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THE IMPORTANCE OF TERRESTRIAL MOISTURE SOURCES FOR PRECIPITATION IN COLOMBIA: A COMBINED ISOTOPIC AND MODELLING APPROACH

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THE IMPORTANCE OF TERRESTRIAL MOISTURE SOURCES FOR PRECIPITATION IN COLOMBIA: A COMBINED ISOTOPIC AND MODELING APPROACH

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Abstract: The hydroclimatology of Northern South America is directly associated with the coupled dynamics of oceanic and terrestrial surface-atmosphere exchange, as moisture sources derived from these two sources interact to produce rainfall in the mountainous areas of the Andes. However, the relative contribution of these two sources, as well as their temporal dynamics have been described only through modeling studies, and no observational tools have been used to corroborate these results. The study of moisture sources through stable isotopes analysis has been a common approach to understand the changes in the water cycle and dynamics of climate, as its allows tracking the connection between evaporation, transpiration and precipitation, as well as the influence of large scale hydroclimatic phenomena, such as the seasonal migration of the InterTropical Convergence Zone (ITCZ). In this study, we characterize the isotopic composition of moisture sources becoming precipitation in the Northern Andes and the Caribbean regions of Colombia, using information of stable isotopes in precipitation (δ^{18}O, δ^{2}H) from the Global Network of Isotopes in Precipitation (GNIP) (1971-2016) and contrast them with results from the Lagrangian FLEXPART model that uses input from ERA-Interim reanalysis. Our results indicate that most precipitation in the region comes from terrestrial sources including recycling (>30% monthly all year), the northern Amazon (up to 17% monthly for June, July and August) and Orinoquia (up to 28% monthly for April) basins; followed by oceanic sources such as the Tropical South Pacific (up to 30% monthly in October, November, December) and Tropical North Atlantic (up to 30% monthly for January). Our results highlight the utility of stable isotopes in precipitation to discriminate terrestrial and oceanic sources of precipitation. More generally, our results indicate the previously overlooked hydrological coupling between terrestrial ecosystems in Northern South America, which highlights that the potential impacts of current rates of land use transformation in the region can also express in other areas of the continent, and include aspects previously overlooked such as atmospheric moisture transport and hydrological consequences in a country like Colombia where, for example, rainfed agriculture and hydropower generation support an important proportion of the nation's economy.

Keywords: Atmospheric Moisture transport, Terrestrial Sources, Oceanic Sources, Stables isotopes in Precipitation.

1. Introduction

The hydrological cycle governs water distribution and its availability across the globe. Processes such as evaporation, transpiration, and precipitation connect the terrestrial and atmospheric components of the hydrological cycle through water and energy exchange. Atmospheric circulation allows regional-to-global water redistribution, establishing teleconnections among remote areas. These teleconnections are vital for the sustainability of ecosystems and biodiversity as well as for water security, and socioeconomic development (Chapin III et al., 2011; Wagener et al., 2010). Therefore, questions about the moisture origin and the mechanisms driving atmospheric transport are fundamental to understanding the interdependence of a territory with its surroundings, as well as in the definition of proper spatio-temporal dynamics that define regional atmospheric processes.

The conventional methods to identify moisture source regions, and to estimate the proportion of incoming atmospheric moisture associated with each source are: i) analytical or box models, ii) numerical water vapor tracers, and iii) physical water vapor tracers (Gimeno et al., 2010). The first two are theoretical-computational models based on the Eulerian and Lagrangian notion of trajectory, respectively. These models often use input information from gauge stations and reanalysis data (Fuka et al., 2014; Wang et al., 2004; Liu et al., 2020). The third method is based on the physical water vapor tracers remaining in the isotopic composition of precipitation. The interpretation of moisture tracers, in particular, is useful to infer the sources and the processes inducing fractionation in isotopic composition of water throughout the movement of air masses, such as evaporation, transpiration, and precipitation (I. Clark and Fritz, 1999; Simpson and Herczeg, 1991; Martinelli et al., 1996). More specifically, the isotopic composition of rainwater allows the interpretation of prevailing meteorological conditions in the formation of air masses (temperature, humidity, wind speed) and the origin of moisture (either evaporation or transpiration) (Durán-Quesada et al., 2010; Gimeno et al., 2012; Gimeno et al., 2010; Van der Ent et al., 2010; I. Clark and Fritz, 1999; J. Gat and Carmi, 1970). The study of moisture sources through stable isotopes has been a proper approach to understand long-term changes in the water cycle and in the dynamics of climate (Salati et al., 1979; J. R. Gat and Gonfiantini, 1981; Aggarwal et al., 2005; Négrel et al., 2016; Sánchez-Cuervo et al., 2012; Alexandre, 2020), however, the lack of data is a disadvantage for a proper long-term analysis (Benjamin et al., 2005).

A current challenge for ecosystem and water resource managers is defining and understanding the potential implications of environmental change on the availability of water resources (Hamududu and Ngoma, 2020; Newman et al., 2006; Gain et al., 2020). This challenge has been generally addressed with local-scale management plans and strategies. However, in a region like Northern South America (particularly in Colombia), water security (which supports in large the country's economy) depends almost exclusively on rainfall. The connection with the Pacific and Atlantic oceans, the interactions Amazon-Andes, and the orographic barrier due to the topography of this region are the major drivers of atmospheric circulation (Arias et al., 2015; Hoyos et al., 2018; Espinoza et al., 2020). Therefore, understanding the origin and dynamics of moisture that becomes rainfall in the two most populated regions of the country is fundamental to maintaining water security or, for instance, informing strategies to decrease risk associated with potential losses of water. Yet, these analyses have only been performed with models but, to date, have not been contrasted with actual measurements such as those on environmental tracers.

The analysis of atmospheric moisture transport in this zone is also relevant because of its ecological importance, as it is one of the most biodiverse places in the world (Hutter et al., 2017; Bax and Francesconi, 2019; Hoorn et al., 2018). Topographic gradients are the habitat of thousands of plants (Churchill, 2009; Ehrendorfer, 2013) and animals (Herzog and Kattan, 2011; Bruijnzeel et al., 2011). In this zone, endemic plants comprise 6.7% of all plant species world-wide, and its endemic vertebrates 5.7% (Myers et al., 2000). For biodiversity conservation, healthy ecosystem and socioeconomic development, the availability of water is an important basis that depends on the hydrologic cycle (Pringle, 2001). Furthermore, in the economic system, the production and consumption of goods and services depend on water that generates moisture security through agriculture and energy generation from hydroelectric power that supplies the majority of the country's power.

In this study, we explore the hydroclimatic mechanisms underlying the composition of Colombian atmospheric moisture by establishing the isotopic baseline for the regional precipitation in a seasonal time scale. We include data from

33 stations distributed along the inter-Andean mountain region and the Caribbean region in Colombia, available in the GNIP project. We analyze the monthly variation of δ^{18}O and δ^{2}H values, and the spatio-temporal reconstruction of D-excess during 1971-2016. Comparing the Local Meteoric Water Line (LMWL) with the Global Meteoric Water Line (GMWL), provides criteria of depletion or enrichment of hydrogen and oxygen isotopic composition of precipitation that, in turn, allows the identification of the oceanic or terrestrial origin of air water masses that effectively precipitates over the target area. We use the results from the Lagrangian FLEXPART model in order to contrast the information inferred from isotopic composition with the regional moisture contributions structure based on the air masses trajectories, providing a more comprehensive understanding of moisture sources to the country and the potential implications of alterations in these dynamics associated with land use and vegetation cover change.

2. Study area and methods

2.1. Study area

This research focuses on atmospheric moisture transport over the northernmost portion of Colombia. The target area corresponds to the largest hydrological system in the country, draining the Andes mountain chain towards the Caribbean sea (IDEAM, 2013; Restrepo and Kjerfve, 2004) and encompasses two regions with marked orographic differences: the Magdalena - Cauca river catchment and the Caribbean Colombian basin (Fig.1). Due to the location of these zones, the oceanic influences in regional climate are characterized by the transport of moisture from the Tropical and Subtropical Atlantic and Pacific Oceans, and terrestrial sources from the Orinoco and Amazon basins, the Pacific Colombian basin, as well as the local recycling (Hoyos et al., 2018; Hoyos and Rodrıguez, 2020).

