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COMPOUND NATURAL DISASTERS IN AUSTRALIA: A HISTORICAL ANALYSIS

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ABSTRACT

Compound disasters pose complex disaster coordination and recovery challenges. To inform disaster planning for catastrophic disasters it is essential to understand their frequency and characteristics. In this study we utilise natural disaster loss databases to identify the frequency of historical compound disasters in Australia, considering their characteristics and climate influences. Results show that compound disasters have occurred frequently and are associated with the highest seasonal losses in terms of both insured financial losses and fatalities. They may occur coincidently with other societal stressors such as wars, recessions and pandemics further exacerbating their consequences. Though their component disasters most frequently occur in eastern Australia, events can comprise disasters in both the east and west of the continent. There is no temporal trend in their frequency when considering financial losses, but there is a downward trend when considering only fatalities. It is essential that future disaster risk assessments and plans consider compound disaster scenarios. Relationships with climate drivers may assist to forecast their occurrence.

INTRODUCTION

In 2019, global insured losses from natural disasters totalled some 56 billion dollars (Swiss Re, 2019a). Disasters are disruptions to society due to hazardous events interacting with conditions of capacity, vulnerability and exposure, that result in impacts to human, material, economic or environmental domains (United Nations, 2015). Traditionally, disasters have been categorised as natural or technological though the present-day complexity of disasters threatens such simplicity of categorisation (Shimizu and Clark, 2015).

Risk is a function of hazard, exposure and vulnerability (McAneney et al., 2015). Hazard is the physical phenomena that causes damage such as a flood, cyclone, earthquake or bushfire. Exposure is the elements at risk including social, economic, environmental and infrastructure components and their spatial disposition vis-à-vis the hazard footprint. Vulnerability refers to the susceptibility of elements at risk to suffer loss as a consequence of a given hazard intensity (Gallina et al., 2016).

Traditional disaster risk management methodologies assess risk based on the assumption that hazards and their consequences occur discretely, as for example, a bushfire or a flood (Leonard et al., 2014, Sutanto et al., 2020, AghaKouchak et al., 2018), This approach ignores multi-hazard scenarios (Sadegh et al., 2018), and in so doing may underestimate the risk (Zscheischler et al., 2018). Part of this complexity are what we term here *compound* events, the foci of our study.

As a case in point, let's consider the Australian bushfire season of 2019-2020. This comprised multiple concurrent and sequential bushfires crossing state boundaries. The fires caused 35 deaths and destroyed some 3000 homes, businesses and farms along with significant damage to the environment (Gissing, 2020). The threat of bushfires resulted in some tourist destinations being evacuated and warnings to international tourists to avoid travel. Smoke from the fires is estimated to have been responsible for 417 further excess fatalities and 3151 hospitalisations (Borchers Arriagada et al., 2020); some native species were threatened with extinction; and the burning of vegetation in water catchments reduced water quality and contributed to fish kills. Damage to infrastructure caused widespread blackouts and telecommunication failures, with those at-risk unable to obtain bushfire warnings. Road closures resulted in isolation, concerns for food security and forced medical evacuations. The full cost of these fires is not captured by the insured value of $2.3B (Insurance Council of Australia, 2020).

The 200 odd bushfires were a consequence of widespread drought and heatwaves and occurred contemporaneously with coral bleaching on the Great Barrier Reef and at the same time as severe storms, flash floods and cyclones threatened other Australian communities as well as the emergence of the global COVID-19 pandemic (Quigley et al., 2019). The bushfires weakened Australia's capacity to respond to the COVID-19 pandemic by reducing stocks of personal protective equipment that had been allocated to reduce the impacts of bushfire smoke, whilst the pandemic complicated the recovery of tourism-based economies impacted by the bushfires. Such complexities stretched resources and posed national coordination and recovery challenges for emergency managers.

In a first of its kind, this study examines the prevalence of compound disasters in Australia based upon analyses of disaster losses recorded in the Risk Frontiers' PerilAUS database (Coates et al., 2014, Crompton et al., 2010) and the Insurance Council of Australia's natural disaster database (McAneney et al., 2019). It also explores the frequency of compound disasters and their meteorological and climatic drivers. Implications for risk assessment and disaster management are outlined. There has been increasing research interest partly due to need to understand the combination of different extremes in a changing climate and the impacts on disaster management capabilities (Leonard et al., 2014, AghaKouchak et al., 2018). Disaster mangers are particularly concerned with scenarios that may overwhelm resources and by combination of events result in catastrophe.

Existing studies of compound disasters have: utilised observational data to analyse their occurrence (Sutanto et al., 2020, Ye et al., 2019, Ganguli and Merz, 2019, Khanal et al., 2019), utilised climate projections to forecast their future occurrence (Baldwin et al., 2019, Poschlod et al., 2020, Bevacqua et al., 2019), discussed definitional aspects (Zscheischler et al., 2018, Cutter, 2018, de Ruiter et al., 2019b, Leonard et al., 2014) or established analytical frameworks (Hao et al., 2018, Zscheischler et al., 2020). Observational studies have been challenged by limited coverage (Poschlod et al., 2020). The use of disaster databases to contribute to the study of compound disasters has been recommended (Sutanto et al., 2020).

We posit that compound disasters are likely to become more common as a consequence of globally interconnected networks, rising populations, asset exposure and a changing climate(de Ruiter et al., 2019b, Glasser, 2019, Sadegh et al., 2018, Matthews et al., 2019, Swiss Re, 2019b, Australian Government Department of Home Affairs, 2018, AghaKouchak et al., 2020).

LITERATURE REVIEW

Pescaroli and Alexander (2018) provide a framework for understanding the complexities of disasters in terms of compound and cascading events and interacting and interconnected risks. We use this framework to understand compound disasters and their relationships to other disaster types that involve multiple facets.

Compound disasters could comprise:

- two or more extreme disaster events occurring simultaneously or successively;
- combinations of extreme events with underlying conditions that amplify their impact; or
- combinations of events that are not themselves extreme but which collectively lead to an extreme impact (Seneviratne et al., 2012; pp. 118).

Zscheischler et al. (2018) provide a more generalised definition of the combining of numerous drivers and/or hazards that add to societal or environmental risk. *Collins et al. (2019) describes compound disasters as multiple failures that may intensify the overall risk and/or generate cascading consequences.* Events can be similar or different hazard categories and occur in the same location or across multiple different locations within a region or country (Wuebbles et al., 2017). The scope of events is dependent upon defined temporal and spatial boundaries. No temporal or spatial parameters are defined though it is acknowledged that they are dependent on the nature of analysis and the magnitude of events (Gill and Malamud, 2014). Despite these definitions, compound disasters are often confused with cascading or interconnected risks (Pescaroli and Alexander, 2018, Cutter, 2018). de Ruiter et al. (2019b) refers to compounding or cascading disasters as consecutive disasters.

A recent example of what we consider to be a compound disaster occurred in the United States in 2017, when in the space of three weeks three major hurricanes -- Hurricanes Harvey, Maria and Irma -- made landfall, followed by wildfires in Northern California a month later (AghaKouchak et al., 2020). Hurricane Harvey made landfall on August 25 in Texas as a Category 4 storm flooding some 200,000 homes (Swiss Re, 2018a). On September 6 Hurricane Irma became one of the strongest Hurricanes ever recorded in the Atlantic basin impacting the US Virgin Islands, Puerto Rico and the Florida Keys. Hurricane Maria then passed southeast of the US Virgin Islands on September 19, striking Puerto Rico the next day as a Category 4 storm causing significant damage to infrastructure. The combined impact of the three hurricanes was some $265B in direct losses, affecting some 47 million people (FEMA, 2018), with an estimated 4844 deaths (FEMA, 2018, Kishore et al., 2018). In October of the same year, some 250 wildfires occurred across Northern California destroying some 8900 structures with insured losses of more than $10.9B (Swiss Re, 2018b). The event was said by FEMA to have presented challenges on an unprecedent scale (FEMA, 2018).

