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REANALYSIS OF WIND-WAVE GROWTH IN A LAKE USING KITAIGORODSKII'S SIMILARITY THEORY

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Abstract: Wind-generated wave processes remain challenging due to the intricate interplay of turbulent wind interactions and small-scale initial wave formation, and while empirical formulations like those of Pierson–Moskowitz and JONSWAP have advanced our understanding in ocean settings, some studies in lakes and reservoirs suggest that they fall short in capturing the dynamics in inland water bodies. This study reexamines the underlying framework of those well-established formulations—Kitaigorodskii's similarity theory—by reanalyzing wind-wave data from a large Swiss lake. Analysis of dimensionless fetch length and wave height parameters showed that, under sustained wind conditions, the observed wave growth aligns well with JONSWAP predictions; however, under weak winds, significant scatter is observed, likely due to sensor underestimation and uncertainties in estimating a constant fetch, combined with local morphological and orographic influences. These findings highlight the need for refined measurement techniques and data preprocessing methods to better account for local variability, showing that ocean-derived scaling laws could be applied to lake environments under careful consideration of their basic assumptions.

Resumo: Os processos de geração de ondas pelo vento continuam a ser desafiadores devido à complexa interação entre a turbulência atmosférica e a formação inicial de ondas em pequena escala. Embora formulações empíricas como as de Pierson–Moskowitz e JONSWAP tenham avançado a compreensão das ondas oceânicas, estudos em lagos e reservatórios sugerem que essas abordagens nem sempre capturam adequadamente a dinâmica de corpos de água interiores. Este estudo reexamina a base dessas formulações—a teoria da similaridade de Kitaigorodskii—por meio da reanálise de dados de ondas geradas pelo vento em um grande lago suíço. A análise de parâmetros adimensionais de *fetch* e altura significativa das ondas revelou que, sob condições de vento sustentado, o crescimento das ondas segue bem as previsões do modelo JONSWAP; entretanto, sob ventos fracos, observa-se uma dispersão significativa, possivelmente devido à subestimação das medições dos sensores e incertezas na definição do *fetch*, além de influências morfológicas e orográficas locais. Essas observações destacam a necessidade de técnicas de medição aprimoradas e métodos de pré-processamento de dados para melhor considerar a variabilidade local, mostrando que as leis de similaridade derivadas dos oceanos podem ser aplicadas a ambientes lacustres desde que suas premissas fundamentais sejam cuidadosamente avaliadas.

Keywords – wind waves; lakes; JONSWAP.

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INTRODUCTION

The generation of waves by wind blowing over an initially still water surface is still not fully understood. In fact, the study of wind-wave interactions—especially at the very first stages of generation—is challenging because of the minuscule length and temporal scales that are difficult to resolve in both laboratory and field setups, as well as the stochastic nature of turbulence and, ergo, of wave motion. The initial stages of wind-wave generation are investigated, for instance, in sofisticated laboratory experiments (SHEMER, 2019), direct numerical simulations (LI; SHEN, 2023), and carefully designed field campaigns (CAVALERI *et al.*, 2024). Thus, predicting the final state of a wind-wave field from the earliest stages of generation with a mechanistic approach appears as an unfeasible task for most practical applications, e.g., in the fields of engineering and forecasting.

At practical scales, however, empirical relationships between wind conditions and wave fields have been better understood since mid-20th century. In particular, in the early 1960s, Russian oceanographer Sergei A. Kitaigorodskii (1962) published a seminal study applying similarity theory to investigate the dependence of the wave spectrum on wind-wave generation conditions in the sea. Kitaigorodskii (1962) proposed that, for steady (fetch-limited) wave motion and sufficiently simple geometry, the wave spectrum can be defined solely by the fetch length, a characteristic wind speed, and gravitational acceleration. His theory served as basis for two major works, namely the Pierson–Moskowitz spectrum for fully developed wind seas (PIERSON; MOSKOWITZ, 1964) and the Joint North Sea Wave Project (JONSWAP) that investigated fetch-limited wind-wave growth (HASSELMANN *et al.*, 1973).

Results from those works are still applied and are relevant for current developments in design of marine structures (RUEDA-BAYONA *et al.*, 2020), wave modeling (SAMIKSHA *et al.*, 2021), remote sensing (CHEN *et al.*, 2022), and wave climate analyses (MAZZARETTO *et al.*, 2022). The Pierson–Moskowitz and JONSWAP formulations are also relevant for inland bodies of water such as lakes and reservoirs since wind is the main input of mechanical energy in these environments. In lakes, part of the wind energy is transferred to surface waves, which is then dissipated by turbulence and propagating waves arriving at the shores (IMBODEN, 2003). The JONSWAP experiment provides some quantifications: for short fetches, about 80 % of the wind momentum goes into waves; for long fetches, at least about 25 % of the momentum is transferred to waves (HASSELMANN *et al.*, 1973). This suggests that waves play a major role in the energy budget of lakes and reservoir—considered typically fetch-limited.