The Magdalena - Cauca river basin system is located in northern Andes. This area is characterized by a complex orography determined by the division of the Andes mountain range into three branches, i) the western branch crosses Colombia from south to north with a length of approximately 1200 km, ii) the central branch (Preciado, 1989), and iii) the eastern branch with an extension of approximately 1500km and heights up to to 4500m (Narváez-Bravo and León-Aristizábal, 2001). The Magdalena river flows in a Valley between the Eastern and central branches, while the Cauca flows between the Central and Western branches. Their confluence occurs at the lowlands that mark the transition to the Caribbean plains. High elevational gradients alternating with deep and closed valleys are characteristic of this area. The interaction of the large-scale circulation systems, the trade winds, and the orographic systems generate differentiated climatic regions on the territory, the rainiest areas are on the eastern slopes of the eastern branch and on the western slopes of the western branch, while rainfall is lower in the inter-Andean valleys (Snow, 1975). Likewise, the Amazon region exports water vapor to the Andean and interAndean zones generating high rainfall intensity, due to ascent of trade winds and the orographic effect of the Andes (Espinoza et al., 2020). The distribution of precipitation in this region has significant spatial and temporal variability (Poveda et al., 2005; Hoyos et al., 2013; Poveda et al., 2014; Espinoza et al., 2020). The most influential seasonal event in the region is the migration of ITCZ that determines the annual distribution of rainfall, characterized by a bimodal regime with two wet seasons between March to May and September to November (Álvarez-Villa et al., 2011; Giannini et al., 2000; Espinoza et al., 2020) and its interaction with the Atlantic and the Pacific Ocean, the moisture contribution from the Caribbean sea, and the basins of Amazon and Orinoco (Hoyos et al., 2018).

The Caribbean region, located in the northernmost portion of Colombia (and South America), is low and flat in the North, in contrast with the southern part of this zone, which is framed by the foothills of the Andes mountain range. Also in this area, is the Sierra Nevada de Santa Marta complex, with a height of 5,775m recognized as the highest mountain complex in Colombia that influences local atmospheric circulation. The annual cycle of rainfall in this zone has a different pattern from the Andes: a dry period from November to April and a rainy period between May to October, explained by the ITCZ migration and by the occurrence of synoptic disturbances associated to the Tropical Easterly Waves, TEWs and the Caribbean Low-Level Jet (Poveda et al., 2006; Arias et al., 2015; Cárdenas et al., 2017).

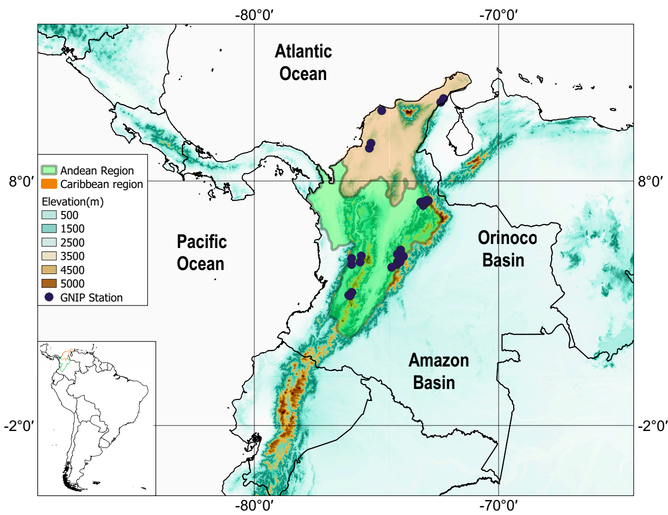


Figure 1: Study area. Regional orography (m) from Global Land One-kilometer Base Elevation (GLOBE, (Hastings and Dunbar 1998)). Andean and Caribbean region colored in yellow and green respectively. GNIP Stations highlighted in dark blue dots.

2.2. Physical Water Vapor Tracer method

2.2.1. Local Meteoric Water Line

The Global Meteoric Water Line (GMWL) provides the relationship between the global isotopic contents of δ^{18}O and δ^{2}H in precipitation as (Craig, 1961):

$$\delta^2 H = 8\delta^{18} O + 10‰. \quad (1)$$

At the local scale, this relationship is provided by the Local Meteoric Water Line (LMWL) which determines how (i) the linear statistical relationship of isotopic ratios varies spatially, and (ii) the variation in slope provides information about seasonal climatology of a site (Putman et al., 2019; Rozanski et al., 1993). Therefore, the extent (and direction) of the deviation of the LMWL from the GMWL is indicative of the thermodynamic state of vapor formation processes, as well the strengthening/weakening of processes or mechanisms involved in the atmospheric vapor transport. Figure 2 qualitatively summarizes the interpretation of the deviation of LMWL from GMWL in terms of processes and vapor formation conditions that air masses suffer in their evolution before precipitating, which can be used to infer whether water vapor was originated in terrestrial or oceanic sources, as well as the potential source of oceanic origin. This scheme shown compiles the main findings from Putman et al. (2019) and Clark and Fritz. (I. D. Clark and Fritz, 2013) for the global distribution of LMWLs.

To understand how all these hydrological processes explain the depletion/enrichment of isotopic composition of precipitation with respect to the GMWL, we summarize this information in the diagram of Fig 2. δ^{18}O and δ^{2}H pairs located in the upper right of the scheme highlight the provenance of sources from warm regions, low altitude, low latitude and coast zones (I. D. Clark and Fritz, 2013). In contrast, pairs located in the lower left part of the graphic indicate the provenance of sources from cold regions, high altitude, high latitude and from terrestrial origin (I. D. Clark and Fritz, 2013). Likewise, terrestrial sources in this graphic are located above the GMWL and observations linked to the provenance of sources from lakes, rivers and reservoirs below the GMWL (Putman et al., 2019).

Pairs of δ^{18}O and δ^{2}H in the LMWL result from the interaction of fractionation generated in the advance into the continent of moisture flow and meteorological conditions at the site (Dansgaard, 1964). Since the GMWL is used as the 'expected' equilibrium relationship (Putman et al., 2019), the LWML is often evaluated in the context of their deviation from the GMWL, in terms of the variability of δ^{18}O and δ^{2}H pairs around the GMWL. Pairs of δ^{18}O and δ^{2}H in the LMWL bring information of the history of fractionation of water in the air mass due to phase changes such as evaporation, condensation and transpiration, as well as variations due to meridional and altitudinal changes that are arising from the progressive rainout of heavy isotopes during the evolution of a precipitating air mass. This process is known as Rayleigh distillation (J. R. Gat et al., 1994).

Additionally, other factors provide information about the genesis and history of atmospheric moisture that is transported through circulation (I. Clark and Fritz, 1999; Rozanski et al., 1993; J. R. Gat and Gonfiantini, 1981; Guan et al., 2013):

1. Meteorological conditions in the source region, especially temperature, relative humidity and wind regime.
2. Combination from different atmospheric moisture sources with a different degree of contribution in the isotopic composition.
3. Proximity between the moisture source and the target region.

Depletion or enrichment of isotopes in precipitation are expressed by the Vienna Standard Mean Ocean Water (VSMOW). A positive value, say $+10‰$VSMOW, means that the sample has $10‰$VSMOW more than the reference, or is enriched by $10‰$VSMOW. Similarly, a sample that is depleted from the reference by this amount would be expressed as $-10‰$VSMOW (I. D. Clark and Fritz, 2013) (View Appendix 1, p(23)). In general, expected values from terrestrial regions exhibit depletion in isotopic composition due to Rayleigh distillation, and expected oceanic values from cold sources (for instance the Pacific ocean or the South Atlantic ocean for the study area) are more depleted than the isotopic composition originated from warmer sources (for example the Tropical Atlantic).

Here, we constructed the LMWL for the study area, based on the linear regression of the monthly average of δ^{18}O and δ^{2}H isotope composition for the period (1971-2016). Data of isotope composition of local precipitation were obtained from the Global Network of Isotopes in Precipitation (GNIP) project, initiated in 1960 by the International Atomic Energy Agency (IAEA) and the World Meteorological Organization (WMO) (Agency, 2020). We included up to as much as 33 sampling points, distributed as shown in Fig 1.

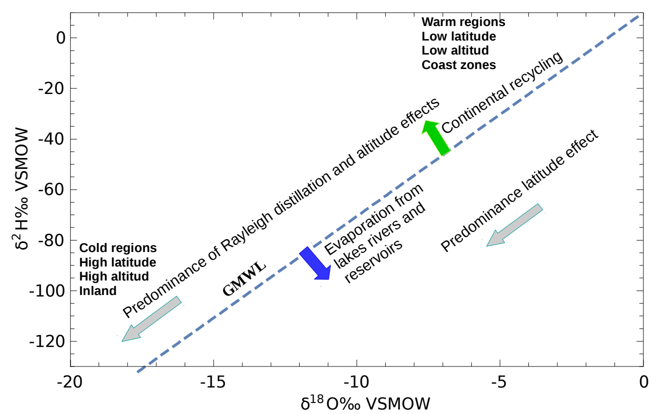


Figure 2: Qualitative summary of how hydrologic processes affect oxygen and hydrogen isotopic composition of rainwater. Pairs of δ^{18}O and δ^{2}H can be distributed along the entire possible variation range, according to the depletion or enrichment of observations and the meteorological conditions of the atmospheric moisture sources.

