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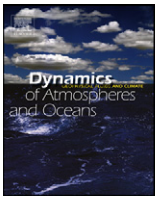

Wavelet-based verification of the quantitative precipitation forecast

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ABSTRACT

This paper explores the use of wavelets for spatial verification of quantitative precipitation forecasts (QPF), and especially the capacity of wavelets to provide both localization and scale information. Two 24-h forecast experiments using the two versions of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) on 22 August 2010 over Poland are used to illustrate the method.

Strong spatial localizations and associated intermittency of the precipitation field make verification of QPF difficult using standard statistical methods. The wavelet becomes an attractive alternative, because it is specifically designed to extract spatially localized features. The wavelet modes are characterized by the two indices for the scale and the localization. Thus, these indices can simply be employed for characterizing the performance of QPF in scale and localization without any further elaboration or tunable parameters. Furthermore, spatially-localized features can be extracted in wavelet space in a relatively straightforward manner with only a weak dependence on a threshold. Such a feature may be considered an advantage of the wavelet-based method over more conventional "object" oriented verification methods, as the latter tend to represent strong threshold sensitivities. The present paper also points out limits of the so-called "scale separation" methods based on wavelets.

Our study demonstrates how these wavelet-based QPF verifications can be performed straightforwardly. Possibilities for further developments of the wavelet-based methods, especially towards a goal of identifying a weak physical process contributing to forecast error, are also pointed out.

1. Introduction

Objective forecasts of precipitation are probably the most important operational product in practical applications. For this reason, the problem is often singled out as the quantitative precipitation forecast (QPF). Olson et al. (1995) provides a historical review of QPF. Fritsch et al. (1998), and Ebert et al. (2003) review more recent progress.

A particular challenge faced by the QPF is, along with understanding of the precipitating-system dynamics and the complexity of the cloud microphysics (*cf.*, Khain et al., 2015), to properly verify the numerical forecast results: see Casati et al. (2008), and Ebert et al. (2013) for relevant reviews on forecast verifications in general. The QPF verification poses

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particular problems not found with the other forecast variables, because the precipitation field is far more localized and intermittent in space and time. For example, a model forecast may properly predict the size and intensity of a precipitation system, but its center may be shifted from the observation. As a result, conventional verification measures such as the root-mean-square error would over-penalize such a forecast in spite of a successful prediction of the system itself.

In order to take these aspects into account, new types of QPF verification methods focused on the spatial structure of the precipitation have been developed over the last decade (Ahijevych et al., 2009; Gilleland et al., 2009; Rezacova et al., 2015). These methods have been classified in four groups: scale-separation method, neighborhood (or "fuzzy") verification approaches, object-oriented methods, and field deformation approaches. Scale-separation methods include Briggs and Levine (1997), Zepeda-Arce et al. (2000), Casati et al. (2004), Jung and Leutbecher (2008). The fractional skill score (FSS: Roberts and Lean, 2008; Zacharov and Rezacova, 2009) is one of the most used neighborhood verification approach. Ebert (2008) reviews the fuzzy verification methods. Specific examples of object-oriented methods are: contiguous rain area (CRA: Ebert and McBride, 2000; Ebert and Gallus, 2009), the method for object-based diagnostic evaluation (MODE, Davis et al., 2006a,b, 2009; Ahijevych et al., 2009), and the structure–amplitude–location approach (SAL: Wernli et al., 2008, 2009). Field deformation technique includes image warping (Gilleland et al., 2010) and optical flow (Keil and Craig, 2007, 2009; Marzban et al., 2009). This classification has however flexible boundaries: for example, the field deformation technique introduced by Keil and Craig (2007, 2009) is applied to spectral components, bridging a gap between the field-deformation and scale-separation techniques.

The focus of the object-oriented methods is to quantify how well a model forecast reproduces an observed precipitation system in size (scale), position, and amplitude (strength). A basic premise behind these methods, is to treat a precipitation system (*e.g.*, a storm event) as a solid "object". Effort is invested to quantify both a scale and a localization of an "object" simultaneously as accurately as possible.

Since the main focus of the object-oriented validation methods is on spatial-localization, wavelet comes out as a natural, basic tool. It is specifically designed by a set of modes for efficiently extracting such spatially-isolated structures. From this point of view, the object-oriented validation may more systematically be performed by wavelet. The purpose of the present paper is to pursue this possibility, and therefore bridging between scale separation and object-oriented verification techniques. The wavelet method allows one to address the various concepts utilized under the object-oriented validations under wider contexts. For example, the wavelet approach elucidates the fundamental limits (under the Heisenberg's uncertainty principle) of treating a precipitation system as a solid object, and re-define the concept of "object" in wavelet space.

Briggs and Levine (1997), Zepeda-Arce et al. (2000), Casati et al. (2004), and Casati (2010), have already applied wavelets to QPF verification. Among them, Zepeda-Arce et al. (2000) is closest to the spirit of the present study by exploring various wavelet-based statistical measures. However, as Gilleland et al. (2009) point out, the capacity of wavelets for providing both scale and localization information is yet to be fully explored in the QPF verification context. Current wavelet-based QPF verifications tend to take wavelet simply as a spatial filter for singling out a particular scale.

In order to pursue wide possibilities with wavelet, we adopt a discrete orthogonal set of wavelets, more precisely, the Meyer wavelet (Meyer, 1992). By adopting a discrete orthogonal wavelet rather than a more frequently-used continuous wavelet, various general advantages of the discrete orthogonal mode sets (as with the Fourier analysis) can easily be exploited. Those include a straightforward invertibility of the signals from the wavelet space back to the physical space, as emphasized by Yano et al. (2001a, 2004b). On the other hand, typical graphical representations based on continuous wavelet is often misleading by multiplying original data information amount in an arbitrary manner. The discrete wavelet avoids this trap by exactly conserving the amount of the original data information under wavelet transformation. As a standard reference on wavelet methods, see Mallat (1998).

This paper is constructed as follows. The next section reviews the study case and the two forecast cases to be examined, along with some basic analyses. Section 3 introduces the wavelet method, where we also emphasize how simultaneous characterizations of the scale and localization are constrained by Heisenberg's uncertainty principle. Section 4 presents a basic analysis of the variability in wavelet space. Section 5 presents an "object" analysis by exploiting the capacity of extracting a spatially-localized feature in wavelet space. Section 6, in turn, exploits the capacity of wavelet for quantifying a forecast quality scale by scale. The paper is concluded by a summary and discussions.

2. Study case and experiments

2.1. Model description

Our study is motivated from an analysis of forecast experiments performed by using the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) developed at Naval Research Laboratory (NRL: Hodur, 1997). Recently the model was upgraded (Hodur and Jakubiak, 2013) for the surface layer, boundary layer, turbulent kinetic energy, and moist physics parameterizations. Notably, more detailed surface databases based on the NASA-Goddard Land Information System (LIS: Mohr et al., 2013) are included.

The goal of the COAMPS project is to study the impacts of the parameterization of different physical processes on the forecast of mesoscale convection over central Europe during spring and summer months. For this reason, four additional test cases are run along with the run with the default COAMPS physics. Each forecast uses the three nested domains as shown in Fig. 1 with the horizontal resolutions of 18, 6, and 2 km for the outermost, middle, and innermost domains, respectively. A