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Impact of historical climate variability on rice production in Mainland Southeast Asia across multiple scales

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ABSTRACT

Climate change is expected to put significant pressure on global food production. Although previous work has explored impacts of climate, management, and genetics on food production, additional research is needed to examine the effects of large-scale climate modes at local and regional scales. This study explores the impact of climate variability on rice yield in Mainland Southeast Asia from 1961 to 2017 at three different spatial scales: the whole Mainland Southeast Asia region, country-level (Cambodia, Laos, Myanmar, Thailand, and Vietnam), and province-level for Vietnam. Annual rice yields over this period have nearly tripled with Vietnam experiencing the largest increases. Correlations between annual rice yield anomalies at the regional and country levels and climate data reveal clear influences of tropical climate variability associated with the El Niño-Southern Oscillation and the Pacific Meridional Mode. At the provincial level in Vietnam, many provinces show similar correlation patterns for the spring-summer season of rice (e.g., a co-occurring La Niña and positive phase of the Pacific Meridional Mode in the preceding boreal winter and spring are associated with increased yields in spring-summer rice). However, the late summer-fall season rice yield anomalies show much weaker correlations with tropical climate patterns. Variations across provinces were also noted, particularly between the Red River and Mekong River Deltas. The history of this 56-year period, which included the Vietnam-American War and changes in land management policies, makes it challenging to disentangle the effects of climate variability and social factors on rice yields in these areas. However, these results highlight the importance of using a multidisciplinary and multiscale approach to help inform local and regional decision-making.

1. Introduction

The world is dependent upon staple cereal crops to meet its caloric demand. Indeed, just three plant species (rice, wheat, and maize) account for over 40% of total calories consumed worldwide (Ray et al., 2013; FAO, 2018), and in much of the poorest populations, cultivated Asian rice (*Oryza sativa* L.) dominates human diets (Dawe et al., 2010; Seck et al., 2012). While it has been over fifty years since the Green Revolution, the world today continues to face many of the same struggles surrounding food security, with ~815 million people (i.e., more than one-tenth of the global population) deprived of enough to eat (World Food Programme, 2017). These challenges are further exacerbated by increasing impacts from climate variability and change. Greater understanding of the human and natural influences that have historically affected crop yields is needed as part of the strategy for successful future adaptation of the global food system.

Yield variation in rice is a function of several factors and their interactions. These factors are (1) genetics (i.e., varieties and cultivars); (2) management choices (e.g., the production system, chemical technology, and machinery), which are influenced by social factors; and (3) environment (e.g., soil, temperature, and precipitation variability, and pest and disease outbreaks). While growers have degrees of control over

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genetics and management, they are less able to influence environmental factors. As such, much effort has been placed into enhanced understanding of the effects of abiotic factors on rice physiology, growth and development, and yield at the individual plant or plot scale (e.g., Wang et al., 2016; Shi et al., 2016; Zeng et al., 2017; Chen et al., 2017, Gao et al., 2007; Zhang et al., 2000; Lafitte et al., 2004). Previous work has also been able to leverage historical data to characterize the negative effects of drought and heat on national-level production of cereal staples, including rice (e.g., Naylor et al., 2007; Roberts et al., 2009; Iizumi et al., 2014; Lesk et al., 2016; Stuecker et al., 2018). However, research using this type of production and yield data is relatively underrepresented as compared to controlled experiments. Moreover, few studies to our knowledge have specifically examined the potential associations between yields and large-scale modes of climate variability, whose impacts are expected to change over the century, in addition to secular warming and precipitation trends. Parsing the sensitivity of rice yields during the historical record to these naturally occurring modes of climate variability might provide some insights into their sensitivity to anthropogenic climate change.

Examples of large-scale modes of climate variability include the El Niño-Southern Oscillation (ENSO) and the Pacific Meridional Mode (PMM). ENSO is a natural climate variation (consisting of co-varying ocean temperature, precipitation, and wind changes in the tropics) that originates in the equatorial Pacific and affects weather patterns across the globe due to atmospheric teleconnections (McPhaden et al., 2020). Its warm phase, El Niño, is characterized by anomalous warming of the eastern tropical Pacific sea surface temperatures (SSTs) and weaker than usual trade winds. As tropical precipitation occurs preferentially over the ocean areas with the warmest SSTs, an El Niño causes pronounced shifts of the pan-tropical precipitation patterns and the associated large-scale atmospheric circulation. Under normal (i.e., ENSO-neutral) conditions, one of the warmest surface ocean areas – the Indo-Pacific warm pool – is characterized by heavy precipitation throughout the year. However, during an El Niño year (most pronounced in boreal winter), this climatological tropical precipitation pattern shifts eastwards towards the central and eastern tropical Pacific, where the largest positive SST anomalies are present. This results in anomalously dry conditions over the maritime continent and surrounding areas. In contrast, during ENSO's cold phase, La Niña, the eastern tropical Pacific SSTs are anonymously cold and trade winds are anonymously strong, resulting in increased precipitation over the maritime continent and Southeast Asia. The PMM (Chiang and Vimont, 2004) has a close association with ENSO (Stuecker, 2018), but has SST anomalies focused on the subtropical North Pacific. In general, the impacts of the PMM on regional climate have been studied less than the impacts of ENSO, with some exceptions (e.g. Promchote et al., 2018). In summary, these tropical and subtropical SST patterns associated with large-scale climate modes can shift precipitation, wind, and air temperature patterns across the Indo-Pacific region and thereby have the potential to affect rice yields in Mainland Southeast Asia.

Rice is one of the most important foods in the world, providing 20 % of the calories consumed in the world with several billion people depending on rice for their main source of food and livelihood (Redfern et al., 2012). In 2020, Southeast Asia alone represented 27% of the rice harvested globally (44 million ha), and the countries composing Mainland Southeast Asia (MSEA) - Thailand, Vietnam, Myanmar, Cambodia, and Lao PDR - were responsible for 60% of the rice grown in Southeast Asia (FAOSTAT, 2022). Indeed, Thailand and Vietnam were ranked second and third among the world's top rice-exporting countries (with Myanmar and Cambodia in the top 10). High levels of labor productivity have historically been a major source of comparative advantage in Myanmar, Thailand, and Vietnam. The countries of MSEA share similar biophysical characteristics such as ecosystems, climate, seasons, soil types, hydrology, topography, etc., but there are substantial differences in the technologies used to produce rice, the market capacity, the historic and current events that shape the production and labor landscape, and the policies that influence the production and distribution of rice. Vietnam, for example, has advanced irrigation infrastructure, widespread mechanization, and high yields, while Cambodia and Lao PDR are still largely dependent on manual labor, rainfed systems, and have much lower average yields. Due to the complex nature of human factors that influence changes in rice production and distribution, such as land tenure, access to capital, political instability, postwar government market interventions, and the organization of rice trade (Van der Eng, 2004), we chose to focus on MSEA regional production trends and climatic factors to study correlations that may help explain some of the environmental causes for variability in production. Understanding the historical impact of these factors on rice yields is key to developing adaptation plans that increase local resilience in the face of climate change.

