.2 (2.29)	14.2 (0.56)	64.3 (2.53)	-44.5 (1.75)	32.5 (1.28)	148.4 (5.84)
70-Year Max Monthly	337.2 (13.27)	324.7 (12.78)	311.0 (12.24)	356.5 (14.03)	271.9 (10.70)	283.0 (11.14)	489.6 (19.27)	265.8 (10.46)	257.4 (10.14)	176.6 (6.95)	310.5 (12.22)	321.2 (12.64)	1939.4 (76.33)
70-Year Max 24-h	108.0 (4.25)	131.6 (5.18)	120.4 (4.74)	158.5 (6.24)	112.0 (4.41)	94.0 (3.70)	124.8 (4.91)	190.1 (7.48)	160.1 (6.30)	67.6 (2.66)	130.1 (5.12)	130.1 (5.12)	190.1 (7.48)
70-Year Min Monthly	23.6 (0.93)	21.3 (0.84)	54.1 (2.13)	46.2 (1.82)	20.3 (0.80)	13.5 (0.53)	31.3 (1.23)	13.7 (0.54)	Trace	Trace	34.8 (1.37)	17.0 (0.67)	911.4 (35.87)
Snowfall, cm (in.)													
30-Year Average	7.4 (2.9)	6.6 (2.6)	2.5 (1.0)	7.6 (0.3)	0	0	0	0	0	0	Trace	4.1 (1.6)	21.3 (8.4)
2017 Totals	6.6 (2.6)	Trace	Trace	0	0	0	0	0	0	0	0	Trace	6.6 (2.6)
70-Year Max Monthly	24.4 (9.6)	43.7 (17.2)	53.4 (21.0)	15.0 (5.9)	Trace	0	0	0	0	Trace	16.5 (6.5)	53.4 (21.0)	105.2 (41.4)
70-Year Max 24-h	21.1 (8.3)	28.7 (11.3)	30.5 (12.0)	13.7 (5.4)	Trace	0	0	0	0	Trace	16.5 (6.5)	30.5 (12.0)	30.5 (12.0)
Days w/temp													
30-Year Max ≥ 32°C	0	0	0	0.2	0.8	8.0	14.5	13.1	3.9	0	0	0	40.5
2017 Max ≥ 32°C	0	0	0	0	0	1	11	3	0	0	0	0	15
30-Year Min ≤ 0°C	21.6	16.6	10.7	2.7	0	0	0	0	0	1.7	10.4	18.8	82.5
2017 Min ≤ 0°C	12	11	11	0	0	0	0	0	0	1	11	19	65
30-Year Max ≤ °C	2.8	0.9	0.1	0	0	0	0	0	0	0	0	1.6	5.4
2017 Max ≤ 0°C	2	0	0	0	0	0	0	0	0	0	0	1	3
Days w/precipitation													
30-Year Avg ≥ 0.01 in.	11.5	11.0	11.7	10.4	11.7	11.1	12.4	9.6	8.4	8.4	9.6	12.0	127.8
2017 Days ≥ 0.01 in.	15	12	14	14	14	12	12	11	7	6	9	8	134
30-Year Avg ≥ 1.00 in.	1.3	1.4	1.2	1.2	1.3	1.0	1.4	0.8	1.3	1.0	1.5	1.6	15.0
2017 Days ≥ 1.00 in.	2	0	1	4	1	2	2	3	1	3	1	2	22

Table B.2. Decadal climate change (1970–2017) for City of Oak Ridge, Tennessee, with 2017 comparisons

