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Nonlinear Responses of Droughts Over China to Volcanic Eruptions at Different Drought Phases

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Abstract Previous studies show that volcanic eruptions can intensify and extend drought events triggered by internal variability over Eastern China. However, it has remained unclear whether volcanic eruptions occurring in different drought phases have different impacts. Here, based on multiple reconstructions, simulations, as well as volcanic sensitivity experiments with volcanic forcing imposed in the early and late phases of droughts, we propose a nonlinear effect of volcanic eruptions on drought events. Late-phase volcanic eruptions exert greater impact on drought persistence and intensity while early-phase volcanic eruptions induce modest and weaker impacts. The evolutions of drought differ substantially from the typical volcanic-only influence or the linear combination of the drought triggered by internal variability and volcanic-only influences, which are hypothesized to be associated with positive feedbacks of soil moisture to precipitation, as well as its interaction with the evolution of the East Asia Summer monsoon.

Plain Language Summary The effects of volcanic eruptions on precipitation changes are usually considered only on short timescales, however, recent studies have found that volcanic eruptions can influence decadal mega-drought when superposed on drought events triggered by internal variability in the climate system (Ning et al., 2019; F. Chen et al., 2020). Our modeling and observational studies further show that the response of droughts to volcanic eruptions also depends significantly on the timing of the eruption. A volcanic eruption occurs in the late-phase of a drought intensifies the drought and extends the drought the most, and this impact decreases when the followed eruptions occur toward the early-phase. These nonlinear responses may be explained by the nonlinear feedbacks of local soil moisture to precipitation and nonlinear changes of East Asia Summer Monsoon after volcanic eruptions.

1. Introduction

Eastern China is one of the regions that are influenced most by droughts (Liu et al., 2006; Meehl & Hu, 2006; Shen et al., 2007; Peng et al., 2014). Previous studies have found that droughts in eastern China, which are often linked with weakening of East Asia Summer Monsoon (EASM) (Zhou et al., 2009; L. Zhang & Zhou, 2015), are primarily caused by internal variability in the climate system (R. Ault et al., 2018; Ning et al., 2019). For instance, droughts in eastern China are closely related to the positive Pacific Decadal Oscillation (PDO) patterns (Zhu & Yang, 2003; Z. Ma, 2007; R. Zhang, 2015a), and the cold phases of Atlantic Multi-decadal Oscillation (AMO) (Lu et al., 2006; Li & Bates, 2007; Y. Wang et al., 2009). Meanwhile, it has been shown that external forcing, in particular, strong volcanic eruptions, may also induce persistent drought events (Trenberth & Dai, 2007; Peng et al., 2014). On inter-annual timescales, strong volcanic eruptions can directly decrease precipitation in eastern China by cooling the atmosphere (Oman et al., 2005; Fan et al., 2009; Schneider et al., 2009; Iles & Hegerl, 2014), and indirectly influence precipitation by inducing increased occurrences of El Niño states and the transitions from El Niño to La Niña (Iles et al., 2013; Maher et al., 2015; Stevenson et al., 2016; Sun et al., 2018, 2019). On decadal timescales, volcanic eruptions can generate negative PDO patterns and cold AMO
phases, which would then weaken EASM and lead to droughts in eastern China (Mignot et al., 2011; T. Wang et al., 2012; Knudsen et al., 2014; Ning et al., 2017; Stevenson et al., 2017; Swingedouw et al., 2017; Prado et al., 2018; R. Zhang, 2015b).

These studies suggest that, in general, droughts in eastern China are influenced by both internal climate variability and external forcing. However, these studies have mainly studied the roles of internal variability and external forcing separately, with little attention paid to their combined effects. Our recent studies suggest that the superposition of volcanic eruptions on droughts induced by internal climate variability can significantly intensify and extend drought events in eastern China (Ning et al., 2019). It has remained, however, unclear if the volcanic impact remains the same when the eruption is imposed in different phases of the drought. Here, combining reconstructions with three groups of volcanic sensitivity experiments in CESM 1.0.3 (Gent et al., 2011; Hurrell et al., 2013), we aim to understand the evolution of droughts in response to volcanic eruptions occurring in different phases of the droughts. This will help to improve our understanding of the mechanisms behind the combined influences of internal climate variability and external volcanic forcing.

