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Coherence between lake ice cover, local climate and teleconnections (Lake Mendota, Wisconsin)

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SUMMARY

Ice duration has shortened and the ice-off date has become earlier for Lake Mendota from 1905 to 2000 as air temperatures have warmed and snowfall has increased. In addition, the ice record has cyclic components at inter-annual and inter-decadal scales. We examined the frequency domain relations between ice, local climate and the teleconnections, Southern Ocean Oscillation (SOI), Pacific Decadal Oscillation (PDO), North Atlantic Oscillation (NAO), and Northern Pacific Index (NP), through a three-tiered analysis of coherence. The coherence results provide evidence of linear relations between the three levels at inter-annual and inter-decadal frequencies. Of the three local climate variables analyzed, namely temperature, snowfall and snow depth, temperature is the variable that most significantly affects ice duration and ice-off date, at both inter-annual and inter-decadal frequencies. The most significant effect of teleconnections on local climate are the effects of PDO on snowfall and snow depth, and SOI on temperature, at inter-annual frequencies, and the effect of NAO on snowfall at inter-decadal frequencies. The teleconnections that most significantly affect ice-cover duration and ice-off date, particularly at inter-decadal frequencies, are the PDO and the NAO. The influence of PDO on ice-cover appears to be transmitted through temperature, while the influence of the NAO appears to be transmitted through temperature and snowfall. A cascading set of links between teleconnections, local climate, and lake ice explain some, but not all, of the dynamics in these time series.

Introduction

Large and persistent ocean–atmospheric anomalies such as the El Niño-Southern Oscillation or ENSO and Pacific Decadal Oscillation or PDO exist over large areas that affect regional climate conditions in adjacent or remote regions. These anomalies are called "teleconnections" (Wallace and Gutzler, 1981). An important aspect of climate change and variability is how teleconnections are related to and influence local climate and ecosystems such as lakes. Physical reasoning and past work indicates that ice cover on lakes should be related to local climate variables, such as air temperature and snow cover, and that local climate and ice cover should be related to teleconnections, whose influence is "transported" to localities away from their source (Robertson, 1989; Mantua and Hare, 2002; Livingstone, 2000; Magnuson et al., 2000, 2003; Hurrell et al., 2003; Bonsal et al., 2006; Tsonis et al., 2006).

Earlier studies in the time domain reveal that these teleconnections have an influence on the ice dynamics of lakes over large regions. Ice-off dates for Lake Mendota, Wisconsin, have been associated with El Niño events (Robertson, 1989; Anderson et al., 1996; Robertson et al., 2000). Relations between ice-off date and the Southern Oscillation Index (SOI) and the North Atlantic Oscillation (NAO) are apparent over portions of 131-year records of five lakes widely scattered across North America and Eurasia using linear regression (Livingstone, 2000). Similarly, ice-off dates were related negatively to the Pacific North American (PNA) and the Western Pacific (WP) indices across broad regions of North America based on 20-year records on 205 lakes (Benson et al., 2000). These relations have been summarized in Magnuson (2002) and Magnuson et al. (2006). Bonsal et al. (2006) observed similar relations using linear regression from 1950 to 1999 for ice-on and ice-off dates for lakes and for rivers but added the spatial pattern of the relations across Canada. Regions of positive and negative relations occurred broadly across Canada, between the six teleconnections and lakes and rivers. In addition, long-term warming trends are apparent in the lake ice records around the Northern Hemisphere (Magnuson et al., 2000) and in Canada (Duguay et al., 2006). Namdar Ghanbari and Bravo (2008) found significant coherence between Great Lakes levels, regional climate and teleconnections. In this study we investigate the applicability of coherence analysis to the ice cover of a single, smaller-scale lake.

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We examine the frequency domain relations between ice cover on Lake Mendota, local climate variables, and four large-scale teleconnections from 1905 to 2000. This is done not by noting that the time series have or do not have similar spectral components but by examining time series coherence among the three levels. Of interest is whether significant coherencies occur in similar frequency ranges in the climate–ice, teleconnections–climate and teleconnections–ice relations.

Background and data

Data analyzed are Lake Mendota ice-cover duration and ice-off date; Madison, Wisconsin local temperature, snowfall, and snow depth; and four teleconnection indices – the Southern Oscillation Index (SOI), the Pacific Decadal Oscillation (PDO), the North Atlantic Oscillation (NAO), and the North Pacific Index (NP). The year of observation for ice data is given as the year of ice off. Correspondingly, we used averages over the winter months (December–March, DJFM) for the Madison local climate variables and the teleconnection data. Coherence relations between ice, local climate, and teleconnections were more significant when using DJFM values than when using full-year averages. The length (Table 1) of each time series made it possible to analyze coherent dynamics from 1905 to 2000 (96 years) among all series and from 1863 to 2000 (137 years) for several series to determine whether the longer records changed the conclusions. All time series data were normalized in terms of their mean and standard deviation.

