

Large-scale atmospheric drivers of recent hydroclimatic changes in the Horn of Africa: evidence from the Awash Basin terminal lake system, Ethiopia

Juan P. Sierra^{1,2}, Pierre Brigode², Pape Saara Ngom², Pascale Braconnot³, Christian Le Carlier De Veslud², Camille Bouchez², Sly Wongchuig⁴, Mohamed Osman Awaleh⁵, Mohamed Jalludin⁵, Natacha Volto⁶, Eric Chaumillon⁶, and Marie Revel¹

¹Géoazur, Université Côte d'Azur, CNRS, OCA, IRD, Valbonne, 06152, France

²Univ Rennes, CNRS, Géosciences Rennes, UMR 6118, 35000 Rennes, France

³Laboratoire des Sciences du Climat et de l'Environnement, Institut Pierre-Simon Laplace UMR CEA, CNRS, UVSQ, Université Paris-Saclay, Gif-sur-Yvette, 91190, France

⁴Université de Toulouse, LEGOS, CNES/CNRS/IRD/UT, Toulouse, France

⁵Institut des Sciences de la Terre, Centre d'Etudes et de Recherches de Djibouti (CERD), Route de l'aéroport B.P. 486, Djibouti, ville, Republic of Djibouti.

⁶La Rochelle Université, CNRS, UMR 7266 LIENSs, La Rochelle, France

Correspondence: Juan P. Sierra (juanpablosierrap@gmail.com)