Monthly variables	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Temperature, °C (°F)													
1970–1979 Avg Max	6.6 (43.8)	9.7 (49.5)	15.6 (60.1)	21.4 (70.6)	24.8 (76.7)	28.5 (83.3)	30.0 (85.9)	29.7 (85.5)	26.8 (80.2)	20.8 (69.4)	14.5 (58.2)	10.0 (49.9)	19.9 (67.8)
1980–1989 Avg Max	6.9 (44.4)	10.2 (50.3)	15.9 (60.7)	21.0 (69.8)	25.6 (78.1)	29.8 (85.7)	31.6 (88.8)	30.7 (87.3)	27.1 (80.8)	21.3 (70.3)	15.6 (60.2)	8.6 (47.5)	20.3 (68.6)
1990–1999 Avg Max	9.4 (48.8)	12.3 (54.1)	16.2 (61.2)	21.9 (71.3)	26.2 (79.1)	29.7 (85.5)	32.1 (89.8)	31.4 (88.6)	28.4 (83.2)	22.6 (72.8)	15.2 (59.4)	10.4 (50.8)	21.3 (70.4)
2000–2009 Avg Max	8.8 (47.9)	11.2 (52.1)	17.0 (62.7)	21.4 (70.6)	25.8 (78.4)	29.8 (85.6)	30.8 (87.5)	31.4 (88.5)	27.6 (81.8)	21.8 (71.2)	15.9 (60.6)	9.8 (49.6)	21.0 (69.7)
2010–2017 Avg Max	8.0 (46.5)	11.4 (51.7)	16.4 (61.6)	23.0 (73.5)	26.3 (79.5)	30.4 (86.8)	31.3 (88.5)	30.9 (87.6)	28.4 (82.3)	22.2 (72.0)	15.8 (60.3)	11.2 (51.2)	21.2 (70.1)
1980s vs. 2010s	1.1 (2.0)	0.8 (1.4)	0.5 (1.0)	2.0 (3.6)	0.8 (1.4)	0.6 (1.1)	-0.2 (-0.3)	0.2 (0.3)	0.9 (1.6)	0.9 (1.7)	0.1 (0.2)	2.1 (3.7)	0.9 (1.5)
2000s vs. 2010s	-0.8 (-1.4)	-0.2 (-0.4)	-0.6 (-1.0)	1.6 (2.9)	0.6 (1.1)	0.6 (1.2)	0.6 (1.1)	-0.5 (-0.9)	0.3 (0.6)	0.4 (0.8)	-0.1 (-0.3)	0.9 (1.6)	0.2 (0.4)
2017 Avg Max	12.1 (53.8)	14.9 (58.9)	17.1 (62.8)	24.2 (75.6)	25.0 (77.0)	28.5 (82.6)	30.9 (87.6)	29.2 (84.6)	26.2 (79.1)	22.5 (72.6)	15.9 (60.7)	9.1 (48.4)	21.3 (70.3)
1970–1979 Avg Min	-3.4 (25.8)	-2.4 (27.6)	3.0 (37.4)	6.7 (44.1)	11.6 (52.8)	15.7 (60.2)	18.3 (64.9)	18.1 (64.6)	15.5 (59.9)	7.5 (45.5)	2.6 (36.8)	-0.8 (30.5)	7.7 (45.8)
1980–1989 Avg Min	-4.1 (24.7)	-2.1 (28.3)	1.7 (35.0)	6.0 (42.9)	11.4 (52.4)	16.2 (61.2)	19.0 (66.2)	18.4 (65.1)	14.4 (57.9)	7.5 (45.4)	3.1 (37.5)	-2.3 (27.8)	7.4 (45.3)
1990–1999 Avg Min	-0.9 (30.3)	0.0 (32.0)	2.9 (37.1)	7.2 (45.0)	12.5 (54.5)	17.2 (63.0)	20.0 (67.9)	18.9 (66.1)	15.1 (59.2)	8.2 (46.8)	2.2 (36.0)	0.1 (32.2)	8.6 (47.6)
2000–2009 Avg Min	-1.4 (29.5)	0.0 (32.0)	4.4 (39.9)	8.6 (47.5)	13.6 (56.4)	18.0 (64.3)	20.0 (67.9)	20.0 (68.0)	16.1 (61.0)	9.5 (49.0)	3.9 (39.0)	-0.4 (31.4)	9.4 (48.9)
