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Amplified mid-latitude planetary waves favour particular regional weather extremes

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There has been an ostensibly large number of extreme weather events in the Northern Hemisphere mid-latitudes during the past decade[1]. An open question that is critically important for scientists and policy makers is whether any such increase in weather extremes is natural or anthropogenic in origin[2–13]. One mechanism proposed to explain the increased frequency of extreme weather events is the amplification of mid-latitude atmospheric planetary waves[14–17]. Disproportionately large warming in the northern polar regions compared with mid-latitudes—and associated weakening of the north-south temperature gradient—may favour larger amplitude planetary waves[14–17], although observational evidence for this remains inconclusive[18–21]. A better understanding of the role of planetary waves in causing mid-latitude weather extremes is essential for assessing the potential environmental and socio-economic impacts of future planetary wave changes. Here we show that months of extreme weather over mid-latitudes are commonly accompanied by significantly amplified quasi-stationary mid-tropospheric planetary waves. Conversely, months of near-average weather over mid-latitudes are often accompanied by significantly attenuated waves. Depending on geographical region, certain types of extreme weather (for example, hot, cold, wet, dry) are more strongly related to wave amplitude changes than others. The findings suggest that amplification of quasi-stationary waves preferentially increases the probabilities of heat waves in western North America and central Asia, cold outbreaks in eastern North America, droughts in central North America, Europe and central Asia, and wet spells in western Asia.

A series of weather extremes have hit the Northern Hemisphere mid-latitudes in recent years[1], such as the European heat wave in summer 2003[8], cold and snowy winters in 2009/10, 2010/11 and 2013/14 in the northeast United States[6,16,21], the Russian heat wave in summer 2010[2–5], the Texas drought of 2011[6], and the summer 2012 and winter 2013/14 floods in the United Kingdom[7,10]; all have had significant socio-economic impacts. There is increasing scientific evidence[1–13] and a growing public perception[22] that extreme weather events are occurring more frequently. However, the mechanisms that drive weather extremes and through which climate change may influence climate variability are poorly understood. A potential cause of increased weather extremes is the amplification of atmospheric planetary waves[14–17]. It has been proposed that the weakening north–south temperature gradient—a key characteristic of anthropogenic climate change[23,24]—may cause larger amplitude planetary waves[14–17], although the observational evidence for this and the dynamical mechanism have been questioned[18–21]. It is further proposed that high-amplitude planetary waves favour the occurrence of extreme weather[14–17]. It is this hypothesis that we examine here (and not wave amplitude trends).

First, it is necessary to define precisely 'extreme weather' for this application. We are concerned with persistent anomalies in land surface temperature (T_L) and land precipitation (P_L), such as heat waves, cold spells, droughts and prolonged wet periods, which are evident on monthly timescales and large spatial scales (Methods). Initially we focus on absolute (that is, irrespective of their sign) T_L and P_L anomalies (denoted $|T'_L|$ and $|P'_L|$). This is appropriate because planetary waves tend to induce positive temperature (and perhaps precipitation) anomalies at some longitudes and negative anomalies at other longitudes. Figure 1a,b shows normalized time series for monthly $|T'_L|$ and $|P'_L|$, respectively, area-averaged over northern mid-latitudes (35°–60° N; area shown in Fig. 2). The 40 months with largest values (approx. 10% of cases) are highlighted by circles and labelled on the lower x axis, and are hereafter referred to as months of extreme temperature/precipitation. The months of extreme temperature and the months of extreme precipitation lie relatively evenly through the 34-year period, and there is no long-term trend. A full discussion of 34-year trends is provided in Supplementary Discussion 1.

