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Lead–lag relationships between global mean temperature and the atmospheric CO_2 content in dependence of the type and time scale of the forcing

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ABSTRACT

By employing an Earth system model of intermediate complexity (EMIC) developed at the A.M. Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences (IAP RAS CM), mutual lags between global mean surface air temperature, *T* and the atmospheric CO_2 content, *q*, in dependence of the type and time scale of the external forcing are explored. In the simulation, which follows the protocol of the Coupled Models Intercomparison Project, phase 5, *T* leads *q* for volcanically-induced climate variations. In contrast, *T* lags behind *q* for changes caused by anthropogenic CO_2 emissions into the atmosphere. In additional idealized numerical experiments, driven by periodic external emissions of carbon dioxide into the atmosphere, *T* always lags behind *q* as expected. In contrast, if the model is driven by the periodic non-greenhouse radiative forcing, *T* leads *q* for the external forcing time scale $\leq 4 \times 10^2$ yr, while *q* leads *T* at longer scales. The latter is an example that lagged correlations do not necessarily represent causal relationships in a system. This apparently counter-intuitive result, however, is a direct consequence of i) temperature sensitivity of the soil carbon stock (which decreases if climate is warmed and increases if climate is cooled), ii) conservation of total mass of carbon in the system in the absence of external carbon emissions, iii) increased importance of the oceanic branch of the carbon cycle at longer time scales. The results obtained with an EMIC are further interpreted with a conceptual Earth system model consisting of an energy balance climate model and a globally averaged carbon cycle model. The obtained results have implications to the empirical studies attempting to understand the origins of the contemporary climate change by applying lead–lag relationships to empirical data.

1. Introduction

According to the available evidence, the Earth system has warmed during the last century: the overall change associated with a trend of the global mean surface air temperature is 0.85 K (with an uncertainty range from 0.65 to 1.06 K) during 1880–2012 and as large as 0.72 K (with an uncertainty range from 0.49 to 0.89 K) during 1951–2012 (Hartmann et al., 2013). The major contribution to this warming is a man-made greenhouse effect with the additional, sometimes compensating contribution of other anthropogenic activities such as release of aerosols and other chemical constituents into the atmosphere, and land use (Bindoff et al., 2013). This is supported by different lines of evidence including empirical models (Lean and Rind, 2008; Mokhov and Smirnov, 2009; Smirnov and Mokhov, 2009; Schönwiese et al., 2010; Mokhov et al., 2012; Canty et al., 2013; Mikšovský et al., 2016) and applications of the fingerprinting technics to simulations with global climate models (Hegerl et al., 1997; Stott et al., 2001; Stone et al., 2007; Stone et al., 2009; Sedlacek and Knutti, 2012; Jones et al., 2013; Ribes and Terray, 2013).

However, other hypothesis for origins of the ongoing climate change exist, in which the major contribution to this change is attributed to natural causes. The most well-known are the hypotheses either explaining this warming as a solar-induced signal

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