2010–2017 Avg Min	-2.3 (27.9)	0.2 (32.4)	4.4 (39.9)	9.2 (48.6)	13.8 (56.8)	18.4 (65.2)	20.4 (68.8)	19.6 (67.3)	16.0 (60.6)	9.2 (48.6)	3.1 (37.5)	1.1 (34.0)	9.4 (49.0)
1980s vs. 2010s	1.8 (3.3)	2.3 (4.2)	2.7 (4.8)	3.2 (5.7)	2.4 (4.4)	2.3 (4.1)	1.5 (2.6)	1.2 (2.1)	1.5 (2.6)	1.7 (3.1)	0.0 (0.0)	3.4 (6.2)	2.0 (3.7)
2000s vs. 2010s	-0.8 (-1.5)	0.2 (0.4)	0.0 (0.0)	0.6 (1.1)	0.2 (0.4)	0.5 (0.9)	0.5 (0.9)	-0.4 (-0.8)	-0.2 (-0.4)	-0.3 (-0.5)	-0.8 (-1.5)	1.5 (2.6)	0.1 (0.1)
2017 Avg Min	-2.9 (37.2)	2.0 (35.6)	4.4 (39.0)	11.1 (52.0)	12.5 (54.6)	16.3 (61.4)	19.6 (67.3)	18.4 (65.2)	14.6 (58.3)	9.2 (48.7)	3.7 (38.7)	-0.4 (31.3)	9.5 (49.1)
1970–1979 Avg	1.6 (34.9)	3.7 (38.6)	9.3 (48.8)	14.1 (57.4)	18.1 (64.7)	22.1 (71.8)	24.1 (75.4)	23.9 (75.0)	21.1 (70.0)	14.2 (57.5)	8.6 (47.5)	4.6 (40.3)	13.8 (56.8)
1980–1989 Avg	1.4 (34.6)	4.1 (39.3)	8.8 (47.9)	13.5 (56.4)	18.5 (65.3)	23.0 (73.4)	25.3 (77.5)	24.6 (76.2)	20.8 (69.4)	14.4 (57.9)	9.4 (48.8)	3.1 (37.7)	13.9 (57.0)
1990–1999 Avg	4.2 (39.6)	6.2 (43.1)	9.6 (49.2)	14.5 (58.2)	19.4 (66.8)	23.5 (74.3)	26.0 (78.9)	25.2 (77.4)	21.9 (71.4)	15.5 (59.8)	8.8 (47.8)	5.3 (41.5)	15.0 (59.0)
2000–2009 Avg	3.7 (38.7)	5.6 (42.1)	10.7 (51.3)	15.3 (59.6)	19.7 (67.5)	23.9 (75.1)	25.4 (77.7)	25.7 (78.3)	21.9 (71.4)	15.6 (60.1)	9.9 (49.8)	4.7 (40.5)	15.2 (59.3)
2010–2017 Avg	2.9 (37.1)	5.1 (42.1)	10.5 (50.9)	15.9 (60.9)	20.0 (68.0)	23.7 (75.6)	25.7 (78.1)	24.9 (76.9)	21.9 (70.9)	15.4 (59.7)	8.7 (48.6)	5.8 (42.4)	15.2 (59.3)
1980s vs. 2010s	1.4 (2.6)	1.5 (2.8)	1.7 (3.0)	2.5 (4.6)	1.5 (2.7)	1.2 (2.2)	0.3 (0.6)	0.4 (0.7)	0.8 (1.5)	1.0 (1.8)	-0.2 (-0.3)	2.7 (4.8)	1.3 (2.3)
2000s vs. 2010s	-0.8 (-1.5)	0.0 (0.0)	-0.2 (-0.4)	0.8 (1.4)	0.3 (0.5)	0.3 (0.6)	0.2 (0.4)	-0.8 (-1.4)	-0.3 (-0.5)	-0.3 (-0.5)	-0.7 (-1.3)	1.1 (2.0)	0.0 (0.0)
2017 Avg	7.5 (45.7)	8.5 (47.3)	10.4 (50.7)	17.3 (63.2)	18.6 (65.6)	21.8 (71.2)	24.5 (76.1)	23.1 (73.7)	19.4 (67.0)	14.9 (58.8)	9.2 (48.7)	4.1 (39.5)	15.0 (59.0)
Precipitation, mm (in.)													
1970–1979 Avg	143.4 (5.65)	94.6 (3.72)	169.4 (6.67)	118.3 (4.66)	149.8 (5.89)	120.5 (4.74)	130.4 (5.13)	109.8 (4.32)	107.2 (4.22)	99.8 (3.93)	129.6 (5.10)	145.3 (5.72)	1516.4 (59.68)