Compound disasters impacting different locations result in coordination challenges and resource depletion. When they strike the same location, they can slow recovery, exacerbate impacts due to already weakened support systems and increase vulnerability to future disasters (Australian Government Department of Home Affairs, 2018, Cutter, 2018, Gill and Malamud, 2014). For example, Haiti was devastated by an earthquake in 2010 whilst still recovering from hurricane impacts inflicted eighteen months earlier (de Ruiter et al., 2019a). In Australia, the townships of Creswick and Charlton experienced flooding three times in space of five months in 2010-11 inhibiting recovery efforts and escalating costs. The smaller floods that were followed by a larger more destructive event were said to have contributed to community apathy (Buloke Shire, 2011). In other instances, however, earlier events may improve resilience, for example, by way of temporary flood mitigation systems.

Since 1970, peak catastrophe loss years have been associated with compound disasters on a global scale. In 2005, the sequence of Hurricanes Katrina, Wilma and Rita; in 2011 earthquakes in New Zealand and Japan within a two-month period; and in 2017 the cluster of hurricanes as described above (Swiss Re, 2019b). This is a problem for a global reinsurer.

Cascading disaster risks are extreme events, in which a sequence of physical, social or economic disruptions increase over time and generate secondary events of strong impact (Pescaroli and Alexander, 2015). They are often described by way of analogy as "toppling dominos" in which once triggered subsequent events result in the spatial and temporal amplification of a disaster along the same or different paths (Cutter, 2018, Pescaroli and Alexander, 2018). Events are related to essential infrastructure and interdependent systems (Pescaroli and Alexander, 2018, Australian Government Department of Home Affairs, 2018).

Often the scale of consequences are non-linear and the impacts are felt well beyond the footprint of the 'initiating' disaster (Cutter, 2018). International examples include: the eruption of the Icelandic volcano Eyjafjallajokull in 2010; the Tohoku earthquake in 2011 and Hurricane Sandy in 2012 (Pescaroli and Alexander, 2015, Cutter, 2018). An Australian example is the 2016 South Australia blackout which resulted from a series of tornadoes that damaged 23 transmission towers, cutting power to the City of Adelaide for days. The blackout caused issues with access to food, public transport, finances, telecommunications, water, medications and fuel. There had been no plan for widespread extended blackouts and related consequences (Burns et al., 2017).

Compound disasters can have cascading disaster features for example during the 2017 US Hurricane season Hurricane Maria caused significant damage to energy infrastructure in Puerto Rico and the longest blackout in US history (Pescaroli et al., 2017). Electrical disruption led to a lack of clean water, closure of schools, business failures, healthcare impacts and deaths (Hernandez et al., 2017). Hurricane Harvey too caused power outages, contamination from water treatment plants and significant disruption to oil production, increasing petrol prices (Glasser, 2019).

Interacting hazards are typically referred to as primary and secondary, whereby the primary hazard triggers a secondary hazard such as heavy rainfall triggering a landslide. Such secondary perils were estimated to account for more than half of global insurance losses in 2017 and 2018 (Swiss Re, 2019b). Interconnected risks have been referred to as those involving physical interdependencies and are considered to be a precondition for cascading risks (Pescaroli and Alexander, 2018).

METHOD

For our purposes here we adopt the Zscheischler et al. (2018) definition of a compound disaster with a focus on those that have caused death or financial damage within Australia.

FREQUENCY ANALYSIS

Fatality data was sourced from the Risk Frontiers' proprietary natural peril database PerilAUS and financial loss data was obtained from the Insurance Council of Australia (ICA) Natural Disaster Event List (hereafter 'Disaster List').

The PerilAUS database contains information on natural peril events that have caused either fatalities or damage to property and is considered complete between 1900 and 2019 (Coates et al., 2014, Crompton et al., 2010). Perils covered include floods, bushfires, tsunami, earthquakes, heatwaves, landslides, gust, hail, rain, tornado and tropical cyclone. The database comprises some 16000 records.

PerilAUS data was cleaned to merge events that were related with each other so as to ensure analysis of independent events having a spatiotemporal coincidence (de Ruiter et al., 2019b). Following the data screening process some 10000 events remained to be analysed.

Rules applied to PerilAUS entries in order to distinguish events potentially contributing to component disaster events were:

- Where a casual linkage could be inferred from commentary in PerilAUS
- When a tropical cyclone led to flooding
- When landslides result from an earthquake
- Severe or frontal storms affecting the same region on the same day
- East coast Lows affecting the eastern seaboard within the same week
- Riverine floods occurring in the same region no greater than two days apart
- Heatwaves occurring within the same week
- Bushfires occurring in the same region on the same day

Compound disasters were identified when any two or more of the above occurred within a three-month window. Three months was chosen as a practical compromise given that event end dates are not recorded in the underlying datasets and that communities impacted by such events occurring within this window could still be plausibly experiencing significant recovery and re-building.

The ICA Disaster List maintained by the Insurance Council of Australia is a database of Australian insurance sector event losses since January 1966. The database covers Australia and is multi-peril in scope including bushfires, floods, severe storms including hailstorms and tropical cyclones, and earthquakes. 94% of the normalised event losses --see later discussion -- arise from weather-related hazards (McAneney et al., 2019). Some 300 events were included in our analysis.

Fields utilised from PerilAUS and the ICA Disaster List included event name and summary; start date; peril type; location (state); and event size. Data were reviewed independently by two individuals.

Multiple data sets were utilised to ensure that several consequence types were considered to more completely capture the frequency of events. For example, hailstorms record few fatalities but incur significant insured losses. Utilising only fatality data would exclude such events.

Data were normalised to estimate the impacts of historical events if they were to occur under present day societal conditions. Fatalities were normalised based on the ratio of 2017 population to that at the event date in the affected state sourced from the Australian Bureau of Statistics. Financial losses were extracted from the normalisation of the Disaster List by McAneney et al. (2019) which adjust historical event loses for changes in exposure, wealth and building codes. Data for 2017/18 and 2018/19 were added in a non-normalised form. We follow McAneney et al. (2019) in employing Australian financial years (12 months from July 1) to separate successive summers when most but not all disaster events take place.

Analysis was undertaken according to multiple loss thresholds. Loss thresholds chosen for individual events were 10, 50 and 100 normalised fatalities (ND) and $100M, $1B and $5B for normalised insurance losses (NL). These thresholds were analysed individually and in pairs: 10 ND and $100M NL, 50 ND and $1B NL, and 100 ND and $5B NL. Lower thresholds were not considered to remove any reporting bias introduced by the greater frequency of smaller events reported in PerilAUS and the Disaster List in more recent decades. PerilAUS records were grouped to match with ICA Disaster List records when considering combined thresholds. For these particular analyses, only PerilAUS records from 1966 onwards were considered.

The spatial boundary adopted was the whole of Australia as the region of concern for Australian emergency management agencies. Where compound disasters were identified they were plotted to illustrate their frequency overtime and compared with the occurrence of other societal stresses such as recessions (for the Australian Bureau of Statistics, war (from the Australian War Memorial) and pandemics (from US Centres for Disease Control).

CLIMATE DRIVERS ANALYSIS

Australia's climate is strongly influenced by large scale ocean-atmosphere conditions, typically described by the El Niño Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD) and the Southern Annual Mode (SAM) indices (Risbey et al., 2009).

ENSO describes coupled ocean-atmosphere conditions in the tropical Pacific: the oceanic component is represented by normalised sea surface temperature anomalies (SSTa) in the Nino3.4 region (Trenberth, 1997), while the atmospheric component is represented by the SOI, which is the twice normalised mean sea level pressure difference between Tahiti and Darwin (Trenberth, 1976). Longer-term variability in Pacific climate is represented by the Interdecadal Pacific Oscillation (IPO) tri-pole index (Folland et al., 2002; Henley et al., 2015). The IOD describes coupled ocean-atmosphere variability in the Indian Ocean and is represented by the Dipole Mode Index (DMI) (Saji et al., 1999). Behaviour of the westerly storm track is represented by the SAM index (Jones et al., 2009; Visbeck and Hall, 2004).

ENSO, IOD and SAM were calculated for each of the five most significant compound event seasons in terms of insured losses and fatalities.

