

Earth's Future

RESEARCH ARTICLE

10.1029/2023EF003901

Key Points:

- Crop failure events in the Australian wheat belt relate to anomalies in precipitation and its contribution from land and oceanic origins
- Land surfaces provide less moisture but more heat than the oceans and this difference tends to be aggravated during crop failure events
- Upwind droughts amplify the precipitation deficits and heat accumulation in the Australian wheat belt

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

H. Li and D. Miralles,
Hao.Liwork@UGent.be;
Diego.Miralles@UGent.be

Citation:

Li, H., Keune, J., Gou, Q., Holgate, C. M., & Miralles, D. (2024). Heat and moisture anomalies during crop failure events in the Southeastern Australian wheat belt. *Earth's Future*, 12, e2023EF003901. <https://doi.org/10.1029/2023EF003901>

Received 14 JUN 2023

Accepted 18 FEB 2024

Author Contributions:

Conceptualization: Hao Li, Jessica Keune, Diego Miralles
Data curation: Hao Li
Formal analysis: Hao Li
Investigation: Hao Li, Qiqi Gou, Chiara M. Holgate
Methodology: Hao Li, Jessica Keune, Diego Miralles
Software: Jessica Keune, Diego Miralles
Supervision: Jessica Keune, Diego Miralles
Validation: Jessica Keune
Visualization: Hao Li
Writing – original draft: Hao Li, Jessica Keune

© 2024 The Authors. Earth's Future published by Wiley Periodicals LLC on behalf of American Geophysical Union. This is an open access article under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Heat and Moisture Anomalies During Crop Failure Events in the Southeastern Australian Wheat Belt

Hao Li¹ , Jessica Keune¹ , Qiqi Gou², Chiara M. Holgate^{3,4} , and Diego Miralles¹ 

¹Hydro-Climate Extremes Lab, Ghent University, Ghent, Belgium, ²College of Hydrology and Water Resources, Hohai University, Nanjing, China, ³Research School of Earth Sciences, Australian National University, Canberra, ACT, Australia, ⁴ARC Centre of Excellence for Climate Extremes, Australian National University, Canberra, ACT, Australia

Abstract Prolonged droughts and heatwaves are common causes of agricultural failure in Australia, yet the origins of these climate anomalies remain understudied. Here, we use a Lagrangian trajectory model driven by atmospheric reanalysis and constrained by satellite data to unravel the sources of precipitation and heat over the Southeastern Australia wheat belt. Furthermore, we assess the impact of local and upwind drought conditions on the moisture and heat imports to the region. Results indicate that the most extreme crop failure events over the wheat belt (i.e., 1994, 2002, and 2006) were associated with persistent high-pressure systems. The ocean provided on average 72% of the moisture for precipitation and 39% of the heat arriving over the wheat belt, with the moisture sources substantially decreasing during crop failure events. Upwind drought further intensified rainfall deficits and heat stress during these events due to lower moisture and higher heat imports to the region. This was particularly clear during the initial phase of the Millennium Drought in 2002. Then, yield deficits exceeded 50%, and ~4% of the precipitation originated from drought-affected regions upwind, compared to the 9% that was expected climatologically from those regions. Simultaneously, the heat import from these regions upwind increased by ~10 W m⁻², from the climatological 23%–25%, during this event. While these results indicate a limited potential for upwind land management to mitigate downwind agricultural loss in the Southeastern Australia wheat belt, other agricultural regions with a higher climatic dependency on remote land may benefit from such strategies.

Plain Language Summary Droughts and heatwaves are posing threats to wheat production worldwide. In Australia, one of the largest wheat producers, the relationship between crop yield and climate anomalies remains understudied. Here, we use a novel framework dedicated to track heat and moisture across the atmosphere, which enables the identification of the sources of precipitation and temperature over the Southeastern Australia wheat belt, and the quantification of the influence of droughts on agricultural productivity. Results show that upwind droughts intensify precipitation deficits and heat stress by providing less moisture and more heat to the wheat belt during the years in which wheat production decays. This holds potential implications for land use management strategies dedicated to ensuring agricultural food supply by influencing weather patterns.

1. Introduction

Improving crop productivity is a requirement to meet the rapid increases in population and biofuel consumption in the face of global warming (Lobell et al., 2011; Porter et al., 2017; Ray et al., 2013). While irrigation may help mitigate water and heat stress on crops (Thiery et al., 2020), it also adds pressure on freshwater resources and is not applicable in many developing countries (Dalin et al., 2017). Rainfed agriculture, instead, may prevent the overexploitation of water resources, and it currently accounts for ~75% of global cropland area contributing to ~60% of global food production (Portmann et al., 2010). However, weather and climate fluctuations put pressure on agricultural production (Li et al., 2022; Proctor et al., 2022; Ray et al., 2015), and disproportionately impact rainfed agriculture in drylands, which shows a high sensitivity to dry and hot climate extremes (Bradford et al., 2017). Global warming is expected to increase the frequency and intensity of droughts and heatwaves, and thus negatively affect crop yield and endanger food safety (Hasegawa et al., 2021). Understanding the relationship between climate anomalies and agricultural production in rainfed regions is critical to strive toward securing the global food supply.

Writing – review & editing:

Jessica Keune, Qiqi Gou, Chiara
M. Holgate, Diego Miralles

Australian rainfed agriculture plays a crucial role in global wheat production and trade, and thus global food security. The Southeastern Australia (SEA) wheat belt (Figure 1a) makes Australia one of the top 10 wheat-producing countries worldwide (Trnka et al., 2019). Australia exports ~65% of its wheat, which accounts for more than 10% of the global wheat trade (Bentley et al., 2022). However, year-to-year climate variability significantly impacts crop production in the SEA wheat belt (Ray et al., 2015; Vogel et al., 2019). Long periods of rainfall deficits (Chenu et al., 2013) and extremely high temperatures (Innes et al., 2015) have led to the stagnation of wheat production in recent years (Hochman et al., 2017). These climate anomalies are often triggered by large-scale atmospheric circulation and oscillations in SEA. Particularly, the El Niño in the Pacific Ocean, the positive phase of the Indian Ocean Dipole (IOD), and the negative phase of the Southern Annular Mode (SAM) are associated with below-normal rainfall in the region (Anderson et al., 2019; Hendon et al., 2007; Holgate et al., 2022; Ummenhofer et al., 2009).

Large-scale circulation aside, local soil desiccation can also amplify meteorological drought and cause additional heating through land–atmosphere feedbacks (Dirmeyer et al., 2022; Miralles et al., 2019; Zhou et al., 2019), which may enhance the risk of crop failure in water-limited regions (Lesk et al., 2021; Rigden et al., 2020). Moreover, land–atmosphere feedbacks in upwind regions can also trigger the advection of hot and dry air downwind (Schumacher et al., 2019, 2022). This upwind–downwind spatial propagation of weather and climate extremes fueled by land–atmosphere feedbacks (Miralles et al., 2019) has been shown to affect vegetation productivity (Schumacher et al., 2020) and water availability (Cui et al., 2022). For example, during the 2003 Western European and 2010 Russian heatwave events, the influence of upwind droughts on heat advection amounted to 30% of the total heat budget (Schumacher et al., 2019), and half of the mega-heatwaves in North China are associated with upwind soil drought (Zhou & Yuan, 2022). Similarly, reduced evaporation in upwind land areas accounted for approximately 60% of the total precipitation shortages during the 2012 North American drought (Herrera-Estrada et al., 2019), and at the global scale, droughts have been shown to self-propagate via these land–atmosphere feedbacks (Schumacher et al., 2022). Moreover, a recent global study suggested that upwind conditions aggravate moisture deficits and heat stress for crops, causing higher yield deficits worldwide, especially when agricultural regions are already under water stress (Li et al., 2023). The dependence of the SEA wheat belt on local climate (and potentially local land–atmosphere feedbacks) is to some degree already known (Hirsch et al., 2014), but the influence of upwind land–atmosphere feedbacks has not yet been unraveled. In addition, the sources of precipitation in Australia have been explored (Dirmeyer et al., 2009; Holgate et al., 2020; Miralles et al., 2016), yet emphasis has seldom been placed on agricultural regions (Mehrabi, 2020). Moreover, the sources of heat in the SEA wheat belt remain understudied, even though high temperatures are a well-known cause of agricultural failure (Lobell et al., 2015).

Here, we aim to explore the sources of precipitation and heat and the specific influence of upwind land conditions on the occurrence of yield deficits over the largest rainfed wheat belt in Australia. To do so, we apply the novel Heat And Moisture Tracking framework (HAMSTER, Keune et al., 2022), based on the Lagrangian model FLEXPART (Stohl et al., 2005) driven by atmospheric reanalysis data and constrained by satellite observations, to unravel the origins of precipitation and heat over the SEA wheat belt from 1983 to 2015. We specifically emphasize the origins of climate anomalies associated with crop failure (i.e., the low-yield years of 1994, 2002, and 2006) and the impact of drought conditions on moisture and heat imports to the wheat belt during these events. Altogether, the study contributes to understanding the influence of climate on wheat production and the potential of land management to mitigate agricultural loss in the SEA wheat belt.

