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Key Points:

- Increasing water vapor directly contributes to winter precipitation
- Reduced summer precipitation is related to accelerated decreasing RH

Supporting Information:

- Readme
- AppendixA_new.tif

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Impact of increased water vapor on precipitation efficiency over northern Eurasia

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Abstract This study investigates the relationships among water vapor, precipitation efficiency, precipitation amount, and air temperature anomalies on monthly time scales over northern Eurasia for winter and summer 2003–2010. Daily precipitation and temperature records at 505 historical stations, and atmospheric total precipitable water vapor and relative humidity data from Atmospheric Infrared Sounders, are used for analysis. Results show that higher atmospheric precipitable water associated with warmer temperature directly contributes to winter precipitation amount but has little impact on winter precipitation efficiency. However, accelerated decreasing relative humidity associated with higher temperature is the primary factor in the reduction of precipitation efficiency and precipitation amount regardless of higher precipitable water in summer. This study suggests that there are evident seasonal differences in precipitation trend associated with air temperature changes over the study region. Air temperature modifies a key atmospheric water variable that directly controls precipitation for that particular season.

1. Introduction

Atmospheric water vapor increases with warmer temperature as dictated by the Clausius-Clapeyron (C-C) theorem if relative humidity remains constant [*Bauer et al.*, 2002; *Dai*, 2006]. Thus, we would expect higher precipitation under a warming climate assuming that water vapor eventually becomes precipitation. Research on precipitation change associated with a warming climate shows that wetter places become wetter and drier places become drier, based on both data records and climate model projections [*Trenberth et al.*, 2007; *Trenberth*, 2011; *Trenberth and Shea*, 2005]. However, atmospheric water vapor is not expected to keep up with increasing air temperature in certain geographical regions due to the lack of evaporable water sources [*Berg et al.*, 2009; *Bauer et al.*, 2002; *Hardwick Jones et al.*, 2010; *Ye and Fetzer*, 2010]; thus, precipitation will not increase everywhere with increasing air temperature. This is especially true in summer when horizontal moisture transport is minimal and local evaporation becomes a significant contributor to atmospheric water vapor [*Kay et al.*, 2008; *Numaguti*, 1999; *Walsh et al.*, 1994; *Ye*, 2002; *Zveryae et al.*, 2008]. The increase in the globally averaged rate of precipitation is much lower compared to that of water vapor based on climate models' simulation outputs [*Stephens and Ellis*, 2008] and explained by the theory of energetic constraints [*Held and Soden*, 2006; *O'Gorman and Schneider*, 2008; *Schneider et al.*, 2010]. *Berg et al.* [2009] argue that the C-C relationship sets a limit to the increase in large-scale precipitation in winter, while the availability of moisture is the dominant limiting factor in summer. However, decreasing summer precipitation seems also to be happening even in places where water vapor has been increasing [*Pal et al.*, 2004; *Rowel*, 2009].

Atmospheric water vapor is only one of the three main factors affecting precipitation quantity; the other two factors are degree of saturation and the presence of dynamic mechanisms which provide the cooling necessary to produce saturation [*Tuller*, 1973]. This explains why atmospheric precipitable water is poorly correlated with actual recorded precipitation in general. Precipitation efficiency (P-Efficiency) is commonly used to focus on the efficacy of dynamic process mechanisms and illustrate the relative importance of available moisture and these mechanisms in producing precipitation. It is defined by total precipitation divided by atmospheric total precipitable water (PW) during the same time period and at the same location [*Sellers* 1965; *Tuller*, 1973; *Lutz*, 1981]. This variable measures the proportion of atmospheric water vapor that can be removed from the atmosphere at a given location and time period. Since PW is relatively stable and correlated over large areas while precipitation is variable over smaller space and time scales, higher P-Efficiency indicates an effective local dynamic mechanism that facilitates the condensation process leading to precipitation.

