Appendix B. Climate Overview of the Oak Ridge Area

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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 evapotranspiration that is normally experienced throughout the year. The "subtropical" nature of the local climate indicates that the region experiences a wide range of seasonal temperatures. Such areas typically experience significant changes in temperature between summer and winter.

Local winters are characterized by synoptic weather systems that often 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 occur. Winter cloud cover tends to be enhanced by the regional terrain (cold air wedging and trapping of moisture).

Severe thunderstorms are most frequent during spring but can occur at any time during the year. The Cumberland Mountains and the Cumberland Plateau often inhibit the intensity of severe systems that traverse the region, due to the downward momentum created as the storms move off the 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 represent the driest period of the year. The occurrence of precipitation during the fall tends to be less cyclical than during 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 continue to do so until 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 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 30–70 years, affects Atlantic sea surface temperature. All of these patterns can collectively modulate regional temperature and precipitation trends with respect to East Tennessee (especially the AMO). The AMO shifted from a cold to a warm sea surface temperature phase (mid-1990s) and could continue in its present state for another 10 to 15 years. The PDO appears to have entered a cool sea surface temperature phase just after 2000. Also, the ENSO pattern has more frequently brought about warmer Eastern Pacific sea surface temperatures in the last couple of decades. 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, and aerosols). 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). Largely due to the effects of the AMO and ENSO, the Oak Ridge climate warmed about 1.2ºC (34ºF) during the 1990s but has stabilized just above the 1990s values since then (little warming has occurred since 2000). The recent warming appears to have lengthened the growing season [i.e., the period with temperatures above 0ºC (32ºF)] by about 2 to 3 weeks over the last 30 years. In addition, a warming of minimum temperature has been noted over the last 30 years, this latter effect being presumably related to changes in the interaction of the surface boundary layer with greenhouse gases and/or aerosol concentration changes.

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 ORR's ridge-and-valley terrain (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.

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 the Oak Ridge Reservation (Kossman and Sturman 2002).

Forced channeling within the Central Great Valley represents the most dominant large-scale wind mechanism, dominantly influencing 50–60% of all winds observed in the area. For up-valley flow cases, these winds are frequently associated with large wind shifts. At small-scales, ridge-and-valley terrain usually produces forced-channeled local flow (>90% 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% 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 more associated with deep mixing depths (>500 m). Most vertically coupled flows are associated with major wind shifts (90–135°) when such flow patterns 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 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 flow 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, especially the Oak Ridge Reservation, winds dominated by down-valley pressure-driven channeling range in frequency from 2 to 10%, 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% 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 the Oak Ridge Reservation when compared to other parts of the Great Valley (Birdwell 2011). Most pressure-driven channeled winds occurred in association with moderate synoptic pressure gradients (0.006–0.016 mb/km).

Thermally driven winds are common in areas of significantly 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, and/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 air flow, depending on the ambient weather conditions. Large-scale thermally driven wind frequency varies from 2 to 20% with respect to the seasons in the Central Great Valley. Frequencies are highest during summer and fall when more intense surface heating helps drive the flow patterns (Birdwell 2011).

Annual wind roses for each of the nine ORR meteorological towers during 2011 (Towers MT1, MT2, MT3, MT4, MT6, MT7, MT9, MT10, and MT11) have been compiled. These can be viewed online at http://www.ornl.gov/~das/web/page7.cfm. The wind roses represent large-scale trends and should be used with caution with respect to 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 that 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.

B.3 Temperature and Precipitation

Temperature and precipitation normals (1981–2010) and extremes (1948–2011) and their durations for the city of Oak Ridge are summarized in Table B.1. Decadal temperature and precipitation averages for the four decades of the 1970s to 2000s are given in Table B.2. Hourly freeze data (1985–2011) are given in Table B.3.

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 2000s. In general, temperatures in Oak Ridge rose in the 1990s but have leveled off during the 2000s. Based on these average decadal temperatures, temperatures have risen 2.5ºF or 1.4ºC between the decades of the 1970s and the 2000s from 13.7 to 15.2ºC (56.8 to 59.3ºF). More detailed analysis reveals that these temperature increases have been neither linear nor equal throughout the months or seasons.

