Key Points:
- The influence of projected temperature variability changes on future heat waves varies across the globe
- Future heat waves are primarily controlled by annual mean changes, except in Europe and North America
- Mean seasonal warming is responsible for over 95% of projected heat wave changes in most region

Seasonal mean temperature changes control future heat waves

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Abstract Increased temperature will result in longer, more frequent, and more intense heat waves. Changes in temperature variability have been deemed necessary to account for future heat wave characteristics. However, this has been quantified only in Europe and North America, while the rest of the globe remains unexplored. Using late century global climate projections, we show that annual mean temperature increases is the key factor defining heat wave changes in most regions. We find that commonly studied areas are an exception rather than the standard and the mean climate change signal generally outweighs any influence from variability changes. More importantly, differences in warming across seasons are responsible for most of the heat wave changes and their consideration relegates the contribution of variability to a marginal role. This reveals that accurately capturing mean seasonal changes is crucial to estimate future heat waves and reframes our interpretation of future temperature extremes.

1. Introduction

Heat waves have multiple human, economic, and environmental implications. In 2003, consecutive days of extreme heat in Europe incurred a death toll exceeding 35,000 [*Confalonieri et al.*, 2007] and produced estimated uninsured losses in agriculture of ~13 billion [*Easterling et al.*, 2007]. In Russia, the 2010 heat wave caused 50,000 excess deaths and resulted in ~US$15 billion losses [*Barriopedro et al.*, 2011]. In Australia, extreme heat produces more deaths than all other natural hazards combined [*Coates et al.*, 2014] and in 2013–2014 represented an annual burden of ~US$6.2 billion [*Zander et al.*, 2015]. Environmentally, heat waves often lead to devastating wildfires [*Fischlin et al.*, 2007], such as in Portugal in 2003 and in southeast Australia in 2009 [*Parliament of Victoria*, 2010]. The severity of recent extreme temperature events cannot be explained without the effect of rising greenhouse gas concentrations [*Schär et al.*, 2004; *Imada et al.*, 2014; *Perkins et al.*, 2014].

Climate change will increase the length, frequency, and magnitude of heat waves over most land areas [*Intergovernmental Panel on Climate Change*, 2012]. Changes in temperature extremes, including heat waves, can arise from both a shift of the temperature distribution and changes in variability, such as a widening of the distribution. Although most studies [*Meehl and Tebaldi*, 2004; *Schär et al.*, 2004; *Lau and Nath*, 2012, 2014; *Schoetter et al.*, 2015] agree that both will contribute to heat wave changes, they place strong emphasis on the importance of temperature variability in shaping future temperature extremes and heat waves [*Katz and Brown*, 1992; *Schär et al.*, 2004; *Della-Marta et al.*, 2007; *Kodra and Ganguly*, 2014; *Schoetter et al.*, 2015]. However, our current knowledge is biased to the climate characteristics of North America and Europe, where most studies on heat waves have focused. Furthermore, the influence of changes in temperature variability on projected heat wave characteristics strongly depend on the choice of the climate model [*Fischer et al.*, 2012; *Schoetter et al.*, 2015] highlighting the need for large multimodel ensembles to obtain robust and meaningful estimates.

Here we analyze future projections (2071–2100) of heat wave features across the world using 27 models (Table S1 in the supporting information) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) under a RCP8.5 scenario (RCP8.5) and examine them in the context of present climate (1971–2000) conditions from historical (HIST) experiments. We explicitly consider the contribution of temperature variability changes to future heat waves and quantify its role by comparing to a scenario where only annual mean shift in temperature is considered (MS). Because projections suggest different warming across seasons [*Intergovernmental Panel on Climate Change*, 2013] and heat waves occur mostly in summer, a mean seasonal shift (SS) was also accounted for in a second scenario. As a result, we separate the contributions from seasonal

differences in warming and variability. Heat wave characteristics such as the frequency of heat wave days, the intensity of hottest heat waves in a year, and the mean duration are measured using the Excess Heat Factor [*Nairn and Fawcett*, 2013]. In section 2, we detail the temperature data set and climate scenarios and the metrics to define heat wave and the proportion of changes explained by variability. Section 3 describes the changes in heat waves using an annual mean and a seasonal mean shift to determine the role of temperature variability. Finally, section 4 summarizes our findings on the role of mean and variability changes in future heat waves.