1 Figures accompanying the response to the reviewer

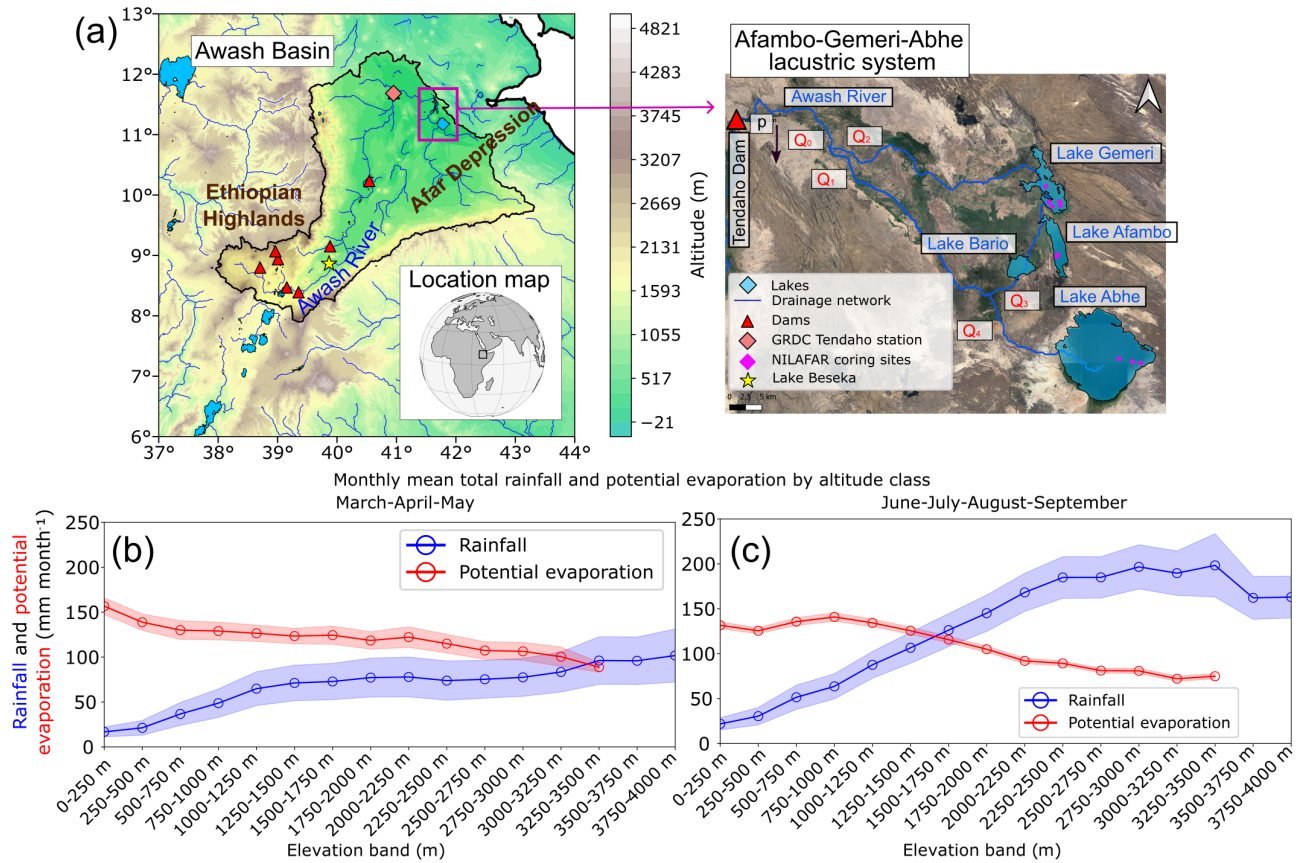


Figure 1. NEW FIGURE 1. (a) Location of the Awash River Basin, view of the Abhe–Afambo–Gemeri lake system and schematic representation of the flow partitioning used in the lake model (satellite image from Sentinel-2). Topography derived from the Shuttle Radar Topography Mission (SRTM; Farr et al., 2007) is shown as shaded relief (m, a.s.l.), and river and lake polygons are from the HydroRIVERS (?) and HydroLAKES (Messenger et al., 2016) databases. (b–e) Climatology of precipitation and total potential evaporation as a function of elevation for the period 1981–2024: (b) October–November, (c) December–February, (d) March–May, and (e) June–September. Shading indicates ± 1 standard deviation. Precipitation and potential evaporation data are derived from CHIRPSv2 (?) and GLEAMv4.2a (?), respectively.

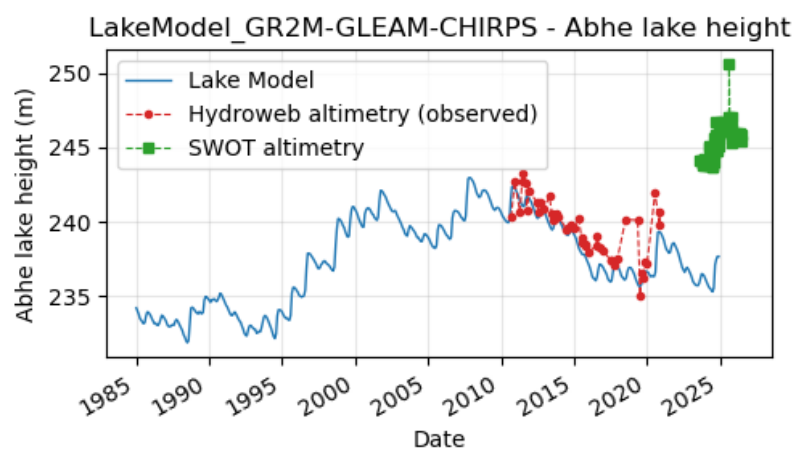


Figure 2. NEW FIGURE SUPP. FIGURE. Time series of Lake Abhe water level for 1985–2024, based on the lake model and satellite altimetry observations from HydroWeb and SWOT.

