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Solar and atmospheric forcing on mountain lakes

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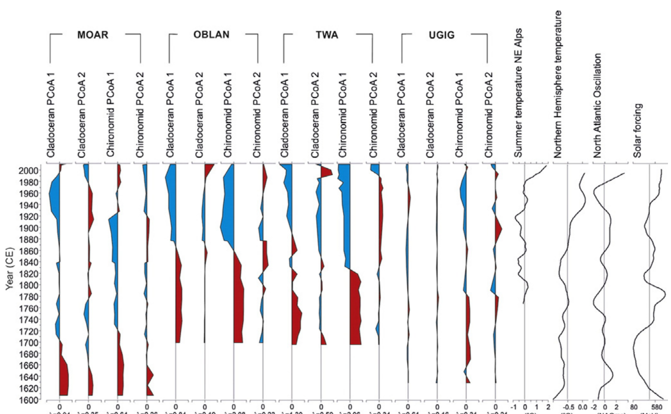
HIGHLIGHTS

- Influence of long-term external forcing on Alpine lakes was examined.
- Summer temperature variability affected aquatic communities in all study sites.
- North Atlantic Oscillation and solar forcing were significant in some of the lakes.
- External forcing plays an important role in through their impacts on limnology.
- These findings are important for climate change impact assessments in freshwaters.

GRAPHICAL ABSTRACT



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ABSTRACT

We investigated the influence of long-term external forcing on aquatic communities in Alpine lakes. Fossil microcrustacean (Cladocera) and macrobenthos (Chironomidae) community variability in four Austrian high-altitude lakes, determined as ultra-sensitive to climate change, were compared against records of air temperature, North Atlantic Oscillation (NAO) and solar forcing over the past ~400 years. Summer temperature variability affected both aquatic invertebrate groups in all study sites. The influence of NAO and solar forcing on aquatic invertebrates was also significant in the lakes except in the less transparent lake known to have remained uniformly cold during the past centuries due to summertime snowmelt input. The results suggest that external forcing plays an important role in these pristine ecosystems through their impacts on limnology of the lakes. Not only does the air temperature variability influence the communities but also larger-scale external factors related to atmospheric circulation patterns and solar activity cause long-term changes in high-altitude aquatic ecosystems, through their connections to hydroclimatic conditions and light environment. These findings are important in the assessment of climate change impacts on aquatic ecosystems and in greater understanding of the consequences of external forcing on lake ontogeny.

1. Introduction

Lake ecological states and services are compromised by multiple local human activities they host, and by the complex effects of climate change (Perga et al., 2015). Lakes are effective sentinels for climate

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change because they are sensitive to climatic variability, respond rapidly to change, and integrate information about changes in the catchment (Adrian et al., 2009). However, the response to environmental changes is lake-specific and varies from one taxonomic group to another (Catalan et al., 2009). In addition to the human contribution for the recent changes in climate, there persists concurrent natural variability. Some of the most important natural factors are year-to-year variations in the weather, which follow a quasi-cycling pattern. In European lakes, decadal changes have been observed that are largely associated with atmospheric circulation patterns across the North Atlantic (Dokulil and Teubner, 2003). According to a study from the European Alps, there exists a pattern of spatial coherency in lake surface temperatures with respect to regional air temperature and the North Atlantic Oscillation (NAO) over the past decades (Livingstone and Dokulil, 2001). These patterns affect mixing conditions, thermal stability and the replenishment of oxygen to deep waters and result in accumulation of nutrients, subsequently altering the trophic status and the food web (Dokulil et al., 2006). The ecological responses to the NAO include changes in timing of reproduction, population dynamics, abundance, spatial distribution and interspecific relationships, such as competition and predator-prey relationships (Ottersen et al., 2001). However, there is little evidence on the associations between external forcing and lake ecosystem status from time periods prior to the human induced climate change, although there are implications for the impact of North Atlantic circulation modes on climate conditions in the Alps during the late Glacial (Schmidt et al., 2012).

Interactions between climate impacts, such as changes in ice cover and solar irradiance renders sensitive ecosystems acutely vulnerable to abrupt ecosystem change (Clark et al., 2013). Seasonally ice-covered lake ecosystems receive direct sunlight for only a portion of the year that limit the growing season. Hence in general, primary producers obtain their annual light budget during summer. Light attenuation in lakes is also controlled by dissolved carbon concentrations (Rantala et al., 2015) and, for example in high-altitude lakes, by phytoplankton ultraviolet (UV) absorption (Laurion et al., 2000). In addition to the effects from changes in timing of the ice-covered period, UV radiation exposure of transparent lakes is affected by the direct solar intensity during the open water season.

Paleolimnological methods based on lake sediment archives provide means to observe ecological changes beyond monitoring periods and to reconstruct past environmental conditions (Smol, 2008). Microcrustaceans and macrobenthos, which are keystone components of aquatic ecosystems (Wallace and Webster, 1996; Jeziorski et al., 2008), are well represented in the sedimentary community assemblages through preservation of fossil Cladocera (Crustacea: Branchiopoda) body parts and Chironomidae (Insecta: Diptera) head capsules. Both cladocerans and chironomids are sensitive indicators of climate change since their distribution patterns and life cycles are strongly linked with prevailing temperature conditions (Eggermont and Heiri, 2012; Nazarova et al., 2015; Metzke and Pederson, 2012).