2. Materials and Methods

2.1. Experimental Design

In this study, two volcanic sensitivity experiments, where volcanoes erupt in different drought phases, were carried out through CESM 1.0.3 (Hurrell et al., 2013) with a low resolution of T31_g37 (~3.75 degree). Many previous studies (Otto-Bliesner et al., 2016; Stevenson et al., 2018; Zuo et al., 2019; Ning et al., 2020) have verified the performance of CESM, and they confirmed that this model can well reflect the response monsoon circulation and monsoon precipitation over Eastern China to volcanic forcing.

In our sensitivity experiment, firstly, a 2400-year control experiment is carried out based on the initial condition of 1850 CE, with the first 400 years are for spinning up. Then, ten fully independent initial conditions were selected every two hundred years from the last 2000 years of the control run. After that, 10 50-year CTRL experiments based on the 10 selected initial conditions were performed. Following previous studies (K. F. Chen et al., 2020; Ning et al., 2020), 15 drought events with an average length of ~5 years (longer than 3 years with precipitation below average, and at least one year below −1 standard deviation) were selected from the 10 CTRL experiments. Taking both statistical analysis and computational cost into consideration, 15 sample sizes are feasible. On one hand, the magnitudes and lengths of the randomly selected droughts from the CTRLs are similar under same criteria, therefore, the 15 members satisfy the statistical test and are enough to reflect the variability of drought at different drought phases. On the other hand, the computational cost for the sensitivity experiments of 15 members are also affordable. Here, “early” and “late” phases are defined as the first 40% years and last 40% years of droughts, respectively. As the lengths of droughts selected from the CTRLs are not exactly the same, the Ice-core based Volcanic Index 2 (Gao et al., 2008) at Mt. Parker, which is used as the only external forcing, is added to the last year of each of the 15 drought cases in late-phase experiments, and to the second year of the 15 drought cases in the early-phase experiments (K. F. Chen et al., 2020; Ning et al., 2020). These years are chosen because they can definitely represent “early” and “late” phases of droughts. Following previous studies (Grieser & Schonwiese, 1999; Gao et al., 2008), the spatial-temporal distribution of the monthly mean volcanic forcing is calculated basing on stratospheric transport parameterization. The aerosols at Mt. Parker have 5.16 Tg total amount of stratospheric aerosol, and were injected in the equatorial band and then released into both hemispheres (Figure S3 in the Supporting Information S1). Both CTRL and volcanic sensitivity experiments were run in parallel with the same initial conditions. Finally, the supposed epoch analysis (Adams et al., 2003; Hartmann, 2016) of the 15 drought members centered with the years of volcanic eruptions in the late- and early-phases of the droughts were conducted, respectively. Notably, the low resolution of the simulations in this study may induce some uncertainties on spatial patterns, which could be potentially improved through high-resolution simulations in the future.

2.2. Definition of Droughts and Study Area

The definition of drought differs from different scholars in different fields and a clear definition for extreme drought events is not available (Meehl & Hu, 2006; T. Ault et al., 2014; Stevenson et al., 2016). In this study, we define drought as negative precipitation anomalies that persist longer than three consecutive years with at least 1 year larger than 1 standard deviation, consistent with previous studies (Ning et al., 2019, 2020). Following
previous studies (e.g., Zheng et al., 2006), the study area of eastern China was defined as the region (31–40°N, 105–125°E; Figure S1 in the Supporting Information S1).

2.3. Soil Moisture Feedback Model

In this paper, a quantified estimating model was used to quantitatively reflect the degree of soil moisture feedback to precipitation (Frankignoul, et al., 1998; Liu et al., 2006). As found in previous study (Liu et al., 2006), the changes of local precipitation in eastern China constitutes two parts: the climate noise generated internally by the atmosphere and the feedback of local soil moisture. Following previous methods, the feedback efficiency of soil moisture to precipitation can be computed as below:

\[ P(t + \Delta t) = \lambda_P \cdot S(t) + N(t + \Delta t) \]  

