Ice formation at Lake Neusiedl since 1931 and large-scale oscillation patterns

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CONCLUSIONS

- **Although ice cover at Lake Neusiedl showed a high interannual variability, significant trends for later timing of ice-on (+2.6 d per decade) and earlier timing of ice-off (-2.0 d per decade) could be found, resulting in fewer days with ice cover per winter.**
- **Ice formation was closely related to mean seasonal air temperatures.**
- **Sensitivity of ice-duration and ice-off increased with rising temperatures.**
- **The large scale oscillation patterns with the most distinct relationships to ice cover at Lake Neusiedl were the East Atlantic pattern, the Mediterranean Oscillation and the North Atlantic Oscillation.**

INTRODUCTION

Ice formation at Lake Neusiedl (Neusiedler See, Fertő tó) (Fig.1), a shallow steppe lake (area 320 km^2, mean depth 1.2 m) at the border of Austria/Hungary, is of ecological and economic importance. Ice sailing and skating help to keep a touristic off-season alive. Reed harvest to maintain the ecological function of the reed belt (178 km^2) is facilitated when lake surface is frozen.

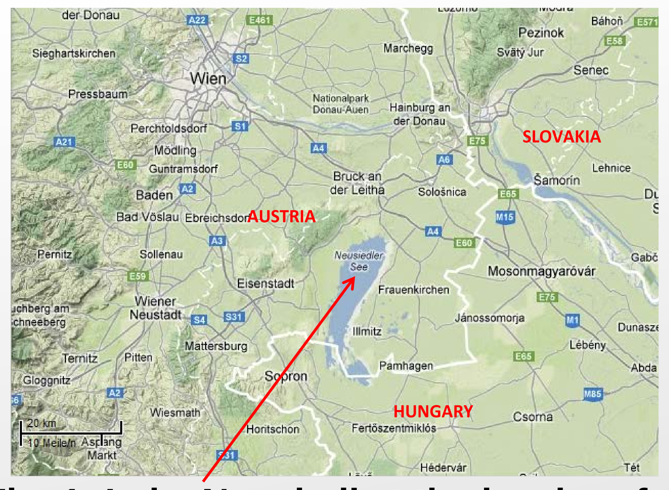

Fig. 1: Lake Neusiedl at the border of Austria/Hungary (Google ©2012)

MATERIAL & METHODS

Changes in ice formation were analysed in the frame of the EULAKES-project (European Lakes under Environmental Stressors, www.eulakes.eu), financed by the Central Europe Programme of the EU. Ice data records (dates of beginning of complete freezing and of starting of melting of the lake ice) of Lake Neusiedl (hydrographic service of the provincial government of Burgenland) and air temperature (nearby monitoring station Eisenstadt - Sopron (HISTALP database[1] and ZAMG[2])) were used to investigate the period 1931-2012 (13% uncompleteness of old ice data records). Additionally the influences of 8 teleconnection patterns[3] , i.e. the Atlantic Multidecadal Oscillation, the East Atlantic pattern (EAP), the East Atlantic/West Russia pattern (EA/WR), the Eastern Mediterranean Pattern (EMP), the Mediterranean Oscillation (MO) for Algiers and Cairo, and for Gibraltar and Israel, resp., the North Atlantic Oscillation (NAO) and the Scandinavia pattern (SCA) were assessed.