1980–1989 Avg	100.4 (3.95)	109.1 (4.29)	112.6 (4.43)	88.8 (3.49)	110.6 (4.35)	84.1 (3.31)	120.4 (4.74)	82.6 (3.25)	108.9 (4.29)	79.8 (3.14)	128.0 (5.04)	107.6 (4.23)	1236.2 (48.66)
1990–1999 Avg	141.4 (5.57)	136.5 (5.37)	149.0 (5.86)	126.3 (4.97)	113.4 (4.47)	110.0 (4.33)	134.8 (5.31)	83.6 (3.29)	71.9 (2.83)	67.3 (2.65)	109.8 (4.32)	161.0 (6.34)	1429.4 (56.26)
2000–2009 Avg	116.9 (4.60)	121.8 (4.80)	115.6 (4.55)	125.0 (4.92)	117.8 (4.64)	95.2 (3.75)	138.9 (5.47)	78.4 (3.09)	108.8 (4.28)	74.0 (2.91)	121.4 (4.78)	124.4 (4.90)	1333.4 (52.48)
2010–2017 Avg	127.3 (5.01)	120.2 (4.73)	117.6 (4.63)	138.5 (5.45)	89.7 (3.53)	125.3 (4.93)	161.6 (6.36)	77.0 (3.35)	118.4 (4.66)	71.4 (3.15)	124.8 (4.91)	147.9 (5.82)	1421.8 (55.96)
1980s vs. 2010s	26.7 (1.05)	11.2 (0.44)	5.0 (0.20)	49.8 (1.96)	-20.8 (-0.82)	41.1 (1.62)	41.4 (1.62)	2.5 (0.10)	9.5 (0.38)	0.1 (0.01)	-3.2 (-0.13)	40.2 (1.58)	182.9 (7.20)
2000s vs. 2010s	10.4 (0.41)	-1.6 (-0.06)	2.1 (0.08)	13.5 (0.53)	-28.1 (-1.11)	30.0 (1.18)	23.1 (0.89)	6.6 (0.26)	9.6 (0.38)	5.9 (0.23)	3.4 (0.13)	23.3 (0.92)	90.4 (3.56)
2017 Totals	101.9 (4.01)	67.8 (2.67)	122.5 (4.82)	244.4 (9.62)	114.6 (4.51)	106.5 (4.19)	159.1 (6.26)	140.3 (5.52)	112.3 (4.42)	140.3 (5.52)	82.8 (3.06)	98.6 (3.88)	1485.9 (58.48)
Snowfall, cm (in.)													
1970–1979 Avg	11.1 (4.4)	12.5 (4.9)	4.2 (1.7)	0.2 (0.1)	0	0	0	0	0	0	0.5 (0.2)	4.4 (1.8)	35.1 (13.8)
1980–1989 Avg	11.4 (4.5)	8.8 (3.5)	2.2 (0.9)	2.2 (0.9)	0	0	0	0	0	0	0	7.5 (3.0)	32.8 (12.9)
1990–1999 Avg	6.9 (2.7)	7.8 (3.1)	8.1 (3.2)	Trace	0	0	0	0	0	0	0.3 (0.1)	3.1 (1.2)	10.9 (4.3)
2000–2009 Avg	2.1 (0.8)	4.5 (1.8)	Trace	Trace	0	0	0	0	0	0	Trace	1.7 (0.7)	8.3 (3.3)
2010–2017 Avg	5.6 (2.2)	7.8 (3.1)	0.5 (0.2)	0.0 (0.0)	0	0	0	0	0	0	0.3 (0.1)	2.3 (0.9)	15.0 (5.9)
1980s vs. 2010s	-5.6 (-2.2)	-1.0 (-0.4)	-1.8 (-0.7)	-2.3 (-0.9)	0	0	0	0	0	0	0.3 (0.1)	-5.3 (-2.1)	-2.3 (-4.2)
2000s vs. 2010s	3.6 (1.4)	3.3 (1.3)	0.5 (0.2)	0.0 (0.0)	0	0	0	0	0	0	0.3 (0.1)	0.5 (0.2)	1.8 (3.3)
2017 Totals	6.6 (2.6)	Trace	Trace	0	0	0	0	0	0	0	0	Trace	6.6 (2.6)

