Science Bulletin xxx (xxxx) xxx

Contents lists available at ScienceDirect

Science Bulletin

journal homepage: www.elsevier.com/locate/scib

Short Communication

Rapid expansion of wetlands on the Central Tibetan Plateau by global warming and El Niño

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ARTICLE INFO

Article history:
Received 24 July 2022
Received in revised form 29 November 2022
Accepted 5 December 2022
Available online xxxx

The Tibetan Plateau (TP), known as the "Third Pole" of the Earth and "Asian Water Tower", is the magnifier of global climate change and birthplace of many large rivers in Asia. There are unique alpine wetlands on the TP, accounting for 20% of Chinese wetlands area, and the lakes alone constitute half of the national lake area. Wetlands are critical to human survival and development as one of the three major ecosystems [1]. As an ideal natural environment for sequestration and storage of carbon dioxide (CO_2) from the atmosphere, wetland ecosystem plays an important role in global carbon cycles [2]. Understanding the changes and drivers of wetlands on the TP is important for action to ensure ecosystem resilience like vegetation cover and species diversity in Asia. Yet, measuring the long-term dynamics of wetlands remains a challenge due to uncertainty of wetland boundaries, complexity of spectral and texture characteristics as well as the lack of the labeling wetland data on the TP. To our knowledge, the spatial distribution, inter-annual variation and multi-decadal trends of the TP wetlands remain very limited, and consequently their responses to climate variability remain little known. Previous maps and datasets on the TP wetlands are developed either for a specific year [3–5] or at coarse spatial resolutions (e.g., 1 km) [6]. Such coarse resolutions and time incompleteness cannot capture the complexities of spatio-temporal dynamics of wetlands as well as how climate affects wetland changes.

Here, we present a deep learning-based scene classification framework to extract wetlands from images of the multi-temporal orthorectified Landsat 5, 7, and 8 satellites at 30 m spatial resolution from 1990 to 2019. Compared with traditional pixel-based and object-based classification methods, our framework has several methodological advantages. First, automatic learning of parameters significantly reduces the intensive parameter tuning costs. Second, the scene classification method has significant advantages in semantic-level understanding the meaning and content of remote sensing images. Through the supervised learning from a large number of samples, the deep learning model can learn features such as color, shape, spatial relationships, and context from the imagery scene, and then use the fused features to perform classification. Therefore, the deep learning model has the ability to distinguish the wetland boundaries in Landsat images (see Supplementary materials online). Experimental validations indicate that our approach achieves high performance of wetland classification, i.e., the user's accuracy of 96.1% and the producer's accuracy of 90.8%, allowing us to quantify spatio-temporal variations of the TP wetlands.

Substantial new wetlands have emerged on the TP over the past 30 years, especially in the regions in the west of the Xining-Xigaze line over 2005–2019. The Hoh Xil (i.e., the region within the red dash lines in Fig. 1), as a part of the Qiangtang Plateau and the source region of Yangtze River, which is the largest natural reserve with the highest altitude and richest wildlife resources in China, had the fastest growth of wetlands by 113% ± 11.9% (16,358 ± 1723 km^2).

As shown in Fig. 1b, the changes in wetland areal extent also exhibited large disparities across the zones. From 1990 to 2019, the wetland areal extent in Qiangtang Plateau had the largest increase by 55.3% ± 7.5% or 29,832 ± 5043 km^2, which contributed 61.9% of the TP's total wetland growth. In the source region of the

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https://doi.org/10.1016/j.scib.2023.02.021