January and February average temperatures have seen increases of 2.1ºC (3.8ºF) and 1.9ºC (3.5ºF), respectively. This significant increase is probably dominated by the effects of the AMO. Also, the Arctic has seen the largest increase in temperatures of anywhere in the Northern Hemisphere over the last 30 years. 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 these months. Spring temperatures (March–April) have risen by about 1.4ºC (2.5ºF). Summer and fall temperatures have exhibited temperature rises of 1.6ºC (2.8ºF) and 1.4ºC (2.5ºF), respectively. December temperatures changed the least, +0.1ºC (+0.2ºF). Most of these average increases were driven by significant increases in minimum daily temperatures (which may be due to the redistribution of heat in the boundary layer resulting from increased presence of greenhouse gases and aerosols). Overall, annual minimum temperatures seem to have increased more dramatically (1.7ºC or 3.1ºF) than maximum temperatures (1ºC or 1.9ºF). For the most recent decade (2000s), August average temperatures are now slightly warmer than those of July.

Decadal precipitation averages suggest some important changes in precipitation patterns in Oak Ridge over the period of the 1970s to 2000s. Although overall precipitation has remained within a window of about 48 to 56 in. annually, there have been some recent decadal shifts in the patterns of rainfall on a monthly or seasonal scale. In particular, precipitation has tended to increase during the late winter and early spring (February through April) by about 2.54 cm/month (1 in./month). Conversely, the late summer and early fall months (August through October) have seen slight decreases in precipitation [about 1.27 cm/month (0.50 in./month)]. Overall, annual precipitation during the 2000s is consistent with the 30-year average [around 132 cm (52 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 year 2011 yielded precipitation totals around 40% above the 30-year mean. These statistics encompass the period from 1948 to 2011.

The previously discussed increase in winter temperatures has affected monthly and annual snowfall amounts until recently. During the 1970s and 1980s, snowfall averaged about 25.4–28 cm (10–11 in.) annually in Oak Ridge. However, during the most recent decade (2000s), snowfall has averaged only 6.6 cm (2.6 in). This decrease seems to have occurred largely since the mid-1990s. Although snowfall during 2010 reversed this trend with 11.1 in (28.2 cm), 2011 snowfall returned to the recent averages (4.3 in.). 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 (1123) was the highest recorded since 1988.

Wind roses for all of the ORR towers that show wind direction for hours with and without precipitation have been compiled for 2011 and may be reviewed at http://www.ornl.gov/~das/web/page7.cfm.

Hourly values of subfreezing temperatures in Oak Ridge are presented in Table B.3 for the years 1985 through 2011. During the middle to late 1980s, a typical year experienced about 900 to 1000 h of subfreezing temperatures. In recent years, the value has fallen to approximately 500–700 h, though higher values occasionally occur.

B.4 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 air flow. 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 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 true 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 air flow.

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 because it is 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).

Table B.1. Climate normals (1981–2010) and extremes (1948–2011) for Oak Ridge, Tennessee (Town Site), with 2011 comparisons