Notwithstanding, two known studies on the influence of waves on the energy dynamics of lakes—Simon (1997) and Guseva *et al.* (2021)—showed significant deviations in wave energy (or, equivalently, wave height) relative to JONSWAP for similar fetch lengths. Simon (1997) compared wind-wave data from Lake Neuchâtel (Switzerland) with the JONSWAP formulation and found that field wave heights lie significantly below the JONSWAP prediction for wind speeds of up to 7 m/s. Moreover, Guseva *et al.* (2021) found that their wave height data from Bautzen Reservoir and Lake Dagow (Germany) were greatly overestimated by the JONSWAP formula for the whole range of observed wind speeds.

In this article, the similarity theory of Kitaigorodskii is reviewed, as it is considered the basis for wind-wave growth studies, and its scaling principles are applied to wave height data from the Lake Neuchâtel campaign (SIMON, 1997). The goal was to analyze wind-wave growth in a lake environment with similarity arguments, providing a robust comparison with the results of JONSWAP (HASSELMANN *et al.*, 1973) and Pierson and Moskowitz (1964). The adopted approach brings a discussion on the universality of fetch-limited growth laws under their underlying assumptions. Reanalyzing the Lake Neuchâtel data as a case study provided insights into the theoretical and methodological challenges of applying well-established wind-wave formulations for the study of wind waves in lake environments.

METHODOLOGY

Kitaigorodskii's similarity theory

Considering the water surface elevation as an ergodic weakly-stationary stochastic process, a single realization, $\eta(t)$, allows for computing the wave spectrum as

$$S(f) = 2\int_{-\infty}^{+\infty} R(\tau)\exp(-2\pi i f\tau)\,d\tau\,, \tag{1}$$

with autocorrelation function $R(\tau) = \overline{\eta(t)\,\eta(t+\tau)}$, where the overline denotes averaging along the entire time domain. If $\eta(t)$ is a discrete record, $S(f)$ may be estimated with a periodogram using the fast Fourier transform. Knowing $S(f)$, it is possible to compute parameters describing the wave field (e.g., frequency and height statistics) and study their relationship with wind conditions.

Initially, let us consider a body of water with a quiescent surface and a practically infinite straight shore. Now, suppose the onset of a turbulent wind blowing offshore, perpendicular to the shore, with constant and uniform mean speed, U. At a time t after the onset of the wind, the surface of the water body is divided in two regions: up to a distance x_s from the shore, the statistical characteristics of the water surface are regarded as time-invariant, and $S(f)$ depends only on fetch length, x; past x_s, the statistical characteristics and $S(f)$ depend only on t. The wave field in the first region ($x \leq x_s$) is said to be fetch-limited, while in the second ($x > x_s$) it is duration-limited. The transition at x_s is called the *steady-state wave front*, and its location is a function of t.

For the fetch-limited region, Kitaigorodskii (1962) proposed that

$$S(f) = g^2 f^{-5} F_1\left(\frac{Uf}{g}, \frac{gx}{U^2}\right), \tag{2}$$

where $\tilde{f} = Uf/g$ is the dimensionless frequency; $\tilde{x} = gx/U^2$ is the dimensionless fetch length; and F_j denotes an universal dimensionless function. It follows that the properties of the wave field are functions of $\tilde{x}$ alone, e.g., for the significant wave height, H_s, we have

$$\tilde{H}_s = \frac{gH_s}{U^2} = F_2(\tilde{x}). \tag{3}$$

By using Kitaigorodskii's theory, wind-wave growth and forecasting reduce to finding the appropriate universal functions (F_j) based on wind and wave observations. For instance, the JONSWAP formulation for the significant wave height was found to be

