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Preview

Pushing Climate Change Science to the Roof of the World

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The National Geographic and Rolex Perpetual Planet Everest Expedition is a multidisciplinary project dedicated to understanding climate change and its impacts, improving climate predictions, and providing a framework for future research in mountain environments. This issue of *One Earth* offers a first look at the science emerging from the expedition.

The Hindu Kush Himalaya (HKH) contains the highest mountains on Earth, including the highest of all (8,848 m [29,029 ft]), and it has three names. In Nepal, they call it Sagarmatha: "Head (sometimes Red Head) of the Earth in the Sky" as named by the Nepalese historian Baburam Acharya. In the Tibet Autonomous Region of China, it is called Qomolungma: "Mother Goddess of the Universe." In the West, it is called Mt. Everest after the Surveyor General of India (1865). Mt. Everest is truly iconic, and as such it might be assumed that basic scientific questions would already be largely answered.

As explored in this issue of *One Earth*, there is still much to learn about Mt. Everest and mountain systems in general.[1] Glacierized mountains store and provide water for >22% of the world's population and 50% of its biodiversity.[2] As a consequence of climate change and human activity in general, these environments have been changing notably in recent decades and will continue to do so in the future. Information that contributes to understanding current and projecting future changes in temperature, precipitation, winds, glacier extent and volume, water availability, air and water quality, species abundance and distribution, and risks associated with climate change, increasing population, and resource utilization is essential to the people and ecosystems affected—250 million in the Himalayas alone—and to the world at large.

The National Geographic and Rolex Perpetual Planet Everest Expedition, hereafter called the 2019 Everest Expedition, was undertaken in April through May during the pre-monsoon season within the elevation range of 3,200–8,430 masl.[3] Figure 1 highlights the wide range of expedition sampling types and their locations in the Khumbu region. Figure 2 highlights the major activities (geology, glaciology, mapping, meteorology, and biology) with interdisciplinary examples and scientific findings as summarized below.

The investigation of past environments provides perspective for assessing modern and predicting future change through analogs. Therefore, the geology team examined past changes in climate as expressed by glacial moraines and deposits from modern and ancient lakes spanning from tens of thousands of years ago to the last hundreds of years. The approach combined high-resolution drone photography, cosmogenic dating of moraines, coring of two high-elevation glacial lakes, and dating of lake deposits. Analysis of ancient lake deposits stranded on valley walls suggests the strong role that landslides have played in shaping the landscape of this region. The first ever lake cores taken in the Gokyo Valley show sediment disturbance and changes in tree species consistent with warming.

The geology team benefitted from partnerships with the mapping team by facilitating the spatial display of analytical results and the connection to local landforms, with the glaciology team in developing records of past change, with the meteorology team in constraining models for past glacier extent, and with the biology team in providing a survey of diatoms and pollen species.

Glaciers contain records of past physical and chemical climate, and as glaciers melt, they release entrapped chemistry derived from both natural and human sources. Therefore, the glaciology team recovered water and snow samples along the access route to Everest Base Camp and up through the climbing route (4,400–8,440 m), from stream samples, and from a 32-day continuous series that included a major storm event (Cyclone Fani) near Everest Base Camp. The team also recovered ice cores from the Khumbu Glacier near Everest Base

