Biologists say climate change may already be affecting high-mountain ecosystems around the world, where plants and animals adapted to cold, barren conditions now face higher temperatures and a surge of predators and competitors

All Downhill From Here?

Pikas are the essence of cuteness: The miniature, pink-eared cousins of rabbits nibble on flowers, greet visitors with high-pitched squeaks, and scamper like curious chipmunks. They are also some of the world's toughest mammals, dwelling beneath boulder piles on high, treeless peaks where winter winds howl most of the year and the herbage of brief summer is too scant to attract lowland competitors.

Pikas thrive where it's cold and bare. So it's no surprise to some biologists that, as global temperatures rise, the pikas' numbers are nose-diving in far-flung mountain ranges.

Alpine ecosystems are particularly vulnerable to climate change, and recent studies suggest that mountain dwellers—from delicate flowers in the Swiss Alps to pygmy possums in Australia—are in trouble. Although it can be difficult to tease out other factors, including fire suppression and livestock grazing, a growing number of researchers fear that if the heat keeps rising, many alpine plants and animals will face quick declines or extinction.

Tundra at the top. Islands of alpine vegetation are sprinkled across high peaks.

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"People always thought the whole world could go to hell, and pikas would be fine. Actually, they may be canaries in the coal mine," says wildlife biologist Andrew Smith of Arizona State University in Tempe.

Initial findings have prompted a surge of studies of the alpine—the high windswept regions above the timberline—and researchers are beginning to coordinate their efforts. They are finding that creatures everywhere are responding to warming, but mountain biota, like cold-loving polar species, have fewer options for coping (*Science*, 19 January 2001, p. 424).

Global average temperatures have increased by 0.6°C in the past 100 years, and they could go up another 1.4° to 5.8° in the next 100. In an apparent bid to adjust, many creatures have shifted flowering, breeding, or migration dates; mobile ones such as butterflies and birds have moved ranges poleward an average of 6.1 kilometers per decade since the 1960s, according to an analysis of 1700-some species published last year in *Nature* (2 January 2003, p. 37).

High-mountain biota are trapped, however, and those living in the alpine are in the tightest corner of all. Comprising just 3% of the vegetated terrestrial surface, these islands of tundra are Noah's ark refuges where whole ecosystems, often left over from glacial times, are now stranded amid uncrossable seas of warm lowlands.

These islands are shrinking. The lowest elevation at which freezing occurs in mid-latitude mountains has climbed 150 meters since 1970. (On average, each rise of 100 meters in altitude corresponds to a 0.5°C drop in mean temperature.) This appears to be hastening local extinctions that have been proceeding slowly since the last glacial age. Fossils show that pikas, for example, once ranged widely over North America but have contracted to a dwindling number of high peaks during warm periods of the last 12,000 years, says U.S. Geological Survey (USGS) ecologist Erik Beever.

Alpine creatures are poor dispersers, anyway. With slowed life cycles, many plants reproduce by cloning, not by seed, and the tiny pikas rarely roam more than a kilometer to find new homes. Many species have been isolated on the same mountains for so long that they have become new species. Mountains are rich in endemics as well as total biodiversity, because they contain many slopes, aspects, and elevations that compress abundant microclimates and specialized habitats into small areas. "A lot of populations are just little frostings on peaks," says James Brown, a population ecologist at the University of New Mexico in Albuquerque who studies alpine mammals.

These small populations can be pushed out by any number of temperature-driven forces: invasions of trees, lower-elevation plants, or predators; frequent extreme weather events; and, perhaps in the case of creatures such as pikas, simple overheating. "Take a mountain and warm it up, and maybe [alpine ecosystems] shift upward—but only until they reach the top," says Brown.

Headed to heaven

The first danger signs have come from plants. About 80 to 100 years ago, European botanists inventoried plants on many summits in the Alps. In 1994, researchers from the University of Vienna showed that on more than two-thirds of the sites resurveyed, grassland species from lower slopes had crept up as much as 4 meters per decade—an apparent response to a 0.7°C regional warming. If the ascent continues, says study leader Georg Grabherr, cold-loving plants at the highest elevations will be pushed upslope and in the end "go to heaven."

These plants include rarities such as *Arenaria tetraquetra*, which clusters near summer snow patches that provide dribbles of meltwater. "They're fantastic," says Grabherr, describing the plant as "a round cushion with little white flowers on the margin, exactly like a halo—so they are ready for paradise."

Grabherr says that based purely on rising temperatures, invaders should be climbing slopes twice as fast as they are. But, he adds, "alpine plants take a long breath before doing anything," so it could take 40 or 50 years for more dramatic responses. His results are bolstered by colleagues who include Martin Camenisch, a botanical consultant in Chur, Switzerland. He says that in the past 80 years, common newcomers have invaded one 2800-meter mountaintop from the lower slopes, nearly tripling species richness—and occupying up to 20% of the space formerly held only by high-alpine species.

To track projected changes, Grabherr has organized 40-some scientists into the Global Observation Research Initiative in Alpine Environments (GLORIA, at www.gloria.ac.at). With identical inventory plots and protocols, collaborators have agreed to return for surveys every 5 to 10 years and feed results into a central database. Seeded by money from the European Union, scientists launched GLORIA in 2001 on 71 summits from Spain to Russia, and they have since added sites in Australia, the United States, and South America.