2. Materials and Methods

2.1. Delineating the Study Region

We identify the wheat belt in SEA as a coherent region that meets the following criteria. First, the region must include at least 18 spatially connected 1° grid cells. Second, the area of rainfed harvest must exceed 75% of the total agricultural land, which includes both irrigated and rainfed areas. Finally, the area must have a uniform growing period, which is considered based on the same sowing and harvest months. The percentage of the rainfed harvest area in each grid cell is calculated based on the global irrigated and rainfed areas in 2000 (MIRCA2000, Portmann et al., 2010), and the sowing and harvest months are determined using a global crop calendar (Sacks

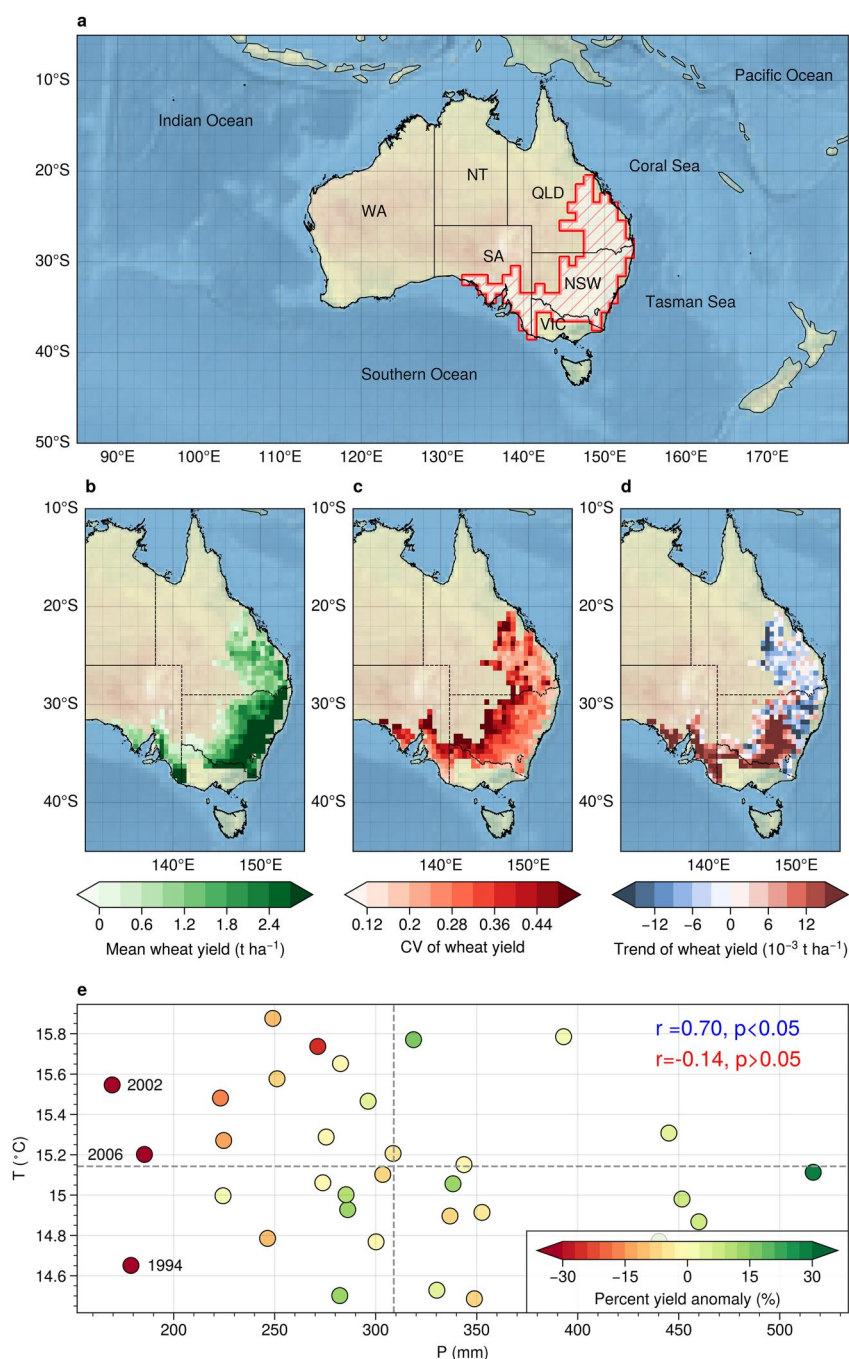


Figure 1. The Australian wheat belt, its yield variability and relation to climate. (a) Location of the Southeastern Australia wheat belt (red shading). Abbreviations indicate the Australian states: WA, Western Australia; SA, South Australia; VIC, Victoria; NSW, New South Wales; QLD, Queensland; NT, Northern Territory. (b–d), Mean, coefficient of variation (CV, the ratio of the standard deviation to the mean), and trend of wheat yield during 1983–2015 using the Theil–Sen estimator (Li et al., 2021). e, The relationship among precipitation (P), 2 m air temperature (T), and relative yield anomaly (Y_p) over the rainfed breadbasket. Crop failure events ($Y_p < -30\%$) are identified in 1994, 2002 and 2006. The dashed lines show the climatological mean P (309 mm) and T ($15.14^{\circ}C$) during 1983–2015 over the breadbasket, respectively. Pearson's correlation between Y_p and P (T) is indicated by blue (red) labels.

et al., 2010). The resulting wheat belt represents a large part of New South Wales, southern Queensland and small parts of South Australia and Victoria, which consists of 122 1° grid cells (approximately $1.3 \times 10^6\ km^2$) (Figure 1a). The growing period is from April to October.

The Global Dataset of Historical Yield (GDHY, Lizumi & Sakai, 2020) is used to represent the changes in wheat yield in the SEA wheat belt. GDHY is a hybrid of agricultural census statistics and satellite remote sensing with a spatial resolution of 0.5°; it is used to represent the changes in wheat yield in the SEA wheat belt. The data is available for 1981–2016, but due to many missing values in the beginning and ending years, we constrain the study period from 1983 to 2015. As shown in Figure 1b, the average wheat yield is about 1.7 t ha⁻¹, with higher values along the eastern coastlines and lower values in the interior arid lands. The spatial coefficient of variance (CV) of wheat yield is 0.34 (Figure 1c), which is higher than for most other wheat croplands in the world (Ray et al., 2015), while the trends of wheat yield show stagnation in the northern part of the region (Figure 1d).

2.2. Identifying Crop Failure Events

Crop failure events in the SEA wheat belt are defined as years for which the relative yield anomaly ($Y_{p,t}$, %) is below -30%. Using yield data from GDHY and the rainfed harvest area from MIRCA2000, the time series of rainfed wheat yield ($Y_{o,t}$, t ha⁻¹) are calculated as follows:

$$Y_{o,t} = \frac{\sum(Y_{o,g,t} \times H_g)}{\sum H_g}, \quad (1)$$

where $Y_{o,g,t}$ is the observed yield (Y_o) over each g th 1° grid cell in the breadbasket in the year t , and H_g is the corresponding rainfed harvest area in the grid cell g . The relative yield anomaly $Y_{p,t}$ (green solid line in Figure S1 in Supporting Information S1) is calculated by removing the long-term trend (μ_t , red dash line in Figure S1 in Supporting Information S1), potentially associated with technological improvements in productivity ($Y_{o,t}$, red solid line in Figure S1 in Supporting Information S1), using the locally weighted scatter plot smoothing (LOWESS) approach. This method can account for possible nonlinearity in time, and hence it is more suitable to nonstationary time series than other approaches (Anderson et al., 2019; Ben-Ari et al., 2018). The detrended relative yield anomaly is calculated as follows:

$$Y_{p,t} = \frac{Y_{o,t} - \mu_t}{\mu_t} \times 100. \quad (2)$$

According to the threshold, three years are identified as crop failure events: 1994, 2002 and 2006 (see Figure 1e and Figure S1 in Supporting Information S1). The year 2002 corresponds to the initial phase of the Millennium Drought and 2006 to its final phase (Van Dijk et al., 2013).

2.3. Computing Climate Anomalies

In addition to 2 m air temperature (T) and precipitation (P), the geopotential height (GPH) at 850 and 500 hPa and wind speed and direction are used to evaluate the circulation anomalies during crop failure events. Data of GPH, wind and T come from the European Center for Medium-Range Weather Forecasts ReAnalysis 5 (ERA5, Hersbach et al., 2020). P is retrieved from the Multi-Source Weighted-Ensemble Precipitation data set (MSWEP v2.8, Beck et al., 2017). Similarly, anomalies in land and ocean states and fluxes are diagnosed using data of soil moisture, evaporation (E), sensible heat (H) and sea surface temperatures (SST). A period starting 1 month before the growing season is considered (March–October) to account for the memory in variables such as soil moisture or SSTs. Surface soil moisture (0–5 cm) is obtained from the European Space Agency (ESA) Climate Change Initiative (CCI) (Dorigo et al., 2017). Land E and H are acquired from the Global Land Evaporation Amsterdam Model (GLEAM v3, Martens et al., 2017; Miralles et al., 2011), and ocean E and H data come from the Objectively Analyzed Air–Sea Heat Fluxes (OAFlux v3, Yu & Weller, 2007). All data sets except GPH and the winds are regridded to a 1° resolution, compatible with the atmospheric transport analyses (see Section 2.4). Anomalies in all variables during crop failure events are calculated by subtracting their 1983–2015 mean.

2.4. Identifying Heat and Moisture Sources

The identification of heat and moisture source regions is based on a Lagrangian particle dispersion model FLEXPART (Stohl et al., 2005) that traces air parcels back in time. Using simulations from FLEXPART, we apply the newly developed HAMSTER (Keune et al., 2022) to infer source–sink relationships.