2.2.2. D-excess

Deuterium excess (hereafter D-excess) is understood as a measure of the deviation of the LMWL from the GMWL. D-excess is also a key parameter to infer the origin of atmospheric vapor as it is related to the evaporation conditions of the precipitation source region (Froehlich et al., 2002; Petit et al., 1991; Froehlich et al., 2008). D-excess is directly linked to δ^{18}O and δ^{2}H through the relation:

$$D - excess = \delta^{2}H - 8\delta^{18}O. \quad (2)$$

Higher values of D-excess come from air masses originated under lower relative humidity, where the kinetic fractionation is more pronounced. Lower values of D-excess are from air masses where the fractionation was under or close to equilibrium (I. Clark and Fritz, 1999). However, there are some secondary processes that can increase or decrease the initial value. For instance, D-excess is an indicator of moisture recycling due to the evaporation from the land surface to the atmosphere increases its value (Froehlich et al., 2008; Froehlich et al., 2002).

Spatial reconstruction of D-excess values was developed through coKriging interpolation, using precipitation and temperature such auxiliary variables. CoKriging technique directly accounts for data of one or more secondary variables to estimate a main variable and improve the estimation in areas where there is no sampling data. Spatial Resolution of D-excess value in the study zone is 1x1 degree.

2.3. Regional moisture contributions using FLEXPART

Based on the climatological summary of moisture sources for this study area provided by Hoyos et al., (2018), we set the regional source of atmospheric moisture as follows: Tropical North Pacific (TNP), Tropical South Pacific (TSP), Subtropical North Atlantic (STNA), Tropical North Atlantic (TNA), Tropical Atlantic (TA), Tropical South Atlantic (TSA), Caribbean Sea (CARS), Northern South America (NOSA, target region), Orinoco Basin (ORIC), Northern Amazon Basin (NAMZ), Southern Amazon Basin (SAMZ). In Hoyos et al. (2018), these zones were determined by the best agreement among the Dynamical Recycling Model (DRM), the Quasi Isentropic Model (QIBT) and the Flexible Particle Dispersion Model (FLEXPART). The Fig 3 shows the corresponding location and extension of these areas.

The FLEXPART is a 3D Lagrangian dispersion model that accounts for the net loss or gain of specific humidity q along a large number of trajectories from target region backward to source region (Nieto et al., 2006; Drumond et al., 2008; Gimeno et al., 2010; Gimeno et al., 2013; Vázquez et al., 2016).

The moisture contribution from a source area can be estimated by evaluating the vertically integrated long-term balance of precipitation P and evaporation E, along the trajectory of a great number of computational particles (2 millions). $|E-P<0|$ represents loss of moisture (precipitation exceeds evaporation along the trajectory), and $|E-P>0|$ represents gain of moisture (evaporation exceeds precipitation) (Stohl and James, 2004; Stohl and James, 2005). The diagnostic precipitation ($\overline{P}$) corresponds to the climatological values of $|E - P < 0|$.

We estimated the compositions of moisture contributions using the experiment developed by Hoyos et al (2018). However, our seasonal values were calculated considering the optimal transport day (when the moisture transference is maximum) instead of the canonical 10-day mean lifetime of water vapor in the atmosphere (Numaguti, 1999; Gimeno et al., 2013). This choice is due to the time scale at which the regional atmospheric moisture is exchanged, depends on the dynamic relationship between the source region with the target region (including not only distance but also on the intensity of the advective processes and the mechanisms that cause the precipitation). It is expected that, as the integration time of the moisture trajectories increases, the contribution of each source region increases too, until reaching the maximum contribution value, after which the contribution moisture shows a decreasing asymptotic behavior (Hoyos et al., 2018). This procedure allows us to avoid over (under) estimations in the relative contributions of moisture sources, by setting the integration times to the optimum. The period simulated 1980-2012, includes the availability period of rainwater isotope records.

3. Results

3.1. Modeled Sources of regional atmospheric moisture

Moisture contributions to both regions have a marked seasonal behavior, with relative contributions of both oceanic and terrestrial sources, alternating throughout the year in both regions (although the dominance of terrestrial sources is persistent). The predominant moisture source for the first season of the year JFM is the Atlantic Ocean, with contributions greater than 41% of the month total for the Caribbean region and >26% for the Andean region (Tables 1-2). More specifically, the TNA region has the largest contributions, with >27% per month for the Caribbean region and >17% for the

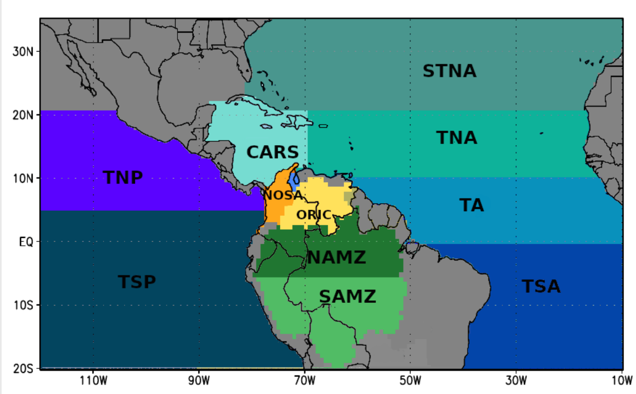


Figure 3: Regional source of atmospheric moisture considered in the experimental setting for FLEXPART models. Tropical North Pacific (TNP), Tropical South Pacific (TSP), Subtropical North Atlantic (STNA), Tropical North Atlantic (TNA), Tropical Atlantic (TA), Tropical South Atlantic (TSA), Caribbean Sea (CARS), Northern South America (NOSA, target region), Orinoco Basin (ORIC), Northern Amazon Basin (NAMZ), Southern Amazon Basin (SAMZ) .

Andean region. In the Andean region, the Pacific ocean is the most predominant oceanic moisture source along the year, specifically the major contributions are over 36% for the months SOND (Table 1). Particularly the TSP for the Andean region is the major moisture contributor exceeding 33% per month in November. Between May and October, the Caribbean region receives predominant moisture sources from the Pacific Ocean, intensifying these contributions in October – November due to the ITCZ stays in the northern hemisphere over the Atlantic and eastern Pacific, particularly the major contributions are from the TSP (>14% per month). Terrestrial moisture sources represent major contributions along the year for both regions, (>44% per month). Particularly the moisture recycling from the same area Northern South America (NOSA) is the major contributor over 35% for both zones. The contributions from Amazon basin integrated for Northern Amazon (NAMZ) and Southern Amazon (SAMZ) present unimodal precipitation cycle with one peak during AMJ (Espinoza Villar et al., 2009), which is exactly the season that generated more contributions from NAMZ to the Andean and Caribbean Regions. Monthly contributions during JJA from the Orinoco Basin (ORIC) source (the second most predominant source of terrestrial moisture) is >19% for the Caribbean region.

Diagnostic monthly precipitation from the Atlantic ocean for different integration times for the Caribbean region is greater than for the Andean region, except moisture from STNA with transference up to 6 mm/month for Andean region and up to 4mm/month for Caribbean. For both regions, the Atlantic ocean reach the maximum contribution in 10 days (Fig. 4, Fig. 5), except for CARS, that reaches the optimal moisture transference in 5-6 days for the Andean region (Fig. 4d) and 3-4 days for the Caribbean region (Fig. 5d), and TSA that reaches the optimal moisture transference in 3-4 days for the Andean region (Fig. 4a) and 5-6 days for the Caribbean region (Fig. 5a). Atmospheric moisture transport from the Pacific ocean, especially from TSP reach the optimal moisture transference in 8-9 days for the Andean region (Fig. 4f), and for the Caribbean region in 9-10 days (Fig. 5f), and for both regions reaches the maximum moisture contribution from TNP in 1-2 days (Fig. 4g, Fig. 5g). TSP is the oceanic source that transfers the maximum amount of moisture in both regions with values of 70 mm/month and 50 mm/month to the Andean and Caribbean regions, respectively (Fig. 4f, Fig. 5f).

