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Universal Kriging of functional data: Trace-variography vs cross-variography? Application to gas forecasting in unconventional shales

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ABSTRACT

In this paper we investigate the practical and methodological use of Universal Kriging of functional data to predict unconventional shale gas production in undrilled locations from known production data. In Universal Kriging of functional data, two approaches are considered: (1) estimation by means of Cokriging of functional components (Universal Cokriging, UCok), requiring cross-variography and (2) estimation by means of trace-variography (Universal Trace-Kriging, UTrK), which avoids cross-variogram modeling. While theoretically, under known variogram structures, such approaches may be quite equivalent, their practical application implies different estimation procedures and modeling efforts. We investigate these differences from the methodological viewpoint and by means of a real field application in the Barnett shale play. An extensive Monte Carlo study inspired from such real field application is employed to support our conclusions.

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1. Introduction

Functional data analysis (FDA, Ramsay and Silverman, 2005) has gained renewed attention in the modeling of phenomenon that can be regarded as statistical observations displaying systematic variation. In particular in terms of time series, FDA has been considered as an alternative to multivariate analysis, where in FDA the data is seen as a single functional object with an underlying smooth dynamic that drives variation in time. While first applications have been in bio-informatics (see Ullah and Finch, 2013, for a recent review), FDA has been gaining attention both in the development of theory and in its application in the Earth & Environmental Sciences, for example in climate science (Besse et al., 2000), water resources (Josset et al., 2015; Satija and Caers, 2015), environmental science (Henderson, 2006; Yan et al., 2015; Sancho et al., 2015), oceanography (Nerini et al., 2010), land use (Besse et al., 2005) and geology (Manté and Stora, 2012; Menafoglio et al., 2014, 2015).

Particular to the application in the Earth Sciences is the spatial context and the need for spatial models for functional data, as has historically been developed in geostatistics (Matheron, 1969; Cressie, 1993). A recent body of theoretical work has been published, extending Ordinary Kriging to the functional case (e.g., Delicado et al., 2010; Nerini et al., 2010; Menafoglio et al., 2014; Menafoglio and Petris, 2015, and references therein). However, in several practical applications, there is a need to address phenomena that require non-stationary approaches in space. To address such need, Universal Kriging of spatial functional data has been proposed by Caballero et al. (2013); Menafoglio et al. (2013). An alternative approach to deal with non-stationarity is proposed by Ignaccolo et al. (2014).

In this work, we present a timely and economically important application of functional data, namely to the modeling and forecasting in unconventional shale resources. The term "unconventional" emanates from the way such resources are exploited: a sand–water mixture is injected into horizontal wells, fracturing nearly impermeable shale formations enabling production of commercially significant hydrocarbon volumes. Shale production can be considered as one of the driving factors for low oil/gas prices in 2015 (Mănescu and Nuño, 2015) which has put financial pressures on further resource development ("The Shale Industry Could Be Swallowed By Its Own Debt", Bloomberg news, July 18, 2015). As a consequence, technical innovation is required for such resources to remain competitive with conventional exploitation which tends to have lower costs. In addition, better modeling, understanding and more optimal drilling practices will lead to lesser environmental impact (see, e.g., Vidic et al., 2013). Part of such technical innovation lies in understanding the impact of the geological and hydraulic fracturing factors on production, which drives the spatial variability of production in wells. Due to the complexity involved, statistical approaches based on data are preferred over physical modeling approaches (Mohaghegh, 2011, 2013; Kormaksson et al., 2015; Grujic et al., 2015). Production rates in wells start from an initial peak in production right after hydraulic fracturing followed by a long multi-month decline. In this paper, we focus on modeling the spatial distribution of production decline rates only. The latter are commonly observed at discrete time points, at which the actual data are affected by a measurement error. In this case, a data preprocessing is required to obtain a set of smooth production rate curves from raw observations. This situation is quite common in FDA, and several smoothing methods are available in the literature, such as projection over a functional basis (e.g., Fourier, B-splines) or local polynomial smoothing (Ramsay and Silverman, 2005).

In this context, the first aim of this paper is to investigate the use of Universal Kriging of functional data to the spatial interpolation of gas production rate curves (GPRCs) which is required to estimate production for undrilled location. Here, we consider data from the prolific Barnett Shale and our dataset contains 922 wells drilled over the basin. Such dataset consists of functional data (decline rate) varying over space (geographic coordinates). Our second aim is to compare two approaches to the problem of functional Kriging: (1) estimation by means of Cokriging of the components over a functional basis (Universal Cokriging, UCok) which requires cross-variography, and (2) estimation by means of trace-variography (Universal Trace-Kriging, UTrK), which follows the approach of Menafoglio et al. (2013) and avoids cross-variogram modeling. The former constitutes an original extension to the non-stationary setting of the strategy of Nerini et al. (2010). Here, we show how to adapt the approach when relying upon a functional principal component analysis, that allows to