2.4.1. Lagrangian Simulations: FLEXPART

In this study, FLEXPART version 10.4 (Stohl et al., 2005) driven with ERA-Interim reanalyses at 1° resolution (Dee et al., 2011) is used to track air parcels through the atmosphere. The model is initialized with 3 million air parcels distributed homogeneously around the globe, which are then tracked in space and time. We identify parcels residing over the SEA wheat belt at every time step and trace these back in time for up to 15 days. This results in millions of backward trajectories from the SEA wheat belt for each 6-hourly ERA-Interim reanalysis time step (00:00, 06:00, 12:00, and 18:00 UTC). In the simulations, additional 3-hourly forecasts (03:00, 09:00, 15:00, and 21:00 UTC) were used to increase the interaction between horizontal and vertical wind components in the Lagrangian model, resulting in a better representation of turbulence and improved accuracy of simulated trajectories (Stohl et al., 2005), while for the analysis 6-hourly time steps are used. Data includes three-dimensional fields of horizontal and vertical wind, temperature, and specific humidity, as well as two-dimensional fields of surface pressure, cloud cover, temperature at 2 m, dew-point temperature, precipitation, latent and sensible heat, and North/South and West/East surface stress. In addition, the Emanuel convection scheme is employed to enhance the simulation of convection (Emanuel, 1991), and a sub-grid terrain-effect parameterization is used to increase mixing heights arising from topographic variance at the grid-cell level (Stohl et al., 2005). The outputs of FLEXPART contain the positions (longitude, latitude, and height), properties (temperature, density, and specific humidity), and the surrounding boundary layer height of all tracked air parcels, enabling the attribution and quantification of source–receptor relationships based on HAMSTER (Keune et al., 2022).

2.4.2. Establishing Source–Receptor Relationships: HAMSTER

Keune et al. (2022) proposed a unified framework for the process-based evaluation of atmospheric trajectories from Lagrangian models (e.g., FLEXPART). It includes three stages: (a) diagnosis, (b) attribution, and (c) bias correction. In the first stage, all simulated air parcels are evaluated independently over two consecutive time steps. This diagnosis analysis enables the detection and quantification of processes such as precipitation, evaporation, and sensible heating, and produces a global data set of process detection accuracy and reliability further used for bias correction. Second, in the attribution part, air parcels arriving or residing over the SEA wheat belt are selected and tracked backwards for 15 days from March to October (1983 to 2015). These trajectories are then evaluated to establish source–receptor relationships. Moisture and heat sources are identified if evaporation and sensible heating along those trajectories are detected, that is, if an air parcel experiences any moisture gain or any potential temperature increase in the planetary boundary layer (see ALL-PBL in Keune et al., 2022). A trajectory length of 15 days is chosen as a proxy for the globally-averaged maximum lifetime of water vapor in the atmosphere (Gimeno et al., 2021). Third, the accuracy and reliability information in the first step is used to bias-correct heat and moisture source regions, using P from MSWEP (Beck et al., 2017), E and H from GLEAM over land (Martens et al., 2017), and E and H from OAF flux v3 over the ocean (Yu & Weller, 2007). We refer to the SEA wheat belt as “local region,” while other terrestrial sources are referred to as “upwind region.” The resulting source regions reveal the importance of ocean and land (both upwind land regions and the local wheat belt) for the variability of moisture and heat imports over the SEA wheat belt.

3. Results

3.1. Climate Anomalies and Synoptic Circulation

Average crop yield shows a significant positive temporal correlation with P in the SEA wheat belt ($r = 0.70$, $p < 0.05$)—and also with soil moisture ($r = 0.63$, $p < 0.05$)—but only a weak correlation with T ($r = -0.14$, $p > 0.05$, Figure 1e). This confirms that water availability is key for wheat growth in SEA (Vogel et al., 2019). During crop failure events (1994, 2002, and 2006), rainfall decreases on average by 130 mm (~40%) below the climatological mean of 309 mm (Figure 1e). Growing season average T is more unrelated to yield failure: around 15.55°C in 2002 (i.e., 0.40°C slightly warmer than the climatological expectation of 15.14°C), but not anomalous in 2006 and even cooler than usual (−0.49°C) in 1994. Despite the T differences between 2002 and 1994, crop yield is more than halved in both years, indicating the more dominant role of P.

Figures 2a, 2d, and 2g show predominant high-pressure conditions (white contours) over the Australian continent and westerly winds (red arrows) around the wheat belt during crop failure events under study. The polar jet is located south of the continent, causing strong westerly winds in the southern part of the wheat belt (areas with

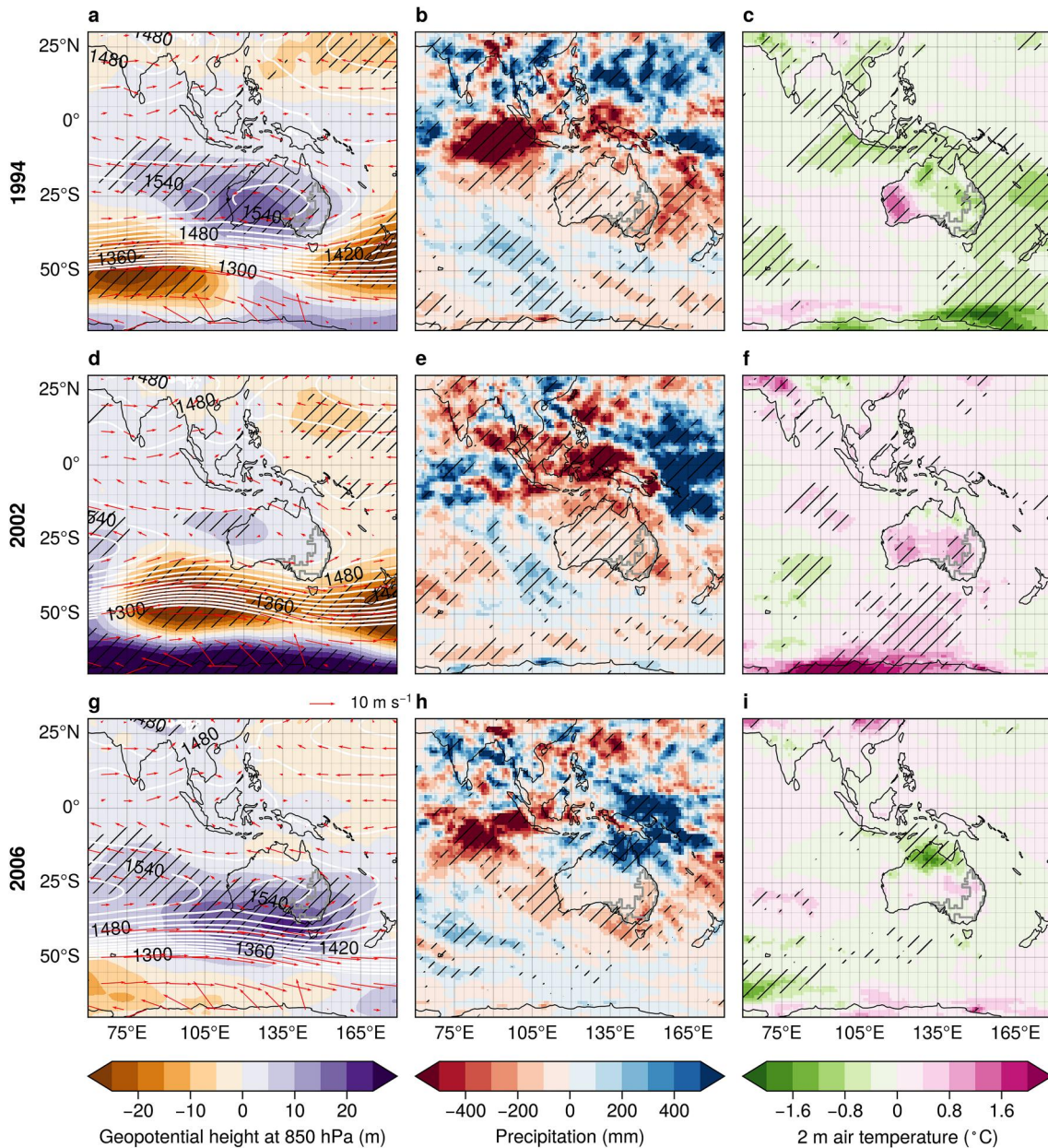


Figure 2. Atmospheric circulation and climate anomalies during crop failure events. (a, d, g) Anomalies in geopotential height (GPH, shades) at 850 hPa for 1994, 2002, 2006. Observed GPHs at 850 hPa are illustrated as white lines and the wind is illustrated as red arrows, showing lower-tropospheric flow across crop failure events. (b, e, h) Anomalies in precipitation. (c, f, i) Anomalies in air temperature at 2 m. Hatched regions mark anomalies larger than one standard deviation.

narrow isobars and arrows at 850 hPa in Figures 2a, 2d, and 2g). Moreover, anomalous high pressures, indicated by positive GPH anomalies at 850 hPa over one standard deviation, are present in southwestern Australia during the growing seasons of 1994 and 2006 (purple shades in Figures 2a and 2g), strengthening the westerly winds from the Southern Ocean, and easterly winds from the Western Pacific Ocean over the northern part of the wheat belt (Figures S2a–S2c, S2g–S2i in Supporting Information S1). However, the geopotential height also illustrates somewhat different synoptic configurations during these 2 years. In 1994, an omega blocking pattern associated with the Rossby wave configuration results in anomalously high pressure over southwest Australia that is enforced by predominant low-pressure conditions to the southwest and southeast (located over the southern Indian and Pacific oceans, see brown shades in Figure 2a). A similar anomalous configuration is also present during the growing season in 2006, but the neighboring low-pressure centers at 850 hPa are much weaker. These

patterns are also seen at 500 hPa for the crop failure events of 1994 and 2006 (Figures S3a and S3g in Supporting Information S1). In 2002, the high-pressure conditions at 850 hPa are weaker (Figure 2d), yet a stronger blocking pattern is predominant at 500 hPa, which encompasses the wider northwest Australian regions and adjacent Indian oceans (Figure S3d in Supporting Information S1).