$$\tilde{H}_s = 1.6 \times 10^{-3}\,\tilde{x}^{0.5}, \tag{4}$$

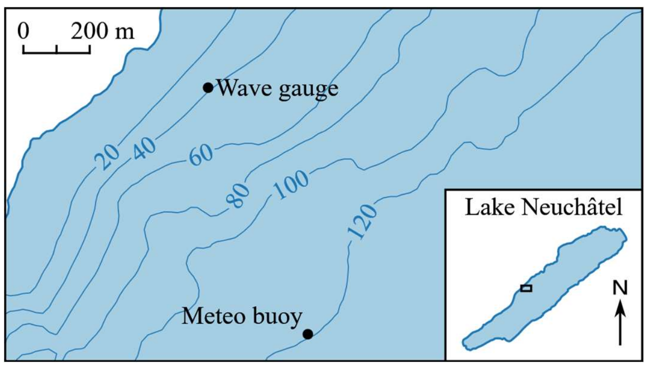
with U measured at a 10 m height, i.e., U_{10}. The Pierson–Moskowitz (PM) spectrum, on the other hand, considers a sufficiently long fetch in a steady-state wave field, so equations 2 and 3 are no longer functions of $\tilde{x}$. This implies the termination of wave growth—i.e., a fully developed sea—, and the resultant spectral shape is a function of $\tilde{f}$ alone, as formulated by Pierson and Moskowitz (1964). The fully developed sea will have a constant dimensionless wave height of $\tilde{H}_s \approx 0.235$ for $U = U_{10}$.

Site description and available data

Lake Neuchâtel is in the western, Frech-speaking region of Switzerland, mainly in the eponymous Swiss canton. It is the largest lake located completely within Switzerland, with an area of 242 km² and a maximum depth of 57.4 m. Along its main NE–SW axis, it has a length of 37.8 km and a width of 8.2 km. The study area is characterized by northeasterly and southwesterly winds, mostly synoptic, but the thermal northwesterly winds—known as Joran—are usually stronger in magnitude (AMINI *et al.*, 2017). The Joran blowing over Lake Neuchâtel is associated with regular mixing of the water column (LIECHTI, 1994).

A field campaign was conducted between March 8 and 20, 1996, in Lake Neuchâtel by the Swiss Federal Institute of Aquatic Science and Technology (EAWAG, from a German acronym). The field campaign aimed to collect data of atmospheric and hydrodynamic variables to study hydrodynamic processes in the surface boundary layer of lakes such as wind-wave interactions, surface currents, and turbulence. Measurements were made in the northwest of the lake and consisted of a weather station mounted in a buoy 1.0 km from the shore, as well as a water pressure probe moored to the lake's bottom at about 200 m from the shore (see Figure 1). Three cup anemometers and a wind vane were placed 2.8 m above the water surface in the buoy's weather station, and the pressure transducer was submerged 0.8 m. The field campaign and instrumental setup are described in more detail in the doctoral thesis of Simon (1997) and the article by Stips *et al.* (2005).

Figure 1 – Measurement locations for the available Lake Neuchâtel data (isobaths in meters)



Given the tendency of cup anemometers to underestimate wind speed, the three anemometers provided redundancy. Two-minute averages of each anemometer were recorded, and Simon (1997) composed a wind speed time series ("best wind") by taking the highest value of each triplicate. Regarding waves, pressure records were sampled at 4 Hz—except for the first two days, when they were sampled at 2 Hz (SIMON, 1997)—with a resolution of 1.5 cm (STIPS *et al.*, 2005). Simon (1997) converted the pressure data to water surface elevation with the hydrostatic approximation and computed the wave spectra for blocks of 2048 data with the method of averaged periodograms. The spectra were consequently obtained every 8.5 minutes and were further corrected by Simon (1997) to account for submergence attenuation. Wave parameters such as the significant wave height were computed from spectral moments.

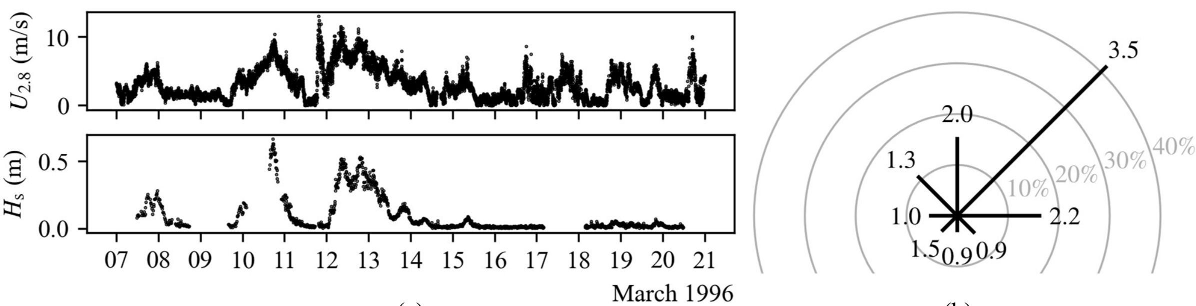
The "best wind" and wave height time series were provided by the Joint Research Centre of the European Commission, which had the data of the Lake Neuchâtel campaign (LAMEX Project) in its archives.

