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Continuous wavelet characterization of the wavelengths and regularity of meandering rivers

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ABSTRACT

Meanders are oscillatory systems characterized with multiple spatial frequencies in their planforms. Although the concept of dominant meander wavelength (DMW) is central to morphodynamic research on river meandering, shorter and longer spatial scales of oscillations are also relevant. Using Continuous Wavelet Transform (CWT), we present an objective quantitative characterization of the relevant wavelengths of meandering rivers. Analysis of synthetic meanders generated through Kinoshita curves and real meandering rivers show that DMW can be better detected by applying CWT to the spatial series of the direction-angle, instead of curvature, because the latter shifts the meander oscillation energy toward shorter harmonics. This is related to the typical observed high ratio of meander arclength to channel width, as emerging from field observations and from morphodynamic modeling of meanders, implying the dimensionless wavenumber of meander oscillations to be an $\mathcal{O}(10^{-1})$ number. The capability of CWT of capturing local as well as global information in a spatial series is exploited by analyzing two CWT-based indicators, which express the relevance of other wavelengths with respect to the local DMW within the same reach (M_λ) and the variability of the local DMW with respect to the global DMW (S_λ). Thresholding the M_λ indicator shows that the global DMW corresponds to local DMW for only the most regular meanders. At longer scales, the S_λ indicator also reveals the existence of spatial modulations of the direction-angle oscillations in real meandering rivers, which have been previously detected only in synthetic planforms generated by morphodynamic models. This correspondence between observations and modeling indicates the potential of CWT analysis of meanders to provide further insight into the connections between the form and processes of channel meandering, as it suggests that spatial modulations might be inherent in meander-planform dynamics and related to the tendency of meanders to evolve in wavegroups, a potential cause of the so called 'cutoff avalanches' observed in natural and modeled meandering streams.

1. Introduction

Quantitative and objective characterization of the planform pattern of meandering rivers is an old debate that goes back to the beginning of meandering rivers research. As suggested by Speight (1965), a meandering river, 'like a musical instrument, may be considered as a resonant oscillatory system, with the most notable difference being that the oscillations of interest represent fluctuations relative to distance rather than to time'. Subsequent empirical and theoretical research on meandering rivers has given strong support to this statement: the presence of several spatial scales of meander planform oscillations has been long investigated and shown to present an intrinsic legacy to the degree of meandering planform regularity. The work presents a new approach to the quantitative characterization of meander regularity and of the relevant wavelengths embedded within a complex meandering planform by exploiting the potential capabilities of Continuous Wavelet Transform (CWT), a scale-independent method of space-frequency localization, which has been widely used for time-series analysis in a wide range of geophysical fields (Farge, 1992; Kumar & Foufoula-Georgiou, 1997; Torrence & Compo, 1998; Zolezzi et al., 2011).

The intriguing regularity of numerous meandering rivers worldwide led earlier meander morphometric analysis to focus on individual meanders in regular subreaches, which are assumed to represent the properties of the whole reach (Leopold & Wolman, 1960). In this respect, most of the early debate tended to focus on the opposing views of meander geometry as completely regular (Leopold & Wolman, 1960) or purely random (Thakur & Scheidegger, 1970). Both views have been criticized for their subjectivity in morphometric characterization because of their reliance on arbitrary selection of the reaches to be analyzed. To overcome such subjectivity, Fourier analysis has been widely used during the 1960s and 1970s in the analysis of the spatial series of planform direction (also called inflection) angle and of centerline curvature (Speight, 1965; Chang & Toebes, 1970; Thakur & Scheidegger, 1970; Ferguson, 1975). These studies have clearly shown multiple

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stable peaks in the direction-angle and curvature spectra, indicating the irregularity in meandering river systems. Ferguson (1975) attributed this irregularity to variability in environmental conditions, which must lead to a range of dominant wavelengths. The estimation of the *dominant* meander wavelengths became a central topic of early river meandering research (Schumm, 1967) also because of its fundamental relevance to causal and scaling relations of meander pattern with controlling environmental conditions, such as river discharge or channel width (Leopold & Wolman, 1960).

Besides the dominant wavelength, other spatial scales of oscillations have been shown to be relevant to the morphodynamics of meander planforms. The pioneering observations of Kinoshita (1961) pointed out that fattening and skewing of meander loops, which commonly are observed at meander-bend scale, can be explained by the presence of a relevant scale of oscillation that corresponds to one-third of the locally dominant wavelength (i.e., third harmonic). The development of odd harmonics (the third harmonic being the most relevant one) during meander growth has been theoretically demonstrated 40 years later by Seminara et al. (2001), who showed the intrinsic tendency of purely sine-generated meander bends to develop only odd harmonics (third, fifth) in their curvature and direction-angle spectra.