Here we evaluate the impact of past climate variability on rice production at three different spatial scales – regional, country, and provincial – from 1961 to 2017. Specifically, we address the following questions: (1) How do rice yield anomalies change over time in this region across different spatial scales? (2) What patterns of sea surface temperature, surface wind, and precipitation are associated with rice yield anomalies in MSEA? (3) How are different scales of rice production (MSEA, country-level, and province-level) impacted by large-scale modes of climate variability over a long time series? As we expect the impacts of tropical climate variability on precipitation to increase in a warmer world (Cai et al., 2014, 2015; Yun et al., 2021), the work here could be used to inform estimates of future impacts of large-scale modes of climate variability in addition to the impacts of secular warming trends.

2. Materials and methods

2.1. Rice data

Annual country-level rice yield data (tonnes/ha) for Myanmar, Thailand, Lao PDR, Cambodia, and Vietnam were obtained from FAOSTAT for the years 1961–2017 (study area shown in Fig. 1). Seasonal province-level yield data for Vietnam were obtained for the same time period (1961–2017) from the Vietnam General Statistics Office (https://www.gso.gov.vn/en/homepage/) and the Department of Crop Production. The exact months corresponding to each season in Vietnam vary by province (see cropping calendar for Vietnam: Fig. 1c, Table 1). In Vietnam, the cropping calendar is strongly influenced by climate patterns in the different agro-ecological regions. Being characterized by a long period of low temperature and shortage of irrigation water from November to February, the northern and central regions often have two successive rice seasons: the first season is called either "Spring," beginning in February, or "Winter-Spring," beginning in January; the second season is called either "Summer," starting in July or "Summer-Autumn," starting in May. Characterized by a warmer climate and ample availability of surface water for irrigation, the southern region can cultivate up to three rice seasons per year: the first season is also called "Winter-Spring" and typically starts in November/December, the second season is "Summer-Autumn" starting in May, and the third is called "Autumn-Winter" and starts in August. Descriptions of rice seasons by region are summarized in Table 1. To identify yield anomalies, raw yield data were detrended by removing a seven-year running mean (to account for genetics), and resulting values were converted to z-scores (per Stuecker et al., 2018). Yield data were considered at three spatial scales: (1) Regional (average across MSEA); (2) country-level (Myanmar, Thailand, Lao PDR, Cambodia, and Vietnam); and (3) province-level (63 provinces across 6 regions in Vietnam) (Fig. 1).

2.2. Climate data

Monthly precipitation (mm/day; both land and ocean) were obtained from the National Oceanic and Atmospheric Administration

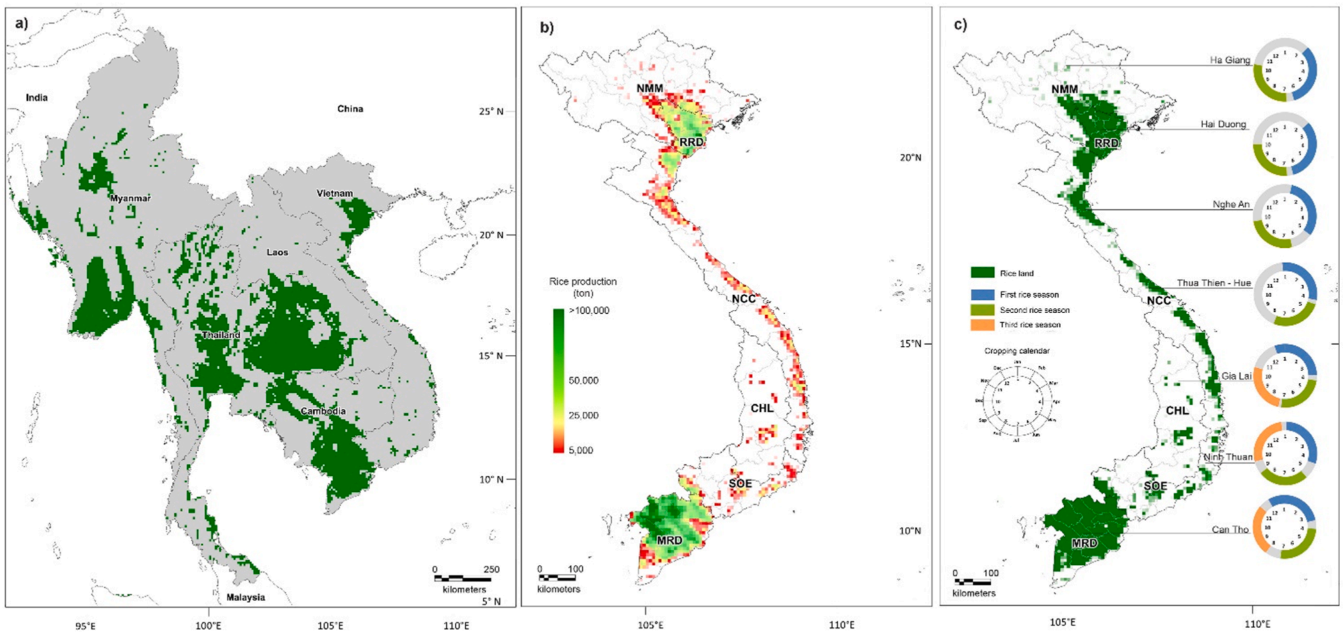

Fig. 1. Rice land (green area) of mainland Southeast Asia including Lao PDR, Cambodia, Thailand, Myanmar, and Vietnam (a), and annual rice production of rice areas in Vietnam (b). Panel (c) shows the rice cropping calendar in agro-ecological regions of Vietnam representing growing months and colors of the different seasons. Vietnam regional abbreviations: Northern Midlands and Mountain Areas (NMM), Red River Delta (RRD), Northern and Central Coastal Areas (NCC), Central Highlands (CHL), Southeast (SOE), and Mekong River Delta (MRD). Rice land map of MSEA was extracted from the Global Spatially Disaggregated Crop Production Statistics Data (IFPRI, 2019).