Here, \( P(t) \) is the given precipitation variable (unit: mm/day) as a function of time \( t \). \( \Delta t \) is the precipitation response time. \( S(t) \) is the soil moisture variable (unit: Kg/m\(^2\)), \( \lambda_P \) is the feedback parameter from soil moisture to precipitation, representing the magnitude of soil moisture feedback on precipitation (unit: 1 mm/day (1 Kg/m\(^2\)). Therefore, \( \lambda_P \cdot S(t) \) indicates the precipitation response to a change in soil moisture \( S(t) \). \( N(t) \) is the climate noise generated internally by atmospheric processes, and is independent from the soil moisture variability. The noise term \( N(t + \Delta t) \), which is unknown, can be eliminated by multiplying Equation 1 with \( S(t-\tau) \) and taking the covariance (or correlation), following the same procedure in Liu et al. (2006; Equation 2). Here, \( \tau \) is the lead-time (unit: season) of soil moisture to precipitation. The elimination of \( N(t + \Delta t) \) works because when \( \tau > \Delta t > 0 \), the climate noise cannot force the precipitation changes at an earlier time.

\[ <S(t-\tau), P(t + \Delta t)> = \lambda_P <S(t-\tau), S(t)> + <S(t-\tau), N(t + \Delta t)> \]  

As the forcing parameter response to soil moisture changes is fast, the response time (\( \Delta t \)) can be neglected. Hence, the forcing parameter (\( \lambda_P \)) can be computed as:

\[ \lambda_P = \frac{<S(t-\tau), P(t + \Delta t)>}{<S(t-\tau), S(t)>} \]  

In this study, seasonal soil moisture and precipitation anomalies, with soil moisture leading precipitation for 2 seasons, are used to calculate the feedback efficiency \( \lambda_P \). Larger \( \lambda_P \) means that the soil moisture has larger feedback effects on precipitations. Same methods are used in this work when computing the feedback of soil moisture to evaporation.

3. Data

The tree ring based summer (JJA) Palmer Drought Severity Index (PDSI) in period 1300–2005 (Cook et al., 2010), and the tree-ring based reconstructed precipitation in period 1470–2000 (F. Shi et al., 2017) are used in this work. This reconstruction has a ~2.5 degree resolution and covers the area of eastern Asia (61.25°E–143.75°E, −8.75°S–56.25°N). The reconstructed summer (JJA) precipitation has a resolution of ~2 degree and covers the area of Asia (~8.75°S–55.25°N, 61.25°E–143.25°E). 13 all-forcing simulations from the Community Earth System Model-Last Millennium Ensemble Project (CESM-LME) spanning from 850 to 2005 AD (Otto-Bliesner et al., 2015) are also used. The CESM-LME archive has a ~2 degree resolution for both atmosphere and land components, and a ~1 degree resolution for ocean components. The volcanic aerosol used in this paper is reconstructed from ice-core in the last 1500 years by Gao et al. (2008).

4. Results

4.1. Nonlinear Responses of Droughts in Reconstructions and Model Historical Simulations

In this paper, we study the responses of drought over the Yellow River basin and Yangtze-Huaihe river areas (105°-120°E, 32°-40°N, Figure S1 in the Supporting Information S1), which strongly reflect the changes of East Asia Summer Monsoon (EASM) due to the typical “Northern drought and Southern flood” pattern of summer precipitation over Eastern China (S. Ma et al., 2015). The responses to volcanic eruptions at different drought phases are first investigated using two reconstructed data sets as well as model simulations. The two
proxy reconstructions are the PDSI index reconstruction spanning the periods 1300–2000 CE (Cook et al., 2015) and the precipitation for the period of 1470–2000 (H. Shi et al., 2018). In the reconstruction, we investigate the drought cases that were initially induced by internal variability but later superimposed with historical volcanic eruptions larger than 10 Tg. In order to get enough sample, we compose the drought events with volcanic eruptions centered at the late- (the 3rd year or later of the drought), and early- (the 1st or 2nd year of drought) phases of the droughts with maganitudes smaller than −0.5 standard deviation. In spite of the limited number of events, our compositions seem to suggest an interesting phenomenon: the longer a drought dominated by internal variability is before the eruption, the severer and longer this drought is afterward the eruption. More specifically, when volcanic eruptions occurred at the late phases of the droughts, precipitation decreases persisted after the eruption for ∼4 additional years (Figures 1a and 1d) with the maximum precipitation decreases reach −1 standard deviation. In comparison, when volcanic eruptions occurred at the early phases, the droughts persisted merely ∼1 year after the eruption (Figures 1b and 1e), shorter than the late phase ones. Finally, when volcanic eruption did not occur during drought events, drought (index becoming negative) hardly developed (Figures 1c and 1f).

