The study of wind dynamics over freshwater lakes – an overview of past, present and future trends

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Abstract

The effect of wind on lakes has undergone many changes since the early 1900's. There are three major areas of development in wind research: theories and knowledge, methodology and the presentation of data. Wind stress exerted on the surface layers of stratified lakes have been studied and developed to incorporate the topography, size and depth of lakes. A variety of methods to study wind stress on lakes have been performed and developed to assist the growing state of knowledge regarding wind effects on lake ecosystems. The presentation of wind data is advancing much slower relative to the previous areas of development. In examination of the major areas of wind research development, further attention should be directed to the following issues: (1) increasing high-resolution technology to better monitor wind stress on lakes; (2) provide deeper understandings of food web interactions and lake characteristics to avoid lake deterioration caused by extreme wind events (storms); and (3) improvement of wind research accuracy in order to forecast general changes in climate.

Introduction

Studies that examine the effect of wind on lakes have undergone many changes since the early 1900's. The most obvious change over time is that wind research is becoming more advantageous and recognized due to the development of knowledge and understanding of lake ecosystems. Many studies have monitored the effects of wind on oceans (Toba *et al.* 1990; Wiafe and Frid 1996; Frederickson *et al.* 1997; Nghiem *et al.* 2004; Dorman *et al.* 2005), however fewer studies have focused merely on lakes (Heaps and Ramsbottom 1966; Spigel and

Imberger 1980; Blenckner 2008). Stratified lakes are of particular interest since wind dramatically affects the surface layer or epilimnion while relatively having no effect on the lower layers of the lake (Heaps and Ramsbottom 1966; Spigel and Imberger 1980).

The aim of this paper is to review the many aspects of wind research in and around lakes that have developed over time with a particular focus on three major areas: theories and knowledge, methodology and the presentation of data. This paper will overview the general aspects of each major focus while also presenting their advancements and limitations in an attempt to illuminate any future trends of wind research and the implications of its advancement.

Developing theories and the state of knowledge: Advancements and limitations

Wind stress is exerted on the surface layers of stratified lakes. Past studies have termed this stress as a resistance that occurs between the atmosphere and the Earth`s surface (Taylor 1916; Sutcliffe 1936; Langmuir 1938). Specifically, Taylor (1916) suggested this resistance was a `skin friction` caused by wind blowing on the water surface that was calculated using wind velocities, air densities and a derived skin friction coefficient. However, Taylor`s (1916) theory did not incorporate crucial factors, such as lake size, depth and topography that should be considered when examining the effect of wind stress on the movement of flowing water (Sutcliffe 1936). Two decades later, Sutcliffe (1936) re-evaluated Taylor`s (1916) theory and prompted an extension of lake understanding into the skin friction calculation. Sutcliffe (1936) combined the ideology of Taylor’s (1916) theories regarding skin friction with lake characteristics such as the height and depth of the basin, the roughness of the surrounding landscape, and the height over the water surface at which the wind data was taken. A new revolution of ideas pertaining to wind research among varieties of lakes was therefore initiated by Taylor (1916) and enhanced by Sutcliffe (1936). In fact, recent studies have found that surface roughness greatly affects the wind stress exerted on lake surfaces and should be considered a major contributing factor to the wind effects (Rybak and Dickman 1988; Tanentzap *et al.* 2008).

Wind effects are confined to the surface layers of stratified lakes and therefore can only initiate circulation of surface waters. Stratified lakes are characterized by three distinct layers: epilimnion (surface water), metalimnion (thermocline) and the hypolimnion (bottom water) (Spigel and Imberger 1980; Naithani *et al.* 2003). Earlier studies have documented that wind effects cannot penetrate the surface layers of a stratified lake (Langmuir 1938). According to Langmuir (1938), the metalimnion that includes the thermocline marks the deepest point where wind effects can reach the water column. Agreeably, wind effects may not be able to reach depths below the thermocline, however wind stress on the water surface can cause thermocline tilting thereby resuspending bottom water through entrainment (Bengtsson 1978; Spigel and Imberger 1980; Naithani *et al.* 2003). Presently, the mixing nature of stratified lakes is under continuous debate over which mechanism dominates the mixing behaviour; however, this debate requires further study.

Internal seiches or surface water waves are directly related to the wind stress exerted on the lake surface layers. Heaps and Ramsbottom (1966) suggest that surface wave amplitudes and surface water circulations are directly proportional to the wind variation above the lake surface. Internal waves in the surface waters can be displaced by wind events, however contrary to Heaps and Ramsbottom (1966), other factors may also be contributing to the movement of surface water waves, such as the proximity of the sampling area to an inflow or outflow region which itself can initiate entrainment (Dirnerger and Threlkeld 1986). In addition to wind events and adjacent river dynamics, the fetch of the lake can also increase or decrease surface water waves

(Mazumder *et al.* 1990). Large, deep lakes have a greater fetch compared to small, shallow lakes, which allow the wind to travel a farther distance across the lake and therefore increase the effect of wind on surface waters (Mazumder *et al.* 1990; Blenckner 2008).

