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Dear Editor,

Response to comment on "Tracing the sources of water using stable isotopes: first results along the Mangalore-Udupi region, south-west coast of India"

We thank Ramesh *et al.* for their comments^[1] on our original paper.^[2] The task of tracing the source of water along the tropical coast at the foot of the Western Ghats is not a simple one. We collected many water samples from shallow groundwater and river water on three different dates, in order to investigate whether there was a dual monsoon influence, i.e. the wet summer monsoon and the drier winter monsoon. We have attempted to answer the queries of Ramesh *et al.* paragraph by paragraph, before ending with a general conclusion.

Paragraph 1

Ramesh *et al.*^[1] refuted our contention that our paper^[2] reported the first use of stable isotopes to study rainfall in the Mangalore-Udupi region, as they claimed to have reported such a use in an earlier paper.^[3] However, as their article referred only to ¹⁸O measurements and not to deuterium measurements, our claim is still valid. In addition, a bibliographic search made using the keywords 'isotopes' and 'Mangalore' did not locate that earlier article. The title of that article, "A positive 'amount effect' in the Sahayadri (Western Ghats) rainfall", did not indicate that it dealt with the oxygen isotopic signal of rainfall over Mangalore.

To our knowledge, there are no direct GNIP datasets from Mangalore. Data can be obtained only by interpolation of the data from Belgaum (320 km North), Bangalore (290 km East) and Kozhikode (200 km South).

The statement is made by Ramesh *et al.* that "significant difference in the d-excess values between the two monsoons" (dual monsoon) has only been observed by Lambs *et al.* However, such differences have been reported in at least three other papers (Warrier *et al.*,^[4] Deshpande *et al.*,^[5] and Sengupta and Sarkar^[6]).

(Note that the link (www.iaea.org.water) for the IAEA Isotope Hydrology Information System given in Ref. [3] of the paper by Ramesh *et al.*^[1] is no longer valid and the correct link is now http://nds121.iaea.org/wiser/)

Ramesh *et al.*^[1] showed (their Table 1) d-excess values of various places over the Indian subcontinent, with quite different climatic behavior: Haryana (New Delhi), Assam (Meghalaya), Tamil Nadu (Tirunelveli) and West Bengal (Kolkota).

However, if one takes the list of the places where isotopic rainfall data have been collected from north to south along the west coast of India (see our Table 1), higher mean excess values can be seen during the winter monsoon (October to December) than during the summer monsoon (June to September), and a clear increase in these values is observed when the latitude decreases. Moreover, our results from the Udupi-Mangalore area (Table 1, line 5) obtained on groundwater and rivers are coherent with these rainfall data, with d-excess values from summer and winter monsoons confirming the dual monsoon characteristics.

The case of Bangalore has been also reported, even if that city is located a little inland and at a higher altitude, but it displays similar values to those found for Kozhikode. On the contrary, the station of Belgaum ($15^{\circ}52'50''$, 747 m) as seen from IAEA data displays a higher mean d-excess value during summer than during winter. A close examination of the data reveals exceptionally high d-excess values of 19.7, 20.3 and 18.7, respectively, for June, July and August 2004. If these three data points are omitted, the above described tendency is again found, and the new mean values (summer 8.00 \pm 2.89, n = 4; winter 10.2 \pm 3.4, n = 5) are close to the values from Mumbai.

Paragraph 2

When we mentioned in the conclusion of Lambs *et al.* that "the winter monsoon is 'linked' with the continental air masses", this statement referred to the Bay of Bengal vapor influx brought by the north-eastern dry winter winds. The differences in the isotopic composition of the precipitation from the southwest and northeast monsoons can be ascribed to the differences in the rainout histories of the two air masses before reaching the Indian west coast. The southwest summer monsoon's first precipitation results in enriched heavy isotope values whereas the northeast winter monsoon travels over large land masses including the Indian peninsula before reaching the west coast, resulting in a large continental effect.^[3]

The area of Mangalore receives a rainfall of between 3440 and 4428 mm/year (data between 2006 and 2010, at Mangalore station). Figure 2 of the original paper by Lambs *et al.*^[2] is very similar to that showing data from Kozhikode (see Fig. 2 in Warrier *et al.*^[4]).The mean seasonal total for the Mangalore area is 81% during the June–September summer monsoon period and 11% for the October–December winter monsoon period. In 2010, the latter season was especially wet, with 752 mm of rainfall, representing 18% of the annual rainfall. Figure 1 gives a better illustration of these rainfalls events before and during the sampling periods. As the groundwater displays a buffering capacity of the rainfall signals over weeks or more, the high input in October and November 2010 will certainly be reflected in the December sampling.