Figure 1c shows planetary-wave amplitude anomalies (normalized by removing the mean amplitude and dividing by the standard deviation, σ, for each wave number) for wave numbers 3–8 during months of extreme temperature (that is, the months shown by circles in Fig. 1a). The wave number corresponds to the number of atmospheric ridges and troughs around the circumference of the Earth (for example, wave number 3 has three ridges and three troughs). The overwhelming majority of the statistically significant amplitude anomalies are positive. The number of significant positive anomalies (32) is appreciably larger than would be expected by chance alone (12). For half of the extreme months considered there is at least one significant positive amplitude anomaly for wave numbers 3–8. The three months with significant negative amplitude anomalies also have at least one significant positive amplitude anomaly. Thus, it would seem that some wave numbers are amplified at the expense of other wave numbers. Although significantly amplified planetary waves are common during months of extreme temperature, it is not always the same wave number(s) that is/are amplified. The greatest number of significant positive amplitude anomalies are found for wave numbers 5–7. Positive monthly-mean amplitude anomalies imply, in physical terms, highly meridional and persistent (slow-moving) circulation regimes (Supplementary Discussion 2).

The statistically significant planetary-wave amplitude anomalies during months of extreme precipitation (that is, the months shown by circles in Fig. 1b) are also predominantly positive (Fig. 1d). Significantly amplified waves, in at least one wave number 3–8, are identified in 40% of the months with extreme precipitation. This percentage increases to 50% for the 20 months with most extreme precipitation. In contrast, only one of these 20 months exhibits a significant negative amplitude anomaly and, furthermore,

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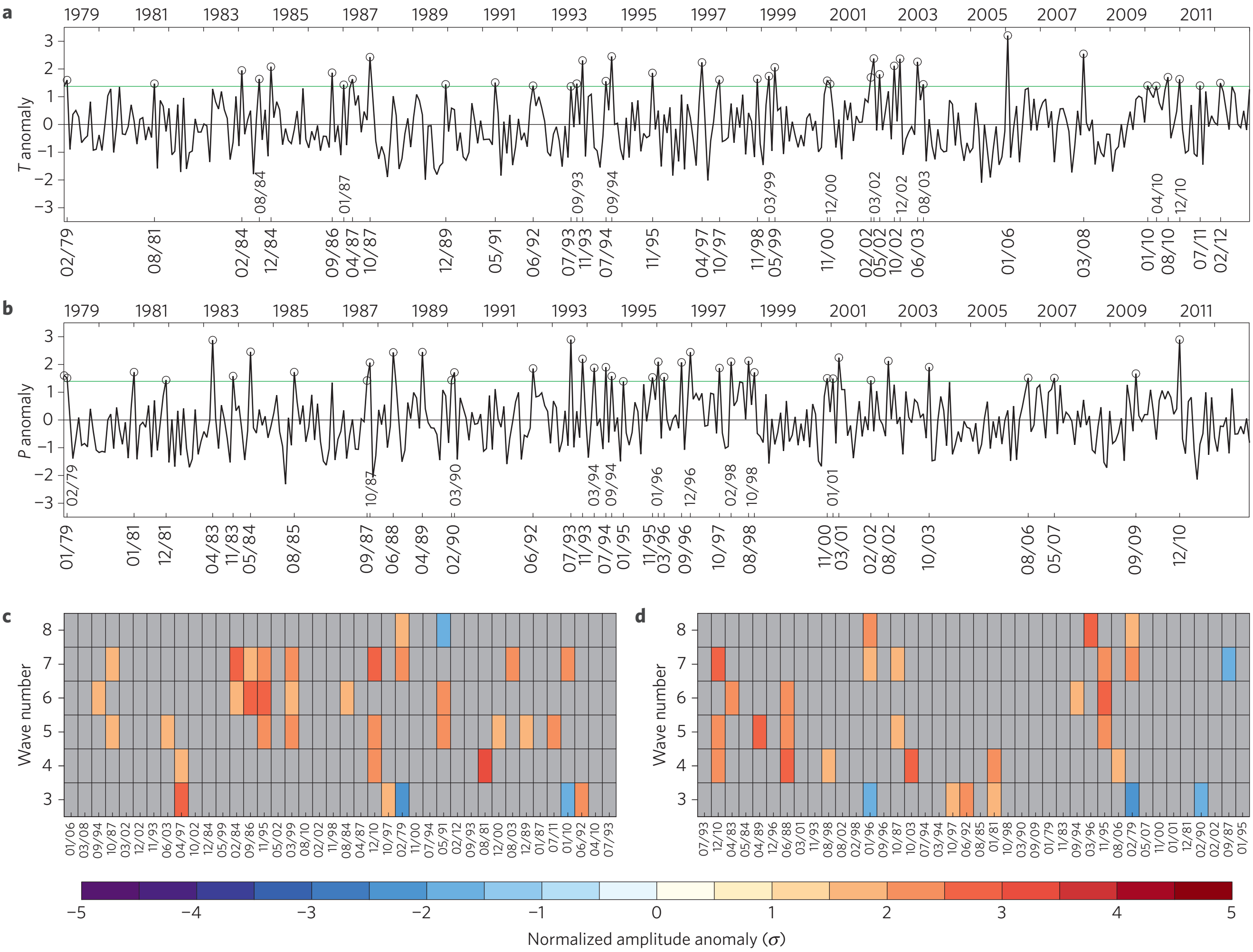