COMPOSITION ANALYSIS

With a view to understanding if there were physical mechanisms that would increase the probability of specific peril combinations, each natural hazard was classified into one of seven perils: Tropical Cyclone, Flood, Storm, Bushfire, Heatwave, Earthquake, or Landslide; where Flood refers primarily to riverine flooding and Storm encompasses all non-Tropical Cyclone storms including Thunderstorm (hail and lightning), East Coast Low and Frontal Systems (See Figures 1-6).

All combinations of perils, and peril-pair combinations were then identified for all compound disasters within a three-month window. The state in which each peril impacted was also recorded to identify any preferred combination of locations.

A bootstrapping approach was then used to explore whether observed peril-pair combination frequencies occur by chance, or might instead be responding to potentially predictable forcing such as interannual climate variability. 1000 synthetic event sets were created where perils retain their probability of occurrence and the time of year and state in which they occur. For each year of the synthetic event sets the frequency of each peril was sampled from a Poisson distribution based on its historical mean frequency. To preserve realistic seasonality and timing, this number of perils was then randomly sampled from the observed dataset to obtain the day-of-year and state in which they occurred. From the synthetic event sets we are then able to examine the combinations of event types and locations that would constitute an effectively random compound disaster as a comparison to observed occurrences.

LIMITATIONS

Limitations exist regarding the use of historical disaster impact databases to analyse compound disasters including: the PerilAUS database only includes event start dates so the duration of events was unknown; it is possible that databases though comprehensive may be incomplete; there are assumptions made in the normalisation of the impacts data; there is potential reporting bias in historical data sets, though this was removed by focusing on extreme events; and analysing deaths and financial losses does not cover the full range of possible disaster impacts.

RESULTS

FREQUENCY OF COMPOUND DISASTERS

We first analysed threshold combinations from 1966/1967 to 2018/2019 utilising the ICA Disaster List and PerilAUS. Over this time there were 43 compound disasters comprised of component disasters that exceeded either an insured loss of $100M NL or 10 ND (Figure 1). Compound disasters matching this threshold were recorded in all years but nine over the timespan.

The average number of component disasters to comprise a compound disaster was three with a maximum of eight. Ninety five percent of compound disasters impacted multiple jurisdictions. The time between the start date of the first disaster and the start date of the last disaster in the sequence averaged some 71 days.

The majority of compound disasters occurred during the months of November (n=10), December (n=14) and January (n=9) consistent with Australia's bushfire, severe heat, tropical cyclone and severe storm seasons.

All financial years that recorded a compound disaster had one compound disaster only apart from 2005 where there were two. 23 of the 42 compound disasters occurred at the time of one or more longer-term stressor.

There is no trend in the number of compound disasters over this period for the combined insurance loss and death thresholds or when considering insurance losses alone.

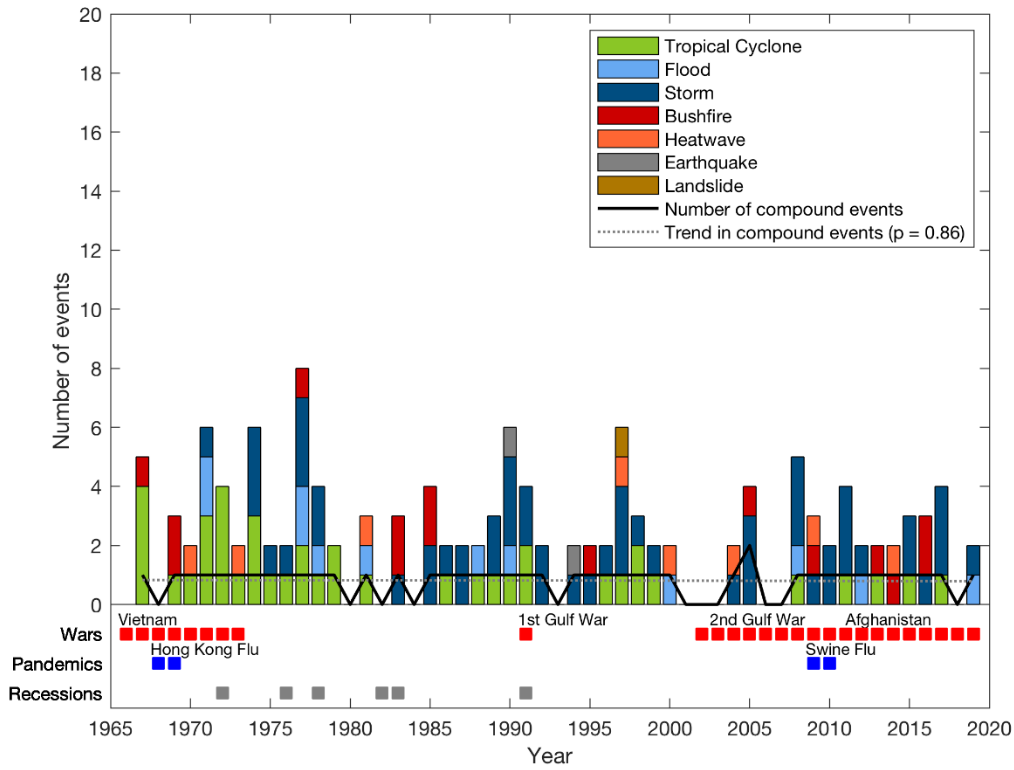


FIGURE 1: COMPOUND DISASTERS WITHIN A THREE-MONTH WINDOW AND HAVING AT LEAST 10 ND AND/OR $100MN NL. YEARS ALONG THE X-AXIS REFER TO FINANCIAL YEARS. LONG-TERM STRESSORS INCLUDED.

From 1966/1967 to 2018/2019 there were six compound disasters comprised of individual disasters that exceeded either $1B NL or 50 ND (Figure 2). There was an average and maximum number of two component disasters per compound disaster.

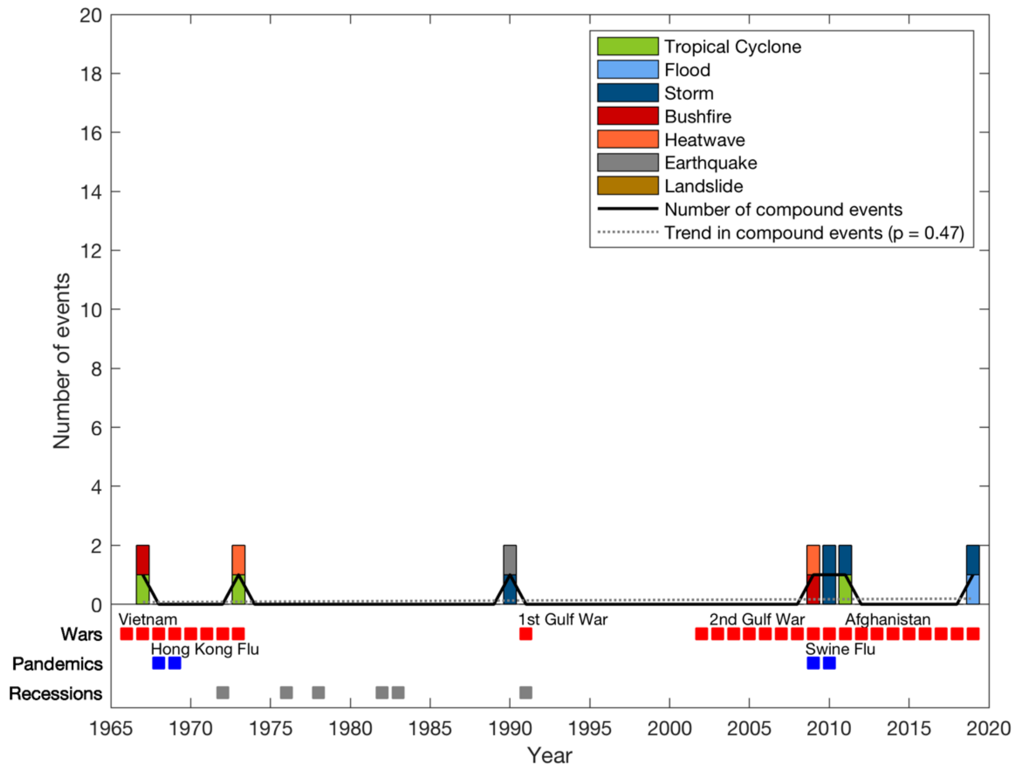


FIGURE 2: COMPOUND DISASTERS WITHIN A THREE-MONTH WINDOW WITH LOSSES IN EXCESS OF 50 ND AND/OR $1B NL BY FINANCIAL YEAR. LONG-TERM STRESSORS INCLUDED.