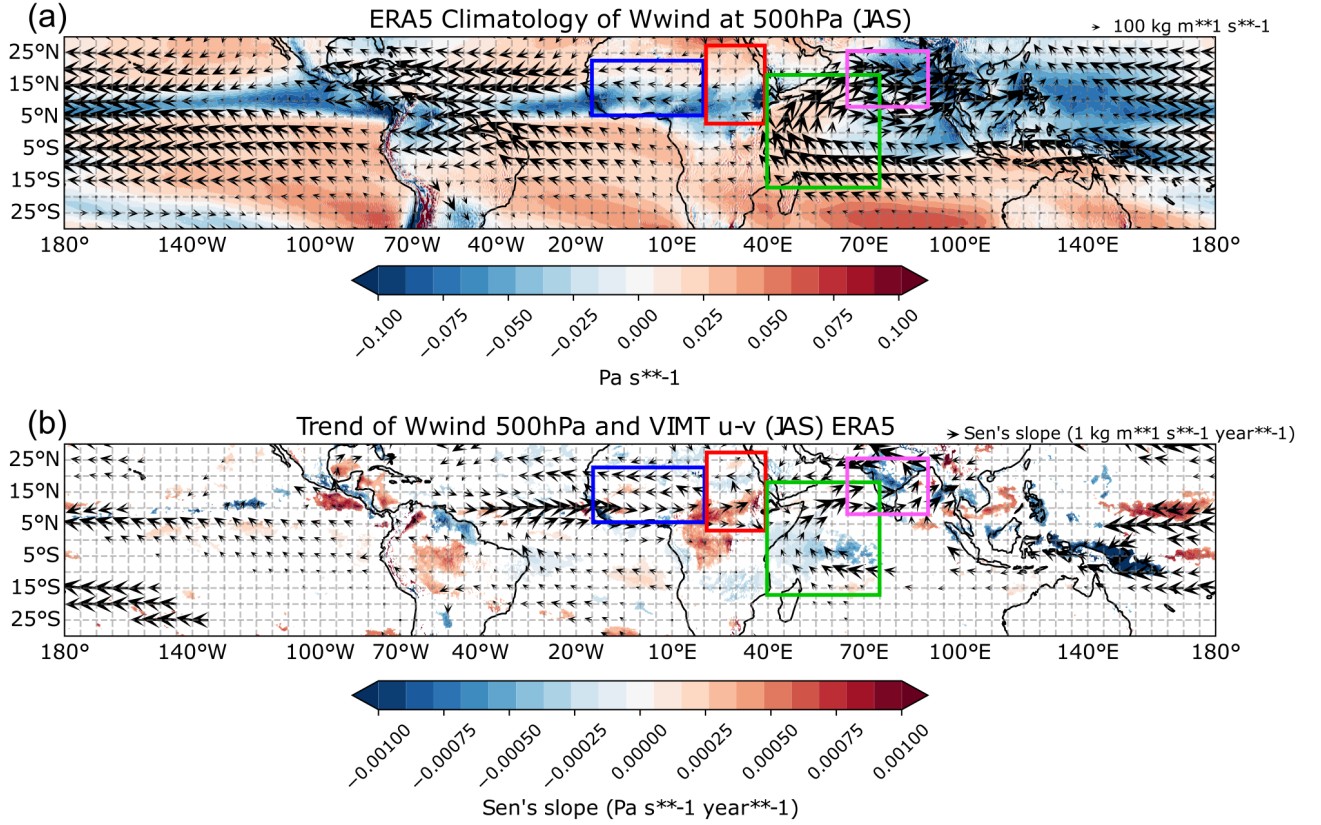


Figure 3. NEW FIGURE 8. Climatological fields of (a) vertically integrated moisture transport (vectors, $\text{kg m}^{-1} \text{ s}^{-1}$) and vertical velocity at 500 hPa (Pa s^{-1}). (b) Linear trends estimated using Sen's slope for vertically integrated moisture transport (vectors, $\text{kg m}^{-1} \text{ s}^{-1} \text{ year}^{-1}$) vertical velocity at 500 hPa ($\text{Pa s}^{-1} \text{ year}^{-1}$). Fields are derived from ERA5 for the period 1979–2024 during JAS. Only statistically significant trends at the 95% confidence level are shown in (b). Blue, red, green, and pink boxes indicate regions associated with the African Easterly Jet (AEJ), the northern branch of the Hadley circulation, the Somali Jet, and convection over India, respectively.