2. Data and Methods

2.1. Temperature Data and Climate Scenarios

Daily maximum and minimum temperatures from 27 Atmosphere-Ocean Global Climate Models (AOGCMS) from the Coupled Model Intercomparison Project Phase 5 [*Taylor et al.*, 2012] were used in this study (Table S1). One realization (r1i1p1) from the historical (1971–2000, HIST) and RCP8.5 (2071–2100, RCP8.5) experiments were selected for each model. Heat wave analysis was performed on the original data and then regridded to a common 1° by 1° grid using a simple nearest neighbor approach. Only land grid cells were considered in the analysis and they are defined as those where at least half of the models indicated 80% or more of land.

In addition to HIST and RCP8.5 scenarios which provide information on the present and future climatology of heat waves according to the CMIP5 ensemble, two additional scenarios were created. An annual mean shift change scenario (MS) was created by adding the mean temperature difference between RCP8.5 and HIST at each location to HIST daily temperatures. Mean temperatures were estimated over all years within each period, so that temperature is simply shifted. Finally, a seasonal mean change scenario (SS) was constructed by adding the seasonal cycle of future temperature changes (RCP8.5-HIST) at each location to HIST daily temperatures. The seasonal cycle of changes was calculated using a climatological 90 day window around each calendar day and all years within each period. Other windows lengths were also tested with similar results with variability contribution decreasing as the window is shortened.

2.2. Heat Wave Metrics

Heat waves were identified and measured using a modified version of the Excess Heat Factor (EHF) [*Nairn and Fawcett*, 2013]. The EHF index was devised to monitor heat waves using recent past climate to define hot conditions through the 95th percentile of daily average temperature. It was primarily designed with human impacts in mind and thus incorporates an intensifying term to account for short-term acclimatization. We did not include this because our goal is to focus on long-term changes and we therefore considered the significance term:

$$\text{EHF}_{\text{sig}} = \frac{1}{3}\left(\overline{T}_t + \overline{T}_{t-1} + \overline{T}_{t-2}\right) - q_{95}, \tag{1}$$

where $\overline{T}_t$ is the average temperature for day t from daily maximum and minimum temperature and q_{95} is the climatological 95th percentile of $\overline{T}_t$ at each location. A heat wave occurs when EHF_{sig} is positive for at least three consecutive days. In other words, when the 3 day average temperature exceeds the 95th percentile during three or more consecutive days. Multiple metrics can be derived from EHF_{sig} such as frequency of heat wave days (frequency), mean duration of heat waves (duration), intensity of the hottest heat wave (defined as the heat wave with highest EHFsig value) in a year (intensity), and number of heat waves in a year (number of heat waves).

Using percentiles to define extreme conditions is key to calculating heat wave metrics globally and with multiple models because it does not rely on absolute thresholds that might be region and model dependent. This facilitates comparison across regions and minimizes the impact of model biases on the results. EHF_{sig} is calculated with respect to present climate percentiles for both present and future heat waves, which allows the full climate change signal to be accounted for. This is a common approach to most studies investigating projected changes in heat waves [*Meehl and Tebaldi*, 2004; *Fischer and Schär*, 2010; *Lau and Nath*, 2012, 2014; *Schoetter et al.*, 2015].

2.3. Proportion of Change

The proportion of change for each heat wave metric explained by temperature variability changes as compared to changes in annual mean temperature is calculated using the following equation:

$$P = 100\% \cdot \frac{\text{HW}_{\text{RCP8.5}} - \text{HW}_{\text{MS}}}{|\text{HW}_{\text{RCP8.5}} - \text{HW}_{\text{HIST}}|}, \tag{2}$$