Similar responses appear to be simulated in the archive of the CESM-LME. These simulations also show that droughts extend over ∼6 years after late-phase volcanic eruptions, with significant precipitation anomalies (p < 0.05; Figure 1g). However, drought merely sustained ∼1 year after early-phase volcanic eruptions (Figure 1b), while no significant drought is triggered if induced by volcanic forcing only, although there appeared to be a drying trend following the eruption (Figure 1i).

The impact of volcanic eruptions can also be seen by comparing the drought events forced by volcanic eruption with those without volcanic eruption (Figure S2 in the Supporting Information S1). For these drought events of 3 years length without volcanic eruptions, there are no significant droughts extending to after year-0 (Figures S2a,
S2d, and S2g in the Supporting Information S1). Similarly, for those droughts of 1–2 years, or even wet events, there are no significant droughts afterward (Figures S2b, S2e, and S2h in the Supporting Information S1). The significant differences between the results with (Figure 1) and without (Figure S2 in the Supporting Information S1) volcanic eruptions at different drought phases and at wet events not only show the role of volcanism as an amplifier on drought events triggered by internal variability, which is different from the typical precipitation decreases induced by volcanic eruptions, but also implies nonlinear responses of drought persistence and intensity to volcanic eruptions at different drought phases, which is different from the linear combinations of the original droughts and the precipitation decreases induced by volcanic eruptions only, especially for the late-phase volcanic eruptions. These observational and modeling results lead to our “nonlinear response” hypothesis: volcanic eruption occurring at a later phase of the drought tend to intensify the drought condition more in both the magnitude and duration.

4.2. Nonlinear Responses of Droughts in Sensitivity Experiments

To confirm our hypothesis of the nonlinear drought responses, we examine the composited responses of the volcanic sensitivity experiments in response to the same volcanic eruption forcing (Figure S3 in the Supporting Information S1) at different phases of the droughts (Figure 2). Here, volcanic forcing is uniformly added to the last and second year of 15 drought events triggered by internal variability in the late- and early-phase sensitivity
experiments, respectively (details in Section 2.1). The definitions of “early-phase” and “late-phase” in sensitivity experiments and reconstructions are intrinsically consistent, because droughts persist 1–2 years before early-phase eruptions, and persist more than or equal to 3 years before late-phase eruptions in both reconstructions and model simulations. These experiments show that volcanic eruptions do extend the drought events, and the extension period increases with the phase of the volcanic eruption.

In the experiments of late-phase volcanic eruption, each drought event originating from internal variability which has persisted for 4 years would have been terminated by a wet event at year 0 without volcano eruption (Figure 2a). The eruption of a volcano at this late-phase, however, extends the dry condition by ∼5 years, with the precipitation decrease significantly ($p < 0.05$) in year-0 to year-3 and year-5 based on Student $t$-test (Figure 2b). The ensemble mean precipitation anomalies from year-0 (i.e., eruption year) to year-5 is $−0.22$ mm/day (Figure 2g) and is smaller than $−0.5$ standard deviation, indicating that volcano extends and enhances droughts when erupting at the late phases of the droughts. Compared with the CTRLs (Figure 2c), precipitation is strongly decreased, with maximum value smaller than $−1$ standard deviation.

Qualitatively, the precipitation anomalies induced by early-phase volcanic eruptions are small and insignificant compared with late-phase droughts, although the precipitation are still below climatological mean (Figures 2d–2f). For early-phase eruptions, the precipitation decreases persist merely 3 years and the decreases are statistically insignificant except year-2. The intensities of droughts are smaller than the late-phase cases, with a magnitude of $−0.11$ mm/day (Figure 2g), lower than 0.5 standard deviations. Compared with the CTRL experiments (Figures 2f and 2g), the magnitudes of negative precipitation anomalies are smaller from year-0 to year-4, indicating that the early-phase volcanic eruptions actually weakened the intensities of original droughts, although there could be uncertainties due to the limited sample sizes here. However, it does show a dramatical difference from the late-phase experiments.

