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RESEARCH ARTICLE

DEVELOPMENT OF A CLIMATE BUFFERING INDEX TO ENHANCE UNDERSTANDING OF NOCTURNAL COLD AIR FORMATION IN WET ENVIRONMENTS OF THE APPALACHIAN MOUNTAINS OF EASTERN NORTH AMERICA – LINKAGE TO BIOLOGICAL DIVERSITY IN A CHANGING CLIMATE

WALTER WAYNE BROWNING

Virginia State University College of Agriculture, Small Farm Outreach Program, Petersburg, Virginia 23860, USA

Corresponding author: Walter Wayne Browning (*wbrowning@vsu.edu*)

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ABSTRACT

Nocturnal collection of cold air in low-lying locations has been cited in literature for more than a century, with many field and modeling studies during recent decades revealing the three-dimensional, complex nature of associated physical processes. Applications of findings are extensive in the fields of agriculture and biology. Whereas most studies have dealt with cold air formation in dry climatic settings, this research focuses on an anomalously wet upper elevation basin in the southern Virginia Appalachian Mountains of the Eastern United States, where nocturnal temperatures can drop surprisingly low during any month. Dew-point depressions at 850 mb are tested as a controller of nocturnal minimum and basin inversion strength, with cold air pool (CAP) formation frequency used to calculate a Climate Buffering Index (CBI) that is dependent upon the amount of time a temperature inversion decouples the surface from the overlying atmosphere. The longer a site is detached from the surrounding regional climate, the greater its CBI and microclimatological buffering potential against larger-scale changes in climate. A CBI is calculated annually and for different seasons, with special emphasis on breeding and growing seasons to generate a direct linkage to biological diversity. A decoupling inflection point (DIP) is introduced as part of this process, with potential forecast applications. A CBI can be calculated for any location possessing vertical relief and meteorological data. For long-duration monitoring, across years and decades, this provides a means to better understand how large-scale climatic changes impact site specific micro-climatic conditions.

Keywords: Appalachians, high-elevation basin, High Knob Massif, micro-climatology, cold-air-pooling (CAP), temperature inversions.

INTRODUCTION

A melodious, three-parted song of a hermit thrush, *Catharus guttatus* (Pallas), echoes through a mixed forest while wisps of steam fog rise above a wetland as dawn breaks to frosty air. This is not a high latitude location, nor is it winter. This is a chilly summer sunrise in a high basin frost pocket in the Appalachian Mountains of southwestern Virginia.

Although not climatically well-studied within the Appalachians, upper elevation basins like that of Big Cherry Lake in the High Knob Massif feature air temperatures which can drop surprisingly low during any given month of the year. They are part of cold air drainage corridors that extend outward and downward from their origins through different elevation zones where enhanced microclimatologic gradients act to increase habitats for a complex array of life forms. Of particular interest, during this period of warming climate (especially at night), are biota possessing endemic and northern affinities.

Many other breeding bird species with northern affinities, and floral species such as yellow birch, *Betula alleghaniensis* Britt., American beech, *Fagus grandifolia* Ehrh., hobblebush, *Viburnum lantanoides* Michx., painted trillium, *Trillium undulatum* Willd., and Canada mayflower *Maianthemum canadense* Desf., to note a few not recognized as abundantly growing within the Cumberland Mountains between 900 and 1,300 meters (Braun, 1950), suggest upper elevations within the High Knob Massif function as microrefugia for northern species and should be considered a high conservation priority in Virginia and the southern Appalachians.

This research addresses a gap in southern Appalachian climatology by seeking to better understand how nocturnal cold air pools (CAP) develop in Big Cherry Lake Basin where moist air rules and the annual moisture budget exceeds 2000 mm, especially when secondary inputs from fog drip and rime drop from trees are included (Vogelmann et al., 1968) and (Browning, 2025).

Nocturnal temperatures that average colder than the much drier, classic basin of Burkes Garden, 120 km to the northeast, were discovered and investigated, with dewpoint depression at 850 mb tested as the primary control of high basin cooling potential. Other studies of extreme central Appalachian and Allegheny Mountains elevated cold-air-pool basins like Canaan Valley, WV, have also been examined (Schaefer, et al., unpublished data) and (Browning, 2020b).

Boundary layer decoupling frequency and strength were determined from high-resolution field data collected using basin floor, mid-slope, and summit-level sensor sites as pseudo-vertical sounding points (Whiteman & Hoch, 2014). Their impacts on cooling potential were analyzed. The duration of time in which the basin floor was decoupled, and thus different, from the surrounding atmosphere, was then calculated to develop a Climate Buffering Index (CBI) for enhanced understanding of nocturnal cold air formation, as well as for assessment of climate buffering potential. Special emphasis is placed on the growing-breeding and migratory seasons to form a direct linkage with biological diversity. Research focus was on high basins with northern species, but a CBI can be developed and used to monitor any location possessing vertical relief and meteorological data.

Resource managers and those working to sustain terrestrial, aquatic, and subterranean biodiversity for the well-being of all living things, including human beings, can benefit from a better understanding of nocturnal cold air formation in wet climates, like the southern Appalachians, and now have a means to identify, rank, and indefinitely follow sites favorable for buffering a changing climate.

LITERATURE REVIEW

Early history and classic works

Collection of cold air in low-lying locations has been documented by published literature within the United States of America for more than a century, beginning with Notes on The State of Virginia originally written by avid weather observer Thomas Jefferson in the late 18th century. Jefferson noted killing frosts in low-lying locations at the same time as elevated hills around Monticello remained free of frost damage (Jefferson, 1781).

Original studies of these micro-climatic influences were primarily motivated by agricultural interests, such as related to the placement and protection of orchards and other important crops, as described in southern California (Young, 1920) and western North Carolina (Cox, 1923).

The first comprehensive assemblage of studies related to surface climate by German meteorologist Rudolf Geiger in 1927, titled Das Klima der bodennahen Luftschicht, was revised by the author 23 years later in 1950 and translated into English to form a major work (The Climate Near the Ground) considered by many to be the formative foundation of micrometeorology. This work connected insolation to surface-based processes, such as skin or drainage flow along terrain surfaces, with Atkinson (2003) stating that this recognized layer of interest was vertically expanded in subsequent editions of the book to also include taller boundary layer features such as trees and human structures (Geiger et al., 2009).

Of direct relevance to this research, Geiger (1950) discussed "frost holes" and "cold lakes" observed during 1925 in low-lying areas east of Munich in Germany, where thick vegetation was able to dam cold air. He documented the first studies of extreme nocturnal temperatures in the now infamous Gruenloch Sink (also called Gstettneralm Sink or Basin) of lower Austria by Wilhelm Schmidt in 1930.

Frost pockets were identified by Hough (1945) on the northern Allegheny Plateau of western Pennsylvania and found to be partly responsible for the persistence of open areas following widespread logging and burning of virgin forests. A later two-year study in the Harvard Forest by Spurr (1957) supported this frost pocket effect, along with previous microclimatic work by Aikman & Brackett (1944) in Iowa, Wolfe et al. (1949) in Ohio, among others, in illustrating that low-lying areas, especially with a concave nature, tended to have higher frost susceptibility, significantly shorter growing seasons and associated colder minimum temperatures than adjoining slopes and hill-tops with convex topographic line forms.

Of regional significance, R. Weedfall & Dickerson (1965) published “The Climate of the Canaan Valley and Blackwater Falls State Park, West Virginia in a University of West Virginia publication series. His work documented the frost hollow nature of another very large, wet Alleghany Plateau upland cold basin just 241 km northeast of this study's location (Canaan Valley). That extreme cold air drainage basin harbors relic plants and animals from the last Pleistocene Ice Age (Vogel & Leffler, 2015).

The assimilation of cold air pooling, drainage, and thermal belts into a theory describing mountain, valley, and slope winds as part of interconnected systems originated within classic works on Alpine meteorology by Wagner (1938), Ekhart (1944), Ekhart (1948) and Defant (1949). These studies, originally published in German and French, were later translated into English by Whiteman & Dreiseitl (1984). They represented pioneering efforts in combining data collected at varied elevations across the surface with aerological data, via development of vertical soundings using kites, balloons, and aircraft during the late 19th and early 20th centuries within mainly Europe and the United States (Stickler et al., 2010) and (Krauchi et al., 2016).

Evolution of theory and major field experiments

Refinement and classification of this theory into a diurnal mountain wind system featuring distinct daytime, evening transition, night-time, and morning transition phases has been described by Zardi & Whiteman (2012), with specific components studied by Yoshino et al. (1981), Whiteman (1982), Whiteman & McKee (1982), Yoshino (1984), Bader & McKee (1985), Whiteman (1986), Kelly (1988), Stull (1988), Clements et al. (1989), Kuwagata & Kimura (1994), Kuwagata & Kimura (1997), Whiteman (2000), Whiteman et al. (2008), Whiteman & Zhong (2008), Zhong & Whiteman (2008), Lehner & Whiteman (2012), Whiteman & Hoch (2014), among others.

A technological revolution in recent decades advanced diurnal mountain wind system theory, and mountain meteorology in general, with innovations in instrumentation, satellites, modeling as well as critical data transmission and storage. Increased computing power has been invaluable to advancement of knowledge (Smith, 2019). Major field experiments became possible. Whiteman & Dreiseitl (1984) cited important international cooperative experiments in Alpine valley meteorology during 1978-1982, and Whiteman (1990) listed many additional valley experiments. Smith (2019) listed field projects from 1982-2016, including a major persistent cold air pooling study (PCAPS) in the Great Salt Lake Basin, Utah (Lareau et al., 2013).

Steinacker et al. (2007) detailed a sinkhole basin field experiment in Austria's Hetzkogel Plateau, during 2001-02, that dispelled the notion of a stagnant, passive cold pool with discovery of a continuously eroded shear layer that featured pulsating, seiche-like undulations along top of highly stratified air.