RESULTS

Data analysis

The provided time series of 2.8 m wind speed, $U_{2.8}$, and significant wave height, H_s, are shown in Figure 2 (a). Overall, a correlation can be observed between high wind and high waves periods, though some periods of absence of wave data are present. The highest wind speeds were observed in March 10–12, and those periods coincided with highest recorded waves. Figure 2 (b) shows that most of the observed winds (41 %) blew from approximately northeast with median speed of 3.5 m/s. The mean wind direction (circular mean) was found to be 34° clockwise from true north.

Figure 2 – Time series of wind speed and significant wave height (a) and wind rose (b) for Lake Neuchâtel (median speed in m/s for each direction of the wind rose)



(a) (b)

Descriptive statistics were computed for the time series and are presented in Table 1. Wind speeds are relatively low, typical of lakes, and wave heights remain below one meter. The difference between the mean and median suggests positively skewed distributions for both wind speed and significant wave height. For both variables, about 90 % of the time the values were less than half of the maximum observed.

Table 1 – Wind and wave statistics for the Lake Neuchâtel data

Variable	Mean	Median	Maximum	90th percentile
Wind speed ($U_{2.8}$, m/s)	2.87	2.31	13.0	6.0
Significant wave height (H_s, m)	0.093	0.027	0.66	0.33

Fetch dependence analysis

The fetch length, x, and significant wave height, H_s, were scaled like in equations 2 and 3 with $U_{2.8}$ from the 2.8 m wind time series. The JONSWAP formulation, however, was originally fitted for U_{10} at 10 m height. In order to compare results from Lake Neuchâtel with those of JONSWAP, both must have wind at the same reference height. In the main JONSWAP experiment, the aerodynamic 10 m drag coefficient, C_{10}, was on average 10^{-3} (HASSELMANN *et al.*, 1973), so we may apply the "law of the wall" to find the ratio

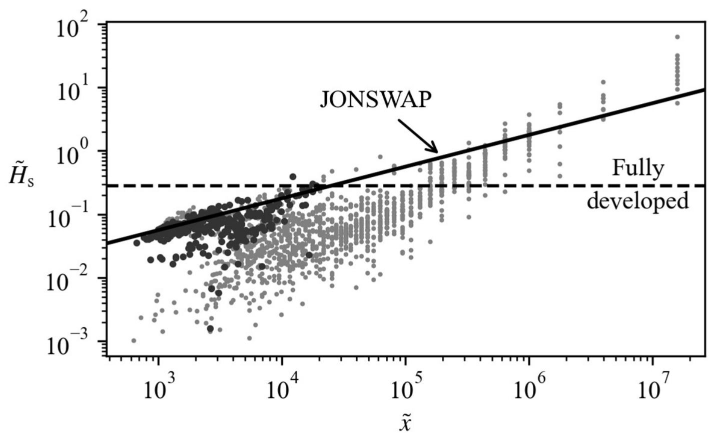
$$\frac{U_{2.8}}{U_{10}} = 1 - \frac{\sqrt{C_{10}}}{\kappa} \ln\left(\frac{10}{2.8}\right) \approx 0.9, \tag{5}$$

with von Kármán constant, $\kappa = 0.4$. Thus, replacing U_{10} with $U_{2.8}$ in the JONSWAP formulation of equation 4, it becomes

$$\tilde{H}_s = 1.78 \times 10^{-3}\, \tilde{x}^{0.5}. \tag{6}$$

Fetch length was estimated by Simon (1997) as a constant value of 9 km given that wind blew predominantly from northeast; this value will be used for the present analysis. Having defined the fundamental wind-wave parameters, fetch lengths and significant wave heights were computed in dimensionless form and plotted in Figure 3. For Lake Neuchâtel, the computed values of $\tilde{x}$ reach the order of 10^7, significantly higher than those observed during JONSWAP (10^2 to 10^4). Furthermore, in JONSWAP, values of $\tilde{H}_s$ did not exceed $O(10^{-1})$, while for Lake Neuchâtel values up to $O(10^2)$ were calculated. The Pierson–Moskowitz (PM) spectrum for fully developed seas (PIERSON; MOSKOWITZ, 1964) can be used to define a reference value for the limits of wave growth. By integrating the PM spectrum and replacing the 19.5 m wind from its original formulation with Lake Neuchâtel's $U_{2.8}$, we get $\tilde{H}_s = 0.287$, which is shown as a horizontal line in Figure 3.

