Spatiotemporal Evolution Characteristics of Different Grades of Cold Days in Qinghai Province (Postprint)

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Abstract

Utilizing daily minimum temperature data from 42 meteorological stations in Qinghai Province during 1961–2019, this study analyzes the spatiotemporal evolution characteristics of cold days across different grades. The results indicate: (1) During 1961–2019, the number of cold days in Qinghai Province progressively increased with decreasing grade, predominantly composed of slightly cold days; the total cold days exhibited an overall decreasing trend, with a significant abrupt change of rapid reduction occurring in 1995; the decrease in total cold days was primarily attributed to the reduction in severely cold days; following the climate abrupt change in 1997, the trends of bitterly cold, major cold, minor cold, light cold, slightly cold, and total cold days decreased, while the trend of severely cold days increased, and the trends of extremely cold and cool days showed comparable distributions of decrease and increase. (2) Cold days in Qinghai Province demonstrated pronounced spatial heterogeneity, with total cold days progressively increasing with elevation; higher-grade cold days exhibited more pronounced increasing/decreasing trends, and as the cold grade decreased, the increasing/decreasing trends extended toward lower-latitude and relatively lower-elevation regions. (3) Extremely cold, severely cold, bitterly cold, light cold, slightly cold, and total cold days gradually decreased with increasing annual mean temperature, whereas major cold, minor cold, and cool days gradually increased with increasing annual mean temperature. (4) Except for bitterly cold days, cold days of all other grades in Qinghai Province exhibit persistence, and the future decreasing trend will continue, albeit with varying persistence intensity.

Full Text

Spatial and Temporal Evolution Characteristics of Different Grades of Cold Days in Qinghai Province

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Abstract

Based on daily minimum temperature data from 42 meteorological stations in Qinghai Province from 1961 to 2019, this study analyzes the spatial and temporal evolution characteristics of different grades of cold days. The results indicate that: (1) From 1961 to 2019, the number of cold days in Qinghai Province gradually increased as the grade decreased, with slightly cold days being the dominant category. The total number of cold days exhibited an overall decreasing trend, with a significant rapid reduction 突变 occurring in 1995. This decrease was primarily driven by the reduction in extremely cold days. Following the climate 突变 in 1997, the trends for severe cold, major cold, minor cold, light cold, slightly cold, and total cold days all decreased, while the trend for extremely cold days increased. The trends for extreme cold and cool days showed roughly equal patterns of decrease and increase, respectively. (2) Significant spatial differences in cold days were observed across Qinghai Province. The total number of cold days gradually increased with altitude, and the trends for higher-grade cold days were more pronounced. As the cold grade decreased, the trends of increase and decrease expanded toward lower latitudes and relatively lower altitude areas. (3) The numbers of extreme cold, extremely cold, severe cold, light cold, slightly cold, and total cold days gradually decreased with rising annual mean temperature, whereas the numbers of major cold, minor cold, and cool days gradually increased with rising annual mean temperature. (4) Except for severe cold days, all other grades of cold days exhibited persistence, indicating that the downward trend will continue in the future, though the persistence intensity varies among different grades.

Keywords: cold days; space-time evolution; mutation characteristics; future trends; Qinghai Province

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Introduction

The IPCC assessment report indicates that with ongoing global warming, extreme high-temperature events are likely to increase while extreme low-temperature events may decrease. However, some studies suggest that climate warming could lead to increased frequency and intensity of anomalous weather and climate events, and the intensity and impact of extreme low temperatures should not be underestimated. Previous research by Ma Zhuguo et al. [], Zhai Panmao et al. [], Yang Jinhu et al. [], and Chen Shaoyong et al. focused on minimum temperatures and extreme low-temperature event frequencies in northern China, revealing significant reductions in minimum temperature frequency, extremely low nighttime temperatures, and extreme low-temperature events, with a 突变 in annual extreme low-temperature frequency occurring around 1990. In recent years, scholars have analyzed extreme temperature events in provinces surrounding the Qinghai-Tibet Plateau, including Xinjiang [], Ningxia [], Gansu [], Sichuan [], and Tibet [], as well as in the desert and sandy regions of northern China [] and the alpine endorheic region of the Qinghai-Tibet Plateau [], concluding that extreme temperature indices generally show significant trends, with decreasing (increasing) frequencies of extreme cold (warm) indices and the largest increase in annual extreme low temperatures. Some studies have examined extreme temperature events in Qinghai Province [], finding significant decreasing trends in extreme cold indices, with the most rapid decrease occurring in the Qaidam Basin and eastern agricultural areas. Kong Feng [] analyzed cold days across different grades in China from 1961 to 2017, revealing that the number of cold days increased as the grade decreased, with higher-grade cold days showing decreasing trends, and the range of increasing and decreasing trends expanding as the cold grade decreased. An Bin et al. [] studied cold days in the Loess Plateau, finding that most areas were dominated by major cold days, with total cold days showing decreasing trends primarily caused by reductions in major cold days.

