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Integration of spatial functional interaction in the extrapolation of ocean surface temperature anomalies due to global warming

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ABSTRACT

The aim of this paper is to derive spatiotemporal extrapolation maps of ocean surface temperature to investigate two global warming effects: On the one hand, the reduction of daily heat fluxes from the sea into the air at the end of the day and during the night, in tropical regions. On the other hand, the strengthening of ocean current flows, due to the increase of ocean surface minimum daily temperature differences between two connected ocean regions. These maps are constructed from the spatial functional time series framework. Specifically, the spatial functional extrapolation of ocean surface temperature from Hawaii Ocean to the Gulf of México reflects an increase of Hawaii Ocean surface temperature in the last 15 years, caused by the reduction of daily heat fluxes from the sea into the air. Furthermore, for the two connected regions of Indian Ocean, and the eastern coast of Australia, the spatial functional extrapolation results derived show more pronounced differences between ocean surface minimum daily temperatures in the year 2003 than in the years 1995–1997. Thus, a strengthening of the flow of the East Australian Current is appreciated.

1. Introduction

It is well-known that advantages and limitations are present in the application of pure data synthesis and model/data integration approaches. For example, pure data synthesis methods are more sensitive (i.e., less robust) to the characteristics of measurement devices, or to blending procedures for data sets from different sensors, etc. Model/data integration can be performed following different approaches. In particular, physical ocean models can provide ocean surface temperature estimates that are consistent with the dynamical and thermodynamical constrains. However, a model error term reflecting unresolved physics is needed (also in relation to sub-griding parameterizations). Thus, physical modeling must be combined with stochastic modeling and statistical estimation.

In this paper, physical and stochastic modeling are integrated, and data-driven methodologies are applied to obtain a compromise between pure data synthesis and physical stochastic model fitting. Specifically, spatial functional time series modeling (see Ruiz-Medina, 2011) is applied for stochastic spatiotemporal extrapolation of ocean surface temperature. Under suitable conditions, this framework provides a statistical approximation of the usual physical equations governing sea surface temperature dynamics. In particular, recent studies of mid-latitude sea surface temperature dynamics are developed in terms of the thermal feedback between a two level atmospheric model and a dynamically passive slab ocean (see, for example, Nilsson, 2001). In this context, within the atmosphere coupled to a slab ocean modeling, the long-term evolution of sea surface temperature field (driven by air–sea transfer) is governed by an advective-diffusive equation, which can be applied to a broad class of atmospheric models. This fact constitutes our main motivation to consider the selected spatial functional time series framework intimately connected with the theory of diffusion equations (see Nualart and Sanz-Solé, 1979; Leonenko and Ruiz-Medina, 2006; Ruiz-Medina, 2011).

The main drawback of the applied framework is that functional data must be located on a regular spatial grid. Spatial averaging over the boxes of a computational grid is then performed to obtain a spatial lattice configuration. The grid box size is adjusted to the spatial distribution of weather stations. Spatial Autoregressive Hilbertian (SARH) model fitting (see Ruiz-Medina, 2012) is then performed for spatial functional extrapolation of ocean surface temperature profiles from the coastal weather stations to the deep ocean. The separable Hilbert-valued process context is crucial in the introduction of suitable orthogonal function bases allowing the implementation of numerical projection methods for dimension reduction in the high-dimensional data context. For example, in the implementation of the SARH(1) extrapolation methodology, the projection into the autocovariance eigenfunction system is considered in Ruiz-Medina and Espejo (2012), while the projection into the eigenfunction system of the SARH(1) parameters is applied in Ruiz-Medina (2012). In the mentioned approaches,

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in terms of projections, the operators defining the parameters of SARH(1) state equation are estimated without assuming any parametric form for them. In that sense, we will refer in the following to the non-parametric SARH(1) model fitting.

A crucial problem in the SARH(1) extrapolation implementation by projection is the selection of a suitable basis. Specifically, it is well-known that the projection into the autocovariance eigenfunction system leads to the maximum dimension reduction for a prescribed level of explaining variability, in absence of high correlated curves (see Ruiz-Medina and Espejo, 2012). While the eigenfunction system providing the spectral decomposition of the operators defining the infinite-dimensional parameters of the SARH(1) state equation leads to a regularization of the associated moment-based projected equation system, when its determinant is close to zero (see Ruiz-Medina, 2012). The projection methodology presented here, based on the discrete interval wavelet transform, removes strong spatial correlations between ocean surface temperature curves, due, for example, to high concentration level of weather stations. That is, in the wavelet domain, the projected covariance operators are defined in terms of infinite-dimensional sparse matrices. Hence, this domain allows to fit a spatial Markovian dependence to the functional data analyzed. Note that, in the approach presented, an underlying Markovian state space equation is assumed, where each functional value of the spatial process of interest is generated from the negative spatial lags of order one in the vertical, horizontal or diagonal directions (see also Remark 1 below).