This study examines the relationships among PW, relative humidity (RH), precipitation amount, P-Efficiency, and air temperature to understand the role of temperature and water vapor in P-Efficiency. Northern Eurasia is chosen as the study region for several reasons. First, it is the largest landmass over high latitudes, where climate change has been amplified and seasonality is significant. Second, relatively long and continuous historical data exists over the region, and extensive research has been done on changes in the hydrological cycles including atmospheric water vapor/humidity [*Serreze et al.*, 2003; *Ye and Fetzer*, 2010; *Zhang et al.*, 2012], precipitation [*Groisman and Rankova*, 2001; *Ye*, 2001, 2008], river discharges [*Rawlins et al.*, 2009; *Yang et al.*, 2002; *Ye et al.*, 2004], and permafrost conditions [*Zhang et al.*, 2005]. Finally, conclusions derived from this region have implications for other high-latitude regions and are potentially significant to our understanding of climate change at a global scale.

2. Data and Methodology

Daily precipitation records are from the Daily Temperature and Precipitation Data for 518 Russian Meteorological Stations available from the Carbon Dioxide Information Analysis Center [*Bulygina and Razuvaev*, 2012]. This data set is comprised of daily mean, minimum, and maximum air temperature and daily total precipitation (liquid equivalent) records that have been quality controlled and wetting loss adjusted for different periods until 2010 [*Bulygina and Razuvaev*, 2012].

Atmospheric total precipitable water (PW) vapor and surface relative humidity (RH) are from the Atmospheric Infrared Sounder (AIRS) Version 6 Level 3 product available from June 2003 to the present [*Chahine et al.*, 2006; *Ye and Fetzer*, 2010]. The AIRS's PW data may have about 5–10% dry bias over high latitudes and the Antarctic compared to Radiosondes records and Advanced Microwave Scanning Radiometer records (AMSR-E) [*Ye et al.*, 2007; *Fetzer et al.*, 2006]; however, they are very consistent in temporal variability compared with Radiosondes records [*Ye et al.*, 2007]. The AIRS Level 3 data have a spatial resolution of 1° latitude by 1° longitude and a temporal resolution of twice per day. The grid points of AIRS data are matched to each of the station locations. Thus, each station's daily precipitation and temperature records have a corresponding AIRS daily mean of PW and RH.

The time period of June 2003 to December 2010, matching the AIRS era, is used to extract summer and winter monthly mean precipitation and air temperature. If there is a record missing for one day, the entire month is considered as missing. Due to the fact that some stations have been discontinued over the last two decades, a total of 505 of 518 stations are retained for analysis.

Precipitation efficiency is calculated by dividing monthly precipitation by monthly total precipitable water vapor, an approximation for the percentage of water vapor that is condensed and falls out of the air [*Tuller*, 1973]. For all variables used in analysis (PW, RH, P-Efficiency, precipitation amount, and air temperature), the monthly climatological value derived from the study period is subtracted from the corresponding monthly value to derive the monthly anomaly. Thus, all the relationships are examined using monthly anomalies. This removes any relationships that may be related to inter-seasonal variations in the nature of the data sets or potential dry bias in water vapor variables. The winter season includes monthly anomalies of December, January, and February with a total of 22 months; summer includes anomalies of June, July, and August with a total of 24 months for the June 2003 to December 2010 period.

Simple linear regression analysis with precipitation or P-Efficiency anomaly as the dependent variable, and water vapor anomaly (PW or RH) as the independent variable, is used to calculate the rate of change per each unit of water vapor increase for each station. Pearson correlation analysis is used to reveal the relationships among these variables. To separate the interrelationships among variables, first-order partial correlation analysis is used to reveal the relationship between two variables by controlling the influence of the other interrelated variables [*SAS Institute Inc*, 2009]. The equation used to calculate partial correlation coefficient is

$$PYxy, z = \frac{Yxy - Yxz * Yyz}{\sqrt{\left(1 - Y^2xz\right)\left(1 - Y^2yz\right)}}$$

where $PYxy, z$ is the partial correlation between x and y after control z. Yxy, Yxz, Yyz are the correlations between x and y, x and z, and y and z, respectively. The degree of freedom is $N - 3$.

