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Late-glacial and Holocene vegetation and climate variability, including major droughts, in the Sky Lakes region of southeastern New York State

Kirsten M. Menking [a,*], Dorothy M. Peteet [b,c], Roger Y. Anderson [d]

[a] Department of Earth Science and Geography, Vassar College, Box 59, 124 Raymond Ave., Poughkeepsie, NY 12604, United States
[b] NASA/Goddard Institute for Space Studies, 2880 Broadway, NY, NY 10025, United States
[c] Lamont Doherty Earth Observatory, Palisades, NY 10964, United States
[d] Department of Earth and Planetary Sciences, Northrup Hall, University of New Mexico, Albuquerque, NM 87131, United States

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ABSTRACT

Sediment cores from Lakes Minnewaska and Mohonk in the Shawangunk Mountains of southeastern New York were analyzed for pollen, plant macrofossils, macroscopic charcoal, organic carbon content, carbon isotopic composition, carbon/nitrogen ratio, and lithologic changes to determine the vegetation and landscape history of the greater Catskill Mountain region since deglaciation. Pollen stratigraphy generally matches the New England pollen zones identified by Deevey (1939) and Davis (1969), with boreal genera (*Picea*, *Abies*) present during the late Pleistocene yielding to a mixed *Pinus*, *Quercus* and *Tsuga* forest in the early Holocene. Lake Minnewaska sediments record the Younger Dryas and possibly the 8.2 cal kyr BP climatic events in pollen and sediment chemistry along with an ~1400 cal yr interval of wet conditions (increasing *Tsuga* and declining *Quercus*) centered about 6400 cal yr BP. Both Minnewaska and Mohonk reveal a protracted drought interval in the middle Holocene, ~5700–4100 cal yr BP, during which *Pinus rigida* colonized the watershed, lake levels fell, and frequent fires led to enhanced hillslope erosion. Together, the records show at least three wet–dry cycles throughout the Holocene and both similarities and differences to climate records in New England and central New York. Drought intervals raise concerns for water resources in the New York City metropolitan area and may reflect a combination of enhanced La Niña, negative phase NAO, and positive phase PNA climatic patterns and/or northward shifts of storm tracks.

1. Introduction

A network of reservoirs and aqueducts originating in New York State's Catskill Mountains supplies New York City (NYC) with ~1.5 billion gallons of drinking water daily (Blake et al., 2000). Despite the dependence of nearly 10 million people on this supply, little is known of the Holocene drought history of the area. Ibe (1985) and Ibe and Pardi (1985) described pollen spectra from two Catskill sites, noting general responses to Laurentide deglaciation and Holocene insolation changes, but no similar studies have been published for the area.

The Catskill region forms the western boundary of New York's Hudson River Valley and lies between well-studied sites in central New York and New England that show contrasting moisture balance since deglaciation (Fig. 1). In central New York, for example, deposition of marls in Cayuga and Owasco Lakes and adjacent fringing wetlands, as well as a variety of proxies in Lake Ontario, indicate that the early to middle Holocene was a time of warm but wet conditions (Dwyer et al., 1996; Mullins, 1998; McFadden et al., 2005). Cayuga Lake experienced lowstands at 8575, 6830, 4770, and 1955 cal yr BP (7800, 6000, 4200, and 2000 ^{14}C kyr BP), however, all were higher than modern lake level, reflecting overall wetter than modern conditions in the region (Mullins, 1998). In contrast, pollen and lake level evidence from New England (Newby et al., 2000; Shuman et al., 2004) suggests dry climate prior to 8500 cal yr BP, wet conditions from 8500 to 5500 cal yr BP, and widespread drought between 5500 and 3000 cal yr BP, the latter interval likely responsible for the decline of hemlock forests (Miller, 1973; Foster et al., 2006) previously attributed to a pathogen. Post 3000 cal yr BP conditions again became more mesic, with lakes expanding to their highest levels during the Holocene.

Sediment cores and submerged shoreline features from Davis Pond, Massachusetts, reveal even finer-scale variations in lake level in New England superimposed on a general trend toward wetter conditions throughout the Holocene (Newby et al., 2011). Notable lowstands occurred from 13.4 to 10.9 cal kyr BP, at 9.2 and 8.2 cal kyr BP, and from 5.6 to 4.9 cal kyr BP, >3.5 cal kyr BP, 3.0–2.3 cal kyr BP, and 1.6–0.6 cal kyr BP. Several of these lowstands appear to correlate to dry climate cycles recorded in sediment magnetic parameters at White Lake, New Jersey (~6100, 4400, 3000, and 1300 cal yr BP; Li et al., 2007).