Theories and the state of knowledge surrounding wind effects on lake ecosystems have improved over time and have certainly led to the advancement of methods to study the interactions between wind events and lake dynamics.

Methodology: Advancements and limitations

A variety of methods have been implemented and developed in order to study wind effects in both the atmosphere and over surface waters of a lake (Table 1). The use of kite flights to study wind direction and speed are among the first tools utilized by scientists in order to gain a better understanding of wind behaviour (Meisinger 1921). The development of methods towards the 1950's tended to shift towards models that were more automatic, less subjective and higher quality. By the year 2000, scientists were using remote satellites and automatic land and water stations to record wind data within and around lake areas. Presently, the debate over which method of sampling would yield more accurate data has become problematic. For instance, the use of pilot balloons to study wind direction and speed are useful to measure wind velocity over adjacent areas to the balloon; however, measurements taken using this method are limited by the clarity of the sky (Brooks *et al.* 1946). In addition to pilot balloons, wind-wave tanks can be useful when studying the effect of wind on a pre-determined body of water that can be used to represent natural conditions in a laboratory setting (Tseng *et al.* 1992). On the other hand, results using this method are limited to the tank size and dimensions, which may confine the water movement initiated by wind effects and therefore incorrectly portray the simulated natural conditions being studied (Tseng *et al.* 1992).

Table 1. Summary of wind research methods for both atmospheric and surface experiments.

Method	**Brief Description**	**Utilized or Reviewed by**
Kite Flights	Flown in the sky to study free-air pressure and to make wind charts.	Meisinger 1921
Leaves	Tossed in water to study the downward motion of water.	Langmuir 1938
White Cord	Dropped in water column to examine waves by the motion of the white cord with reference to the direction of wind.	Langmuir 1938
Pilot Balloon	Balloons released in the air while wind direction and velocity is measured with the movement of the balloon.	Van Bemmelen 1920; Brooks *et al.* 1946; Durst 1948
Smoke Puffs	Smoke released at appropriate heights and followed by a camera from an aircraft to study the structure of wind at heights above 5000 ft.	Durst 1948
Wind Tunnel	Ring-shaped channel filled with water that involves measurement of the total pressure of the fluid stream and a fan to generate waves. Tunnel is used to study the dynamics of wind.	Francis 1951; Francis 1954
Anemometer	Vertical measuring device placed on exposed areas to record the hourly mean wind speed and direction.	Heaps and Ramsbottom 1966
Wind-Wave Tanks	Long tanks filled with water involving a fan to generate waves and study wind stresses over the water surface.	Tseng *et al.* 1992
Shipboard	Wind speed and direction measurements taken while aboard a ship.	Frederickson *et al.* 1997
QuikSCAT satellite	SeaWinds Scatterometer satellite introduced by NASA (June 1999) for the use over the Great Lakes to record high-resolution measurements (<12.5 km) of daily wind speeds and directions.	Nghiem *et al.* 2004
Surface Stations	Vertical stations on land that measure winds along the lakeshore.	Nghiem *et al.* 2004
Buoys	Buoyant stations in the water that measure winds at several locations on a lake during ice-free months.	Nghiem *et al.* 2004

Alongside the variety of methods utilized since the early 1900's, numerical parameters to study wind dynamics in lake systems have also been derived and improved upon over time. For instance, to measure the extent of mixing in a stratified lake, many factors that act on lakes while under wind stress needed to be integrated into a calculation, namely the Richardson number (Spigel and Imberger 1980). The Richardson number (R) involves the acceleration due to gravity, the basin depth and length, mixing and bottom layer depths and wind speed (Spigel and Imberger 1980). Altogether, these factors indicate the level of lake mixing and the effect of a particular wind speed at a sampling station. Smaller R values indicate that wind stress is sufficient to overcome the composition of strata, whereas larger R values are less susceptible to wind effects (Spigel and Imberger 1980).

Methodology developments have increased the accuracy of wind research over lakes and continue to illuminate the wind dynamics within and surrounding lake ecosystems. In conjunction with developing methods, the presentation and display of wind data trends is very important and must progress as the state of knowledge develops.