Table 1
Cultivation period of three rice seasons in Vietnam (northern, central, and southern regions).

Rice season in Vietnam		Northern	Central	Southern
1st season	Local name	Spring	Winter–Spring	Winter–Spring
	Cultivation period	February–June	January–April	November/December– March/April
2nd season	Local name	Summer	Summer–Autumn	Summer–Autumn
	Cultivation period	July–October	May–August	May–August
3rd season	Local name	–	–	Autumn–Winter
	Cultivation period	–	–	August–November

(NOAA) Global Precipitation Project (GPCP) version 2.3 monthly Combined Precipitation Dataset (1979–2019), which combines observations and satellite precipitation data into 2.5° x 2.5° global grids (Adler et al., 2003). Monthly sea surface temperature (SST; °C; 1°x1° grids) data were obtained from the Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST) for 1870–2019 (Rayner et al., 2003). Monthly wind data (0.25° x 0.25° grids) for 1979–2019 came from the ERA5 Reanalysis Data, which provides U- and V- components of 10 m wind (Hersbach et al., 2018). These datasets are subject to several sources of uncertainty due to the satellite data, observational in situ data, reanalyses, and algorithms used to blend the different sources of data (Hegerl et al., 2015; Sun et al., 2018). However, these are all widely used global gridded datasets that have been shown to perform well in Southeast Asia and the Pacific region (Ma et al., 2009; Adler et al., 2012; Li et al., 2022). Seasonal climate anomalies relative to 1981–2010 seasonal means were calculated for 3-month seasons: December-January-February (DJF); March-April-May (MAM); June-July-August (JJA); and September-October-November (SON). Spatial Pearson correlations were calculated between rice anomalies and climate anomalies at each grid point in the domain (5°S to 30°N and 60°E to 150°E).

3. Results

3.1. *Rice yield anomalies across space and time*

Annual rice yields in MSEA since 1961 have nearly tripled, with Vietnam experiencing the largest increases (Fig. 2). The rice yield anomalies reveal pronounced interannual variations. For instance, most countries experienced a pronounced decline (~2 standard deviations) in yields around 1977–1979 and a smaller decline between 1966 and 1969 (Fig. 2b). Looking at smaller spatial scales, seasonal rice yield results for Vietnam provinces indicate similar increases over time, with most regions showing the highest yields in the first rice season; e.g., the Red River Delta (RRD) region has the largest yields in the first and second season (Fig. 2). RRD and the Mekong River Delta (MRD) are the two rice regions with the largest average annual yields; the 1995–2017 average annual yield is 4.57 tonnes/ha for MRD and 5.5 tonnes/ha for RRD. In contrast, the South East (SOE) region has the smallest average annual yields (1995–2017 average is 3.7 tonnes/ha). Among the regional anomalies, two regions (RRD and NMM) experienced pronounced declines in yield during 1991 in the first season. The correlations between annual country-level rice yield anomalies (Fig. 3a) show that while MSEA yield is correlated with all countries, there is considerable variation in yield anomalies across the different countries. Within Vietnam, seasonal yield anomalies among regions are generally not well correlated with each other (Fig. 3b). There are a few notable exceptions. The RRD and Northern Midlands and Mountain Areas (NMM) regions are

