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Orbital and solar forcing of shifts in Mid- to Late Holocene flood intensity from varved sediments of pre-alpine Lake Ammersee (southern Germany)

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A B S T R A C T

Microfacies analyses and X-ray fluorescence scanning (μ-XRF) at sub-mm resolution were conducted on the varved Mid- to Late Holocene interval of two sediment profiles from pre-alpine Lake Ammersee (southern Germany). The coring sites are located in a proximal ($AS10_{prox}$) and distal ($AS10_{dist}$) position towards the main tributary River Ammer, in 1.8 km distance from each other. To shed light on sediment distribution within the lake, particular emphasis was (1) the detection of intercalated detrital layers and their micro-sedimentological features, and (2) intra-basin correlation of these event deposits. Detrital layers were dated by microscopic varve counting, verified by accelerator mass spectrometry ^{14}C dating of terrestrial plant macrofossils.

Since ~5500 varve years (vyr) BP, in total 1573 detrital layers were detected in either one or both of the investigated sediment profiles. Based on their microfacies, geochemistry, and proximal-distal deposition pattern, detrital layers were interpreted as River Ammer flood deposits. Earlier studies on flood layer seasonality have proven that flood layer deposition occurs predominantly during spring and summer, the flood season at Lake Ammersee. Most prominent features of the record are the onset of regular flood layer deposition at ~5500 vyr BP in $AS10_{prox}$ and ~2800 vyr BP in $AS10_{dist}$ as well as three major increases in mean flood layer thickness at ~5500, 2800, and 400 vyr BP. Integrating information from both sediment profiles allowed to interpret these changes in terms of shifts towards higher mean flood intensity. Proposed triggering mechanisms are gradual reduction in Northern Hemisphere orbital summer forcing and superimposed centennial-scale solar activity minima. Likely responses to this forcing are enhanced equator-to-pole temperature gradients and changes in synoptic-scale atmospheric circulation. The consequences for the Ammersee region are more intense cyclones leading to extremer rainfall and flood events in spring and summer.

1. Introduction

Main driver of floods are hydrometeorological extremes and understanding past changes in frequency and intensity of these events on short and long time-scales and on a regional basis is crucial for anticipating the evolution of floods in response to climate change. To date, however, this understanding is limited due to the scarcity of hydrological data in space and time (IPCC, 2012). Allowing to reduce these limitations, natural climate archives like lake sediments provide flood time-series beyond the range of instrumental and historical records (e.g. Siegenthaler and Sturm, 1991; Thorndycraft et al., 1998; Noren et al., 2002; Chapron et al., 2005; Moreno et al., 2008; Gilli et al., 2013). During river floods, detrital catchment material is eroded and transported in suspension by fluid turbulence into downstream lakes. In the water body the transport capacity of the inflowing turbidity stream successively diminishes leading to the deposition of characteristic detrital layers on the lake floor (Sturm and Matter, 1978; Schiefer et al., 2011).

Annually laminated (varved) lake sediments allow to reduce the commonly decadal-scale resolution of non-varved lake records to the season enabling to date detrital layers by varve counting and the microstratigraphic position within an annual sedimentation cycle (Mangili et al., 2005; Czymzik et al., 2010; Swierczynski et al., 2012). The seasonal resolution facilitates to directly calibrate the detrital layer time-series using instrumental runoff data and to

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distinguish intra-annually varying flood triggering atmospheric circulation pattern (Czymzik et al., 2010).

However, interpreting the succession of detrital layers on the lake floor in terms of extreme environmental events requires a mechanistic understanding of the depositional processes. In addition to (1) calibrating the detrital layer stratigraphy using instrumental runoff data (Czymzik et al., 2010; Kämpf et al., 2012a), (2) monitoring individual turbidity currents in lakes and streams using current meters and turbidity sensors (Lambert et al., 1976; Gilbert and Crookshanks, 2009), and (3) inferring turbidity flow characteristics from model experiments (Lamb and Mohrig, 2009), the dynamics behind detrital layer deposition can be deduced from the micro-sedimentological features (microfacies) of the deposits themselves (Middleton, 1993; Mangili et al., 2005). Intra-basin correlation of complementary flood layers in two sediment profiles located on a proximal-distal transect towards the main tributary river of a lake enables interpretation of detrital layer microfacies and thickness with respect to transport processes in the basin and sediment source (Mangili et al., 2005; Wirth et al., 2011; Kämpf et al., 2012b).

