Declining rock movement at Racetrack Playa, Death Valley National Park : an indicator of climate change ?

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Abstract

We have inspected Racetrack Playa at Death Valley over the last 7 years and have not observed major episodes of rock movement and trail generation. We compare this null observation with the literature record of the rock movement using a Monte Carlo method and find 4-to-1 odds that the rock movement probability has systematically declined . This statistically significant drop in movement rate may indicate a change in the probability of the required conditions for movement: we note decline in the occurrence of strong winds and in ice-forming cold in nearby weather records. Rock movement and trail formation may serve as an indicator of climate change.

Keywords : Climate Change; Statistics; Sliding Stones; Racetrack Playa; Death Valley

1. Introduction

Rocks on flat surfaces do not, in general, move. The evidence that rocks on Racetrack Playa, a usually dry lakebed in Death Valley National Park, occasionally do so and leave trails in the playa mud (Fig. 1), is therefore remarkable and accounts in part for this striking location's appeal to tourists and geologists alike.

Descriptions of the rock trails appear in the scientific literature beginning around 60 years ago (e.g.,Kirk, 1952), although earlier anecdotal accounts exist. A widely cited investigation is that by Sharp and Carey (1976) who documented changing rock positions and trail formation between 1967 and 1973, noting major movements over several winters.

We have visited the playa regularly since 2007 (in part because it is an analog for certain extraterrestrial landforms; Lorenz et al., 2010) and have not observed significant rock movement or trail formation. The purpose of this note is to assess whether this is 'just bad luck' or whether the probability that rock movement events occur has declined. We first summarize the literature record of rock movements and then apply statistical tests to evaluate the mutual probabilities of the various observations. We then explore regional meteorological data and find trends consistent with a decline in rock movement conditions.

The overall rarity of moving rocks attests to the infrequent occurrence of the necessary combination of conditions for rock movement. It follows that such conditions are found in the low-probabilty tails of distributions for the relevant factors and thus that they may be strongly sensitive to climate change.

< Figure 1 >

2. Rock movement events

A number of studies have documented rock movement events over periods of a few years. Unfortunately, no single complete record is known to exist over multiple decades, nor are strong negative observations (i.e., records asserting that no movement occurred over a period) generally reported. Because the trails left by the rocks degrade with time, the formation of new trails is generally obvious.

We summarize available reports in Table 1. The first entry is that by Sharp and Carey (1976), later expanded in the book by Sharp and Glazner (1997), which documents significant movements in the winters of 1968/69, 1972/73 and 1973/74.

The next record is almost two decades later, by Reid et al. (1995), who noted parallel sets of tracks and inferred the need in those instances of large sheets of ice. They suggest two events occurred: one in 1992/1993 and one in the late 1980s. Messina and Stoffer (2000) made a GPS survey of the tracks on the playa in 1997 and reported that minimal movement occurred between 1996 and 1998.

We found one report on the internet (Jones 2009, see Table 1) indicating trail formation in late January or early February 2005. This appears to be the most recent significant rock movement event. We have visited the playa twice-yearly since 2007. Our disappointment leads us to question whether our observations are consistent with those in the literature. The report by Sharp and Carey (1976) of three events in five winters implies a roughly even chance of seeing movement in a given winter, i.e., a 'fair coin', whereas we have had six 'tails' in a row.

3. Statistical significance of rock movement events

Statistical tools exist to study probabilities and assess the significance of limited observations. A succinct tool that gives some initial insight is the Bernouilli trial, which evaluates the probability of binomial events (i.e., where the outcome is one of two possibilities). Here we consider each year (or rather, each winter, as events seem principally to occur in that season) as a trial, with rock movement and the formation of trails as one outcome, and little or no movement as the other.

3.1. Bernoulli trials

For some given period, we assume the probability of rock movement is denoted p and the resultant probability of nonmovement is $q = 1 - p$. In a sequence of n events, the likelihood $P(n,k)$ of observing k movement events is given by

$$P(n,k)= [n!/(k!\{n-k\}!)]p^k q^{(n-k)} \qquad (1)$$

Although the moving rocks and their trails at Racetrack Playa are famous, very few movement events are known (and to date, none have been directly observed). We summarize the numbers of trials and the numbers of 'successes' (movements) in Table 1, which includes our own observation with timelapse cameras of playa conditions over the last six winters and twice-yearly visits to the playa, where no large-scale episodes of trail formation seem to have occurred.

