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Wind: A Jekyll-and-Hyde Factor for Northeastern Mountains

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On a worldly scale, mountain heights in the northeastern United States don't grab a whole lot of attention, but their winds are less forgettable. Until recently, New Hampshire's Mount Washington even held the world record wind speed at 231 miles per hour, which remains the highest mountain wind ever recorded.[1] This is all the more impressive considering that the forces delivered by wind increase exponentially, not linearly, with wind speed. Winds exert a complex Dr. Jekyll and Mr. Hyde influence on this region's mountains. On the good Dr. Jekyll side, winds are natural stress agents that contribute to the long-term survival of the remnant arctic-alpine ecosystems still occupying the higher peaks. Without the inhibitory effect of strong winds, these rare northeastern ecosystems likely would have been overgrown by the subalpine forest thousands of years ago.

Hikers traversing the region's higher summits and ridgelines well know how strong mountain winds can also take on a dark, life-threatening, Mr. Hyde personality. Wind's Mr. Hyde personality has transformed even further to threaten mountain ecosystems themselves. With the industrialization and urbanization of the eastern United States, wind is now the conveyor belt that transports a concoction of air pollutants long distances to the region's higher elevations. This chemical milieu reduces visibility, impairs hikers' lung capacity, and stresses mountain ecosystems by acidifying their watersheds, releasing toxic metals from the soils, and overfertilizing the vegetation with excessive nitrogen. Confounding wind's impacts on mountains, government subsidies and advances in wind turbine technology in the 1990s have made northeastern mountains the focus for industrial-scale wind power development, a major game changer for these mountains' ecosystems and landscapes.

The Appalachian Mountain Club, with its mission to protect the region's mountains, conducts multifaceted research to identify key drivers that will influence the long-term fate of the region's subalpine and arctic-alpine ecosystems. Research that not surprisingly follows Bob Dylan's sage advice: "The answer, my friend, is blowin' in the wind." Joni Mitchell was on to another

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[1] Mount Washington's record wind speed, 231 MPH, apparently lost out to the reported 253-MPH speed recorded April 10, 1996, on Barrow Island, Australia, during Typhoon Olivia. This new claim did not come out until January 2010, when the World Meteorological Organization announced its review of worldwide weather extremes. See www.mountwashington.org.

The Appalachian Mountain Club's air pollution monitoring equipment below Mount Washington, in the White Mountains. KEN KIMBALL

critical element of the puzzle when she penned the lyrics, "I've looked at clouds from both sides now. . . . I really don't know clouds at all."

Mitchell's dilemma is ours; fortunately, our research lets us better know the two sides of mountain clouds. On the one hand, clouds deposit air pollutants; on the other hand, they cause icing events that help stall the forests from invading the alpine zone.

Global warming dominates common hearsay as the major threat to northeastern mountain ecosystems, but clouds and wind are likely more important than temperature in shaping the past and future fate of the subalpine and arctic-alpine ecosystems. The old-school explanation that hiking up Mount Washington in New Hampshire or Katahdin in Maine is climatically parallel to driving from the lower elevation forest of New England to the tundra of the Arctic Circle misses the actual causal agents for mountain ecosystem change with elevation.[2] The changing vegetation patterns on northeastern mountains—from the deciduous, broad-leaved forest at lower elevations, to the mid-elevation spruce-fir forest, to the stunted krummholz, and then to the arctic-alpine zone—may mimic the changing plant communities one would experience while driving north, but reduced growing seasons at various elevations are less responsible than commonly suggested in this "hike upward" analogy.

In a perfect textbook scenario, with every 1,000 feet of elevation gained, the adiabatic lapse rate (drop in temperature resulting from diminishing air pressure with altitude) should result in a temperature drop of roughly 3.5 degrees Fahrenheit. As one hikes up, the air cools, yes. But why are the lowest of the Western and Central European alpine zones at elevations well *above* the Northeast's tallest peaks? Those two zones lie farther north in latitude than those in New England. Or, how do we explain that treeline—the elevation of the boundary between forest and alpine—varies by more than 1,800 feet on both Mount Washington and Katahdin? This variation in treeline elevation represents a temperature difference, based on lapse cooling rates, of almost 7 degrees Fahrenheit. Such contradictions illustrate that more complex factors are involved.

