

Comparison of Relationship Between the Concentrations of Water Isotopes in Precipitation in the Cities of Tehran (Iran) and New Delhi (India)

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Introduction

The term ‘Tracerhydrology’ is used as a short expression for the use of tracers in hydrology. It is understood as an advanced method that allows for an integrative investigation of the hydrologic system (Leibundgut et al. 2009). Environmental and artificial tracer can be used for investigating the movement of water in the hydrological cycle. Artificial tracers are described as those elements deliberately injected into the hydrologic system (Luhua et al. 2010). By studying the motion of the injected particles, one may measure some physical processes of hydrologic system such as the escape of water from a reservoir (Evans 1983). There are more than 1,000 isotopes known for about 92 chemical elements. Most of these isotopes are called as environmental isotopes which are either stable or unstable (Leibundgut et al. 2009). The stable isotopes of hydrogen and oxygen are recognized as important traces in hydrological cycle. The heavy stable isotopic components of water, HD^{16}O and H_2O^{18} , occur in natural waters in concentration of about 320 and 2,000 ppm, respectively (Evans 1983). The variation of isotopic concentration is due to fractionation caused by phase changes, evaporation, condensation, precipitation, and snow and ice formation (Chidambaram et al. 2009). Isotopic fraction is affected by meteorological factors such as temperature and altitude change (Leibundgut et al. 2009). The small variations of isotopic concentrations are usually

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measured by mass spectrometry. In general, the isotopic abundance ratios are expressed as parts per mil of their deviations as given by (Vienna Standard Mean Ocean Water, VSMOW)

$$\delta = \frac{R_{\text{sample}} - R_{\text{SMOW}}}{R_{\text{SMOW}}} \times 100\text{‰} \quad (1)$$

where R refers to the isotopic ratio (D/H) or ($^{18}\text{O}/^{16}\text{O}$) (Machavaram and Krishnamurthy 1995). In 1954, the International Atomic Energy Agency (IAEA), in co-operation with the World Meteorological Organization (WMO), conducted a worldwide survey of oxygen and hydrogen isotope content in precipitation. Since 1961, more than 780 meteorological stations in 101 countries have been monthly collecting precipitation samples. These samples are analyzed at the isotope hydrology laboratory (IAEA 2006).

Monitoring the variation of isotopic composition of precipitation requires to investigate $\delta^{18}\text{O}$ and δD values of precipitation. Many researchers such as Argiriou and Lykoudis (2006), Yu et al. (2008), Takeuchi et al. (2009), Van der Veer et al. (2009), Kumar et al. (2010a, b), Warriar and Babu (2011), and Vodila et al. (2011) have recently studied the variation of $\delta^{18}\text{O}$ and δD in precipitation for different parts of the world.

In this study, the effect of meteorological factors on precipitation isotopic data have been investigated in two stations of the Atomic Energy Agency, namely Tehran and New Delhi stations. The precipitation of Tehran is controlled by the Atlantic and the Eastern Mediterranean moisture sources, while in New Delhi it is controlled by Southwest monsoon rainfall that comes from the direction of Arabian Sea. The source of the moisture in the cities of Tehran and New Delhi are different. The most important aim of this study is to discuss the effects of these different sources of moisture on water isotopes' concentration in precipitation.

Materials and Methods

Sampling Stations

In this research, rainfall recorded at two GNIP stations (Tehran-New Delhi) are used to study the effect of the meteorological factor on the concentration of isotope composition.