The modeling approach proposed by Seminara et al. (2001), when applied to more irregular meander planforms, has also suggested the intrinsic tendency of meander bends to evolve in wavegroups, implying that a group of nearby bends would tend to grow much more rapidly compared to the ones in the adjacent group. Such tendency is intrinsic in the modeled process of meander development and can invariably be observed in the early stages of meander development simulated through state-of-art meander models, regardless of the adopted flow/bed deformation submodel (Howard, 1992; Sun et al., 1996; Seminara et al., 2001; Frascati & Lanzoni, 2009; Xu et al., 2011). However specific evidence of such behavior has not been reported from observations on real meandering rivers, although the observations of Hooke (2004) suggest an intrinsic tendency of meandering rivers to develop clusters of nearby bends at a comparable evolution stage. The presence of wavegroups in modeled early stage meanders can be viewed in terms of a *long* wavelength in the meandering planform, which is much longer than the dominant meander wavelength and is dictated by the spacing between consecutive wavegroups. The question arises whether such long oscillations in the planform may represent a detectable signature also in real meandering rivers at different evolutionary stages and what their morphodynamic implications are.

Despite few more recent contributions (Howard & Hemberger, 1991), the debate on the characterization of meander regularity and relevant wavelengths has not fully resolved the issue of characterizing the spatial scales of meanders in the presence of irregularity. Moreover, the presence and relevance of wavelengths longer than the dominant wavelength still requires a thorough investigation.

Widely used spectral analysis based on Fourier Transform (FT) has well-known limitations in capturing local (i.e., subreach level) and global (i.e., whole-reach level) information embedded in analyzed series. In the case of meandering rivers, when FT is applied over a data window that contains multiple meander bends, it can provide global information within that data window but cannot capture local variability at the bend-scale. In a pioneering study, Chang & Toebes (1970) aimed at describing local statistics of the meander shape using an earlier version of Windowed Fourier Transform (WFT), which, however, still imposes a scale into the analysis by using a fixed-width window.

In this paper we aim to contribute to this long-lasting debate by investigating the potential of Continuous Wavelet Transform (CWT), part of the family of Wavelet Transforms, for capturing both local and global information embedded in the spatial series relevant for meandering river studies, including direction-angle and curvature series. While CWT has been applied in geophysical studies since more than two decades (Kumar & Foufoula-Georgiou, 1997), its application in the analysis of spatial series derived from meandering river planforms has been developing only very recently (Van Gerven & Hoitink, 2009; Gutierrez & Abad, 2014), although with a focus different from that of the present analysis. More specifically, herein we address the following research questions: (i) Which spatial series (direction-angle or curvature) is more suitable for characterizing the relevant wavelengths for meander morphodynamics, including the dominant wavelength? (ii) How can CWT be used to quantify the differences in regularity between different meandering river reaches and to detect the location and extension of the regular reaches? (iii) Can CWT reveal relevant properties of meander planform and related dynamics that could not have been highlighted in previously employed morphometric approaches?

To this aim, we first explore the outcomes of CWT to a series of idealized, sine-generated, meandering planforms to understand the CWT expected output in the limit case of perfectly regular meandering planforms with known wavelengths and related amplitudes. Then, we investigate the results of the CWT analysis on long reaches of three freely evolving meandering alluvial rivers from different geographical settings and with different morphodynamic properties.

2. Study sites, methods, and theoretical background

2.1. Notations, spatial series, and study river reaches

River planforms are represented through the centerlines (x_a^*, y_a^*) of meandering channels, which are defined as a curve in the Cartesian (x^*, y^*) plane through the following parametric relation where s^* denotes meander arclength (i.e., the curvilinear coordinate that is locally tangent to meander centerline):

$$(x_a^*, y_a^*) = \left[x_a^*(s^*), y_a^*(s^*)\right]. \tag{1}$$

The analysis is referred to dimensionless quantities for results to be more easily comparable among different streams. For this reason it is convenient to use an asterisk (*) to denote dimensional quantities. All spatial quantities are made dimensionless with the reach-averaged channel width W^*, i.e., the average value over the whole length of each study reach. The dimensionless channel centerline therefore reads

$$(x_a, y_a) = \left(\frac{x_a^*}{W^*}, \frac{y_a^*}{W^*}\right) = [x_a(s), y_a(s)]; \quad s = \frac{2s^*}{W^*}. \tag{2}$$

The dimensionless intrinsic meander wavelength, i.e., the distance between the upstream and downstream endpoints of one meander measured along the curvilinear coordinate s, is denoted with $L = L^*/W^*$. The corresponding dimensionless intrinsic meander wavenumber is denoted with $\lambda = \pi/L$. The dimensionless Cartesian meander wavelength L_x^*, on the other hand, is the Cartesian distance between the upstream and downstream endpoints of the considered meander, and $\lambda_x = \pi/(L_x^*/W^*)$ denotes its corresponding dimensionless wavenumber. Note that the factor 2 in the scaling relation for s (Eq. (2)) is related to the use of the whole channel width instead of the half-width to normalize dimensional quantities and to the convenience of retaining the same definition of the intrinsic meander wavenumber λ as in theoretical models of meander morphodynamics (Seminara et al., 2001).

Two types of meandering river planforms have been considered in this study: planforms of idealized, sine-generated meanders and those of real rivers. The spatial series used to describe the planform properties and analyzed through CWT are those of the direction angle θ and curvature $\mathcal{C}^*$ computed at equally spaced points along the intrinsic coordinate s^*. Dimensionless curvature C and direction angle θ are related by a first derivative operation performed along the dimensionless curvilinear coordinate s, which takes the expression

$$W\mathcal{C}^*(s^*) = \mathcal{C}(s) = -\frac{d\theta}{ds}. \tag{3}$$