Adiabatic cooling principles prevail in calm conditions, but calm conditions are not the norm on mountains. Regional prevailing surface winds move across the landscape and, upon hitting an obstruction such as a mountain,

[2] See my article, "Northeastern Alpine Ecosystems—Survivors or Victims of Climate Change?" *Appalachia*, 228: 140–144 (Summer/Fall 2009).

accelerate to get all of their air over the top and to the other side. As the flowing surface air masses are uplifted over mountains their air pressure drops, they cool. The moisture they contain frequently condenses to form orographic—mountain—clouds. Latent heat energy is released when water changes from the gas (humidity) to the cloud liquid (droplet) phase in air, which lowers the adiabatic cooling rate. Nighttime temperature inversions are also common in mountains, whereby temperatures instead increase with elevation.

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Air masses also stratify, similar to how summer water temperature changes abruptly at a certain depth in deep lakes with warm, less-dense water above and colder water below that do not mix even with strong surface winds. The planetary boundary layer, the layer of the atmosphere closest to the earth whose air physically interacts with the surface of the earth it is passing over, is slowed by friction and well mixed because of turbulence caused by variations in topography. Above the planetary boundary layer and absent most topography, a separate, more laminar, and faster airflow can be occurring. The depth of the planetary boundary layer is not static at the same altitude; rather, it varies daily. Northeastern high elevations are usually within the planetary boundary layer during midday, but above it by evening. Nighttime uncoupling from the planetary boundary results in summit evening winds typically being faster, and they move polluted air masses from afar much quicker to the summits with minimal pollutant scavenging compared with the mountain base. This explains why Mount Washington air is more polluted on the summit, more so in the evening, than in the mountain's valleys.

Of interest is that in the Northeast, the top of the planetary boundary layer—where fair weather and orographic clouds typically form—coincides with the same elevational range in which subalpine forest and alpine ecosystems survive. This alpine and cloud relationship provides clues to why the regional global warming trend is weaker at higher elevations and why we have such low-elevation alpine ecosystems surviving in the Northeast, more so when we put wind in the equation as well.

The higher summits frequently hide in the clouds; Mount Washington's summit is one of the cloudiest places in the United States. Clouds during cold weather can result in the accumulation of rime ice. Regionally, the best measurements of rime ice accretion rates with elevation come from Mount Washington and, in Vermont, Mount Mansfield and nearby Madonna Peak. In the 1980s, researchers placed rime ice detectors on the ski area lift towers on Mansfield and Madonna. Rime ice accumulated more sharply above 2,700 feet. This is the same elevation at which spruce-fir forest—which prefers cool, damp conditions—starts. Rime ice formed more frequently on Mount Washington than on Mount Mansfield because Washington is higher and because of its closer proximity to the moisture-bearing Atlantic Ocean, a factor enhanced when the weather to the east involves a low-pressure system.

Balsam fir trees are another indication that factors other than growing season prevent forest from invading the alpine zone. Though stunted in the form of krummholz, they do grow almost to the top of the highest mountain in the region, Mount Washington. But they only survive this high in the shelter of depressions and larger rock formations. Blow clouds over a mountain with strong winds and below-freezing temperatures and substantial rime ice can rapidly collect. The taller and spindlier the surface area is, like a tree, the better the collecting efficiency is. This ice can build up so thickly that limbs break, and accumulated ice-encased branches swaying in high winds are chafed. Add blowing snow across the surface of the alpine zone and the sandpaper effect on any tall vegetation not sheltered can be lethal. Break off the tallest leading buds with frequent icing and these trees will grow horizontally and short instead of vertically, forming krummholz that hikers find impenetrable. On the more wind-exposed and hostile ridges and summits, the tiny alpine plants survive because they offer minimal collecting surface areas for ice and they hunker down where the air moving across the ground is slowed dramatically because of friction.

The wide range of elevations of treeline correlates with comparisons of valleys to ridges. In valleys or gulfs, treeline is higher. The clouds are there, but the winds that enhance rime ice deposition are weaker. On ridges, treeline is lower. The frequency of clouds may be less, but the accelerating winds over the ridges increase the efficacy of deposition of those clouds present.