Regarding terrestrial atmospheric sources, local atmospheric moisture transport from NOSA to both regions reaches to the maximum contribution in the 1-day, NOSA is the largest contributor of terrestrial sources, with diagnostic monthly precipitation for different integration times exhibiting notably high values of up to 140 mm/month for the Andean region (Fig. 4j) and up to 150 mm/month in Caribbean region (Fig. 5j). The second, still high, largest source is ORIC with values up to 50 mm/month for the Andean region reaching the maximum moisture contribution in 3-4 days (Fig. 4h), and up to 40 mm/month in Caribbean region (Fig. 5h) that reaches the maximum moisture contribution in 4-5 days (Comparable to the largest contribution from the pacific Ocean). For moisture source regions located in the Amazon basin, as expected, the largest contributor is NAMZ with values up

ANDEAN REGION														
	Atlantic ocean(%)					Pacific ocean(%)			Terrestrial(%)					
	TSA	TNA	TA	STNA	CARS	Total	TSP	TNP	Total	ORIC	SAMZ	NOSA	NAMZ	Total
Jan	0,10	20,50	3,68	0,60	2,72	27,59	15,39	5,44	20,83	12,48	0,05	37,64	1,41	51,58
Feb	0,14	21,12	4,51	0,62	2,35	28,73	5,47	3,58	9,06	19,03	0,09	40,51	2,58	62,21
Mar	0,11	17,62	5,44	0,40	2,54	26,11	3,28	2,53	5,82	23,77	0,16	39,62	4,52	68,08
Apr	0,22	8,42	5,01	0,13	2,60	16,38	6,32	4,31	10,63	27,76	1,16	33,74	10,33	72,99
May	0,50	2,85	4,26	0,06	1,55	9,22	15,00	7,91	22,90	23,51	2,53	27,95	13,90	67,88
Jun	0,72	2,75	3,68	0,13	0,32	7,60	19,57	8,29	27,86	22,03	2,52	22,85	17,12	64,53
Jul	0,73	2,21	2,73	0,08	0,35	6,10	22,06	7,95	30,01	20,60	3,56	23,15	16,57	63,88
Aug	0,62	1,13	2,38	0,02	0,51	4,66	24,01	8,65	32,66	16,98	2,38	26,71	16,60	62,67
Sep	0,38	1,60	2,36	0,01	0,60	4,95	26,76	9,82	36,59	16,49	0,58	32,43	8,97	58,47
Oct	0,12	2,93	1,70	0,03	0,99	5,76	31,59	10,88	42,48	14,03	0,13	34,23	3,37	51,76
Nov	0,20	4,93	2,15	0,11	2,77	10,17	33,85	11,05	44,91	10,25	0,11	32,95	1,62	44,93
Dec	0,07	12,21	3,00	0,39	3,25	18,92	29,58	7,63	37,21	9,50	0,04	33,36	0,97	43,87
Media	0,33	8,19	3,41	0,22	1,71	13,85	19,41	7,34	26,75	18,04	1,11	32,10	8,16	59,40

Table 1: Moisture source for Andean region from FLEXPART model considering the seasonal period 1980-2012 and hydrographic units of Fig 3.

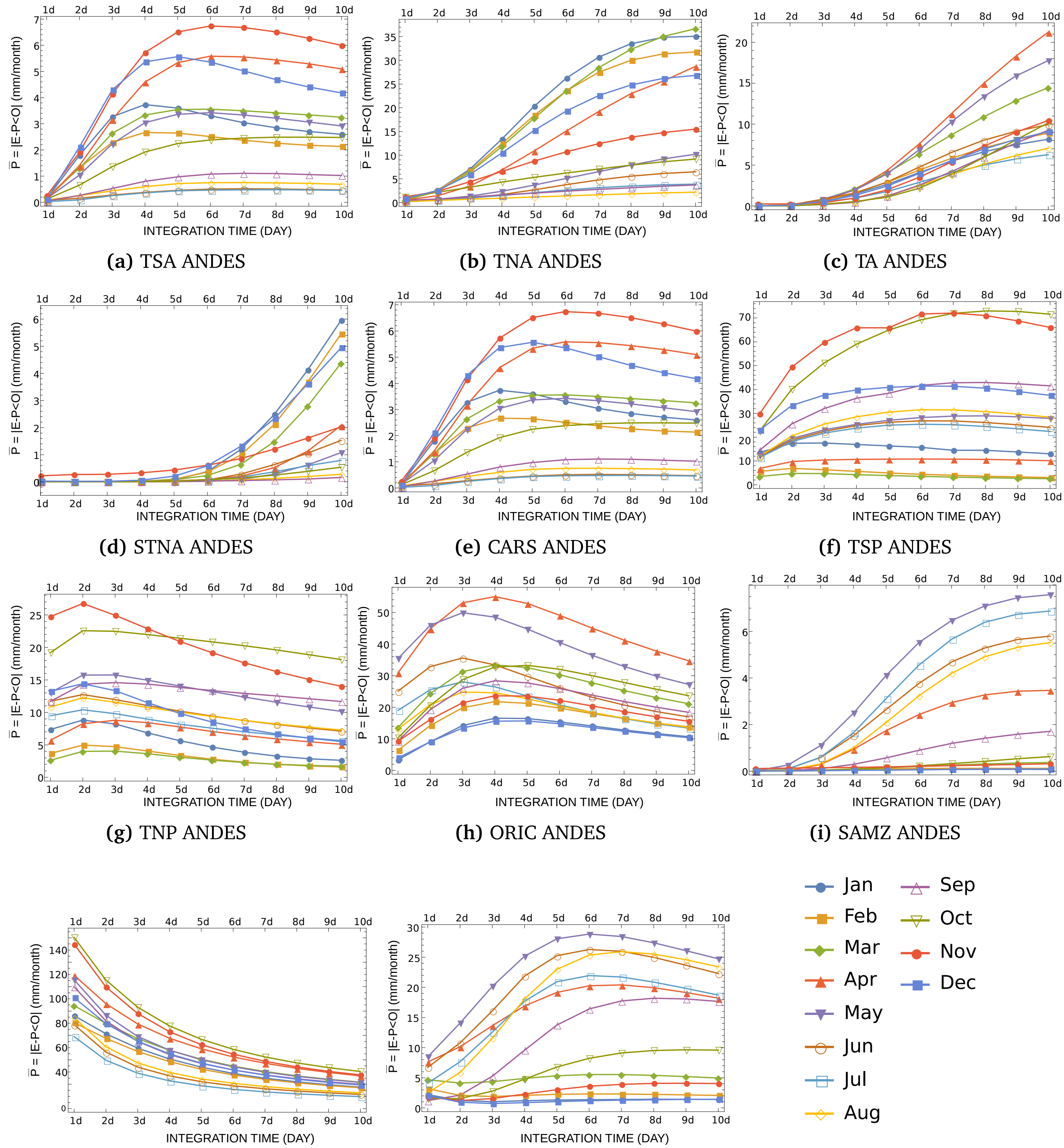
CARIBBEAN REGION														
	Atlantic ocean(%)					Pacific ocean(%)			Terrestrial)%)					
	TSA	TNA	TA	STNA	CARS	Total	TSP	TNP	Total	ORIC	SAMZ	NOSA	NAMZ	Total
Jan	0,11	31,81	5,09	2,63	5,53	45,17	1,73	3,14	4,88	12,07	0,07	36,52	1,30	49,95
Feb	0,12	29,05	5,78	2,35	6,11	43,41	0,68	1,61	2,28	14,29	0,07	38,67	1,28	54,31
Mar	0,08	27,94	6,80	1,43	5,17	41,43	0,25	0,74	0,99	16,12	0,08	39,73	1,65	57,58
Apr	0,14	21,55	6,75	0,61	5,40	34,45	0,94	2,54	3,48	17,21	0,11	42,30	2,45	62,07
May	0,40	9,24	6,75	0,19	5,59	22,17	5,30	7,83	13,14	19,03	0,47	40,23	4,97	64,70
Jun	0,85	6,54	7,55	0,35	3,22	18,51	6,68	10,07	16,75	20,76	0,46	37,38	6,15	64,75
Jul	1,02	7,45	6,84	0,41	2,83	18,56	7,21	9,27	16,47	22,06	0,75	35,01	7,15	64,97
Aug	0,72	8,37	5,39	0,27	4,14	18,89	8,45	9,95	18,40	19,54	0,42	36,38	6,36	62,70
Sep	0,43	9,22	4,53	0,13	4,73	19,05	10,94	11,26	22,21	16,37	0,08	38,63	3,67	58,75
Oct	0,12	9,86	2,93	0,21	6,50	19,61	16,80	15,44	32,24	9,91	0,02	36,55	1,67	48,15
Nov	0,20	13,33	3,48	0,97	9,28	27,25	14,80	13,80	28,59	7,52	0,08	35,70	0,86	44,16
Dec	0,11	22,09	4,82	1,82	5,98	34,81	8,29	8,17	16,45	9,30	0,03	38,69	0,72	48,73
Media	0,36	16,37	5,56	0,95	5,37	28,61	6,84	7,82	14,66	15,35	0,22	37,98	3,18	56,74

Table 2: Table 2: Moisture source for Caribbean region from FLEXPART model considering the seasonal period 1980-2012 and hydrographic units of Fig 3.

to 30 mm/month for the Andean region and reach the maximum moisture contribution in 5-6 days (Fig. 4k), and up to 15 mm/month for Caribbean region and reach the maximum moisture contribution in 8-9 days (Fig. 5k). Finally, the lowest contributions come from the farthest source, SAMZ, with the highest time (due to distance) with up to 8 mm/month in Andean region (Fig. 4i) and up to 3 mm/month in Caribbean region (Fig. 5i).