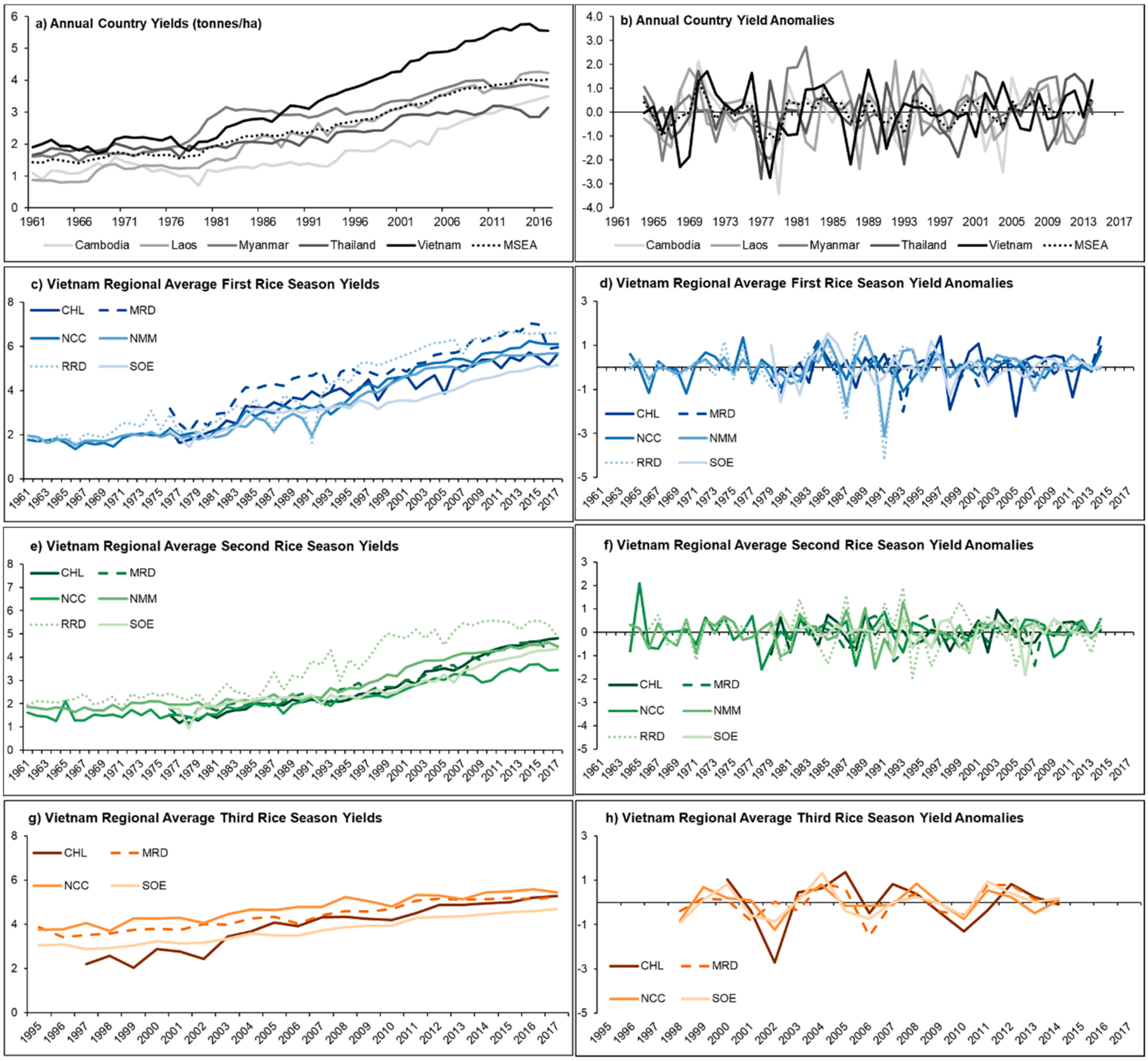

Fig. 2. Rice yields (tonnes/ha) (a, c, e, g) and yield anomalies (b, d, f, h) from 1961 to 2017 (except for g and h which are from 1995 to 2017). Annual rice yield (a) and yield anomalies (b) for each country in mainland southeast Asia; Vietnam regional average seasonal yields and yield anomalies for first rice season (c, d), second rice season (e, f), and third rice season (g, h). The third season results are only available from 1995 to 2017. Vietnam regions are abbreviated as in Fig. 1.

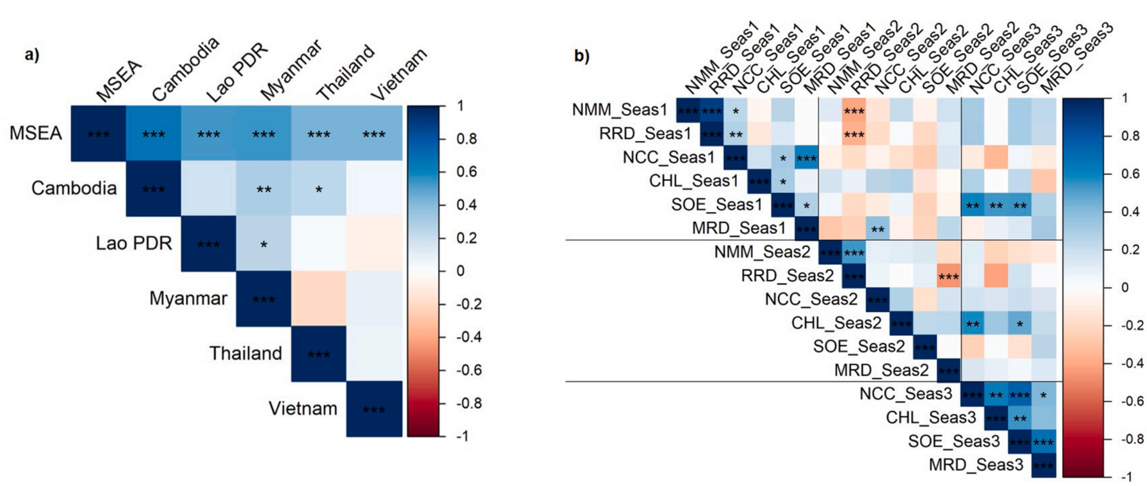

Fig. 3. Correlation plots between rice yield anomalies: annual yield anomalies by country (a), and seasonal yield anomalies by region in Vietnam for the three seasons (b). Significance levels indicated with symbols (*** for p < 0.01, ** for p < 0.05, and * for p < 0.1). Vietnam regions abbreviated as in Fig. 2.

positively correlated during the first and second seasons. The RRD second season rice yields are negatively correlated with first season rice in RRD and NMM, and negatively correlated with second season MRD rice. During the third rice season, most regions are strongly positively correlated with each other, and the Southeast (SOE) region is positively correlated with its first season rice yields.

3.2. Regional rice yield anomaly associations with seasonal climate

Correlation maps between annual rice yield anomalies and climate anomalies reveal clear influences of tropical climate variability associated with ENSO and the PMM at the MSEA and country levels (Figs. 4, 5). We see negative correlations in the eastern equatorial Pacific in both DJF (Fig. 4a; the peak ENSO season) and MAM (Fig. 4c; the peak PMM season), that is, positive yield anomalies in MSEA are associated with a major reorganization of the tropical precipitation pattern due to these large-scale climate modes. As discussed in the introduction, interannual variations in large-scale tropical precipitation are driven to a large degree by tropical (and to a lesser degree also subtropical) SST patterns like ENSO and the PMM. In boreal winter, colder than normal eastern equatorial Pacific SSTs and anomalously strong easterly trade winds, which are signature characteristics of a La Niña event (Fig. 4b), result in enhanced precipitation in the Indo-Pacific warm pool region and reduced precipitation in the eastern tropical Pacific (Fig. 4a). In a slanted meridional direction (most pronounced in MAM), we see climate anomalies associated with a positive PMM phase, characterized by positive precipitation and SST anomalies ranging from the equator in the warm pool towards the northeast (the subtropical eastern part of the Pacific basin). Together, the co-occurring negative phase of ENSO (La Niña) and positive PMM lead to increased rice yields in MSEA, likely by increased low-level moisture supply to the MSEA land areas and associated increased precipitation (Fig. 4). Conversely, the positive phase of ENSO (El Niño) and negative PMM are associated with decreased rice yields in MSEA.

In Fig. 5 we see distinctly different patterns of temporal association between climate anomalies and annual rice yields across the different countries of MSEA. There is a clear impact of seasonal variation, although it impacts the individual countries differently, as well as impacting the MSEA in a different way. We see clear differences across spatial scales, which has broad implications for policy across the region. Depending on the season, micro and macro climatic patterns have differential impacts on rice anomalies (Fig. 5). Pacific Ocean SST anomalies for most of the countries – except Myanmar – show somewhat similar ENSO/PMM correlation patterns (Fig. 5) to the aggregated MSEA region.

