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Climatological simulation of Stable Water Isotopes with COSMOiso

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Motivation

Stable water isotopes ($H_2{}^{16}O$, $HD^{16}O$, $H_2{}^{18}O$) are a powerful means for better understanding the global water cycle. They are naturally available tracers of moisture in the atmosphere and can provide valuable information about the history of air parcels. This is due to their different mass and symmetry, which leads to quantum mechanical effects during phase transitions, termed isotopic fractionation. Heavy isotopes occur preferentially in the liquid and solid phases and the light isotopes in the vapour phase. This partitioning leads to a progressive isotopic evolution of air parcels in the atmosphere. Most fundamental is the increasing isotopic depletion of drying air as it is transported from the ocean to the land (Figure 1). However, the processes influencing the isotope signals measured in water vapour and precipitation are complex and still need further investigation. This is where numerical models can help.

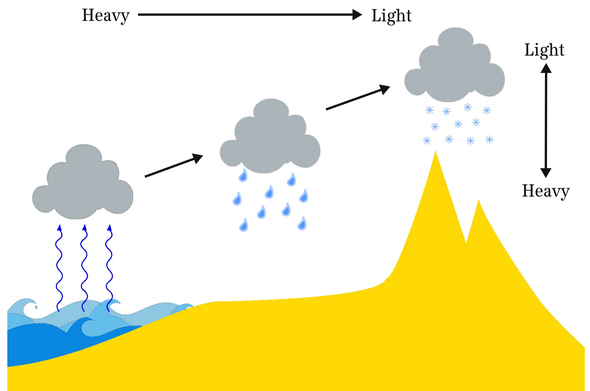

Figure 1: Partitioning of stable water isotopes depending on distance from the ocean and altitude.

Definitions

The isotope ratio R is defined as the ratio between the concentrations of the heavy and the light isotope:

$$ {}^{18}\mathrm{R} = \frac{[\mathrm{H_2^{18}O}]}{[\mathrm{H_2^{16}O}]} \qquad {}^{2}\mathrm{R} = \frac{[\mathrm{HD^{16}O}]}{[\mathrm{H_2^{16}O}]} $$

Conventionally, isotope ratios are expressed relative to the Vienna Standard Mean Ocean Water (V-SMOW) ratio R_{std}, which has been defined by the International Atomic Energy Agency (IAEA):

$$ \delta = \left(\frac{\mathrm{R}_{sample} - \mathrm{R}_{std}}{\mathrm{R}_{std}} \right) \cdot 1000‰ = \left(\frac{\mathrm{R}_{sample}}{\mathrm{R}_{std}} - 1 \right) \cdot 1000‰ $$

Equilibrium effects

- Result from a reversible process (A <=> B)
- Heavy isotopes generally have higher binding energies, thus they prefer stronger bonds (solid > liquid > vapour)
- Mainly determined by temperature: It is strongest in a cold environment and disappears in a very warm environment.
- Stronger for $HD^{16}O$ than for $H_2{}^{18}O$.

Nonequilibrium effects

- Result from an irreversible process (A -> B).
- Heavy isotopes have a slower diffusion velocity -> need more time to reach equilibrium state.
- Stronger for $H_2{}^{18}O$ than for $HD^{16}O$.

Nonequilibrium effects can be quantified in terms of the Deuterium excess (d-excess):

$$ d = \delta\mathrm{D} - 8 \cdot \delta^{18}\mathrm{O} $$

Model Description

In the isotope-enabled version of COSMO a parallel hydrological cycle is introduced that is used as a purely diagnostic tool and does not affect other model components. All prognostic moisture fields are duplicated twice for each of the heavy isotopes. They are affected by the same physical processes as the light isotope, i.e. they are transported by winds and contribute to the formation of clouds and precipitation. The only difference appears during phase transitions, when isotopic fractionation takes place. Details about the implementation can be found in Pfahl et al. (2012)

References

Aemisegger, F. (2013). Atmospheric stable water isotope measurements at the timescale of extratropical weather systems. PhD thesis, Swiss Federal Institute of Technology, Zurich, Switzerland.

IAEA/WMO (2011). Global Network of Isotopes in Precipitation, the GNIP database. http://www.iaea.org/water.

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Yoshimura, K., Kanamitsu, M., Noone, D., and Oki, T. (2008). Historical isotope simulation using Reanalysis atmospheric data. J. Geophys. Res., 113:D19108.