3.2. Local Meteoric Water Line and hydroclimatic mechanisms

The resulting LMWLs (Fig. 6) follow the expected trends based on depletion or enrichment of isotopic composition of δ^{18}O and δ^{2}H from theoretical considerations such as: i) Orographic destillation that generating depletion of the values of δ^{18}O and δ^{2}H due to fractionation generated in the advance inside the continent of moisture flow (Mook, 2002; Dansgaard, 1964; I. Clark and Fritz, 1999; Aggarwal et al., 2005; Rozanski et al., 1993). ii) proximity



(a) TSA ANDES

(b) TNA ANDES

(c) TA ANDES

(d) STNA ANDES

(e) CARS ANDES

(f) TSP ANDES

(g) TNP ANDES

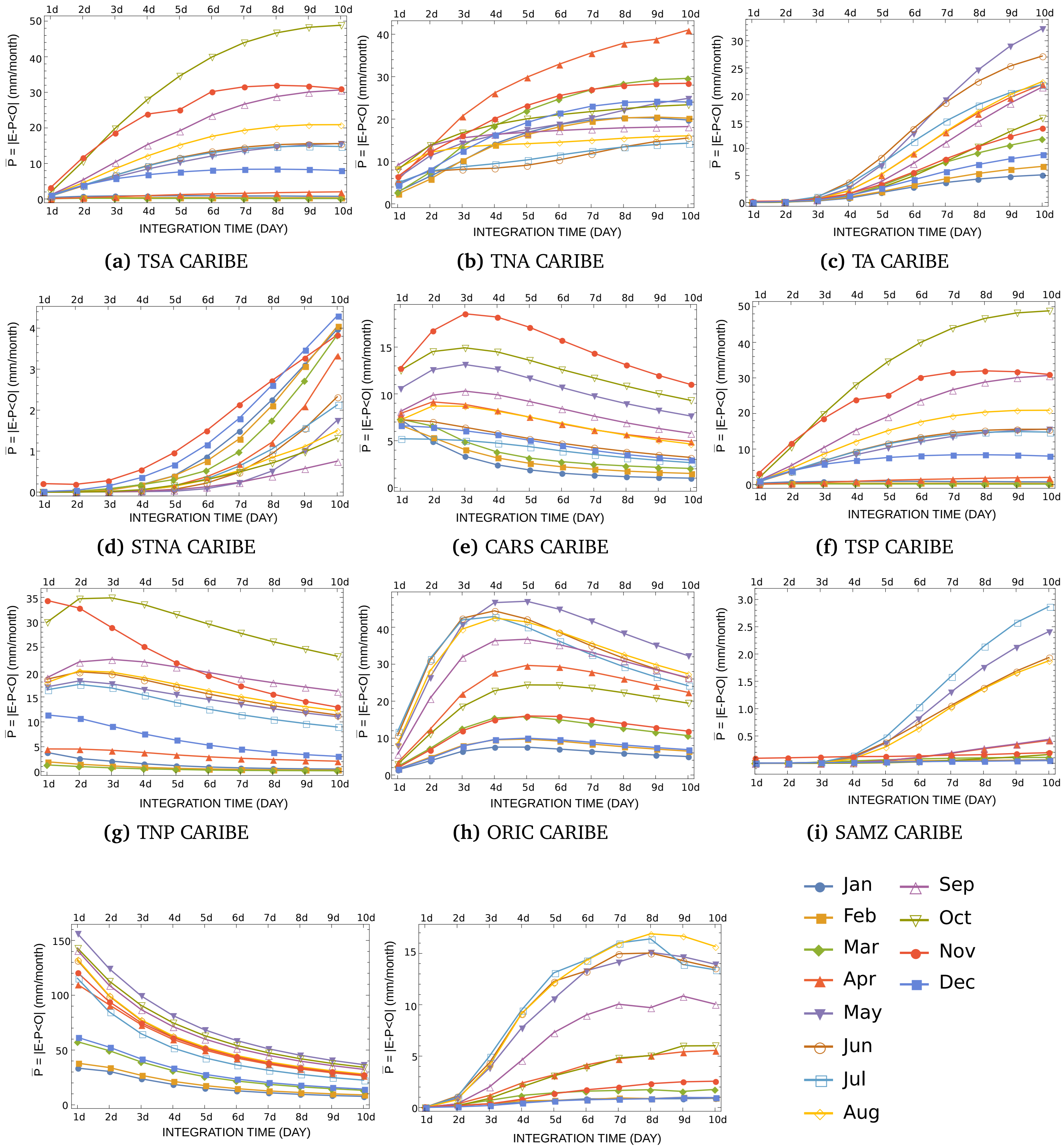
(h) ORIC ANDES

(i) SAMZ ANDES

(j) NOSA ANDES

(k) NAMZ ANDES

Figure 4: Diagnostic monthly precipitation $\overline{P}$ = |E-P<0| in FLEXPART for different integration times for regions of moisture sources for the Andean region, considering the maximum transfer time according to the FLEXPART results. Every colored line represents the evolution of atmospheric moisture transport for every month of the year in a seasonal scale for the period 1980-2012 and the hydrographic units Tropical North Pacific (TNP), Tropical South Pacific (TSP), Subtropical North Atlantic (STNA), Tropical North Atlantic (TNA), Tropical Atlantic (TA), Tropical South Atlantic (TSA), Caribbean Sea (CARS), Northern South America (NOSA, target region), Orinoco Basin (ORIC), Northern Amazon Basin (NAMZ), Southern Amazon Basin (SAMZ).



(a) TSA CARIBE **(b)** TNA CARIBE **(c)** TA CARIBE

(d) STNA CARIBE **(e)** CARS CARIBE **(f)** TSP CARIBE

(g) TNP CARIBE **(h)** ORIC CARIBE **(i)** SAMZ CARIBE

(j) NOSA CARIBE **(k)** NAMZ CARIBE

Figure 5: Diagnostic monthly precipitation $\overline{P}$ = |E-P<0| in FLEXPART for different integration times for regions of moisture sources for the Caribbean region, considering the maximum transfer time according to the FLEXPART results. Every colored line represents the evolution of atmospheric moisture transport for every month of the year in a seasonal scale for the period 1980-2012 and the hydrographic units Tropical North Pacific (TNP), Tropical South Pacific (TSP), Subtropical North Atlantic (STNA), Tropical North Atlantic (TNA), Tropical Atlantic (TA), Tropical South Atlantic (TSA), Caribbean Sea (CARS), Northern South America (NOSA, target region), Orinoco Basin (ORIC), Northern Amazon Basin (NAMZ), Southern Amazon Basin (SAMZ).

to atmospheric moisture sources (Guan et al., 2013) iii) thermodynamic conditions of sources (Dansgaard, 1964) iv) mixing ratio of sources (Rindsberger et al., 1983; Rindsberger et al., 1990) v) amount effect: generates depletion in hydrogen and oxygen isotopes with the increase in monthly and annual precipitation of different places and with the intensity of the storms (Dansgaard, 1964).