where HW_{HIST}, $HW_{RCP8.5}$, and HW_{MS} are the values of any heat wave metrics from HIST, RCP8.5, and MS scenarios. The contribution of variability with respect to seasonal mean changes is calculated replacing HW_{MS} with HW_{SS}, which are the values of heat wave metrics from SS scenario. Therefore, a value of $P = 0$ means that projected changes for that particular heat wave metric are entirely explained by a shift in the temperature distribution and variability changes play no role. Alternatively, any other value of P corresponds to the contribution of variability changes to strengthening ($P > 0$) or weakening ($P < 0$) projected changes produced by annual or seasonal mean temperature increases. This proportion is relative to projected changes from the RCP8.5 runs, so $P = 100\%$ means that variability changes are equal to 100% of the total changes. Because mean temperature changes are systematically positive, negative values of P mean that changes in variability moderate changes due to the temperature shifting. A value of P is obtained separately for each of the CMIP5 models and then averaged to calculate the ensemble mean. Statistical significance and model agreement in heat wave changes across scenarios was determined using Tebaldi's convention [*Tebaldi et al.*, 2011], where at least 50% of the models show statistical significant differences in changes in heat wave metrics between RCP8.5 and MS (or SS), and at least 80% of those models agree in the sign of the differences. The statistical significance was determined using a nonparametric Kolmogorov-Smirnov test at a level of significance of 5%. The K-S test is applied over each model and grid point separately. Two 30 year samples of annual heat wave metrics from scenarios RCP8.5 and MS (or SS) were compared. If the null hypothesis is rejected, RCP8.5 and MS (or SS) project future changes that are statistically different from each other, and therefore, P is statistically meaningful. In this study, significance is used when both statistical significance and model agreement conditions are met.

3. Results

3.1. Changes in Temperature Extremes

Using an ensemble of global climate models, the probability of current unusually hot conditions defined as the 95th percentile of daily mean temperature increases by a factor 4 in the future (Figure 1) in a location in the Mediterranean. In this particular location, changes in variability increase the frequency of hot extremes by ~20% with respect to a mean shift of the temperature distribution. A similar behavior is obtained for a location in California (Figure S2a in supporting information), although variability explains only ~10% of the changes. These two locations were selected to illustrate the most commonly studied regions in the globe, where variability significantly contributes to enhancing the occurrence of hot extremes [*Schär et al.*, 2004; *Della-Marta et al.*, 2007; *Lau and Nath*, 2012, 2014; *Schoetter et al.*, 2015]. In other regions, such as South Australia (Figure 1b) and South Africa (Figure S2e), changes in variability also increase the occurrence of hot conditions, but the influence is substantially weaker and the mean temperature shift is the dominant factor. In areas such as the tropics where the mean climate change signal is large compared to current climate variability (Figure 1c), virtually the entire temperature distribution (~90%) is shifted above the extreme temperature present-day threshold. This implies that the mean temperature shift prevails over changes in temperature variability. These results suggest that the two most studied regions are particular cases, and they are likely not representative of the impact of variability changes on future hot extremes and thus on future heat waves at the global scale.

