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Estimation of a non-stationary model for annual precipitation in southern Norway using replicates of the spatial field

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A B S T R A C T

Estimation of stationary dependence structure parameters using only a single realisation of the spatial process, typically leads to inaccurate estimates and poorly identified parameters. A common way to handle this is to fix some of the parameters, or within the Bayesian framework, impose prior knowledge. In many applied settings, stationary models are not flexible enough to model the process of interest, thus non-stationary spatial models are used. However, more flexible models usually means more parameters, and the identifiability problem becomes even more challenging. We investigate aspects of estimation of a Bayesian non-stationary spatial model for annual precipitation using observations from multiple years. The model contains replicates of the spatial field, which increases precision of the estimates and makes them less prior sensitive. Using `R-INLA`, we analyse precipitation data from southern Norway, and investigate statistical properties of the replicate model in a simulation study. The non-stationary spatial model we explore belongs to a recently introduced class of stochastic partial differential equation (SPDE) based spatial models. This model class allows for non-stationary models with explanatory variables

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in the dependence structure. We derive conditions to facilitate prior specification for these types of non-stationary spatial models.
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1. Introduction

At the core of any statistical analysis is the wish to learn about a process or phenomena based on available data. The purpose of the analysis can be to gain insight about the process of interest and/or make predictions related to this process. In this paper, we study annual precipitation in southern Norway, and we aim both to learn about this process from data, and make predictions at spatial locations without observations.

To be able to learn about a process from data we need a model that is (1) realistic, (2) interpretable, and (3) possible to draw inference from with the available data. For most realistic processes, compromises between these three aims are necessary. We can simplify the model, impose more knowledge or restrictions, or get more data. In this paper, we use a model that is based on physical understanding, but is very simplified. A Bayesian approach is taken, and knowledge about the system is expressed through carefully chosen prior distributions. Further, we are able to utilise more data to learn about the precipitation process by extending the model such that several years of annual precipitation observations can be used.

The precipitation process is driven by humidity, changes in circulations, weather patterns and temperature, as well as interactions with the topography. Southern Norway is separated by the mountain range Langfjella: to the west there is a mountainous coastline dominated by large fjords, while eastern Norway has a more gentle landscape consisting of valleys and lowlands. This topographical difference is reflected in the climate. Humid oceanic winds hit the west coast and are forced to ascend due to the mountains. The result is that the western part of Norway receives high amounts of precipitation, while the eastern part is relatively dry being located in the "rain shadow". This phenomenon is known as orographic precipitation. Statistical modelling and spatial prediction of precipitation in Norway are challenging tasks (Orskaug et al., 2011; Ingebrigtsen et al., 2014; Dyrrdal et al., 2015). In some areas there are large variations in the amount of precipitation within relatively short distances, while other areas are more homogeneous. These features can be explained by the physics of the precipitation process in a complex and diverse terrain.

The main purpose of precipitation interpolation in Norway is as input to hydrological forecasting models to predict run-off either for flood warnings or to better schedule hydro-power production. Because of the topography, most of the catchment (where prediction is of interest) is often in mountainous areas, while the precipitation gauges (observations) are located in lower areas due to easier and cheaper maintenance. It is not uncommon that all the closest precipitation gauges are at lower elevation than the lowest point of the catchment of interest. Since changes in elevation is one of the driving forces of precipitation, this causes a problem of non-preferential sampling, and to do spatial interpolation we will need to do extrapolation with respect to elevation. This calls for a model with a physical basis, and a way to tackle this challenge is to include elevation in the model.

A statistical model for annual precipitation over southern Norway should have two important properties. We have already argued that elevation should be included in the model. In addition, as locations close in space are more alike than locations further apart, the model should also include a spatial process. If the dependence structure of a spatial process changes within the domain it is defined, the process is non-stationary. Because of the complex Norwegian topography, it is reasonable to use a non-stationary spatial process, and that the non-stationarity depends on the topography.

A flexible and popular framework for statistical modelling is hierarchical models. The general scheme consists of two levels. The first level is the likelihood part, which specifies the model for the observations given a latent field. The second level specifies the model for the latent field, which can consist of several terms, e.g. a term for elevation and a spatial process. Both levels of the hierarchy

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