Table B.3. Hourly subfreezing temperature data for Oak Ridge, Tennessee, January 1985–March 2018[a]

(Hours at or below 0, −5, −10, and −15°C)

Year	January				February				March			April		May		October		November			December				Annual			
	≤0	<-5	<-10	<-15	≤0	<-5	<-10	<-15	≤0	<-5	<-10	≤0	<-5	≤0	<-5	≤0	<-5	≤0	<-5	<-10	≤0	<-5	<-10	<-15	≤0	<-5	<-10	<-15
1985	467	195	103	39	331	127	26	0	105	6	0	43	3	0	0	0	0	22	0	0	431	201	66	2	1399	532	195	41
1986	308	125	38	10	161	29	3	0	124	28	0	17	0	0	0	0	0	32	10	0	232	34	0	0	874	226	41	10
1987	302	53	7	0	111	19	3	0	95	0	0	55	4	0	0	36	0	103	18	0	151	16	0	0	853	110	10	0
1988	385	182	43	0	294	102	19	0	97	9	0	6	0	0	0	45	0	62	3	0	301	55	0	0	1190	351	62	0
1989	163	27	0	0	190	66	10	0	35	0	0	18	0	3	0	7	0	125	14	0	421	188	71	30	962	295	81	30
1990	142	13	0	0	115	5	0	0	35	0	0	35	0	0	0	19	0	62	1	0	172	43	5	0	580	62	5	0
1991	186	44	0	0	158	47	15	0	49	0	0	0	0	0	0	4	0	148	16	0	192	38	0	0	737	145	15	0
1992	230	65	8	0	116	22	0	0	116	4	0	27	2	0	0	7	0	100	0	0	166	9	0	0	762	102	8	0
1993	125	11	0	0	245	47	8	0	124	32	9	3	0	0	0	0	0	152	2	0	223	44	0	0	872	136	17	0
1994	337	191	85	26	196	46	3	0	66	0	0	18	0	0	0	0	0	53	1	0	142	0	0	0	812	238	88	26
1995	240	45	6	0	217	84	18	0	37	0	0	0	0	0	0	0	0	142	3	0	288	84	10	0	924	216	34	0
1996	301	91	0	0	225	110	62	27	182	49	6	23	0	0	0	3	0	101	0	0	194	40	4	0	1029	290	72	27
1997	254	101	24	0	67	0	0	0	25	0	0	6	0	0	0	6	0	96	10	0	232	14	0	0	686	125	24	0
1998	97	10	7	0	25	0	0	0	74	20	0	0	0	0	0	0	0	38	0	0	132	4	0	0	366	34	7	0
1999	181	68	0	0	113	14	0	0	62	0	0	0	0	0	0	4	0	41	0	0	177	23	0	0	578	105	0	0
2000	273	62	5	0	127	30	0	0	18	0	0	8	0	0	0	11	0	94	11	0	345	124	7	0	876	227	12	0
2001	281	60	5	0	79	9	0	0	53	0	0	2	0	0	0	18	0	28	0	0	137	35	0	0	598	104	5	0
2002	185	28	0	0	121	16	0	0	91	17	0	2	0	0	0	0	0	41	0	0	82	6	0	0	522	67	0	0
2003	345	123	26	0	117	12	0	0	19	0	0	0	0	0	0	0	0	37	0	0	102	9	0	0	620	144	26	0
2004	285	50	2	0	76	0	0	0	18	0	0	0	0	0	0	0	0	9	0	0	247	41	4	0	635	91	6	0
2005	151	65	6	0	52	1	0	0	81	1	0	0	0	0	0	1	0	55	0	0	176	28	0	0	516	95	6	0
2006	70	0	0	0	169	19	0	0	44	0	0	0	0	0	0	15	0	37	0	0	126	41	1	0	461	60	1	0
2007	189	30	5	0	283	70	0	0	29	0	0	32	0	0	0	0	0	60	0	0	83	8	0	0	673	111	5	0
2008	242	86	11	0	114	7	0	0	69	6	0	0	0	0	0	15	0	89	18	0	157	34	5	0	686	151	16	0
2009	238	93	29	0	178	64	5	0	55	15	0	5	0	0	0	0	0	8	0	0	178	22	0	0	662	194	34	0
2010	384	181	14	0	289	32	0	0	40	2	0	0	0	0	0	0	0	46	0	0	364	109	11	0	1123	324	25	0
2011	300	61	0	0	108	14	0	0	2	0	0	0	0	0	0	5	0	29	0	0	91	0	0	0	535	75	0	0
2012	169	27	0	0	78	19	0	0	9	0	0	1	0	0	0	0	0	46	0	0	76	0	0	0	379	46	0	0
2013	245	49	0	0	120	12	0	0	95	7	0	0	0	0	0	11	0	121	0	0	173	6	0	0	765	74	0	0
2014	371	208	76	12	109	5	0	0	68	0	0	5	0	0	0	0	0	122	10	0	94	1	0	0	769	224	76	12
2015	228	52	16	0	371	120	31	6	52	16	0	0	0	0	0	0	0	11	0	0	41	0	0	0	703	188	47	6
2016[a]	333	82	12	0	211	17	0	0	35	0	0	9	0	0	0	0	0	44	3	0	163	32	0	0	795	134	12	0
2017	130	47	11	1	64	5	0	0	82	8	0	0	0	0	0	8	0	67	0	0	252	20	0	0	603	44	10	0
2018[b]	362	199	86	4	67	7	0	0	49	2	0	11	0															
Avg.	250	81	18	3	155	35	6	1	63	7	1	10	0	0	0	7	0	67	4	0	192	39	6	1	744	161	28	5