3.2. Future Heat Waves

Figure 2 shows a distinct spatial pattern of future change for each of the heat wave metrics. Heat wave frequency (i.e., number of heat wave days) will be considerably larger in regions with small temperature variability (Figure 2b), such as the tropics, where up to 95% of all days become heat wave days in the future. This contrasts with present climate values (Figure 2a), which are by definition below 5%. Heat waves will also be substantially longer in these regions (Figure 2d). Extreme heat conditions will persist on average more than 45 days as opposed to below 10 days in the present (Figure 2c). The Northern Hemisphere (NH) midlatitudes and high latitudes will experience the most intense heat waves on average, with future heat wave intensity exceeding the current extreme temperature threshold by 9°C over large areas (Figure 2f). Most of these regions currently undergo heat waves with intensity not exceeding 4°C above the extreme threshold (Figure 2e). Our results indicate that in the NH there will be fewer but longer heat waves than in the Southern Hemisphere (SH) (Figure S3), which suggest that heat waves in the NH may merge into a handful of longer and more intense heat waves. Interactions between atmospheric blocking and local feedbacks could be responsible for these changes since they were identified as drivers of recent extreme heat waves [*Miralles et al.*, 2014].
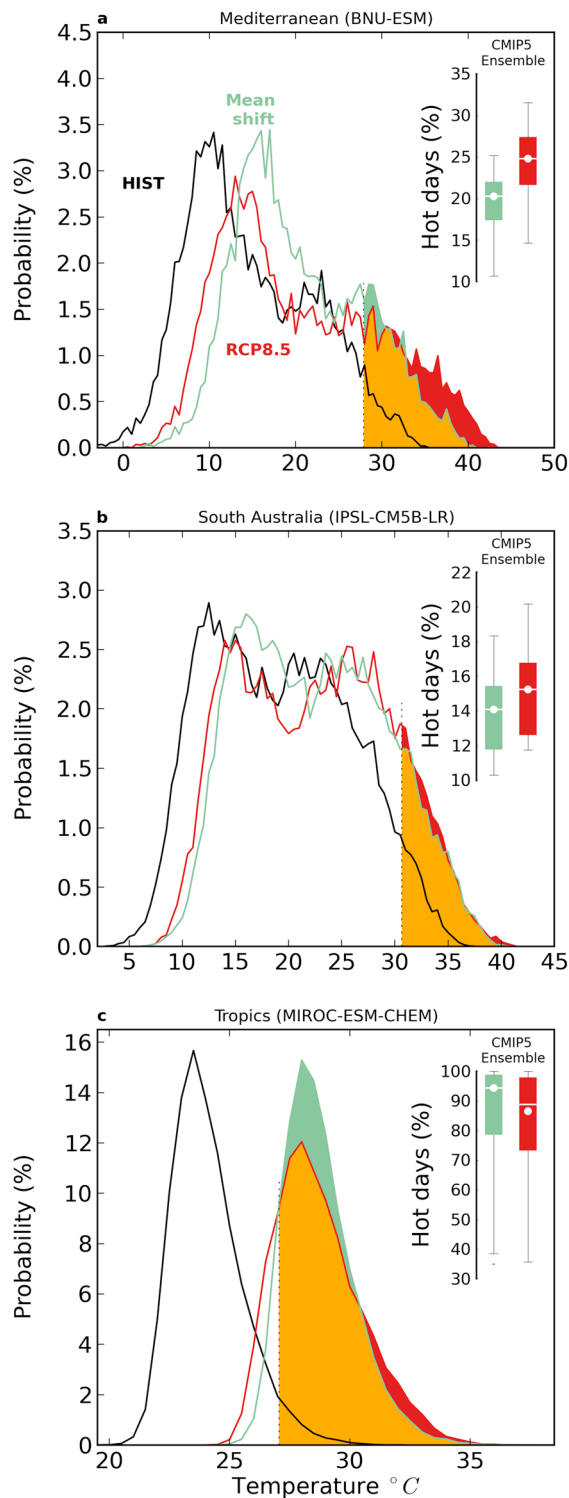
Figure 1. Temperature variability changes effect on the probability of hot conditions. Probability density functions (PDFs) of daily mean temperature from present climate (HIST, 1971–2000) experiments, future RCP8.5 scenario (2071–2100), and the annual mean shift scenario (MS) from a representative model of the CMIP5 ensemble. PDFs were calculated for a 3° × 3° area in the (top) Mediterranean, (middle) South Australia, and (bottom) Tropical areas (see Figure S1a) and for each model separately using 0.5°C bins. Shaded areas represent the probability of hot conditions (95th percentile of temperature from HIST simulations from each model) for RCP8.5 (red), MS (green), and the overlapping between the two (orange). The spread across models in the probability of hot conditions from MS (green) and RCP8.5 (red) scenarios is shown in the top right, with white lines representing the ensemble median. The most representative model in each region (white circles) is the closest to the ensemble median for both scenarios.
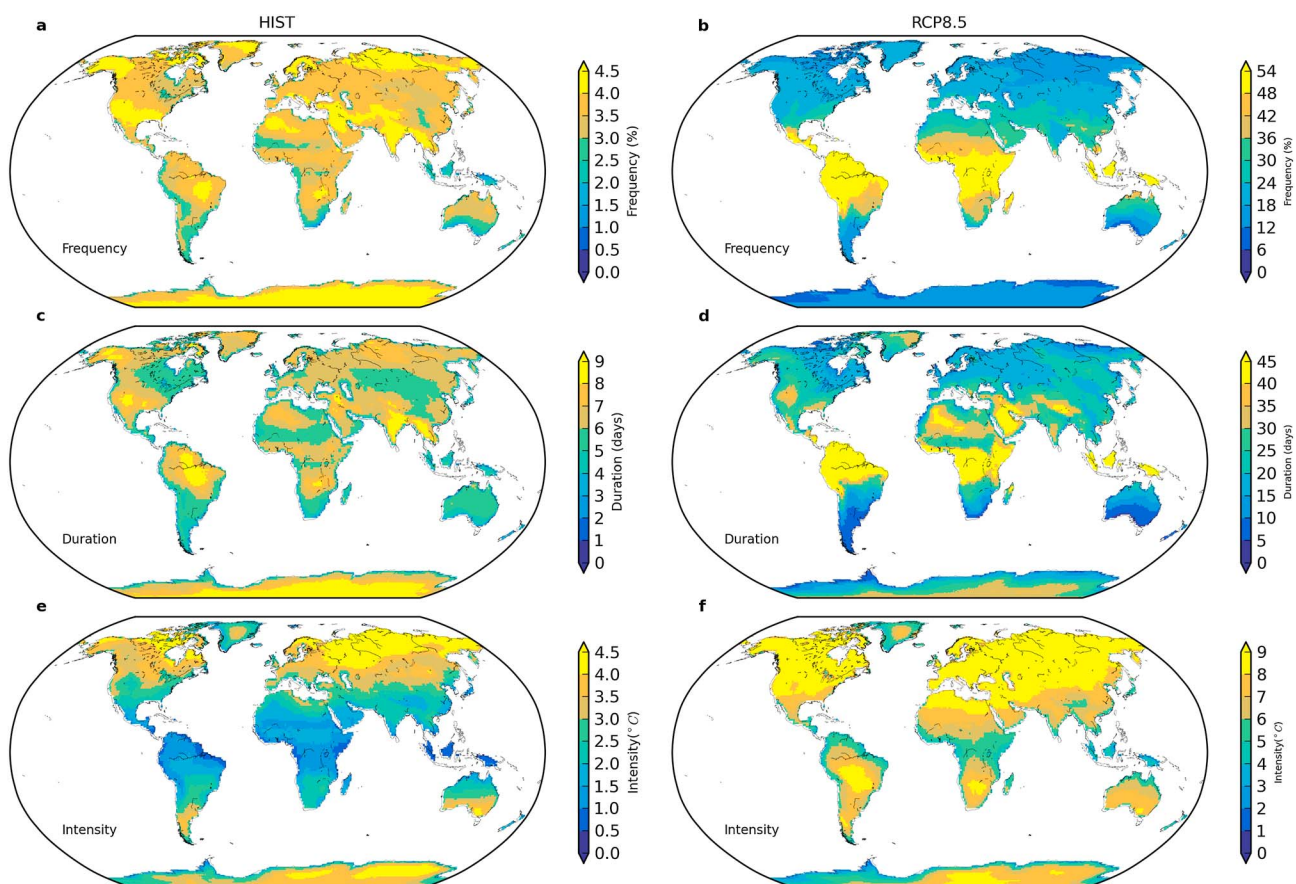
Figure 2. Present climate and future projections of heat wave characteristics. Mean present (HIST) and future (RCP8.5) values of (a, b) frequency, (c, d) mean duration, and (e, f) intensity of heat waves from the CMIP5 ensemble. Scales are different for each period.