Figure 3 – Dimensionless significant wave height versus dimensionless fetch length for Lake Neuchâtel (darker dots correspond to March 12 and 13, 1996)



Although there is an overall large scatter, wind-wave growth in March 12–13 better followed the JONSWAP formulation, which is consistent with the visible correlation between $U_{2.8}$ and H_s in Figure 2 (a). For this couple of days, the agreement with JONSWAP is clear even though the wind field is not steady, increasing its speed on day 12 and then decreasing towards day 14. Also, in this period, wind waves approached full development. Beyond the intersection between the JONSWAP formulation and the PM limit, found at $\tilde{x} = 2.6 \times 10^4$, correlations are likely to be spurious. Note that the transition from fetch-limited wind-wave growth to a fully developed sea was already discussed by Donelan *et al.* (1992) based on results from the Great Lakes. Therefore, the exceptionally long fetches ($\gtrsim 10^4$) computed for Lake Neuchâtel can be seen as the result of underestimation of the wind speed or overestimation of fetch length.

With $x = 9$ km, the PM limit is achieved at 1.84 m/s, so wind speeds below this value are the most likely responsible for the unexpected long fetches. Such weak winds usually do not have sufficient temporal constancy to bring the steady-state wave front to the wave gauge location before a significant change in wind speed or direction occurs. The tendency of cup anemometers to underestimate low wind speeds may have played a role. On the other hand, uncertainties in the estimation of fetch do not seem to explain much of the scatter, as redoing the plot with only wind speeds within $\pm 15°$ of NE does not significantly reduce it.

Auxiliary wind measurements closer to the shore indicated substantial wind speed gradients along the fetch, which might be associated with wind shadowing effects from the local orography. Consequently, it can be argued that those gradients are responsible for the deviations. However, as pointed out by Hasselmann *et al.* (1973), if there is homogeneity of the wind field in the parallel-to-shore direction, gradients in the fetch direction can be neglected—e.g., an internal atmospheric boundary layer at the transition from land to water. This lack of homogeneity can be accounted for by, e.g., using the average wind speed along the fetch (DONELAN *et al.*, 1992). Additionally, given a finite shore length, transverse gradients can be neglected with reasonable confidence if wind blows approximately perpendicular to the shore, which can be controlled in our analyses by filtering out winds with significant angular deviations.

As wind speed is used to scale both wave height and fetch, its underestimation explains why the overestimated values of $\tilde{x}$ in Figure 3 correspond to overestimated $\tilde{H}_s$. Because of the attenuation of water pressure oscillations by depth, it is not expected for wave heights derived from pressure transducers to be significantly overestimated. Therefore, most of the scatter below the data of March

12–13 is likely associated with insufficient sensor accuracy to resolve smaller wind waves—which was also mentioned by Guseva *et al.* (2021).

CONCLUSIONS

This study reexamined the classic similarity theory of Kitaigorodskii (1962) and its application to wind-wave growth in a lake environment by reanalyzing the data from a field campaign in Lake Neuchâtel, Switzerland (SIMON, 1997). Our analysis shows that, while well-established formulations such as JONSWAP and Pierson–Moskowitz remain useful from a benchmarking perspective, significant challenges arise when these frameworks are applied to inland water bodies. Notably, the reanalysis revealed that the observations tend to display considerable scatter relative to the formulations, particularly under weak wind conditions. This disagreement appears to result largely from both the underestimation of wind speeds using cup anemometers and uncertainties in estimating a constant fetch length. These factors contribute to overestimated dimensionless fetch and wave height values, suggesting that application of ocean scaling laws to lakes must be treated with caution. These limitations are not necessarily because of lack of universality of such laws but because of the typically challenging conditions in lakes (e.g., low wind speeds, high temporal variability of wind fields, and small amplitude waves).

Furthermore, the analysis highlights that periods of relatively strong and consistent wind—such as those observed from March 12 to 13—yielded a closer match with JONSWAP predictions. This correspondence reinforces the idea that under conditions of near-steady wind and an adequately defined fetch, similarity laws can capture the main features of wind-wave growth in lakes and reservoirs. However, this highlights the importance of establishing appropriate data preprocessing techniques to identify periods that comply with the geometrical and physical assumptions for the application of similarity arguments. The potential influence of local shore morphology and orography effects further complicates the spatial variability of wind conditions, thereby suggesting that methods for spatially averaging wind speed along the fetch may be necessary, which requires knowledge of the wind speed and direction at several points in the fetch.

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