Additional components were discussed by Whiteman et al. (2004a), Whiteman et al. (2004b), and Whiteman et al. (2004c). Pinto et al. (2006) described the Vertical Transport and Mixing field Experiment (VTMX) in October 2000 within the southern Great Salt Lake Valley, where the nocturnal boundary layer cold pool was found to be disturbed by a down valley jet that formed on half of observed nights. Finally, Whiteman et al. (2008) detailed a month-long study in Arizona's Meteor Crater during October 2006 called METCRAX. The unique geomorphology and climatologic setting of its idealized closed, bowl-like shape made direct applicability of some crater results questionable to more complex basin types, especially those within wet climates like the Big Cherry Lake Basin. Most basins across the world have at least one outflow path (stream or river) and are not completely closed.

Differences between basins and valleys

Collected empirical data have differentiated cooling and collection of cold air between valleys and basins. De Wekker et al. (2006) found greater temperature drops in basins versus valleys under ideal cooling conditions. As explained by Zardi & Whiteman (2012), Whiteman (2000) and Clements et al. (2003), this is partly due to lack of a well-developed down valley wind system in basins for outward mass transport and its replacement by potentially warmer air aloft. Entirely enclosed basins, which are relatively rare, lack low-level outward transport.

During a cold pool development study within Peter Sinks, Utah, one of the coldest entirely enclosed basins in the world, Clements et al. (2003) discovered a vertical structure featuring a cold pool stable layer (CPSL) on the basin floor that was topped by a capping inversion layer (CIL). Collectively, the CPSL + CIL = CAP, the cold-air-pool forming within the enclosed basin. A superadiabatic layer at top of the CPSL, and warming of air above the basin slopes relative to that above the basin center, were the most surprising discoveries that served to contradict the accepted theory of cold air buildup via the convergence of downslope flows. While authors could not fully explain a superadiabatic layer on top of the stable cold pool, nor could they resolve precise roles that divergences of radiative and sensible heat flux played in basin cooling; they demonstrated cooling within an enclosed basin is markedly different from cooling within a valley, despite a basin being subjected to many of the same disturbing forces arising from interactions with the larger-scale, synoptic environment (Dorninger et al., 2011). Superadiabatic conditions were observed during this study (Supplement) on prime cooling nights in Big Cherry Basin with temperature drops as great as 5.6 °C (10 °F) per 30.5 meters (100 feet) into the basin.

Maki & Harimaya (1988) modeled cold air pool development in a basin, with enhanced cooling as deepening of the cold pool reduced incoming longwave radiation reaching the surface. Clements et al. (2003), Whiteman et al. (2004a), Whiteman et al. (2004b), and Steinacker et al. (2007) found that as cold pool static stability increased within an enclosed basin it effectively prevents downslope flows from reaching the basin floor, with diversion of slope flow over top the cold pool.

Warmer days and colder nights are common to valleys and basins with respect to analogous volumes in the free atmosphere over plains. Zardi & Whiteman (2012) explained that this is due to reduced mass and energy exchange with the surrounding atmosphere caused by terrain sheltering, as well as the Topographic Amplification Factor (TAF), a concept first introduced by Wagner (1932). Essentially, a larger diurnal temperature range can be expected within a valley or basin due to heating and cooling of a smaller mass of air contained within its volume. McKee & O'Neal (1989) stated that internal pressure changes within a valley could be driven by differential cooling related to TAF. Although this concept is simple, Zardi & Whiteman (2012) noted it is difficult to fully apply outside of idealized settings. Therefore, it is not surprising that simplified basins, such as the Gruenloch, Peter Sinks, and Arizona's Meteor Crater have been a primary focus of applied research.

Cooling potential and different moisture regimes

A hypothesis of this research is that 850 mb dewpoint depression acts as a major controller of upper elevation cooling potential in persistently wet basins of the Appalachians. This was indirectly posited by Steinacker et al. (2008) with respect to air mass characteristics observed over the Alps as being the determining factor for basin minimums. This aspect, which is a major motivation of present research, has not been well studied in wet climates of the southern-central Appalachians.

Whiteman et al. (2007) studied the effect of dew and frost formation on nocturnal cooling within the small, wet Gruenloch Basin and found that air on the basin floor and lower slopes tended to dry as dew and frost formed with subsequent latent heat release that reduced the nocturnal cooling rate and formed a dewpoint inversion. Zängl (2005) modeled this using the National Center for Atmospheric Research MM5 at Penn State University over various surfaces, including grass and snow, with outgoing radiation being nearly balanced by a positive heat flux from the ground over grass. Following initial rapid drops in air temperature after sunset, as also often observed in Big Cherry Basin, this resulted in significantly reduced fall rates through the night in the Gruenloch

(Whiteman et al., 2007). Modeling over snow by Zängl (2005) produced much stronger, more persistent cooling, as verified by observations, with strong outgoing longwave radiation and a means to extract moisture from the basin air as it cools being key components necessary for achievement of extreme minima, especially in absence of dry ambient air. Cooling potential between basins of differing size was shown by Whiteman et al. (2004b) to be largely dependent upon sky view factor, with greater cooling correlated to increasing sky view.

A direct comparison between dry and wet basin environments was made by Whiteman et al. (2004c) during a study of inversion breakup, where a much weaker inversion formed above the cold pool in the wet Gruenloch Basin of the Alps versus the typically dry Peter Sinks of the Rockies. Despite these differences, inversion breakup took about the same amount of time in both settings. Weaker outgoing longwave radiation and reduced sensible heat loss in the moist Gruenloch Basin at night-time was countered after sunrise by a portion of insolation being applied to evaporation instead of sensible heating at the surface. This contrasted with stronger surface heating in Peter Sinks, where a convective boundary layer formed to enhance subsidence breakup of its stronger inversion.

An additional observation between these dry and wet basins, applicable to current research, was the presence of a strong vegetation inversion in both Gruenloch and Peter Sinks basins. While more deceptive in Big Cherry Lake Basin, there also exists a biotic inversion with more species of flora and fauna possessing northern affinities within the cold air pooling zone versus sites upslope in the thermal belt (which caps the CAP inversion layer).

Linking nocturnal cold air formation and decoupling to biodiversity

Dobrowski (2011) defined microrefugia as typified by sites possessing relics of formerly more widespread climatic conditions, which allow relic species to live outside their home range. Locations that frequently decouple from the synoptic-scale atmosphere are best candidates for microrefugia. Pooling and drainage of cold air forming in complex terrain is a primary driver of these sites, with Daly et al. (2010) suggesting that decoupling processes could help alter climate change impacts as sites prone to prolonged decoupling become more important versus summit sites standing amid the changing, free atmosphere. This being especially true for species that would benefit most from an environment detached and different from regional, large-scale climate conditions (Kristoffer et al., 2015).

An algorithm for detection of cold air pooling in complex terrain, using digital elevation models, was developed by Lundquist et al. (2008) and used by Curtis et al. (2014) in a downscaled climate model to better resolve pockets of long-lasting snow cover within the Sierra Nevada for snow-dependent species. Patsiou et al. (2017) used a cold air pooling derivation in a geographic information system to improve the species distribution model of a rare, endemic Alpine plant, and Zellweger et al. (2019) included cold air drainage detection as a key component of advancing Microclimate Ecology and reducing the modeled climatic debt of species which may not be migrating fast enough to keep pace with change.

MATERIALS AND METHODS

This research addresses nocturnal cold air pool (CAP) formation in climatically wet environments where research has been lacking and will evaluate the validity of the hypothesis that: nocturnal cold air formation possesses low repeatability in a wet climatic setting of the southern

Appalachians, mainly confined to winter, and is dependent upon 850 mb dewpoint depression. This suggests boundary layer decoupling is most common during the cold season (cold and dry air is dense) and least common during the warm, moist growing season.

Geomorphologic setting

The main study area for nocturnal cold air development is Big Cherry Lake Basin (Figs 1, 2), embedded in the summit of the High Knob Massif which rises as a large sedimentary mass of folded and faulted stratigraphy on the Appalachian structural front of extreme southwestern Virginia.

Figure 1. Cold air pooling area of Big Cherry Basin (area of sites 3-4 on Fig. 5).

A product of Alleghanian orogeny, High Knob has recently been defined as the High Knob Massif and High Knob Landform in climate and natural history research by Browning (2025). This landform is the most dominant structural feature of the great Cumberland Overthrust Block (Pine Mountain Thrust Sheet), as originally defined by Butts (1927) and Rich (1934), and later described by Harris & Milici (1977) as well as Mitra (1988).

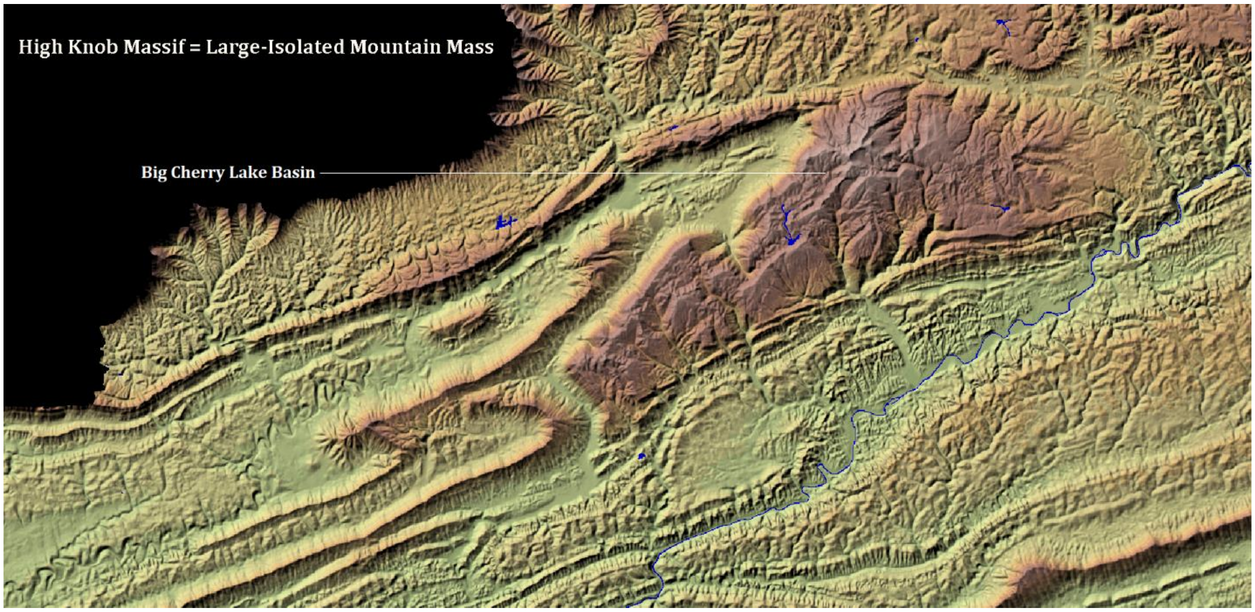

Figure 2. High Knob Massif in southwestern Virginia (USGS).