Figure 1 | Planetary-wave amplitude anomalies during months of extreme weather. a,**b**, Normalized monthly time series of mid-latitude-(35°–60° N) mean land-based absolute temperature anomalies (**a**) and absolute precipitation anomalies (**b**), 1979–2012. The 40 months with the largest values are identified by circles and labelled on the lower *x* axis, and the green line shows the threshold value for extremes. **c**,**d**, Normalized wave amplitude anomalies, for wave numbers 3–8, during 40 months of mid-latitude-mean temperature extremes (**c**) and precipitation extremes (**d**). The months are labelled on the abscissa in order of decreasing extremity from left to right. Grey shading masks anomalies that are not statistically significant at the 90% confidence level; specifically, anomalies with magnitude smaller than 1.64σ, the critical value of a Gaussian (normal) distribution for a two-tailed probability $p = 0.1$. Red shading indicates wave numbers that are significantly amplified compared to average and blue shading indicates wave numbers that are significantly attenuated compared to average.

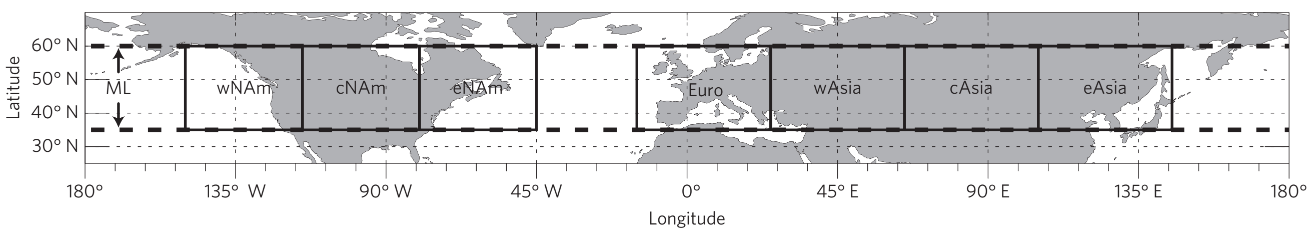

Figure 2 | The geographical regions used in this study. Black boxes show the regions and are labelled with their abbreviations. These regions were chosen a priori on the basis of conventional (sub-)continental boundaries, are approximately equal in area, and together cover all the mid-latitude landmasses.

this is accompanied by positive anomalies in two other wave numbers. As for temperature, this suggests a link between extreme precipitation and significantly amplified planetary waves. However, clearly not all months with temperature or precipitation extremes are associated with significantly amplified, or attenuated, planetary-wave amplitudes.