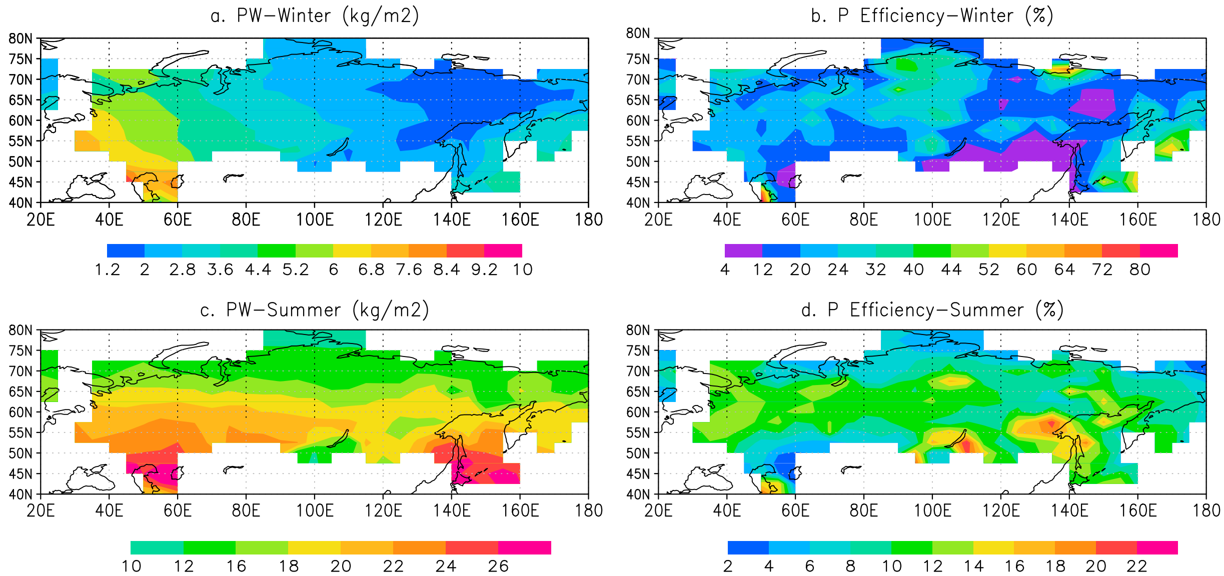

Figure 1. Distributions of PW (kg/m^2) and P-Efficiency (%) for winter and summer.

A confidence level of 95% and higher is used to determine statistical significance. This study focuses on winter and summer seasons during which the largest contrasts in results are found.

3. Results

Winter mean PW ranges from 1.15 to 10.25 kg/m^2, with an average of 3.9 kg/m^2 over the study region. Maximum values are located between the Caspian Sea and the Aral Sea and the western edge of southern European Russia. The PW then decreases toward the northeast until reaching the east coast where it starts to increase slightly (Figure 1a). This spatial pattern follows that of total winter precipitation, high in the west and decreasing toward the east [*Ye*, 2001]. Winter P-Efficiency ranges from 3.2% to 87.3%, with the highest efficiency found over the Arctic coast of eastern Siberia (Figure 1b). However, there could be a precipitation overestimate error (of up to 30%) related to blowing snow, wetting, condensation of gauge interior, etc. for some Arctic coastal stations with strong winds [*Bogdanova et al*., 2002]. Nevertheless, the coastal areas have a higher P-Efficiency in general with efficiency decreasing toward the south. The average winter P-Efficiency is 23% for the study region.

Summer season PW has a more latitudinal distribution pattern, from a high of 28.7 kg/m^2 decreasing northward to a low of 10.3 kg/m^2, with an average of 20.1 kg/m^2 for the study region as a whole (Figure 1c). Summer P-Efficiency is more localized, ranging from 1.5% to over 2% with a maximum in eastern Siberia exceeding 20% on average. European Russia, central Siberia, and the interior have higher P-Efficiency compared to the northern coastal regions. Average summer P-Efficiency is 10.5% over the study region. The P-Efficiency distribution pattern resembles that of summer total precipitation [*Ye*, 2002]. This may be related to the fact that cumulus cloud frequency is up to 70% of total cloud cover in summer [*Sun et al*., 2001; *Sun and Ya Groisman*, 2000; *Warren et al*., 1986] and 80% of summer precipitation is produced in localized cumulus convective systems compared to that of only 19% in winter over northern Eurasia [*Sun et al*., 2001]. In addition, the high summer local recycling of water vapor (about 16%) contributes to precipitation due to higher evapotranspiration [*Trenberth*, 1999].