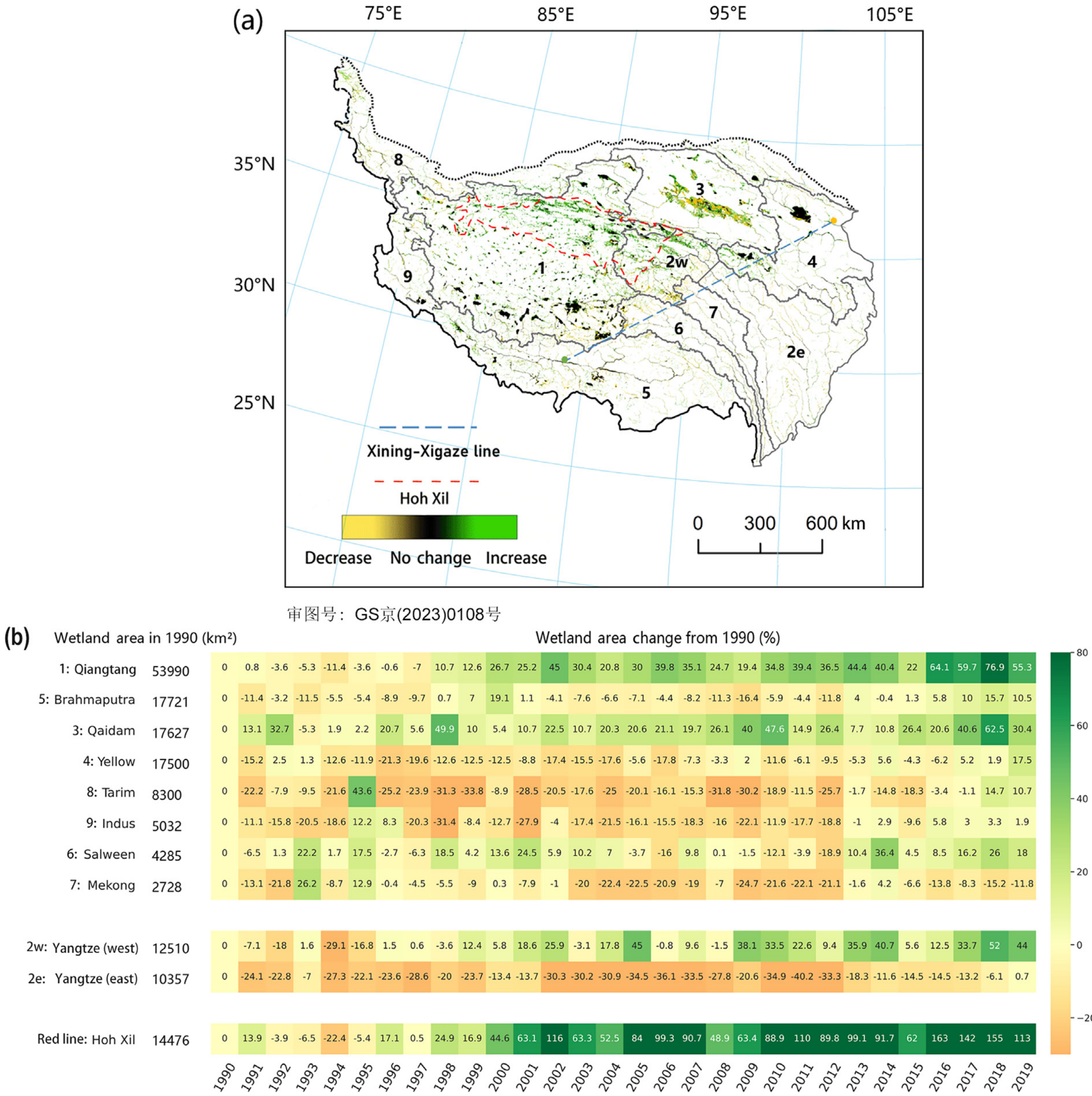

Fig. 1. Rises and falls of the TP wetland areas from 1990 to 2019. (a) The wetland occurrence change intensity (WOCI) defined as the difference in the number of years of wetland occurrence between 2005 and 2019 and 1990–2004. The map only illustrates the wetlands whose occurrence number during 1990–2019 is not <5. A total of nine zones are presented based on the division of watersheds, including 1: Qiangtang Plateau, 2: Yangtze River Basin, 3: Qaidam Basin, 4: Yellow River Basin, 5: Brahmaputra River Basin, 6: Salween River Basin, 7: Mekong River Basin, 8: Tarim Basin, and 9: Indus River Basin. Zone 2 is further separated into the western region of Yangtze River Basin (2w) and the eastern region (2e) due to the large heterogeneity in topography, geomorphology, and wetland area fraction. The orange and green dots represent Xining and Xigaze cities. (b) Changes of wetland areas over time in each region of the TP relative to 1990. The value in each cell of the heatmap denotes the percentage of wetland area extent that has increased (green cell) or decreased (orange cell) relative to 1990. The values on the left denote the wetland areal extent of each region in 1990.