Figure 3a shows the probability density function (PDF) of amplitude anomalies for each of wave numbers 3–8 in each of the 40 months of extreme temperature. Months of extreme temperature over mid-latitudes are associated with significantly amplified planetary waves, in the sense that positive amplitude anomalies occur relatively more often during months of extreme temperature than they do climatologically. The difference in mean amplitude anomalies, between extreme months and climatology, is very highly statistically significant ($p < 0.001$). The difference in amplitude variance is also highly significant ($p < 0.01$), with greater variance in months of extreme temperature than climatologically. This increase in variance is primarily due to larger frequencies at the positive tail of the

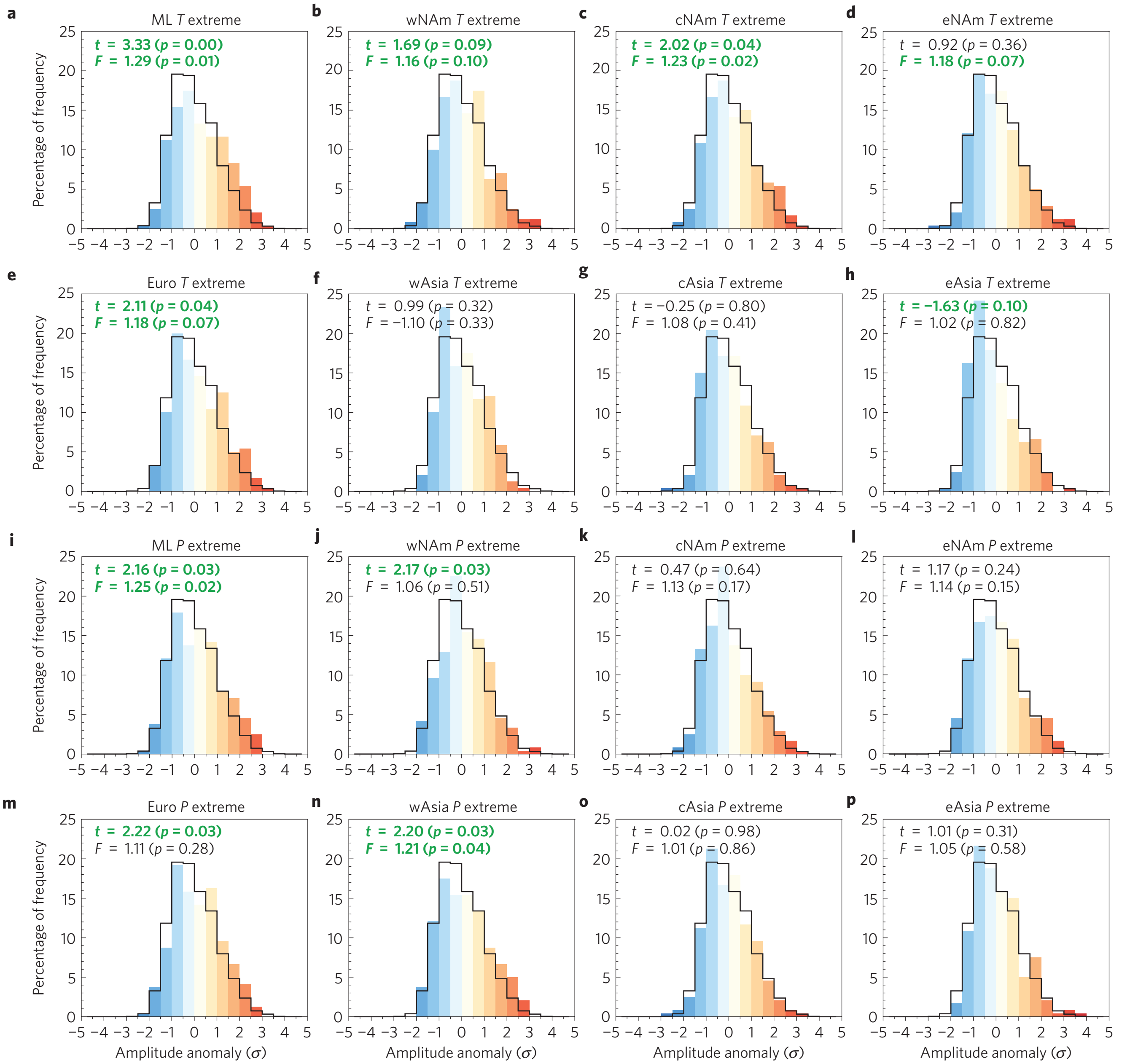

Figure 3 | Frequency distributions of planetary-wave amplitude anomalies during months of extreme weather. a–h, Probability density functions (PDFs) for normalized wave amplitude anomalies (wave numbers 3–8) during 40 months of extreme temperature over eight geographical regions: ML (**a**), wNAm (**b**), cNAm (**c**), eNAm (**d**), Euro (**e**), wAsia (**f**), cAsia (**g**) and eAsia (**h**). **i–p**, PDFs for 40 months of extreme precipitation over the same eight regions, respectively. The coloured bars show the relative frequency (expressed as a percentage of the total number of anomalies) of amplitude anomalies in bins of 0.5σ. The black lines show the climatological frequencies. The *t* and *F* statistics and their associated *p* values are provided, with bold green text highlighting values that are statistically significant at the 90% confidence level. The regions and their abbreviations are shown in Fig. 2.

distribution. This suggests that not only are temperature extremes associated with amplified waves on average, but also that there is a particularly strong association between the most highly amplified planetary waves and temperature extremes.

On the basis of daily reanalysis data, it can be seen that planetary-wave amplitude and mid-latitude-mean $|T'_L|$ co-vary almost simultaneously, but with the temperature anomalies lagging the amplitude anomalies by one to two days (Supplementary Discussion 3). This time lag implies that surface temperatures are responding to the atmospheric circulation anomalies and not the other way round. Furthermore, whereas surface temperatures respond very rapidly to circulation changes (hours to days), the timescale for the mid-tropospheric circulation (wave amplitude is defined at 500 hPa; see Methods) to respond to surface temperature anomalies is much slower (tens of days to months). Thus irrespective of the small time lag, the timescale of the response is strongly suggestive of a causal link between planetary-wave amplitude and temperature extremes.

Figure 3b–h shows PDFs for the planetary-wave amplitude anomalies during months with extreme temperature over seven geographical regions (shown in Fig. 2). Over western North America, central North America and Europe, temperature extremes are associated with significantly larger mean amplitude and greater amplitude variance, consistent with the results for the mid-latitudes as a whole. Temperature extremes over eastern North America are linked to increased amplitude variance, but not significantly