As it is indicated by our FLEXPART experiment, isotopic signals interpreted from the LMWLs also indicate the seasonal behavior of moisture sources for the two regions. More specifically, for the season DJF, the Caribbean region reports the range with the highest values for δ^2H that oscillates between 0 and -20‰VSMOW, and for δ^{18}O between 0 and -5‰VSMOW, while the Andean region exhibited variation range of δ^2H (δ^{18}O) that oscillates between -20 and -60 (-5 and -9)‰VSMOW. In the Caribbean region, these values represent the first condensate from marine moisture and are indicative of meteorological conditions (such as relative humidity (72%-79%) and sea surface temperature (25°C C-28°C)) from warm sources (J. R. Gat and Gonfiantini, 1981; Rozanski et al., 1993), highlighting the oceanic origin of moisture. Conversely, in the Andean region, the depletion of the heavy isotopes from coastal regions toward the continental interiors (orographic distillation) is evidenced in more depleted values (Fig. 6). The values of oxygen and hydrogen isotopes for both regions are close to those presented by Bowen (Bowen and Revenaugh, 2003) for the TNA zone, and the FLEXPART results indicate that TNA was the most active source in this month for the study area (>27%, see Tables 1 and 2).

For the MAM season in the Caribbean region, March reports similar variations to DJF, and April-May report observations distributed along the LMWL that oscillates for δ^2H between 0 and -120‰VSMOW, and for δ^{18}O between 0 and -20‰VSMOW. In the Andean region, March reports the most enrichment for this season, and April- May also exhibit an oscillation range for 2H between 0 and -120‰VSMOW, and for δ^{18}O between 0 and -20‰VSMOW. The main regional terrestrial contribution for MAM corresponds to ORIC and NOSA sources (see Tables 1 - 2). For both regions, the footprint of these terrestrial contributions can be seen in the local LMWL above the GMWL (Interpretation of Fig. 6, following guidelines on Fig. 2). Moisture from ORIC is located in the lower part of the figure, indicating that it comes from a warm source, and moisture from NOSA along the LMWL indicating provenience from sources with different temperatures.

The wide range of variation for both regions in April-May responds to the mixing ratio effect. This spread in the isotopic composition of rainwater is produced by the mixing of different air masses that precipitate over Colombia. During this season, the study area is characterized by a complex combination of terrestrial and oceanic sources of moisture that contribute in different relative amounts to regional precipitation (see Tables 1 - 2).

During JJA the variations range for both regions oscillates for δ^2H between -20 and -80‰VSMOW, and for δ^{18}O between -3 and -12 ‰VSMOW. Especially for the months June-July the observations are located in the middle of the variation range, due to is a dry period, and the contributions are due to the effect a combination of terrestrial and oceanic sources of moisture with distinctive physicochemical and proximity criteria. For the Caribbean region, although in this season are not predominant sources from the Atlantic ocean, the moisture provenience from this ocean make important contributions, reflects in enrichment observations of the LMWL due to is a warm source, likewise, although in this season are not predominant sources from the Pacific Ocean, precisely in this season this sources begin to be active and as well has contributions reflects in depletion of observations in hydrogen and oxygen isotopes. Similarly, the terrestrial sources make their contributions from ORIC and NOSA causing a complex combination of terrestrial and oceanic sources. This is similar for the Andean region, that receive more contributions in this season from the terrestrial sources and have major influence from the Pacific ocean. Particularly, for the Andean region the major contributions of terrestrial sources from NAMZ occurred during June (>17%), and coincide with observations localized above of the GMWL, and the lower part of the LMWL due to the minor temperature of NAMZ source.

During the SON season, for both regions the isotope composition of precipitation shows more depleted values in comparison with all the year, presenting a variation range for δ^2H (δ^{18}O) between 0 and -120 (-2 and -15)‰VSMOW. Particularly, for the Andean region, October-November are the months that report observations with a variation range more depleted, these values are due to the provenience from the Pacific Ocean that is a cold source (see Fig. 2). Also, this season corresponds to one of the two rainy seasons of the year, generated by the seasonal migration of the ITCZ, producing an increase of monthly precipitation and intensity of the storms, causing depletion in hydrogen and oxygen (amount effect). Likewise, the Caribbean zone receives predominant moisture sources from Pacific Ocean, intensifying these contributions in October – November due to the ITCZ stays in the northern hemisphere over the Atlantic and eastern Pacific.

3.3. D-excess analysis

Upper left inserts in Fig. 6 panels shows the spatial interpolation of seasonal D-excess. Spatial variations of reconstructed D-excess are explained by theoretical considerations such as effects of i) distance or proximity to main moisture sources to the study areas (Guan et al., 2013) ii) influence of oceanic or terrestrial sources (Aemisegger et al., 2014) iii) depletion of the heavy isotopes from coastal regions toward the continental interiors (Rozanski et al., 1993; J. R. Gat and Matsui, 1991). Particularly, for the Caribbean region, the proximity effect of main moisture sources to the target region is the most visible, given that, for this region, D-excess reconstruction shows predominant values close to the Caribbean Sea and the Atlantic Ocean, which agrees with previous reports from Bowen (2003). For the Andean region, the effects of oceanic or terrestrial sources and the depletion of the heavy isotopes with distance to coastal regions are most evident. This can be explained by the predominance of terrestrial sources depleted in δ^{18}O and δ^2H and the moisture transport route (e.g. from the Atlantic Ocean is larger than Caribbean region causing majors fractionations).

The seasonal variation of D-excess value ranged from 7 to 15‰VSMOW, reaching its maximum in December/January and its minimum in June/July. These changes are given by air–sea conditions at distinct water vapour sources with specific D-excess values (J. R. Gat and Gonfiantini, 1981) and modified by the mixing of inland water vapour from evapotranspiration with the air-mass (J. R. Gat et al., 1994) and by secondary evaporation (Frits et al., 1987). In continental areas D-excess value is strongly controlled by temperature effects (increases to about 0.5‰VSMOW/°C) (Frits et al., 1987). This effect is visible in our interpolation with lower D-excess in Caribbean region where there are characteristic high temperatures and higher D-excess in Andean region, which have lower temperatures. In addition to the temperature effect, and considering the Rayleigh distillation model, δ^{18}O values become lower when water vapour rains out at lower temperatures from oceanic sources (Dansgaard, 1964), there is an inverse relationship between δ^{18}O and D-excess. As expected, our data in the Andean region shows this pattern as it has a predominant moisture source from terrestrial sources along the year, and is located away from the ocean. In the Andean region, the value of D-excess reduces in June and July months, due to the effect of secondary evaporation can be especially large during small amounts of precipitation in hot summer months. Indeed, the D-excess shows pronounced variation during the year. For the Andean region, the months that showed the highest values of D-excess correspond to the season with the low values of rainfall in the area, with December and January being the months with the highest values of D-excess, reaching up to 15‰VSMOW. The fractionation of the air masses for these months has a similar behavior. There is an impoverishment gradient towards the north-western region from the direction of the Amazon basin. April and May months (the rainy season) report the lowest concentrations of D-excess, with a range variation between