Tehran situated in the north of Iran on the southern slopes of Alborz Mountains is located between $35^{\circ}34'$ and $35^{\circ}50' \text{N}$ and $51^{\circ}20'$ and $51^{\circ}36' \text{E}$ and encompasses an altitude range between 1,050 and 2,000 m above mean sea level (amsl). Tehran features a semi-arid and continental climate which is largely defined by its geographic

location with Alborz Mountains in its north and the central desert in the south. It can be generally described as mild in spring and autumn, hot and dry in the summer, and cold in the winter. As the city is large with significant differences in elevation for various zones, the weather is often cooler in the hilly north than in the flat southern part of Tehran. Average annual amount of precipitation recorded at the meteorological station is approximately 227 mm. Monthly rainfall is strongly influenced by season (month and moisture). The maximum and minimum recorded temperatures are approximately 39 °C in July and −1 °C in January. Tehran's main moisture source of precipitation is due to the Atlantic and the Eastern Mediterranean rainfalls. It has 12 meteorological stations, where measurements of meteorological data are available since 1951–2012.

New Delhi is located in the north of India (lat. 77°12'N; long. 28°36'E) with an average elevation of 216 m above msl. New Delhi's version of a humid subtropical climate is noticeably different from many other cities with this climate classification. In other words, it features long and very hot summers, relatively dry and cool winters, a monsoonal period, and dust storms. Summers are long, from early April to October, with the monsoon season in the middle of summer. Winter starts in November and peaks in January. New Delhi's highest temperature ever recorded is 47.2 °C, while the lowest recorded temperature is −0.6 °C. The average annual rainfall is approximately 714 mm, most of which occurs during the monsoons in July and August.

Data

In the Tehran and New Delhi stations, precipitation samples were collected to monitor oxygen, deuterium, and tritium isotopes in precipitation.

In Iran, precipitation samples were collected from 1960 to 1987 in Mehrabad station located at 35.41°N, 51.19°E and 1,200 m above msl. Tehran has 12 meteorological stations, among which Mehrabad meteorological station is the nearest one to Tehran GNIP station.

Since 1960, 40 meteorological stations in India are monthly collecting precipitation samples for the GNIP. The data has been derived from New Delhi station (N:28.58°, E:77.7° and 212 m above msl). The isotope and meteorological data have been recorded from 1960 to 2009 at New Delhi station.

This research contains two main initial objectives: firstly, the local meteoric water lines (LMWLs) were derived by using regression models of these cities and secondly, an investigation was conducted to examine the effects of variations in temperature on oxygen isotope value ($\delta^{18}\text{O}$). The time-series variation of the $\delta^{18}\text{O}$, δD and D-excess values of precipitation with the observed monthly amount of precipitation (mm) and temperature (°C), which were collected at the same time, are presented in Table 1 (IAEA 2012).

Table 1 The time-series variation of the $\delta^{18}\text{O}$, δD and deuterium excess (‰) values of precipitation with the observed monthly amount of precipitation (mm) and temperature ($^{\circ}\text{C}$) (IAEA/WMO 2012)