Presentation of data: Advancements and limitations

Since the early 1900's, the presentation of wind data has slowly progressed, unlike the state of knowledge and methodology that were previously discussed. A handful of techniques have been utilized to portray wind direction and speed at sampling stations. Many studies have focused on displaying either wind directions or wind speed as the combination of the two is difficult to show. The following presentation tools focus on the display of wind directions (excluding wind speed): wind charts derived from isopleths (Meisinger 1921); wind rose distributions with wind directions about a central point (Brooks *et al.* 1946); contingency tables that breakdown the percentage of wind directions into wind rose categories (Crutcher 1956); and finally standard vector-deviation wind rose plots which group cumulative wind directions about a central point (Crutcher 1956). In present day, an adaptation of the standard vector-deviation wind rose plot has been improved while incorporating both wind direction and speed about a central point (USDA). This combination effect between wind direction and speed allows for a clearer portrayal of wind trends over the spatial and temporal scales being examined.

Future trends and implications

As mentioned previously, methods of wind research have developed from pilot balloons that measure wind direction and speed by means of personal observation (Brooks *et al.* 1946) to QuikSCAT satellites designed by The National Aeronautics and Space Administration (NASA) to take high-resolution surveys of an entire lake area (Nghiem *et al.* 2004). In fact, current research is being done with autonomous platforms, such as the Automatic Water Quality Monitoring Station (AWQMS) to gather detailed minute-by-minute information about bodies of water (Moreno-Ostos *et al.* 2009). The AWQMS can be used to forecast extreme wind events or storms that may be hazardous to the flora and fauna of a lake (Moreno-Ostos *et al.* 2009).

Deeper investigations that examine lake ecosystems under wind stress can provide the necessary knowledge to restore lakes after severe wind events and also avoid deterioration (Gulati *et al.* 2008). For instance, the study of zooplankton dispersal and spatial heterogeneity under wind stress can be useful when considering the health of a lake (Dupuis and Hann 2009). Since zooplankton are major players in the aquatic food chain, a drastic increase or decrease in zooplankton abundance can have adverse effects on the fellow members of the aquatic food chain (Prepas and Rigler 1978; George and Hewitt 2006). Therefore, the study of zooplankton dispersal and movement by wind events is essential when considering its effect on the lake ecosystem.

Conclusions

Wind research is increasingly more accurate with the growing recognition of its importance to lake ecosystems. The development of wind knowledge allows for better methods that are specifically suited to the dynamics of a particular lake and in turn can lead to advancements in wind research (Figure 1). Since wind influence varies with lake size, depth and topography, it is important to understand the differences of each lake in order to establish a means of predicting the effect of wind. The accuracy of wind research will lead to better predictive models and thereby illuminate and possibly explain any changes or disturbances to organisms within.

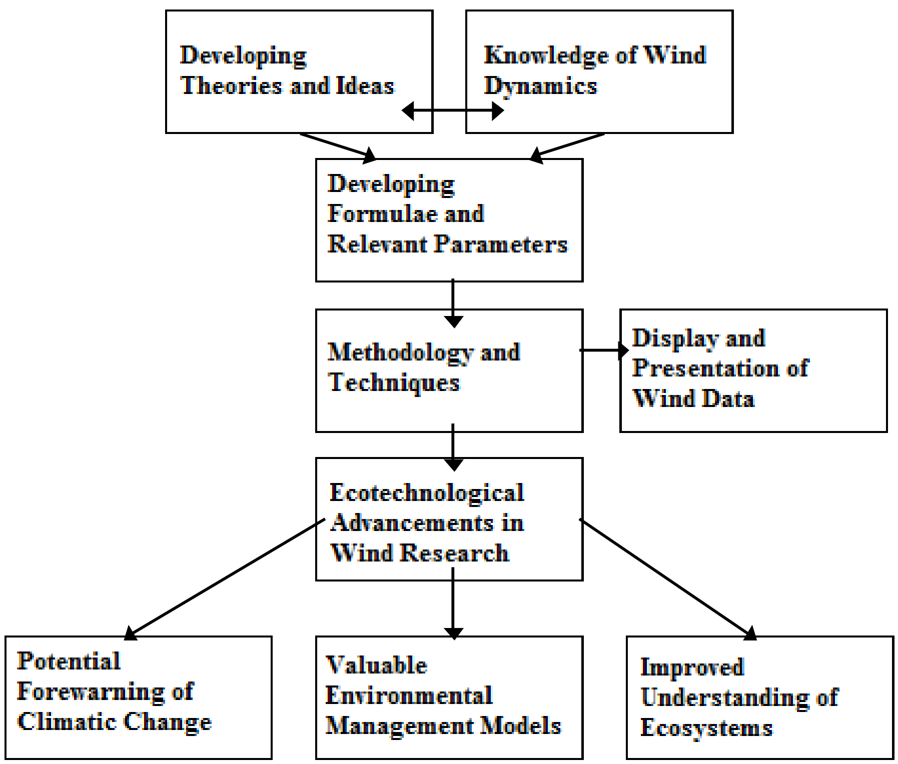

Figure 1. A schematic of wind research progression over time. Arrows denote the effect of one factor onto another.

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