3.3. Annual Mean Shift Proportion

The proportion (P) of the above projections than can be attributed to changes in variability with respect to a mean shift is estimated by comparison of projected changes from RCP8.5 and MS scenarios. Similarly, the proportion of changes from variability with respect to a seasonal mean shift is determined through comparison of RCP8.5 and SS.

Temperature variability changes have been found to play a dominant role in intensifying future heat waves [*Schär et al.*, 2004; *Fischer and Schär*, 2010; *Schoetter et al.*, 2015] but there is no consensus on the impact on frequency and duration of extreme heat events [*Katz and Brown*, 1992; *Weisheimer and Palmer*, 2005; *Della-Marta et al.*, 2007; *Fischer and Schär*, 2010; *Fischer et al.*, 2012; *Lau and Nath*, 2014]. While our results indicate that variability changes significantly enhance the effect of the mean warming on all heat wave metrics in well studied areas (i.e., Mediterranean, western U.S., and southern South America), the rest of the globe responds differently (Figure 3). Variability changes explain more than 25% of the increases in intensity and duration compared to the mean shift scenario in these regions, although they are generally significant only for intensity. Regions that show contribution from variability changes to increasing frequency larger than 10% are very confined (Figure 3a). On the other hand, projected heat wave changes are dominated by mean temperature changes over large areas (i.e., contributions below 10%). It is worth noting that negative contributions from variability also occur. In high latitudes and the Tibetan Plateau variability will decrease, which will retract the tails of the distribution and result in shorter, less frequent, and milder heat waves compared to a scenario where the temperature distribution is only shifted. Physical reasons for this variability reduction might include snow and sea ice-albedo feedbacks or changes in large-scale circulation patterns [*Screen*, 2014].