Sample date	Tehran: N:51.32°, E:35.68°, 1,200 m amsl					New Delhi: N:28.58°, E:77.22°, 212 m amsl				
	δD	$\delta^{18}\text{O}$	D-excess	Precip.	Temp.	δD	$\delta^{18}\text{O}$	D-excess	Precip.	Temp.
Nov 1961	22.3	2.1	5.5	1	11.1	-45.9	-7.1	10.9	1	18.7
Dec 1961	-11.8	-4.3	22.6	19	7.8	-45.9	-6	2.1	9	12.8
Jan 1962	-26.1	-6.1	22.7	14	4.4	-16.2	-3.9	15	33	12.9
Feb 1962	-31	-5.7	14.6	108	7.2	15	1.6	2.2	13	17.7
Mar 1962	-12.4	-3.9	18.8	5	13.1	20.5	1.6	7.7	8	22.4
Sep 1962	-52.1	-7	3.9	2	23.1	-75.6	-11.5	16.4	183	28.3
Nov 1962	-11.8	-2	4.2	5	9.7	-76.9	-10.9	10.3	2	20
Dec 1962	-36.6	-4.6	0.2	15	6.7	12.5	2.9	-10.7	25	14.8
Feb 1963	-23	-3.6	5.8	12	8.5	13.1	3.9	-18.1	12	18.5
Jun 1963	-10	-1.8	4.4	1	27.1	27.3	6.2	-22.3	118	33.1
Aug 1963	-13	-2.4	6.2	12	29.1	-49.6	-7.7	12	298	28.9
Sep 1963	-2.5	-1.5	9.5	1	25.6	-120	-15.3	2.4	278	28.1
Nov 1963	-16.8	-2.6	4	19	11	-109	-14.2	4.6	1	21.7
Dec 1963	-53.3	-9.6	23.5	63	2.9	-19.2	-1.4	-8	27	15.2
Feb 1964	-85.5	-12.2	12.1	33	4.9	-9.4	-0.2	-7.8	1	16.7
Mar 1964	-39.7	-6.6	13.1	10	12.2	-8.7	0.4	-11.9	1	24.1
Apr 1964	-40.3	-5.4	2.9	17	13.9	-30.2	-3.6	-1.4	5	29.5
Dec 1964	-99	-14.5	17	25	1.9	-36	-4.3	-1.6	16	15.2
Jan 1965	-74.4	-11.2	15.2	117	0.2	38.5	4.8	0.1	9	15.6
Feb 1965	-18.6	-4.2	15	8	3.3	55.8	5.8	9.4	9	16.7
Apr 1965	21.8	3.3	-4.6	16	14.8	17.4	2.4	-1.8	14	26.3
May 1965	19.9	3.1	-4.9	7	25.6	19.3	3.6	-9.5	6	31.3
Jun 1965	22.4	4.2	-11.2	1	27.1	46.6	8.2	-19	3	35
Aug 1965	31.1	7.5	-28.9	1	29.2	-47.1	-7.4	12.1	185	29.5

Sep 1965	-19.9	-4.7	17.7	10	24.1	-48.3	-6.6	4.5	197	28.5
Jan 1966	-14.3	-3.1	10.5	14	8.7	31.5	2.6	10.7	3	14.8
Feb 1966	-28.2	-5.8	18.2	33	9	0.4	-0.4	3.6	25	19.1
Apr 1966	10.3	-1	18.3	11	16	36.8	4.3	2.4	1	28.9
May 1966	55.8	9.3	-18.6	16	21.7	21.7	1.7	8.1	59	32.3
Jun 1966	3	-1	11	2	28.5	7	0.01	6.92	163	32.5
Jul 1966	3	-0.6	7.8	1	29.6	-13.5	-2.8	8.9	89	32.2
Oct 1966	-1	0.2	-2.6	22	17.1	-52	-8.5	16	30	26.3
Mar 1967	-18.9	-2.7	2.7	7	9.8	-34.8	-6.23	15.04	50	21.3
Oct 1967	12.3	3.15	-12.9	8	19.3	-38.8	-6.38	12.24	25	25.5
Jun 1968	-3.2	-1.28	7.04	12	25.3	18.7	1.56	6.22	24	34.1
Feb 1969	-74.7	-9.48	1.14	23	2	-21.8	-2.96	1.88	9	17.5
Jul 1969	-34.1	-5.88	12.94	5	28.4	-33.5	-5.33	9.14	227	30.9
Sep 1969	2.9	2.53	-17.34	6	23.1	-82.3	-12.42	17.06	197	33.9
Jan 1973	-57.8	-9.08	14.84	19	-0.5	14.4	-0.05	14.8	29	14.3
Jun 1974	6.1	0.1	5.3	2	26.1	30.7	3.61	1.82	21	33.3
Jul 1974	35	5.2	-6.6	1	29.5	-30.3	-5.85	16.5	375	30.6
Dec 1974	-83.6	-12.48	16.24	27	4.9	8.9	-1.58	21.54	9	14.8
Jan 1975	-93.6	-14	18.4	52	2.6	-47.8	-6.81	6.68	23	13.5
Feb 1975	-52.1	-8.31	14.38	70	4.5	4.5	-0.51	8.58	6	15.9
Mar 1975	-33.9	-6.38	17.14	21	9.8	43.1	7.58	-17.54	11	22.4
Jan 1976	-36.2	-6.41	15.08	26	5.3	3.8	-0.32	6.36	1	15.5
Feb 1976	-23.5	-5.84	23.22	33	3	7.6	-0.8	14	23	17.4
Mar 1976	-58.3	-9.17	15.06	44	6.1	1.5	-0.77	7.66	13	21.7
Apr 1976	-36.2	-6.04	12.12	32	15.2	1.1	0	1.1	7	27.9
May 1976	-24.1	-4.24	9.82	22	20.8	6.8	0.17	5.44	73	31.8