Taking the data set overall, n = 24 (out of 44 years since the principal literature began discussion) and k = 6. Naively, this implies a likelihood of p = 0.25 that the rocks will move in a given winter. In fact, the binomial function $P(24,6)$ shows that this could be observed by chance (i.e, with a probability of 5% or more) for a likelihood of $p = 0.13 - 0.42$.

However, this overall reasonable likelihood is driven by the earliest observation leading us to question if we have merely been exceptionally unlucky to observe 0 events out of 6 winters. In fact, if we introduce the additional constraint by Messina and Stoffer (2000) that no movement was observed from 1996 to 1999, we have 0 events out of 9 years observed. An internet report (Jones 2009) suggests movement did occur in February 2005 (thus 1 out of 10 years). The binomial function for these observations is shown in Fig. 2. We can see that these functions are quite distinct (implying that the observations are likely not mutually consistent) but the overlap is nonzero, it could be 'bad luck.' A challenge, however, in interpreting the data this way is that the results depend on how the time series is broken into 'before' and 'after' periods, during which significant observational gaps exist.

< Figure 2 >

3.2. Monte Carlo analysis

Such incomplete information problems can be conveniently addressed with Monte Carlo methods. The observable that we aim to reproduce is the observation sequence of 'Yes', 'No', or 'unobserved' for the period of record. Because some observations are of the form 'one movement in period 19XX-19XY,' we cannot uniquely specify the sequence, but for the purpose of this analysis, any single consistent sequence will do. We have used the sequence 'YNNYNNYuuuuuuuuuuuYNYNNNYuuNNNuuuuuuYuNNNNNNN.' Now for each trial t in the sequence, we choose a random number *R* between 0 and 1, and compare with the probability $p(t)$ of rock movement : if $R(t) < p(t)$ then we record a 'Y', else we record 'N'. The resultant sequence is compared with the observed one, ignoring 'u' values where no observational data exist. If the sequences are exactly the same, the trial is a success. Because of course this is a somewhat long sequence, an individual random trial has a very low probability of being correct; in fact even with the best-fitting *p(t)* function we must run 20 million trials to get a useful number (~ 50) of successes so that less well-fitting functions can be tested against it. We specify *p(t)* as a linear function of time, i.e., varying linearly between an initial value *p*(start) and a final one *p*(end), corresponding to 1969 and 2013, respectively. A matrix of 20 x 20 choices of these parameters required an overnight run of the computer program and yielded (smoothed for plotting) the results in Fig. 3.

We see at once that the most likely scenario is that suggested by comparing the Bernouilli functions (the values are slightly different as a smoothly varying, rather than stepwise, change is considered), namely that the initial probability of movement *p*(start) is quite high, ~ 0.5, but has declined to a small value *p*(end) ~ 0.1 , suggesting that we may anticipate continued frustration in our attempts to observe rock movement in the future. Lower values of *p*(start) lead to too few movements to be consistent with the Sharp and Carey (1976) observations, and higher values of *p*(end) disagree with the present record. We see that a constant movement probability *p*(start) = *p*(end) ~ 0.3 can reproduce the observed sequence, but does so in only ~ 12 out of 20 million trials , i.e., is about 4 times less likely than the sharply declining movement probability that is most successful at generating the observed sequence.

Rock movement requires that the playa be wet (which our observations show -- assuming snowmelt or rainfall is required -- occurred on only about 46 out of ~ 300 days observed in winters 2007-2011) and that nonzero winds occur. Extensive debate in the literature (e.g., Reid et al., 1995) has argued that freezing is required, or not (Sharp and Glazner, 1997). Freezing conditions certainly allow rock movement to occur with lower (and thus more probable) winds than if ice is not present, more owing to the buoyant effects of ice ('rafting'; Lorenz et al., 2011a) rather than the wind drag area effect ('sailing'); but sufficiently strong winds can (and likely do) cause at least smaller rocks to slide without ice. While the observation of rock movement cannot discriminate between the factors, i.e., the observation only informs the combined probability of [flooding and (freezing and/or strong winds)], an observed change in rock movement frequency can require a change in one or more factors.