In this study, we investigate the long-term response of aquatic invertebrate communities to external forcing in carefully selected study sites in the Alps. The four study sites have previously been judged to be ultra-sensitive to climate change (Thompson et al., 2005) due to their specific catchment features (such as differences in shading, snow cover and groundwater) that make them particularly vulnerable through changes in solar attenuation, hydrological conditions and stratification. Because of their ultra-sensitive nature, the study sites were deemed suitable for our objectives. We use previously available Cladocera and chironomid assemblage data from biostratigraphies that cover the past ~400 years, hence, including the distinct climate periods from the cold Little Ice Age (LIA) to the present climate warming. We test the primary and secondary community variance against variables of external forcing, including summer air temperature changes, the NAO pattern and solar modulation. With this novel study, we aim to increase the understanding on external forcing on lake ecosystems at a long time scale that is essential for better predictions of the future patterns in aquatic environments in connection with the ongoing global change.

2. Material and methods

Fossil assemblages of microcrustaceans (Cladocera) and macrobenthos (Chironomidae) from short sediment cores (17–25 cm) of four Austrian alpine lakes; Moaralmsee (MOAR; Luoto and Nevalainen, 2012), Oberer Landschitzsee (OBLAN; Nevalainen and Luoto, 2012), Twenger Almsee (TWA; Luoto and Nevalainen, 2013a) and Unterer Giglachsee (UGIG; Luoto and Nevalainen, 2013b) were used in the present study. The sediment profiles, including the chronologies (Suppl. 1) and biostratigraphies, are described in the original publications that focus on describing community variability and associated limnoecological changes during the past ~400 years. The oligotrophic and circum-neutral lakes vary in size, depth, and water temperature (Table 1). All the lakes are located above the present treeline (<1800 m a.s.l.) at the Niedere Tauern Alps (Fig. 1) that makes them less influenced to human activities, such as alpine pasturing. The lakes were selected according to their potential sensitivity to climate change, the water temperatures of the sites being either warmer or colder compared to other lakes at the same altitude (Thompson et al., 2005).

MOAR is the smallest and shallowest lake and is less transparent (higher DOC and cholorophyll-a concentrations) than the other lakes. Although MOAR is located at the lowest altitude of the study sites, it has the coldest water temperature due to summertime input of cold melt water from the catchment (Thompson et al., 2005) making its summer water temperature 6–7 °C cooler compared to other lakes in the region at the same altitude. OBLAN is the most acidic and nutrient-poor lake, whereas the largest lake, UGIG, is the most alkaline and has slightly elevated nutrient level compared to the other sites. TWA is located at the highest elevation and although it is small in size, it is clearly the deepest of the lakes.

The general annual Northern Hemisphere temperature data, reconstructed (tree-ring based) and instrumentally observed by D'Arrigo et al. (2006), were applied to describe climate variability during the time coverage of the sediment cores. In addition, the instrumental data by Auer et al. (2007) were used for illustrating alpine summer (June to August) temperature variability. Only the Northern Hemisphere temperature data was used in the statistical analyses due to its better fit with the sediment chronologies. The temperature data were obtained through the National Oceanic and Atmospheric Administration (NOAA) (www.ncdc.noaa.gov/paleo/paleo.html) and HISTALP (historical instrumental climatological surface time series of the greater Alpine region) (www.zamg.ac.at/histalp/) websites. Due to their sensitivity to North Atlantic climate variability (Baker et al., 2015), a winter (December, January, February) NAO reconstruction based on a speleothem precipitation

Table 1
Location and environmental characteristics of the four study lakes located in the Niedere Tauern region of the central Austrian Alps. MOAR = Moaralmsee, OBLAN = Oberer Landschitzsee, TWA = Twenger Almsee, UGIG = Unterer Giglachsee.

	MOAR	OBLAN	TWA	UGIG
Latitude (N)	47°21′28″	47°14′49″	47°13′13″	47°14′00″
Longitude (E)	13°47′32″	13°51′33″	13°36′05″	13°39′00″
Altitude (m a.s.l.)	1825	2067	2118	1922
Surface area (ha)	2.13	8.8	3.11	16.8
Water depth (m)	5.9	13.6	33.6	18.0
pH	7.0	6.3	7.3	7.5
Specific conductivity (μS)	29	14.5	69	73
Total phosphorus (μg l^{-1})	3.7	2.5	3.3	4.5
NO_3 (μg l^{-1})	182	64	7	20
Dissolved organic carbon (μg l^{-1})	1142	623	649	601
Ca^{2+} (μeq l^{-1})	224	104	431	533
Chlorophyll-a (μg l^{-1})	9.1	0.7	0.4	1.4
T_{WATER} August (°C)	8.2	12.8	11.6	14.0
Length of sediment core (cm)	25	17	17	19
Estimated time span (years)	~400	~300	~300	~400