The Hydrologic Origin of Fog Water: A Stable Isotopic Analysis

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Abstract: The stable isotopic measurement of a fog allows for the determination of the hydrologic origin of that fog regardless of the type. Upslope or mountain fogs, coastal advection fogs, and radiation fogs were collected at several locations around the world for stable isotopic analysis. Each type of fog has a unique stable isotopic composition that differs from that of local rain even when the fog and rain are prevalent, and collected in the same season.

1. INTRODUCTION

Fogs may form under several different atmospheric conditions, and may contain water from various sources. These sources may be local, or may be at great distances away from the location of the occurrence of the fog. The stable isotopic composition of the fog has been shown to be an excellent tool in determining the origin and conditions of occurrence of the condensing water. Moreover, using the stable isotopic ratios of fog drip water, the ultimate fate of that water can be determined. An explanation concerning the use of stable isotopes in identifying the source water and conditions of occurrence of several fogs is presented here. Particular attention is provided to radiation fogs recently collected in the Sacramento Valley of California.

The stable isotopic compositions (δD and $\delta^{18}O$) of fog was probably first determined by Gonfiantini and Longinelli [1962] who sampled both fog and rain on the fishing banks of Newfoundland and Labrador. These researchers noticed the isotopically enriched nature of fog, but did not offer an explanation as to the isotopic systematics of fractionation to explain the observation. Later, Ingraham and Matthews [1988] proposed that this difference could be used to trace fog water movement through the hydrosphere. To this end, coastal advection fogs were collected on the coast of California [Ingraham and Matthews, 1990; Ingraham et al., 1993] and the coast of Chile [Ingraham and Cereceda, this issue]. As expected, these waters had compositions reflecting the condensation of a vapor originally evaporated from the ocean. The compositions indicate a single cycle where ocean vapor condenses when it is blown over cool upwelled surface water. The same observation was made for fogs collected on the Otago Uplands on the South Island of New Zealand [Ingraham and Mark, 2000], where fog and rain were collected concurrently. The fog, being an early stage condensate is consistently more enriched than the rain that is a later stage condensate that condenses at higher altitudes. Mountain advection fogs collected in northern Kenya have been shown to be in part, the result of terrestrially evapotranspired water from upwind regions [Ingraham and Matthews, 1988; 1990]. All of these previously discussed fogs are of interest to the hydrologist as they are a form of advection fog. That is, the source of the water is upwind from the location of collection and the fog water represents an addition to the hydrologic balance at the environment of collection.

Radiation fogs have generally not been of interest to the hydrologist as the source of water producing the fog is local vapor, the condensation and precipitation of which does not augment the hydrologic budget. However, recently radiation fogs were collected in the Sacramento Valley of California during the winter for stable isotopic analysis to understand their formation in isotopic terms. Fog drips were collected in the early morning under foggy conditions ensuring an isotopic equilibrium between the fog drips and the fog droplets remaining in the atmosphere. The stable isotopic compositions of the fog drips and the temperatures at which they were collected are shown in Table 1.

Table 1.

Date, 1999	δD	$\delta^{18}O$	T°C
Jan. 3,	-48	-7.0	3.0
Jan. 4,	-38	-6.1	2.0
Jan. 5,	-44	-7.2	1.0
Jan. 6,	-41	-6.7	2.0
Jan. 7,	-33	-5.6	0.5
Jan. 13,	-32	-5.2	4.5

2. DISCUSSION

Fogs must always condense at temperatures cooler than the temperature at which the vapor was evaporated. Since equilibrium fractionation factors for isotopic separation are temperature dependent and larger at cooler temperatures, the isotopic separation is somewhat greater during condensation than during evaporation. However, the increased isotopic separation caused by humidity dependent kinetic effects experienced during evaporation may more than compensate any differences related to temperature. In addition, this increased isotopic separation effectively affects the oxygen ratios to a greater extent than the hydrogen ratios such that greater kinetic effects produces condensates more likely plotting farther above the meteoric water line [MWL, Craig, 1961]. If the source of the vapor is from transpiration, then the isotopic composition of that vapor is near identical to that of the water available to the plant [White et al., 1985]. While evaporation (transpiration) is indeed occurring in the leaf, by mass balance considerations of the water remaining and vapor leaving the leaf, the net effect on the vapor is minuscule. This understanding was applied to the observed stable isotopic compositions of the radiation fog collected in the Sacramento Valley as well as other types of fogs previously collected.