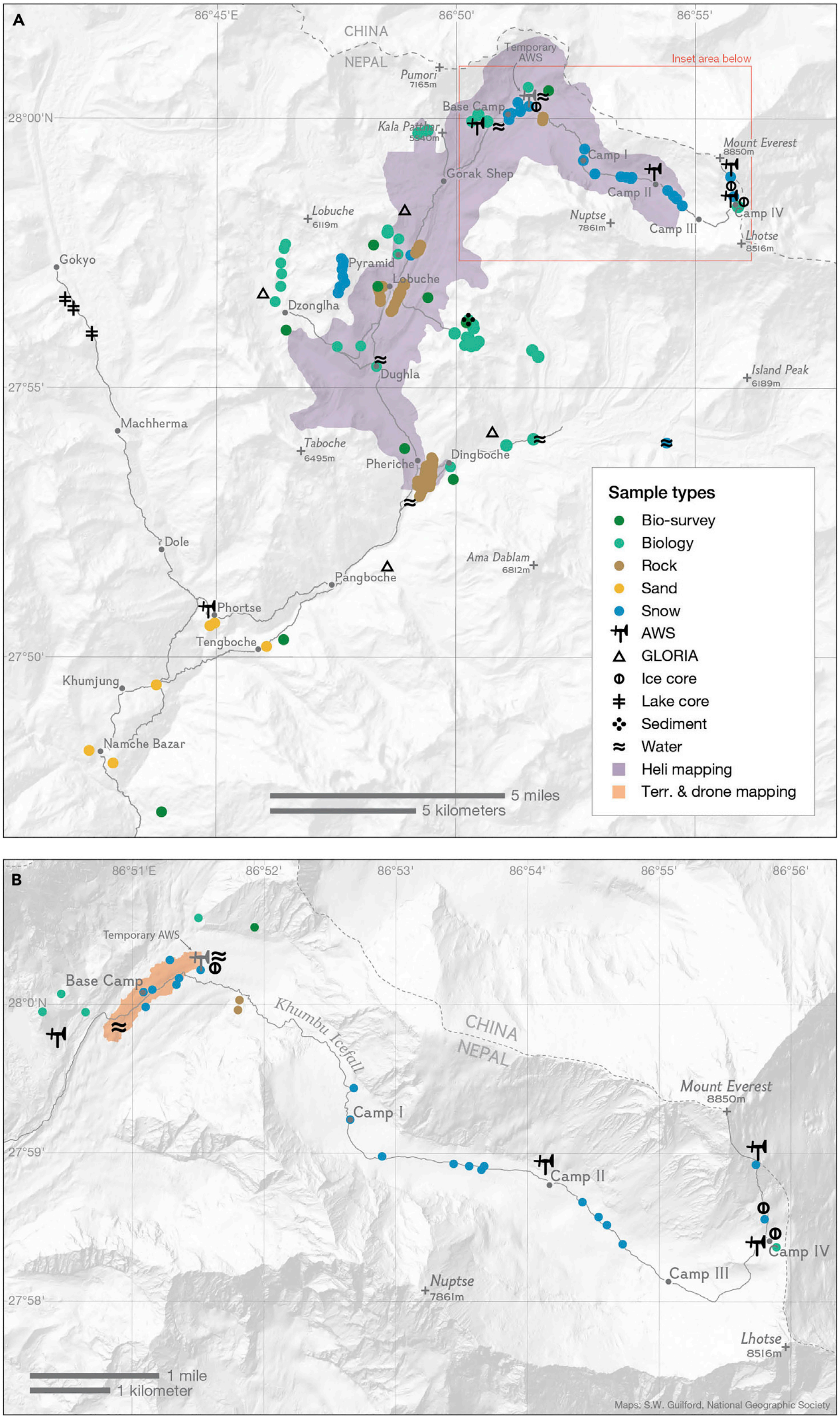

Figure 1. Sampling Locations
Sample types and locations for the full region covered by the 2019 Everest Expedition (A) and the zoomed-in route from Everest Base Camp to the summit (B).

