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Relation between isotopic composition of precipitation and atmospheric circulation patterns

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SUMMARY

Precipitation generating processes depend on atmospheric circulation patterns and consequently it is expected that its water stable isotopic composition of hydrogen and oxygen is related to them. Precipitation generated at similar atmospheric circulation patterns should have similar empirical distribution of δ^2H and δ^{18}O values. Mathematical model based on the linear combination of δ^2H and δ^{18}O values and on precipitation amount weighted average related to elementary air circulation mechanisms – ECM is proposed. The model enables estimation of average δ^2H and δ^{18}O values and their standard deviation for the precipitation generated at distinctive atmospheric circulation patterns. Approach in which atmospheric circulation patterns were classified as ECM based on the Dzerdzeevskii classification was applied. Application of the model is illustrated on the long term precipitation record from Ljubljana GNIP station Slovenia. Estimated values of the parameters for empirical distributions of δ^2H and δ^{18}O of each ECM subtype have shown that calculated estimates are reasonable. Further applications of the proposed model enable new insight into the understanding of isotopes spatial and temporal distribution in precipitation important also for better understanding of climate proxies.

1. Introduction

During studying isotopic composition of the precipitation frequently efforts have been made to elucidate the origin and transport path of water vapour resulting in precipitation at particular location (Liotta et al., 2006; Peng et al., 2005; Vreča et al., 2007) or over certain geographical region (Friedman et al., 2002; Rindsberger et al., 1983; Treble et al., 2005) or globally (Jouzel et al., 2000). It is widely accepted that isotopic composition of precipitation can help to understand the precipitation processes in the atmosphere (Craig and Gordon, 1965; Dansgaard, 1964; Gourcy et al., 2005). Several efforts can be found in the literature to understand also how the origin of the water vapour in the precipitation influences its isotopic composition (Araguas-Araguas et al., 2000; Craig, 1961; Gat, 1996) as well as what is the influence of other meteorological processes and variables on precipitation isotopic characteristics (Rozanski et al., 1993; Liebminger et al., 2007; Siegenthaler and Oeschger, 1980). The interpretation of isotopic composition of precipitation is not straightforward; usually it consists of combination of physical approach based on the understanding of various fractionation processes (Gat, 2005, 2010) and on the interpretation of meteorological conditions resulting in precipitation event (Gedzelman and Arnold, 1994; Lykoudis et al., 2010).

Samples of precipitation for isotope analyses can be collected at various time scales. Most frequent time collection interval is one month. This is the case with International Atomic Energy Agency precipitation sampling program Global Network of Isotopes in Precipitation – GNIP which started in 1961 and resulted in large data base of precipitation isotopic characteristics from the meteorological stations around the globe (Gourcy et al., 2005; Schotter et al., 1996). Monthly samples represent a composite of all the precipitation events for the particular month. Interpretation of the isotopic data on the monthly basis become challenging when sample is a result of several precipitation events and different atmospheric circulation patterns especially at those places where precipitation genesis is a result of water vapour originating from different sources with distinctive isotopic signal. Isotopic composition of

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Nomenclature

A	slope of the regression line	$N(P_j)$	number of precipitation ECM j events
B	intercept of regression line	n	number of months in time series
c	isotopic composition in (‰)	P	precipitation amount in (mm)
$\bar{c}$	overall average isotopic composition in (‰)	$\bar{P}_j$	average precipitation amount of ECM j event in (mm)
d-excess	deuterium excess in (‰)	p	consecutive precipitation event in the i month
i	consecutive month	s	standard deviation
j	consecutive ECM	var	variance
e	number of precipitation events	x	share
f_j	frequency of ECM j event in (%)	x_{ECM}	share of ECM in (%)
$f(P_j)$	frequency of precipitation ECM j event in (%)	NM	northern meridional
m	number of distinctive ECMs in time series	LW	longitudinal western
$\max(P_j)$	maximum precipitation amount of ECM j event in (mm)	SM	southern meridional
$\mathrm{Me}(P_j)$	median precipitation amount of ECM j event in (mm)	SP	stationary position
N	total number – count		

precipitation is the consequence of the complex weather and climatic conditions where not only knowledge of one particular meteorological parameter is needed but the whole weather situation should be known. It can be expected that precipitation which is the consequence of particular atmospheric circulation pattern has isotopic characteristics distinctive to other atmospheric circulation patterns and that similar precipitation generating atmospheric circulation patterns generates precipitation with similar isotopic composition.