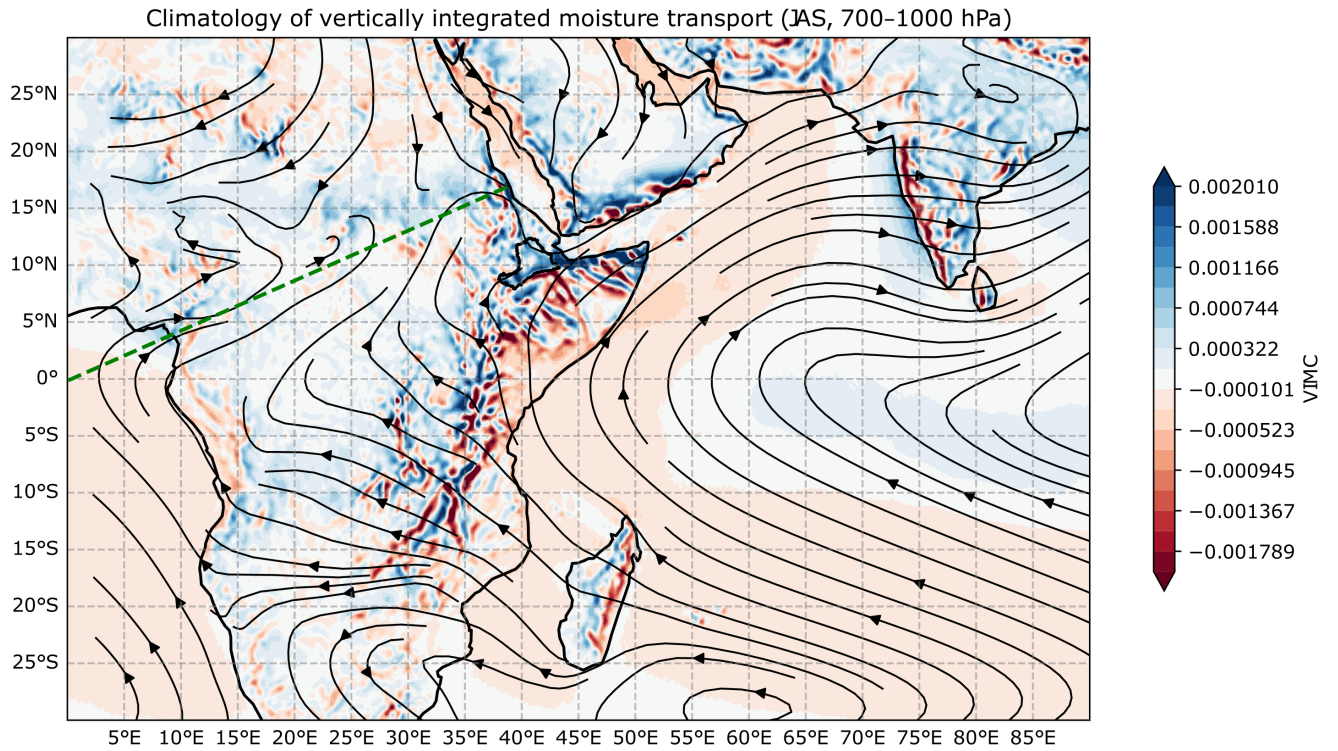


Figure 4. Climatology of vertically integrated low-level moisture transport (1000–700 hPa) and moisture flux (vectors) convergence (shaded colors) over Africa from ERA5 during the JAS season. The green line indicates the cross-section used in Figure 9 of the original version of the manuscript.