Yangtze River, the wetland areal extent increased by 44.0% ± 8.9% or 5505 ± 1109 km^2, accounting for 11.4% of the TP's total wetland growth. The wetlands in Qaidam Basin had a 30.4% ± 8.3% growth or 5352 ± 1465 km^2, accounting for 11.1% of the TP's total wetland growth. The wetland area in Mekong River Basin (Zone 7) had a slight decline of 11.8% ± 6.7% or 322 ± 184 km^2 from 1990 to 2019. The wetlands in the Yellow River Basin (Zone 4) showed a downward trend before 1997 but a gradual resumption afterwards. The above analysis shows that the wetland areal extents on the central TP, i.e., Qiangtang Plateau, the source region of the Yangtze River and Qaidam Basin, had the largest growth over the past 30 years.

To explore the impacts of climate change on wetland variations, we used annual mean surface air temperature (AT), annual precipitation (AP), and annual potential evaporation (APE) as measures of the regional climate in TP. A general linear model (GLM) is utilized to quantify the contribution of AT, AP, and APE to the wetland area change. Results from the GLM show that AT and AP account for 54.5% and 43.9% of the wetland change on Qiangtang Plateau, respectively (Table S1 online). Similarly, for the source region of Yangtze River, the GLM suggests that AT and AP explain 62.0% and 36.4% of the wetland area changes, respectively. Qaidam Basin was the third only to Qiangtang Plateau and Yangtze River Basin in both wetland areal extent and growth. Among the three climatic factors, AP had the highest correlation with the wetland changes, and the correlation coefficient was 0.685. AP accounted for 67.3% variations of the wetland areal extent (Table S1 online). Yet, the impact of the APE was more significant in Qaidam Basin than other two regions with a correlation coefficient of 0.567, explaining 13.8% of the wetland changes.

For the source region of Yangtze River and Qiangtang Plateau, 49.8% of the new wetlands were in the region of the transitional and unstable type of permafrost (Fig. S2 online). Considering that permafrost exerted a high impact on wetland hydrology, we examined the influence of permafrost thaw on the prevalence of the wetlands. The degradation of the ice-rich permafrost due to the climate warming made large contributions to surface runoff and development of thaw lakes in the inner TP [7]. We segmented the lakes whose areas were larger than 5000 m^2 in five years (1990/1991, 1996/1997, 2002, 2015, and 2018) from Landsat imagery (see Supplementary materials online). We find that the change trend of the lake area extent was highly consistent with that of wetlands (Fig. S3 online). In 1990–2018, the number of lakes increased from 4952 to 14,931. 44.3% of the new lakes were located in the region of transitional and unstable type of permafrost. The increased abundance of lakes provided evidence that permafrost degradation was linked to increase in wetlands of the source region of the Yangtze River and Qiangtang Plateau. The above finding indicates that permafrost thaw caused by the rising temperature was one of the main drivers in the wetland area changes on the source region of Yangtze River.

The climate variability over the TP is regulated by the El Niño–Southern Oscillation (ENSO). Thus, we examine whether and how ENSO may affect the dynamics of the wetland areal extent. As shown in Fig. S4 (online), there is close match in interannual variability between the ENSO index and the TP wetland area. The wetland areal extent increases in the year when El Niño ends, especially for the two very strong El Niño years (1997–1998 and 2015–2016).