3.3. Province-level correlations between seasonal rice and climate in Vietnam

Since the rice cultivation seasons correspond to different months in different regions, for a consistent comparison with climate data, the first season in the northern regions was compared with the second season in the southern regions as these relate to approximately the same time of year (crop duration approximately Feb.-Jun. in RRD, Apr.-Jul. in MRD). This pattern can also be seen in the province-level correlations in Fig. 3. At the province level in Vietnam, many provinces show similar correlation patterns, where the co-occurring negative phase of ENSO (La Niña) and positive PMM lead to increased yields in the spring and summer months (Fig. 6), however, rice yield anomalies in the late summer and autumn (approx. Jul.-Oct. in RRD, Aug.-Nov. in MRD; Fig. 7) show most pronounced correlations with tropical SSTs in the

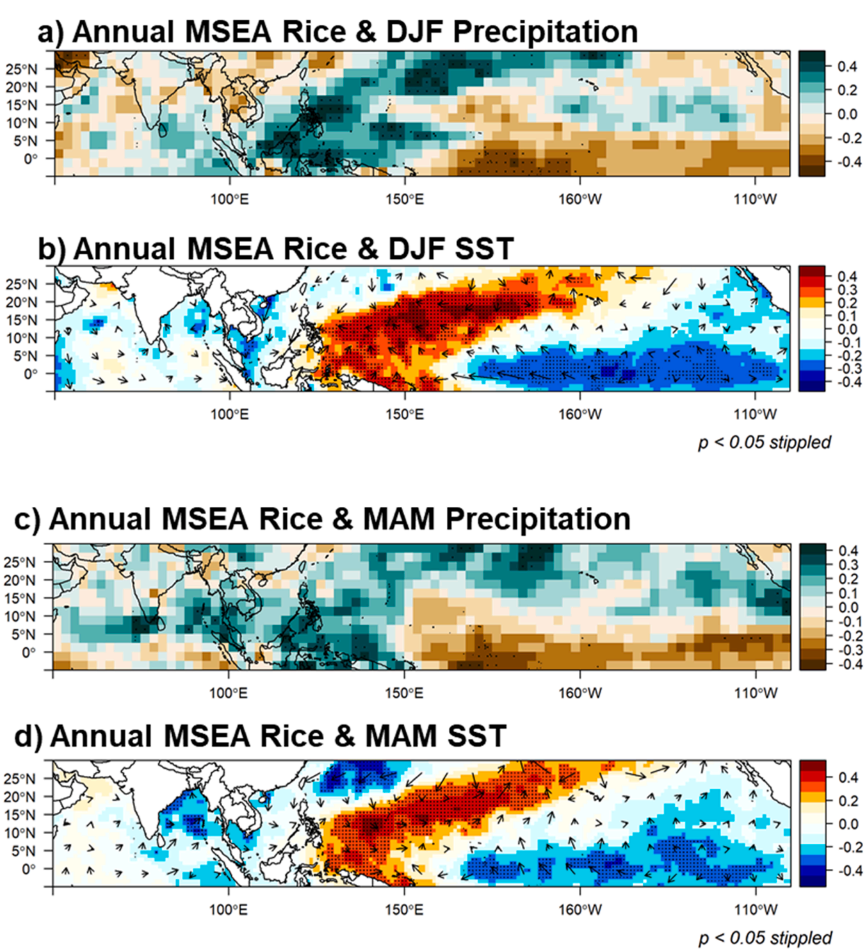

Fig. 4. Maps of correlations between average annual rice yield anomalies for Mainland Southeast Asia (MSEA) and seasonal climate anomalies (precipitation, SST, and low-level wind). Annual MSEA rice and DJF precipitation (a), annual MSEA rice and DJF SST (b), annual MSEA rice and MAM precipitation (c), and annual MSEA rice and MAM SST (d). Areas with statistically significant Pearson correlations ($p < 0.05$) are stippled, and arrows depict regressed anomalous surface wind vectors ms^{-1} for each season.

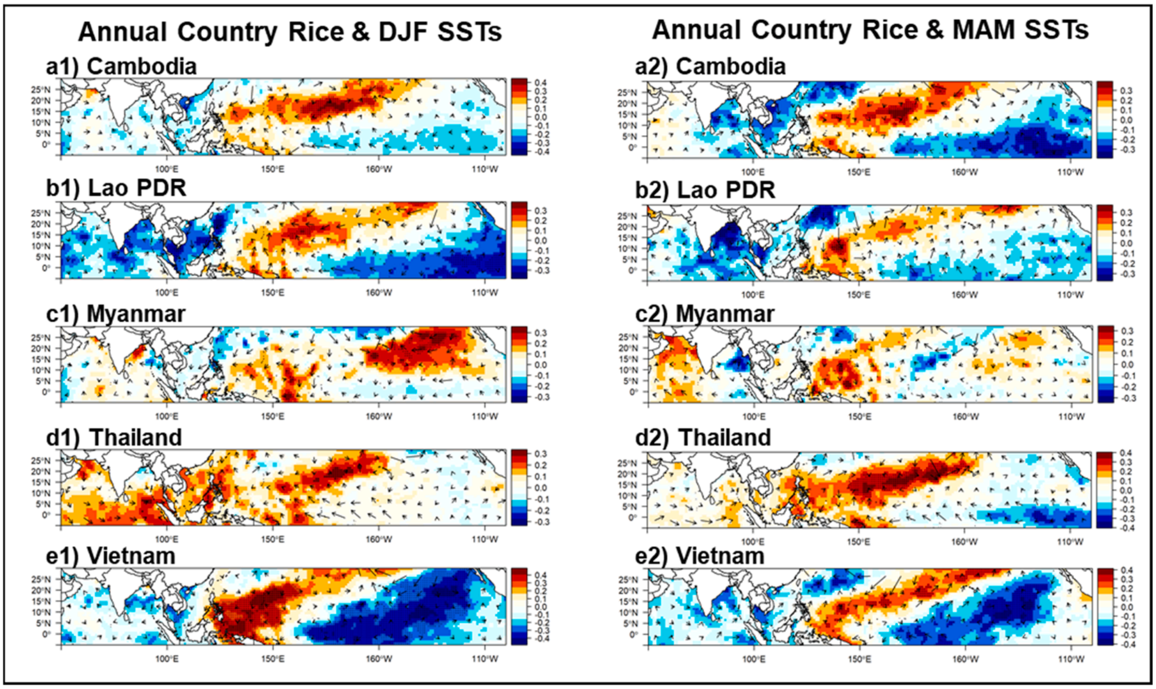

Fig. 5. Maps of correlations between annual rice yield anomalies for individual countries and seasonal climate anomalies (SST and surface wind). Cambodia rice with SSTs (a), Lao PDR rice with SSTs (b), Myanmar rice with SSTs (c), Thailand rice with SSTs (d), and Vietnam rice with SSTs (e) with DJF SST correlations on the left and MAM SST correlations on the right. Areas with statistically significant Pearson correlations ($p < 0.05$) are stippled, and arrows depict regressed anomalous surface wind vectors ms^{-1} for each season.