The High Knob Massif contains the deepest cave system in the Appalachians and the longest in Virginia (Schwartz & Orndorff, 2009). It forms headwaters of the ecologically renowned Clinch and Powell rivers of the Upper Tennessee River Basin and contains the most mountain-top lakes of any singular mountain in the Appalachian range (Browning, 2025). The High Knob Massif is part of a recognized hotspot for biotic rarity and richness of limited range species in the eastern United States (Stein et al., 2000).

Climatic setting

The High Knob Massif is the wettest area in Virginia. Elevation, location, sprawling width, and exposure to prevailing winds that stream northeast from the Gulf of Mexico through the open expanse of the Great Valley of eastern Tennessee allow the massif to lift air to its highest level for this position (with no downstream mountain being higher along mean annual air flow trajectories). The High Knob Massif is also the snowiest area in Virginia and unlike most of the state does not rest lee of the eastern highlands of West Virginia (Browning, 2021). This creates an ideal setting to study nocturnal CAP formation in climatically wet, biologically diverse environments where research has been lacking (Fig. 3).

The climate-precipitation regime of the High Knob Massif can be broken into two primary categories, the orographic forcing season (November-April) when synoptic-scale storm systems develop pressure gradients that physically push against the massif and the convective season (May-October) when convection rules the landscape. At upper elevations over 914 meters (3000 feet) above mean sea level, the convective season is correlated to the growing and breeding season (Browning, 2025).

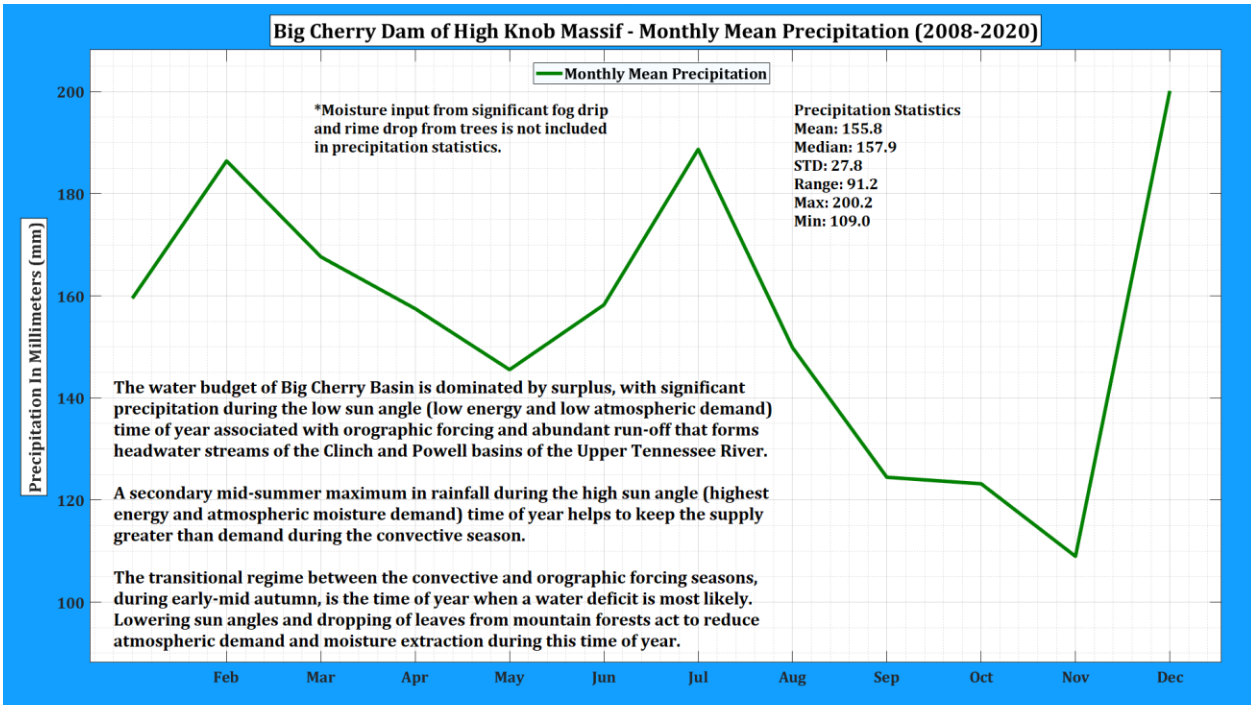

Figure 3. Monthly precipitation (without fog drip-rime Drop from Trees), (from Browning, 2021).

Development of extreme minima have historically been restricted to late autumn, winter, and early to mid-spring across the surrounding region, especially above fresh powdery snow cover. Given its importance, snowfall and snow cover days are plotted in Figure 4 for both a longer-term

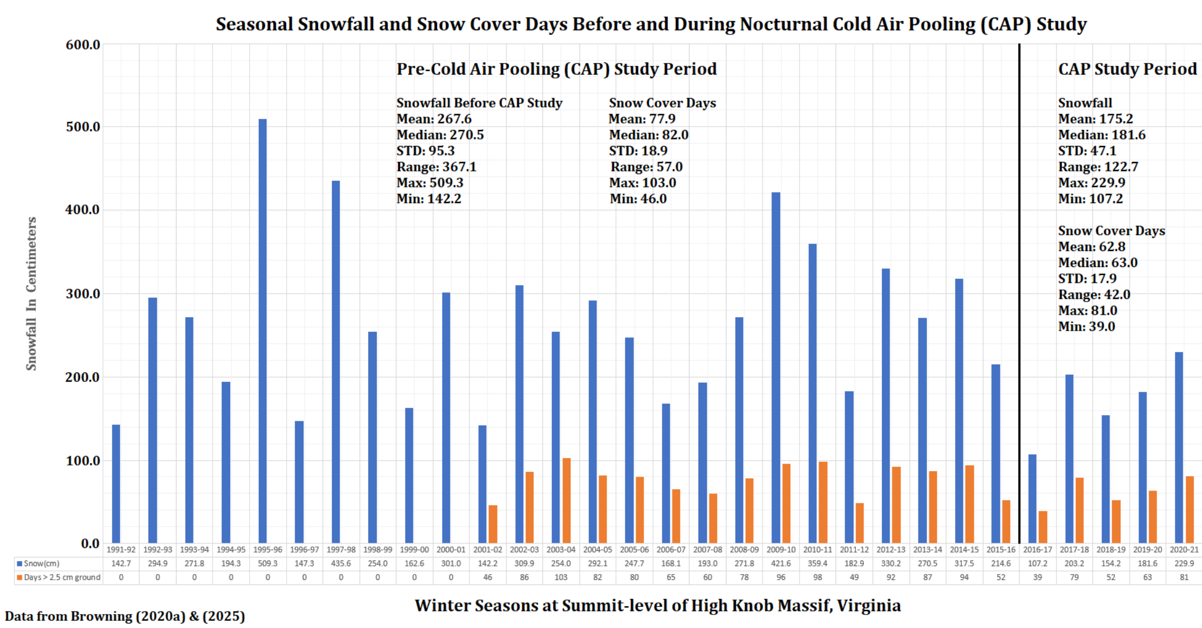

Figure 4. Seasonal snowfall (30-years) and snow cover days (20-years), (from Browning, 2025).

period and the 5-seasons (2016-17 to 2020-21) of this study. Opportunities favorable for development of extreme minima have been limited by much below average seasonal snowfall and snow cover days since 2016, and represent a notable deficiency associated with this current study. A longer-term period of observation will be necessary to fully resolve the influence of significant snow cover on extreme minima within what is typically Virginia's snowiest landscape. Preliminary data collection suggests that Big Cherry Lake Basin possesses significant potential to establish an all-time low temperature record for Virginia.

Snow cover days in Figure 4 represent a maximum value as observed on northern-facing slopes in the adjoining High Knob Lake Basin and are applicable to northern slopes of Big Cherry Basin which drain into the cold air formation area. During this study period the minimum temperature only dropped to -23.6 °C (-10.5 °F) in Big Cherry Basin and to -21.7 °C (-7.0 °F) in Burkes Garden Basin. Just prior to this study, in February 2015, much colder conditions formed over deep snow with official readings to -30 °C (-23 °F) observed in typically milder sites near Big Cherry. The all-time Virginia minimum record would have also been challenged in the CAP area during January 1994 and February 1996.

Field instrumentation and design

A diagnostic evaluation of evening, night-time, and morning transition phases (Zardi & Whiteman, 2012) associated with nocturnal CAP formation, as well as disturbances to it, was facilitated by a series of HOBO Pro-v2 temperature-dewpoint dataloggers (Fig. 5, Table 1) placed