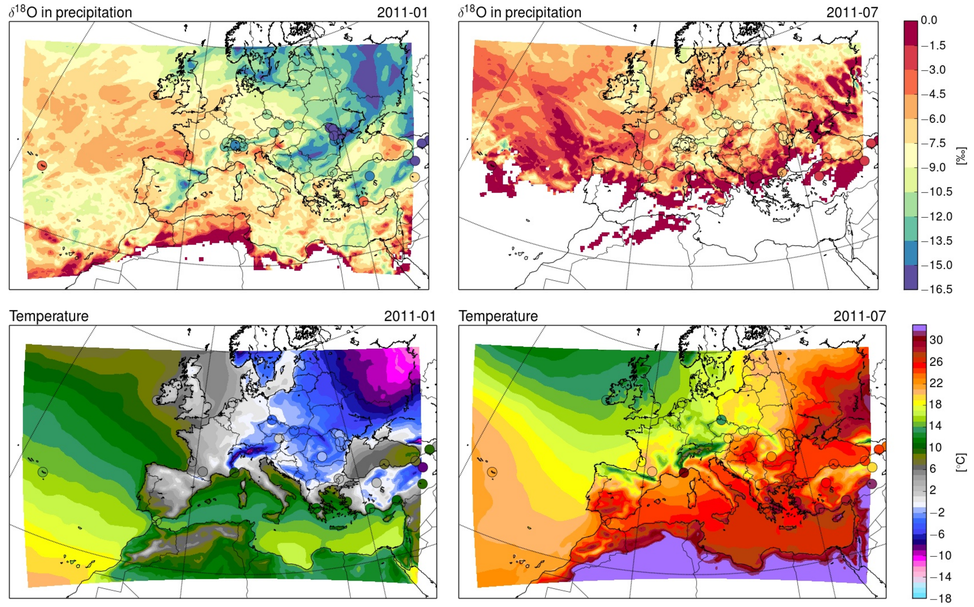

Figure 4: Monthly mean of $\delta^{18}O$ in precipitation and monthly mean 2m temperature from the COSMOiso simulation in January 2011 (left) and July 2011 (right). The circles represent the measurements from the Global Network of Isotopes in Precipitation (IAEA/WMO, 2011).

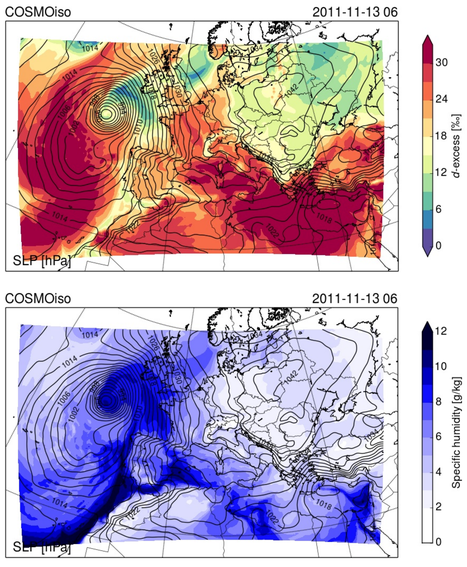

Figure 2: d-excess (top) and specific humidity (bottom) at the lowest model level of COSMOiso on 13 Nov 2011 06:00 UTC.

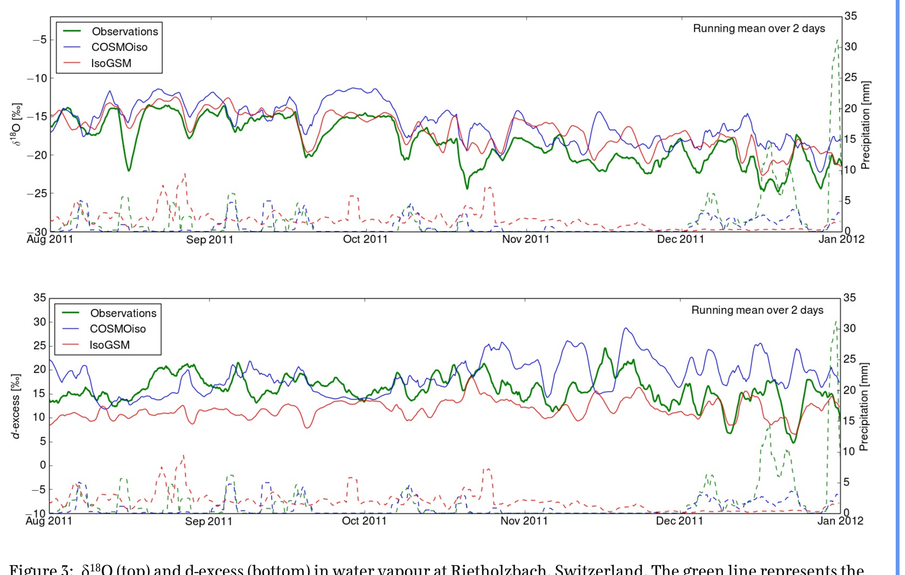

Figure 3: $\delta^{18}O$ (top) and d-excess (bottom) in water vapour at Rietholzbach, Switzerland. The green line represents the measurements from Aemisegger (2013), and the blue and red lines are the simulated values from COSMOiso and an isotope-enabled general circulation model (IsoGSM, Yoshimura, 2008), respectively. The dashed lines show 6h-accumulated precipitation.

Conclusions

- The isotopic signal in winter 2011 is more depleted than in summer 2011, due to the lower temperatures and thus stronger isotopic fractionation
- The increasing depletion of precipitation with increasing distance from the ocean (continental effect) and increasing altitude (altitude effect) is represented in the GNIP measurements, as well as in the COSMOiso simulation
- The isotope ratios simulated by COSMOiso agree well with the measurements, both in water vapour and precipitation. The d-excess in autumn is slightly overestimated by COSMOiso

Outlook

COSMOiso opens new possibilities to investigate the variability of stable water isotopes on the time scale of weather events. The isotopes moreover provide additional constraints on moist processes in the model. In the future, COSMOiso will be applied to study the isotopic pattern associated with fronts and convective systems, which will help to improve our understanding of the complex isotopic processes.