Monthly variables	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Temperature, °C (°F)													
30-Year Average Max	8.1 (46.6)	11.1 (51.9)	16.3 (61.4)	21.4 (70.6)	25.7 (78.3)	29.8 (85.7)	31.3 (88.4)	31.1 (88.0)	27.6 (81.7)	21.7 (71.1)	15.3 (59.6)	9.8 (49.6)	20.8 (69.5)
2011 Average Max	6.8 (44.3)	13.1 (55.6)	16.8 (62.2)	23.8 (74.8)	25.9 (78.7)	31.3 (88.4)	32.8 (91.0)	33.1 (91.5)	26.3 (79.4)	20.9 (69.6)	16.6 (61.9)	11.8 (53.3)	21.6 (70.9)
64-Year Record Max	25 (77)	26 (79)	30 (86)	33 (92)	35 (95)	38 (101)	41 (105)	39 (103)	39 (102)	32 (90)	28 (83)	26 (78)	41 (105)
30-Year Average Min	-1.7 (28.9)	-0.2 (31.7)	4.1 (39.3)	8.3 (46.9)	12.9 (55.2)	18.1 (64.5)	20.3 (68.6)	19.6 (67.2)	15.4 (59.7)	8.9 (48.0)	3.5 (38.3)	-0.5 (31.1)	9.1 (48.4)
2011 Average Min	-2.7 (27.2)	0.8 (33.5)	5.8 (42.5)	9.7 (49.4)	13.9 (57.0)	19.4 (66.9)	21.8 (71.2)	19.7 (67.5)	15.3 (59.6)	8.2 (46.8)	4.8 (40.7)	0.4 (32.8)	9.8 (49.6)
64-Year Record Min	-27 (-17)	-25 (-13)	-17 (1)	-7 (20)	-1 (30)	4 (39)	9 (49)	10 (50)	1 (33)	-6 (21)	-18 (0)	-22 (-7)	-27 (-17)
30-Year Average	3.2 (37.7)	5.4 (41.8)	10.2 (50.4)	14.9 (58.8)	19.3 (66.8)	23.9 (75.1)	25.8 (78.5)	25.3 (77.6)	21.5 (70.7)	15.3 (59.5)	9.4 (48.9)	4.6 (40.3)	14.9 (58.9)
2011 Average	2.1 (35.8)	7.0 (44.6)	11.3 (52.4)	16.7 (62.1)	19.9 (67.9)	25.4 (77.7)	27.3 (81.1)	26.4 (79.5)	20.8 (69.5)	14.6 (58.2)	10.7 (51.3)	6.2 (43.1)	15.7 (60.3)
2010 Dep from Average	-1.1 (-1.9)	1.6 (2.8)	1.1 (2.0)	1.8 (3.3)	0.6 (1.1)	1.4 (2.6)	1.4 (2.6)	1.1 (1.9)	-0.7 (-1.2)	-0.7 (-1.3)	1.3 (2.4)	1.6 (2.8)	0.8 (1.4)
30-year average heating degree days, °C (°F)[a]													
	469 (845)	361 (650)	254 (458)	119 (215)	33 (59)	1 (2)	0	0	12 (21)	111 (199)	268 (483)	424 (764)	2053 (3696)
30-year average cooling degree days, °C (°F)[a]													
	0	0	2 (4)	15 (27)	63 (113)	169 (305)	232 (418)	217 (391)	107 (192)	17 (30)	1 (2)	0	823 (1482)
Precipitation, mm (in.)													
30-Year Average	115.4 (4.54)	116.1 (4.57)	128.6 (5.06)	106.2 (4.18)	109.0 (4.29)	108.7 (4.28)	133.9 (5.27)	70.1 (2.76)	93.8 (3.69)	74.2 (2.92)	114.1 (4.49)	123.5 (4.86)	1294 (50.91)
2011	101.4 (3.99)	144.8 (5.70)	169.0 (6.65)	232.0 (9.13)	54.4 (2.14)	185.5 (7.30)	122.0 (4.80)	23.1 (91.0)	257.4 (10.14)	116.6 (4.59)	276.9 (10.90)	122.0 (4.80)	1805.2 (71.05)
2011 Dep from Average	-14.0 (-0.55)	28.7 (1.13)	40.4 (1.59)	125.8 (4.95)	-54.6 (-2.15)	76.7 (3.02)	-11.9 (-0.47)	-47.0 (-1.85)	163.9 (6.45)	42.4 (1.67)	162.9 (6.41)	-1.5 (-0.06)	+511.7 (+20.14)
64-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 (76.33)
64-Year Max 24-hr	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)
64-Year Min Monthly	23.6 (0.93)	21.3 (0.84)	54.1 (2.13)	22.4 (0.88)	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)
2011 Totals	10.4 (4.1)	5.1 (0.2)	Trace	0	0	0	0	0	0	0	Trace	Trace	15.5 (4.3)
64-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)
64-Year Max 24-hr	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	0.1	0.3	5.9	11.3	10.4	2.9	0	0	0	30.9
2011 Max ≥ 32°C	0	0	0	0	5	14	22	24	3	0	0	0	68
30-Year Min ≤ 0°C	20.8	15.0	6.5	1.3	0	0	0	0	0	1.5	8.2	17.7	71.0
2011 Min ≤ 0°C	25	14	2	1	0	0	0	0	0	1	6	12	61
30-Year Max ≤ °C	2.8	0.5	0	0	0	0	0	0	0	0	0	0.8	4.1
2011 Max ≤ 0°C	4	0	0	0	0	0	0	0	0	0	0	0	4
Days w/precipitation													
30-Year Avg ≥ 0.01 in.	10.9	10.1	11.2	10.4	11.9	10.8	13.0	8.9	8.4	8.3	9.3	11.3	124.5
2011 Days ≥ 0.01 in.	12	9	10	5	13	13	12	8	10	6	11	13	118
30-Year Avg ≥ 1.00 in.	1.4	1.1	1.2	0.9	1.4	0.8	1.5	0.5	1.3	0.7	1.5	1.4	13.7
2010 Days ≥ 1.00 in.	1	2	2	3	1	4	2	2	2	1	5	2	27