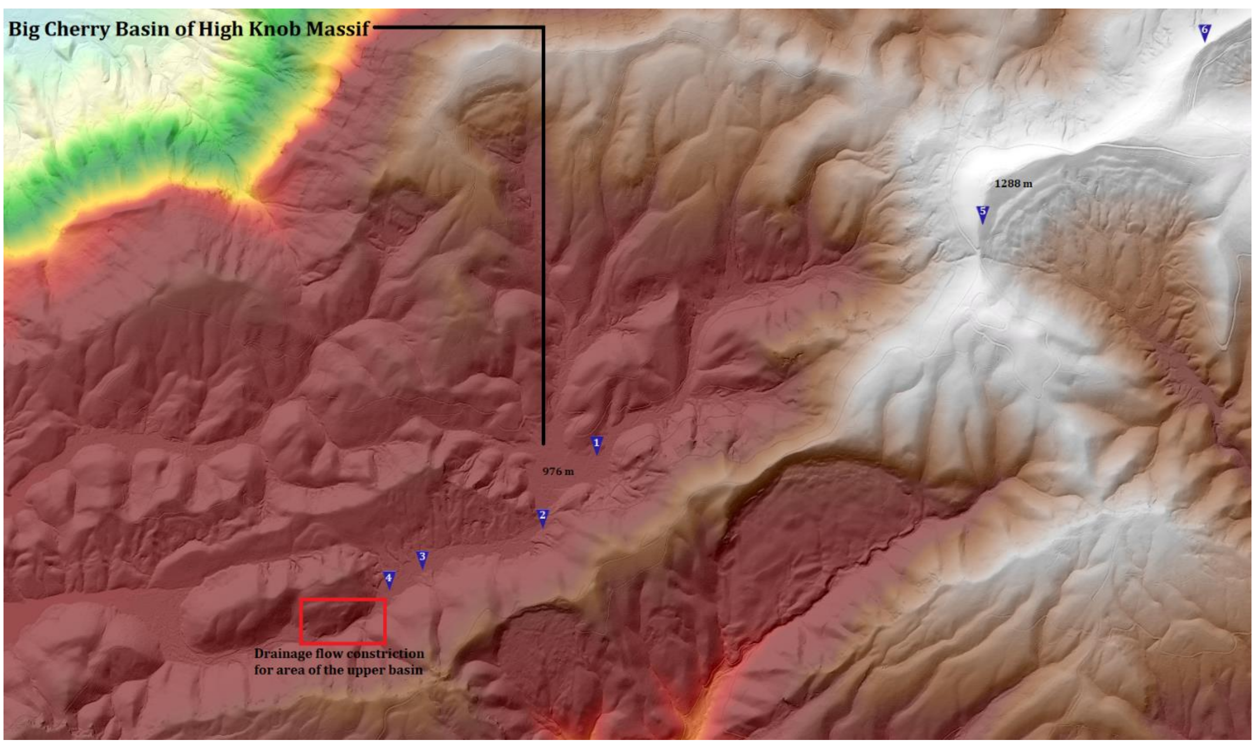

Figure 5. Sensor locations and area of drainage flow constriction (ArcGIS lidar).

in forest, forest edge, and more open habitats on the floor of the main wetland valley, along sidewall slopes, as well as upon highest ridges near the basin head. This design follows Whiteman et al. (2004a), as well as Whiteman & Hoch (2014), who suggested that vertically placed sensors be used as pseudo-vertical sounding points to approximate the three-dimensional temperature and moisture structure of a mountain basin.

Table 1. HOBO Pro-v2 (U23-002 Series) datalogger sites and characteristics.

Sensor site	Physical location	Latitude	Longitude	Altitude (m)
1	Seepage-Swamp	36.87528	-82.64442	980
2	Forest Edge	36.87145	-82.64562	976
3	Open Wetland	36.86780	-82.65150	971
4	Open Wetland	36.86672	-82.65194	970
5	High Knob SE	36.89095	-82.62933	1252
6	Eagle Knob NW	36.89762	-82.62292	1277
7	Little Mountain	36.84292	-82.66187	1066

Although evaluated by Whiteman et al. (2000), additional testing of sensors was performed adjacent to a National Weather Service Maximum-Minimum Temperature System (NWS MMTS) prior to field deployment. A -0.29 °C (-0.51 °F) calibration was applied to all HOBO sensors based on test results (not shown). This testing was performed after sensors were placed inside the largest solar radiation shield available (Onset RS1). Further modification for maximum air flow was made by drilling center holes in bottom plates of the shield to allow the attached datalogger and its cable to be placed inside a sealed container, protected from exposure and removed from the shield for maximum flow-through of air. These procedures achieved data quality well within the specified range (Table 2) via test results. The objective being to develop field sensor sites as accurate as official NWS MMTS sensor sites.

Table 2. Specifications of field instruments (from Onset Computer, Inc.).

Sensor/ Model	Manufacturer	Specifications	
		Operating range	Accuracy
Temperature / U23-002	Onset Computer, Inc.	-40°C to 70°C	±0.21°C from 0-50°C
Dewpoint-relative humidity U23-002	Onset Computer, Inc.	0 to 100%	±2.5% from 10-90%
HOBO Pro-v2 datalogger	Onset Computer, Inc.	-40°C to 70°C	±1 minute per month at 0°C to 50°C
Waterproof shuttle (U-DTW-1)	Onset Computer, Inc.	63 logger readouts (up to 64K per read)	±1 minute per month at 25°C

Sensors were mounted approximately 1.6 meters above ground level in accordance with the World Meteorological Organization (WMO) standards (WMO, 2008). Sensor mounts were painted white, to match RS1 radiation shields, for most accurate recording during daytime insolation.

Adaptations to mounting posts were necessary in Big Cherry Basin due to bear damage. Multiple replacement sensors were calibrated as described and used during the study to replace those destroyed. Beaver activity also impacted sensor sites 3 & 4, in the main CAP area of the basin, with periodic water level changes due to dam construction by beavers and their subsequent destruction by high water events.

Data were downloaded in the field using a HOBO Waterproof Shuttle (Table 2), which resets the time and relaunches the datalogger for the next recording period. All sensors were run on UTC time and the same 10-minute recording interval for direct correlation between sites.

Objective data analysis

Irregularly spaced surface station data collection points used in this study were assimilated into horizontal and vertical time-series and graphically plotted using MATLAB to reveal the nature of cold air pool development and dissipation within Big Cherry Basin under ideal (clear skies and light summit-level winds) and non-ideal conditions (clouds, turbulence), as described by Zardi & Whiteman (2012) and Whiteman (2000). Decoupling times were then calculated and graphically plotted.

Graphical time series plotted by MATLAB were overlain to generate a three-dimensional picture of conditions above the basin floor through time. Temperature inversion frequency and strength were defined by subtracting the basin floor temperature from a composite mean of temperatures obtained from combining summit level, basin rim, and mid-slope sensors. The basin floor was set equal to zero for graphical plotting. Positive values then indicated inversion conditions and increasing temperature above the basin floor, while negative values indicated decreasing temperature above the basin floor that are typically indicative of day-time conditions or episodes of cold air advection with turbulent mixing (rarely, nocturnal inversions can persist through day-time hours).

The development of a Climatic Buffering Index (CBI) was facilitated by querying out all positive values for every 10-minute recording interval through time (week, month, year), and then calculating how many minutes, hours, and days, as applicable, were under inversion conditions. A percentage of time was then generated for the period of interest and a proposed CBI ranking system (categories or bins) developed (Table 3). Additional sites (not shown) were used to aid development of this index.

CBI ranks of CBI-0 to CBI-1 represent mountain peaks and highly exposed sites which rarely decouple from the free atmosphere, while CBI-2 to CBI-5 ranks are based on increasing magnitudes of time in which a location of interest is decoupled and different from the overlying atmosphere. CBI-5 is considered extreme when nearly one-half or more of total time in any location experiences conditions which are different from the overlying and surrounding atmosphere. Future work using more sites could better define the CBI across time.

While the astronomical sunset to sunrise period makes up the majority of decoupled time, it is important to note in complex terrain that the effective local sunset and sunrise act to extend this time. Local sunset, for example, is defined as the time in which the sun slips beneath the local mountain horizon to shade a slope or valley. With loss of insolation, air begins cooling and draining downslope due to increasing density. This can initiate the decoupling process. Likewise, local sunrise can be defined as the time in which the sun rises above the mountain horizon to impact surfaces and initiate mixing. There tends to be less total and direct sunlight in deeply dissected and sheltered terrain locations. Without pressure gradients that force turbulent mixing, there can be a prolongation of the decoupled period with both an earlier onset of decoupling prior to astronomical sunset and a delay in recoupling following astronomical sunrise. During the pre-sunset period, surface (skin) drainage flows are shallow and the depth of decoupling limited. It is not uncommon during this period to feel cooling air in contact with air warmed by daytime heating as they are mixed by lingering boundary layer turbulence. Reference the supplement to this paper for additional information.

Table 3. Climatic Buffering Index (CBI).

CBI ranking	Percentage of time decoupled	Qualitative ranking
CBI-5	41 to 50%+	extreme
CBI-4	31to 40%	high
CBI-3	21to 30%	moderate
CBI-2	11 to 20%	low
CBI-1	1 to 10%	minor
CBI-0	0%	none

MATLAB renderings of the Pearson statistical test were performed to assess the correlation strength between development of nocturnal basin inversion and 850 mb dewpoint depression throughout 2020 under all types of weather conditions. The 850 mb dewpoint depression was derived from NAM-WRF Model interpolated initializations (00-Hour) for nearby Lonesome Pine Airport in Wise (the KLNP model grid point at 1200 UTC). The 12-hour forecast 850 mb dewpoint depression was used in a few cases where 1200 UTC data was not available.

Nocturnal inversions were identified and defined by using the 1200 UTC decoupling value, derived from subtraction of the basin floor temperature from a composite mean of rim and mid-slope (thermal belt) temperatures. Only decoupled settings with (+) inversion values were extracted and used.

Results

The development of nocturnal temperature inversions within the climatically wet environment of Big Cherry Basin in the High Knob Massif was tested for correlation to 850 mb dewpoint depression (Dd) using Pearson Correlation (Fig. 6).

A positive correlation between increasing 850 mb Dd and inversion strength was found to occur and to be independent of season, existing throughout the year, with a r^2 value of 0.235 indicating that only a small portion of this modest relationship could be directly explained by 850 mb Dd. This was field verified by processes that acted to extract moisture from basin floor air regardless of 850 mb Dd, to increase inversion strength, and by periods when turbulent mixing acted to minimize inversion strength even in the presence of dry air. Moisture extraction and outgoing longwave radiation (OLR) processes that were described by Whiteman et al. (2007) were also found to be operating in Big Cherry Lake basin throughout all seasons and years of this study.