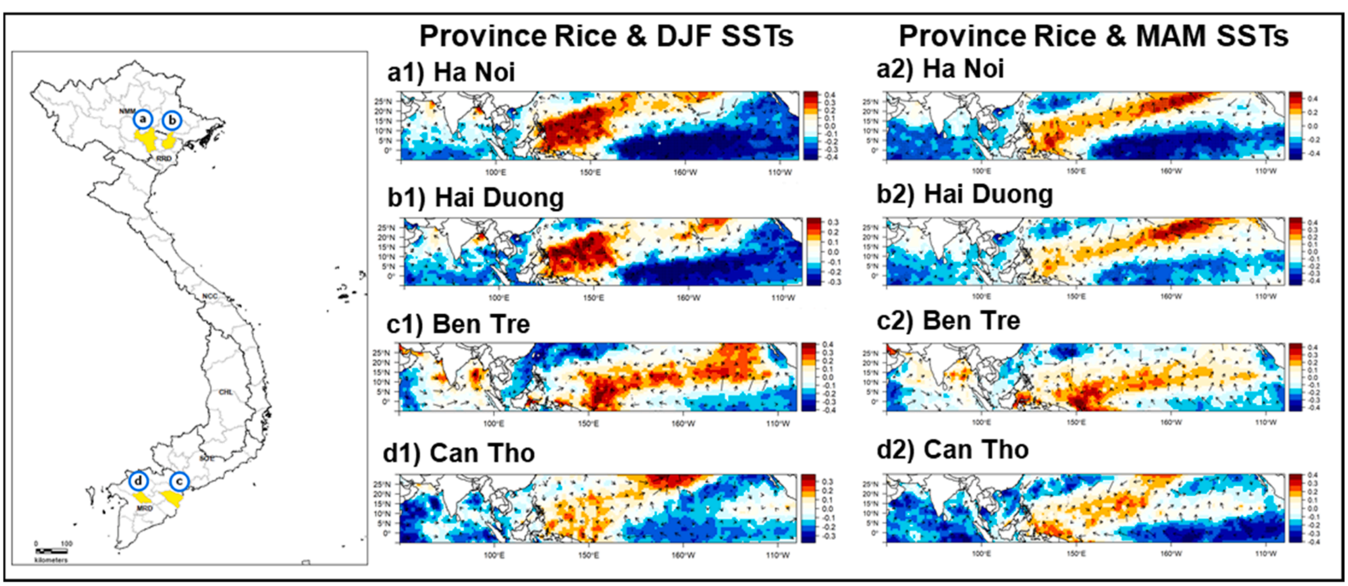

Fig. 6. Maps of correlations between spring-summer rice yield anomalies in selected high rice production provinces and SST anomalies. Correlations with DJF SSTs shown on the left and MAM SSTs on the right). First season rice yield anomalies are shown in the Red River Delta (RRD) provinces (Ha Noi (a) and Hai Duong (b)) and second season rice yield anomalies are shown for the Mekong River Delta (MRD) provinces (Ben Tre (c) and Can Tho (d)), with province locations indicated on the map to the left. Crop duration approximately Feb.-Jun. in RRD, Apr.-Jul. in MRD. Areas with statistically significant Pearson correlations ($p < 0.05$) are stippled, and arrows depict regressed anomalous surface wind vectors ms^{-1} for each season.

Indian Ocean instead of the Pacific. We also emphasize that pronounced variations are evident across provinces, particularly between the Red River and Mekong River Deltas (Figs. 6, 7).

For instance, the northern Red River Delta (RRD) provinces (Ha Noi and Hai Duong) show positive correlations with SST anomalies in the Indian Ocean in late summer-autumn (Fig. 7a, b). Positive SST anomalies in the Indian Ocean, most pronounced in boreal summer, occur often after an El Niño event via the so-called Indian Ocean Capacitor Effect (Xie et al., 2009). These positive SST anomalies can cause enhanced precipitation in parts of MSEA, thereby resulting in positive yield anomalies. Correlations between late summer-autumn rice in RRD provinces and MAM climate do indicate this relationship with El Niño (not shown). Curiously, no statistically significant large-scale SST anomalies are associated with late summer-autumn rice yields in the