When the climatological values of precipitation and P-Efficiency are plotted against the corresponding stations' PW (supporting information Figure 1), stations with higher PW in general correspond to higher precipitation during winter (with a correlation coefficient of 0.54, statistically significant at a 99% confidence level for the sample size of 505 stations). Precipitation is not necessarily higher at stations with higher PW during summer, except for a few very dry stations where PW is below 15 kg/m^2. P-Efficiency has no relationship with PW in winter, but stations with higher PW seem to have slightly lower P-Efficiency in summer (with a correlation coefficient of 0.24, significant at a 95% confidence level).

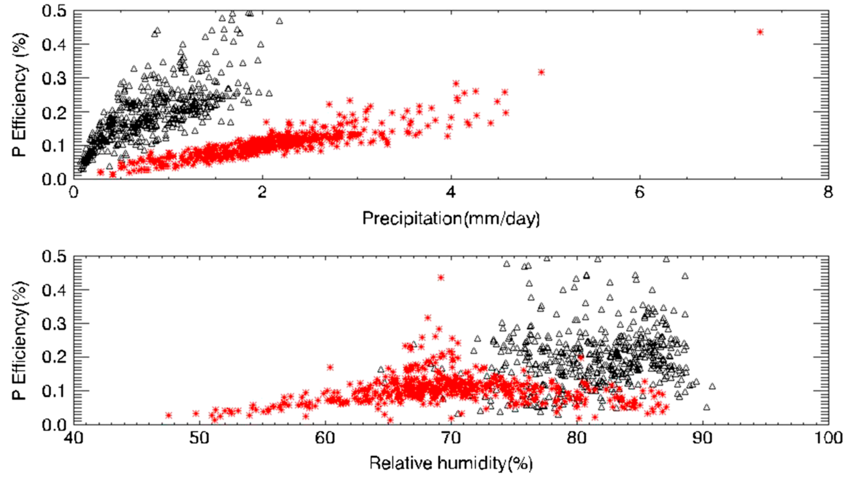

Figure 2. The correspondence of stations' mean P-Efficiency to (upper panel) precipitation and (lower panel) RH in summer (red stars) and winter (black triangles) for all 505 stations.

The stations' mean daily seasonal precipitation follows their P-Efficiency very closely, especially in summer (Figure 2). The same precipitation corresponds to much higher P-Efficiency in winter than in summer. This suggests that in order to produce the same amount of precipitation, much more PW is required in summer than in winter. Summer precipitation increases with RH for stations with RH below 70%, above which no correspondence is found (Figure 2). Similarly, there is a weak linear relationship between RH and P-Efficiency in winter since most stations have RH higher than 70%. The correlation analyses between P-Efficiency and P monthly anomalies for each individual station show that 99.4% of stations (502 out of 505 stations) have statistically positive correlation for both winter and summer.

Results of correlation analysis between water vapor variables and others are summarized in Table 1. PW significantly increases with air temperature anomaly in both winter and summer at more than 95% of stations. On the other hand, the RH shows negative correlation with air temperature at the majority of stations, especially in summer when 74% of stations are statistically significant (Table 1). The rate of PW increase for each degree of positive air temperature anomaly is 4.0% and 4.2% for winter and summer, respectively. The rate of summer RH decrease per each degree of positive air temperature anomaly is −0.99%.

In winter, PW is mostly significantly positively correlated with precipitation rather than P-Efficiency (Table 1, and Figure 3a). But RH has a little significant relationship with either P-Efficiency or precipitation total (Table 1). The correlation between winter precipitation and air temperature anomalies reveals that 78% of stations have a positive correlation and 27% are statistically significant at a 95% confidence level or higher (not listed). The partial correlation result between PW and precipitation after controlling for air temperature influence is comparable to that of the original correlation, implying that the relationship is not influenced by temperature. In other words, precipitation responds directly to PW rather than air temperature in winter.