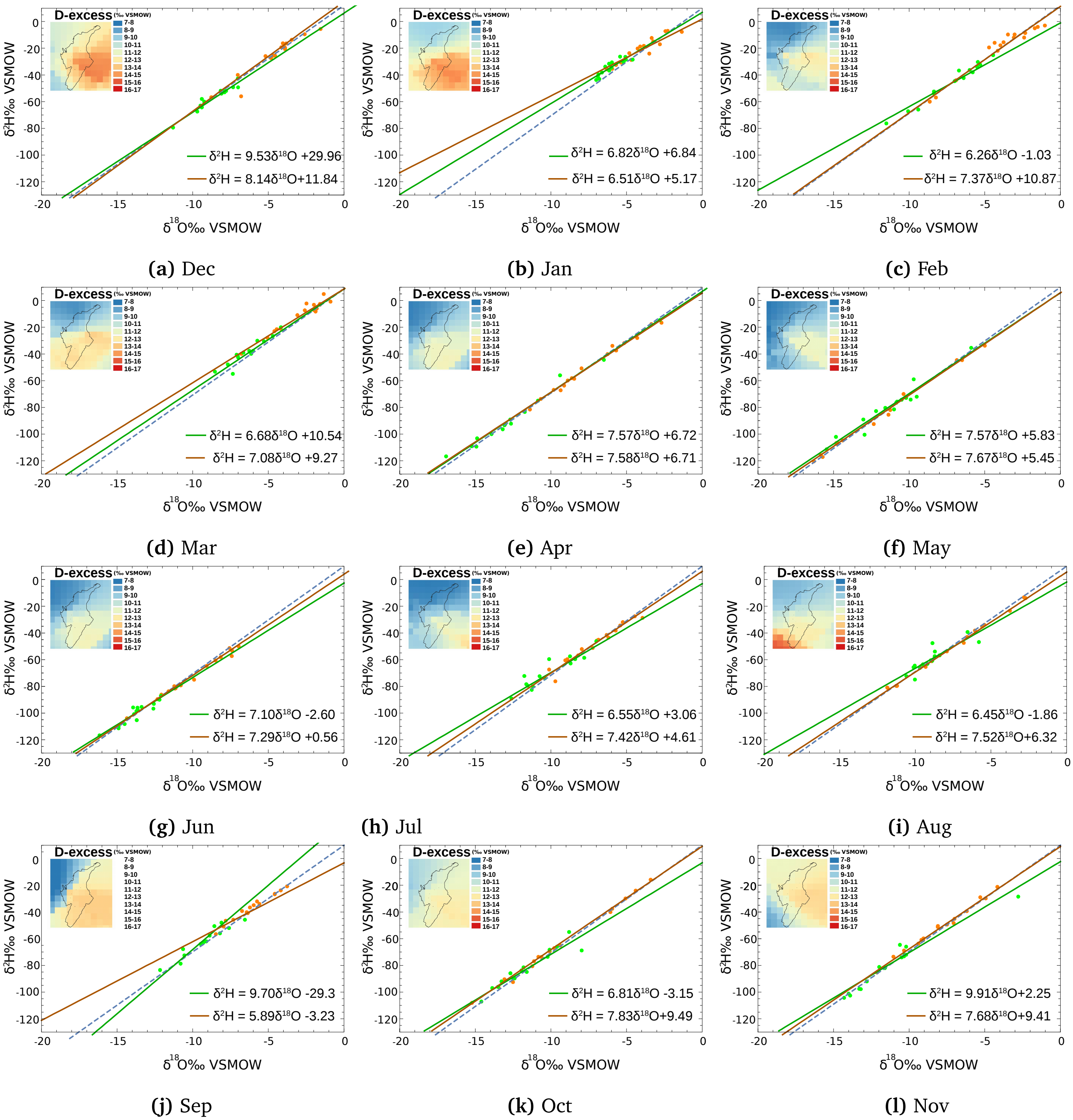


Figure 6: Seasonal reconstruction of LMWL and Deuterium excess. Blue dashed lines correspond to GMWL. Orange lines correspond to Colombian Caribbean region. Green lines correspond to Andean Region. Interpolation of seasonal D-excess is shown in the box located in the upper left.

8‰VSMOW and 10‰VSMOW.

Further, the lower values of D-excess in Caribbean region, respond to the effect of secondary evaporation, which is related to the meteorological conditions at the site during precipitation events. The low D-excess values are typical for events that take place under relatively hot weather conditions (Froehlich et al., 2008; Froehlich et al., 2002).

3.4. Comparison between LMWL, D-excess and Flexpart

Similar results were found for the isotopic techniques and FLEXPART model, this connection allows to sketch the predominance of the atmospheric moisture sources. Tables 1 and 2 shows that for the first season of the year, the atmospheric moisture sources from the Atlantic Ocean are predominant. Similarly, according to Figure 6, in the first season of the year, observations of isotopic composition are more enriched for both target regions, showing higher values for the Caribbean region due to the proximity to the Atlantic ocean. As it is indicated in Figures 5 and 6, the moisture from CARS gets its maximum integration time in 2-3 days for the Caribbean region, while in the Andean region, moisture source provenient from the same source takes 6 days to arrive. For both regions, moisture from TNP and TA take the same number of days for reaching the maximum integration time.

During the April to September season, the mixing effect of atmospheric and terrestrial sources is more evident for the two regions. However, due to the influence of the Atlantic Ocean, as shown by our FLEXPART experiment (Tables 1-2), isotopic observations for the Caribbean region are located predominantly in the upper area of its LMWL, while for the the Andean region, predominantly influenced by the Pacific Ocean, the isotopic observations are located predominantly in lower area of its LMWL. In general, the seasonal analysis of stable isotopes in precipitation through all methods for both study areas shows fractionation phenomena that modify the isotopic concentrations in the different phases of the hydrological cycle. The LMWLs obtained evidence enriched values in the Caribbean region in the majority of observations. In the Andean region, we found more depleted values and a greater deviation from the GMWL. This greater fractionation results from a multiplicity of factors and processes associated with the regional atmospheric transport mechanisms as well as the longer distance of this area to the main oceanic sources.

4. Discussion

Physical water vapor tracers can identify clear signals of the origin of incoming atmospheric moisture when the source is not influenced by the effect of mixing associated with different oceanic and terrestrial sources present in the majority of the seasonal analysis. In our results, the most direct signal in the isotopic composition occurred in the first season of the year when enriched values indicated a predominance of moisture from the Atlantic Ocean, closer and warmer, contrary to the rest of year when there is evidence of more mixed sources with different meteorological conditions and proximity criteria. Further, our results allowed us to identify oceanic sources connected with seasonality migration of ITCZ, as well as terrestrial sources such as Amazonas and Orinoco basins and in consonance with meteorological criteria. Both of these observations are evident in the reconstruction of the D-excess, even when the spatial and temporal coverage of stable isotopes data is very low for Colombia. Although we have reconstructed a baseline for the isotopic structure of precipitation, it is also true that a better sampling network is necessary to improve the monitoring network of stable isotopes to produce a more detailed analysis of the moisture transport processes, as they have done in more instrumented areas (Bowen et al., 2007; Bowen et al., 2011; Dutton et al., 2005; Friedman et al., 1992).

Our results illustrate how physical water vapor tracers, such as stable isotopes in precipitation, allow tracking water sources in atmospheric circulation as they connect evaporation and precipitation and their concentration indicates the meteorological conditions and proximity to the main atmospheric moisture source that originates precipitation, as it is expected. Although the use of stable isotopes in precipitation does not provide quantitative information about the amount of atmospheric moisture from the sources, it complements the information generated by our FLEXPART experiment, and more generally this information has the potential to be integrated to atmospheric models in order to diagnose the percentage of moisture incoming from the different sources (Liu et al., 2020; Molina et al., 2019; Hoyos et al., 2018; Arias et al., 2015; Fuka et al., 2014; Wang et al., 2004). The consideration of the optimal transport day (when the moisture transference is maximum) instead of the canonical 10-day mean lifetime of water vapor in the atmosphere, allowed to improve the quantification of contributions from atmospheric moisture sources, highlighting the predominance of terrestrial sources along the year, respect to previous analysis by Hoyos et al. (2018), who calculated a less multiannual moisture average from terrestrial sources of 38% compared to our results that indicate a multiannual moisture average for the Andean region of 59% and for the Caribbean region of 56%. The combined use of physical tracers and models are particularly useful in regions with complex topographical and meteorological setups where model results can be highly uncertain.

Collectively, our results highlight an advantage of the observational technique with stable isotopes of precipitation over just numerical modeling, given that many models can either underestimate or overestimate the amount of atmospheric moisture (Hoyos et al., 2018), generating misunderstandings above the interpretation of which sources are predominant and the relative importance among moisture sources. Additionally, many atmospheric models have difficulties to represent the topography of the area (Insel et al., 2010). Here, this difficulty is faced by analyzing moisture transport phenomena with stable isotopes in precipitation, precisely due to the inverse correlation between the amount of isotopic composition and altitude (Mook, 2002; Rozanski et al., 1993; Dansgaard, 1964). The simultaneous application of both techniques (physical tracer and atmospheric modeling) generates a better interpretation of the transport of atmospheric moisture, the integration of analysis of stable isotopes in precipitation to the spatial-temporal modelling can be an accurate tool that reduce the uncertainty associated to the understanding of climate system, and the development of forecast below possible changes in hydroclimatic patterns provenience from sources region (Hu and Dominguez, 2015; Sánchez Murillo et al., 2013; Risi et al., 2010).

By using a combination of physical tracer and modelling, we confirm previous modeling results (Hoyos et al., 2018) that indicate how, in the study area, the contribution of terrestrial moisture sources to local precipitation is significant (always greater than 44%), such that most ecosystems and water security for people and the economy may depend on the stability of major regional ecosystems such as the Orinoco plains (8%-28% per month) and the Northern Amazon (17% contribution). More importantly, our results highlight that most terrestrial moisture originates within the same region (NOSA), with contributions greater than 23% per month in some seasons and up to 40% per month in other seasons.