Table B.2. Decadal climate change (1970–2009) for Oak Ridge, Tennessee (Town Site), with 2011 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)
Change (70s vs. 00s)	2.2 (5.1)	1.5 (2.6)	1.4 (2.6)	0.0 (0.0)	1.0 (1.7)	1.3 (2.3)	0.8 (1.6)	1.4 (2.5)	0.8 (1.6)	1.0 (1.8)	1.4 (2.4)	-0.2 (-0.3)	1.1 (1.9)
2011 Avg Max	6.8 (44.3)	13.1 (55.6)	16.8 (62.2)	23.8 (74.8)	25.9 (78.7)	31.3 (88.4)	32.8 (91.0)	33.1 (91.5)	26.3 (79.4)	20.9 (69.6)	16.6 (61.9)	11.8 (53.3)	21.6 (70.9)
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)
Change (70s vs. 00s)	2.0 (3.7)	2.4 (4.4)	1.4 (2.5)	1.9 (3.4)	2.0 (3.6)	2.3 (4.1)	1.7 (3.0)	1.9 (3.4)	0.6 (1.1)	2.0 (3.5)	1.3 (2.2)	0.4 (0.9)	1.7 (3.1)
2011 Avg Min	-2.7 (27.2)	0.8 (33.5)	5.8 (42.5)	9.7 (49.4)	13.9 (57.0)	19.4 (66.9)	21.8 (71.2)	19.7 (67.5)	15.3 (59.6)	8.2 (46.8)	4.8 (40.7)	0.4 (32.8)	9.8 (49.6)
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)
Change (70s vs. 00s)	2.1 (3.8)	1.9 (3.5)	1.4 (2.5)	1.2 (2.2)	1.6 (2.8)	1.8 (3.3)	1.3 (2.3)	1.8 (3.3)	0.8 (1.4)	1.4 (2.6)	1.3 (2.3)	0.1 (0.2)	1.4 (2.5)
2011 Avg	2.1 (35.8)	7.0 (44.6)	11.3 (52.4)	16.7 (62.1)	19.9 (67.9)	25.4 (77.7)	27.3 (81.1)	26.4 (79.5)	20.8 (69.5)	14.6 (58.2)	10.7 (51.3)	6.2 (43.1)	15.7 (60.3)
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)
Change (70s vs. 00s)	-26.5 (-1.04)	27.2 (1.07)	-43.8 (-1.72)	6.7 (0.26)	-32.0 (-1.26)	-25.3 (-1.00)	8.5 (0.33)	-31.4 (-1.24)	1.6 (0.06)	-25.8 (-1.02)	-8.2 (-0.32)	-20.9 (-0.82)	-183.0 (-7.20)
2011 Totals	101.4 (3.99)	144.8 (5.70)	169.0 (6.65)	232.0 (9.13)	54.4 (2.14)	185.5 (7.30)	122.0 (4.80)	23.1 (0.91)	257.6 (10.14)	116.6 (4.59)	276.9 (10.90)	122.0 (4.80)	1805.2 (71.05)
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)	351 (13.8)
1980-1989 Avg	11.3 (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)	328 (12.9)
1990-1999 Avg	6.8 (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)	109 (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)
Change (70s vs. 00s)	-9.0 (-3.6)	-8.0 (-3.1)	-4.2 (-1.7)	-0.2 (-0.1)	0	0	0	0	0	0	-0.5 (-0.2)	-2.7 (-1.1)	-242 (-9.5)
2011 Totals	10.4 (4.1)	5.1 (0.2)	Trace	0	0	0	0	0	0	0	Trace	Trace	15.5 (4.3)