Table 1. Correlation and Partial Correlation Results Among Water Vapor Variables (PW and RH) and P-Efficiency, Precipitation Amount, and Air Temperature, Presented by the Percentage of Stations (505 Total Stations)[a]

	Significant Positive (Total Positive)			Significant Negative (Total Negative)		
	P-eff	Precipitation	Temperature	P-eff	Precipitation	Temperature
Winter						
PW	5% (46%)	**27% (84%)**	**96% (100%)**	5% (54%)	0.2% (16%)	0% (0%)
PW*P		**29% (65%)**				
RH	5% (59%)	5% (56%)	3% (28%)	4% (41%)	5% (45%)	**28% (72%)**
Summer						
PW	0.4% (21%)	4% (51%)	**95% (99%)**	8% (79%)	1% (49%)	0% (1%)
RH	**60% (98%)**	**57% (98%)**	0.4% (5.3%)	0% (2%)	0% (0.2%)	**74% (95%)**
RH*P	**29% (90%)**	**37% (93%)**				

[a]Dominant statistically significant correlations are in bold (at a 95% or higher confidence level). Partial correlation that is independent of temperature is labeled by *P.

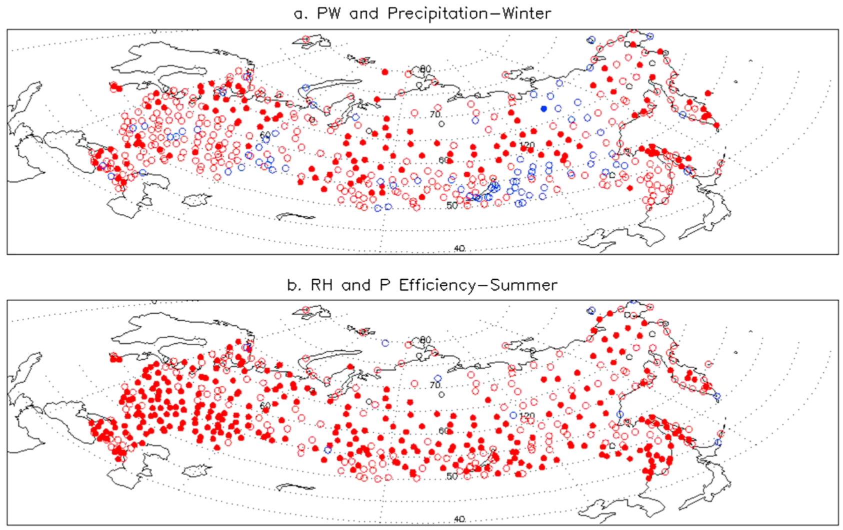

Figure 3. Distribution of correlation between (a) PW and precipitation in winter; (b) RH and P-Efficiency in summer. Red: positive correlation; blue: negative correlation. Shaded circle: statistically significant at a 95% confidence level and higher; open circle: not statistically significant.

The rate of winter precipitation change per kg/m^2 of PW increase averages 0.25 mm/day (or about 28%). The averaged rate of precipitation increase per degree of air temperature anomaly is 3.2%/°C, very close to the 3.9%/°C of PW increase with temperature. This suggests that PW almost directly and proportionately contributes to precipitation as air temperature increases, but RH has little role in either P-Efficiency or precipitation total during the winter season.

In summer, RH has a dominantly positive correlation with both P-Efficiency (Table 1 and Figure 3b) and precipitation amount (very similar pattern to Figure 3b). The relationship between PW and P-Efficiency exhibits mostly negative correlations, with only 7.5% of stations being statistically significant (Table 1). However, air temperature has a dominantly negative correlation with both P-Efficiency (96.6% of stations; 51.1% are statistically significant) and precipitation (87% of stations; 25% are statistically significant). The partial correlation results between RH and P-Efficiency/P after controlling for temperature influence show a reduced number of statistically significant stations, but the positive relationship is still dominant among all