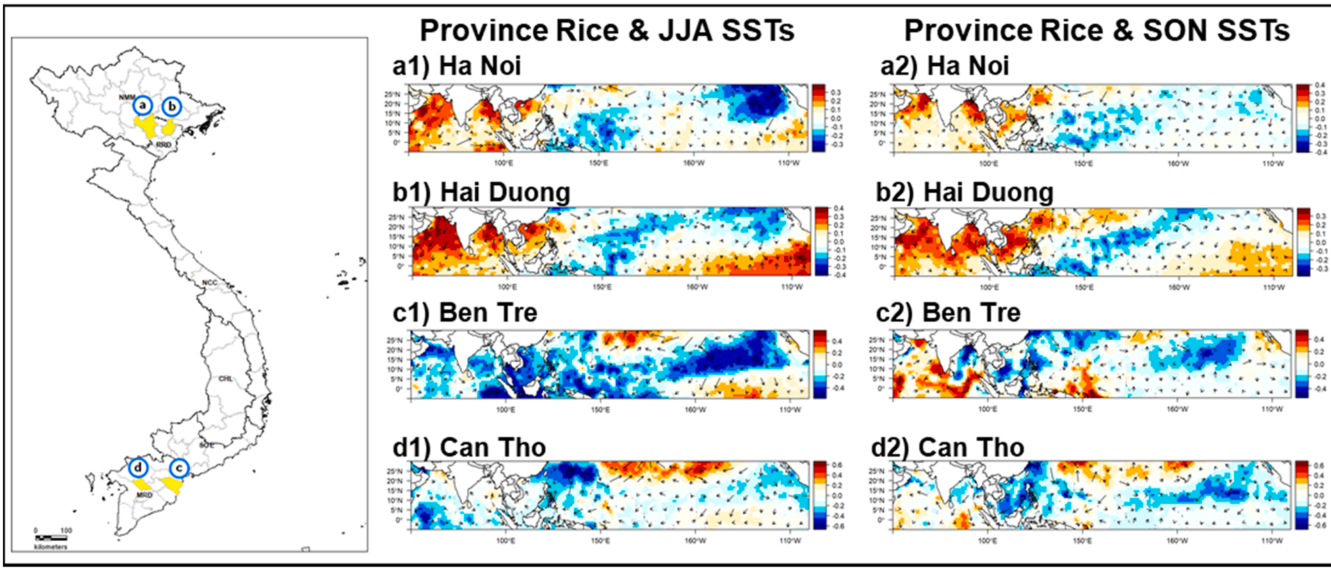

Fig. 7. Same as Fig. 6 but for late summer-autumn rice yield anomalies with JJA (left) and SON (right) SST anomalies. Second season rice yield anomalies are shown for provinces in RRD, and the third season is shown for MRD (crop duration approximately Jul.-Oct. in RRD, Aug.-Nov. in MRD).

Mekong River Delta (Ban Tre and Can Tho as example provinces; Fig. 7c, d). This is perhaps due to the relatively short time period for which data were available for third season rice (1995–2017) used for the southern Mekong River Delta provinces (Fig. 7c, d) as compared with the second season rice (1961–2017) used for Red River Delta provinces (Fig. 7a, b).

4. Discussion

Southeast Asia is expected to be severely negatively affected by climate change (Hijioka et al., 2014). Since most of the economy relies on agriculture and natural resources, climate variability and change have been and will continue to be critical factors affecting productivity in the region. Rainfed rice areas are increasingly experiencing negative effects of submergence. Heavy seasonal monsoon precipitation, which is more frequent and intense during La Niña conditions, often leads to increased lodging, waterlogging, and prolonged stagnant floods in low-lying mega-deltas in MSEA, for example, the Irrawaddy Delta of Myanmar and Mekong Delta of Vietnam (Redfern et al., 2012). These rice-growing areas are typically cultivated by resource-poor farmers (Mutert and Fairhurst, 2002; Redfern et al., 2012). Intuition about the most appropriate policy and technological responses to these future problems could potentially be gleaned from the combined historical record across MSEA and its constituent countries.

At the country level, Vietnam has had the largest increases in yields. Spatial patterns of the correlation results between annual rice yield anomalies and climate data at the MSEA scale and country levels showed clear influences of ENSO and PMM. At the smallest scale of inquiry, many provinces show similar relationships for the spring-summer rice (e.g., the co-occurring negative phase of ENSO (La Niña) and positive PMM lead to increased yields; Fig. 6). However, the provincial correlation patterns are much weaker with rice that is harvested between late summer-autumn (Fig. 7). Variations across provinces within Vietnam were also noted, particularly between the Red River and Mekong River Deltas. This is not a surprising result given the difference in climatological conditions from the north to the south that requires delayed planting in the north, and, therefore, the harvest months differ. This is related to the management, specifically the cropping calendar and shows how the association between rice yield anomalies and climate anomalies with different seasons becomes prominent in production (Fig. 1; Fig. 6; Fig. 7). Temporal and spatial differences in management practices (e.g., planting in different seasons) could help mitigate climate impacts on rice yields, however, a complication is that phenology can change in response to future changes in mean temperature, annual precipitation cycles, and variability in both.

From 1961–2017, MSEA experienced steady gains in rice yields, attributed mainly to genetics and management. This was consistent across all countries, with yield anomalies being attributable to a range of events that may include political conflict, plant disease epidemics, new varieties and changes in production methods. Often the same events impacted the different countries of MSEA in different years; this may be why greater yield stability (fewer anomalies) is observed for MSEA than at the country or provincial scale. Although climate variability seems to be a factor related to yield anomalies, socio-political factors cannot be ignored. Each of the countries in MSEA have had a tumultuous period at some point between 1961 and 2017, with some countries suffering much greater instability than others at times. Factors such as war, land tenure, and market access all greatly influence crop production. With the exception of Myanmar, whose land reform only started very recently, the countries of MSEA made the same economic shift at similar times beginning in the late 1980 s. This change included putting in place a neoliberal type of market economy, promoting a model of modernization that advocates turning land into capital, and developing industrial and export crops through massive, mainly foreign, investments (Castellanet and Diepart, 2015). Despite socio-political differences across countries in MSEA, we see regional trends in production statistics in 1966–1969 and 1977–1979 (Figs. 2a and 2b), especially between the countries that formerly made up Indochina: Vietnam, Cambodia, and Laos. While we cannot answer if the causes of these trends are linked without further detailed investigation into these periods, it is worth noting that all of these young States went through a phase of denying private ownership and revoking all forms of individual tenure in the 1970 s (and earlier in Vietnam) with some subsequently going through a phase of land collectivization (Mellac and Castellanet, 2015). Apart from Myanmar, all other MSEA countries have followed a similar path starting in the 1980 s with official recognition of individual tenure, which led to a process of de-collectivization and sometimes the redistribution of land to households (Mellac and Castellanet, 2015).

Disentangling the socio-political effects is difficult, but if we investigate the example of Vietnam, we can see rice yields beginning to increase by 1982 after a period of 20 years of stagnant production. A series of natural and socio-economic disasters afflicted the country for several years in the late 1970 s (Chapman, 1979). These included a severe drought in 1977, heavy floods in 1978 followed by an infestation by insects that destroyed crops, and farmer resistance to collectivization. The period of the Vietnam-American War saw deliberate targeting of the destruction of agricultural infrastructure (e.g., paddies) followed by a mass exodus of the rural population. In 1981 Vietnam introduced “Doi moi”, the agricultural de-collectivization policies, that had a significant effect on rice production (Castella and Quang, 2002). One of the major changes involved land use rights, which had been taken from large-scale agricultural cooperatives and given to households. The strong focus on irrigation investment to rebuild and modernize rice production and the switch to the contract system of production had a significant positive effect on rice production. The second set of policy reforms initiated in 1988 liberalized the agricultural sector and restored producer incentives (Young et al., 2002). Myanmar experienced a period of rapid growth from 1980 to 1984 (see Figs. 2a and 2b) after the introduction of the Whole Township Rice Production Program, which focused on a new technology package including planting modern varieties, increasing fertilizer, higher density transplanting, and better weed control and involved linking farmers to banks for access to credit (Jayasuriya, 1984). Following this period of rapid growth, the major problems restricting rice production included conflicting government policies that distorted price signals, grossly misallocated resources, political unrest, and inadequate infrastructural development (Young et al., 1998).