Table B.3. Hourly subfreezing temperature data for Oak Ridge, Tennessee, 1985–2011 (Number of hours at or below 0, -5, -10, and -15 °C[a])

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
Avg.	247	76	16	3	158	37	6	1	65	7	1	11	0	0	0	7	0	67	4	0	205	46	7	1	760	171	29	5

[a]Source: 1985–2009 National Oceanic and Atmospheric Administration, Atmospheric Turbulence and Diffusion Division, KOQT Station, Automated Surface Observing System.

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 radiation 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 winds aloft. The reduced wind speeds aloft allow enhanced radiation cooling at the surface, which reintensifies the inversion and allows the process to start again. Van De Weil et al. (2002) have shown that cyclical temperature oscillations up to 4°C (7ºF) 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 affect these oscillations.

Wind roses for stability and mixing depth have been complied for all of the ORR tower sites in 2011. These may be viewed at http://www.ornl.gov/~das/web/page7.cfm. The wind roses in general reveal that both unstable conditions and/or deep mixing depths are associated with less channeling of winds, while stable conditions and/or shallow mixing depths tend to promote channeled flow.

B.5 References

Birdwell, K. R. 2011. “Wind Regimes in Complex Terrain of the Great Valley of Eastern Tennessee.” Doctoral Dissertation, Department of Geography, University of Tennessee, Knoxville, Tennessee.

Birdwell, K. R. 1996. “A Climatology of Winds over a Ridge and Valley Terrain within the Great Valley of Eastern Tennessee.” Master’s Thesis, Department of Geosciences, Murray State University, Murray, Kentucky.

Carlson, M. A., and R. B. Stull. 1986. “Subsidence in the Nocturnal Boundary Layer.” *Journal of Climate and Applied Meteorology* **25**, 1088–99.

Eckman, R. M. 1998. “Observations and Numerical Simulations of Winds within a Broad Forested Valley.” *Journal of Applied Meteorology* **37**, 206–19.

Inosen, S., A. A. Scaife, J. R. Knight, J. C. Manners, N. J. Dunstone, L. J. Grey, and J. D. Haigh. 2011. “Solar forcing of winter climate variability in the Northern Hemisphere.” *Nature Geoscience* **4,** 753–757.

Kossman, M., and A. P. Sturman. 2002. “Pressure Driven Channeling Effects in Bent Valleys.” *Journal of Applied Meteorology* **42**, 151–58.

Lewellen, D. C., and W. S. Lewellen. 2002. “Entrainment and decoupling relations for cloudy boundary layers.” *Journal of the Atmospheric Sciences* **59**, 2966–2986.

Monti, P., H. J. S. Fernando, M. Princevac, W. C. Chan, T. A. Kowalewski, and E. R. Pardyjak. 2002. “Observations of Flow and Turbulence in the Nocturnal Boundary Layer over a Slope.” *Journal of the Atmospheric Sciences* **59**, 2513–34.

Smith, R. B., S. Skubis, J. D. Doyle, A. S. Broad, C. Kiemle, and H. Volkert. 2002. "Mountain waves over Mount Blanc: Influence of a stagnant boundary layer." *Journal of the Atmospheric Sciences* **59**, 2073–2092.

Van De Weil, B. J. H., A. F. Moene, R. J. Ronda, H. A. R. De Bruin, and A. A. M. Holtslag. 2002. "Intermittent Turbulence and Oscillations in the Stable Boundary Layer over Land. Part II: A System Dynamics Approach." *Journal of the Atmospheric Sciences* **59**, 2567–81.

Whiteman, C. D. 2000. *Mountain Meteorology: Fundamentals and Applications*. Oxford University Press, New York.

Whiteman, C. D., S. Zhong, W. J. Shaw, J. M. Hubbe, and X. Bian. 2001. "Cold Pools in the Columbia River Basin." *Weather and Forecasting* **16**, 432–47.