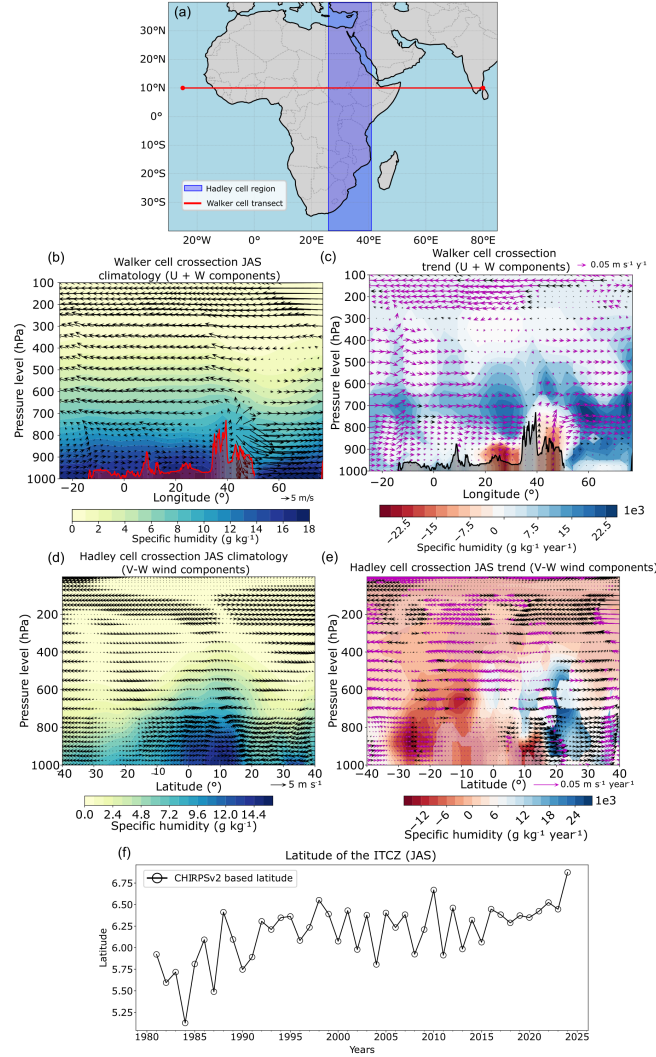


Figure 5. NEW FIGURE 9. (a) Reference map showing the transect used to examine the zonal overturning (Walker-type) circulation (red line) and the domain used to analyze the regional meridional (Hadley-type) circulation (blue box). (b) Climatology and (c) linear trends of zonal and vertical wind components and specific humidity along the transect. (d) Climatology and (e) linear trends of meridional and vertical wind components and specific humidity, zonally averaged within the boxed region. (f) Time series of the ITCZ latitude within the blue domain, following the methodology of ?. Wind trends significant at the 95% confidence level are shown in magenta. For specific humidity, statistically significant trends (95%) are displayed with full-color shading, whereas non-significant trends are shown with reduced opacity using a Mann–Kendall test. Red and black lines in (b) and (c) indicate topography along the transect. Wind and humidity fields are derived from ERA5 (1979–2024), and rainfall used to determine the ITCZ latitude is from CHIRPSv2 (1981–2024). All climatologies and trends correspond to the JAS season.