[a] Source: 1985–2015 National Oceanic and Atmospheric Administration, Atmospheric Turbulence and Diffusion Division, KOQT Station, Automated Surface Observing System; 2016–2018 Oak Ridge National Laboratory, Tower "D"

[b] 2018 values through March 31, 2018

Considering annual mean temperatures only, the mean annual temperature increased by 1.3°C between the 1980s and the 2010s. However, nearly all of that increase occurred between the 1980s and 1990s. Mean annual decadal-averaged temperatures have varied by 0.3°C or less since the 1990s.

Decadal precipitation averages suggest some important changes in precipitation patterns in Oak Ridge over the period of the 1980s to 2010s. Although overall precipitation has remained within a window of about 48 to 60 in. annually, there have been some decadal shifts in the patterns of rainfall on a monthly or seasonal scale. During winter, precipitation declined only slightly in January and February but has seen a greater than 1 in. increase during December. During the remaining months of the year, a decline of more than 0.80 in. in May is notable with significant increases (greater than 0.80 in.) in June and July. Changes during the fall months have been minor. Annual precipitation during the 2010s is above the 30 year average [around 1422 mm (55.96 in.)]. The year 2007 was the driest year on record in Oak Ridge (91.1 cm or 35.87 in.), which represented the core of a 4 year period of below-average precipitation (2005–2008). The most recent calendar year (2017) yielded precipitation totals about 10 percent above the 30 year mean, with a total of 58.48 in. (1,486 mm). The statistics presented here encompass the period from 1948 to 2017.

The previously discussed increase in winter temperatures by the 2000s has affected monthly and annual snowfall amounts until recently. During the 1970s and 1980s, snowfall averaged about 25.4 to 28 cm (10 to 11 in.) annually in Oak Ridge. However, during the most recent full decade (2000s), snowfall has averaged only 6.6 cm (2.6 in) per year. This decrease seems to have occurred largely since the mid-1990s. The slight cooling of winter temperatures in the 2010s thus far has reversed the decrease in snowfall somewhat, with annual averages of 5.9 in. (15.0 cm). Concurrently with the overall decrease in snowfall, the annual number of hours of subfreezing weather has generally declined since the 1980s (Table B.3). However, the number of subfreezing hours during 2010 (1,123 h) was the highest recorded since 1988. January 2014 was the coldest January since 1985, with 371 subfreezing hours, and February 2015 was the coldest February since 1978, also with 371 subfreezing hours.