The most vulnerable places are ones where mountains are low and climate is temperate, so there is little alpine to begin with. These include Greece's Mount Olympus and Spain's Sierra Nevada range, where only 200 to 400 meters separate timberlines from summits. In Australia, only 11,500 square kilometers of mountain terrain even get winter snow, and just a fraction of that is true treeless alpine. Crammed here are mountain pygmy possums, specialized reptiles (including two that have just been described), and countless undescribed invertebrates. A 30% decline in snow cover over the past 40 years has allowed feral cats, rabbits, and foxes to move in, says ecologist Ken Green of the Australian National Parks and Wildlife Service; native species are plummeting. "There is no opportunity for altitudinal shift—everything is already at the limit," he adds.

In neighboring New Zealand, a paper last year in *Arctic, Antarctic, and Alpine Research* predicts that a 3°C temperature rise over the next century—moderate as estimates go—will wipe out 80% of alpine islands and extinguish a third to a half of 613 known alpine plants. Co-author Alan Mark, a botanist at the University of Otago in Dunedin, New Zealand, says that even if temperatures stop rising now, 40 to 70 species will be at risk in coming decades, as ecological shifts catch up with already-milder conditions. "There is no question of if—just when," he says.

Not at their peak. Warming may threaten alpine creatures such as the pika (*above*) and plants such as *Arenaria tetraquetra* (*right*).

CREDITS: (TOP TO BOTTOM) R. J. FRANKEN; PAULI HARALD/GLORIA

Trees on the move

Since the alpine is by definition treeless, rising timberlines themselves could trigger much change, and that is apparently already under way in some places. Christian Körner, a botanist at the University of Basel in Switzerland, argues in an upcoming paper in the *Journal of Biogeography* that tree lines everywhere are controlled by a surprisingly narrow range of root-zone temperatures; trees stop where the mean drops to about 6.5°C. Indeed, Russian researchers writing in *Ecological Studies* last year reported that in the Ural Mountains, temperatures have gone up as much as 4°C during the 20th century and trees have moved 20 to 80 meters upslope, reducing alpine zones by 10% to 30%.

Tree rings reveal similar upward marches in the Alps, says Jean-Paul Theurillat, a phytogeographer at the University of Geneva, Switzerland. At around 1800 meters, trees average 140 years, but they are younger higher up, until at 2700 meters they average only 16 years. Infilling since the mid–19th century is visible from British Columbia to Montana. Near Banff National Park in Canada, alpine firs and Engelmann spruces have moved 50 or 60 meters upslope just since 1990, report researchers from the University of Alberta in Edmonton.

However, Körner and others say that timberline movements are not as straightforward as meets the eye, and tying them unequivocally to a single factor such as global warming is misleading. For one, trees grew higher up before the Little Ice Age, a cold period lasting into the early 1800s; some trees may just now be readvancing rather than responding to more recent warming. Fire suppression may also be allowing some forests to advance to higher elevations.

At Montana's Glacier National Park, ecologist Dan Fagre of USGS points out that much new growth is not actual elevational advance; rather, he says, it is infilling of meadows between outlying fingers of conifers, as well as new vigor in small stems once twisted like shrubs and now straightening up. This may presage a real advance, but Fagre contends that increased moisture, not temperature, may be the primary driver.

Temperature and moisture have complex relations in mountains, says Lori Daniels, a dendrochronologist at the University of Colorado, Boulder. In a paper in press at *Ecology*, she shows that high-altitude deciduous trees in Patagonia have advanced since a round of warming starting in the 1970s—but in the hottest years, growth has declined, because it is too dry. "We thought we understood how temperature works, but once you add in other factors it gets more complex," says Daniels.

In any case, where trees do appear, they change everything. For instance, alpine butterflies feed on alpine plants, and once they are crowded out, both disappear. Now it is becoming clear that even a few trees can dangerously fragment habitat, says ecologist Stephen Matter of the University of Cincinnati, Ohio. That's because alpine butterflies need constant sun to warm flight muscles, and shade from even modest fingers of trees dissecting their territory literally knocks them out of the air. In a paper in press at *Ecological Applications*, Matter shows that in some Canadian study sites, more than 90% of migrating *Parnassius smintheus* butterflies en route to nearby meadows die when they hit intervening trees, a mortality rate that could cause domino-effect local extinctions. *P. smintheus* is not yet rare, but close relatives in Europe are already on threatened lists.

Groundhoglike marmots need treeless terrain for a quite different reason—to see predators coming—and they also are disappearing. The endemic Vancouver Island marmot, declining for decades (or maybe centuries) with the apparent advance of trees into high meadows, is now one of the most endangered mammals in the world, with 21 known wild individuals left. Andrew Bryant, chief scientist at the Marmot Recovery Foundation in Nanaimo, British Columbia, blames wolves and cougars that travel up new logging roads cut at lower elevations, then sneak up on marmots using saplings as cover.