Despite extensive research on extreme low temperatures from various perspectives, regions, and time scales, studies on different grades of cold days remain relatively limited, particularly in Qinghai Province where low-temperature freezing damage occurs frequently with strong responses, significantly impacting agriculture, animal husbandry, and the ecological environment []. Therefore, investigating the spatial and temporal changes in extreme cold weather is crucial for better 应对 cold weather events and disaster prevention and mitigation. This study utilizes daily minimum temperature data from 1961 to 2019 to analyze the spatial and temporal evolution characteristics of different grades of cold days in Qinghai Province, aiming to provide a comprehensive scientific understanding of cold days against the background of warming and to offer a scientific basis for disaster prevention and mitigation, climate change adaptation, and the construction of a comprehensive risk prevention system in Qinghai Province.

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1. Data and Methods

1.1 Study Area Overview

Qinghai Province is located in the northeastern edge of the Qinghai-Tibet Plateau, with geographical coordinates of 31°36 –39°12 N, 89°25 –103°04 E and an average altitude above 3000 m. Influenced by its unique geographical environment and atmospheric circulation, the region has a cold, dry climate with strong solar radiation, representing a typical plateau continental semi-arid climate that is highly sensitive to global climate change. Due to significant spatial differences in climate across Qinghai Province, the study area was divided into four ecological functional zones based on the provincial meteorological and geographical zoning standards: the Qaidam Basin, the Three-River Source Region, the Eastern Agricultural Area, and the Circum-Qinghai Lake Region [Figure 1: see original paper].

1.2 Data and Methods

The study utilized daily minimum temperature data from 42 meteorological stations in Qinghai Province from 1961 to 2019, obtained from the Qinghai Provincial Meteorological Information Center. This dataset underwent rigorous quality control and inspection. Following the meteorological industry standard for "cold degree grades" and referencing relevant literature [], minimum temperatures were classified into eight grades from low to high: extreme cold (min≤-30 ℃), extremely cold (-30 ℃< min≤-20 ℃), severe cold (-20 ℃< min≤-15 ℃), major cold (-15 ℃< min≤-10 ℃), minor cold (-10 ℃< min≤-5 ℃), light cold (-5 ℃< min$ 0℃),*slightlycold*(0℃ < *min* 5℃),*andcool*(5℃ < *min* $10 ℃). Lower temperatures correspond to higher grades, and vice versa. The sum of cold days across all grades was defined as the total number of cold days.

Linear trend analysis and the Mann-Kendall test were employed to examine temporal changes in cold days, while the cumulative anomaly method and moving t-test were used to identify 突变 points. The Hurst index [] was applied to analyze future trends, and inverse distance weighting interpolation was used to examine the spatial distribution and trend characteristics of cold days. Finally, differences in cold days before and after the 1997 climate 突变 were compared and analyzed.

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2. Results and Analysis

2.1 Temporal Variation of Different Grades of Cold Days

The total number of cold days in Qinghai Province averaged 336.9 days, accounting for 92.3% of the total annual days, with a minimum of 318.6 days and a maximum of 349.6 days, showing small interannual fluctuations. Slightly cold days dominated (18.8%), followed by light cold (16.8%) and cool days (16.0%), while extreme cold days were the least frequent. This demonstrates that the number of cold days gradually increased as the grade decreased. In terms of trends, total cold days, extreme cold, extremely cold, severe cold, light cold, and slightly cold days showed decreasing trends, while major cold, minor cold, and cool days showed increasing trends. Extremely cold days decreased most significantly at a rate of 4.1 $d \cdot (10a)^{-1}$, indicating that the reduction in total cold days was primarily caused by the decrease in extremely cold days, followed by extreme cold, severe cold, light cold, and slightly cold days, while major cold, minor cold, and cool days contributed to increases in total cold days.