During all three crop failure events analyzed in this study, Australia experiences lower-than-usual rainfall not only in the wheat belt but also spreading across larger areas, especially in 1994 and 2002 (red shades in Figures 2b and 2e). These widespread rainfall deficits align with the presence of the predominantly anticyclonic conditions. In 2006, however, the largest rainfall deficits are located in the south of the continent, comprising the entire wheat belt, while the northern regions of Australia experience higher-than-usual rainfall and cooler temperatures associated with a weak low-pressure system (Figures 2g–2i). In line with the results in Figure 1e, temperature anomalies are predominantly negative in 1994 (green shades in Figure 2c), positive in 2002 (pink shades in Figure 2f), and near-normal in 2006 (Figure 2i) over most of the wheat belt. Overall, the patterns suggest a causal link between precipitation deficits and crop failure, which seems confirmed by the correspondence between precipitation and soil moisture anomalies, indicating widespread agricultural droughts during all three growing seasons (Figures 3a, 3d, and 3g). The low soil moisture modulates the energy balance at the land surface, causing evaporation decreases (red shades in Figures 3b, 3e, and 3h) and sensible heat increases (pink shades Figures 3c, 3f, and 3i), which may help reduce precipitation and enhance temperatures (Miralles et al., 2019). Heat flux anomalies larger than one standard deviation are spread over large parts of the Australian continent, especially in 1994 and 2002; in 2006, however, the area is confined to the southeast, comprising the wheat belt and the nearby land only (Figures 3g–3i). The spatial disparities of surface energy fluxes among different years are the result of the specific atmospheric circulation anomalies and land–atmosphere feedbacks in the region.

Over the western Pacific Ocean and across the Coral and Tasman seas, both evaporation and sensible heat show an increase during all three crop failure events, that is, 1994, 2002, and 2006 (blue and pink shades in Figure 3, respectively), suggesting high surface net radiation and SSTs. However, these latent and sensible heat flux anomalies in fact concur with lower-than-usual SSTs in the western Pacific Ocean in 1994 and 2006 (Figure 3a), while weakly positive SST anomalies occur in the region in 2002 (Figure 3d). This may reflect the dominant influence of the stronger-than-usual winds in the region, enhancing ocean evaporation and sensible heat flux in all three growing seasons (Figure S2 in Supporting Information S1). Compared to the Pacific, the anomaly patterns in the Indian Ocean are less consistent from year to year. Here, negative anomalies in both E and H are observed in the south in 2006 (red and green shades in Figures 3h and 3i, respectively). However, evaporation is higher than usual in 1994 and 2002 (blue shades in Figures 3b and 3e), except for the adjacent oceans nearby the western Australian continent that show declines in E (red shades in Figures 3b and 3e) while sensible heat (H) anomalies are predominantly negative in 1994 and positive in 2002 (green and red shades in Figures 3c and 3f, respectively).

3.2. Source Regions of Moisture and Heat

Conditioned on the prevailing circulation in Figure 2, the anomalies in land and ocean states and fluxes shown in Figure 3 would affect the imports of moisture and heat to the SEA wheat belt. To quantify how these anomalies contribute to the weather conditions in the wheat belt during crop failure events, we delineate the source regions of precipitation and heat using the Lagrangian framework described in Section 2.4. Figures 4a and 4b show the smallest area contributing 80% of precipitation and heat imported to the Australian wheat belt climatologically (shown by blue and red contour lines, respectively). Precipitation is mostly of oceanic origin, with moisture being sourced from the western Pacific Ocean, for example, Coral and Tasman Sea, and the Southern Ocean (Figure 4a). The climatological source of precipitation also encompasses the wheat belt and large parts of the Australian continent west of the agricultural region (Figure 4a). The climatological heat source covers the wheat belt and the entire Australian continent, further extending into the Southern Ocean and encompassing some parts of the Coral Sea and Tasman Sea (Figure 4b). While the largest moisture contributions are of oceanic origin (Figure 4a), heat is mostly sourced from land surfaces (Figure 4b).

During all three crop failure events under study, the predominantly high pressures over the continent cause decreased precipitation volumes sourced from the ocean, with the largest deficits (>24 mm per growing season) stemming from the Coral Sea, Tasman Sea and a small part of the Southern Ocean near the continent (Figures 4c–4e, and 4g). Likewise, land regions also provide less-than-usual moisture for precipitation. In most of the wheat

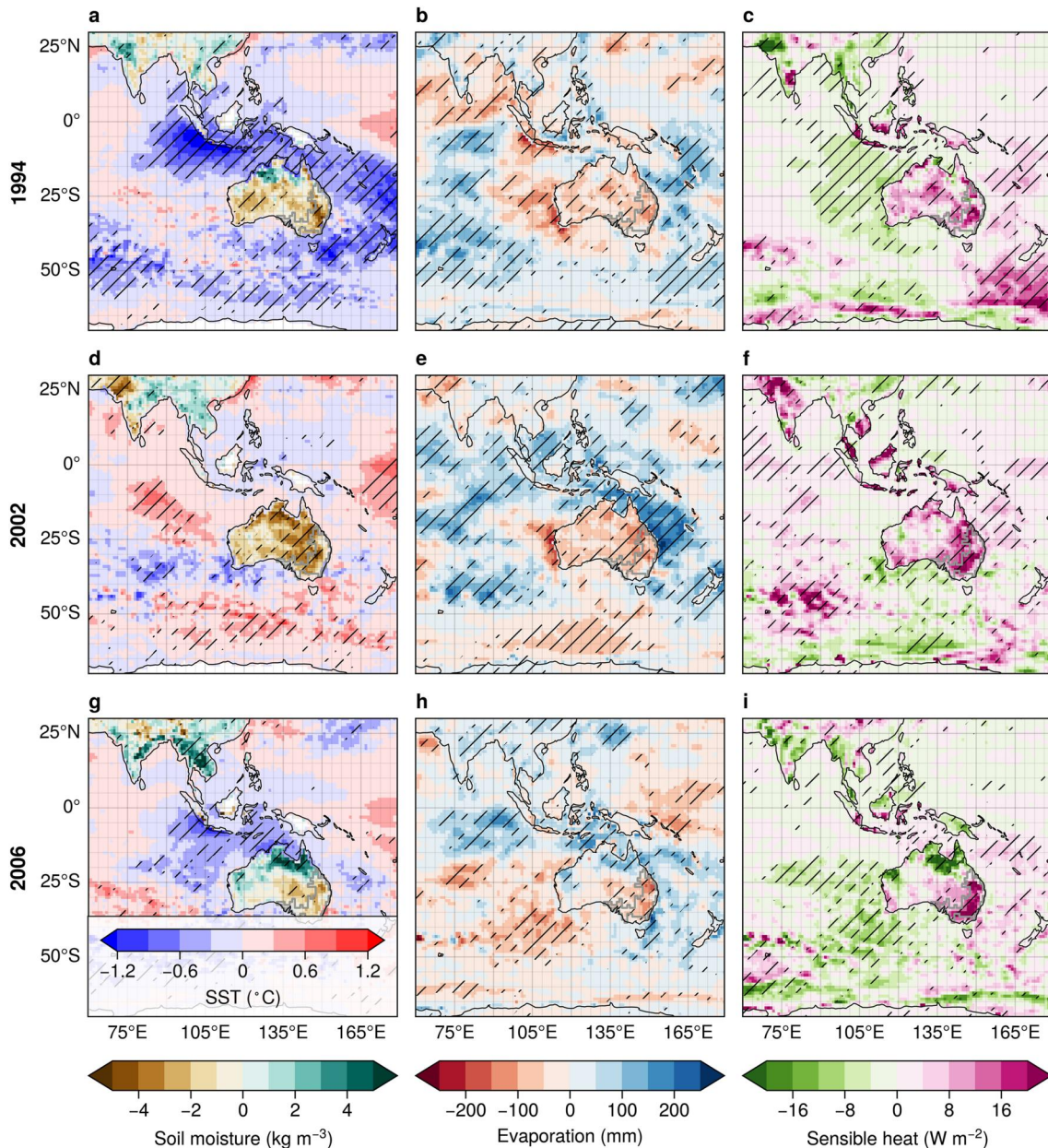


Figure 3. Anomalies of land and ocean fluxes during crop failure events. (a, d, g) Anomalies of soil moisture and sea surface temperature for 1994, 2002, 2006. (b, e, h and c, f, i) As in (a, d, g) but for evaporation and sensible heat, respectively. Hatched regions mark anomalies larger than one standard deviation.