(continued)

Table 1 (continued)

Sample date	Tehran: N:51.32°, E:35.68°, 1,200 m amsl						New Delhi: N:28.58°, E:77.22°, 212 m amsl					
	δD	$\delta^{18}O$	D-excess	Precip.	Temp.		δD	$\delta^{18}O$	D-excess	Precip.	Temp.	
Feb 1979	-15.7	-5.09	25.02	23	5.2		17.8	0.38	14.76	45	16.3	
Mar 1979	-24.8	-4.73	13.04	77	9.6		23.2	1.51	11.12	23	21	
Apr 1979	27.5	2.67	6.14	11	18.8		2.8	-1.06	11.28	12	29.3	
May 1979	-28.2	-3.98	3.64	28	20.3		24.5	3.59	-4.22	15	31.1	
Jun 1979	6.4	0.36	3.52	15	26.2		9.4	-0.65	14.6	96	33.5	
Dec 1979	-30.3	-6.22	19.46	44	5.5		7.6	-0.37	10.56	9	16.5	
Jan 1980	-78.8	-11.84	15.92	48	1.8		-12.2	-2.17	5.16	5	14.2	
Feb 1980	-83	-12.08	13.64	69	3.5		28.4	3.11	3.52	9	18.2	
Mar 1980	-55.2	-7.61	5.68	43	10.7		-2.4	-1.8	12	26	21.6	
May 1980	11.6	0.5	7.6	3	23.1		27.3	5.23	-14.54	12	34.7	
Dec 1980	-51.9	-9.35	22.9	20	8.2		-3.4	-1.53	8.84	8	15.9	
Jan 1981	-21.9	-4.92	17.46	44	5.2		0.8	-1.86	15.68	32	14.9	
Feb 1981	-21.1	-5.07	19.46	32	7.3		24.5	2.07	7.94	16	17.9	
Mar 1981	-20.7	-3.3	5.7	32	12.6		9.5	0.97	1.74	13	21.5	
Nov 1981	-41.4	-6.5	10.6	7	11.7		-2.9	-1.31	7.58	27	21.5	
Dec 1981	-114.2	-15.34	8.52	28	9		22.3	2.48	2.46	2	15.3	
Dec 1985	-67.9	-9.68	9.54	-	-		-1.8	-0.39	1.32	35	16.7	
Jan 1986	-64.7	-7.82	-2.14	-	-		-2.3	-1.26	7.78	27	13.9	
Feb 1986	-46.7	-4.54	-10.38	-	-		-34.8	-5.07	5.76	41	16.2	
Mar 1986	-38.9	-6.72	14.86	-	-		14.3	2.25	-3.7	12	22.5	
Apr 1986	-19.7	-3.7	9.9	-	-		-2.6	1.14	-11.72	6	28.5	
May 1986	40	8.35	-26.8	-	-		11.6	3.6	-17.2	23	30.6	
Dec 1986	-77.7	-12.04	18.62	-	-		-7.5	-2.55	12.9	9	14.5	
Feb 1987	-31.9	-4.55	4.5	-	-		23.2	1.68	9.76	20	18.7	
Mar 1987	-10.8	-0.8	-4.4	-	-		-14.4	-2.75	7.6	20	23.2	