Select wind roses for ORR towers that show wind direction for hours with precipitation and other relevant meteorological parameters have been compiled for 2017 and may be reviewed **here**.

Hourly values of subfreezing temperatures in Oak Ridge are presented in Table B.3 for January 1985 through March 2018. During the middle to late 1980s, a typical year experienced about 900–1,000 h of subfreezing temperatures. In recent years, the value has fallen to about 600–800 h, though higher values have occurred recently (2010 at 1,123 h). Other statistics on winter precipitation may be found **here**.

B.4 Moisture

ORR's humid environment results in frequent saturation of the surface layer, especially at night. Average annual humidity at ORNL is 73.5 percent (1998–2013). In terms of absolute humidity (grams per cubic meter), the average annual humidity for ORR is 10.24 g/m^3. This value varies greatly throughout the annual cycle, ranging from a monthly minimum of about 4.9 g/m^3 during winter to a maximum of about 17.2 g/m^3 during summer. These data are summarized for absolute and relative humidity and dew point **here**.

B.5 Severe Weather

On average, thunderstorms and associated lightning occur in the Oak Ridge area at a rate of 49 days/year, with a monthly maximum between 10 and 11 days occurring in July. About 42 of these thunderstorm days occur during a 7 month period from April through October, with the remainder spread evenly throughout the late fall and winter. The highest number of thunderstorm days at ORNL was observed during 2012 (65); the lowest was observed during 2007 (34). Monthly and annual average numbers of thunderstorm days for ORNL and Knoxville McGhee-Tyson Airport, respectively, during 2001–2017 can be viewed **here**.

Hailstorms are infrequent on ORR and typically occur in association with severe thunderstorms. The phenomenon usually occurs as a result of high-altitude thunderstorm updrafts, which propel water droplets above the freezing level. Some hail events have been known to occur in association with non-thunder rain showers in association with low freezing levels (particularly during winter or spring). Most hailstorm occurrences (77 percent) do not produce hailstones larger than 2 cm (about ¾ in.). During the period from 1961 through 1990, about six hail events (having hailstones larger than about 2 cm) were documented to have occurred at locations within 40 km (25 miles) of ORNL. Nearly all of these events occurred during the summer and fall seasons. During the 2011 significant tornado outbreak in East Tennessee, large hail (greater than 2 cm) was observed in Farragut, Tennessee, about 15 km (9 miles) southeast of ORNL.

East Tennessee experiences tornadoes once every 3 to 6 years on average. They occur more frequently in Middle and West Tennessee. Tornado indices from the National Weather Service in Morristown show that since 1950, three tornadoes have been documented within 10 km (6 miles) of ORNL, represented by two F0 (Fujita Scale) tornadoes and one F3 tornado. A moderately strong F3 tornado occurred in February 1993 and moved through Bear Creek Valley near the Y-12 National Security Complex with winds damaging the roofs of several buildings along Union Valley Road. To date, the February 1993 tornado has been the only documented tornado to occur within ORR.

Nine additional tornadoes have been documented since 1950 at distances within 20 km (12 miles) of ORNL, ranging in intensity from F0/EF0 (Enhanced Fujita Scale) to F2/EF2 in intensity. The most recent of these were three EF0–EF1 tornadoes that occurred during the April 27, 2011, tornado outbreak and an EF0 tornado near Kingston, Tennessee, on June 10, 2014. The storm system that produced the latter tornado brought a squall line through ORNL that produced high winds and some minor damage. The remaining group of tornadoes that were within 20 km (12 miles) of ORNL affected eastern Roane County to the south and the Edgemoor Road area to the northeast of ORR. Another 10 tornadoes, ranging from F0/EF0 to F3/EF3 in intensity, have occurred within 35 km (22 miles) of ORNL since 1950. Most of them occurred to the east and south of ORR in Knox and Roane Counties; however, a few occurred in the Rocky Top and Norris areas. Tornado statistics relevant to ORR are provided **here** for Anderson, Knox, Loudon, and Roane Counties.