Lake ice (Fig. 1)

Ice data for Lake Mendota, at Madison, Wisconsin, USA, were selected for analysis because they provide one of the longest uninterrupted historical, lake-ice time series in North America and because earlier analyses using other methods are published. Ice cover data and documentation including definitions are available at the website of the North Temperate Lakes Long Term Ecological Research Program http://lterquery.limnology.wisc.edu/abstract_new.jsp?id=PHYS. Ice duration is the number of days that the lake was completely ice covered and excludes periods when the lake thawed in mid-winter before freezing again.

Local climate at Madison, Wisconsin (Fig. 1)

Local climate variables used were Madison winter air temperature, snowfall, and snow depth from the Wisconsin State Climatology Office http://www.aos.wisc.edu/~sco/index.html. Winter air temperature is derived from the mean monthly air temperature that is based on the daily mean data, that is, the average of the daily maximum and minimum temperatures. Snowfall is the sum of the daily snowfall. Snow depth is the average snow depth on the ground. The values used for year N are the averages of December of year $N-1$ and January, February, and March of year N.

Table 1
The nine time series analyzed for trends and coherencies with the durations of record.

Time series	Record length
Ice-cover duration	1855–2004
Ice-off date	1855–2004
Local temperature	1896–2005
Snowfall	1885–2005
Snow-depth	1905–2005
NAO	1865–2002
NP	1900–2000
PDO	1900–2005
SOI	1866–2004

Background on teleconnections

Many teleconnections have been identified, but combinations of only a small number of patterns can account for much of the interannual variability in the circulation and surface climate (IPCC, 2007). Quadrelli and Wallace (2004) found that many patterns of Northern Hemisphere variability can be reconstructed as linear combinations of the first two Empirical Orthogonal Functions (EOFs) of sea-level pressure (approximately the Northern Annular Mode, NAM, and the PNA) (Quadrelli and Wallace, 2004). Trenberth et al. (2005) analyzed global atmospheric mass and identified four key rotated EOF patterns: the two annular modes (Southern Annular Mode – SAM, and Northern Annular Mode – NAM), a global ENSO (SOI) – related pattern, and a fourth closely related to the North Pacific Index and the PDO, which in turn is closely related to ENSO and the PNA pattern. The most well-known atmospheric/oceanic teleconnections relevant to climate variability in the U.S. include the ENSO, the PNA, the NAO, and the PDO. Chapter 3 in The Physical Science Basis, Working Group I Contribution to the Fourth Assessment Report of the IPCC (2007) offers clear visualizations of these four teleconnections.

Our study analyzes the ENSO, NP (a proxy for PNA, as discussed below), NAO and PDO because they are well-known atmospheric/oceanic teleconnections relevant to climate variability in the US and because previous research suggests they may affect lake ice cover (Robertson et al., 2000; Livingstone, 2000; Magnuson et al., 2005; Bonsal et al., 2006). Teleconnections are best defined by values over a grid, but it is often convenient to devise simplified indices based on key station values (IPCC, 2007). Below we describe each of the four indices we used and provide some background on each.

The Southern Oscillation Index (SOI)

El Niño involves the warming of tropical Pacific surface waters from near the International Date Line to the west coast of South America, weakening the usually strong sea surface temperature (SST) gradient across the equatorial Pacific, with associated changes in ocean circulation (IPCC, 2007). Its closely associated counterpart, the Southern Oscillation (SO) involves changes in trade winds, tropical circulation, and precipitation and is closely related to El Niño and La Niña events. Historically, El Niño events occurred about every three to seven years and alternate with opposite phases of below-average temperatures in the eastern tropical Pacific referred to as La Niña. Changes in the trade winds, atmospheric circulation, precipitation, and associated atmospheric heating generate extra-tropical responses. The ENSO phenomenon is now understood to span the equatorial Pacific and to have opposite phases, and is associated with, simultaneously, droughts in Australia, New Zealand, and southern Africa, and devastating floods in North America, Peru, and Ecuador (Piechota et al., 2006). Strong ENSO years lead to drought conditions in Southeast Asia during the July–September period, with abnormally low rainfall persisting later in the year (Steffen et al., 2004).

Pacific Decadal Oscillation (PDO)

In the North Pacific Ocean, there are decade-scale transitions or regime shifts such as the Pacific Decadal Oscillation (PDO; Mantua et al., 1997) that can fundamentally alter community structure and nutrient dynamics (Fasham, 2003). The Pacific Decadal Oscillation (PDO) is a pattern of ocean variability in the North Pacific similar to ENSO (SOI) in some respects, but it has a much longer cycle (Mantua et al., 1997; Mantua and Hare, 2002). Specifically, it is defined as the standardized difference between sea surface temperatures (SSTs) in the north-central Pacific and Gulf of Alaska. Influences are primarily on precipitation and temperature conditions on the Pacific Northwest, Alaska, Florida, and the North Pacific Islands.