Results and Discussion

The isotopic data in Tehran station shows a wide variability with $\delta^{18}\text{O}$, ranging from -15.34‰ to 9.3‰ , while the δD values vary from -114.2‰ to 55.8‰ , respectively. In New Delhi station, the $\delta^{18}\text{O}$ values vary from -15.3‰ to 8.2‰ , and δD values range from -120‰ to 55.8‰ . These changes are controlled by hydrological parameters. In general, values of isotope ratios are affected by different factors including temperature, precipitation, altitude, latitude and seasonal effect (Vodila 2011; Leibundgut et al. 2009; Kumar et al. 2010a). A seasonal oscillation of stable isotope ratios is often observed as a result of temperature (Leibundgut et al. 2009). In this paper, the effects of temperature on precipitation isotope data in the stations of Tehran and New Delhi have been investigated and compared.

Local Meteoric Water Line

In order to study the overall stable isotopic characteristic, the isotope concentration values for all seasons are plotted. In general, there is a linear relationship between $\delta^{18}\text{O}$ and δD , which in global precipitation, defines the global meteoric water line (GMWL) (Craig 1961). The GMWL was originally defined as $\delta\text{D} = 8 \times \delta^{18}\text{O} + 10$. In each area, the LMWL may be defined similar to GMWL. Figure 1 shows the δD and $\delta^{18}\text{O}$ values of the monthly precipitation samples collected in the stations of Tehran and New Delhi. The variation in the slope and intercept of LMWL line strongly depends on the weather condition in each area (Craig 1961).

By fitting a straight line on isotopic data collected in Tehran and New Delhi stations, LMWL equations are obtained from the present study as follows.

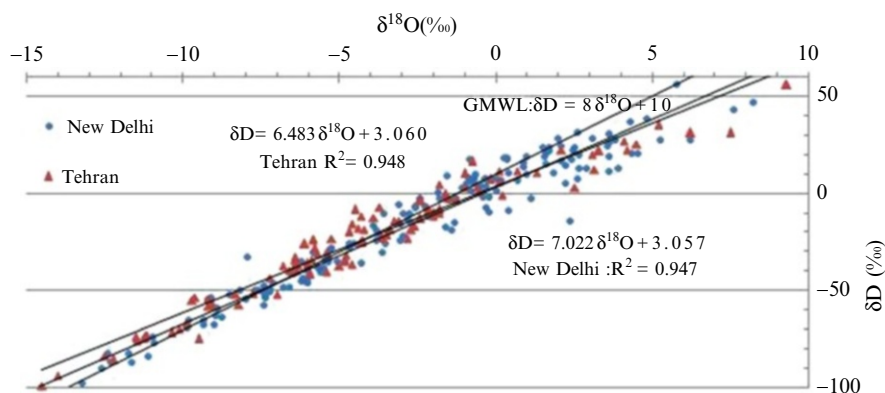


Fig. 1 The LMWL derived from the stable isotope composition in precipitation in the cities of Tehran and New Delhi

$$\text{Tehran : } \delta D = 6.483\delta^{18}O + 3.06 \quad (R^2 = 0.95) \quad (2)$$

$$\text{New Delhi : } \delta D = 7.02\delta^{18}O + 3.06 \quad (R^2 = 0.95) \quad (3)$$