belt, negative anomalies of moisture imports exceed 16 mm, but also upwind land contributions of moisture for precipitation decrease by at least 8 mm, especially in regions surrounding the SEA wheat belt (Figures 4c–4e, and 4g). Moreover, the large-scale circulation anomalies cause shifts in the location of the core precipitation sources, that is, the smallest region contributing 80% of the moisture that yields rainfall during crop failure events (see blue contours in Figure 4). In 1994 and 2002, the prevailing anticyclonic conditions lead to a preferential import of moisture from proximate coastal areas (Figures 4c and 4e), while in 2006 we find a mild eastward expansion of the source (Figure 4g). In contrast to moisture contributions, heat is mostly imported from land (Figure 4). Moreover, during crop failure events under study, the heat over the croplands comes disproportionately from the wheat belt itself, with local anomalies exceeding 9 W m^{-2} (Figures 4d, 4f, and 4h). Local and upwind regions that experience drought (brown shades in Figures 3a, 3d, and 3g) tend to provide less moisture but more heat (red and pink shades in Figures 4c, 4e, 4g and Figures 4d, 4f, 4h, respectively). These local and upwind anomalies in

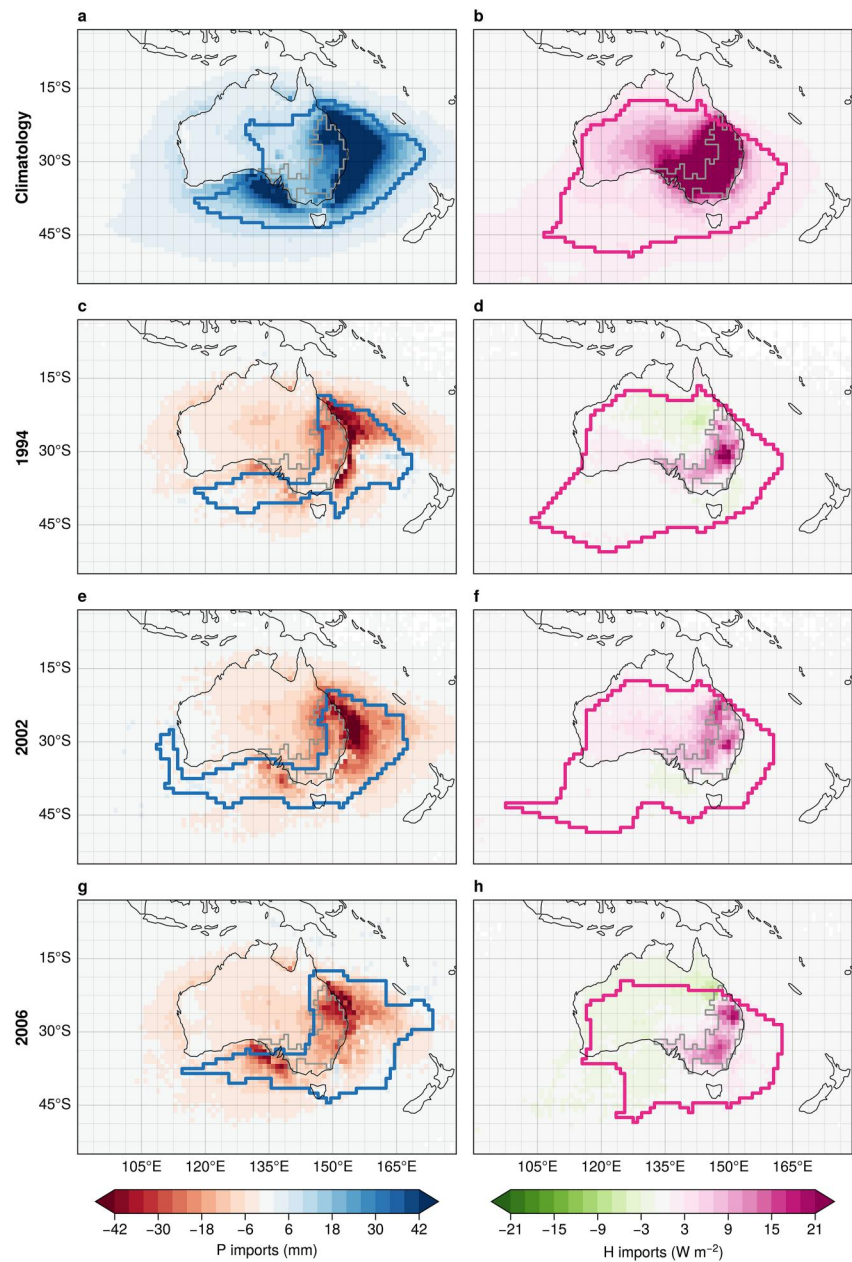


Figure 4. Moisture and heat source regions of the SEA wheat belt. (a, b) Climatological source region contributions of moisture and heat, averaged over 1983–2015. (c, d) Anomalous source region contributions of moisture and heat during 1994. (e, f and g, h) As in (c, d) but for 2002 and 2006, respectively. The blue and red lines indicate the smallest area contributing 80% of precipitation and heat, respectively. The gray line shows the SEA wheat belt, which is referred to as the “local region,” while other terrestrial sources are referred to as “upwind region.”

moisture and heat contributions are largely the result of land–atmosphere feedbacks associated with the soil drought (Dirmeyer et al., 2022; Miralles et al., 2019) and enabled by high-pressure systems (Figures 2a, 2d, and 2g).

Figure 5 shows the average time series of total precipitation and heat imports into the wheat belt, subdivided into the contributions from the ocean, upwind land and local land (i.e., the wheat belt itself). On average, the oceanic source region provides 220 mm of precipitation into the wheat belt during the growing seasons of 1983–2015, which accounts for 72% of the precipitation supply (Figures 5a and 5b). Given the dominance of the Pacific and Southern Oceans in the region, the land plays only a secondary role for precipitation over the wheat belt, with

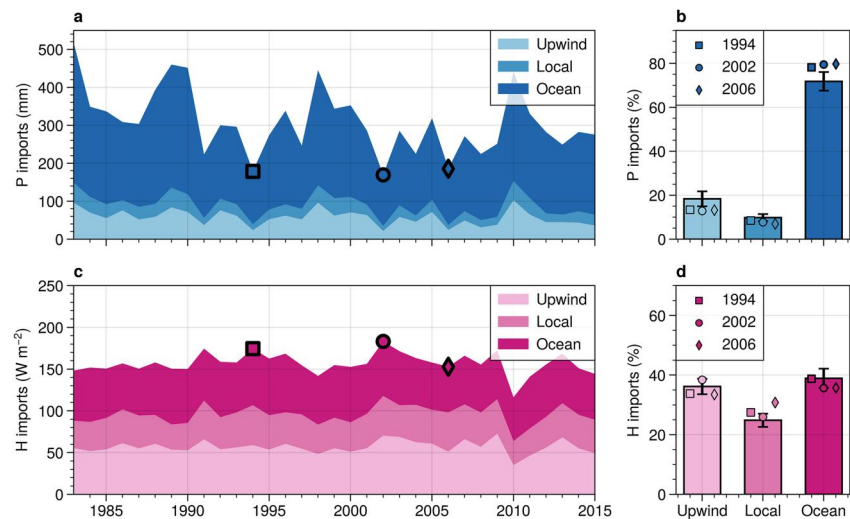


Figure 5. The contribution of ocean and land source regions to the precipitation and heat over the SEA wheat belt. (a, c) Time series of precipitation and heat imports, subdivided into terrestrial and oceanic source regions. (b, d) Relative percentages (%) of upwind (square), local land (circle) and ocean (diamond) source regions to the total precipitation and heat. The vertical error bars indicate one standard deviation.

average contributions of 18% and 10% from upwind and local land, respectively (Figure 5b). During crop failure events, the relative importance of ocean-origin precipitation increases by about 6% (Figure 5b), despite the 80 mm decline in absolute terms (Figure 5a). Conversely, the relative importance of land decreases by about 5% and 2% for upwind and local land, respectively (Figure 5b). This means that the contribution to precipitation is disproportionately low from land sources during the crop failure events under study.

In terms of heat, the air over the wheat belt is preferentially warmed up by land surfaces; on a climatological average, around 39% of the heat over the wheat belt is imported from the ocean, while the remaining 61% originates from terrestrial sources, in which around 36% of the heat comes from upwind land, and 25% originates in the wheat belt itself (Figure 5d). During crop failure events, the local sensible heat flux contribution increases from its climatological $39 W m^{-2}$ (representing 25% of the heat budget) to $48 W m^{-2}$ in 1994 and in 2002, and $47 W m^{-2}$ in 2006 (representing 31% of the heat budget that year). In contrast, the anomalies in the contribution of heat from the ocean and upwind lands are more ambiguous during crop failure events. Ocean heat imports decrease by around 3% during the initial (2002) and final (2006) stages of the Millennium drought, but remain average in 1994 (Figure 5d). However, upwind land areas contribute 36% of the heat imports, increasing to 38% in 2002, but decreasing to 33% in both 1994 and 2006; these changes represent anomalies of around one standard deviation (Figure 5d).

3.3. Influence of Upwind and Local Drought

To better understand the influence of drought-affected regions on the moisture and heat imported into the SEA wheat belt during crop failure events, we further subdivide the land source region into subregions according to soil moisture variability. First, we identify the areas that are affected by agricultural drought as those in which the negative soil moisture anomaly exceeds one standard deviation during crop failure events. This results in four subregions shown in Figures 6a–6c: local drought (LD), upwind drought (UD), local non-drought (LND) and upwind non-drought (UND). As seen in Figure 6, the agricultural drought extent is noticeably higher in 2002, covering most (60%) of the Australian continent (Figure 6d), while only 12% of the continent (mainly in the western New South Wales state) was affected in 2006 (Figure 6g).