The cumulative anomaly curve revealed that total cold days were in an above-normal period before 1995 and entered a below-normal period after 1995, with a substantial decrease over the past 60 years. Extreme cold and light cold days were above normal before 1990 and below normal after 1990. Extremely cold and severe cold days were above normal before 1985 and below normal after 1985, with extremely cold and severe cold years occurring slightly earlier than for total, extreme, and light cold days. Major cold days showed large fluctuations before 1990 and entered an above-normal period after 1990. Slightly cold days were above normal before 1975, below normal from 1975 to 1990, and showed an overall “high-low-high-low” pattern. Minor cold and cool days were below normal before 1995 and above normal after 1995, with cool days showing a smaller increase than minor cold days.

The moving average curve indicated that total cold days have been decreasing since the 1980s, with a rapid reduction beginning in the late 1990s, confirming the undeniable decreasing trend. Extreme cold, extremely cold, and severe cold days showed decreasing trends, with extremely cold and severe cold days decreasing rapidly while extreme cold days decreased more slowly. Major cold days fluctuated significantly in the mid-1980s with no clear trend thereafter. Minor cold and cool days showed overall increasing trends, with minor cold days increasing rapidly in the 1990s and then slowly, while cool days decreased after the 1990s. Light cold and slightly cold days showed slow decreasing trends, with light cold days peaking in the mid-1980s before decreasing, and slightly cold days decreasing from the mid-1970s to 1990, then slowly increasing before fluctuating downward after 2000.

Decadal anomaly analysis further confirmed that total cold days evolved from positive to negative anomalies with advancing decades, indicating a decreasing trend. Extreme cold, extremely cold, severe cold, light cold, and slightly cold days showed decreasing trends, with extreme cold days transitioning from positive to negative anomalies in the 1990s, and extremely cold, severe cold, light cold, and slightly cold days transitioning in the 1980s. Major cold, minor cold, and cool days evolved from negative to positive anomalies, with major cold days transitioning in the 1990s. This demonstrates that minor cold and cool days increased while other grades decreased.

2.2 Spatial Distribution of Different Grades of Cold Days

Spatially, total cold days exhibited a saddle-shaped distribution, concentrated in the Three-River Source Region and Circum-Qinghai Lake Region (exceeding 328.5 days), particularly at Wudaoliang, Tuotuohe, and Maduo in the Three-River Source Region where values exceeded 355 days. The Eastern Agricultural Area had the fewest cold days, with a minimum of 252.5 days at Xunhua. Extreme cold days exceeded 60.9 days in the Three-River Source Region, particularly at Qingshuihe where values reached 80.1 days, while other areas had fewer than 3.9 days. Extremely cold days were most prevalent in the Qaidam Basin, exceeding 56.2 days at Dulan, with no extremely cold weather recorded at some stations in the Eastern Agricultural Area. Severe cold days were concentrated in the Circum-Qinghai Lake Region, Three-River Source Region, and Qaidam Basin, exceeding 34.6 days, particularly at Tuotuohe and Wudaoliang in the Three-River Source Region where values reached 60.9 days. Major cold days were most common in the Qaidam Basin, exceeding 43.7 days at Dulan, while Minhe in the Eastern Agricultural Area had only 7.5 days. Minor cold and light cold days were mainly distributed in the Three-River Source Region, with fewer minor cold days in the Circum-Qinghai Lake Region and fewer light cold days in the Qaidam Basin. Slightly cold days were concentrated in the Circum-Qinghai Lake Region and eastern Three-River Source Region, with the Circum-Qinghai Lake Region having the most (exceeding 80.1 days) and Wudaoliang in the western Three-River Source Region having the least (43.7 days). Cool days were primarily distributed in the Eastern Agricultural Area (exceeding 43.7 days), particularly at Tongren and Huangzhong where values exceeded 56.2 days, while Wudaoliang and Qingshuihe in the Three-River Source Region had fewer than 7.5 days. This demonstrates that higher-grade cold days were more prevalent in the Three-River Source Region and the Qilian Mountains north of the Circum-Qinghai Lake Region, while lower-grade cold days became more common in the Qaidam Basin and Eastern Agricultural Area as the grade decreased.