The isotopic compositions of the radiation fogs are shown with those from California coastal fog collected on the Pt. Reyes Peninsula [Ingraham and Matthews, 1990] as well as those of mountain fog collected in Kenya [Ingraham and Matthews, 1988] in Figure 1. The stable isotopic compositions of the radiation fogs collected in the Sacramento Valley are significantly more depleted than the fogs collected on the Pt. Reyes Peninsula. These radiation fogs, collected less than 100-km inland, are clearly related to the local water in the Sacramento Valley and in no way are related to ocean vapor.

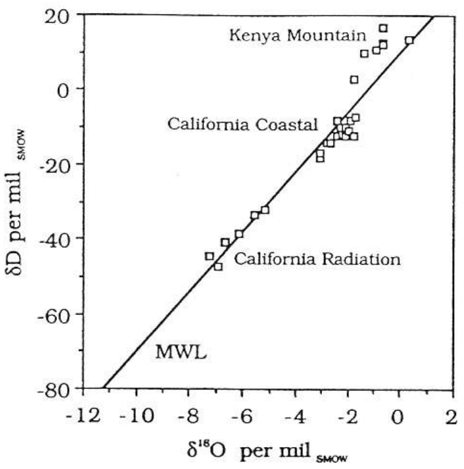

Figure 1. The stable isotopic compositions of the radiation fog, the coastal fog and the mountain fog.

The differing stable isotopic origins of the three types of fog can be observed in Figure 2. The coastal fog, as exemplified by that collected on the Pt. Reyes Peninsula, plots below the MWL displaying evaporation / condensation cycle that include only minor kinetic effects, and somewhat less than the more average amount identified by the MWL. The observation that these fogs are more depleted than Standard Mean Ocean Water (SMOW), and given that even under equilibrium evaporation and condensation the fogs should be more enriched than the original water (assumed to be close to δD and $\delta^{18}O = 0$), indicates that the vapor producing the fog is not an absolute first condensate ['fog-out' of Ingraham and Matthews, 1990] or the fog water does not have its origins directly from the ocean.

The mountain fogs collected in Kenya, by virtue of their stable isotopic compositions plotting considerably above the MWL and significantly more enriched than SMOW, have been shown to contain water that has been evapotranspired upwind. The stable isotopic compositions of water vapor produced by terrestrial evaporation under less humid conditions may plot as shown in Figure 2, while those of transpiration will be similar to the local water. Together these processes will serve to produce a vapor that when condensed will produce a fog that is more enriched and plot above the MWL. The explanation of the origin of these mountain fogs as shown in Figure 2, provides background to understanding the isotopic compositions of the radiation fogs collected in the Sacramento Valley.

