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# Monitoring the Landscape Freeze/Thaw State by Radar Remote Sensing: a Novel Sensor Fusion Approach Based on Hidden Markov Models

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The freezing and thawing of the landscape is closely interconnected with bio- and geophysical processes: e.g. the hydrologic cycle, trace gas exchange and the metabolic activity of plants and microbes. Consequently, observations of the dynamics of the Freeze/Thaw (T/W) state can be beneficial for various disciplines. Due to the scarcity of in-situ monitoring sites, remote sensing methods have been applied to observe the F/T state at large scales; in particular, microwave remote sensing has been shown to be an apt tool.

The sensitivity of the radar backscatter $\sigma^0$, as measured by scatterometers, to various influence factors depends strongly on the frequency. We thus propose a novel sensor fusion approach based on scatterometry observations in $C$ band (by ASCAT on MetOp) and $K_u$ band (by SeaWinds on QuikScat). As the dynamics of the F/T state vary considerably over different climatic zones and biomes and because of the irregular temporal sampling, probabilistic time series models are a promising tool due to their flexibility.

The model is an adaptation of the well-known Hidden Markov model (HMM) – the F/T state is assumed to be a Markov chain, whose value is not directly observable. It is a discrete variable, taking on the values 'frozen', 'non-frozen' and 'thawing'. The observables are modelled as random variables, whose probability distributions depend on the current state. The simple structure assures that inference can be done efficiently, e.g. the calculation of the probability of the state on a given day by the Forward-Backward algorithm. Our approach does not use training data; the parameters are estimated for each time series in an unsupervised fashion. This is achieved by maximizing the marginal likelihood in the framework of the Expectation Maximization algorithm. The choice of the parameterization and initial values as well as the conditional independence assumptions have a considerable impact on the results – it is where domain knowledge based on backscatter models and empirical data analysis comes into play.

We study the algorithm by testing it in the region of $120 - 130\,E$ and $50 - 75\,N$. This area in Russia and northern China covers a variety of biomes such as Tundra, Taiga and Steppe. The time series of the probability of the state are compared with in-situ snow and temperature data as well as global climate models. In general, the accuracy exceeds $90\%$, but the algorithm can fail in agriculturally used land (fields, pastures) and bare rock outcrops in mountainous regions. The benefits of using two different data sources become evident in certain cases, where correct classification based on a single frequency would be almost impossible.

The proposed algorithm yields satisfactory results in general, particularly in the Tundra and Taiga. Overall, the study confirms the importance of exploiting two different data sources in a systematic fashion. The key advantage of probabilistic models is their flexibility, so that the approach is applicable for large scale applications. The combination of a powerful mathematical framework with domain knowledge – which is, for example, used in the choice of initial values and constraints of parameters – is very promising. This approach for sensor fusion is very flexible: different sensors could easily be incorporated and there are many applications with the aim of detecting a dynamic, discrete state, such as the mapping of burnt or inundated areas.