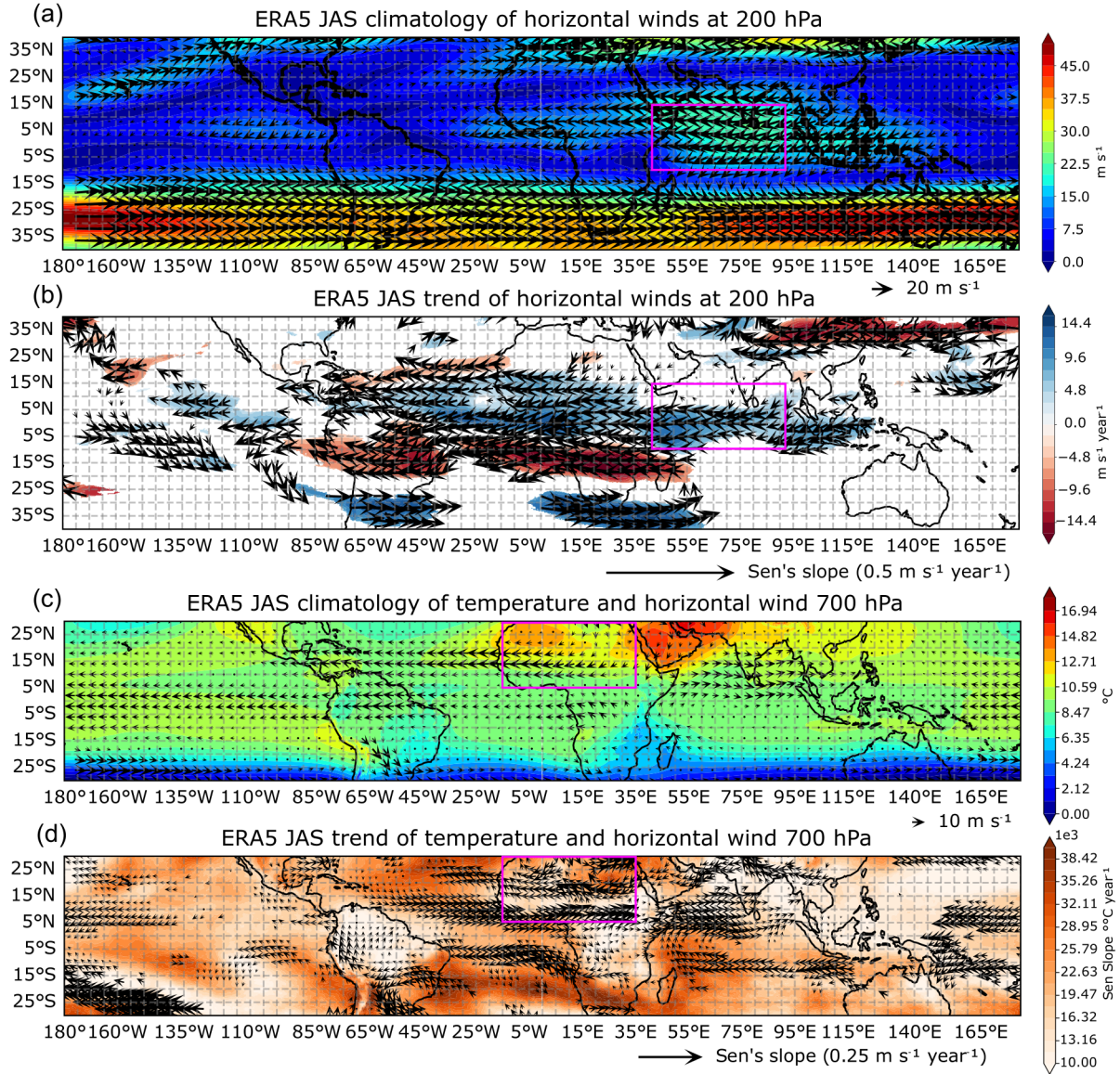


Figure 6. NEW FIGURE 10. JAS climatology and linear trends (1979–2024) of atmospheric circulation associated with the Somali Jet, Tropical Easterly Jet (TEJ), and African Easterly Jet (AEJ) from the ERA5 reanalysis. Panels (a–b) depict the TEJ, showing (c) climatological wind speed (shading; m s^{-1}) and horizontal wind vectors at 200 hPa, and (d) their linear trends ($\text{m s}^{-1} \text{ year}^{-1}$). Panels (c–d) depict the AEJ, showing (e) climatological air temperature (shading) and horizontal wind vectors at 700 hPa, and (f) their linear trends. For the AEJ, only trends significant at the 95% confidence level according to the Mann–Kendall test are displayed. The magenta boxes indicate the regions used to characterize each atmospheric jet.