The relationship of the TP wetland change with the ENSO is presented by the first Singular Value Decomposition (SVD, see Supplementary materials online) between the wetland areal extent and the global sea surface temperature (SST). The first SVD mode accounted for 42.0% of the total covariance (Table S2 online). There is a strong positive temporal correlation (r = 0.81, P < 0.001) between the wetland change and SST (Fig. S5 online). We conclude that expansion of TP wetland areal extent is associated with SST. The wetland areal extents for Qiangtang Plateau and Qaidam Basin (Fig. 2a) are highly correlated with the variability of SST in the eastern equatorial Pacific Ocean (Fig. 2b), which denotes the signal of ENSO [8]. This correlation is likely because the changes of the wetland areal extent in these two zones are most sensitive to temperature and precipitation and thus to ENSO. ENSO modulates air temperature and precipitation on the TP mainly by causing anomalous atmospheric circulation [9], which affects the influx of warm and moist air mass to the TP. During the strong South Asian summer monsoon in El Niño years, precipitation and temperatures increases significantly in most parts of the TP [10–12].

We further investigate the mechanism of wetland expansions due to El Niño. El Niño affects the TP climate through circulation changes. When the El Niño event occurs in the winter, an anomalous anticyclone is forced from the North Indian Ocean to the Northwest Pacific (Fig. 2c, d) and can be extended to the following summer through the inter-basin ocean–atmosphere interaction [13,14]. The anomalous westerly winds on the north side of the anticyclone enhance the transport of tropical water vapor to the TP and increase precipitation on the southeast TP. The topographic effects on the southeast and southwest TP further strengthen the vertical moisture transport anomaly and enhance precipitation on the south-central TP through moisture convergence [15]. Indeed, Fig. 2d shows that the El Niño ending years (1992, 1995, 1998, 2003, 2010, and 2016) exhibit higher specific humidity than other years. Rapid lake expansion, as an important form of wetland expansion, occurred on the central TP over the past 30 years due to increased precipitation (Fig. S3 online). The mean normalized difference vegetation index (NDVI) in this