4. Meteorological record

The question naturally arises whether any meteorological evidence of such a change in conditions exists. While until recently there has been no systematic record of conditions at the playa itself, nearby weather stations provide pertinent information (see also Roof and Callagan, 2003). These records were recently reviewed with specific reference to rock movement conditions by Lorenz et al. (2011b).

Here we examine two records, the Remote Automatic Weather Stations (RAWS) stations on Hunter Mountain (16 km from the playa) and Panamint (78 km away). The RAWS stations have online meteorological data dating back to 1989 and 1988, respectively, covering the present epoch and the events observed by Reid et al. (1995).

Precipitation is a prerequisite for any of the scenarios of trail movement in that the playa mud must be soft, whether the rock is moved by direct drag from very strong winds or partly floated off the lake bed by ice. Precipitation (see Fif. 3 of Lorenz et al., 2011b) does not appear to have changed dramatically with time, although interpretation of such locally sporadic records is challenging. We furthermore know (Lorenz et al., 2011b) that the playa was flooded for some days in 2008/2009 and some weeks in 2009/2010, yet no major trail formation occurred.

However, for the other two parameters (wind and temperature) the conditions at the playa are more closely correlated with those at the playa itself. By histogramming the daily data from the two stations considered in two periods (pre-1996 and a recent period of comparable length, i.e. 2003-2010 -- the results are not sensitive to the exact date range chosen) we can evaluate whether conditions have changed.

Formation of ice sheets or cakes (Lorenz et al., 2011a; see also Kletetschka et al., 2013) thick enough to meaningfully buoy up rocks or apply wide-area windloads requires prolonged periods where the air temperature is below zero. According to standard calculations (e.g., http://icepredictor.com/,) several centimetres of ice can grow in ideal conditions overnight. Thus a daily-averaged temperature below zero is a good indication of a sustained ice growth condition. Figure 3 plots the relative frequency of occurrence of daily averaged temperatures in winter. We see that the probability of encountering the lowest daily average temperatures has declined. Note that the Hunter Mountain and Panamint sites are at elevations of 2000 m, rather higher than Racetrack Playa at ~ 1300 m. Thus when these sites indicate a temperature of -10°C, the air temperature at Racetrack may be as high as -3°C ; there are of course micrometeorological effects at Racetrack such as shadowing and cold-air-pooling, but these factors will not have changed with time. The indication in Fig. 4 is that the likelihood of thick ice sheets forming has reduced. This is consistent with general trends in global climate, e.g., the Fourth International Panel on Climate Change (IPCC, 2007) noted, ‘Almost everywhere, daily minimum temperatures are projected to increase faster than daily maximum temperatures, leading to a decrease in diurnal temperature range. Decreases in frost days are projected to occur almost everywhere in the middle and high latitudes, with a comparable increase in growing season length.’

< Figure 4 >

Should trails be instead formed by rocks moved by exceptionally strong winds (in fact, as noted by Sharp and Glazner, 1997, it is all but certain that ice is involved in some trail formation events, but other events do not require it), then trends in windspeed should be examined. Specifically, since trail formation may require only a few seconds of motion, the peak gust statistics are most relevant. We see in Figure 5 that the peak recorded gusts have strongly declined at both stations.

< Figure 5 >

It is possible that microclimate changes have occurred at the RAWS sites due to, e.g., nearby tree growth that may attenuate local winds. However, winds in the USA more generally, and especially the strongest winds, have declined in recent decades (Pryor et al., 2011) so the local record is consistent with broader trends.

5. Conclusions

The popular interest in the sliding stones at Racetrack, and the relative simplicity of the record presented here, makes it a pedagogically useful example of the application of statistical methods to establish the significance of rare events -- we note five events in 7 years prior to 1995, but only one event in 10 years since. There remains a modest chance (~ 25%) that the last few years of non-movement are simply ‘bad luck.’ However, the most likely scenario is that the annual probability of a trail-forming event has declined over the period 1969-2013, perhaps by as much as a factor of five. The meteorological record does not discriminate between rock-movement mechanism (winds vs. ice), but nearby measurements appear to be consistent with reducing probabilities of strong winds and of ice formation, either of which may be the dominant factor. The uncomfortable possibility exists that the rate of trail formation may be in systematic decline; and presently, trail formation may occur only every decade or so instead of every couple of years as observed in the 1970s.