2.3 Spatial Distribution of Variation Trends in Different Grades of Cold Days

The total number of cold days in Qinghai Province showed an overall decreasing trend, primarily in the Qaidam Basin (decreasing by more than 6.3 $\mathrm{d \cdot (10a)^{-1}}$), followed by the Circum-Qinghai Lake Region (5.8 $\mathrm{d \cdot (10a)^{-1}}$), with the smallest decrease in the Three-River Source Region (2.4 $\mathrm{d \cdot (10a)^{-1}}$). The most significant decreases occurred at Golmud, Mangya in the Qaidam Basin and Tongren in the Eastern Agricultural Area, with reduction rates exceeding 9.1 $\mathrm{d \cdot (10a)^{-1}}$. Extreme cold, extremely cold, and severe cold days showed decreasing trends, with extreme and extremely cold days decreasing mainly in the Three-River Source Region, Circum-Qinghai Lake Region, and Qaidam Basin, while severe cold days decreased primarily in the Qaidam Basin and Eastern Agricultural Area, particularly at Huangzhong in the Eastern Agricultural Area and Golmud in the Qaidam Basin where rates exceeded 7.7 d · $(10a)^{-1}$ and 6.9 d · $(10a)^{-1}$, respectively.

Major cold and cool days showed decreasing trends only in the Eastern Agricultural Area, with increasing trends in other ecological functional zones. Major cold days decreased significantly in Xunhua and Jianzha in the Eastern Agricultural Area at rates of 5.7 d · $(10a)^{-1}$ and 5.3 d · $(10a)^{-1}$, respectively, while cool days decreased in Tongren and Ledu in the Eastern Agricultural Area at 3.3 d · $(10a)^{-1}$. Minor cold days showed an increasing trend from west to east, with rates exceeding 3.0 d · $(10a)^{-1}$ in Tongren, Huangzhong, and Ledu in the Eastern Agricultural Area. Light cold days decreased in the Circum-Qinghai Lake Region and Three-River Source Region but increased in the Qaidam Basin and Eastern Agricultural Area, particularly in Golmud where the increase rate reached 5.3 d · $(10a)^{-1}$. Slightly cold days increased in the Three-River Source Region but decreased in other zones, particularly in the Qilian Mountains north of the Circum-Qinghai Lake Region where the decrease rate was 4.4 d · $(10a)^{-1}$.

The spatial pattern of total cold day trends showed an "increase-decrease" pattern from east to west, with decreases dominating overall. Except for increases at Delingha, Mangya, Golmud, Dulan in the Qaidam Basin, Yushu in the Three-River Source Region, and Xining in the Eastern Agricultural Area, most other areas showed decreasing trends, particularly in the Eastern Agricultural Area. The trends for extreme cold and cool days were roughly equally distributed between decrease and increase. Extremely cold days showed increasing trends, particularly in the Qaidam Basin. Severe cold, major cold, minor cold, light cold, and slightly cold days showed decreasing trends, with severe cold increasing in the Eastern Agricultural Area and decreasing elsewhere, particularly in the eastern Three-River Source Region and Circum-Qinghai Lake Region where rates exceeded 2.5 d · $(10a)^{-1}$. Major cold days decreased across most functional zones except for increases in the western Three-River Source Region, with a decrease center in the western Qaidam Basin. Minor and light cold days increased in the Circum-Qinghai Lake Region but decreased or remained stable elsewhere. Slightly cold days increased in the Qaidam Basin but decreased in other areas, particularly in the Qilian Mountains north of the Circum-Qinghai Lake Region where the decrease rate was 5.2 d · $(10a)^{-1}$.