Timely planting relies on farmers being able to predict seasonal weather patterns with some level of certainty. Tropical sea surface temperatures can cause variations of climate over land areas – and thereby on rice yields and production – via their control of large-scale atmospheric circulation and precipitation. The spatial patterns in sea surface temperature in the tropics (e.g., those associated with ENSO) change the large-scale atmospheric circulation, thereby affecting continental precipitation and low-level winds in the MSEA region. Our analysis shows that the broader regional (MSEA) and country-level scales share similarities in the correlation between climate and yield anomalies, but more differentiation is seen at the provincial scale which leads to complex interpretation. Increased variability associated with global climate change (e.g., Rodgers et al., 2021) will alter planting calendars substantially and may even require changes to new cropping systems. At the MSEA scale, this may not have huge effects on overall yield as country or provincial losses may be balanced by increases in other countries or provinces (Zhao et al., 2017). At the sub-country level during ENSO events, the yield impacts appear most acute in the first season of rice, when the timing for planting is more limited, especially in the colder northern region of Vietnam. This could shift the first season harvest into the second season planting window which would preclude a second planting season (Truong An, 2020). Decreasing productivity from two seasons to one season would greatly affect the national rice production which would, in turn, hamper the country’s exporting capacity. Vietnam rice exports are critical to global food security with over 70% of rice exports in 2019 going to the Philippines, Côte d`Ivoire, China, Malaysia, and Ghana (https://trendeconomy.com/data/h2/Vietnam/1006). Although most of the exported rice comes from the Mekong Delta region in the south, a reduction in rice production in the north would lead to a shift of increased domestic demand from rice grown in the south. However, production in the south is more susceptible to saltwater intrusion and inundation because of climate change (Toan, 2014). ENSO precipitation impacts are projected to increase in the future (Cai et al., 2014), where the increased volatility of climate will increase the variance of rice production. Future work is needed to examine province-level data from other countries in the region where historical statistical data are available, such as Thailand, to provide a more in-depth picture and comparison of the historical impact of climate variability on rice yields.

All the major river deltas in MSEA face two major threats: saltwater intrusion and increased flooding of river deltas. In the current climate the region experiences increased yields with increased precipitation during La Niña/positive PMM. However, in the future the same La Niña/positive PMM pattern could be responsible for a reduction in rice production due to intense flooding. Rice in Southeast Asia is affected by various types of flooding stress (e.g., flash flooding, stagnant flooding), which can greatly decrease yields (Xu et al., 2006; Kuroha et al., 2018). Flooding often causes seawater to mix with freshwater increasing salinity levels which negatively affects paddy rice growth. This potential nonlinearity as well as projected increased temperature variability might mean that temperature could become a more important driver of yield variability than precipitation variability in a warmer future world (Naylor et al., 2007; Stuecker et al., 2018). Rice is a salt-sensitive crop where the timing of the salt stress has different effects on growth and development (Yamaguchi and Blumwald, 2005). There has been extensive work showing decreases in yields (~24–29%) with increased salinity (Phan and Kamoshita, 2020). Tan Yen et al. (2019) compared historical rice yield data to delineate the consequences of saltwater intrusion during El Niño and flooding events during La Niña in the thirteen provinces of the Mekong River Delta. In the coastal provinces, these impacts are typically from severe drought and salinity intrusion. Even amongst the thirteen provinces that make up the Mekong River Delta region, there are large differences in yield reduction with the coastal provinces being severely affected and the in-land provinces less affected during years with anomalous precipitation. The nonlinearity in the impacts of climate, that is, that extreme drought and extreme floods can both result in a reduction of yields, implies that the linear methods used here may result in an underestimation of the true effect of climate variability on rice production.

5. Conclusions

Climate variability impacts crop production, and this is of increasing importance due to anthropogenic climate change. Comparing multiple spatial scales, multiple growing seasons, and multiple climate phenomena allows for a more complete understanding of a complex problem. Hence the importance of a specialized and interdisciplinary team that is familiar with the local conditions so the results can be used to guide what types of policy recommendations should be made, what agricultural research and development should be done, and to develop a better idea of which places are vulnerable to food insecurity and when.

In response to the first research question of how rice yields have changed over time in the region, we found that rice yields have nearly tripled since 1961, with Vietnam experiencing the largest increases. At finer spatial scales, we see that the two rice regions in Vietnam with the largest average annual yields are the Red River Delta and the Mekong River Delta. Generally, rice yields were not well correlated across countries or regions within Vietnam, indicating the strong spatial heterogeneity in this region.

The second research question asked what patterns of sea surface temperature, surface wind, and precipitation are associated with rice yield anomalies in MSEA. Results clearly showed climate patterns associated with large-scale modes of tropical climate variability associated with the El Niño-Southern Oscillation (ENSO) and the Pacific Meridional Mode (PMM). Together, the co-occurring negative phase of ENSO (La Niña) and positive PMM lead to increased rice yields in MSEA. Conversely, the positive phase of ENSO (El Niño) and negative PMM are associated with decreased rice yields in MSEA.

In response to the third research question about how large-scale modes of climate variability impact rice at different spatial scales, we found distinctly different patterns across the different countries of MSEA compared with the MSEA regional average results, though most countries showed a similar ENSO-PMM pattern. At the province level in Vietnam, many provinces showed similar correlation patterns for the spring-summer season of rice, however, the late summer-fall season rice yield anomalies show much weaker correlations with tropical climate patterns. Strong variations were noted between provinces, again highlighting the strong spatial variations in this region.

At the MSEA scale, shifting patterns will require adaptation, and despite the long-term increases in yields, losses in some countries are mitigated by increased yields in others. At the country level, it is clear that new technologies and public policy have greatly impacted yield anomalies in addition to climate, however, as climate variability increases the importance of climate will increase. At the finest scale of provinces in Vietnam, the history of this 56-year period, which included the Vietnam-American War, changes in land management policies in the Red River and Mekong River Deltas, economic reforms, and global market integration make it challenging to disentangle the effects of climate variability and social factors on rice yields in these areas. However, these results highlight the importance of using a multidisciplinary approach and considering several spatial scales to help inform local decision making as combining data across scales and have clear utility to understanding the way climate variability impacts both plant growth and food security.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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