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References

I.P.C.C., 2007. Working Group I: The Physical Science Basis in IPCC Fourth Assessment Report: Climate Change 2007. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Kirk, L.G., 1952. Trails and rocks observed on a playa in Death Valley National Monument, California. Journal of Sedimentary Petrology 22, 173-181.

Kletetschka, G., Hooke, R., Ryan, A., Fercana, G., McKinney, E. and Schwebler, K.P., 2013. Sliding stones of Racetrack Playa, Death Valley, USA: The roles of rock thermal conductivity and fluctuating water levels. Geomorphology 195, 110-117

Lorenz, R.D.,Jackson, B.K. and Hayes, A., 2010. Racetrack and Bonnie Claire: Southwestern US Playa Lakes as analogs for Ontario Lacus, Titan. Planetary and Space Science 58, 723-731.

Lorenz, R.D., Jackson, B.K., Barnes, J.W., Spitale, J.N. andKeller, J.M., 2011a. Ice rafts not sails : floating the rocks at Racetrack Playa. American Journal of Physics 79, 37-42.

Lorenz, R.D., Jackson, B.K., Barnes, J.W., Spitale, J.N., Radebaugh, J. and Baines, K.H., 2011b. Meteorological conditions at Racetrack Playa, Death Valley National Park: implications for rock production and transport. Journal of Applied Meteorology and Climatology 50, 2361-2375.

Messina, P. andStoffer, P., 2000. Terrain analysis of the Racetrack basin and the sliding rocks of Death Valley. Geomorphology 35, 253-265.

Pryor, S.C., Barthelmie, R.J., Young, D.T., Takle, E.S., Arritt, R.W., Flory, D., Gutowski Jr., J.W., Nunes, A. and Roads, J, 2009. Wind speed trends over the contiguous United States. Journal of Geophysical Research 114, D14105, doi:10.1029/2008JD011416.

Reid, J.B., Bucklin, E.P., Copenagle, L., Kidder, J., Pack, S.M., Polissar, P.J.,, and Williams, M.J., 1995. Sliding rocks at the Racetrack, Death Valley: What makes them move? Geology 23, 819-822.

Roof, S. and Callagan, C. 2003. The climate of Death Valley, California. Bulletin of the American Meteorological Society 84, 1725-1739.

Sharp, R.P. and Carey, D.L.,1976. Sliding stones, Racetrack Playa, California. Geological Society of America Bulletin 87. 1704-1717.

Sharp, R.P. and Glazner, A.F., 1997. Geology Underfoot in Death Valley and Owens Valley. Mountain Press, Missoula, MT, 319 pp.

Figure Captions

Fig. 1. View of the playa looking north in May 2013 from the base of the dolomite cliffs at its southern margin. Many rocks are present, having fallen and rolled from the source cliffs (or having been placed there). Only a few faint and topographically subdued trails are present.

Fig. 2. Probabilities of observing (k of n) successes in n trials, as a function of the underlying probability p of success. For our nondetection of movement (0 of 6), clearly the most likely scenario on this data alone is that $p = 0$, but 'bad luck' ($P(k)>0.05$) is still viable for $p \lesssim 0.34$. A range of $0.17 < p < 0.58$ is suggested by the combined Sharp and Carey (1976) and Reid et al. (1995) data.

Fig. 3. A contour plot of the relative success of a linearly varying probability model to reproduce the observed movement sequence. The contours are relative to the most successful trial, which actually had an absolute success rate of only 2.6E-6. The dashed line shows the locus of constant-probability models, which are at best ~ 25% as successful as the best model of p(start) ~ 0.55, p(end) ~ 0.06.

Fig. 4. Two weather stations near Racetrack Playa are examined for the lowest daily average temperatures (a proxy for ice formation potential) during the last 95 or first 90 days of the year, with data prior to 1996 and after 2003 examined separately. For both stations, the probability of encountering the coldest temperatures has declined, and thus ice seems less likely to form in the recent epoch.

Fig. 5. Two weather stations near Racetrack Playa are examined for the largest wind gust encountered during the last 95 or first 90 days of the year, with data prior to 1996 and after 2003 examined separately. For both stations, the probability of encountering the highest winds has declined.

Table

Table 1. Documented occurrences and nonoccurrences of rock movement at Racetrack Playa.