The limitations of the linear modeling framework are well known, but allows, as commented before, the representation of some features that are commonly present in the interaction between sea surface temperature anomalies and the atmosphere. In particular, in relation to our objective of detecting anomalies in the velocity decay of the daily ocean surface temperature curves at the end of the day and during the night, it is essential to have a spatial extrapolation method that reflects the global interaction between different locations of the daily temperature curves. The same global prediction in space of daily temperature curves is needed in the detection of increase daily functional trends in ocean surface temperature. This global daily temporal information, that is needed to be spatially extrapolated, constitutes the motivation of the presented stochastic spatial functional extrapolation methodology, based on Spatial Autoregressive Hilbertian models. Note that classical statistical methodologies, based, for example, in kriging interpolator or Generalized Linear Mixed models do not provide spatial extrapolation of daily temperature functional evolution, as well as information on spatial propagation of micro-scale temporal features is lost. As commented before, in our approach, spatial Markovian interaction is assumed according to the spatial unilateral dynamics displayed by Spatial Autoregressive Hilbertian processes of order one (SARH(1) processes), see Eq. (1) below, in contrast with the spatial functional extrapolation methodologies recently developed in absence of an underlying state-space model (see, for example, Delicado et al., 2010; Giraldo et al., 2010; Monestiez and Nerini, 2008; Nerini et al., 2010). One of the main reasons for considering a state-space-based spatial functional framework is the integration of the physical law in the stochastic modeling approach, allowing the derivation of spatial functional extrapolators, requiring the incorporation of a spatial dynamics or association. In our case, SARH(1) processes can be constructed from irregular spatial functional sampling of two-parameter diffusion processes, in the class introduced by Nualart and Sanz-Solé (1979), including the two-parameter Ornstein-Uhlenbeck process (see Ruiz-Medina, 2012). Note that the so-called linear Gaussian state-space model framework has been extensively studied in the literature (see, e.g., Durbin and Koopman, 2001, and references therein). For example, Ide et al. (1997) proposed unified notations for state-space models and data assimilation in oceanography and meteorology, which also were partially adopted by Tandeo et al. (2011).

Returning to our initial goal, global warming alters air temperature faster, decreasing the differences between ocean and air surface temperatures. Thus, heat fluxes from the sea into the air are reduced. In particular, coastal ocean surface temperature increases. The designed spatial functional stochastic inter/extrapolation methodology is applied to the construction of mean annual daily ocean surface temperature maps to investigate global warming effects. Specifically, as commented, two global warming effects are investigated. First, the damping of sea–air temperature differences is studied over the connected mid-latitude ocean and coastal regions of Hawaii Ocean and the Gulf of México. Additionally, an increase trend in ocean surface temperature can be appreciated along the time, due to global warming. This effect is studied in relation to the increase of Australian Ocean surface temperatures, and the pronounced differences between the western and eastern Australian sea temperatures, jointly with the fact that the flow of the East Australian Current has strengthened in the past years, altering marine biodiversity.

2. Areas studied and data

The performance of the proposed spatial functional time series methodology for stochastic inter/extrapolation of the mid-latitude ocean surface temperature dynamics is tested, considering the spatiotemporal extrapolation problem associated with the construction of a daily ocean surface temperature map from Hawaii Ocean (latitude–longitude interval $[16, 32] \times [-170, -140]$) to the Gulf of México (latitude–longitude interval $[16, 32] \times [-100, -80]$), and from Indian Ocean (latitude–longitude interval $[-34, -15] \times [75.4, 99.5]$) to the Pacific Ocean at the eastern coast of Australia (latitude–longitude interval $[-20, -4] \times [136, 153]$).

We briefly comment why we have selected these regions in our study. Extreme temperature series of the Gulf of México reveals the presence of periodicities similar to those found in meteorological and solar activity phenomena (see, for example, Maravilla et al., 2008, in relation to Maximum Entropy based analysis). This fact suggests that the solar activity signals are possibly present in the minimum extreme temperature records of this Mexican region. Since the Gulf of México constitutes the most plausible source location of the anomalous waters observed in the Hawaii Ocean surface temperature, both regions are analyzed in this paper. In particular, the derived mean annual daily temperature maps reveal the damping through time of sea–air temperature differences, due to global warming. Additionally, the influence of Indian Ocean sea-surface temperature variability on winter rainfall across eastern Australia is also well-known. Therefore, we also study these regions connected by the ocean surface temperature maps obtained by SARH(1)-based stochastic extrapolation. In particular, we investigate the possible increase of western and eastern ocean Australian temperature differences, due to the fact that eastern Australian waters warming faster than Indian Ocean.

3. Computational methodology

The details on the implementation of the spatial functional time series model framework for stochastic inter/extrapolation of temperature profiles are now provided. First, we introduce the class of SARH(1) models fitted.

Definition 1. A spatial functional process $\mathbf{Y}_{\text{SARH}} = \{Y_{ij},\ (i, j) \in \mathbb{Z}^2\}$, with values in a separable Hilbert space $\mathcal{H}$, is said to be a unilateral