Only one compound disaster in 2008/09 was observed between 1966/67 and 2018/19 where component disasters exceeded either 100 ND or $5B NL (Figure 3).

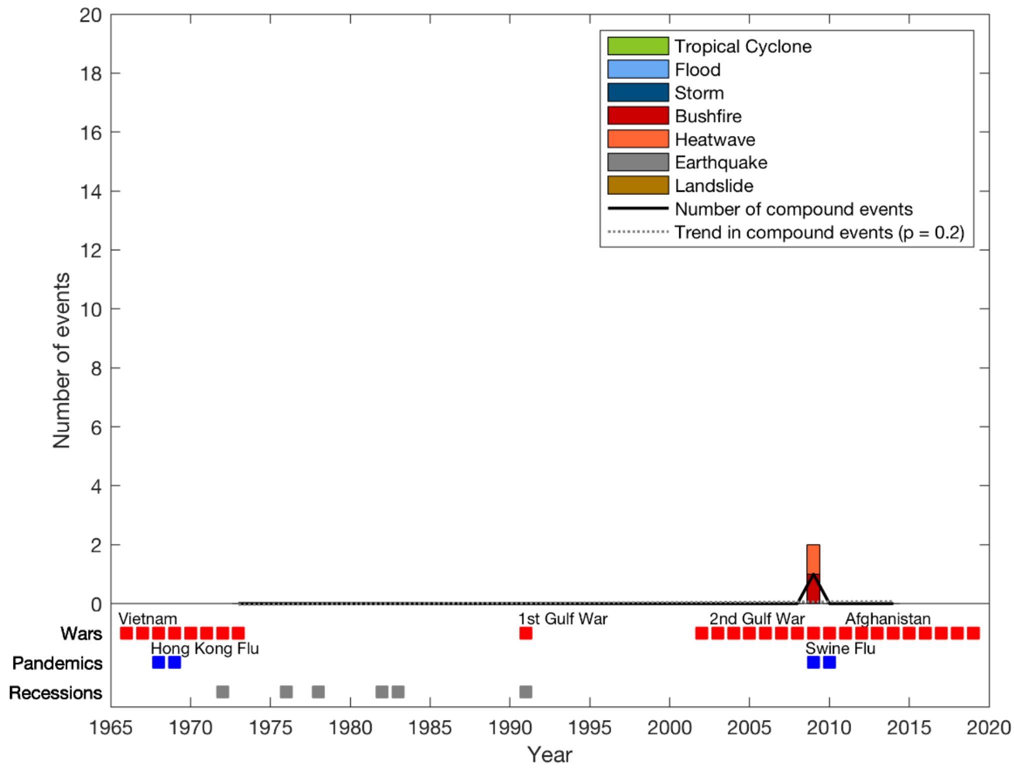


FIGURE 3: AS FOR FIGURES 1 AND 2 WITH LOSS THRESHOLDS OF 100 ND AND/OR $5B NL. LONG-TERM STRESSORS INCLUDED.

We then considered compound disasters using fatality data only from PerilAUS to achieve a longer timeframe of 119 years. From 1900/01 to 2018/19 there were 65 compound disasters where component disasters exceeded 10 ND (Figure 4). The average number of normalised deaths associated with these compound disasters was 355. On average each compound disaster consisted of five component disasters with a maximum of 19. In 92 percent of compound disasters component disasters impacted multiple jurisdictions. The time between the start date of the first disaster and the start date of the last disaster in the sequence averaged some 96 days.

Over the 119 years of record there were 60 years that did not record a compound event. There were six years where two occurred. 31 out of the 59 compound disasters occurred in conjunction with at least one longer-term stressor.

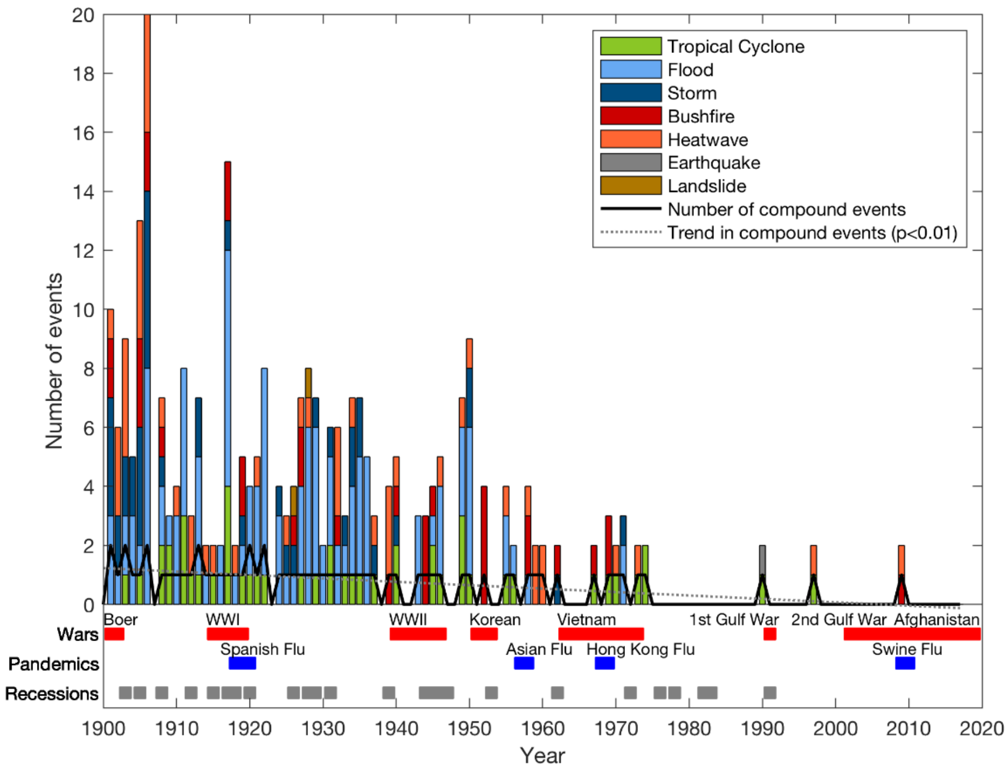


FIGURE 4: COMPOUND DISASTERS WITHIN A THREE-MONTH WINDOW AND GREATER THAN 10 ND. LONG-TERM STRESSORS INCLUDED.

There were 12 compound disasters whose component disasters exceeded 50 ND (Figure 5) and six compound disasters where component disasters exceeded 100 ND (Figure 6). The average number of normalised deaths associated with these compound disasters was 799 and 1232 respectively. The average number of component disasters for both thresholds was two.

The number of compound disasters defined by deaths has decreased in frequency particularly after the end of World War II. This reflects the downward trend in normalised deaths associated with natural hazards in Australia (Haynes et al., 2017, Coates et al., 2014). Since 1940, there has only been one compound disaster associated with events that comprised more than 100 ND; this occurred in 2009/2010.

The longer-term fatality analysis produced similar results in terms of seasonality as the joint normalised death/ insurance losses with peak months being December (n=19), January (n=22) and February (n=5).

The number of compound disasters recorded using fatality data alone will not account for those significant disasters in which few fatalities occurred, but where severe financial losses were experienced. Therefore, the use of fatality data alone possibly underestimates the frequency of compound disasters.