The fact that a significant proportion of rainfall comes from recycling, highlights how precipitation and, more generally, water availability in the Andean and Caribbean regions of Colombia could potentially be altered by changes in vegetation and land cover, directly affecting transpiration and atmospheric circulation. This indicates that the region is particularly vulnerable to ongoing widespread ecosystem transformation in the region and the surrounding basins. According to Ruiz-Vásquez et al. (2020), under scenarios that consider deforested areas of approximately 28% and 38% of the Amazon basin, terrestrial sources reduce their annual contributions to northern South America by an incredible average of 40 and 43%. Likewise, Badger and Dirmeyer (2016), confirm that the rise of air masses over northern South America is inhibited with Amazon deforestation, which could also induce an inhibition of precipitation over the region. Similarly, the teleconnections with the Orinoco basin reveal that the regional regime of precipitation is highly dependent on a zone in which raising cattle is one of the main economic sources since this is the predominant activity in the area, occupying more than 50% of the productive territory. The expansion of the areas dedicated to this activity is the main source of deforestation. In addition, the eastern part of the Orinoco basin has an annual cycle featured by up to six dry months throughout the year (Mafla Noguera et al., 2017).

In summary, most studies have focused in atmospheric moisture from oceanic sources (Yepes et al., 2019; Arias et al., 2015; Sakamoto et al., 2011; Rueda and Poveda, 2006) and although a few shows the importance of terrestrial sources (Ruiz-Vásquez et al., 2020; Molina et al., 2019; Hoyos et al., 2018; Badger and Dirmeyer, 2016). Our results illustrate the influence of transference of moisture recycling in two important areas of Colombia, with the largest population in the country, and whose economy and ecosystems vitally depend on water availability for ensuring moisture security. Regional atmospheric moisture composition largely controls ecosystem structures, increasing the vulnerability to climate and environmental change in the study area. Furthermore, these natural systems are directly threatened by human activities such as deforestation and intensive agriculture, altering the exchange of water in the land-atmospheric interactions, the energy balance, the evapotranspiration, and therefore, the atmospheric moisture content and transport. Overall, our results indicate the importance of the hydrological coupling of terrestrial ecosystems in Northern South America, which has not been accounted as it deserves in previous literature. For Colombia, rainfed agriculture and hydropower generation are an important proportion of the nation's economy. For this reason, we highlight the potential impacts of current rates of land use transformation in regions as Amazon and Orinoco basins and the Andean mountain system over the Colombian territory, since these areas are dynamically linked via atmospheric teleconnections and aspects as the atmospheric moisture transport and the hydrological consequences are of vital importance in the assessment of moisture security risk.

5. Conclusions

In this work, we developed a more detailed description of the atmospheric moisture sources that define rain over the Caribbean and Andean regions, compared with previous research developed for the whole Colombian country (Hoyos et al., 2018; Arias et al., 2015). The differentiation between regions in the country allowed us to identify a variation in the amount and seasonality of moisture contribution from different sources. Our results indicate a predominance of terrestrial moisture sources (56% and 59% for the Caribbean and Andes regions, respectively) , followed by oceanic moisture sources, dominated by contribution from the Pacific in the Andean Region (26% contribution) and the Atlantic in the Caribbean region (28%).

In the Caribbean region the precipitation regime is mainly influenced by: i) the atmospheric moisture sources coming from the Atlantic Ocean and Caribbean Sea, these contributions become more important in the season DJF when the ITCZ is located at the south of the study zone, with contributions of up 32% of the monthly total moisture of the TNA and with contributions from CARS of up 6% of the total monthly moisture related with atmospheric transport structures related with the Caribbean Jet (Poveda et al., 2014; Poveda et al., 2006; Sakamoto et al., 2011) ii) the local recycling related to transpiration processes, which represents more than 35% of the total monthly moisture along the year, and, iii) contributions from the Orinoco River Basin of up 22% of the total monthly moisture for the season JJA, iv) contributions from the Pacific Ocean for the season SON, related to the second season of the ITCZ over the north of south America. The isotopes also can show the influence of the closeness between the sources and the Caribbean Sea, based on the high amount of observations in the upper part of the LMWLs linked to warmer and closer sources as are the Caribbean Sea and the Tropical North Atlantic-TNA.

In the Andean Region, the precipitation regime is mainly influenced by: i) high contributions from terrestrial sources along the year, mainly from ORIC and from the local recycling, with monthly contributions of up 28% from ORIC and 40% from NOSA in the MAM season, and with monthly contributions of up 17% in the JJA season coming from the Amazonas basin, specifically from the transpiration of the North Amazonas-NAMZ, iii) the Pacific Ocean which has a higher moisture transfer in the season SON with contributions from the Tropical South Pacific-TSP of up 34% of the total monthly moisture, and its related to second season of the ITCZ over the north of south America, where additionally the local recycling becomes more important and the Amazonia contribution decreases. The importance of the terrestrial sources and the local recycling was observed in the high values of deuterium excess as an indicator of moisture recycling in this zone.

The quantification of moisture sources in each region reveals that precipitation regimes depend on the seasonality of regional composition of moisture sources and the diverse underlying mechanisms, and the physical variables related to each zone, including variables such as topography, geographic location and environmental features. The isotopic analysis results reveal that the processes which give origin to precipitation in the Andean region are linked to the advance into the continent of moisture flow and related to changes in the altitude for orographic ascent, that can be seen in the LMWLs. For the Caribbean region, the closeness factor to the main sources such as the Caribbean Sea and the Atlantic Ocean has a high influence in the precipitation regime.

In general, the amount of moisture that is transported from a source region to a target region tends to decrease while the water masses move further inland, this phenomenon explains why greater contributions are generated from the Amazon basins, particularly from NAMZ and ORIC basins to the Andean region (Fig. 4-5). Likewise, the fact that for both areas local recycling is the largest contributor with an annual average of 33% for the Andean region and 37% for the Caribbean region, confirms the importance of terrestrial processes as drivers of local moisture recycling. which in turn depend on the regional atmospheric composition, which largely controls the structures of ecosystems.

The teleconnections found between the sources and targets make it clear that water resources management should be made considering not only surface hydrology, but also these links that directly influence the precipitation regime. The dynamics of the climate system at the local level is conditioned by phenomena that depend on synergy with other places, and this mechanism involves the transfer of vital ecosystem services. In particular, in this work it was identified that the precipitation regime of the Andean region is highly conditioned by transpiration rates from the Amazon and the Orinoquia and the modification of ecosystem conditions such as deforestation and the establishment of monocultures could have consequences and negative impacts on the amount of moisture that is transported from these regions.

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Appendix 1

The isotopic theory basis is defined by the change of the atomic weight of the molecules. The atomic weight of a given nuclide is the sum of protons that defines the element, and neutrons that defines the isotope of the element, this mean that there are many isotopes for the same element. For example, most oxygen has 8 protons and 8 neutrons, giving a nuclide with 16 atomic mass units, while about 0.2‰of oxygen has 10 neutrons. The variation in neutrons in an element generates changes in the element, and the molecule of which they may be a part, for example in water there are the two following molecule forms; ^{2}H2^{16}O (atomic weight: 20) denominate heavy water and the normal water ^{1}H2^{16}O (atomic weight: 18) (I. D. Clark and Fritz, 2013).

According to the Agency International of Atomic Energy –AEIA, stable environmental isotopes are measured as the ratio of the two most abundant isotopes of given element, in oxygen this ratio is (^{18}O /^{16}O), and the isotopic concentrations are expressed as the difference between the measured ratios of the sample and reference over the measured ratio of the reference, for example for oxygen:

$$\delta^{18}O = (\frac{(^{18}O/^{18}O)sample}{(^{18}O/^{18}O)VSMOW} - 1) * 1000‰VSMOW. \quad (3)$$

The reference is the Vienna Standard Mean Ocean Water-VSMOW. A value that is positive, say $+10$‰VSMOW, signifies that the sample has 10‰VSMOW more than the reference, or is enriched by 10‰VSMOW. Similarly, a sample that is depleted from the reference by this amount would be expressed as -10‰VSMOW (I. D. Clark and Fritz, 2013).

The GMWL is expressed through the relation between the isotopic contents of δ^{18}O and δ^{2}H in precipitation. The regression line with slope 8 and intercept 10 developed by Craig (1961). The GMWL is conformed by the average of many LMWL, and is defined by this relationship:

$$\delta^{2}H = 8\delta^{18}O + 10‰. \quad (4)$$

Values of δ^{18}O and δ^{2}H are the result from fractionations generated due to the advance inside the continent of moisture flow. They depend on seasonal factors associated with temporary changes and factors regional as the topography and the latitude of the zone. Many natural processes cause different distribution of isotopes, for this relationship particularly the values of the slope and the intercept vary in relation to the region and the origin of atmospheric steam, always keeping the linear trend of the relationship between the contents.

Different fractions of δ^{18}O and δ^{2}H during condensation, mainly dependent of temperature, give rise to increases or decreases in the slope of the GMWL, and in the intercept generates different cut of point that allows to characterize and compare the waters with respect to their provenance. These alterations generate specific slopes for the different regions (Dansgaard, 1964).