There are several classification approaches based on the atmospheric circulation patterns (see Section 2). Among these classifications some are available for relatively long time periods and they can represent a firm basis for the interpretation of isotopic composition of precipitation record for longer time periods. Information about isotopic characteristics of precipitation generated at certain atmospheric circulation pattern is important; it can help to understand isotopic composition of precipitation and at the same time knowledge of isotopic composition of precipitation generated at certain atmospheric circulation pattern can help to understand source of water vapour and genesis of precipitation. In longer time period different patterns of atmospheric circulation appear with different frequencies, therefore we can expect that isotopic characteristics of precipitation events generated at certain atmospheric circulation pattern resulted in empirical distribution which can be characterised by the statistical measures of average and standard deviation.

In the paper mathematical model for the estimation of average stable isotopic composition reported for stable oxygen ($\delta^{18}O$) and deuterium ($\delta^{2}H$) in precipitation generated at different atmospheric circulation patterns is represented. Consistency of the proposed model and consequently calculated average and standard deviation of $\delta^{18}O$ and $\delta^{2}H$ as well as deuterium excess for these atmospheric circulation patterns are checked by observing seasonally dependent groups of the atmospheric circulation (winter, summer, mixed) and by groups dependent on the incoming air flow direction (southern, northern, western, stationary) over the observation station. Proposed model was applied on long-term isotope precipitation record for Ljubljana GNIP station Slovenia (Vreča et al., 2008, 2014) and atmospheric circulation patterns were defined according to Dzerdzeevskii classification of elementary circulation mechanisms – ECM. (Dzerdzeevskii et al., 1946; Dzerdzeevskii, 1962; Kononova, 2009, 2010). According to the best of the author's knowledge this is the first application where isotopic composition of precipitation is related to atmospheric circulation patterns classified with ECMs under which precipitation is generated.

2. Theory and methods

2.1. Classification of atmospheric circulation patterns

There are several approaches in classification of atmospheric circulation patterns and they can be divided into three groups; (a) subjective classifications, (b) mixed classifications, and (c) numerical classifications (Huth et al., 2008). In spite of all numerical and computer techniques those subjective manual classifications are among the most frequently used in meteorological practice (Huth et al., 2008). They are also classifications with the longest available sets of data, some of them spanning for more than hundred years. Such classification can be established only by the skilful interpreter who analyses all the available meteorological data (e.g. synoptic maps, pressure maps, satellite images, physical parameters, etc.) at the disposal and who at the end of the classification processes decides for the classification category of the analysed time period. However, the weak point of this approach is certain level of the subjectivity and dependence on the interpreter's experiences and skills.

Some of atmospheric circulation patterns are established only for particular countries or larger territories and only a few exist over the whole Northern hemisphere (Sepp and Jaagus, 2002; Huth et al., 2008). Among hemispheric classifications are most known, established and recognised Russian classification approaches of Wangengeim–Girs (Wangengeim, 1952; Girs, 1974) and Dzerdzeevskii (Dzerdzeevskii et al., 1946; Dzerdzeevskii, 1962). These classifications are currently applied in many theoretical and applied studies (Kononova, 2009, 2010). Those classification schemes are usually represented by calendar dates (e.g. days, weeks or months). For certain time periods of several decades catalogues of these classifications were established and are published (e.g. Werner and Gerstengarbe, 2010; Kononova, 2009).

The Dzerdzeevskii classification characterises the entire Northern Hemisphere and trajectories of cyclones and anticyclones over specific regions. By the classification 41 elementary circulation mechanisms – ECM are defined. They differ in direction and quantity of air flow blocking mechanisms and have different numbers of southern cyclone outlets. Each ECM has unique cyclone and anticyclone trajectory pattern which is described within the particular classification. ECMs are grouped in 4 groups and 13 types with subtypes; altogether 41 ECMs. First group is defined as *zonal*, second group is defined as *zonal disturbance*, the third group is defined as *northern meridional*, and the fourth group is defined as *southern meridional*. In the *zonal* group ECM categories numbered as *1* and *2*