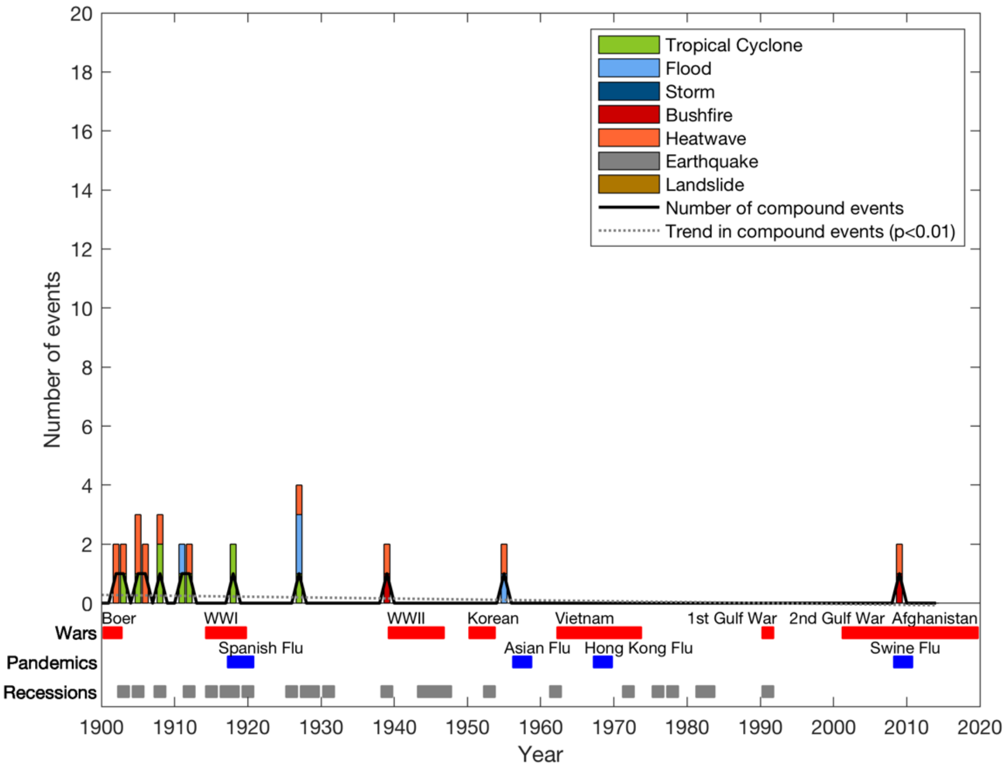


FIGURE 5: COMPOUND DISASTERS WITHIN A 3 MONTH WINDOW AND GREATER THAN 50 ND. OTHER SYMBOLS AS FOR FIGURES 1 TO 4.

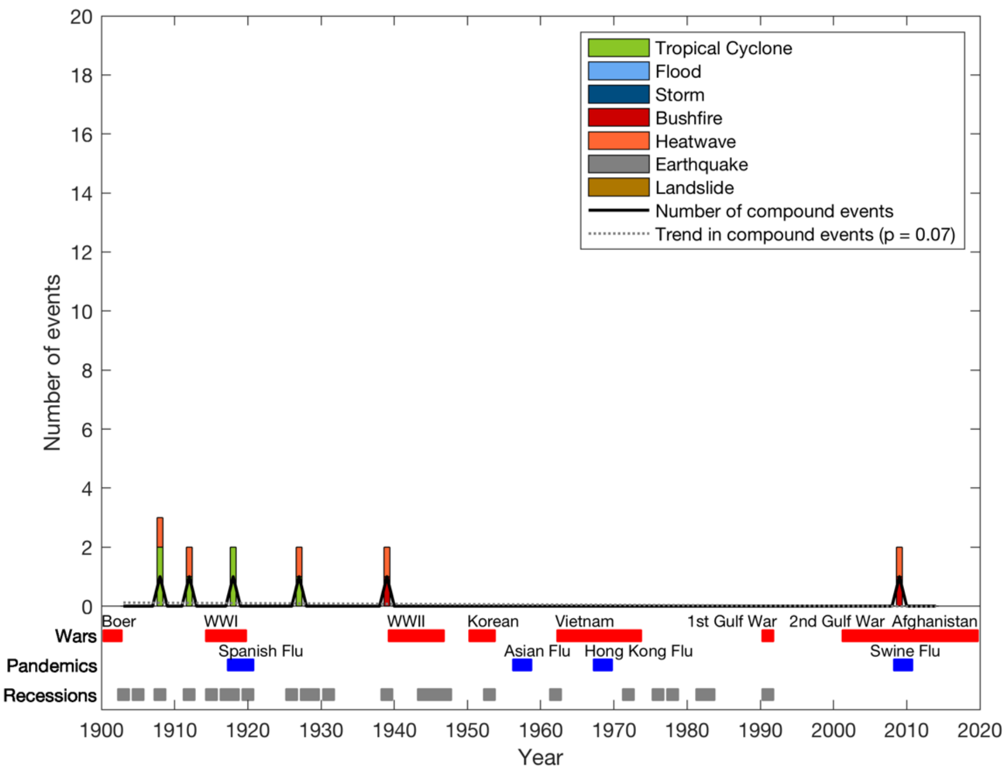


FIGURE 6: COMPOUND DISASTERS WITHIN A THREE-MONTH WINDOW AND HAVING AT LEAST 100 ND. OTHER SYMBOLS AS FOR FIGURES 1 TO 4.

SIGNIFICANT COMPOUND DISASTERS

The most significant historical compound disasters in terms of total normalised insured losses are listed in Table 1. 1967 ranks as Australia's most significant in terms of normalised insurance losses, followed by financial years 1989/90, 1998/99, 1974/75 and 2010/11.

The 1967 compound disaster commenced in January 1967, when category 3 Tropical Cyclone Elsie struck Western Australia. Although no deaths were inflicted, a normalised damage of nearly $200M was incurred as roads, railways and airfields across the state were damaged by the cyclone's concomitant floodwaters. Later that month, Queensland was struck by a tropical cyclone of its own, as Dinah brought highly damaging winds and rainfalls across the state coastline with a normalised insurance loss of just over $4.5B. Not much more than a week later, the Black Tuesday bushfires ravaged the states of Victoria and Tasmania on 7 February 1967. The fires claimed 62 lives, alongside more than $2B normalised damage to houses, cars, buildings and bridges across the south-eastern states. Tens of thousands of livestock perished, while 8 firefighters were injured in road accidents.

Then in NSW in the middle of February, a category 1 cyclone brought extensive coastal erosion, localised flooding and a half-billion-dollar damage bill. Although Tropical Cyclone Barbara caused a lot less damage than its Queensland counterpart Dinah, it came at a time when multiple other states were still grappling with recovery efforts for recent disasters. It was finished off in early April with category 2 Tropical Cyclone Glenda, a disaster that killed 6 people in Queensland.

TABLE 1: TOP 5 MOST SIGNIFICANT COMPOUND DISASTERS BASED ON INSURANCE LOSSES

Rank	Financial Year	Component Event	Original insured Loss	Total Normalised insured loss
1	1966/67	Tropical Cyclone Elsie WA, Tropical Cyclone Dinah QLD, Black Tuesday Bushfires VIC / TAS, Tropical Cyclone Barbara NSW, Tropical Cyclone Glenda QLD	$77.5M	$7.6B
2	1989/90	Newcastle Earthquake, Ballarat Hailstorm VIC, Tropical Cyclone Nancy NSW / QLD, Sydney Storms, Flood Eastern States, Aircraft Crash in Storm QLD	$1.3B	$6.4B
3	1998/99	Sydney Hailstorm, Tropical Cyclone Vance WA	$1.7B	$5.7B
4	1974/75	Tropical Cyclone Tracy NT, Floods across NSW	$215M	$5.4B
5	2010/11	Floods QLD, Floods VIC, Tropical Cyclone Yasi QLD, Severe Storm VIC	$4B	$4.6B

The most significant historical compound disasters in terms of normalised fatalities are listed in Table 2. The most significant compound disaster in terms of normalised fatalities occurred during financial years 1907/08 followed by 1911/12, 1916/17, 1938/39 and 1910/11.