3.4. Seasonal Mean Shift Proportion
Projected increases in temperature vary seasonally and differences in the mean seasonal changes are also partly responsible for changes in the scale and shape of the temperature distribution. The upper tail changes
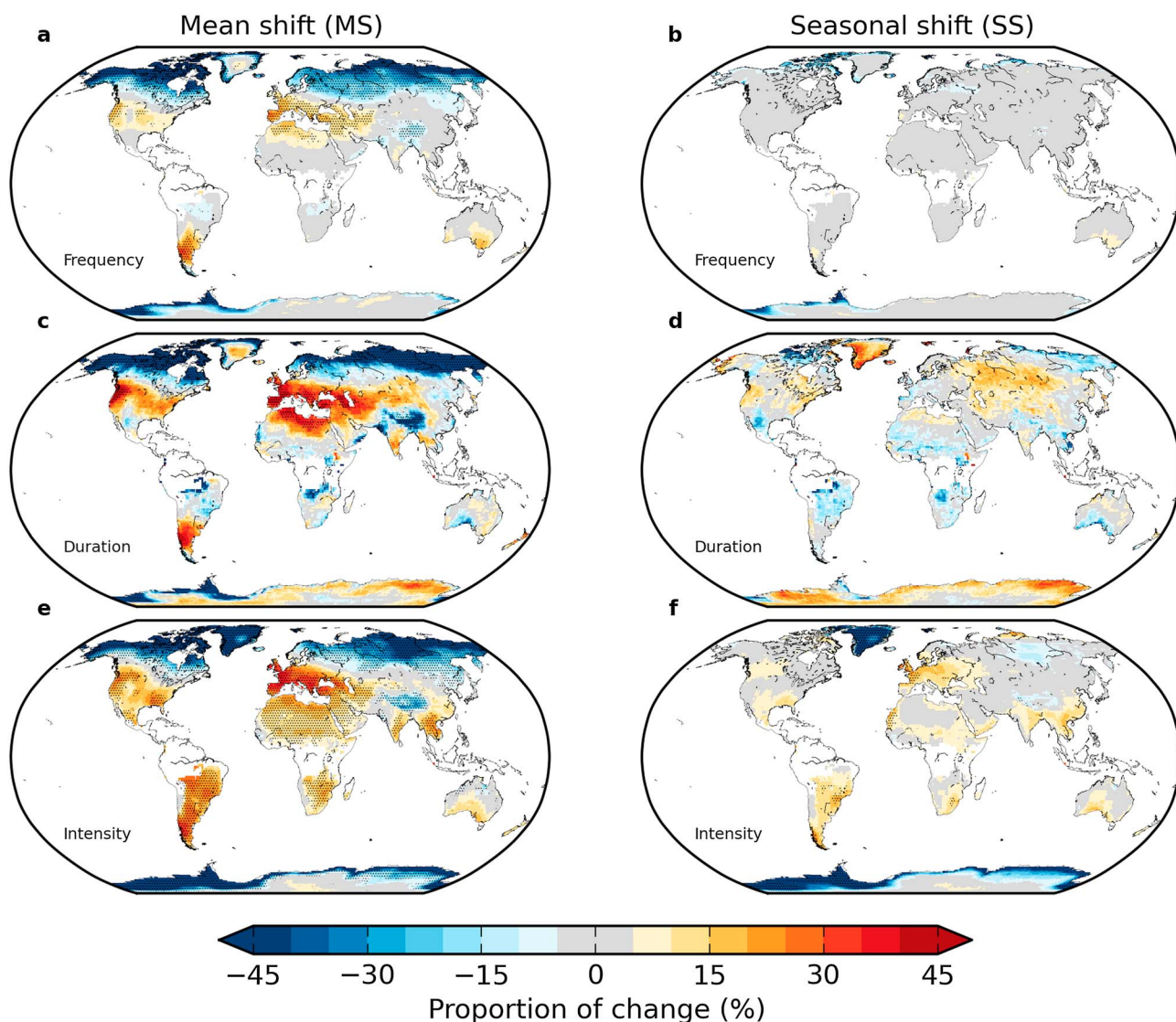
Figure 3. Proportion of heat wave changes explained by temperature variability changes. (a, b) Proportion of changes in heat wave frequency, (c, d) mean duration of heat waves, and (e, f) heat wave intensity explained by temperature variability changes using an annual (a, c, and e) and seasonal (b, d, and f) mean shift. Stippling indicates areas where more than half of the models show a significant difference between scenarios with and without variability changes and at least 80% of them agree in the sign of the difference (see section 2). White masked areas indicate regions where the longest heat wave in all models spans a period of half a year or longer.