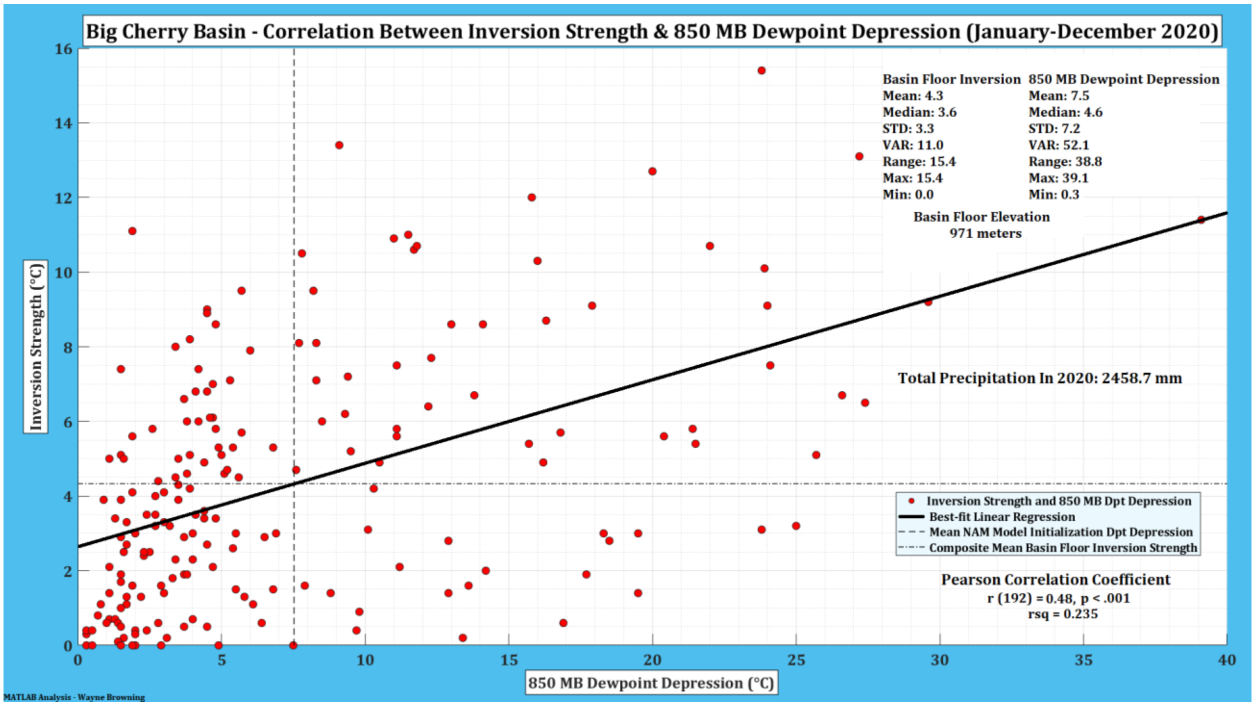

Figure 6. Pearson correlation of 850 MB dewpoint depression and basin inversion development.

An inverse relationship between basin floor minimum and 850 mb Dd (lower basin floor temperatures associated with larger 850 mb Dd, and vice versa) possessed moderately strong correlation, but less than half of the minimum temperature variability was explained by this relationship (Fig. 7). Reference the supplement section of this paper for another example from Summer 2020.

While coldest nights during summer, and generally throughout the year, are associated with large 850 mb Dd, indicative of driest air with the greatest cooling potential, this could not explain reduced basin floor temperature means across weeks to months to years that averaged as cool or cooler than mean temperatures at higher elevations.

Some multi-day periods during this study featured mean basin floor temperatures that were much lower than summit-level temperatures and were analogous to traveling northward by 500 km or more relative to summit-level means. This was observed despite higher daytime temperatures and was driven by nocturnal conditions associated with formation of cold air pools and decoupling of basin floors from the overlying atmosphere. The long-term impact of this is biologically significant, especially with respect to species possessing northern affinities.

Alpine timberline studies in the Appalachians by Leffler (1981b) found maximum temperatures to be more important than minimum temperatures in determining the altitude at which tree growth is inhibited. While true timberline is only found in the northern Appalachians of New England, understanding this remains important when considering biotic inversions.

Temperature inversions in Big Cherry Lake and Canaan Valley basins are not strong enough to reverse tree growth (like in the Gruenloch Basin of the Alps where trees give way to tundra on the basin floor), but they are significant enough to enhance the number and density of northern species with more subtle biotic inversions present. This is also true in High Knob Lake Basin where daytime temperatures are often suppressed and the basin drains at night (Supplement).

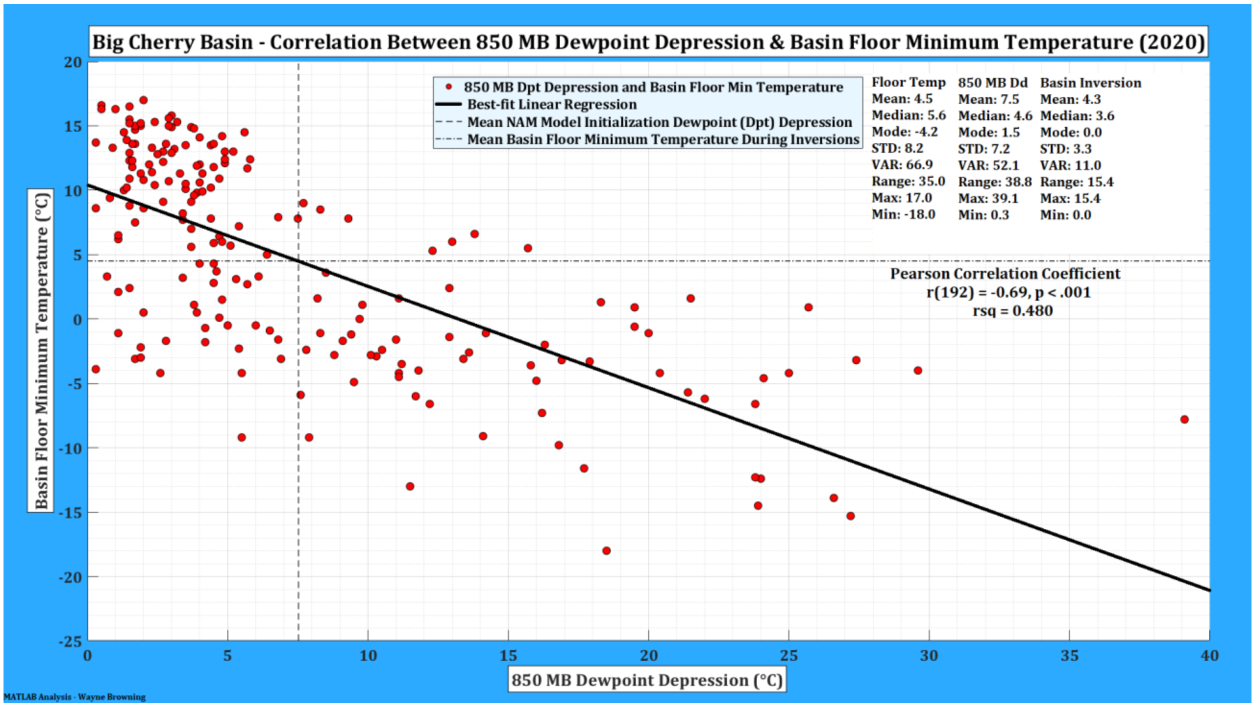

Figure 7. Inverse relationship (negative correlation) of 850 MB dewpoint depression and temperature.

Decoupling time and climate buffering index

A typical three-dimensional temperature structure from high-resolution field data is shown in Figure 8 for 15-22 October 2017. Nocturnal CAP is clearly visible. A more complete picture of inversion frequency-strength, presented in Figure 9, is used to calculate and graphically plot decoupled time.

In this October 2017 example, 60.7 percent of total time during this one-week period found the basin floor decoupled from the overlying atmosphere to result in a mean temperature that was 3.9 $^{\circ}$C (7.0 $^{\circ}$F) lower than the mid-slope and summit-level composite mean temperature (Fig. 9). This easily rates as an extreme CBI-5 period on the proposed climate buffering index of Table 3.

True significance of this becomes more evident when plotted across weeks, seasons, and years as illustrated by Figure 10 where 37.0 percent of 4.2 years found the basin floor decoupled from the surrounding atmosphere. This gives a CBI-4 (high) ranking on the climate buffering index (Table 3).

A logical preconception prior to this study was that cold air generation and frequency would generate decoupling time biased to the cold season, centered on the meteorological/climatological winter period of December through February. Just the opposite was actually observed (reference Table 4). Maximum decoupling occurred during the meteorological summer and autumn periods (this was due to a minimum in pressure gradient and associated winds that mix the lower atmosphere as briefly discussed below).

When looking specifically at the growing and breeding-migratory (convective) season this possesses vast biological significance, with 42 percent of this critical time being decoupled from the overlying atmosphere to generate a CBI-5 (extreme) ranking (Fig. 11). Although still

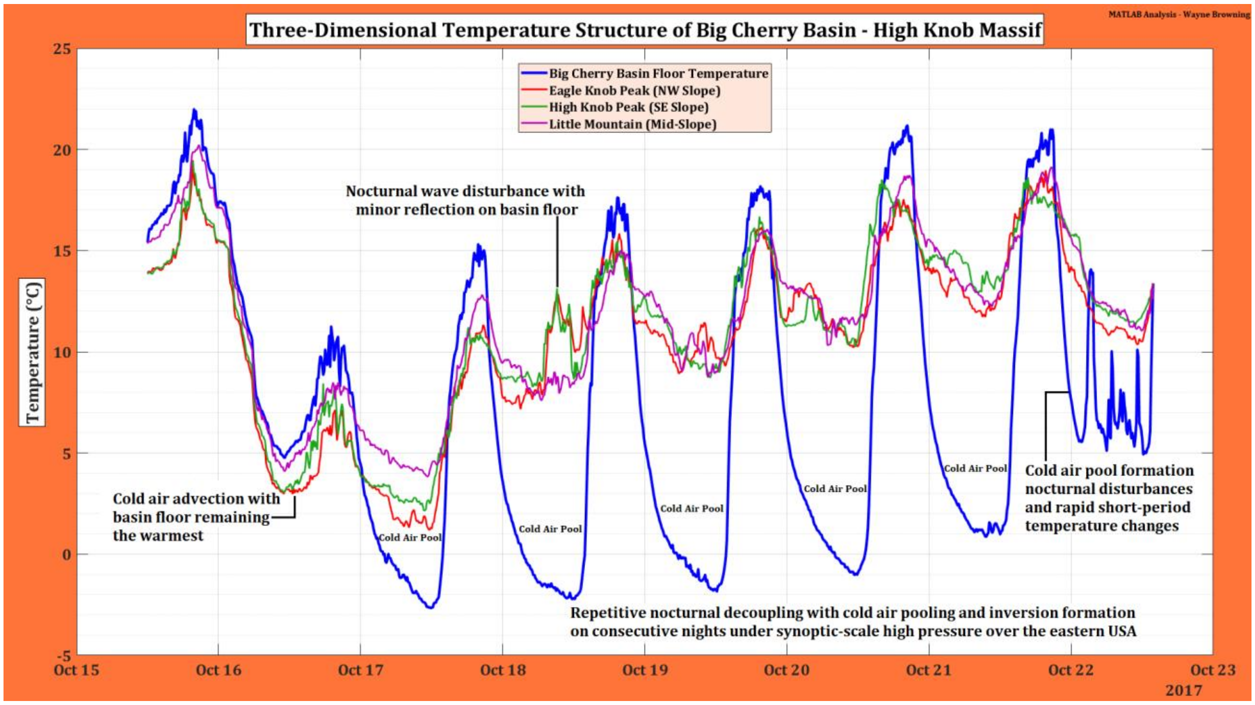

Figure 8. Example of three dimensional thermal structure in Big Cherry Lake Basin.