2.5 Relationship Between Different Grades of Cold Days and Average Temperature

Analysis of annual mean temperature and total cold days [Figure 5: see original paper] revealed a negative correlation, with total cold days decreasing as annual mean temperature increased. For every 1 ℃ increase in annual mean temperature, total cold days decreased by 8.9 days. The correlation coefficients between total cold days and annual mean temperature across different ecological functional zones ranged from -0.728 to -0.889, all passing significance tests. Annual mean temperature was negatively correlated with extreme cold, extremely cold, severe cold, light cold, and slightly cold days (correlation coefficients of -0.889,

-0.728, -0.798, -0.798, and -0.798, respectively), and positively correlated with major cold, minor cold, and cool days (correlation coefficients of 0.728, 0.798, and 0.798, respectively). Annual mean temperature was significantly correlated with all grades except major cold days.

2.6 Relationship Between Different Grades of Cold Days and Topographic Factors

To further illustrate the spatial differences in cold days and more intuitively reflect the influence of topographic factors, multiple regression analysis was used to examine relationships between cold days and longitude, latitude, and altitude . The multiple correlation coefficients between cold days and topographic factors ranged from 0.353 to 0.890, with all regression equations reaching the 0.01 significance level. Partial correlation analysis showed that longitude was significantly correlated with extreme cold, extremely cold, severe cold, major cold, minor cold, and cool days; latitude was significantly correlated with extreme cold, light cold, and slightly cold days; and altitude was significantly correlated with all grades except major cold and slightly cold days.

Multiple regression analysis of cold day trends and topographic factors revealed multiple correlation coefficients ranging from 0.518 to 0.804, indicating significant correlations. Partial correlation analysis showed that topographic factors were negatively correlated with trends in extreme cold, extremely cold, minor cold, and light cold days, and positively correlated with trends in severe cold, major cold, slightly cold, and cool days, with the most significant impact on light cold day trends. In summary, altitude had the greatest influence on different grades of cold days and their trends, followed by longitude and latitude.

2.7 Mutation Characteristics of Different Grades of Cold Days

The Mann-Kendall non-parametric test was applied to identify 突变 points in cold days. The UF and UB curves for total cold days intersected in 1995 outside the 0.05 significance lines [Figure 6: see original paper], indicating a significant 突变. Combined with moving t-test [Figure 2: see original paper] and cumulative anomaly analysis [Figure 2: see original paper], the results confirmed a significant 突变 in total cold days in 1995. Extreme cold, extremely cold, light cold, and cool days underwent 突变 around 1990, with light cold days 突变 slightly earlier than extreme and extremely cold days, and cool days 突变 latest. Extreme cold and cool days 突变 from a relatively cold period to a relatively warm period, while extremely cold and light cold days 突变 from a relatively warm period to a relatively cold period. No 突变 was detected for severe cold, major cold, minor cold, or slightly cold days.

Previous studies have identified a warm 突变 in the Tibetan Plateau around 1997. In this study, the intersection point of the Mann-Kendall test for annual mean temperature in Qinghai Province was located in 1997, passing the significance test. Moving t-test results detected 1997 as a significant 突变 year when n=10.

Comparative analysis by Ding Yihui et al. [] suggests that the Tibetan Plateau experienced a more significant warm 突变 in the mid-1990s compared to other regions in China.

2.8 Future Trends of Different Grades of Cold Days

Research has shown that the presence of trend terms significantly impacts Hurst index estimation. Therefore, before conducting Hurst analysis, the time series data were preprocessed to eliminate trend effects. Linear differencing was applied to the 1961–2019 cold day data to remove linear trends, and Hurst analysis was then performed on the detrended series to assess persistence.

Hurst index values showed that severe cold days had Hurst < 0.5, while all other grades had Hurst > 0.5. This indicates that severe cold days exhibit anti-persistence (future trends opposite to past trends), while other grades show persistence (future trends consistent with past trends). The overall increasing trends in the past suggest that major cold, minor cold, and cool days will continue to increase in the future, while the overall decreasing trends in total cold, extreme cold, extremely cold, severe cold, light cold, and slightly cold days will continue to decrease. The persistence intensity varies among grades, with total cold and light cold days showing particularly strong persistence.