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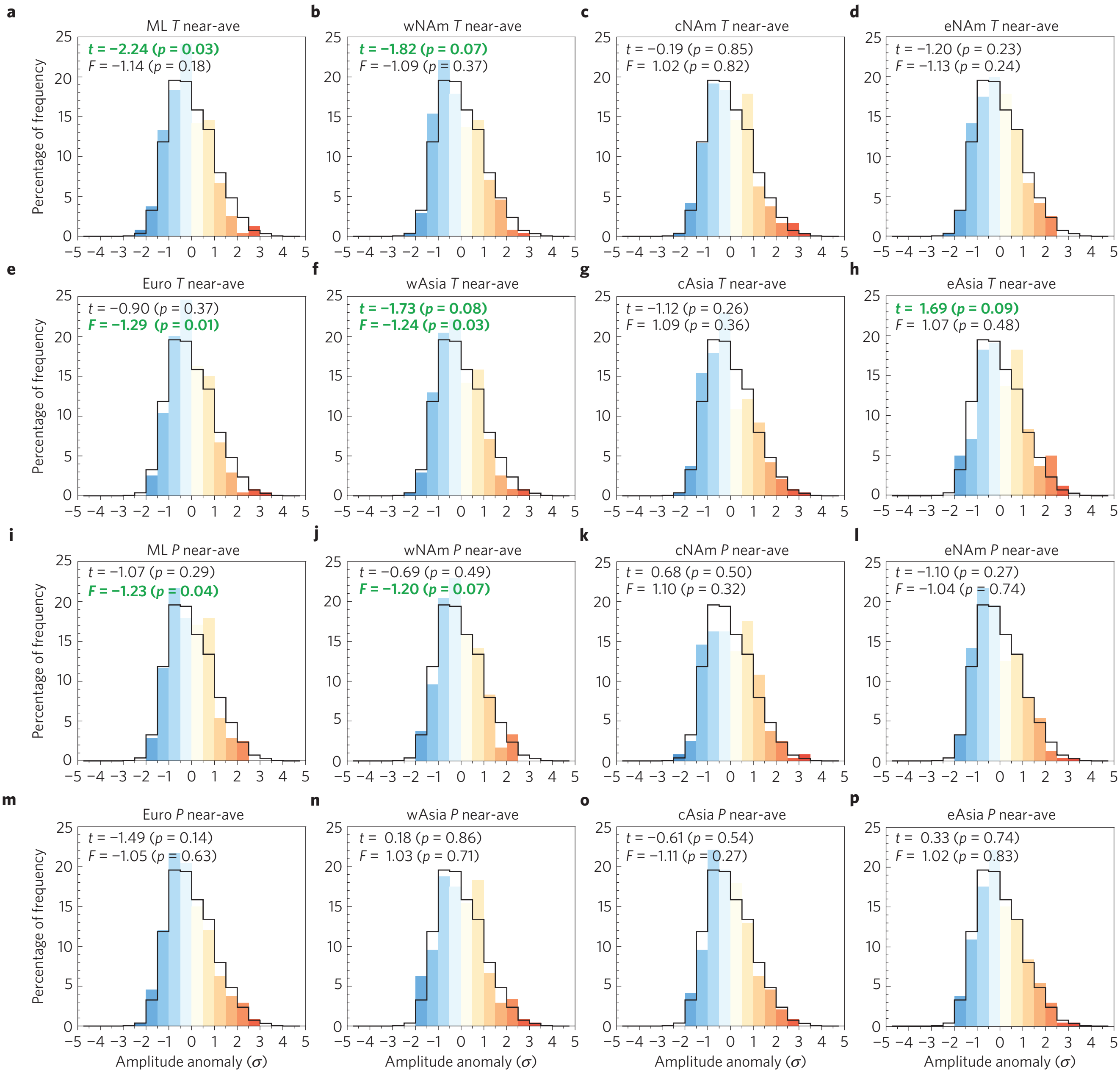

Figure 4 | Frequency distributions of planetary-wave amplitude anomalies during months of near-average weather. As Fig. 3, but for months of near-average temperature (**a**–**h**) and precipitation (**i**–**p**).

different mean amplitude. Over eastern Asia, significantly attenuated planetary-wave amplitudes accompany temperature extremes. Analogous PDFs for months of extreme precipitation are shown in Fig. 3i–p. As for temperature extremes, we find that precipitation extremes over mid-latitudes are associated with significantly larger mean amplitude and significantly larger variance (again, the latter is primarily due to greater frequencies at the positive tail of the PDF). Regional precipitation extremes over western North America, Europe and western Asia are also linked to significantly amplified waves.

The association between planetary-wave amplitude and temperature anomalies exists over a wide range of timescales—from daily to sub-seasonal. The strength of this relationship is relatively insensitive to timescale, although is it marginally strongest on 5–14 day timescales (Supplementary Discussion 4). In contrast, the amplitude-precipitation relationship weakens for timescales less than 12 days. This implies that planetary waves are more important for longer-duration precipitation extremes, such as those that contribute to drought, than they are for short-lived precipitation extremes. We speculate that precipitation variability is closely related to synoptic- or local-scale drivers on short timescales whereas longer-lived events are more closely tied to the large-scale atmospheric circulation.

If extreme weather is linked to amplified waves, is near-average weather accompanied by attenuated planetary waves? Months of near-average temperature (see Methods for definition) over mid-latitudes and western North America are associated with, on average, significantly attenuated planetary-wave amplitudes, whereas months of near-average temperature over eastern Asia are accompanied by significantly amplified waves (Fig. 4). All these relationships are opposite to those found for months with extreme temperature. In Europe and western Asia, amplitude variance is significantly lower in months of extreme temperature than climatologically. From the PDFs, it can be seen that

Table 1 | *t* and *F* statistics comparing planetary-wave amplitude anomalies between months of extreme weather and climatology.