Combined, the sensitivity experiments suggest a nonlinear response of droughts to volcanic eruptions at different phases. Indeed, were the response linear, the responses to volcanic forcing at the different phases should be exactly the same, because they are forced by exactly the same volcanic forcing in all the three phases (Figure S3 in the Supporting Information S1). Furthermore, these nonlinear responses are largely consistent with those in reconstructions and the CESM-LME ensembles. Therefore, we believe that our hypothesis of the nonlinear responses is strongly supported by reconstructions, historical simulations and sensitivity experiments.

4.3. Mechanisms Behind the Nonlinear Responses

4.3.1. Linear Responses of Circulations to Volcanic Eruptions

Many researchers focused on the mechanisms behind the volcano-induced drought in eastern China (Man et al., 2014; K. Chen et al., 2020; Ning et al., 2020). Consistent with previous findings, we find out that the volcano-extended drought is directly related to the decreases of land-sea thermal contrast and the weakening and eastward retreating of the West Pacific Subtropical High (WPSH). Firstly, the responses of the evolutions of temperature, sea level pressure (SLP) over eastern China and the surrounding ocean indicate that the cooling rates of surface air temperature between land and ocean after volcanism are different, giving rise to a higher pressure in eastern China, a prevailing northernly anomaly and a reduced moisture import into this region (Figure S4 in the Supporting Information S1). Consistent with previous findings, we find out that the volcano-extended drought is directly related to the decreases of land-sea thermal contrast and the weakening and eastward retreating of the West Pacific Subtropical High (WPSH). Secondly, compared with both the climate and CTRLs, the weakening and eastward retreating of WPSH during the first 2 years after eruption, along with the cold SST over the key region in the northwestern Pacific (123°E–150°E, 15°N–30°N), play important roles in intensifying the rainfall deficit over northern China (Figure S5 in the Supporting Information S1). As the WPSH strengthens and moves westward in the next several years, the southeastward wind prevails and meets with the northwesterly in the Yangtze River Basin, causing moisture convergence and ascending motion, and, in turn, increased precipitation, in eastern China. However, these mechanisms, which are all related to the continental scale background climate fields, are consistent in both of the 2 groups of sensitivity experiments. This leads to an interesting question: what are the mechanisms for the nonlinear responses of the droughts?

4.3.2. Nonlinear Evolutions of EASM Caused by Anticyclone Anomalies

In spite of the linear responses of the background climate fields, regional responses associated with the East Asia Summer Monsoon (EASM) seems to exhibit similar nonlinear responses as the droughts. As a further
examination of the nonlinear responses in eastern China, we turn to regional climate variables directly associated with the East Asia Summer Monsoon (EASM), which directly contribute to the different post-eruption droughts. Here, following previous studies (Liu et al., 2014), the EASM index (EASMI) was defined as the summer 850 hPa meridional wind anomalies averaged over the East China region (25–43°N, 105–120°E), which is highly correlated with summer precipitation over northern China via its transport of moisture (not shown).

We also analyze the changes of the 500 hPa vertical speed (Pa/s) averaged over Northern China (31–40°N, 105–120°E, Figure 3), which is usually associated with large scale precipitation. In the late-phase sensitivity experiments, the EASMI responses relative to CTRL climatology remain negative from year-1 to year-5, except for year-4 (Figures 3b and 3c, yellow lines), consistent with the precipitation responses (Figures 3b and 3c, bars).
In the early-phase experiment, however, the volcanic eruption doesn't induce a sustained EASM weakening after year-0 (Figures 3d–3f), with EASMI anomalies rebounded in year-1 (Figures 3e and 3f). These responses may be related to the uncertainty due to limited ensemble member. Nevertheless, they both seem to be associated with anti-cyclonic circulation anomalies in the southeast China (not shown), which increases the vapor transport from the ocean, opposing the drying conditions and therefore resulting in insignificant precipitation anomalies in the corresponding years (Figure 2e). Moreover, the anti-cyclonic anomalies after early-phase eruptions are stronger than those in late-phase eruptions, inducing a larger EASMI rebound at year-1. In sum, the different drought responses seem to be associated with the different regional responses of the EASM in the two volcanic sensitivity experiments, suggesting a direct association of the nonlinear drought responses with that of the EASM system.