The NOAA backward trajectories presented in Fig. 1 of Ramesh *et al.*^[1] on the contrary show that the Mangalore area received high amounts of moisture from the Bay of Bengal area with a possible continental effect when this moisture travelled above south India from east to west, during the winter monsoon period. Since the groundwater displays a buffer ability for the rainfall over weeks or more, the input in October and November is also important.

Table 1. Mean d-excess values (with standard deviation and number of sample) of rainfall for summer and winter monsoon periods on Western India, except for Udupi-Mangalore area: mean d-excess value for groundwater and river water

	City, latitude, altitude	Summer (Jun-Sep)	Winter (Oct-Dec)	Reference
1	New Delhi, 28°34′48″, 212 m	6.83 ± 3.25	8.40 ± 0.80	IAEA
2	Ahmedabad, 23°02′22″, 50 m	(n = 145) 7.19 ± 4.79 (n = 32)	(n = 37) n.d.	Deshpande <i>et al</i> . ^[7]
3	Mumbai, 18°54′00″, 10 m	(11 - 52) 8.53 ± 0.93	9.77 ± 3.49	IAEA
4	Kakinada, 17°01′16″, 8 m	(n = 40) 9.03 ± 0.79 (n = 13)	(n = 7) 12.50 ± 1.15 (n = 5)	IAEA
5	Udupi-Mangalore, 13°19′56, 34 m	(n = 13) 9.27 ± 5.64 (n = 8)	(n = 3) 13.31 ± 6.34 (n = 24)	Lambs <i>et al</i> . ^[2]
6	Bangalore, 12°58′18″, 897 m	10.54 ± 5.24	13.39 ± 6.34	IAEA
7	Kozhikode, 11°15′00″, 20 m	(n = 8) 10.48 ± 1.87 (n = 14)	(n = 3) 14.06 ± 2.17 (n = 8)	Warrier <i>et al.</i> ^[4]



Figure 1. Rainfall profile near Mangalore and sampling dates used in Lambs *et al.*^[2]

Lambs et al.^[2] reported 46 isotopic measurements, with 13 for groundwater samples and 21 for river waters. The seasonal variations are in part buffered by the groundwater storage, and these groundwater isotopic values are a good approximation of the mean rainfall inflow. In July 2008, the groundwater was also sampled on the east coast at about the same latitude, at Pondicherry, to determine the specificity of each coast. There is a significant difference between the groundwater values in 2008 near Mangalore, $\delta^{18}O = -2.34$ and -2.69 ‰, and Pondicherry $\delta^{18}O = -5.43$ and -6.24 ‰, with a slightly smaller mean d-excess value, i.e. 10.4 instead of 11.7 (Lambs, unpublished data). This depletion of around 3 ‰ from the west coast to the east coast can be explained by a progressive rainout of inflowing moisture from the Arabian Sea during the period of summer monsoon with southwest winds.^[5]

Paragraph 3

Effectively, we accept that our original Fig. 4 was not precise enough. A newer version of the Figure is given here as Fig. 2.

The data used from the 2008 sampling (during the summer monsoon) give the following regression:



Figure 2. Change in the isotopic characteristic of the groundwater and river water between the summer monsoon (red diamonds, July 2008) and the winter monsoon (blue triangles, December 2010) with water more depleted in heavy isotopes and higher d-excess value (new version of Fig. 4 from Lambs *et al.*^[2])

$$\delta^2 H = (7.17 \pm 2.53)\delta^{18}O + 9.27 \pm 5.64,$$

with $R^2 = 0.53$ $(n = 9)$

and the data from the 2010 sampling (winter monsoon) give the following:

$$\delta^2 H = (7.07 \pm 1.80)\delta^{18}O + 13.31 \pm 6.34,$$

with $R^2 = 0.41$ ($n = 24$)

The two slopes are very similar, and they differ only in their mean d-excess values.