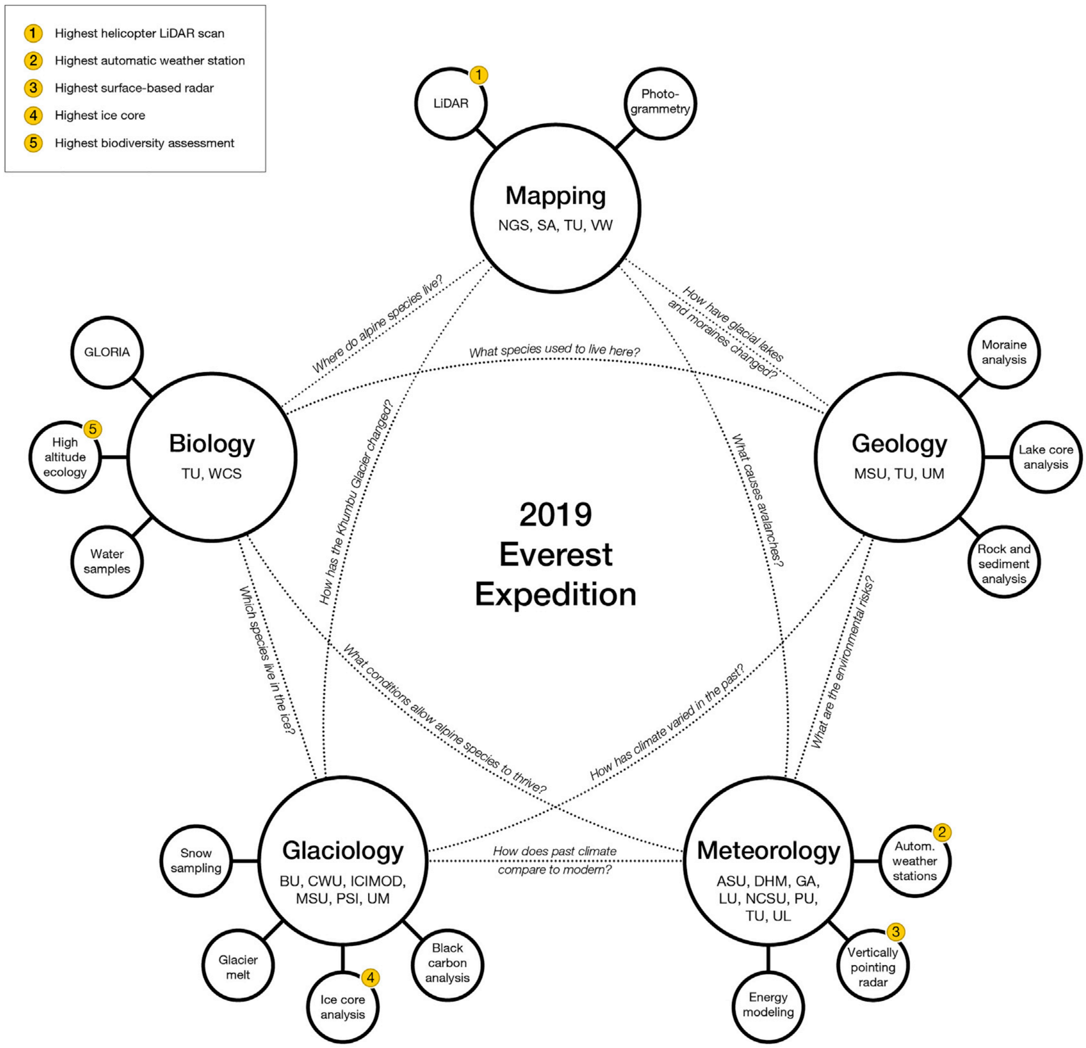

Figure 2. Interdisciplinarity and World Records

2019 Everest Expedition scientific disciplines (with institutions involved in field sampling and/or analyses), sub-disciplines, and interdisciplinary interactions. DHM, Department of Hydrology and Meteorology, Nepal; BU, Brown University, US; CWU, Central Washington University, US; ICIMOD, Nepal; MSU, Montana State University, US; PSI, Paul Scherrer Institute, Switzerland; UM, University of Maine, US; NGS, National Geographic Society, US; WCS, Wildlife Conservation Society, US; VW, Virtual Wonders, US; TU, Tribhuvan University, Nepal; SA, University of St. Andrews, UK; ASU, Appalachian State University, US; LU, Loughborough University, UK; NCSU, North Carolina State University, US; UL, University of Leeds, UK; PU, Purdue University, US; GA, Grenoble-Alpes University, France.

Camp and the highest ice core ever collected at 8,020 m from the South Col of Mt. Everest (recovered by glaciology team member Mariusz Potocki and the Sherpa team).

Sample analysis included 49 major and trace elements, stable isotopes of water, polyfluoroalkyl substances, biological material, plastics, and radiocarbon dating. Both atmospherically deposited and direct-contact humanly deposited pollution was found at several sites along the climbing route and near a village used as a trekking logistics base. It is clear that human activity has left a mark in local snow and ice in the form of toxic metals, plastic fibers,[4] pesticides, plasticizers, and waterproof gear coatings.

The glaciology team is partnering with several universities and all of the 2019 Everest Expedition disciplines to enhance data interpretation by comparing water, snow, and ice results with the meteorology and geology teams to provide past perspective for assessing modern and predicting future climate. Past precipitation, atmospheric circulation, and atmospheric chemistry determined from an ice core recovered at 6,518 m on the north side of Mt. Everest[5] will be used for comparison with the South Col ice-core results for understanding local climate and glacier volume-change gradients. Glacier ablation studies including black carbon and dust sampling will aid in determining past, modern, and future glacier dynamics being modeled by the mapping team. Biological sampling of the ice cores will be compared with modern environment sampling by the biology team.

Maps provide the basis upon which scientific data can be placed for assessing spatial distribution and, in the process, providing a basis for assessing change. The mapping team completed light detection and ranging (LiDAR; optical sensing) and photographic surveys of the Everest Base Camp area (5,300 m) at 1–2 cm resolution and over the full extent of the Khumbu Glacier from the base of the Lhotse face to the toe of the glacier at 5–10 cm resolution. The set of geographic data includes elevation models (from LiDAR point cloud and photogrammetric processing), visible imagery, and infrared imagery. The team produced the highest helicopter LiDAR scanning in the world, the first LiDAR scan of the highest glacier in the world, and the first complete LiDAR and photographic survey of Everest Base Camp.