In 1994, the region in Western Australia affected by drought (brown region in Figure 6a) climatologically provides on average 12 mm (4%) of precipitation to the SEA wheat belt, but its contribution is reduced to only 4 mm during the crop failure year (see UD in Figure 6b). Likewise, the heat imported from that region slightly increased (Figure 6c). The influence of upwind droughts on the weather conditions in the SEA wheat belt is particularly clear during the initial phase of the Millennium Drought in 2002 (Figures 3e and 3f). Climatologically, 30 mm

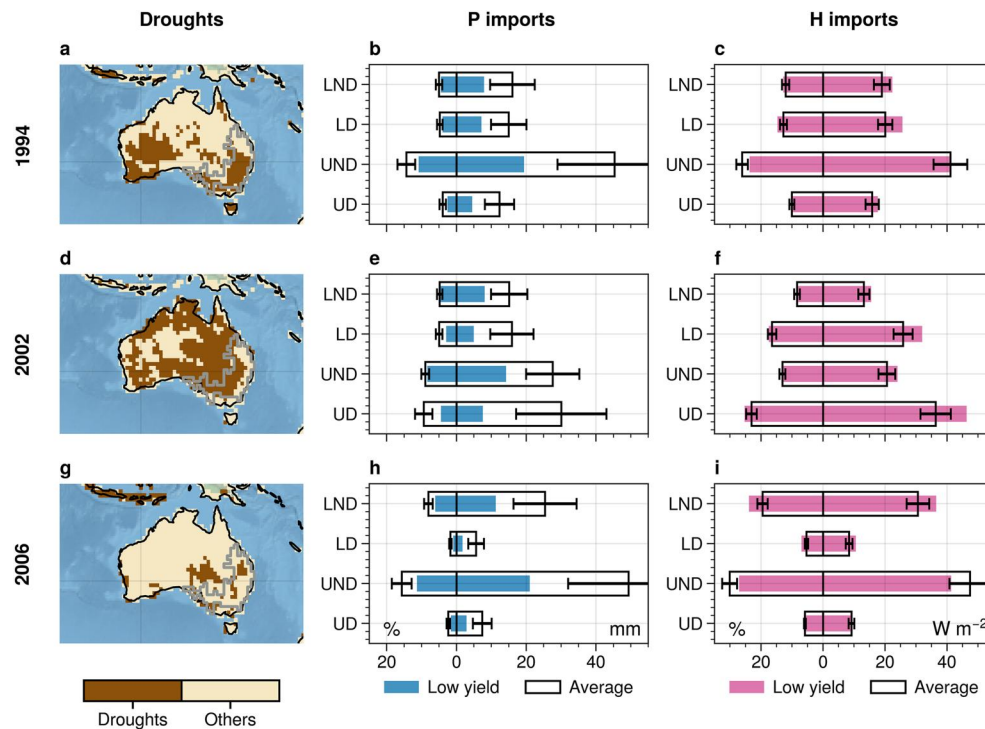


Figure 6. Influence of upwind and local drought on heat and moisture imports. (a, d, g) Brown shades indicate regions that experience soil moisture anomalies below one standard deviation compared with the climatology, while the light yellow shows other regions (for in 1994, 2002 and 2006, respectively). The wheat belt is marked by gray contours. (b, e, h) Precipitation contribution from upwind drought (UD), upwind non-drought (UND), local drought (LD) and local non-drought (LND) regions to the total precipitation in the wheat belt. Results to the left of the zero value indicate relative (%) and to the right absolute (mm) values. (c, f, i) As in (b, e, h) but for heat instead of precipitation. The horizontal error bars indicate one standard deviation.

(9%) of the SEA wheat belt precipitation during the growing season come from those regions, but this lowered to 7 mm (4% of the less than 170 mm received that year) in 2002. This means that not only was the contribution from those regions anomalously low, but also disproportionately low compared to other land (and ocean) sources. Likewise, the heat imports to the SEA wheat belt from those upwind drought-affected regions escalated from the climatological 36 W m^{-2} (23% of the total 156 W m^{-2}) to 46 W m^{-2} (25% of the 183 W m^{-2} in 2002). Relative anomalies of similar value are found in terms of moisture (Figure 6e) and heat (Figure 6f) contributions from the drought-affected regions within the wheat belt itself (i.e., LD) in 2002 (Figures 6e and 6f). While these patterns are less clear during the 2006 growing season due to the more reduced drought extent (Figures 6g–6i), the overall results in Figure 6 indicate a lower contribution to SEA precipitation from drought-affected regions compared to their climatological contribution, and an overall positive anomaly in heat imports from those regions. This suggests an influence of local and upwind droughts on the climate anomalies that contributed to past crop failure events in the SEA wheat belt.

4. Discussion

Dry and hot climatic conditions, predominantly driven by atmospheric circulation, are associated with low wheat yields in Australia. Our study aims to understand the origins of the anomalies in moisture and heat sources over the largest rainfed wheat belt in the SEA during crop failure events. This enables to enhance our understanding of the physical mechanisms behind adverse climate extremes for crops, guide agricultural priorities in risk management, and aid adaptation efforts. Utilizing a unified tracking framework along with satellite data sets, our analysis reveals that the oceanic source regions (e.g., Tasman and Coral seas) play a pivotal role in the variability of precipitation over the SEA wheat belt. On a climatological scale, approximately 72% of the precipitation originates from the ocean, importing roughly 222 mm of moisture into the breadbasket during the growing season. While the significant contribution of the ocean to precipitation in the SEA has been widely accepted, the precise rate varies depending on model selection, parameter settings and spatio-temporal scale (Dirmeyer & Brubaker, 1999; Holgate et al., 2020). For instance, Holgate et al. (2020) employed a similar Lagrangian model

with explicit moisture accounting and demonstrated that the Murray–Darling Basin receives at least 77% of moisture imports from the ocean. In our study, where we incorporated a bias-correction approach to estimate precipitation origins guided by observed precipitation data, the importance of the oceanic source region is corroborated. The substantial decline in oceanic moisture leads to precipitation shortages, drought over land, associated land–atmosphere feedbacks, and crop failure. The decrease in oceanic moisture primarily results from changes triggered by atmospheric circulation and anomalous wind patterns.

Furthermore, the impacts of high temperatures on crops have garnered attention in recent years, yet the origins of the heat imports to global breadbaskets have seldom been studied (Li et al., 2023). Here, we delineate the regions from which the heat is sourced into the SEA wheat belt during the growing seasons from 1983 to 2015, with a specific focus on crop failure years (1994, 2002, 2006). In contrast to the dominant role of the ocean in precipitation variability, the terrestrial source region, including the wheat belt itself and the surrounding lands, on average, accounts for 61% of the total heat import (157 W m^{-2}). For instance, regions experiencing droughts in upwind land regions exported 5% lower-than-usual moisture and 2% higher-than-usual heat to the breadbasket during the initial year (2002) of the Millennium Drought, exacerbating the climate risks of wheat failures in this breadbasket. These anomalies are expected to be larger in more continental regions, suggesting the potential of land management and practices in upwind areas to mitigate heat accumulation and moisture deficits downstream, thereby safeguarding rainfed agricultural yields.

The Lagrangian model and analysis methods employed in this study come with inherent uncertainties and limitations. While we utilized the ERA-Interim reanalysis data set to drive FLEXPART (Stohl et al., 2005), it is worth considering that the estimation of air trajectories could potentially be enhanced by employing the fifth generation of the European ReAnalysis (ERA5). Furthermore, the lack of ground observations poses a significant challenge in validating and bias-correcting the sources of precipitation, evaporation, and sensible heat. Therefore, future research may consider incorporating the isotopic composition of precipitation (Konecky et al., 2019) to verify moisture source contributions and enhance the representation of the moisture tracking model. Although the growing season in this study is fixed, spanning from October to April, it is worth exploring the impact of agricultural adaptation practices on climate, such as the early sowing system combined with slower-developing wheat genotypes utilized in Australia to increase the yield even during dry and hot periods (Hunt et al., 2019). Moreover, the conversion of rainfed to irrigated practice was not considered in the study. In addition, our study highlights the impact of upwind drought-affected regions on amplifying climate risks for agriculture, concentrating on three extreme harvest failure years (i.e., 1994, 2002, and 2006). While the influence varies depending on the events, results indicate that upwind land management can aid future agricultural adaptation and management. Finally, while the use of Lagrangian trajectories aids in uncovering the causal linkages between upwind climate conditions and downwind crop yield variability, it is important to note that the framework does not provide a comprehensive causal analysis. Future research endeavors should consider employing machine learning-based and/or causal inference methods to gain a deeper understanding of the impacts of upwind land use changes under climate warming scenarios.

Despite these uncertainties and limitations, our study provides a preliminary understanding of the linkages between upwind droughts and downwind wheat failures in the SEA wheat belt. Consequently, the results hold potential implications for agricultural management and practices. Satellite monitoring of upwind terrestrial sources can enhance the lead time and prediction accuracy of seasonal crop yield forecasts, particularly in agricultural regions with limited local observations. Moreover, upwind lands exhibit an influence on the local climate in the SEA wheat belt, particularly during the initial year of the Millennium Drought (2002). Therefore, implementing land use strategies may help mitigate the climate risks associated with downwind agricultural failures. This approach could be particularly effective in agricultural regions that heavily rely on remote land areas for their supply of precipitation (and heat).

5. Conclusions

This study highlights the critical influence of dry and hot weather conditions, driven by stable high-pressure systems, on agricultural failures in the Southeastern Australia wheat belt. Using a novel tracking framework, we have delineated the source anomalies of moisture and heat during crop failure events, providing valuable insights into the underlying mechanisms. Our results demonstrate that the ocean source region, specifically the Tasman and Coral seas, is responsible for 72% of the precipitation in the wheat belt during the growing season.