Period	Interpreted rate	Movement description	Source
1969-1976	3 / 7	'10 of 25 rocks moved in first winter; major episodes of movement recorded in two of the following six winters'	Sharp and Glazner, 1997 (Sharp and Carey, 1976)
1987-1994	2 / 7	'evidence for two major movement events, one in the late 1980s and another in late 1992 or early 1993'	Reid et al., 1995
1996-1999	0 / 3	'Little modification, only 4 rocks repositioned 1997-1998'	Messina and Stoffer, 2000
2005	1 / 1	'January 2005 covered with up to 6 inches of water…twelve days later an abundance of long new tracks'	Jones, 2009[a]
2007-2013	0 / 6	Only isolated small movements noted	This work
Summary 1969-2013	6 / 24	24 winters observed and reported 6 movement events noted	This work
Pre-1995	5/14		
Post-1995	1/10		

[a]http://www.groundtruthinvestigations.com/photography/travel/death_valley.html, downloaded 12 May 2013

Figure 1

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Figure 2

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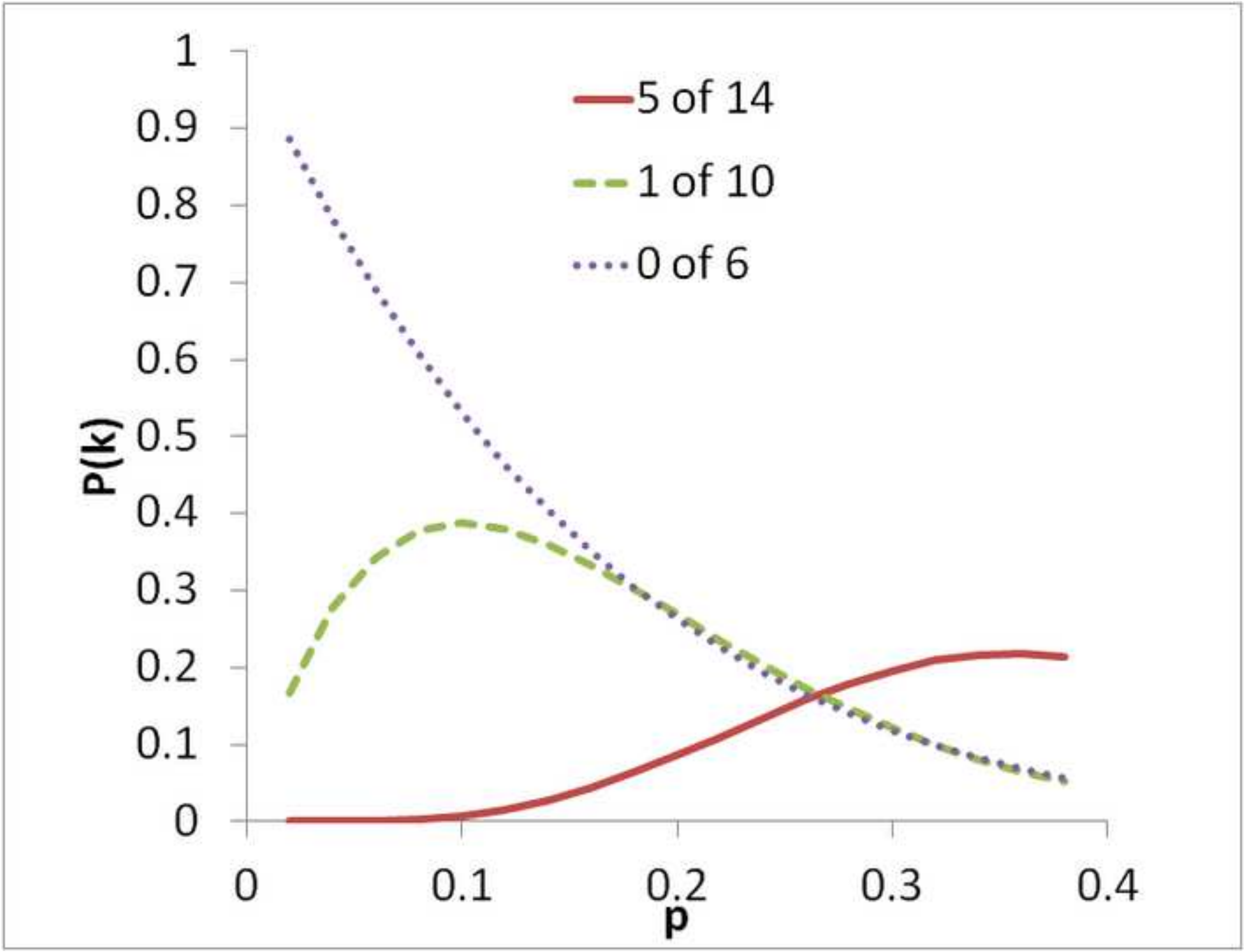