The 1907/08 event comprised of an extreme heatwave in January 1908 with Melbourne experiencing some six days with temperatures exceeding 40 C, peaking at 44 C on January 17. Adelaide also experienced six days with maximum temperatures greater than 40 C. Some 246 people died as a result of the heatwave while further deaths and displacement as a result of bushfires in the Otway Ranges and South Gippsland. In February and March flooding affected central parts of NSW causing several deaths. In April came two cyclones occurring sixteen days apart. The first cyclone impacted Cooktown, Queensland, taking some 58 lives and the second Broome, Western Australia, taking a further 50 lives.

Since, 1940 the most significant compound disaster based on fatalities occurred in 2008/09. The event comprised a heatwave and bushfires, the heatwave occurring across both Victoria and South Australia lasted from January 27 until of February 8. Many locations reached their hottest temperature since 1939. Temperatures in Melbourne exceed 43 C for three consecutive days with widespread power outages and disrupted transport networks. An estimated 406 deaths occurred (Australian Institute for Disaster Resilience, n.d-b). On February 7 approximately 400 bushfires occurred across Victoria, resulting in 173 deaths and 2029 houses destroyed (Australian Institute for Disaster Resilience, n.d-a).

TABLE 2: TOP 5 MOST SIGNIFICANT COMPOUND DISASTERS BASED ON FATALITIES

			Raw Deaths	Total Normalised Deaths
1	1907/08	VIC / SA Heatwave, Bushfires SE Australia, Floods NSW, Floods NSW, Tropical Cyclone QLD, Tropical Cyclone WA	364	2320
2	1911/12	SA Heatwave, Melbourne Heatwave, Tropical Cyclone WA	295	1844
3	1916/17	Floods VIC, Floods NSW, Flood QLD, Christmas Eve Thunderstorm NSW, Tropical Cyclone QLD, Flood QLD, Tropical Cyclone NT, Flood VIC, Flood WA, Bushfires QLD, Floods NSW, Floods QLD, Tropical Cyclone QLD, Tropical Cyclone QLD	201	1646
4	1938/39	NSW Heatwave, NSW / VIC / SA Heatwave, Black Friday Bushfires NSW / VIC / SA, WA Heatwave	515	1510
5	1910/11	Tropical Cyclone WA, Floods QLD, Flood QLD, Flood QLD, Tropical Cyclone QLD, Tropical Cyclone QLD, Floods QLD, Flood NT	173	1501

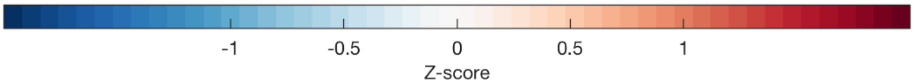
CLIMATE AND METEOROLOGICAL DRIVERS OF COMPOUND DISASTERS

The frequency of weather-related perils in the Australian region is influenced by large scale climate drivers (primarily ENSO, IOD/DMI and SAM/AAO); for example Tropical Cyclone activity and precipitation for much of Australia, especially the populated eastern states, increases under La Nina, whereas precipitation deficits and landscape drying often occur under El Nino (Risbey et al., 2009).

Normalised mean monthly climate index values were calculated for all observed weather-related perils contributing to compound disasters exceeding $100M NL or 10 ND (Table 3). Tropical Cyclones occur preferentially under La Nina and IOD/DMI positive. Flood is more frequent for negative phases of La Nina and IPO. Storm shows no clear preference for climate driver state, possibly due to the wide variety of storm event types. Bushfire occurs preferentially under El Nino and IPO positive and SAM/AAO negative. Heatwave shows no significant preference for climate driver state but may be more frequent under IOD/DMI positive.

TABLE 3: MEAN NORMALISED (Z-SCORE) CLIMATE INDEX VALUES FOR ALL EVENT PERILS SHOWN IN FIGURE 1 (COMPOUND DISASTERS WITH MORE THAN 10 ND AND/OR $100MN NL). VALUES WHICH ARE SIGNIFICANTLY DIFFERENT FROM THE MEAN (P<0.05) ARE IN BOLD TYPE.

	Nino 3.4	IPO	SOI	IOD	SAM
TC	**-0.38**	**-0.33**	**0.35**	**0.4**	-0.17
Flood	-0.53	-0.49	0.1	0.18	-0.19
Storm	-0.09	-0.17	0.18	-0.1	0.07
Bushfire	**0.58**	0.49	-0.51	-0.07	-0.44
Heatwave	-0.05	0.01	0.09	0.33	-0.07



At seasonal timescales, highest losses often coincide with an increase in the frequency and/or intensity of specific types of weather systems. For example, 2011 saw some of the largest insured losses through compound disasters when a succession of heavy rain events occurred across Northern Australia as part of the Australian monsoon system (Shaik and Lisonbee, 2012). Events and seasonal variability are related because weather systems themselves are part of continental to hemispheric scale phenomena operating across multiple timescales.

For compound disasters with the highest insured losses (Table 1), all but one-year (1989-90) show clear La Nina like conditions (Figure 7), with negative Nino 3.4 SSTa, negative IPO, and neutral to positive SOI. The mean index values across all five highest seasons also indicate La Nina like conditions. The IOD was neutral to negative for the springtime during most seasons, trending to more neutral values by summer. The SAM index was mostly positive during the springtime, while there are both positive and negative SAM values during the late Summer and Autumn periods.

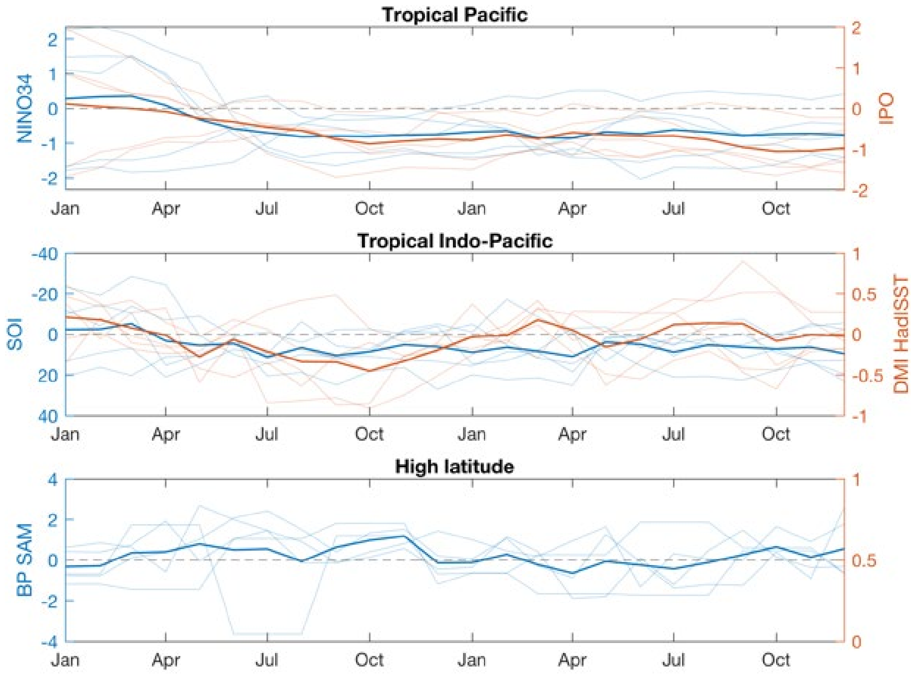


FIGURE 7: SUPERIMPOSED EPOCH ANALYSIS FOR THE FIVE YEARS OF HIGHEST INSURED LOSSES

For compound disaster seasons with the highest fatalities, three of five are La Nina-like, whereas two out of five seasons are strongly El Nino (Figure 8). The springtime IOD is negative for most high fatality seasons while there is no clear signal for the SAM. However, it should be noted that the SAM is highly uncertain prior to ~1980 due to lack of observational data (Ho et al., 2011).