Clouds also play a role in climate warming trends, which are less in the White Mountains than in lower surrounding elevations. Greenhouse gas emissions of carbon dioxide, methane, and nitrous oxides in the lower

Rime ice rapidly collects on krummholz, the stunted balsam fir trees that cling to life just below treeline. AMC RESEARCH DEPARTMENT

troposphere act as a thermal blanket that reduces the radiation of some of the day's sunlight energy back into space during clearer nights. Water vapor and clouds are also very good thermal blankets. Because these mountaintops are naturally in the clouds much of the time, nighttime cooling is less influenced by the addition of greenhouse gases at these locations. Wind and frequent rime ice events and how cloud immersion ameliorates warming trends may best explain why northeastern alpine ecosystems have not succumbed to forest invasion, even several thousand years ago when this region's climate was warmer than today. During that warm period, the lower-elevation forest did transform to more southern forest species, until a cooler climate returned to give us the Northern Forest we know today.

Today, wind power already has transformed some of our northeastern mountains, and it could transform more. The best regional winds, excluding the ocean, are above 2,700 feet. Stronger winds allow for the use of larger turbines with better capacity factors. For context, subalpine forests above 2,700 feet in elevation make up 1.4 percent of the total area of Vermont, New Hampshire, and Maine, and about a quarter of that land area is privately

Wind turbines, if built in the numbers to meet goals, could industrialize the ridges in the Northeast. KEN KIMBALL

owned. Building wind turbines requires wide roads to move the massive components and erect them at heights of 300-plus feet above the ground.

How significant could this new impact on mountains be? Maine has set an aggressive goal of generating 3,000 megawatts of land-based wind power generating capacity by 2030. Using the average generating capacity of existing wind farms at approximately 11 to 12 megawatts per ridgeline mile, it would require the industrialization of about 250 miles of ridgeline, with extensive road systems, power lines, and 1,000 to 2,000 nearly 400-foot-high turbines with blinking red lights. In Maine, 53 percent of the area above 2,700 feet lacks conservation protection status, and it is questionable whether the state

could achieve its 3,000-megawatt goal without industrializing a number of these higher ridgelines.

Few regulations or guiding principles direct the northeastern states as they consider wind power. The upper-elevation spruce-fir forests where the wind blows best also represent some of the most natural remaining and old-growth parts of the Northeast's landscape, and provide critical habitat for a number of wildlife species of concern, including the pine martin, Canada lynx, and Bicknell's thrush.

As the climate warms, these subalpine forests will serve as refuges for the lower-elevation spruce-fir forests, whose required cooler habitat is expected to decline. The subalpine forest served this role during the postglacial hypsithermal period, 9,000 to 5,000 years ago. Then, deciduous forests moved northward and to mid-elevations in response to global warming, restricting the spruce-fir forest to the cooler coast and higher elevations. Gradually, the earth cooled again, and about 1,000 years ago, the spruce-fir forest species were able to recolonize the lower elevations of the Northern Forest. Should wind power development severely curtail or eliminate the present upper-elevation spruce-fir forests, these forests' ability to serve again as refugia in a warming climate could be seriously compromised.

Like the good and evil conflict of Jekyll and Hyde's personalities, the development of mountain wind power presents significant challenges. Wind power helps address air pollutant and greenhouse gas emissions, but if not properly constrained could throw the proverbial baby out with the bathwater. To meet this dilemma head on, the AMC Research Department is proactively using satellite and aerial imagery to identify and analyze the numerous islands of high-elevation spruce-fir forest in New England and New York and to advocate for the protection of the most ecologically important subalpine forests and other high-resource mountains from wind power development (see www.outdoors.org/conservation/wind/index.cfm).

Dr. Kenneth Kimball is the director of research for the Appalachian Mountain Club. He and the Research Department staff have been studying northeastern alpine ecosystems for almost 30 years and, more recently, the impacts of industrial-scale wind power development on the region's mountains and how to address them. More information on the AMC's mountain research can be found at www.outdoors.org/conservation/