Lake Ammersee in the pre-alpine region of southern Germany is an ideal location to build up a long time-series of flood-triggered sedimentation. Previous studies on $\delta^{18}O$ from ostracods have proven the sediment column as a reliable paleoclimate archive enabling high-resolution temperature reconstruction (von Grafenstein et al., 1996, 1999). Extensive flysch, molasse, and late moraine formations in the meso-scale catchment provide abundant fine-grained detrital material for downstream transport into the gully shaped lake by only one main tributary, River Ammer (Fig. 1). High water tables in the northern catchment and limited storage capacities of the alpine soils favor the translation of precipitation extremes into floods through saturation excess overland flow (Ludwig et al., 2003). Annual layering of the sediments enables both accurate detection and precise dating of detrital microfacies (Czymzik et al., 2010). Calibration studies on two short sediment cores from Lake Ammersee using instrumental River Ammer runoff data verified the succession of detrital layers as an archive of major flood events in spring and summer, the main flood season at Lake Ammersee (Czymzik et al., 2010). To exploit this potential also for longer time-scales, two new long sediment profiles have been retrieved from Lake Ammersee located on a proximal-distal transect towards the Ammer river mouth in order to establish a detailed Mid- to Late Holocene flood layer calendar and to examine changes in flood-triggered sedimentation in response to climate forcing.

2. Study site

Lake Ammersee is a hardwater lake in the pre-alpine region of southern Germany (48°00′N, 11°07′E) located 20 km southwest of Munich, at an elevation of 533 m (Fig. 1). The present day lake has a maximum water depth of 81 m and a surface area of 47 km^2. The North-South orientated basin was eroded into Cenozoic sediments by the Ammersee lobe of the Isar-Loisach glacier (Alefs, 1997).

The headwater of the lake's main tributary is in the southwestern Ammergau Alps. Due to the karstic geology of the region, the river drains into a subterranean channel system to reach the surface again some hundred meters downstream – from there on named River Ammer. After leaving the Calcareous Alps in a northward direction the 84 km long stream with a catchment of 709 km^2 flows through gently shaped flysch, molasse, and late moraine formations (Fig. 1) (Mangelsdorf and Zelinka, 1973). The river inflow into the lake was displaced by about 1 km to the Southeast during River Ammer channelization between AD 1920 and 1924 (Czymzik et al., 2010).

Today, hydroclimate in the Ammer catchment is influenced by both maritime North Atlantic weather characterized by frequent westerly cyclonic disturbances transporting moisture from the North Atlantic into Europe and atmospheric blocking by continental high-pressure regimes favoring dryer conditions (Petrow and Merz, 2009). Mean annual precipitation is approx. 1200 mm/year. Major River Ammer floods are triggered by precipitation maxima from late spring to summer (Fig. 2) induced through synoptic-scale extratropical cyclones (Czymzik et al., 2010).

3. Methods

3.1. Sediment coring and continuous varve profiles

At two locations in the deepest part of Lake Ammersee (Fig. 1), overlapping sediment cores consisting of 2 m segments were retrieved in July 2010 at a distance of a few meters using a modified UWITEC piston corer (Fig. 3). Sediment profile $AS10_{prox}$ (overlapping core series C and D) is located at a more proximal (4.4 km) and sediment profile $AS10_{dist}$ (overlapping core series A and B) at a more distal position (6.2 km) towards the Ammer river mouth. Maximum sediment depth is 9.8 m for the proximal and 12.5 m for the distal coring location (Fig. 3). Retrieving overlapping sediment profiles at one coring location allows to construct continuous composite profiles by bridging two consecutive segments from one core with a segment from the parallel core.

Composite profiles $AS10_{prox}$ and $AS10_{dist}$ were constructed by visual correlation in the overlapping parts of parallel core segments (Fig. 4). A stratigraphical framework between both composite profiles was established by intra-basin correlation of 107 macroscopic detrital layers of >1 mm thickness (Fig. 4). These lithological markers provide on average every 50 years an isochronous correlation horizon.

3.2. Microfacies analyses

Detailed microfacies analyses of varve and detrital layer properties were performed on two overlapping (Fig. 4) series of large-scale petrographic thin-sections from composite profiles $AS10_{prox}$ and $AS10_{dist}$. Microscopic investigations were carried out applying a ZEISS Axiolab polarization microscope at 12.5× to 500× magnification under various light and optical conditions. Thickness measurements were performed at 25× magnification. Preparation of thin-sections from soft and wet sediment blocks followed a standard procedure minimizing process-induced disturbances of sediment micro-structures and includes shock-freezing with liquid nitrogen, freeze-drying for 48 h, and epoxy resin impregnation under vacuum (Brauer and Casanova, 2001). Criterion for defining a flood layer was lateral continuity over the entire thin-section.

3.3. Chronology

The age model for the Lake Ammersee detrital layer record was produced by one investigator (1) at seasonal resolution by two independent and continuous varve counts and determination of the microstratigraphic position of detrital layers within a varve down to 175 cm in composite profile $AS10_{prox}$ and down to 142 cm in composite profile $AS10_{dist}$ and (2) at annual resolution by construction of a varve-based sedimentation rate chronology for the interval from 175–690 cm in $AS10_{prox}$ and 142–357 cm in $AS10_{dist}$. For the latter, in sediment sections with poor varve preservation sedimentation rates were calculated using varve thickness measurements in neighboring sections, excluding detrital layers. Detrital layers in the sediment interval from 357–567 cm in $AS10_{dist}$ were dated by transferring ages of correlating