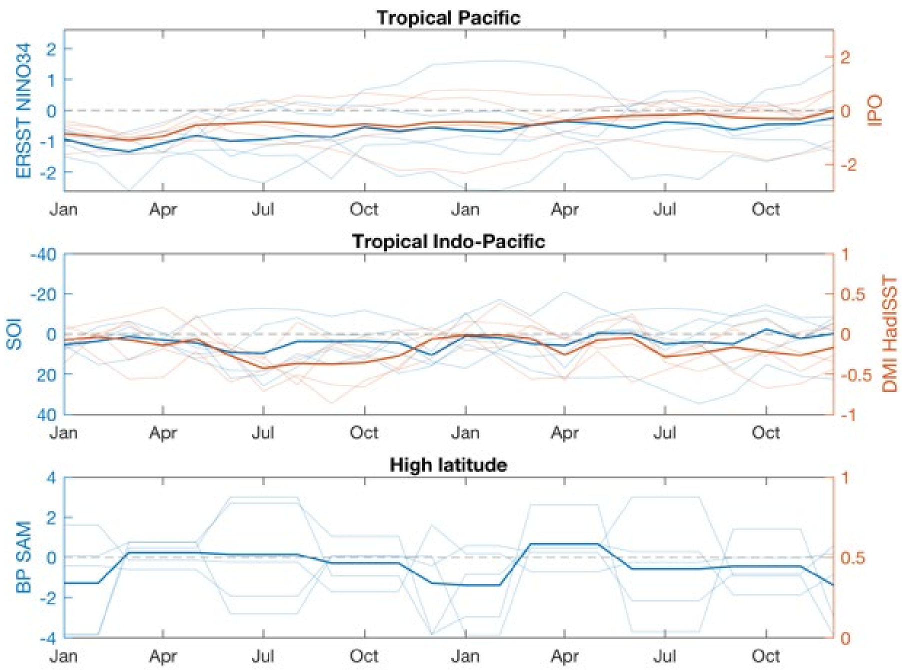


FIGURE 8: SUPERIMPOSED EPOCH ANALYSIS FOR THE FIVE YEARS OF HIGHEST FATALITIES

EVENT COMPOSITION

The frequency of unique peril-pair combinations within compound disasters for the events exceeding $100M NL or 10 ND are shown in Figure 9. The most frequent peril-pair combination of Storm-Tropical Cyclone occurred 50 times over 53 years from 1967 to 2019. The top five most frequent peril-pair combinations involve storm-related weather perils: Tropical Cyclone, Flood and Storm. Bushfire combined with Storm and Tropical Cyclone are the 6th and 7th most frequent peril-pair, and Heatwave combined with Storm and Tropical Cyclone are the 8th and 9th most frequent.

The mean frequency of peril pairs in a 1000-member simulated dataset are also shown in Figure 9. In the simulated dataset perils occur with the same frequency and seasonality as the observed data, but pairing is effectively random. In both the observed and simulated datasets Storm and Cyclone are the most frequent individual perils and form the most common peril parings. However, in the observed dataset they pair more frequently with Flood and in the simulated dataset more frequently with Bushfire. The largest difference between observed and simulated event sets is for the peril-pair of Bushfire-Flood, which have more than double the frequency in the simulated dataset compared with observations. Likewise, Heatwave pairs more frequently with Storm, Tropical Cyclone and Flood in the simulated dataset than it does in observations—with Heatwave-Tropical Cyclone occurring 71% more often in the simulated dataset.

The differences in peril paring between observed and simulated, especially for Flood and Bushfire, can in part be explained by interannual climate variability through its effect on peril-event frequency and antecedent conditions. Under La Nina conditions, where Storm and Tropical Cyclone are more frequent (Table 3), precipitation is increased leading to higher overall soil moisture and frequency of flooding. In the observed event dataset Flood pairs with Storm and Tropical Cyclone ~50% more often than in the simulated dataset which does not take into consideration the real-world physical climate processes. Under El Nino there is a reduction in storm frequency and overall, less precipitation, leading to a dryer landscape and higher risk of bushfire. The combination of Bushfire with Storm and Tropical Cyclone is 20% and 56% more frequent in the simulated dataset than in the observed because the physical conditions for their co-occurrence is less likely than by chance due to climate driver influence. The climate driver relationships for Heatwave are less clear, however they also pair less frequently with storm-related perils in observations than in the simulated event sets.

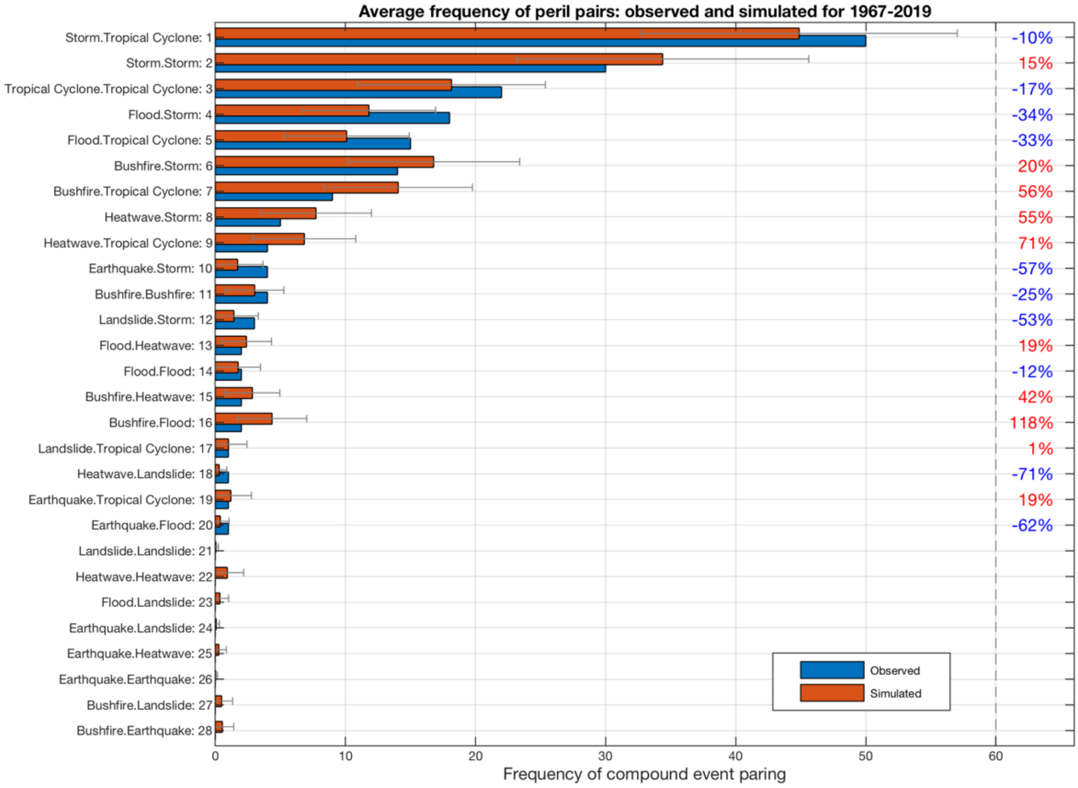


FIGURE 9: OBSERVED AND SIMULATED PERIL-PAIR FREQUENCY FOR ALL PERILS SHOWN IN FIGURE 1 (COMPOUND DISASTERS WITH MAXIMUM THREE MONTH SPACING, 10 ND, $100MN NL) FOR OBSERVED (BLUE) AND SIMULATED (RED). ERROR BARS INDICATE +/- 1 STANDARD DEVIATION OF THE MEAN FREQUENCIES ACROSS 1000 SIMULATED EVENT SETS. PERCENTAGES ON THE RIGHT SIDE INDICATE CHANGE BETWEEN OBSERVED AND SIMULATED PERIL-PAIR FREQUENCIES

STATE COMBINATIONS

Perils comprising compound disasters can occur in different locations around Australia. NSW, QLD, and VIC experience the most individual events and compound events. NSW and QLD comprise the most frequent location paring within compound disasters (Figure 10). The next most common parings are for NSW and VIC, and QLD and VIC. Compound disasters where component perils occur in different states, such as QLD.NSW (Figure 10) are more frequent than compound events where component perils occur within the same state, such as QLD.QLD.