The annual probability that a tornado will strike any location in a grid square may be estimated by multiplying the number of tornadoes per year per square kilometer (in that particular grid square) by the path area of a tornado. The result of such a calculation is seen to be greatly affected by the assumption of the size of the path area of a tornado. In total, about 22 tornadoes have been documented within 35 km (22 miles) of ORNL since 1950. This represents a surface area of 3,848 km^2 (1,485 $miles^2$) and yields a probability of about 0.006 tornadoes per square kilometer per 50 year period.

B.6 Stability

The local ridge-and-valley terrain plays a role in the development of stable surface air under certain conditions and influences the dynamics of airflow. Although ridge-and-valley terrain creates identifiable patterns of association during unstable conditions as well, strong vertical mixing and momentum tend to reduce these effects. “Stability” describes the tendency of the atmosphere to mix (especially vertically) or overturn. Consequently, dispersion parameters are influenced by the stability characteristics of the atmosphere. Stability classes range from "A" (very unstable) to "G" (very stable), with "D" being a neutral state.

The suppression of vertical motions during stable conditions increases the effect of local terrain on air motion. Conversely, stable conditions isolate wind flows within the ridge-and-valley terrain from the effects of more distant terrain features and from winds aloft. These effects are particularly significant with respect to mountain waves. Deep stable layers of air tend to reduce the vertical space available for oscillating vertical air motions caused by local mountain ranges (Smith et al. 2002). This effect on mountain wave formation may be important with regard to the impact that the nearby Cumberland Mountains may have on local airflow.

A second factor that may decouple large-scale wind flow effects from local ones (and thus produce stable surface layers) occurs with overcast sky conditions. Clouds overlying the Great Valley may warm due to direct insolation on the cloud tops. Warming may also occur within the clouds as latent energy, which is released due to the condensation of moisture. Surface air underlying the clouds may remain relatively cool as the layer remains cut off from direct exposure to the sun. Consequently, the vertical temperature gradient associated with the air mass becomes more stable (Lewellen and Lewellen 2002). Long wave cooling of fog decks has also been observed to help modify stability in the surface layer (Whiteman et al. 2001).

Stable boundary layers typically form as a result of radiational cooling processes near the ground (Van De Weil et al. 2002); however, they are also influenced by the mechanical energy supplied by horizontal wind motion, which is in turn influenced by the synoptic-scale "weather"-related pressure gradient. Ridge-and-valley terrain may have significant ability to block such winds and their associated mechanical energy (Carlson and Stull 1986). Consequently, radiational cooling at the surface is enhanced since there is less wind energy available to remove chilled air.

Stable boundary layers also exhibit intermittent turbulence, which has been associated with a number of the above factors. The process results from "give-and-take" between the effects of friction and radiational cooling. As a stable surface layer intensifies via a radiational cooling process, it tends to decouple from air aloft, thereby reducing the effects of surface friction. The upper air layer responds with an acceleration in wind speed. Increased wind speed aloft results in an increase in mechanical turbulence and wind shear at the boundary with the stable surface layer. Eventually, the turbulence works into the surface layer and weakens it. As the inversion weakens, friction again increases, reducing wind speeds aloft. The reduced wind speeds aloft allow enhanced radiation cooling at the surface, which reintensifies the inversion and allows the process to start again. Tornadoes occur more frequently in Middle and West Tennessee than in East Tennessee; East Tennessee experiences tornadoes once every 3 to 6 years on average. Van De Weil et al. (2002) have shown that cyclical temperature oscillations up to 4°C (7°F) may result from these processes. Since these intermittent processes are driven primarily by large-scale horizontal wind flow and radiational cooling of the surface, ridge-and-valley terrain significantly affects these oscillations.

Wind roses for stability and mixing depth have been compiled for all of the ORR tower sites for 2017. They may be viewed **here**. The wind roses in general reveal that both unstable conditions and/or deep mixing depths are associated with less channeling of winds and that stable conditions and/or shallow mixing depths tend to promote channeled flow. Associated mixing height tables can be accessed **here**.

B.7 References

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