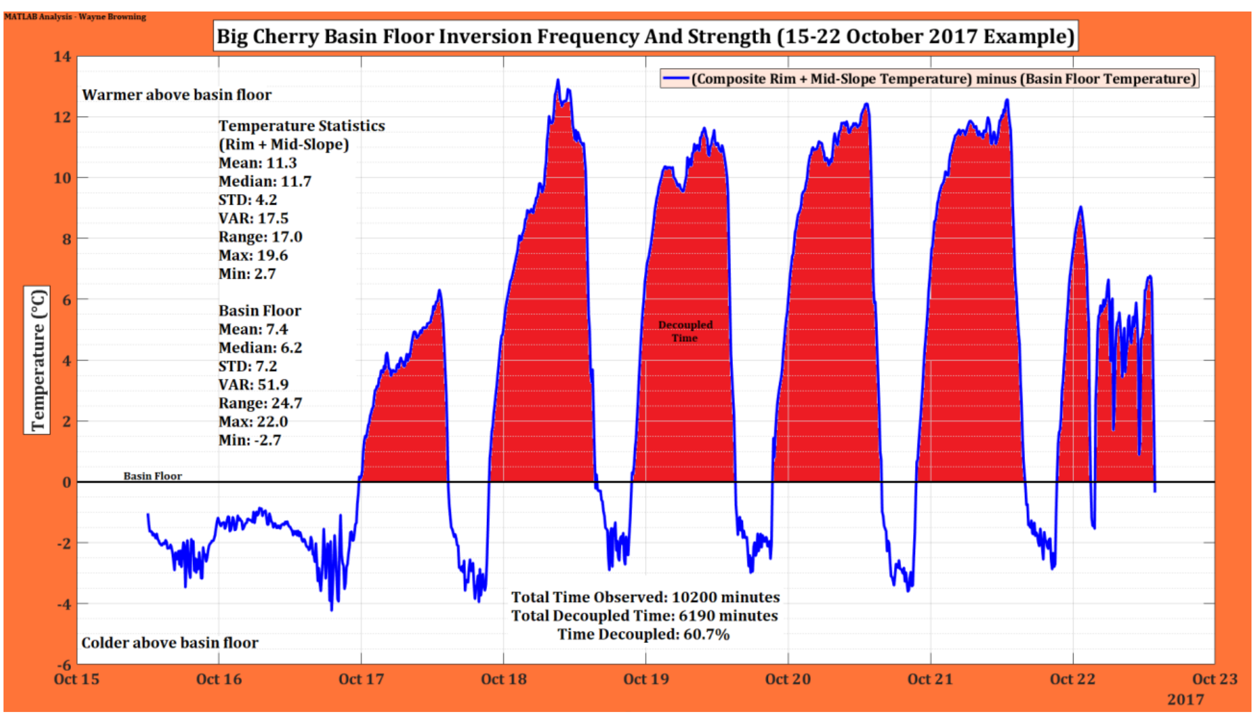

Figure 9. Example of three dimensional thermal structure in Big Cherry Lake Basin. Same as Fig. 8 except for inversion frequency-strength and decoupling time.

significant, the least decoupled periods were found to be meteorological winter-spring and the orographic forcing season of November-April (Table 4) when pressure gradients develop in response to synoptic-scale disturbances that physically push against the High Knob Massif. Since this massive mountain does not move it alters airflow and generates mountain waves and cross-barrier pressure differences which result in net drag against the atmosphere (mountain torque). Associated vertical mixing then reduces total decoupled time during the orographic forcing season as these atmospheric settings rule the mountain landscape. Weak pressure gradients, by contrast, are typical in the convective season, outside of anomalous settings such as those associated with inland moving tropical systems, and decoupled time is maximized.

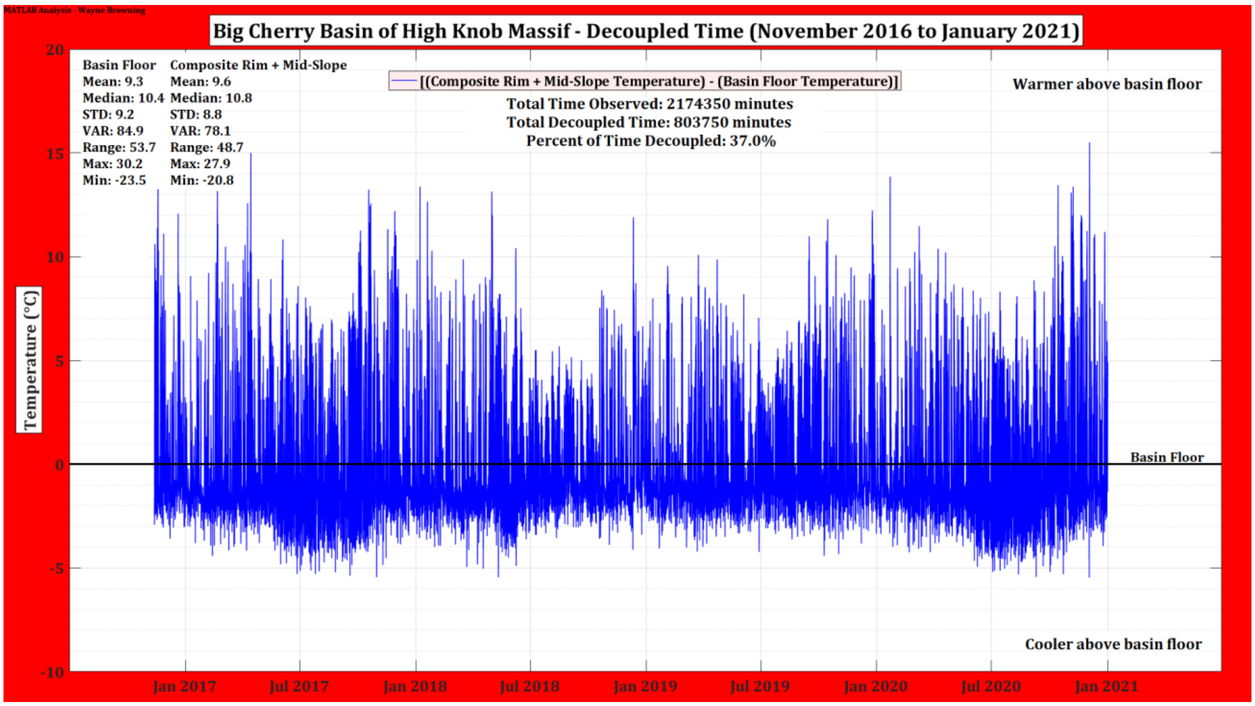

Figure 10. Decoupled time during a 4-year study period (November 16 to January 2021).

Table 4. Decoupled time and CBI rank by period interval, Big Cherry Lake Basin.

Time Period	Winter (Dec-Feb)	Spring (Mar-May)	Summer (Jun-Aug)	Autumn (Sep-Nov)	Orographic Forcing Season (Nov-Apr)	Convective, Growing Season (May-Oct)
2017	0.2555	0.2952	0.4217	0.4645	0.3020	0.4160
2018	0.3403	0.2753	0.4110	0.3721	0.2954	0.4032
2019	0.3144	0.3448	0.4179	0.4971	0.3414	0.4452
2020	0.3056	0.2843	0.4282	0.4635	0.3246	0.4152
Mean	0.3040	0.2999	0.4197	0.4493	0.3158	0.4199
Percentage	30.4	30.0	42.0	44.9	31.6	42.0
CBI Rank	CBI-4	CBI-4	CBI-5	CBI-5	CBI-4	CBI-5

For purposes of this study, the meteorological/climatological winter months of January, February, and December were taken from the same year. In other studies, decoupling differences between winter seasons under varied forcing (e.g., El Nino, La Nina, Neutral) could be easily defined and grouped by season across years.

A graphical view of just the convective (growing-breeding-migratory) seasons during this study is shown in Figure 11, with 42 percent of time decoupled on the basin floor acting to effectively extend it northward to even beyond the northward influence generated by the sheer elevation and exposure effect of the summit-level (Leffler, 1981a). Up to 55 percent or more of total time is decoupled from the overlying atmosphere during some summer seasons (Supplement).

A higher density of observed species possessing northern affinities toward the basin floor during the growing-breeding season, and expansion of habitats capable of supporting them, is a direct result of this high decoupling frequency and the significant amount of time detached and different from the overlying atmosphere. Given the elevation of this basin, in upper elevations above 914 meters, this directly supports and favors species that desire cooler conditions of northern latitudes and high elevations.