Notably, during crop failure events, this contribution increases to 78%, despite a decrease in absolute imports by 80 mm. On the other hand, the terrestrial source region, including the upwind Australian continent and the wheat belt itself, plays a dominant role in the heat accumulation over the wheat belt. During crop failure events, atmospheric blocking exacerbates the spreading of drought across the continent, leading to a more pronounced impact of upwind lands on the moisture and heat imports into the breadbasket. The influence of upwind drought is particularly visible for 2002, when the relative heat contribution increases from those regions by 2%, while the moisture import decreases by approximately 5% compared to the climatological average. Overall, our study suggests a potentially important role of upwind land regions in shaping the downwind climate in the Southeastern Australian wheat belt. The insights gained from this study provide a foundation for informed decision-making and targeted interventions aimed at reducing the vulnerability of the Southeastern Australian wheat belt to adverse climate conditions.

Data Availability Statement

The FLEXPART model can be downloaded via <https://www.flexpart.eu>. The version 1.2.0 of the heat and moisture tracking framework used for analysis of FLEXPART data is preserved at <https://doi.org/10.5281/zenodo.5788506> (Keune et al., 2021). Historical crop yield data used for identifying crop failure years are available at <https://doi.org/10.1594/PANGAEA.909132> (Lizumi, 2019). GLEAM data are available through <https://www.gleam.eu>. OaFlux data can be retrieved from <https://oafux.who.edu/data-access>. ERA data were accessed from <https://cds.climate.copernicus.eu/cdsapp#!/dataset>. MSWEP data are available through <http://www.gloh2o.org>.

Acknowledgments

H.L. thanks the China Scholarship Council (CSC) for financial support under grant agreement 202006350051. J.K. is grateful for the support from the Research Foundation–Flanders (FWO) under Grant 1244122N. D.G.M. acknowledges support from the European Research Council (ERC) under grant agreement 101088405 (HEAT). C.M.H. acknowledges support from the Australian Research Council (CE170100023).

References

- Anderson, W., Seager, R., Baethgen, W., Cane, M., & You, L. (2019). Synchronous crop failures and climate-forced production variability. *Science Advances*, 5(7), eaaw1976. <https://doi.org/10.1126/sciadv.aaw1976>
- Beck, H. E., Van Dijk, A. I., Levizzani, V., Schellekens, J., Miralles, D. G., Martens, B., & De Roo, A. (2017). Mswep: 3-hourly 0.25 global gridded precipitation (1979–2015) by merging gauge, satellite, and reanalysis data. *Hydrology and Earth System Sciences*, 21(1), 589–615. <https://doi.org/10.5194/hess-21-589-2017>
- Ben-Ari, T., Boé, J., Ciais, P., Lecerf, R., Van der Velde, M., & Makowski, D. (2018). Causes and implications of the unforeseen 2016 extreme yield loss in the breadbasket of France. *Nature Communications*, 9(1), 1–10. <https://doi.org/10.1038/s41467-018-04087-x>
- Bentley, A. R., Donovan, J., Sonder, K., Baudron, F., Lewis, J. M., Voss, R., et al. (2022). Near-to long-term measures to stabilize global wheat supplies and food security. In *Nature food* (pp. 1–4).
- Bradford, J. B., Schlaepfer, D. R., Lauenroth, W. K., Yackulic, C. B., Duniway, M., Hall, S., et al. (2017). Future soil moisture and temperature extremes imply expanding suitability for rainfed agriculture in temperate drylands. *Scientific Reports*, 7(1), 1–11. <https://doi.org/10.1038/s41598-017-13165-x>
- Chenu, K., Dehimfard, R., & Chapman, S. C. (2013). Large-scale characterization of drought pattern: A continent-wide modelling approach applied to the Australian wheat belt–spatial and temporal trends. *New Phytologist*, 198(3), 801–820. <https://doi.org/10.1111/nph.12192>
- Cui, J., Lian, X., Huntingford, C., Gimeno, L., Wang, T., Ding, J., et al. (2022). Global water availability boosted by vegetation-driven changes in atmospheric moisture transport. *Nature Geoscience*, 15(12), 1–7. <https://doi.org/10.1038/s41561-022-01061-7>
- Dalin, C., Wada, Y., Kastner, T., & Puma, M. J. (2017). Groundwater depletion embedded in international food trade. *Nature*, 543(7647), 700–704. <https://doi.org/10.1038/nature21403>
- Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The era-interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137(656), 553–597. <https://doi.org/10.1002/qj.828>
- Dirmeyer, P. A., & Brubaker, K. L. (1999). Contrasting evaporative moisture sources during the drought of 1988 and the flood of 1993. *Journal of Geophysical Research*, 104(D16), 19383–19397. <https://doi.org/10.1029/1999jd900222>
- Dirmeyer, P. A., Brubaker, K. L., & DelSole, T. (2009). Import and export of atmospheric water vapor between nations. *Journal of Hydrology*, 365(1–2), 11–22. <https://doi.org/10.1016/j.jhydrol.2008.11.016>
- Dirmeyer, P. A., Sridhar Mantripragada, R. S., Gay, B. A., & Klein, D. K. (2022). Evolution of land surface feedbacks on extreme heat: Adapting existing coupling metrics to a changing climate. *Frontiers in Environmental Science*, 10, 1650. <https://doi.org/10.3389/fenvs.2022.949250>
- Dorigo, W., Wagner, W., Albergel, C., Albrecht, F., Balsamo, G., Brocca, L., et al. (2017). ESA CCI soil moisture for improved earth system understanding: State-of-the art and future directions. *Remote Sensing of Environment*, 203, 185–215. <https://doi.org/10.1016/j.rse.2017.07.001>
- Emanuel, K. A. (1991). A scheme for representing cumulus convection in large-scale models. *Journal of the Atmospheric Sciences*, 48(21), 2313–2329. [https://doi.org/10.1175/1520-0469\(1991\)048<2313:asfrcc>2.0.co;2](https://doi.org/10.1175/1520-0469(1991)048<2313:asfrcc>2.0.co;2)
- Gimeno, L., Eiras-Barca, J., Durán-Quesada, A. M., Domínguez, F., van der Ent, R., Sodemann, H., et al. (2021). The residence time of water vapour in the atmosphere. *Nature Reviews Earth & Environment*, 2(8), 558–569. <https://doi.org/10.1038/s43017-021-00181-9>
- Hasegawa, T., Sakurai, G., Fujimori, S., Takahashi, K., Hijioka, Y., & Masui, T. (2021). Extreme climate events increase risk of global food insecurity and adaptation needs. *Nature Food*, 2(8), 587–595. <https://doi.org/10.1038/s43016-021-00335-4>
- Hendon, H. H., Thompson, D. W., & Wheeler, M. C. (2007). Australian rainfall and surface temperature variations associated with the southern hemisphere annular mode. *Journal of Climate*, 20(11), 2452–2467. <https://doi.org/10.1175/jcli4134.1>
- Herrera-Estrada, J. E., Martínez, J. A., Domínguez, F., Findell, K. L., Wood, E. F., & Sheffield, J. (2019). Reduced moisture transport linked to drought propagation across North America. *Geophysical Research Letters*, 46(10), 5243–5253. <https://doi.org/10.1029/2019gl082475>
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), 1999–2049. <https://doi.org/10.1002/qj.3803>