By comparing the obtained LMWL equations with GMWL, it is observed that the slopes and intercepts of the LMWLs are less than the GMWL. Furthermore, Fig. 1 shows that most of the observed isotope values are below the GMWL. This phenomenon may be principally assigned to the effect of secondary evaporation during rainfall (Vodila 2011). Source of the moisture in the cities of Tehran and New Delhi are different, while the humidity is the same for both cities. Therefore, the intercepts of the fitted LMWL are the same. In addition, the obtained LMWL for New Delhi station in this study is nearly the same as the LMWL reported by Kumar B. et al. (2010a). They developed the LMWL for New Delhi station based on all seasons and monsoon data, respectively as

$$\delta D = 7.20 (\pm 0.10) \delta^{18}O + 4.60 (\pm 0.50) \quad (R^2 = 0.95) \quad (4)$$

$$\delta D = 7.20 (\pm 0.10) \delta^{18}O + 2.70 (\pm 0.80) \quad (R^2 = 0.97) \quad (5)$$

Effects of Temperature

As already discussed, the concentration of water's heavy stable isotopic components may change due to fraction process (Leibundgut et al. 2009). The variation in $\delta^{18}O$ corresponding to precipitation with temperature in the stations of Tehran and New Delhi are shown in Fig. 2. By investigation of data recorded in both stations (see Table 1), more negative values are generally occurred during the winter. As a

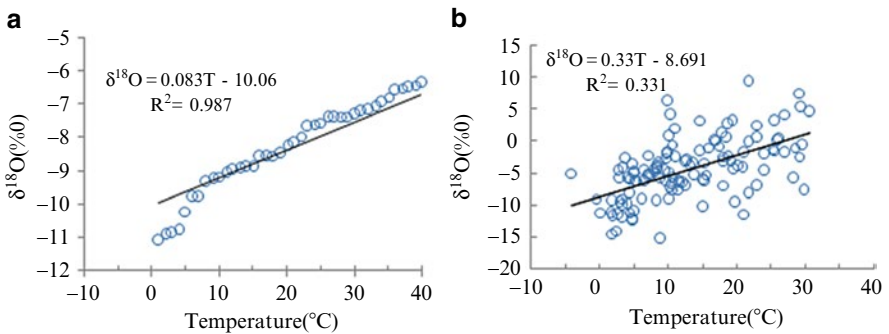


Fig. 2 Correlation between isotope values oxygen-18 and air temperature (T) at (a) New Delhi and (b) Tehran stations

result, the isotopic composition of precipitation in cold environments is more depleted compared to warm environments. It means that isotope concentration decreases with decreasing temperature as confirmed in Fig. 2. This figure also shows a good correlation between $\delta^{18}\text{O}$ and air temperature in the New Delhi station, while the corresponding correlation is relatively weak in the Tehran station.

Conclusions

In this study, time-series of oxygen and hydrogen stable isotope of the precipitation water collected monthly from 1961 to 1987 in the stations of Tehran and New Delhi were analyzed. The concentrations of water isotopes ($\delta^{18}\text{O}$, δD) vary spatially and temporally. These variations result from isotopic fractionation processes at each phase change of water during its atmospheric cycle. The changes in concentration of these isotopes are used to trace the movement of water in hydrological and meteorological processes. The slopes of the least-squares fitting lines range from 6.48 (Tehran) to 7.02 (New Delhi) in all seasons. The obtained LMWLs for these stations show significantly lower intercept and slope values than the GMWL. This result shows good agreement with the results reported in some recent works (Kumar et al. 2010a; Vodila et al. 2011). The source of the moisture in Tehran and New Delhi are different, however the humidity is the same in the both cities. Therefore, the intercepts of the fitted LMWL are the same. By plotting $\delta^{18}\text{O}$ values versus air temperature data of Tehran and New Delhi stations, a good correlation between $\delta^{18}\text{O}$ and air temperature in the New Delhi station ($R^2=0.987$) was obtained, while a relatively weak correlation was observed between $\delta^{18}\text{O}$ and air temperature in the Tehran station ($R^2=0.331$). The obtained results also showed that the maximum and minimum values of $\delta^{18}\text{O}$ are obtained during winter and summer, respectively. A linear relationship exists between monthly isotope data and meteorological parameters at each station. These results are consistent with the findings of Argiriou and Lykoudis (2006) in Greece.

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