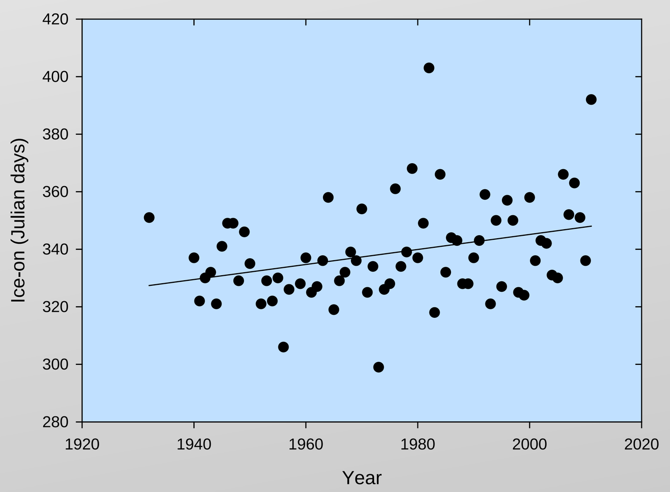

Fig. 2: Ice-on (in Julian days) at Lake Neusiedl for the period 1931 to 2012

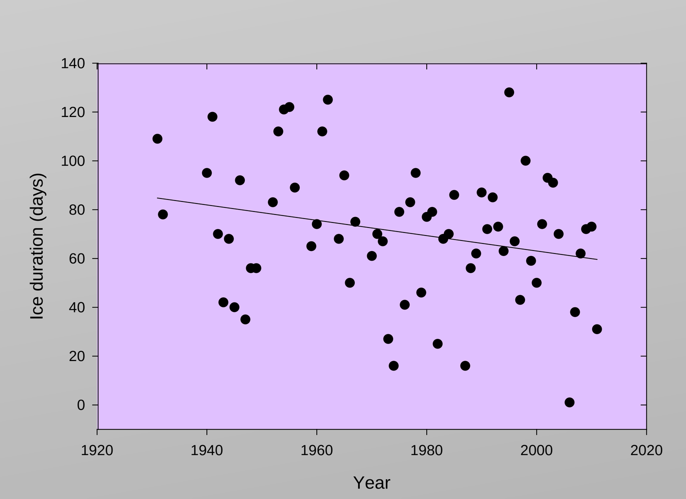

Fig. 3: Ice duration (in days) at Lake Neusiedl for the period 1931 to 2012

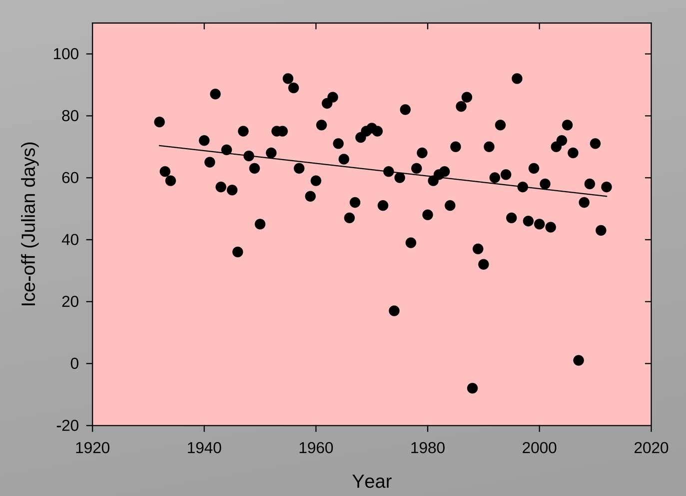

Fig. 4: Ice-off (in Julian days) at Lake Neusiedl for the period 1932 to 2012

RESULTS & DISCUSSION

Ice cover of Lake Neusiedl shows a high variability between the years (mean duration 73±28 days, maximum 128 days (1995/96), minimum 0 days (2006/7). However significant trends ($p<0.05$) could be found for the parameters ice-on, ice-off and ice duration (Table 1). The onset of full ice cover started gradually later (+2.6 days per decade) over the period 1931-2011 (Fig. 2). As melting started earlier over the years (-2.0 days per decade) (Fig. 4), duration of ice cover diminished also (approx. 3 days per decade) (Fig. 3). The values derived for Lake Neusiedl are well above the mean of trends in Northern Hemisphere lakes and rivers (approx. +6 days, -6 days, 12 days for 100 years).[4] All trends could be confirmed by the Neumann test as significant.

Close relationships between ice formation and corresponding mean seasonal air temperatures could be observed (Table 1 and 2). 54% of the variance of ice duration could be explained by winter air temperature. Increases of air temperature by 1°C caused an 8.8 day later timing of ice-on, a decrease of ice duration by 11 days and a 5.8 days earlier ice-off. As Livingstone et al. (2010)[5] described it for Sweden and ice-off – the sensitivity of ice duration and ice-off to rising air temperatures is increasing at Lake Neusiedl: for the period 1991-2012 the decrease of ice-duration per 1°C was 13.6 days instead of 10.9 days for the period 1931-1990, ice-off started 8.2 days earlier per 1°C for 1991-2011, instead of 5.3 days for 1931-1990. This effect of warming could not be verified for the timing of ice-on.