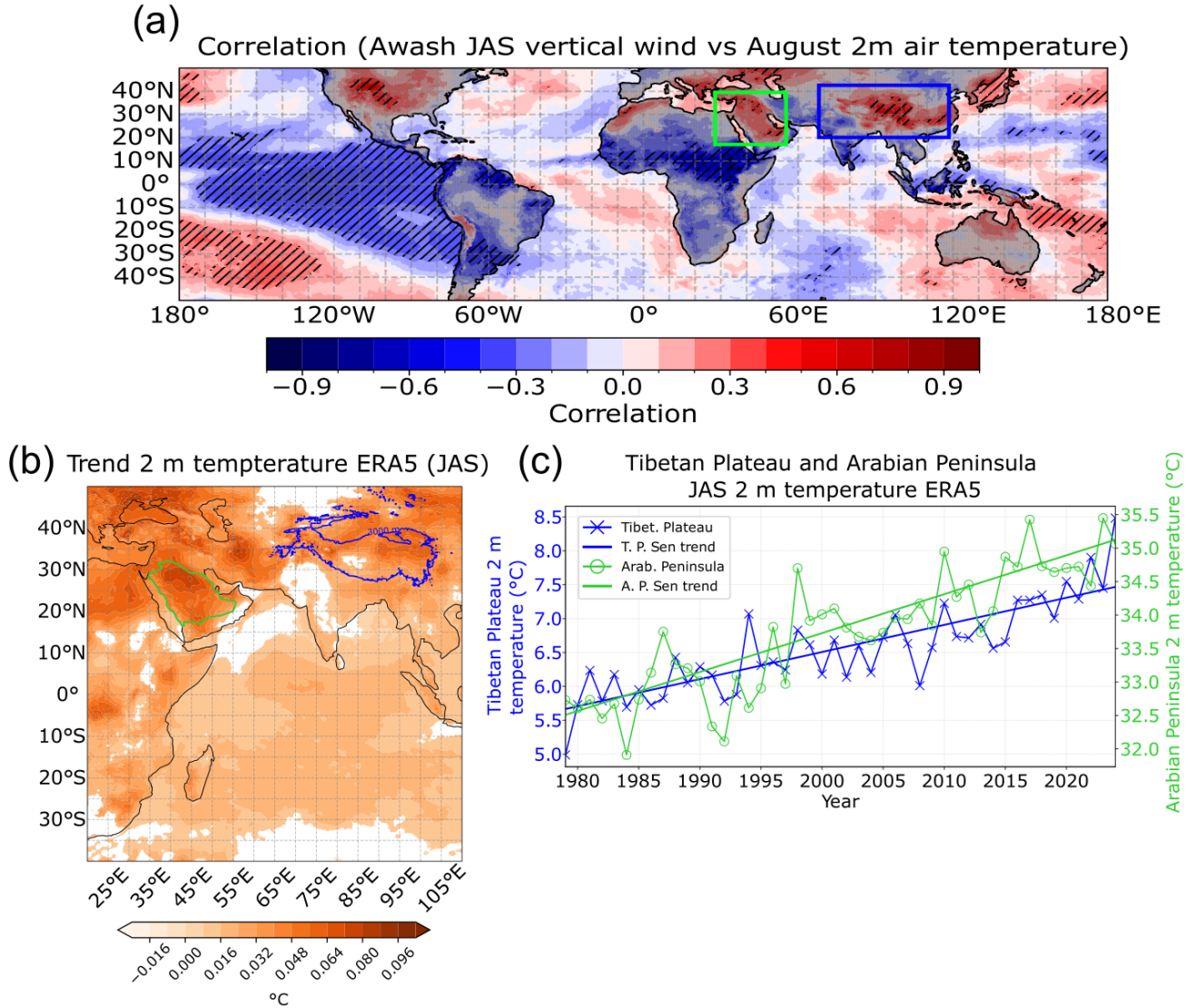


Figure 7. NEW FIGURE SUPP. FIGURE. (a) Correlation between JAS anomalies of ERA5 500-hPa pressure vertical velocity averaged over the Awash Basin and August anomalies of 2-m air temperature over the tropics (30°S–30°N). The 500-hPa vertical velocity (ω_{500}) was multiplied by -1 so that positive values represent upward motion (ascent). (b) Spatial distribution of JAS (July–August–September) linear trends in 2-m air temperature between 20°E–110°E and 40°S–50°N for the period 1979–2025, derived from ERA5 reanalysis. Trends are expressed as Sen’s slopes ($^{\circ}\text{C}, \text{year}^{-1}$). Only grid cells with statistically significant trends (Mann–Kendall test, $p < 0.05$) are shown. The blue and green lines delineate the boundaries of the Tibetan Plateau and Saudi Arabia, respectively, which are used as reference regions to characterize the warming signals over these regions. (c) JAS-mean 2-m air temperature averaged over the Tibetan Plateau and Saudi Arabia for the period 1979–2025, derived from ERA5 reanalysis. The trend lines and corresponding Sen’s slopes ($^{\circ}\text{C}, \text{year}^{-1}$) are shown.