* Corresponding author. Tel.: +1 845 437 5545; fax: +1 845 437 7577.
E-mail addresses: kimenking@vassar.edu (K.M. Menking), Peteet@ldeo.columbia.edu (D.M. Peteet), ryand@unm.edu (R.Y. Anderson).

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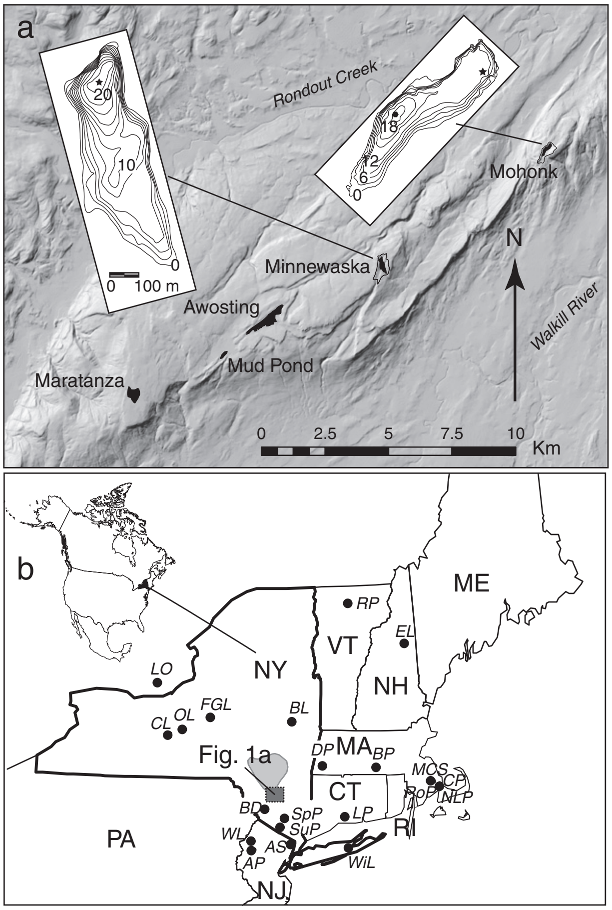

Fig. 1. Study area. a) Shaded relief map of the Shawangunk Mountains showing the five Sky Lakes, the drainage basins of lakes Minnewaska and Mohonk (black line around each lake), and bathymetric maps of lakes Minnewaska and Mohonk. Depth contours on bathymetric maps are shown in meters. Contour interval for Minnewaska is 2 m and for Mohonk is 3 m. Stars mark the locations where Livingstone cores were taken. Circle denotes an additional Glew core that captured the sediment/water interface. Foothills of the Catskill Mountains are in the northwestern corner of the map. b) Global and regional setting. State labels are as follows: NY = New York, PA = Pennsylvania, NJ = New Jersey, CT = Connecticut, RI = Rhode Island, MA = Massachusetts, VT = Vermont, NH = New Hampshire, and ME = Maine. Black dots show the locations of comparison sites referenced in the text: LO = Lake Ontario, CL = Cayuga Lake, OL = Owasco Lake, FGL = Fayetteville-Green Lake, BL = Ballston Lake, BD = the "black dirt" region, SuP = Sutherland Pond, SpP = Spruce Pond, AS = Alpine Swamp, WL = White Lake, AP = Allamuchy Pond, WiL = Wildwood Lake, LP = Linsley Pond, DP = Davis Pond, BP = Blood Pond, RP = Ritterbush Pond, EL = Echo Lake, MCS = Makepeace Cedar Swamp, CP = Crooked Pond, NLP = New Long Pond, RoP = Rocky Pond. New Long Pond and Rocky Pond are so close to Makepeace Cedar Swamp and Crooked Pond that we have not shown individual symbols for their locations. Location of Fig. 1a is shown in dashed dark gray box.
Catskill Mountain region shown in lighter gray shaded region adjacent to the study area, boundary taken from Ibe (1985).

The spatial and temporal variability of climate exhibited in the northeastern United States during the Holocene, along with the importance of the Catskill region for New York City's water supply, argues for additional documentation of the paleoecology and paleoclimate of the area. Here we report on a multi-proxy climate record that spans the period of deglaciation through the late Holocene obtained from sediment cores in two lakes (Minnewaska and Mohonk) in the Shawangunk Mountains of southeastern New York, a range immediately adjacent to the Catskill Mountains with an exceptionally detailed and long phenological record correlated to climate (Cook et al., 2008). Questions addressed in our study include whether the early to middle Holocene interval showed wetter or drier than modern conditions, whether drought intervals resemble those in New England or central New York, and whether a climatic driver led to mid-Holocene *Tsuga* decline as proposed for western New York (Miller, 1973) and New England (Foster et al., 2006).