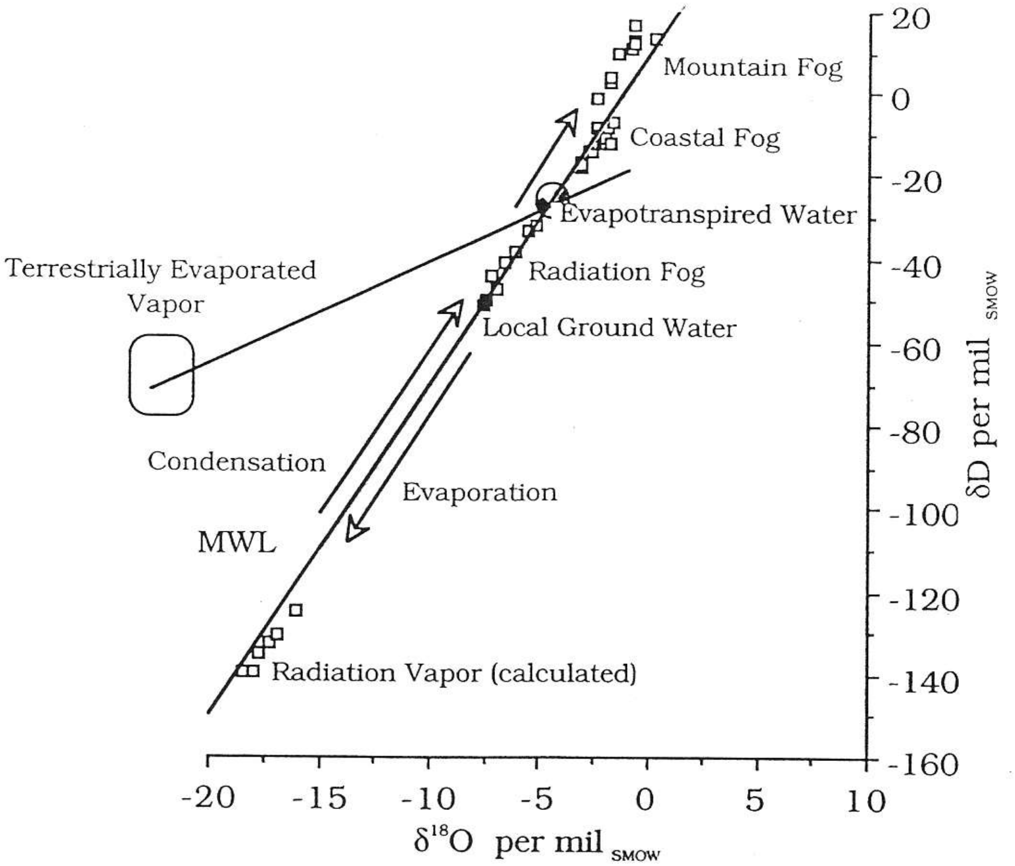

Figure 2: The coastal fogs are depleted compared with the presumed source of δD and $\delta^{18}O$ =0 (SMOW). The mountain fogs are much more enriched than their source water and above the MWL as they contain transpired vapor and vapor evaporated under less humid conditions. Radiation fogs are only a little more enriched compared to their source, the difference can solely be due to the difference in evaporation and condensation temperatures of the water vapor. This fog does not need the admixture of transpired water to explain their compositions.

The stable isotopic composition of the radiation fog drips plot close to the MWL indicating that the water has experienced more kinetic effects than the California coastal fogs, but less than the mountain fogs containing evapotranspired water upwind. The compositions of the radiation fogs and the temperature of (condensation) collection, as shown in Table 1, allow for the calculation of the isotopic composition of the ambient condensing vapor producing the fog. These values were calculated assuming isotopic equilibrium during condensation [Friedman and O'Neil, 1977], and are shown in Figure 2.

The condensing vapor producing the radiation fog is thought to have a local origin. Thus, the stable isotopic compositions of the fogs were compared to those of local water to determine how they could originate given ambient temperature constraints. Ground water in the area has been reported by Davidson and Criss [1993] to have a δD value of -50 per mil and a $\delta^{18}O$ value of -7.5 per mil, a composition somewhat more depleted than the fogs. However, the temperatures required to produce the vapor from the ground water under equilibrium conditions [Friedman and O'Neil, 1977] were calculated as being between 5.5 and 19°C. These temperatures (5.5, 11, 5.5, 8, 14, and 19 °C) would represent the equilibrium conditions under which the local water would be evaporated during the day in order to produce the compositions calculated for the vapor. While these temperatures are entirely reasonable as maximum daytime temperatures, it is difficult to equate them to the actual temperatures under which evaporation occurs, which might be somewhat cooler. Thus, the stable isotopic compositions of the radiation fog can, for the most part be explained by evaporation of local water [δD = -50, $\delta^{18}O$ = -7.5 per mil as identified by Davidson and Criss, 1993] under equilibrium conditions during the day at local ambient temperatures; then the condensation at the measured temperature in the morning. The difference, in almost 20 per mil in δD between the observed compositions of the fog and the parent water, can be mostly explained by the difference in evaporation-condensation temperatures.

Since transpiration would produce a water vapor of a composition similar to the that available to the plant and not of a depleted composition as calculated, the source of the water vapor producing the radiation fog must primarily be from evaporation. It appears that during the period, that weather conditions produce radiation fogs, most plants are dormant or transpire only minimally.

2.1 Significance

By stable isotopic analysis, the water from the three types of fogs discussed, coastal advection, mountain or upslope, and radiation fogs are shown to be from different types of sources. Moreover, the stable isotopic compositions of the three types of fogs are shown to have different modes of occurrence and formation. Most fogs are isotopically more enriched than the source water, however, some fogs might not be an absolute first condensate. However, regardless of the type of fog, the source of the water vapor producing the fog, or the mode of formation, the fog is consistently isotopically more enriched than the local rain. This is has even been observed to be the case with radiation fogs where the source of water vapor is local water similar in isotopic composition to local rain.

The radiation fogs reported here appear to contain local water that is evaporated during the day and condensed during the night and early morning hours. The difference between the evaporation and condensation temperatures alone can account for most if not all of the some 20 per mil difference in δD between the fog water and its source water. Thus, these radiation fogs do not appear to contain water vapor transpired from plants.

3. REFERENCES

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