- Hirsch, A., Pitman, A., Seneviratne, S. I., Evans, J., & Haverd, V. (2014). Summertime maximum and minimum temperature coupling asymmetry over Australia determined using WRF. *Geophysical Research Letters*, 41(5), 1546–1552. <https://doi.org/10.1002/2013gl059055>
- Hochman, Z., Gobbett, D. L., & Horan, H. (2017). Climate trends account for stalled wheat yields in Australia since 1990. *Global Change Biology*, 23(5), 2071–2081. <https://doi.org/10.1111/gcb.13604>
- Holgate, C., Evans, J., Van Dijk, A., Pitman, A., & Di Virgilio, G. (2020). Australian precipitation recycling and evaporative source regions. *Journal of Climate*, 33(20), 8721–8735. <https://doi.org/10.1175/jcli-d-19-0926.1>
- Holgate, C., Evans, J. P., Taschetto, A. S., Gupta, A. S., & Santoso, A. (2022). The impact of interacting climate modes on east Australian precipitation moisture sources. *Journal of Climate*, 35(10), 3147–3159. <https://doi.org/10.1175/jcli-d-21-0750.1>
- Hunt, J. R., Lilley, J. M., Trevaskis, B., Flohr, B. M., Peake, A., Fletcher, A., et al. (2019). Early sowing systems can boost Australian wheat yields despite recent climate change. *Nature Climate Change*, 9(3), 244–247. <https://doi.org/10.1038/s41558-019-0417-9>
- Innes, P., Tan, D., Van Ogtrop, F., & Amthor, J. (2015). Effects of high-temperature episodes on wheat yields in New South Wales, Australia. *Agricultural and Forest Meteorology*, 208, 95–107. <https://doi.org/10.1016/j.agrformet.2015.03.018>
- Keune, J., Schumacher, D., & Miralles, D. (2021). Heat and moisture tracking framework (hamster, version 1.2.0) [Software]. Zenodo. <https://doi.org/10.5281/zenodo.5788506>
- Keune, J., Schumacher, D., & Miralles, D. (2022). A unified framework to estimate the origins of atmospheric moisture and heat using Lagrangian models. *Geoscientific Model Development*, 15(5), 1875–1898. <https://doi.org/10.5194/gmd-15-1875-2022>
- Konecky, B., Noone, D., & Cobb, K. (2019). The influence of competing hydroclimate processes on stable isotope ratios in tropical rainfall. *Geophysical Research Letters*, 46(3), 1622–1633. <https://doi.org/10.1029/2018gl080188>
- Lesk, C., Coffel, E., Winter, J., Ray, D., Zscheischler, J., Seneviratne, S. I., & Horton, R. (2021). Stronger temperature–moisture couplings exacerbate the impact of climate warming on global crop yields. *Nature Food*, 2(9), 683–691. <https://doi.org/10.1038/s43016-021-00341-6>
- Li, H., Keune, J., Smessaert, F., Nieto, R., Gimeno, L., & Miralles, D. G. (2023). Land–atmosphere feedbacks contribute to crop failure in global rainfed breadbaskets. *npj Climate and Atmospheric Science*, 6(51), 51. <https://doi.org/10.1038/s41612-023-00375-6>
- Li, H., Liu, L., Koppa, A., Shan, B., Liu, X., Li, X., et al. (2021). Vegetation greening concurs with increases in dry season water yield over the upper Brahmaputra river basin. *Journal of Hydrology*, 603, 126981. <https://doi.org/10.1016/j.jhydrol.2021.126981>
- Li, H., Shan, B., Liu, L., Wang, L., Koppa, A., Zhong, F., et al. (2022). Significant regime shifts in historical water yield in the Upper Brahmaputra River basin. *Hydrology and Earth System Sciences*, 26(24), 6399–6412. <https://doi.org/10.5194/hess-26-6399-2022>
- Lizumi, T. (2019). Global dataset of historical yields v1.2 and v1.3 aligned version [Dataset]. PANGAEA. <https://doi.org/10.1594/PANGAEA.909132>
- Lizumi, T., & Sakai, T. (2020). The global dataset of historical yields for major crops 1981–2016. *Scientific Data*, 7(1), 1–7.
- Lobell, D. B., Hammer, G. L., Chenu, K., Zheng, B., McLean, G., & Chapman, S. C. (2015). The shifting influence of drought and heat stress for crops in northeast Australia. *Global Change Biology*, 21(11), 4115–4127. <https://doi.org/10.1111/gcb.13022>
- Lobell, D. B., Schlenker, W., & Costa-Roberts, J. (2011). Climate trends and global crop production since 1980. *Science*, 333(6042), 616–620. <https://doi.org/10.1126/science.1204531>
- Martens, B., Miralles, D. G., Lievens, H., Van Der Schalie, R., De Jeu, R. A., Fernández-Prieto, D., et al. (2017). Gleam v3: Satellite-based land evaporation and root-zone soil moisture. *Geoscientific Model Development*, 10(5), 1903–1925. <https://doi.org/10.5194/gmd-10-1903-2017>
- Mehrabi, Z. (2020). Food system collapse. *Nature Climate Change*, 10(1), 16–17. <https://doi.org/10.1038/s41558-019-0643-1>
- Miralles, D. G., Gentile, P., Seneviratne, S. I., & Teuling, A. J. (2019). Land–atmospheric feedbacks during droughts and heatwaves: State of the science and current challenges. *Annals of the New York Academy of Sciences*, 1436(1), 19–35. <https://doi.org/10.1111/nyas.13912>
- Miralles, D. G., Holmes, T., De Jeu, R., Gash, J., Meesters, A., & Dolman, A. (2011). Global land-surface evaporation estimated from satellite-based observations. *Hydrology and Earth System Sciences*, 15(2), 453–469. <https://doi.org/10.5194/hess-15-453-2011>
- Miralles, D. G., Nieto, R., McDowell, N. G., Dorigo, W. A., Verhoest, N. E., Liu, Y. Y., et al. (2016). Contribution of water-limited ecoregions to their own supply of rainfall. *Environmental Research Letters*, 11(12), 124007. <https://doi.org/10.1088/1748-9326/11/12/124007>
- Porter, J. R., Howden, M., & Smith, P. (2017). Considering agriculture in IPCC assessments. *Nature Climate Change*, 7(10), 680–683. <https://doi.org/10.1038/nclimate3404>
- Portmann, F. T., Siebert, S., & Döll, P. (2010). Mirca2000—Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling. *Global Biogeochemical Cycles*, 24(1), GB1011. <https://doi.org/10.1029/2008gb003435>
- Proctor, J., Rigden, A., Chan, D., & Huybers, P. (2022). More accurate specification of water supply shows its importance for global crop production. *Nature Food*, 3(9), 753–763. <https://doi.org/10.1038/s43016-022-00592-x>
- Ray, D. K., Gerber, J. S., MacDonald, G. K., & West, P. C. (2015). Climate variation explains a third of global crop yield variability. *Nature Communications*, 6(1), 1–9. <https://doi.org/10.1038/ncomms6989>
- Ray, D. K., Mueller, N. D., West, P. C., & Foley, J. A. (2013). Yield trends are insufficient to double global crop production by 2050. *PLoS One*, 8(6), e66428. <https://doi.org/10.1371/journal.pone.0066428>
- Rigden, A., Mueller, N., Holbrook, N., Pillai, N., & Huybers, P. (2020). Combined influence of soil moisture and atmospheric evaporative demand is important for accurately predicting US maize yields. *Nature Food*, 1(2), 127–133. <https://doi.org/10.1038/s43016-020-0028-7>
- Sacks, W. J., Deryng, D., Foley, J. A., & Ramankutty, N. (2010). Crop planting dates: An analysis of global patterns. *Global Ecology and Biogeography*, 19(5), 607–620. <https://doi.org/10.1111/j.1466-8238.2010.00551.x>
- Schumacher, D. L., Keune, J., Dirmeyer, P., & Miralles, D. G. (2022). Drought self-propagation in drylands due to land–atmosphere feedbacks. *Nature Geoscience*, 15(4), 1–7. <https://doi.org/10.1038/s41561-022-00912-7>
- Schumacher, D. L., Keune, J., & Miralles, D. G. (2020). Atmospheric heat and moisture transport to energy- and water-limited ecosystems. *Annals of the New York Academy of Sciences*, 1472(1), 123–138. <https://doi.org/10.1111/nyas.14357>
- Schumacher, D. L., Keune, J., Van Heerwaarden, C. C., Vilà-Guerau de Arellano, J., Teuling, A. J., & Miralles, D. G. (2019). Amplification of mega-heatwaves through heat torrents fuelled by upwind drought. *Nature Geoscience*, 12(9), 712–717. <https://doi.org/10.1038/s41561-019-0431-6>
- Stohl, A., Forster, C., Frank, A., Seibert, P., & Wotawa, G. (2005). The Lagrangian particle dispersion model flexpart version 6.2. *Atmospheric Chemistry and Physics*, 5(9), 2461–2474. <https://doi.org/10.5194/acp-5-2461-2005>
- Thiery, W., Visser, A. J., Fischer, E. M., Hauser, M., Hirsch, A. L., Lawrence, D. M., et al. (2020). Warming of hot extremes alleviated by expanding irrigation. *Nature Communications*, 11(1), 290. <https://doi.org/10.1038/s41467-019-14075-4>
- Trnka, M., Feng, S., Semenov, M. A., Olesen, J. E., Kersebaum, K. C., Rötter, R. P., et al. (2019). Mitigation efforts will not fully alleviate the increase in water scarcity occurrence probability in wheat-producing areas. *Science Advances*, 5(9), eaau2406. <https://doi.org/10.1126/sciadv.aau2406>

- Ummenhofer, C. C., England, M. H., McIntosh, P. C., Meyers, G. A., Pook, M. J., Risbey, J. S., et al. (2009). What causes southeast Australia's worst droughts? *Geophysical Research Letters*, 36(4), L04706. <https://doi.org/10.1029/2008gl036801>
- Van Dijk, A. I., Beck, H. E., Crosbie, R. S., de Jeu, R. A., Liu, Y. Y., Podger, G. M., et al. (2013). The millennium drought in southeast Australia (2001–2009): Natural and human causes and implications for water resources, ecosystems, economy, and society. *Water Resources Research*, 49(2), 1040–1057. <https://doi.org/10.1002/wrcr.20123>
- Vogel, E., Donat, M. G., Alexander, L. V., Meinshausen, M., Ray, D. K., Karoly, D., et al. (2019). The effects of climate extremes on global agricultural yields. *Environmental Research Letters*, 14(5), 054010. <https://doi.org/10.1088/1748-9326/ab154b>
- Yu, L., & Weller, R. (2007). Objectively analyzed air-sea heat fluxes 1535 (OAFLUX) for the global oceans. *Bulletin of the American Meteorological Society*, 88(4), 527–539. <https://doi.org/10.1175/bams-88-4-527>
- Zhou, S., Williams, A. P., Berg, A. M., Cook, B. I., Zhang, Y., Hagemann, S., et al. (2019). Land–atmosphere feedbacks exacerbate concurrent soil drought and atmospheric aridity. *Proceedings of the National Academy of Sciences*, 116(38), 18848–18853. <https://doi.org/10.1073/pnas.1904955116>
- Zhou, S., & Yuan, X. (2022). Upwind droughts enhance half of the heatwaves over north China. *Geophysical Research Letters*, 49(2), e2021GL096639. <https://doi.org/10.1029/2021gl096639>