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In situ measurements of tritium evapotranspiration (^3H-ET) flux over grass and soil using the gradient and eddy covariance experimental methods and the FAO-56 model

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ABSTRACT

The behaviour of tritium in the environment is linked to the water cycle. We compare three methods of calculating the tritium evapotranspiration flux from grassland cover. The gradient and eddy covariance methods, together with a method based on the theoretical Penmann–Monteith model were tested in a study carried out in 2013 in an environment characterised by high levels of tritium activity. The results show that each of the three methods gave similar results. The various constraints applying to each method are discussed. The results show a tritium evapotranspiration flux of around 15 mBq m^{-2} s^{-1} in this environment. These results will be used to improve the entry parameters for the general models of tritium transfers in the environment.

1. Introduction

Tritium (^3H) is a hydrogen isotope and its behaviour in the environment is therefore determined mainly by the hydrological cycle. An in-depth understanding and quantification of the processes determining the flow of water through the soil–-plant–atmosphere system are therefore essential prerequisites for modelling ^3H transfers in terrestrial ecosystems. One of these processes, evapotranspiration (ET), is an important component of the hydrological cycle, and one which affects the water balance of all vegetated landscapes. A better knowledge of ET is an important factor in improving management of irrigation or water utilisation in agriculture, for example. There are several methods available to measure the ET of land surfaces directly. These include the gradient, eddy covariance and closed chamber methods (Steduto et al., 2002). The eddy covariance method (EC) is capable of directly measuring fluxes of water vapour, and is often used to calculate the annual ET (Baldocchi, 2003; Burba and Verna, 2001; Burba and Anderson, 2007; Zhang et al., 2014). The EC method has the advantage of acquiring real time measurements for use in evapotranspiration calculations over short time intervals for any type of heterogeneous surface. The EC method has been used successfully over the last decade to measure evaporation from watersheds, grasslands, lakes, and irrigated fields. The EC method is simple in theory but very difficult to use in practice as great care is needed when setting up the fast response instruments required for measuring vertical velocity and specific humidity fluctuations, and when post-processing the data. The gradient method (Perez et al., 1999; Todd et al., 2000; Uddin et al., 2013) is an indirect method based on the measurement of a scalar of interest in the surface layer at two different levels. In our case, the chosen scalar is the HTO vapour water at two levels. This method requires specialised and expensive equipment, together with great care in the sampling and

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measurement process. It requires a great deal of attention, making it unsuitable for use over long periods of time.

In addition to these two experimental methods, models are also available that can be used to calculate the ET from meteorological parameters alone, which are much easier to acquire. These include for example the Hargreaves model (Hargreaves and Allen, 2003; Irmak et al., 2012), the Turc model (Turc, 1961), and the FAO-56 methodology from the Penman–Monteith theory (Allen et al., 1998) which is currently the preferred method.

Since few years, an increased interest of tritium risk assessment produced a series of dedicated tritium research. The Canadian Nuclear Safety Commission (CNSC) generates a "Tritium Study" (CNSC, 2010). Simultaneously, the French Nuclear Authority initiated a study and recently published its results in the so-called "White Book e Tritium" (ASN, 2010). We can also note the important work of the working group 7 from IAEA on the transfer of tritium in the environment after an accident (IAEA, 2014).

The French Institute of Radioprotection and Nuclear Safety (IRSN) is currently studying tritium exchanges between the various compartments of the environment, and is seeking to improve understanding of the mechanisms operating at the interfaces between the air, soil and plants, with the aim of developing a dynamic compartment model (TOCATTA-χ). This model has been implemented in the SYMBIOSE modelling and simulation platform (cofunded by IRSN and Electricité de France EDF). This platform aims to assess the fate and transport of radionuclides in the environment (Gonze et al., 2011). The TOCCATA model has been validated from experimental data for ^{14}C (Aulagnier et al., 2012; Le Dizès et al., 2012), and is currently being tested and improved for ^{3}H.

The aim of this work has been to quantify a ^{3}H evapotranspiration flux experimentally using the EC and gradient methods. An original feature of this work is the simultaneous measurement of evapotranspiration (water flux) and ^{3}H concentrations (in the form of HTO) in the ecosystem being studied (grass and air), with the aim of calculating the ^{3}H evapotranspiration flux. This is the first time that the ^{3}H ET on grassland has been experimentally quantified.

We have implemented both the gradient and eddy covariance (EC) experimental methods, and installed a meteorological data acquisition system in order to calculate the ET using the model FAO-56 (Allen et al., 1998). The results are expressed in terms of the ^{3}H flux evaporated by the plant cover (grass) in Bq m^{-2} s^{-1}. The experimental work was carried out close to the city of Pembroke (Ontario, Canada), on a site with significant ^{3}H activity in the grass and soil of over several hundreds Bq per litre of water (Thompson et al., 2015).