	Hot		Cold		Wet		Dry	
	t	*F*	*t*	*F*	*t*	*F*	*t*	*F*
wNAm	***2.31***	***1.22***	−0.05	1.13	1.07	1.07	1.05	1.05
cNAm	1.11	***1.19***	1.48	***1.21***	−1.13	−1.03	***2.52***	***1.25***
eNAm	−1.18	−1.02	***3.54***	***1.37***	1.35	***1.19***	0.25	1.03
Euro	0.78	1.00	1.15	1.01	0.11	1.03	***2.54***	1.10
wAsia	−0.45	−1.12	0.70	−1.03	***2.55***	1.06	−0.86	−1.01
cAsia	***3.11***	1.02	0.28	1.11	0.14	−1.02	***2.94***	1.11
eAsia	−1.24	−1.12	0.12	1.14	0.15	***1.22***	−0.05	−1.07

The *t* and Fisher *F* statistics corresponding to, respectively, differences in mean planetary-wave amplitude and differences in amplitude variance between composites of months with extreme weather and climatology. Statistics are provided separately for four types of weather extreme (hot, cold, wet and dry) and for seven geographical regions. Differences in mean amplitude or variance that are significant at the 90% confidence level are shown in bold italic type. Regions and their abbreviations are shown in Fig. 2.

this primarily reflects fewer cases of large positive amplitude anomalies during the months of near-average temperature than climatologically. Although months with temperature extremes are often accompanied by highly amplified waves, these rarely accompany months with near-average temperature. Turning to precipitation, none of the geographical regions show a significant difference in mean amplitude anomaly between months of near-average precipitation and climatology (Fig. 4i–p). However, amplitude variance is significantly lower over mid-latitudes and western North America, as a consequence of fewer (in percentage terms) large positive amplitude anomalies during months of near-average precipitation than in all months taken together.

It is reasonable to expect that any particular planetary wave will induce positive temperature (and perhaps precipitation) anomalies at some longitudes and negative anomalies at other longitudes. If wave phase was highly variable in time (that is, the waves were 'free'), amplified waves might favour extremes of both sign (hot or cold, wet or dry) at any specific longitude. However, in reality, the waves have preferred phases (that is, they are quasi-stationary), related to orography and climatological-mean thermal gradients[14,25]. This is especially the case for the smaller wave numbers. Further, at any particular location, temperature and precipitation may be more sensitive to amplitude anomalies of one sign than the other, or to some wave numbers and phases than others. Therefore, amplified waves may in fact favour one type of extreme weather more than another, in any specific location. Table 1 presents *t* and *F* statistics comparing the mean amplitude and variance, respectively, in regionally hot, cold, wet and dry months to climatological mean amplitude and variance (the full PDFs are shown in Supplementary Discussion 5). Consistent with the rationale above, it seems that in most regions there are stronger links between planetary-wave amplitude and weather extremes of one sign than extremes of the other. Significantly amplified waves are found during hot extremes over western North America and central Asia, cold extremes over eastern North America, dry extremes over Europe and central Asia, and wet extremes over western Asia. In each case, extremes of opposite sign in the same region are not accompanied by significantly amplified, or attenuated, planetary waves. Precipitation extremes over central North America are an interesting case: amplified waves tend to accompany dry extremes whereas attenuated waves preferentially occur during wet extremes.

These findings reinforce suggestions that amplified planetary waves favour extreme weather in mid-latitudes[14–17,26]. However, previous studies have not determined which types of extreme weather are caused by amplified waves, or where these extremes are likely to occur. Clearly these details are critically important for decision makers in assessing the risk of, and planning for the impacts of, extreme weather events in the future. If quasi-stationary wave numbers 3–8 are amplified in response to anthropogenic climate change, as has been proposed[14–17], our results suggest that this would preferentially increase the probabilities of heat waves in western North America and central Asia, cold waves in eastern North America, droughts in central North America, Europe and central Asia, and wet extremes in western Asia. However, robust observational evidence for long-term trends in planetary-wave amplitude is lacking[18–21] and further work is required to understand better the physical mechanisms through which human-induced climate change may have an impact on mid-latitude planetary waves.