are predominantly driven by summer warming, while the lower tail is largely affected by winter temperature changes. Considering the seasonal cycle of warming reduces the contribution from variability changes to future heat wave frequency to less than 5% in the vast majority of regions (Figure 3b). Slightly larger contributions are obtained for duration (Figure 3d) and intensity (Figure 3f), but they are consistently nonsignificant. In few localized exceptions (i.e., western Europe, the Western Sahara, and southeast Brazil), a widening of the summer temperature distribution significantly intensifies heat wave intensity with a contribution of ∼20%. Our findings emphasize the peculiarity of Greenland and most of Antarctica, where variability changes counteract the effect of the mean temperature shift even after considering mean seasonal differences. Changes in all heat wave characteristics are thus mostly explained by the mean temperature increase during the warm months.

At the regional level, the model ensemble spread spans both positive and negative contributions from temperature variability with respect to annual mean warming (Figure S4). This underlines the importance of using large ensembles to assess the role of variability with respect to mean annual changes in shaping future heat

waves. However, such uncertainty is partly explained by differences in seasonal mean warming across models, since incorporating the seasonal cycle reduces the spread of the ensemble. This emphasizes the agreement across models in the importance of seasonal warming over changes in variability. CMIP5 models show agreement in other features too. They all suggest that variability changes will amplify all heat wave metrics in the Mediterranean and will enhance intensity in South America and the SH midlatitudes (Figure S4). On the other hand, most models agree that future variance will contribute toward a reduction of all heat wave metrics in Greenland and the intensity in Antarctica.

It has been argued that the intensity of particularly extreme heat waves increases with variability changes [*Schär et al.*, 2004]. Our results indicate that the intensity of the most severe events increases with variability more than the climatological heat wave intensity for most regions, although variability generally contributes to approximately 10% of the changes (Figure S5b). It is equally noteworthy that variability produces a decrease in intensity of such events by more than 20% in high latitudes.

4. Conclusions

In summary, according to CMIP5 models future heat waves show a range of responses to changes in mean annual temperature and variability. Regions where most of the heat wave research has focused (Europe and U.S.) [*Schär et al.*, 2004; *Fischer and Schär*, 2010; *Barriopedro et al.*, 2011; *Fischer et al.*, 2012; *Lau and Nath*, 2012, 2014; *Schoetter et al.*, 2015] are very particular cases where the contribution from increased variability to future heat waves [*Meehl and Tebaldi*, 2004; *Schär et al.*, 2004; *Schoetter et al.*, 2015] is larger than elsewhere. However, areas where variability has a negligible contribution are common. The opposite response was also detected in some areas, where reduced variability moderates future heat waves balancing the effect of a mean shift. A number of physical processes can explain such responses, including changes in atmospheric circulation and blocking, land cover change, sea ice-albedo feedbacks, and soil desiccation [*Seneviratne et al.*, 2006; *Miralles et al.*, 2014; *Screen*, 2014]. Our results suggest that the dominant physical mechanism driving heat wave changes is likely to vary by region. Future work investigating these mechanisms will need to consider this spatial variability.

In the tropics, the annual mean warming is larger than the present climate variability and most of the distribution is shifted above the extreme temperature threshold. This possibility was previously contemplated [*Katz and Brown*, 1992], but perhaps not given enough attention in the context of future heat waves and the contribution of variability changes. This suggests that caution must be exercised when referencing future temperature extremes to present climate conditions. Although this approach is useful to estimate the limits of adaptation of humans and the environment to climate change, it poses nonnegligible complications when interpreting future climate extremes. Events that are rare under present climate conditions might become the norm and are no longer described by the tails of the distribution. As such, the assessment of their impact as extremes is incorrect.

We conclude that mean seasonal warming is responsible for over 95% of the heat wave changes in most cases. The widening of the temperature distribution is produced by different warming rates across seasons, and in this context variability rarely has a statistically significant contribution to heat waves changes. Therefore, future heat waves follow warm season temperature increases in large areas across the globe. It is thus vital to reduce the range of uncertainty of existing seasonal mean temperature projections before we embark on investigating potential effects of variability changes, which is secondary in most regions.

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