Figure 3
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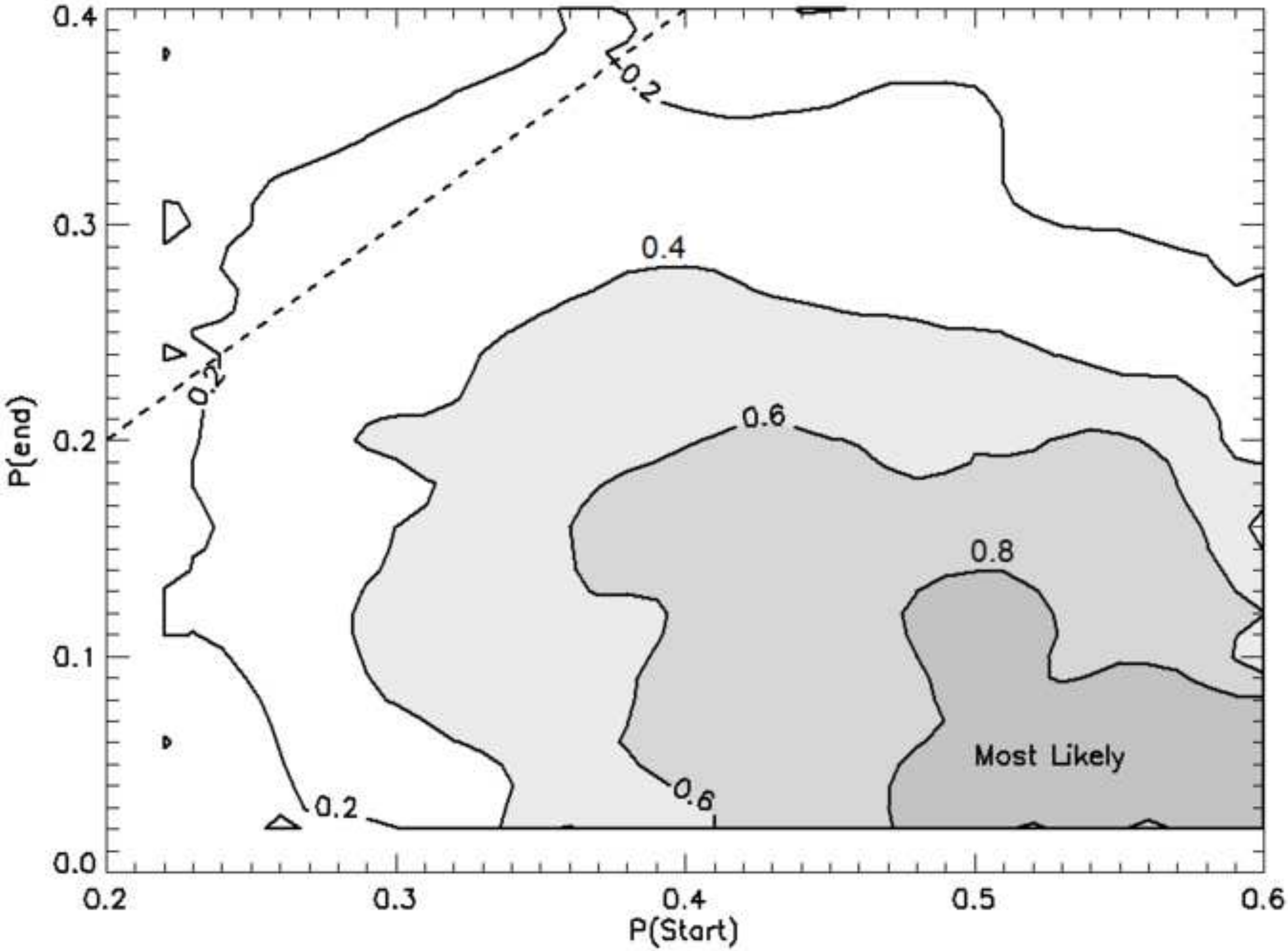