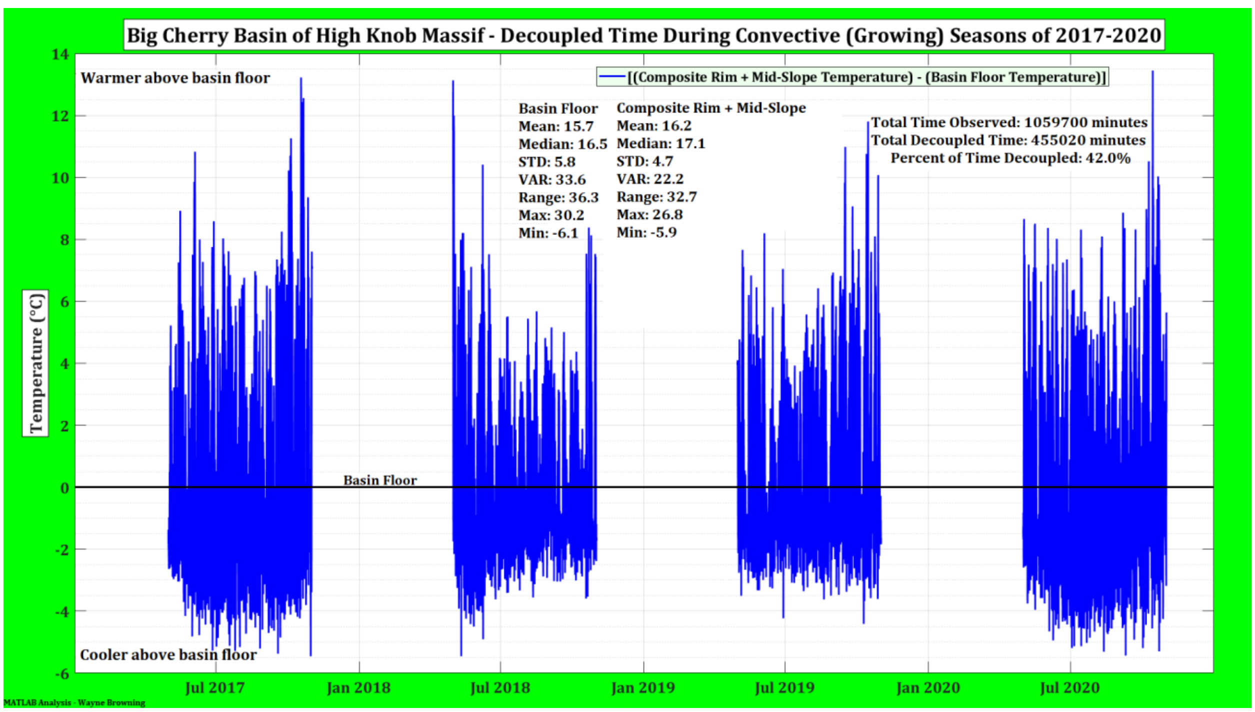

Figure 11. Decoupled time across different growing-breeding-migratory seasons (May-October).

Decoupling in Big Cherry Basin, or any complex terrain site, is dependent on characteristics of the local topography. An important finding during this field study was the presence of a horizontal temperature and dewpoint gradient along the nearly level basin floor between sensor sites 3-4 and 1-2 (Fig. 5, Fig. 12). This generated an up-basin directed pressure gradient that opposed typical down-basin drainage which occurs prior to nocturnal stability increases. Dry air at higher elevations was unable to reach the basin floor once CAP increased vertical stability during strong dry air advection events (Supplement). This combined with natural terrain constrictions (Fig. 5, Fig. 12) to enhance CAP around sites 3-4 during this 2017-2020 study period.

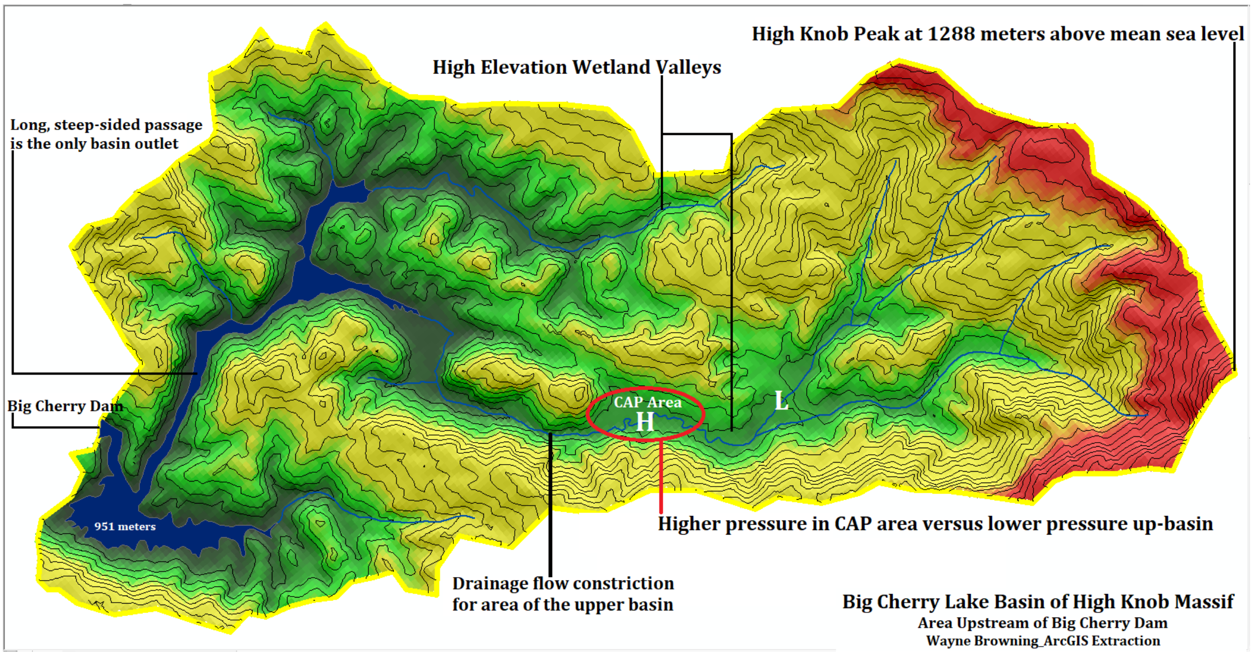

Figure 12. Big Cherry Lake Basin features of interest related to cool air pooling (CAP) study.

Additionally, during this study a proposed Decoupling Inflection Point (DIP) was identified which is unique to the geomorphology and climatic setting of each location.

The DIP marks a transitional point between decoupling and coupling and is largely dictated by wind speed that upon interaction with local terrain either allows decoupling, recoupling, or prevents them from occurring. Variations around the DIP can drive rapid fluctuations, as highlighted by 22 October 2017 in Figure 8, where turbulent mixing caused repetitive recoupling and decoupling on the basin floor with rapid, short-time period rises and drops in temperature (the supplement to this paper illustrates another example from Spring 2021). DIP fluctuations are most common during the orographic forcing season, and these can be part of an Appalachian Chinook effect. This occurs when mountain waves develop and break downward toward valley and basin floors to rapidly mix the atmosphere and dissipate any existing inversion. Rapid short-period temperature rises are characteristic and can be dramatic when the local DIP is reversed after nocturnal inversion development. Positive mountain torque events (higher pressure along eastern slopes) drive the most classic mountain wave breaking across the southern Appalachians. Otherwise, increasing pressure gradient after nocturnal inversion development can enhance turbulent mixing and produce rapid temperature rises when the local DIP is forced to reverse from decoupled to coupled states. Negative mountain torque events (higher pressure along western slopes) tend to be contraindicated for decoupling. Regardless of the specific setting, wind speed is inversely proportional to decoupling (light wind = more likely to decouple, and vice versa).

Different atmospheric conditions and terrain configurations add complexity, with a lag-time typically observed if nocturnal inversion has time to strengthen before conditions cross the inflection point to the coupling side (it can take time for turbulence and conditions contraindicated for decoupling to erode a well-developed basin inversion). This has been demonstrated in Canaan Valley Basin of northern West Virginia where the classic CAP section of the northern frost pocket, in the National Wildlife Refuge, possesses a DIP value of approximately 6.2 ms^{-1} (14 mph) +/- 1.0 ms^{-1} (2.5 mph) (based on preliminary research, not shown). Nocturnal minimums are typically lowest within northeast portions of Canaan Valley Basin (site DY007) which are less developed and about 30.5 m (100 ft.) lower in elevation than the southern, more populated and developed end of the basin.

The Canaan Valley National Wildlife Refuge site is often the coldest upper elevation frost pocket in the southern-central Appalachians due to large sky-view factor and frequently large 850 mb Dd (versus much wetter Big Cherry Lake Basin). Total decoupled time, however, is actually a category greater in Big Cherry (not shown) to result in nocturnal mean temperatures (and daily mean temperatures) that are depressed more than would be expected given the much greater annual wetness and southern latitude of Big Cherry Lake Basin when compared to the higher latitude setting of Canaan Valley Basin.

Research during this study suggested that higher decoupling frequency and much greater decoupled time in Big Cherry Basin also explained why mean nocturnal minimum temperatures are significantly lower than the NWS site in Burkes Garden (Fig. 13). Although coldest minimums are often similar, and may be lower on any given night in either basin, much drier conditions observed during this study period in Burkes Garden, in combination with its larger sky-view factor, would predict consistently colder conditions in the mean. This opposite reality, illustrated by Figure 13, could not be adequately explained without knowledge of decoupling time given such large moisture differences (Fig. 14).