Methods

Observations. Monthly-mean T_L and P_L from January 1979 to December 2012 were taken from the CRUTEM4 and GPCP v2.2 data sets, respectively. CRUTEM4 data[27] are derived from *in situ* observations at meteorological stations. GPCP data[28] are derived from a combination of *in situ* measurements and satellite estimates. For this study, GPCP data were re-gridded to the CRUTEM4 grid (5° by 5° longitude–latitude). The global-mean T_L and P_L have been subtracted from the grid-box values. This procedure removed global-mean variability and trends, but retained regional signatures such as those associated with planetary wave changes.

Extremes. We derived T_L and P_L anomalies (denoted T_L' and P_L') by removing the relevant climatological monthly mean at each grid-box. Absolute values (that is, the modulus) of T_L' and P_L' (denoted $|T_L'|$ and $|P_L'|$) are used to describe the magnitude of the anomalies irrespective of their sign. This is appropriate because planetary waves tend to induce positive temperature (and perhaps precipitation) anomalies at some longitudes and negative anomalies at other longitudes. Grid-point anomalies were area-averaged over eight geographical regions: mid-latitudes (ML; 35°–60° N, 180° E–180° W), western North America (wNAm; 35°–60° N, 115°–150° W), central North America (cNAm; 35°–60° N, 80°–115° W), eastern North America (eNAm; 35°–60° N, 45°–80° W), Europe (Euro; 35°–60° N, 25° E–15° W), western Asia (wAsia; 35°–60° N, 25°–65° E), central Asia (cAsia; 35°–60° N, 65°–105° E) and eastern Asia (eAsia; 35°–60° N, 105°–145° E). These regions (shown in Fig. 2) were chosen a priori based on conventional (sub-) continental boundaries, are approximately equal in area, and together cover all the mid-latitude landmasses. The area-averaged monthly time series were normalized by removing the climatological mean and dividing by the standard deviation for each calendar month. For each region, we then defined 'extreme months' as the 40 cases (approximately 10%) with largest $|T_L'|$ or $|P_L'|$; and 'near-average' months as the 40 cases with smallest $|T_L'|$ or $|P_L'|$. 'Hot', 'cold', 'wet' and 'dry' months are defined based on the 40 months with largest T_L', smallest T_L', largest P_L' and smallest P_L', respectively. The selected years are provided in Supplementary Discussion 6.

Wave amplitude. We analyse amplitudes of planetary waves in the monthly-mean mid-tropospheric mid-latitude circulation, with zonal wave numbers 3–8. Amplitudes were defined based on Fourier analysis of 500 hPa geopotential heights (Z_{500}), meridionally averaged over mid-latitudes (35°–60° N), as a function of longitude. Monthly-mean Z_{500} were taken from the ERA-Interim reanalysis[29]. This approach is consistent with the 'zonal amplitude' metric used in a previous study[18], except here we use monthly-mean Z_{500} averaged over latitudes 35°–60° N rather than daily values at 45° N. Whereas multi-decadal trends in planetary-wave amplitude are sensitive to how amplitude is defined[18,20], month-to-month variability of amplitude is highly consistent using the two frameworks outlined in earlier work[18]. In this manuscript we exclusively consider amplitude variability (not trends) and, thus, use only one definition of planetary-wave amplitude.

Statistics. Differences in sample means were assessed using an unequal variance t-test. This is an adaptation of the Student's t-test that accounts for the two samples having different sizes and possibly unequal variances[30]. Differences in sample variance were assessed using a Fisher F-test. We tested against the null hypothesis that the two sample means or variances are equal. The null hypothesis was rejected if the probability of equal means or variances is less than 10% ($p < 0.1$).

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Author contributions

J.A.S. designed and performed the research, analysed data and wrote the paper. I.S. discussed the results and commented on the manuscript.

Additional information

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Competing financial interests

The authors declare no competing financial interests.