2. Study area

Lakes Minnewaska and Mohonk lie atop the Shawangunk Mountains in southeastern New York, ridges of Silurian-age quartz pebble conglomerate and quartz sandstone (Shawangunk Formation, 99% quartz) that overlie Ordovician-age calcareous shales (Martinsburg Formation) (Fig. 1; Macchiaroli, 1995; Bernet et al., 2007). Bedrock occurs either at the surface or within 30 cm of the surface over more than 70% of the range, reflecting glacial stripping and extremely slow rates of soil formation (Coates et al., 1994; Laing, 1994). During the late Pleistocene, ice from the Hudson-Champlain lobe of the Laurentide ice sheet covered the mountains to a depth >600 m (Coates et al., 1994). Glacial plucking of tectonically fractured bedrock produced five lake basins trending in a NE–SW direction along the ridge crest, collectively known as the "Sky Lakes" (Fig. 1). Steep bedrock walls and small drainage areas surround each lake. Water chemistry reflects the depth of glacial plucking: Lakes Awosting, Maratanza, and Mud Pond lie entirely within the Shawangunk formation and are acidic, whereas Mohonk Lake bottoms in the Martinsburg Formation and has neutral pH (Schiff, 1986; Friedman et al., 1989). Lake Minnewaska lies near a small structural inlier of the shale in the conglomerate, and shows a pH higher than the three southern lakes but more acidic than Mohonk Lake.

Reflecting their ridge top positions, neither Mohonk (380 m elevation, 7.4 ha, 27% of catchment area) nor Minnewaska (500 m elevation, 11.5 ha, 28% of catchment area) has a perennial inflow stream, thus both are fed primarily by direct precipitation supplemented by groundwater flow introduced through fractures and by sheet wash from surrounding rock walls (Schiff, 1986; Coates et al., 1994). Two very short (30–50 m long) and low flow (<10% of total inflow) ephemeral streams originating in springs around the southern margin of Mohonk Lake provide runoff during the spring snowmelt season (Herczeg, 1985; Schiff, 1986). Lake Minnewaska overflows at its southern end through a natural outlet and also leaks water to bedrock fractures along its southern and northwestern margins (Friedman et al., 1989). Mohonk Lake presently drains to the north through an outlet controlled by the Mohonk Mountain House resort, but would also have drained northward through bedrock fractures prior to development (Herczeg, 1985; Schiff, 1986; J. Thompson, personal communication). Water residence time in Mohonk Lake was determined to be approximately 4.5 years (Herczeg and Fairbanks, 1987). No similar study has been done for Minnewaska, but given its volume ($1.064*10^9$ L; Coates et al., 1994) and the rate of flow in its outlet stream (10–37 L/s in summer baseflow measured ~3.5 km downstream of the lake; C. O'Reilly, personal communication), residence time is unlikely to be greater than a decade or two.

The lack of inflow streams means that sedimentation rates are low and that deposition is dominated by organic materials falling or blowing into the lakes from the surrounding cliffs or produced within the lakes by primary production. The drainage area of Lake Minnewaska presently contains chestnut oak forest with lesser amounts of hemlock-northern hardwood forest (Thompson, 1996) growing upon very thin soils developed in low permeability glacial till or high permeability glaciofluvial sediments (Coates et al., 1994). The vegetation surrounding Mohonk Lake consists primarily of hemlock-northern hardwood forest, with small amounts of chestnut oak and other deciduous forest (Thompson, 1996). These botanical communities, along with adjacent pitch pine barrens, Appalachian oak-hickory forest, and beech-maple mesic forest support the highest biological diversity in New York State and contribute to the Shawangunk ridge being designated by the Nature Conservancy as one of the "Last Great Places" on earth (Thompson and Huth, 2011). In the lakes, aquatic producers include cyanobacteria, diatoms, chrysophaceae, and chlorophyceae (Hellerman, 1965; Herczeg, 1985).

Staff at Mohonk Preserve, a private non-profit land conservancy surrounding Mohonk Lake, operate the Mohonk Lake Cooperative Weather Station, which is part of the National Oceanographic and Atmospheric Administration network. A remarkable and unique set of weather records have been collected daily for 114 years by a limited