Figure 4

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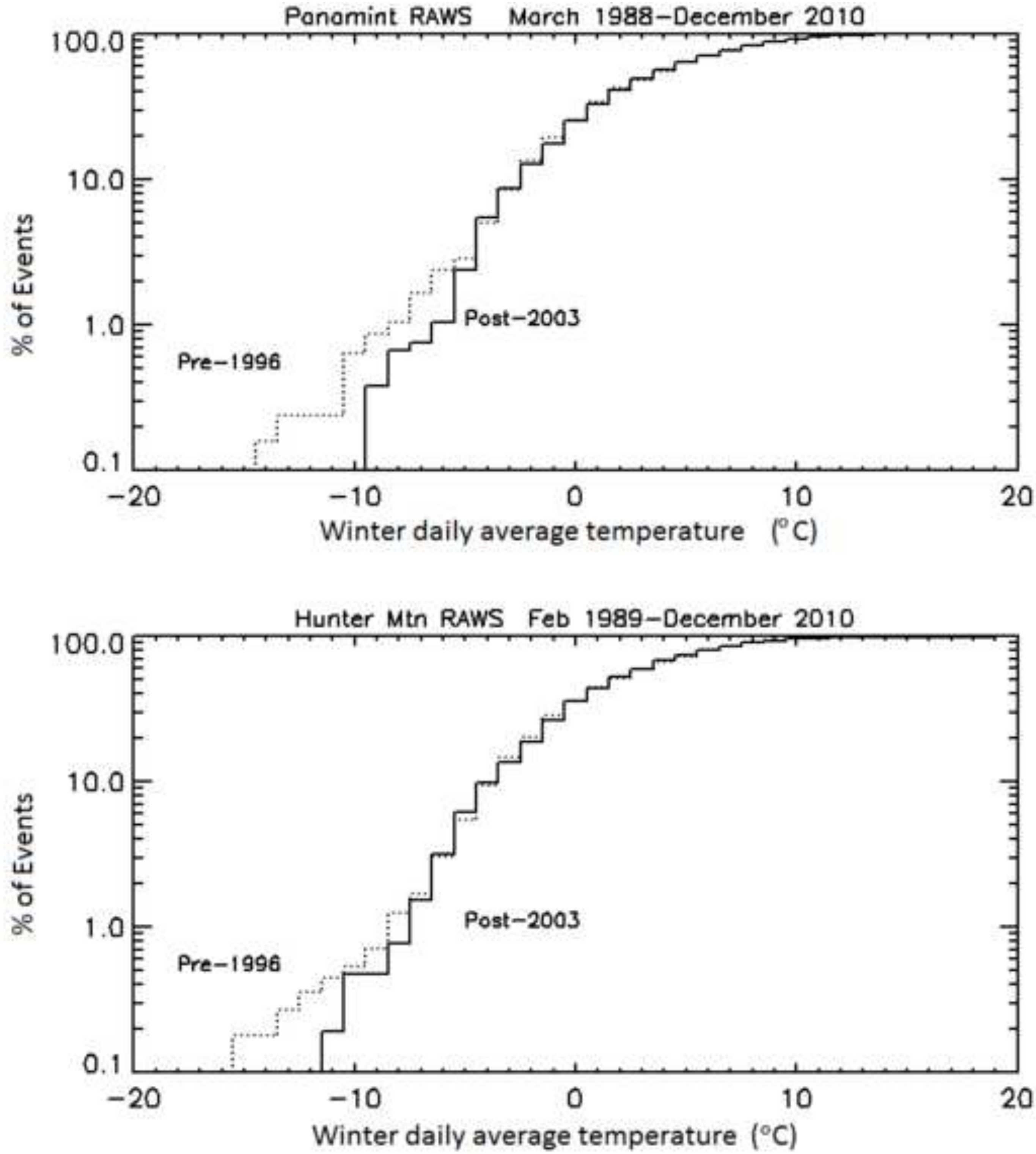

Figure 5
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