

A Practical Guide to Wavelet Analysis



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ABSTRACT

A practical step-by-step guide to wavelet analysis is given, with examples taken from time series of the El Niño–Southern Oscillation (ENSO). The guide includes a comparison to the windowed Fourier transform, the choice of an appropriate wavelet basis function, edge effects due to finite-length time series, and the relationship between wavelet scale and Fourier frequency. New statistical significance tests for wavelet power spectra are developed by deriving theoretical wavelet spectra for white and red noise processes and using these to establish significance levels and confidence intervals. It is shown that smoothing in time or scale can be used to increase the confidence of the wavelet spectrum. Empirical formulas are given for the effect of smoothing on significance levels and confidence intervals. Extensions to wavelet analysis such as filtering, the power Hovmöller, cross-wavelet spectra, and coherence are described.

The statistical significance tests are used to give a quantitative measure of changes in ENSO variance on interdecadal timescales. Using new datasets that extend back to 1871, the Niño-3 sea surface temperature and the Southern Oscillation index show significantly higher power during 1880–1920 and 1960–90, and lower power during 1920–60, as well as a possible 15-yr modulation of variance. The power Hovmöller of sea level pressure shows significant variations in 2–8-yr wavelet power in both longitude and time.

1. Introduction

Wavelet analysis is becoming a common tool for analyzing localized variations of power within a time series. By decomposing a time series into time–frequency space, one is able to determine both the dominant modes of variability and how those modes vary in time. The wavelet transform has been used for numerous studies in geophysics, including tropical convection (Weng and Lau 1994), the El Niño–Southern Oscillation (ENSO; Gu and Philander 1995; Wang and Wang 1996), atmospheric cold fronts (Gamage and Blumen 1993), central England temperature (Baliunas et al. 1997), the dispersion of ocean waves (Meyers et al. 1993), wave growth and breaking (Liu 1994), and coherent structures in turbulent flows (Farge 1992). A

complete description of geophysical applications can be found in Foufoula-Georgiou and Kumar (1995), while a theoretical treatment of wavelet analysis is given in Daubechies (1992).

Unfortunately, many studies using wavelet analysis have suffered from an apparent lack of quantitative results. The wavelet transform has been regarded by many as an interesting diversion that produces colorful pictures, yet purely qualitative results. This misconception is in some sense the fault of wavelet analysis itself, as it involves a transform from a one-dimensional time series (or frequency spectrum) to a diffuse two-dimensional time–frequency image. This diffuseness has been exacerbated by the use of arbitrary normalizations and the lack of statistical significance tests.

In Lau and Weng (1995), an excellent introduction to wavelet analysis is provided. Their paper, however, did not provide all of the essential details necessary for wavelet analysis and avoided the issue of statistical significance.

The purpose of this paper is to provide an easy-to-use wavelet analysis toolkit, including statistical significance testing. The consistent use of examples of

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