Except for the seawater, the overall representation for the 2008–2009 data (red diamonds) is well centered around the Global Meteoric Water Line (in red GMWL: $\delta^2 H = 8 \times \delta^{18}O + 10$), and the 2010 data(blue triangles) are closer to or above the Local Meteoric Water Line (in blue LMWL: $\delta^2 H = 7.76 \times \delta^{18}O + 12.36$) during the winter monsoon, recalculated from the data of Warrier

et al.^[4] Similarly, we recalculated the LMWL for the summer monsoon from the same data. This line ($\delta^2 H = 7.87 \times \delta^{18}O + 10.41$) is very similar to the GMWL, and has been drawn in dotted black.

Paragraph 4

This problem about the amount of rainfall available in November–December has already been discussed above, using up-to-date rainfall data, and not the 1961–1990 historical data. Winter 2010 was especially wet with 422 mm of rainfall in October, 330 mm in November and 18 mm in December, and both rivers and groundwater were not in a drought situation. This was also the case in 2009.

In conclusion the rainfall in southern India is controlled by precipitation during the summer (SW) and winter (NE) monsoons. The causal mechanism for the monsoon systems is the seasonal reversal of temperature and pressure gradients, and associated wind circulation following the annual northward and southward motion of the sun.^[8]

The precipitation arising from these two monsoons is expected to show distinctive isotopic signatures depending on its moisture sources (origin), and the mode of movement of moisture, depending on the climatic parameters such as latitude, wind dynamic and mixing with other vapor, and the orographic barrier. As only a limited set of data of δ^{18} O and δ D values are available from the GNIP IAEA compilation over the huge Indian subcontinent, many gaps remain on the rainfall isotopic map of India. Isotopic investigation of shallow groundwater is a way to overcome the lack of rainfall data, and to improve our understanding of this complex problem.^[5] Other authors have also reported that the isotopic composition of shallow groundwater can be used as a proxy for long-term average precipitation.^[6]

The calculation of deuterium excess is a nice tool to separate the dual vapor sources in monsoonal precipitation. The d-excess value is not only dependent on the vapor origin and the trajectory of the wind, but it can also vary with the last altitude of the cloud and mist condensation.^[7] Moreover, tropical vegetation, water recycling over the cloud forest, or humid tropical forest as in the Western Ghats can drastically increase this d-excess value.^[9] Thus, these complex and interesting systems, which explain and determine the actual climate and its variations, need to be studied in the long term involving several research groups and scientific programs. Currently, we have an ongoing 3-year research program to better understand the water cycle in the area of Mangalore and Udupi and its seasonal variation, and to devise a plan to improve the surface and sub-surface water quality. The first results from November 2011 appear to confirm our findings from December 2010, i.e. the presence of water with high d-excess (mean values from 12 to 18) characteristic of winter monsoon, see the black circles added on Fig. 2. A complete publication with the new data and the findings will be submitted soon.

The arguments of Ramesh *et al.*^[1] are based mainly on an older study carried out by that group (Yadava *et al.*^[3]), where an ¹⁸O rainfall investigation during 2000–2002 concluded that there were positive amount effects

in this area. No other publications have yet confirmed this reverse amount effect on the isotopic fractionation. Their study only refers, however, to rainfall starting from 1 July in 2002, the end of July in 2001 and mid-August in 2000, i.e. 1–2 months after the beginning of the summer monsoon, and continuing to the beginning of the winter monsoon (October). A closer study of their Fig. 3 could suggest that the positive effect found for September and October 2000 is mimicking the presence of rainfall from the winter monsoon, i.e. with higher d-excess values. It would be nice if these authors could measure their remaining samples for δD values, and calculate the d-excess values to test their results.

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