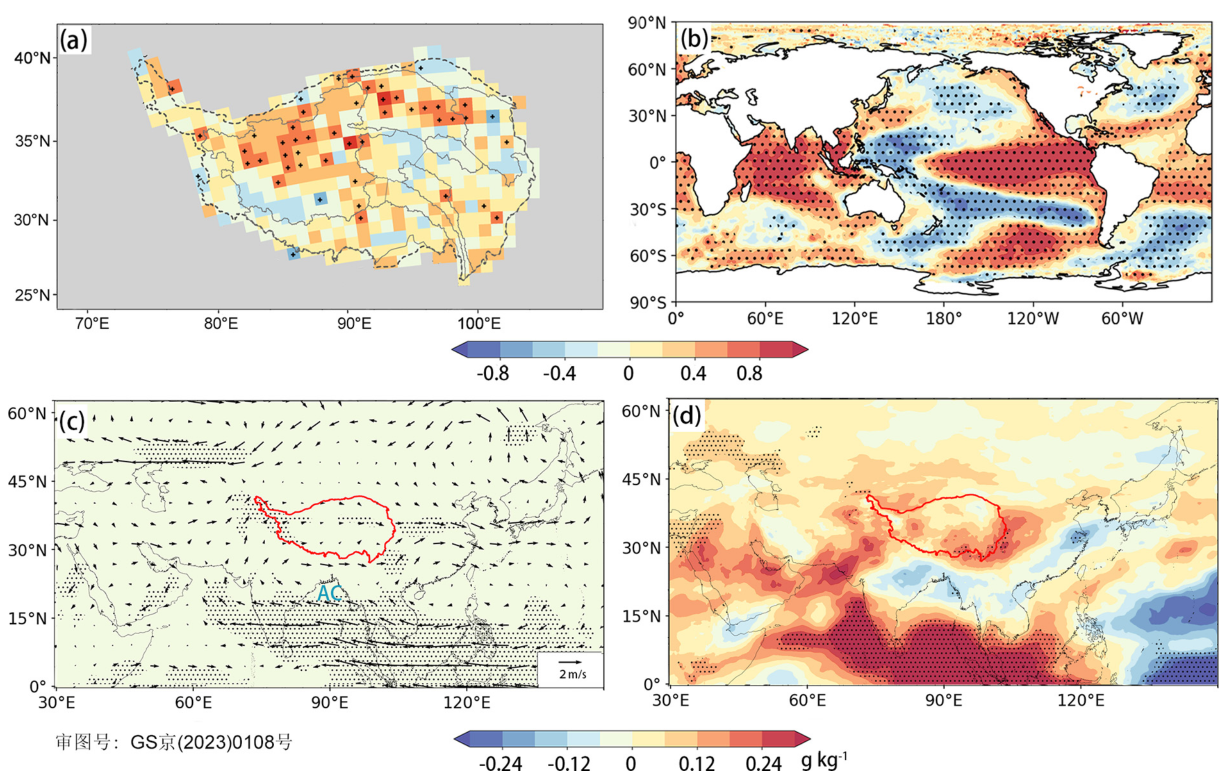

Fig. 2. Variations on the TP wetland areas linked to oceanic and atmospheric patterns. Homogeneous correlation maps of the first SVD mode between the TP wetland area (a) and global SST field (b). (c) The difference in summertime wind field at 500 hPa between El Niño years and other years. The anomalous anticyclone is labeled "AC". (d) The difference in specific humidity at 500 hPa between El Niño ending years and other years. The El Niño ending years were 1992, 1995, 1998, 2003, 2010, and 2016. In (a–d), the black dots denote statistically significant correlation (P < 0.05).

region improved from 0.07 in 1990 to 0.11 in 2018, implying that a major significant greening trend and a general increasing trend of marshes vegetation density on the TP. Temperature and precipitation anomalies brought by El Niño helped wetland expansions. Overall, these results suggest that El Niño exacerbates expansion of wetland areal extent on the TP.

In summary, our findings highlight that the areal extent of TP wetlands has increased by 31.2% over the past 30 years. The growth is particularly noticeable (by 22.5%) during 2015–2019. The wetland area in Qaidam Basin has a 30.4% growth or 5352 km^2, contributing 11.1% of the TP's total wetland growth. Although some wetlands have been degraded or disappeared on Qaidam Basin, more wetlands have occurred or expanded. The wetland area in Mekong River Basin (Zone 7 in Fig. 1a) has a slight decline of 11.8% from 1990 to 2019. The wetland area in the Yellow River Basin (Zone 4 in Fig. 1a) shows a downward trend before 1997 but a gradual resumption afterwards. Permafrost thaw triggered by rising temperature is linked to increase in wetland area in the source region of Yangtze River and Qiangtang Plateau from 1990 to 2019. The expansion in wetland areal extent is relatively small in 2000–2015, likely because of weaker global warming during this period (i.e., the hiatus). The wetland area growth is rapid after 2015 (by 20.7% or 34,745 km^2) in these two zones, consistent with the rapid global warming. The effect of climate warming on the TP wetlands is further exacerbated by the occurrence of El Niño. The two strongest El Niño events since 1990 correspond to the most dramatic annual expansion of TP wetland area. This is likely because El Niño increases the transport of warm, moist air to the TP by forcing an anticyclone over the southeast Indian Ocean. The marked wetland changes highlight that climate mitigation is a priority for high latitude ecosystems. To mitigate human-driven climate change, governments throughout the world need to take efforts to improve energy efficiency and cooperate to reduce heat-trapping greenhouse gas emissions.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

This work was supported by the Second Tibetan Plateau Scientific Expedition and Research Program (2019QZKK0608 and 2019QZKK0604). We sincerely thank the editors and reviewers for valuable comments and suggestions.

Author contributions

Yang Li and Zhengyang Hou designed the study and conducted the main analysis, and contributed equally to this work. Liqiang Zhang, Changqing Song, and Shilong Piao conceived the main research ideas. Jintai Lin, Shushi Peng, and Keyan Fang reviewed and edited the manuscript. Jing Yang, Ying Qu, Yuebin Wang, Jingwen Li, Roujing Li, and Xin Yao participated results discussion and provided useful suggestions.

Appendix A. Supplementary materials

Supplementary materials to this short communication can be found online at https://doi.org/10.1016/j.scib.2023.02.021.

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