A similar decline may be taking place among the endemic Olympic Peninsula marmots of Washington state, where trees, followed by coyotes, are proliferating. However, wildlife biologist Suzanne Griffin of the University of Montana in Missoula cautions that studies there are just starting, so it's too soon to be sure of the culprit.

The case may be clearer for pikas, which are directly, exquisitely sensitive to temperature. Hyped-up body heat helps them survive cold, but apparently they cannot turn it down. In the 1970s, Arizona State's Smith gave a graphic demonstration of this by removing pikas from the cool talus interstices where they hide between daytime foraging expeditions and caging them outside. They died after just a morning in ambient shade temperatures as low as 25.5°C. "They don't have much flexibility," says Smith, who admits he would not do such an experiment now, given heightened awareness of animal rights, never mind declines in pikas.

USGS's Beever, who published a study in the *Journal of Mammalogy* last year, says American pikas have recently winked out at nine of 25 historically known localities, and he points to rising temperatures as the prime suspect. He says heat could kill directly, change the composition of plants the animals eat, or—most likely, in his view—force pikas inside so that they cannot get enough to eat.

Some of the American pika's cousins elsewhere also appear to be in decline. For example, in 1986, a biologist at the Xinjiang Academy of Environmental Protection named Li Wei-Dong described a new species, the Ili pika, in the Tian Shan mountains of northwest China. But when he went back in 2002 and 2003, he saw not a single specimen in 250 kilometers of foot-and-horseback trekking. In a paper submitted to the journal *Oryx*, he blames ongoing warming, possibly compounded by herders and their dogs as they range higher now that glaciers are retreating and lofty pastures are greening up.

In the Yukon, University of Alberta wildlife biologist David Hik documented a 90% decline in collared pikas during the winters of 1999 and 2000, when decades of warming culminated in bizarre midwinter snowmelts, rain, and refreezing. Because pikas stay active all winter under snow, this series of events may have removed insulation even they require, then iced over forage. Alpine ground squirrels collapsed too, their burrows flooded. "Consistent with climate-change models, extreme events like this will happen more and more," says Hik, who has a paper in review at the *Canadian Journal of Zoology*. "These animals are made for extreme conditions, but there are thresholds. Then it starts to look pretty serious for them."

Vulnerable. Marmots, like these from Olympic Peninsula in Washington state, are declining too.

All the same, it's hard to completely rule out other causes for the vanishing pikas. Montana sites that still have pika-friendly weather have also seen extinctions, reports biologist Christine Ray of the University of Colorado, Boulder, who suspects disease. "It's still a mystery," she says.

Alpine aquatic systems are showing changes, too, although not yet declines. Aquatic ecologist David Schindler of the University of Alberta says that in the lower Canadian Rockies, warming summers have so far simply speeded plankton life cycles and made alpine fish grow bigger. "Most people probably think it's good to have bigger fish," says Schindler, but experiments show that cold-water trout die off once temperatures pass a threshold. The same goes for specialized invertebrates such as caddis flies that live in icy glacial melt streams.

Fagre of USGS points out that glacial retreat is by far the most visible result of mountain warming: Two-thirds of the glaciers present in Glacier National Park in 1850 are already gone, and the rest could disappear by 2030. This means, he says, that alpine stream temperatures could soon shoot up and summer flows might cease altogether, wiping out much invertebrate habitat.

A less visible effect is that fast-wasting glaciers are releasing pulses of contaminants such as polychlorinated biphenyls and insecticides. Such contaminants evaporate from soils and waters in industrial lowlands and drift off—until they hit mountains, where they condense in rain or snow and fall back down, says Jules Blais, a geochemist at the University of Ottawa. This long-distance conveyor is harming polar bears and poisoning human breast milk in the Arctic, and it also appears to be working in alpine environments just below glaciers, notes biologist John Elliott of the Canadian Wildlife Service. Sediments in glacially fed high lakes are being found with up to 1000 times more pollutants than those at lower elevations, and fish have developed levels that could threaten bald eagles and other avian predators.

In the short term, not all changes may be bad—at least not in the highest mountains, where there's still room to go up. There, new frontiers are opening in the barren spaces left by the retreat of still-vast glaciers. During the past 5 years, an interdisciplinary team has been following the quick advance of alpine life into newly ice-free zones in the Peruvian Andes near the huge Quelccaya ice cap. At 5250 meters, the team members have counted 54 alpine plant species and 23 species of lichens—"a definite increase" for a place that was near a towering ice front just a century ago, says Anton Seimon, a geographer at Columbia University's Earth Institute.

In newly melted ponds at 5372 meters, the team members have found tadpoles (the world's highest known amphibians) and, on newly exposed ridges, upwardly mobile herds of vicuña, rare cousins of the llama. Indigenous people are close behind, planting crops at ever-loftier elevations. "There's a shortage of arable land. Here, this might be a good thing," says Seimon. Beyond the newly settled biotic zones, craggy glaciated peaks and the vast Quelccaya still roll to the horizons, unconquered by life, except perhaps for microbes beneath the ice. At least for the moment, it is hard to imagine that someday all this could melt away, and the pioneers, like the ice itself, might go to heaven.

–KEVIN KRAJICK

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