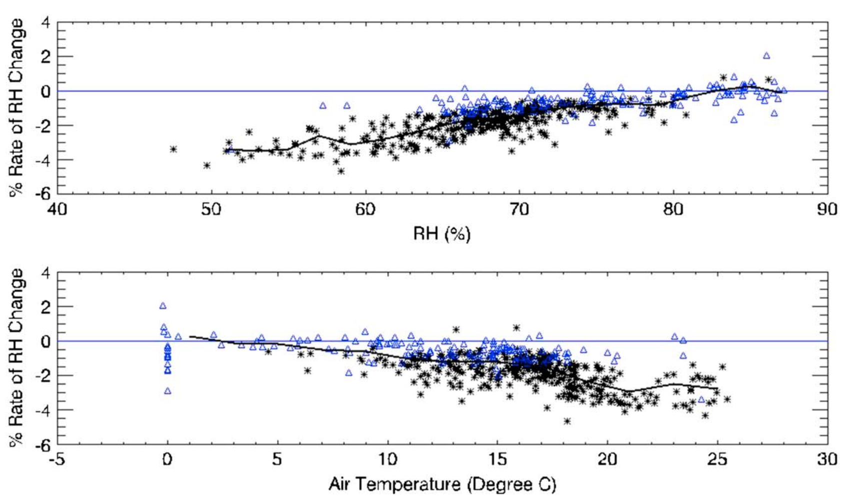

Figure 4. The percentage rate of RH change for each air temperature increase plotted against the (upper panel) corresponding stations' RH and (lower panel) air temperature. Black stars: statistically significant correlation at a 95% confidence level and higher; blue open triangles: not statistically significant. Thick solid line is the averaged RH rate for each 2% RH or 2 °C air temperature increments.

stations. This suggests that RH is the primary contributor to both PE and P, while air temperature may have a secondary role. The simple linear regression analyses to assess the rate of change of P-Efficiency and P associated with RH change suggested that the average rate of change for each 1% relative humidity anomaly is 0.0094 (or 4.5%) for P-Efficiency and 0.18 mm/day (or 8.9%) for P. The percentage rate of RH change per each degree of air temperature anomaly shows a significant positive trend with increasing station's RH (correlation coefficient of 0.7711; significant at a higher than 99% confidence level; Figure 4 upper panel), suggesting that stations with higher RH experience less reduction in RH with each degree of air temperature increment. Similarly, the percentage rate of RH change shows a negative relation with air temperature (correlation coefficient is −0.5646; significant at a higher than 99% confidence level; Figure 4 lower panel), suggesting that warmer stations experience a larger RH reduction given the same amount of temperature increment. Stations having lower summer temperature and/or higher RH are more likely to have no significant correlation between RH and air temperature at the monthly time scales examined here.

4. Conclusions and Summary

This study uses 505 stations' historical records of daily precipitation and their corresponding atmospheric total precipitable water (PW) vapor and relative humidity (RH) from Atmospheric Infrared Sounder to study the relationships of water vapor to precipitation and precipitation efficiency (P-Efficiency) over northern Eurasia at monthly time scales in winter and summer seasons from 2003 to 2010. For winter, PW is dominantly positively correlated with precipitation but not P-Efficiency. The average winter precipitation increase is about 26% for 1 kg/m^2 of atmospheric water vapor increase for the study region. The similar magnitude of the mean rate of PW increase (3.9%/°C) with that of precipitation increase (3.4%/°C) implies that increasing PW associated with each air temperature increment is almost directly and proportionally contributing to winter precipitation increase over the study region.

In summer, however, RH is the most significant factor correlated with both P-Efficiency and precipitation amount. The rate of change for each 1% RH anomaly is 4.5% and 8.9% for P-Efficiency and precipitation, respectively. Summer RH dominantly has a negative correlation with air temperature, and at stations with higher air temperatures and/or lower RH the rate of decrease is larger, resulting in more significant decreases in summer P-Efficiency and precipitation.

Conclusions drawn from this study are: (1) higher winter PW associated with positive temperature anomaly directly contributes to higher winter precipitation amount with little effect on P-Efficiency; (2) lower RH associated with positive temperature anomaly significantly reduces summer P-Efficiency and precipitation amount. Summer P-Efficiency/precipitation amount could be significantly reduced if air temperature increases regardless of increasing PW.

The different relationship of water vapor with P-Efficiency and precipitation is best explained by the difference in RH between winter and summer in the study region. The averaged winter relative humidity is about 81%, while summer is only about 69%, with a mean difference of 12% over the study region. A small increase in water vapor can effectively facilitate the condensation process in winter due to higher RH associated with extreme low temperatures. In summer, atmospheric RH governs evaporation, and low RH is the biggest single factor that reduces the precipitation efficiency of a convective system [*Doswell et al.*, 1996; *Junker*, 2008]. In general, warmer temperatures reduce RH and thus reduce P-Efficiency in summer, although PW increases with temperature. Lower P-Efficiency associated with a lower saturation rate inevitably leads to reduced summer precipitation.

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