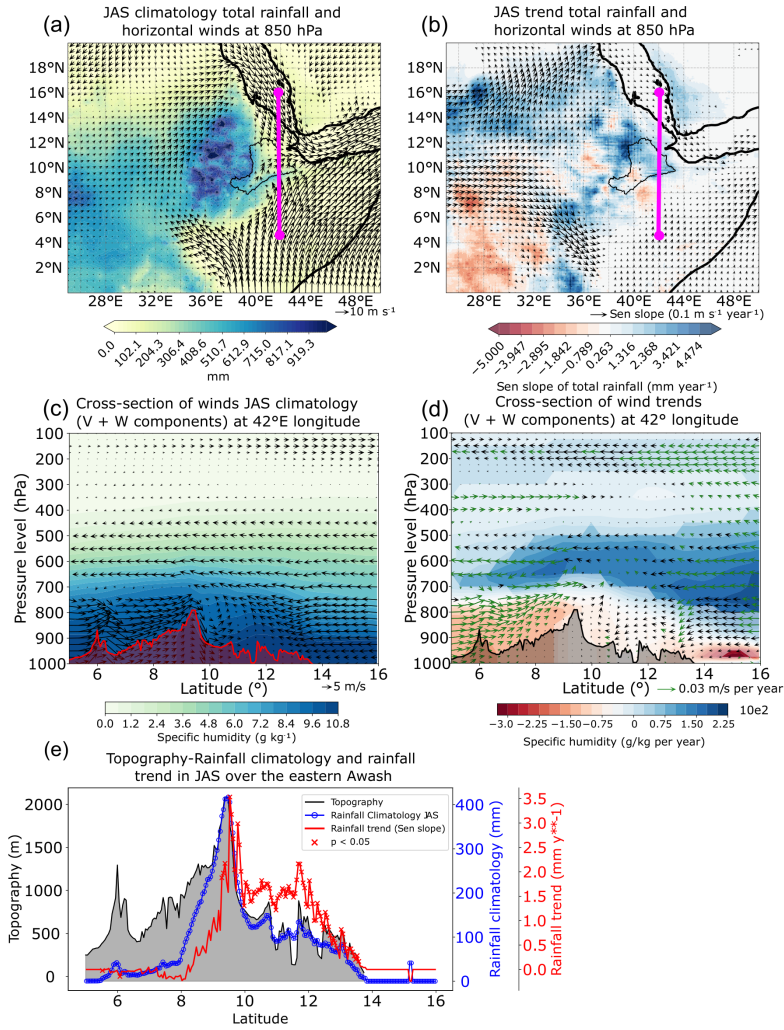


Figure 8. NEW FIGURE 12. (a) Climatological JAS accumulated rainfall (shading; mm) and horizontal winds at 850 hPa (vectors; m s^{-1}) over northeast Africa. (b) Linear trends in accumulated rainfall (shading; mm year^{-1}) and horizontal winds at 850 hPa (vectors; $\text{m s}^{-1} \text{ year}^{-1}$). The Awash Basin is outlined in panels (a)–(b), and the magenta line indicates the location of the cross-section shown in panels (c)–(d). Only grid cells with statistically significant trends at the 95% confidence level are shown in panel (b), based on a Mann–Kendall test. (c) Climatological meridional–vertical circulation (vectors; m s^{-1}) and specific humidity (shading; g kg^{-1}) along a 43°E transect between 5°N and 10°N during JAS. (d) Linear trends in meridional–vertical circulation (vectors; $\text{m s}^{-1} \text{ year}^{-1}$) and specific humidity (shading; $\text{g kg}^{-1} \text{ year}^{-1}$) along the same cross-section. Red and black lines in (c) and (d) indicate local topography. Green vectors in (d) highlight statistically significant trends at the 95% confidence level. For specific humidity, significant trends are shown with full-color shading, while non-significant values are displayed with reduced opacity. (e) Topography (black line), climatological rainfall (blue line), and linear rainfall trends (red line) along the transect; crosses indicate locations where rainfall trends are significant at the 95% confidence level (Mann–Kendall test). Rainfall data are from CHIRPS v2 (1981–2024), and all other variables are from ERA5 (1979–2024).