The mapping team is working closely with the other members of the 2019 Everest Expedition to integrate their data into their high-resolution map products. For example, the geology team is using relief shading and other geomorphological renderings of the lateral and terminal moraines in its analysis of the glacial history of the Khumbu region, and the biology team is using color-infrared imagery from the mapping team to determine distribution as a basis for assessing changes in vegetation. In addition, elevation, glacier surface, and mass balance[6] descriptions and changes feed into analyses by both the meteorology and glaciology teams.

Ground-based weather stations provide calibration for model interpretations of weather and climate and site-specific weather for local forecasting. Therefore, the meteorology team installed five automatic weather stations (AWSs), including the two highest in the world,[7] gathered observations of a snowstorm from the world's highest vertically pointing radar deployment at Everest Base Camp,[8] identified moisture sources for the precipitation arriving in the region,[9] and provided a detailed case study of weather during the 2019 pre-monsoon period (A. Khadka, T.M., L.B.P., et al., unpublished data). Results contribute to an improved understanding of future water availability and the connections between Everest's weather and larger-scale atmospheric circulation.

The first paper emerging from the 2019 Everest Expedition[7] demonstrates that insolation on Everest is intense enough to drive glacier surface melting at elevations above 8,000 m despite air temperatures well below 0°C. Latent heat release from cloud formation is shown to warm the atmosphere at altitudes up to Everest's summit, which helps constrain the vertical temperature and precipitation gradients required for distributed modeling of glacier mass balance. Along with assessing oxygen availability[10] at the summit, another team product found that winds on the upper mountain reflect those in the free atmosphere. This research paves the way for improved forecasting of winds that could be dangerous to climbers.

Providing context for interpreting the world's highest ice core is a key synergy between the meteorology and glaciology teams. Establishing the contemporary climatology is similarly relevant for the biology and geology teams, and the mapping team benefits from AWS data collected during the expedition to correct drone, helicopter, and satellite datasets for atmospheric interference.

High-elevation regions lack the species abundance and distribution data available in most lower reaches of the planet; therefore, the biology team performed environmental DNA analysis of ponds and streams between 4,500 and 5,500 masl. Results demonstrate the diversity of high-alpine organisms, including viruses, bacteria, unicellular organisms, plants, fungi, invertebrates, and vertebrates, as well as differences in community structure both within and among various watersheds. This dataset can be utilized for biomonitoring, species identification, and tracking changes as climate-driven warming, glacier recession, and human influences rapidly reshape this globally important landscape.

The Nepalese botany team established the first long-term vegetation-monitoring plots in the Upper Khumbu as part of the Global Observation Initiative in Alpine Environments (GLORIA) network (https://gloria.ac.at/network/general). These plots will enable researchers to monitor changes in the distribution of plant species, including the introduction or upward expansion of known or invasive species, and changes in plant community structure over time to inform how climate warming is affecting high-alpine plant biodiversity.

Interdisciplinary investigations include the biology team partnering with the mapping team to apply machine learning and artificial intelligence to high-resolution imagery to assess elevation and landscape distribution of plants. The geology team's reconstructions of landscape history will inform characterizations of the individual watersheds where the biology team sampled resident life forms, and the meteorology team will provide descriptions of the bioclimatic envelopes within which species reside. In addition, the eDNA database provides a reference dataset and library of organisms currently residing in the Khumbu above 4,500 m for comparison with fossil pollen, plant and microbial remains in the lake sediment, and ice-core samples obtained during the expedition.

Mountain systems are changing at a rapid rate with significant consequences for humans and ecosystems. Understanding the current and predicting the future state of mountain systems is essential, but collecting the necessary information is non-trivial, particularly from the highest reaches of the planet. The results presented in this issue of *One Earth* and many to follow will allow the 2019 Everest Expedition to leave its legacy for future research in the HKH and worldwide throughout mountainous regions. The expedition's legacy is based on its multi- and interdisciplinary approach and the scientific framework it set in place, which includes (1) high-resolution imagery of the Khumbu Glacier and proximal surroundings for assessing change and as a basis for innovative identification of ground-based features; (2) a suite of automatic weather stations that extend into the upper troposphere, can sense stratospheric incursions, and allow testing of weather models while also improving safety for climbers; (3) biological monitoring networks that provide a basis for assessing plant species' adaptation to climate change; (4) an eDNA reference database that can be used for assessing species distribution or comparing with fossil pollens, diatoms, and plant and microbial remains; (5) a water and snow sampling network for assessing changes in water quality; (6) past climate change perspective based on mapping of ice cores, lake sediments, and surface age exposure; and (7) identification of emerging atmospheric, biological, geological, and health risks on Mt. Everest and the Khumbu Valley.

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AUTHOR CONTRIBUTIONS

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