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3. Discussion

This study found that from 1961 to 2019, cold days in Qinghai Province increased as the grade decreased, with fewer high-grade cold days and more medium- and low-grade cold days. The spatial distribution of different grades of cold days was closely related not only to latitude but also to topography, consistent with findings by Kong Feng []. The total number of cold days in Qinghai Province showed a decreasing trend, evolving from positive to negative anomalies with advancing decades. The decrease was most pronounced in the Qaidam Basin and Eastern Agricultural Area, with cold days gradually decreasing as mean temperature increased. The 突变 occurred in the mid-to-late 1990s, aligning with studies by Jiang Shuai et al. [], Zheng Ran et al. [], and Feng Xiaoli et al. [] on extreme temperatures.

However, the contribution of different grades to the total cold day reduction varies. In Qinghai Province, where slightly cold days dominate, the decrease in total cold days was mainly caused by reductions in extremely cold days. In contrast, the Loess Plateau, dominated by major cold days, showed total cold day decreases primarily driven by reductions in major cold days. Hurst index analysis indicates that total cold days in Qinghai Province will continue to decrease in the future, consistent with Wang Baolong et al. [] who found that extreme cold indicators will continue to decline. In recent years, global warming has led to significantly fewer extreme low-temperature events and more extreme warm indicators in Qinghai Province during the 21st century [].

These trends have mixed implications for agriculture and ecology in Qinghai Province. On one hand, fewer low-temperature events are beneficial for advancing spring sowing dates, extending the growing season of thermophilic crops, and facilitating the safe overwintering of greenhouse vegetables and economic crops. On the other hand, reduced low-temperature events may lead to increased pest and disease populations and expanded disease ranges, exacerbating threats to agricultural production []. Increased high-temperature events have caused glacial area and ice reserves to decrease in the Geladandong and Animaqing regions of the Three-River Source Region, with the freezing period continuously shortening [], permafrost area decreasing, and the permafrost lower boundary rising, particularly in discontinuous or island permafrost zones at the edges of permafrost regions []. Therefore, a thorough understanding of the spatial and temporal distribution patterns of extreme cold days is essential for the sustainable and healthy development of ecological environmental protection in Qinghai Province.

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4. Conclusions

Based on daily minimum temperature data from 42 meteorological stations in Qinghai Province from 1961 to 2019, this study analyzed the spatial and temporal evolution characteristics of different grades of cold days using climatic statistical methods. The main conclusions are as follows:

1) From 1961 to 2019, the number of cold days in Qinghai Province gradually increased as the cold grade decreased, showing significant spatial differences. Higher-grade extreme cold, extremely cold, severe cold, and major cold days were mainly distributed in the Three-River Source Region and Circum-Qinghai Lake Region, while lower-grade minor cold, light cold, slightly cold, and cool days were mainly distributed in the Qaidam Basin and Eastern Agricultural Area, with higher concentrations in high-altitude and high-latitude regions. During the study period, cold days were dominated by slightly cold days (18.8%), followed by light cold (16.8%) and cool days (16.0%), with extreme cold days being the least frequent (16.0%).

2) The total number of cold days in Qinghai Province showed a decreasing trend, with a significant rapid reduction 突变 occurring in 1995. The decreasing trend was most pronounced in the Qaidam Basin and Eastern Agricultural Area, followed by the Circum-Qinghai Lake Region, with the smallest decrease in the Three-River Source Region. The reduction in total cold days was primarily caused by decreases in extremely cold days. After the 1997 climate 突变, the trends for severe cold, major cold, minor cold, light cold, slightly cold, and total cold days decreased, while the trend for extremely cold days increased. The trends for extreme cold and cool days showed roughly equal patterns of decrease and increase, respectively.

3) The numbers of extreme cold, extremely cold, severe cold, light cold,

slightly cold, and total cold days gradually decreased with increasing annual mean temperature, while the numbers of major cold, minor cold, and cool days gradually increased with rising temperature. For every 1 ℃ increase in annual mean temperature, total cold days decreased by 8.9 days. Annual mean temperature was significantly correlated with all grades except major cold days.

4) The Hurst index for severe cold days was less than 0.5, indicating that future changes will be opposite to past trends. All other grades had Hurst indices greater than 0.5, indicating that future changes will be consistent with past trends, though the persistence intensity varies among grades.

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Note: Figure translations are in progress. See original paper for figures.