4.3.3. Feedback Mechanisms of Soil Moisture to Precipitation on the Persistence of Droughts

The nonlinear drought responses in the three sensitivity experiments seem to originate from that of local soil moisture. It has been recognized that soil moisture can exert strong feedback on regional hydroclimate (Guo & Wang, 2003; Koster et al., 2004; Liu et al., 2006). Here, the annual mean soil moisture exhibits similar nonlinear responses to volcanic forcing at different drought phases, especially within a soil depth of 0–1m (not shown). Therefore, we use the local soil moisture integrated for the top 1-m as the soil moisture index in the sensitivity experiments (Figure 4). In the late-phase experiments, compared with both climatology and CTRLs, the soil moisture responses remain strongly negative for 5 years after the eruption (Figures 4a–4c) with an averaged magnitude of $\sim 0.8$ Kg/m$^2$ (Figures 4b and 4g). While the weakened drought responses become much more clear in
the early-phase experiments, in which a small negative moisture response lasts only ~3 years (Figure 4e), with insignificant soil moisture decreases compared with the CTRLs (Figure 4f).

The consistent responses of soil moisture and precipitation lead us to hypothesize that the initial soil moisture conditions play pivotal roles in the nonlinear drought responses to volcanic eruptions. This follows because the soil moisture conditions prior to volcanic eruptions are different at different drought phases. In the late-phase experiments, the accumulated soil moisture deficiencies before volcanism can lead to dry pre-conditioning, less evapotranspiration, and, then, larger rainfall decreases in response to the volcanic eruption, which further enhances the drought with positive soil moisture feedback on precipitation (Koster et al., 2004). In the early-phase experiments, the dry pre-conditioning of soil moisture and its feedback on precipitation are weaker, leading to smaller drought responses post-eruption.

To identify the causality between soil moisture and precipitation and quantitatively evaluate the degree of feedback from soil moisture to precipitation, forcing efficiencies of soil moisture $\lambda_P$ are computed using the feedback model described in Section 2.3. In the late-phase experiments, the soil moisture leads precipitation for 1 and 2 seasons with a feedback parameter of 1.25 mm/day $\cdot$ (kg/m$^2$)$^{-1}$. However, after early-phase volcanic eruptions, the soil moisture leads precipitation for just 1 season, with a smaller feedback efficiency of 0.24 mm/day $\cdot$ (kg/m$^2$)$^{-1}$ due to wetter initial conditions. Similar phenomena occur when it is related to the local soil moisture and evaporation. Feedbacks from soil moisture to evaporation are larger in late-phase experiments (1.54 mm/day $\cdot$ (kg/m$^2$)$^{-1}$) compared with that in early-phase experiments (0.83 mm/day $\cdot$ (kg/m$^2$)$^{-1}$). These results indicate that soil moisture deficit induces evaporation decreases, and further results in reduced specific humidity in the middle and lower atmosphere (1000-1500 hPa), which directly contributes to precipitation decreases. These processes are stronger when volcanic eruptions occur at late-phases of droughts.

5. Conclusions

Our analysis of reconstructions, historical simulations as well as sensitivity experiments suggest a nonlinear response of drought to a volcanic eruption that is superimposed at different phases of the drought. A volcanic eruption at the late-phase of a drought triggered by internal variability can induce a larger drought response of a longer duration and larger magnitude. The drought responses, however, become weaker if the volcanic eruption occurs in the early- phase of the drought. This nonlinear drought response is related to the nonlinear response of regional EASM, and is hypothesized to originate from soil moisture precondition and feedback. The anomalously low soil moisture, especially in the late-phase, can amplify the subsequent response to volcanic eruption, generating a longer-term drought afterward, while the relatively wet soil moisture states in the early-phase exerts little impact on volcanic eruption, leading to muted drought response over northern China. Much further study is needed to better understand the interaction between volcanic eruption and climate response.

Data Availability Statement

The reconstructed Palmer Drought Severity Index (PDSI) is freely available through Cook et al. (2015). The ice-core based volcanic aerosol is available through Gao et al. (2008). The model information is available through Otto-Bliesner et al. (2015). The simulated data from the volcanic sensitivity experiments in this paper are available at Zenodo (https://zenodo.org/) and can be download by the link: https://zenodo.org/record/5839688#.Yd6IwdFByCp.

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