The teleconnections with the most distinct relationships to ice formation at Lake Neusiedl were EAP, MO for Algiers and Cairo, and NAO (Table 3). The positive phase of the EAP is associated with above-average surface temperatures in Europe in all months[3] and was effective in retarding ice-on. Higher EAP-winter-indices caused shorter ice-duration and earlier ice-off at Lake Neusiedl.

Negative correlations of winter EAP, MOA and NAO indices with ice cover duration and ice-off were well pronounced. MOA and NAO winter indices show high cross-correlation (R=0.54), but are not related significantly to EAP. Dokulil & Herzig (2009)[6] also found negative correlations of NAO and MO with ice duration and timing of ice-off for 40 years records of ice data from Lake Neusiedl.

1 HISTALP: http://www.zamg.ac.at/histalp/content/view/35/1/index.html
2 ZAMG: http://www.zamg.ac.at/klima/jahrbuch/
3 AMO: http://www.esrl.noaa.gov/psd/data/timeseries/AMO/; EAP, EA/WR, NAO, SCA: http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml;
EMP: http://www.limno.eu/archives/emp/ ; MO: http://www.cru.uea.ac.uk/cru/data/moi/
4 Magnuson, J.J. et al.: Historical trends in lake and river ice cover in the Northern Hemisphere. Science 289, 1743-1746, 2000
5 Livingstone et al.: Lake Ice Phenology. p.51-61, in: George, D.G. (ed.), The Impact of Climate Change on European Lakes, Springer, 2010
6 Dokulil, M., Herzig, A.: An analysis of long-term winter data on phytoplankton and zooplankton in Neusiedler See, a shallow temperate lake, Austria. Aquat Ecol 43, 715-725, 2009

Table 1: Linear regression of ice formation (ice-on, duration of complete ice cover, ice-off in (Julian) days, see Fig. 2-4) at Lake Neusiedl over the years and in dependence of air temperature (AT)[1], [2] of autumn and winter resp., for the period 1931 to 2012

Year	p	R^2
Ice-on = -178 + 0.261 * Year	0.0059	0.10
Ice-duration = 691 - 0.314 * Year	0.0416	0.06
Ice-off = 466 - 0.205 * Year	0.0317	0.06
AT in °C	p	R^2
Ice-on = 251 + 8.78 * AT	0.00005	0.21
Ice-duration = 73 - 11.1 * AT	<0.00001	0.54
Ice-off = 62 - 5.80 * AT	<0.00001	0.37

Table 2: Correlation coefficients for mean seasonal air temperatures[1], [2] and ice parameters at Lake Neusiedl during the period 1931 to 2012 (red= significant at p<0.05)

	Ice-on	Duration	Ice-off
Spring	0.12	-0.17	-0.05
Summer	0.28	-0.17	-0.13
Autumn	0.51	-0.36	-0.24
Winter	0.12	-0.73	-0.61
Spring +1	0.20	-0.44	-0.44

Table 3: Correlation coefficients for indices (annual; DJF=winter) of large scale oscillations[3] of air pressure differences (AMO= Atlantic Multidecadal Oscillation, EAP=East Atlantic Pattern, EA/WR=East Atlantic/West Russia pattern, EMP=East Mediterranean pattern, MOA and MOG=Mediterranean Oscillation for Algiers and Cairo, and for Gibraltar and Israel, resp., NAO=North Atlantic Oscillation, SCA=Scandinavia pattern) and ice characteristics at Lake Neusiedl for the period 1931 to 2012 (red= significant at p<0.05)

	Ice-on	Duration	Ice-off
AMO	-0.09	0.21	-0.01
EAP	0.34	-0.23	-0.23
EA/WR	0.00	-0.08	0.03
MOA	0.06	-0.1	0.04
MOG	-0.04	0.14	0.23
NAO	0.11	-0.1	0.12
SCA	0.03	-0.12	0.08
AMO DJF	-0.12	0.19	-0.04
EAP DJF	0.15	-0.27	-0.44
EA/WR DJF	0.17	-0.15	-0.03
EMP DJF	-0.01	-0.02	-0.03
MOA DJF	0.20	-0.48	-0.45
MOG DJF	-0.05	-0.27	-0.20
NAO DJF	-0.02	-0.43	-0.37
SCA DJF	0.07	-0.01	0.15

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