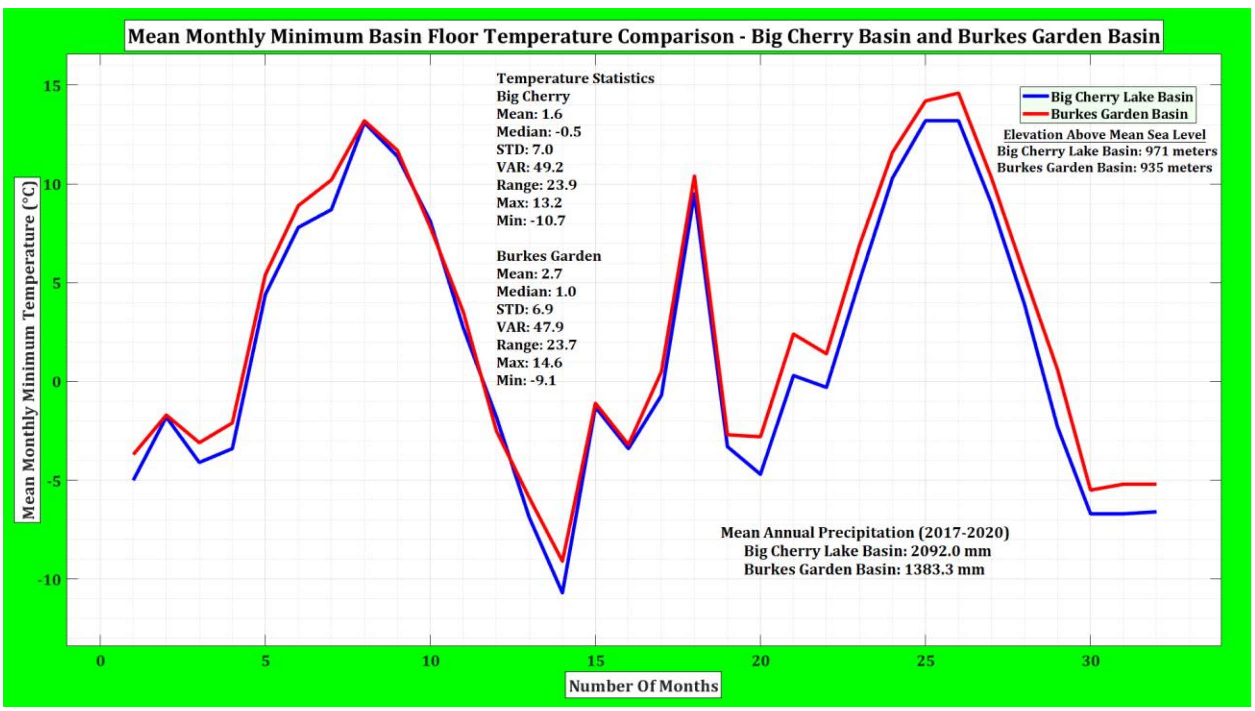

Figure 13. Mean monthly minimum comparison (32 months with no missing data; 2017-2021).

Afternoon dewpoint temperature was found to be a very poor indicator of nocturnal minimum within Big Cherry Lake Basin during this study, given processes cited that extract moisture from the air, with steep increases and decreases in both temperature and dewpoint being common during morning and evening transition periods, respectively, even with no moisture advection. Total decoupled time was most indicative of reduced mean minimums with more time for moisture extraction processes to operate.

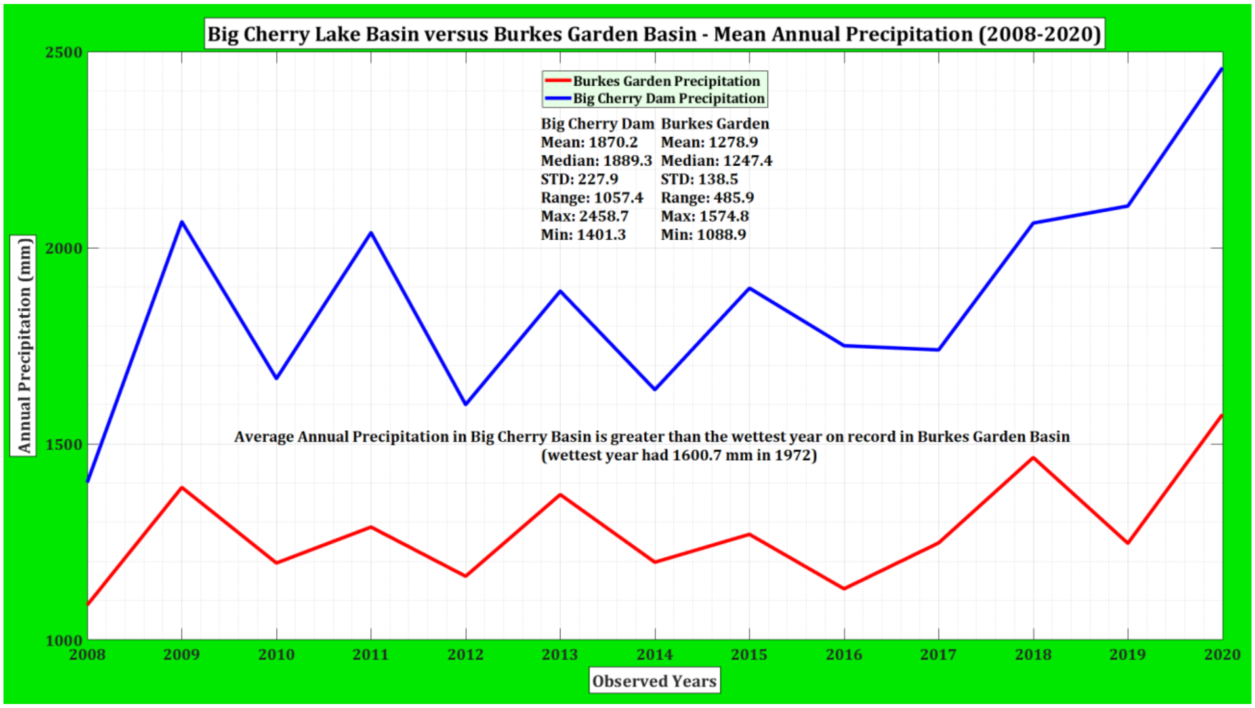

Figure 14. Mean annual precipitation comparison (2008-2020).

Discussion

Major motivation for this work was to develop a better understanding for CAP development within wet environments. This is exemplified across southwestern Virginia by anomalously wet conditions of Big Cherry Lake Basin in the High Knob Massif where mean nocturnal temperatures are consistently lower than observed at nearly the same elevation within much drier Burkes Garden Basin (Fig. 14).

Dewpoint depression at 850 mb was found to possess only a modest correlation with basin inversion strength and CAP development across different seasons. While acting as a control on the basin floor minimum, particularly on coldest nights, it was unable to fully account for the longer-term suppression of mean temperature over weeks to months to years.

Key findings included a steady and progressive drop of dewpoint on the basin floor that was unrelated to advection and occurred throughout a range of 850 mb dewpoint depression. This suggests that processes at work to extract moisture from the basin floor air, as documented by research within other mountain basins by Whiteman et al. (2007), operated regardless of specific dewpoint and its depression when conditions favorable for nocturnal inversion formation and stratification were present. Assuming processes that extract moisture from basin floor air at upper elevations are similar: dew, frost, shallow fog, hoar-frost and rime; then sky-view factor, as cited by Whiteman et al. (2004b), and other outgoing longwave radiation (OLR) factors are candidates to explain differences observed between basins which possess limited down-basin winds (draining valleys tend to be naturally milder).

This field research found decoupled time impacts all moisture extraction and OLR factors through its duration, with longer intervals of decoupled time (higher CBI ranked sites) from the overlying atmosphere providing more opportunity for moisture extraction and OLR processes to operate versus shorter decoupled time periods (lower CBI sites). A direct result of longer decoupled time periods in Big Cherry during this study period was lower mean minimum temperatures than in Burkes Garden, despite the latter's much drier setting and much greater sky-view factor.

Additionally, afternoon dewpoint could not be used as a predictor of nocturnal minimum in absence of moisture advection, with often large dewpoint drops from afternoon values on the basin floor during evening transition and night-time periods in all seasons. Basin floor dewpoint was also found to be unaffected by dry air advection in mid-upper levels of the basin if advection occurred following establishment of CAP and nocturnal temperature inversion (Supplement). This indicated that downslope drainage is not able to reach the basin floor once static stability increases within the CAP, giving further support to Clements et al. (2003) that cold air does not build up via the convergence of downslope flows (especially in basins lacking a distinctive down-valley wind system).

Big Cherry Lake Basin has the potential to generate all-time record low temperatures for Virginia, as exemplified by extreme minima observed in the region just prior to this study period in February 2015. While development of extreme minima is of interest, it is the high frequency of CAP formation in its upper elevation basin that is of greatest importance. This produces conditions capable of supporting northern flora-fauna and expands habitats where they can live beyond the highest ridges and far south of their home ranges.

This study demonstrated that CAP formation possesses high repeatability within the anomalously wet setting of Big Cherry Lake Basin throughout the year, with peak frequency observed during the growing-breeding and migratory seasons. This has significant implications for biological diversity and forms a microrefugial buffer against the present period of climatic warming.

Calculation of total decoupled time, where the basin floor is different from the overlying atmosphere, added valuable insight into the suppression of nocturnal minimum temperature in the basin and proved to be a powerful linkage to biodiversity. An extreme (CBI-5) potential for buffering of climate was suggested by 42 percent of total time spent decoupled from the overlying atmosphere during the growing and breeding season across the extended 4-year period of this research.

A maximum of total decoupled time during the period from late spring into early-mid autumn can be accounted for by a reduction in synoptic-scale disturbances that generate pressure gradients which push on the orography. Decoupling across complex terrain increases as the pressure gradient decreases. This explains the notable minimum in decoupling observed during the orographic forcing season when synoptic-scale storm systems develop pressure gradients that push against the High Knob Massif.

Indirect field verification of long periods possessing different climatic conditions consisted of the observed presence of an enhanced number and density of species possessing northern affinities within the basin relative to higher elevations (this could be an emphasis of future work). This effectively formed a species inversion across time that matched the temperature inversion. A Special Biological Area (SBA) recognized in an adjacent basin holding High Knob Lake is also a partial product of prolonged decoupled time and was identified during this study (not shown).

Research results of this project offer a way to rank any location having vertical relief with respect to climate buffering using a relatively simple index based on observed decoupled time using collected data. Defining climate buffering capacity is critical given documented and expected changes to climate associated with current global warming (IPCC, 2021). Additionally, a decoupling inflection point (DIP) introduced as part of decoupled time has potential application with respect to nocturnal temperature forecasting. Future work could expand on this research by using more sites to better define the CBI and develop the DIP across space and time.

This research reveals that in wet environments such as Big Cherry Lake within the High Knob Massif, cold air pool development is significantly enhanced and amplified by extended periods of atmospheric decoupling. This finding has a direct linkage to biological diversity and possesses immense biotic significance. High-elevation basins of the southern-central Appalachians, including Big Cherry Lake, Burkes Garden, and Canaan Valley, function as vital "sky islands." They foster distinctive microclimates capable of supporting a rich diversity of species with northern affinities in southern regions. Along with the highest mountain ridges, protection of these basins is imperative for the preservation of biodiversity and the physical, mental, and social well-being of all living things. Reference the research supplement for an informal discussion that highlights the scientific method and evolution of this research.

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