The following approach was adopted:

- Evaluation of the ^{3}H flux using the gradient method in which the activity of the ^{3}H in the airborne water vapour was measured at two different heights. The micrometeorological parameters were taken into account when calculating the flux.
- Evaluation of the ^{3}H flux by calculating the water flux through the plant cover using the eddy covariance (EC) method and the measured concentration of ^{3}H in the grass/soil ecosystem.
- Evaluation of the ^{3}H flux using the FAO-56 Penmann–Monteith model (Allen et al., 1998) to calculate the water flux from micrometeorological data measured at the site, and using the concentration of ^{3}H measured in the grass/soil ecosystem.

The objective was to calculate the ET flux using each of these methods and to compare the results in order, in the future, to yield an accurate evaluation of the ^{3}H ET in grassland over a long period of time using the most suitable method given the constraints applying to each.

2. Equipment and methods

2.1. Site description

The experimental site is located in the province of Ontario, Canada, approximately 200 km west of Ottawa (Fig. 1), and close to the city of Pembroke (45.8047° N, 77.1179° W). The site is adjacent to a factory operated by SRB Technology, since 1991 one of the few companies in the world manufacturing gaseous ^{3}H light sources for emergency lighting and similar applications. As a result of this manufacturing process, emissions of gaseous ^{3}H in the form of HTO and HT (17.8 TBq of HTO and 61 TBq of HT in 2013, SRBT, 2014) are released into the air by 11 m stack height, generating detectable ^{3}H activity in the environment, including the air, water, soil and plants. The levels of ^{3}H around the site are monitored by the company and by the Canadian Nuclear Safety Commission (CNSC). In 2013, passive monitoring samplers reported annual mean levels of HTO activity ranging from 310 to 8490 mBq m^{-3} at positions around the site, with a monthly maximum of 21,500 mBq m^{-3}. Sampling points located between 6 and 16 km from the site indicated levels of between 270 and 360 mBq m^{-3} (SRBT, 2014). In plants, the levels of tissue free water tritium (TFWT) around the site ranged from 100 to 4000 Bq L^{-1}. HTO levels in free water measured in 2013 in the soil around the site varied between 106 and 373 Bq L^{-1} (IRSN, 2014).

The experimental site chosen for the estimation of ^{3}H flux as part of this work was an area of grassland approximately 120 m by 250 m, oriented north-west/south-east, and located 250 m to the south-east of the SRBT factory (Fig. 2). The plant cover was homogeneous grass, approximately 20 cm in mean height, with a maximum of 30 cm about. Grass cover the whole of the field. On the western part of the experimental field, there is a very large field (0.7 km × 0.3 km) of bare soil at the time of experiment. In the east part, we find a large area (1.5 km × 0.8 km), constituted by grass at 90%, crossed by a road, with few industrial building.

2.2. Field measurements

The measurements given here were made over a 24 h period from 15:00 on the 24/06/2013 to 15:00 on the 25/06/2013. The micrometeorological parameters of wind speed u (m s^{-1}), wind direction (°), friction velocity u^* (m s^{-1}), Monin–Obukhov length LMO (m), temperature (°C), heat sensible flux (W m^{-2}), and precipitation (mm) were obtained from measurements using a Young 81000V 3D ultrasonic anemometer and a Watchdog 2000 weather station at 2 m height. Acquisition was made at 10 hz, with mean of 1 min for anemometer. Samples of airborne water vapour for the HTO measurements were taken over period of 45 min every two hours at heights of 0.2 m and 2 m using H3R7000 tritium condenser systems (SDEC, France) mounted on stepladders.

The concentrations of water vapour in the air were measured continuously at a height of 2 m using an LI-7200 infrared gas analyser (LICOR Inc.) connected to a Young 8100V 3D ultrasonic anemometer.

During the measurement cycle, ten closed chambers were distributed around the test site in order to measure the quantity of HTO from soil/plant evapotranspiration in the air trapped just above the grass. For that, a small passive sampler was installed in each chamber, together with a hygrometer (Caldeira Ideias et al., 2013, 2014). The passive sampler developed for this purpose consisted of a small enclosure designed with a patented specific geometry and containing a 13× molecular sieve. This system is based on the free diffusion flow principle (Fick's law). The driving force is the partial pressure gradient existing between the environmental atmosphere and the passive sampler. The constant sampling rate under varying moisture conditions ensures that the device is representative (Caldeira Ideias et al., 2013). A desorption process