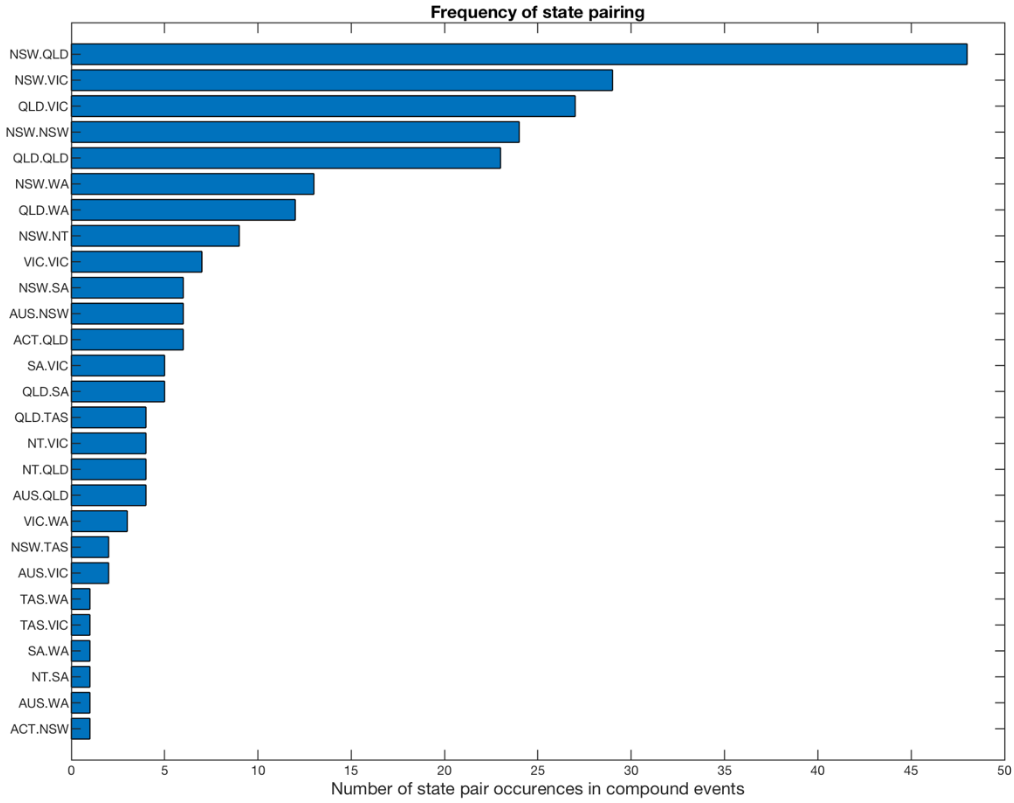


FIGURE 10: OBSERVED FREQUENCY OF STATE PARING FOR COMPOUND EVENTS FOR ALL PERILS SHOWN IN FIGURE 1 OVER THE 1967 TO 2019 PERIOD. WHERE, FOR EXAMPLE, NSW.QLD INDICATES THAT A COMPOUND EVENT OCCURRED WITH PERILS EXPERIENCED IN BOTH NSW AND QLD, WHILE NSW.NSW INDICATES A COMPOUND EVENT WHERE MULTIPLE PERILS WERE EXPERIENCED IN NSW.

DISCUSSION AND CONCLUSION

In the first analysis of its kind our results have shown that Australia has a history of compound disasters. There have been at least 92 years associated with compound disasters from 1900/01 to 2018/19 where component events have consisted of either 10 ND or $100 M NL.

The occurrence of the five largest compound disasters in terms of insurance losses since 1966/67 are associated with the five most significant seasonal insurance losses in Australia's history (1966/67, 1989/90, 1998/99, 1974/75 and 2010/11) (McAneney et al., 2019). Likewise, the deadliest compound disasters in terms of normalised deaths are associated with the five deadliest years since 1900 (1907/08, 1911/12, 1916/17, 1938/39 and 1910/11).

All top five most expensive compound disasters were associated with the disasters listed within the top ten insured normalised losses. Likewise, the deadliest compound disasters were associated with disasters listed in the top ten normalised deadliest disasters since 1900. These points Illustrate the significance of single event extremes within component disasters.

The occurrence of compound disasters at the time of societal stressors would further amplify impacts and result in complex emergency management challenges. Consideration of the coincidence of other societal stressors at the time of compound disasters has not received attention prior to the current COVID-19 pandemic.

This study considered component disasters that occurred within three months of each other. Compound disasters can manifest much quicker. For example, some of the most significant compound disasters that have had component events within one week of each other include:

- Victorian bushfires coupled with a severe Brisbane thunderstorm on January 14 and 18, 1985, respectively, tallying a normalised loss of $3.1B.
- Deadly heatwave killing over 400 people in NSW, Victoria and South Australia, together with the Black Friday bushfires across the same states and a less deadly heatwave in Western Australia, all concentrated in early January 1939. The total death tally was over 500.

Faster compound disasters would clearly increase the vulnerability of disaster management systems and communities to subsequent component hazards (de Ruiter et al., 2019b).

Eastern states appear to be most often involved in compound disasters. Though there are times when component disasters occur both in the east and west of Australia potentially creating resource and coordination challenges. Peril combination results provide evidence to inform the creation of realistic compound disaster scenarios.

Almost all Australian natural peril events are weather- or climate-related. Climate drivers influence the frequency and intensity of individual peril events; for example, under La Niña conditions Tropical Cyclone and Flood are more likely (Dowdy et al., 2012, Risbey et al., 2009), whereas under El Niño Bushfires are more prevalent (Dowdy, 2017). Given that ENSO is the most predictable climate driver at seasonal timescales, this may assist agencies and disaster managers better forecast their occurrence and implement higher degrees of readiness.

These relationships are also reflected in the peril-pairs contributing to compound disasters; for example, pairing of Bushfire and Tropical Cyclone occur far less often in reality then would be expected by chance, because these individual perils occur most frequently under contrasting mean climate states.

Given the clear significance of compound disasters and the challenges that they present further attention must be applied to their incorporation in risk assessments. This should include the adoption of a multi hazard approach that considers the occurrence of multiple disasters (including societal stressors) occurring concurrently or sequentially. This analysis should be forward looking to consider impacts of projected climate change and changes in exposure. Such an approach should inform capability analysis and disaster planning performed by disaster management organisations. National disaster management arrangements should account for compounding disasters and assume that multiple states may be impacted at the time of a severe to catastrophic disaster event. The dynamic nature of compound events underlines the need for flexible and adaptable disaster plans, that are scalable to the impact of multiple disasters (Gissing et al., 2018).

The decrease in the number of compound disasters defined by exceeding death thresholds since the 1940s demonstrates the impacts of societal changes and enhancements in disaster mitigation and the organisation of disaster management organisations. For example Haynes et al. (2017) attributes reductions in flood fatalities to investments in flood mitigation, technology, warning systems and the work of State Emergency Services. Similar conclusion can also be reached regarding deaths associated with tropical cyclones (Coates et al., 2017). This evidence supports that the frequency and severity of compound disasters can be influenced by disaster mitigation investments (Australian Government Productivity Commission, 2014).

COMPOUND DISASTER SCALE

The development of a consequence-based compound disaster event magnitude scale may assist to contextualise and account for the significance of compound disasters. Scales are widely applied in the study and management of natural disasters (Alexander, 2018). The purpose of such a scale would be to enable different compound disasters to be compared and to assist in identifying compound disaster scenarios that would truly test coordination and resourcing.

The thresholds used in our analysis would seem logical to define the scale as outlined in Table 3. At a given scale of magnitude, each event must surpass at least one of the two tabulated thresholds before it can form part of a compound disaster.

TABLE 3: SUGGESTED EVENT MAGNITUDE SCALE FOR COMPOUND DISASTERS IN AUSTRALIA.

Magnitude scale	Number of component events	Death threshold of each component disaster	Loss threshold of each component disaster
I	Between two and three	10	$100M
II	More than three events	10	$100M
III	Two	50	$1B
IV	More than two	50	$1B
V	Two	100	$5B
VI	More than two	100	$5B
VII	Two	500	$20B
VIII	More than two	500	$20B

To illustrate the application of the scale the summer of 2019/20 comprised two disasters that exceeded $1B in insured losses: the 2019/20 bushfires commencing November 8, 2019 ($2.2B) and the January Hailstorms in Victoria, Australian Capital Territory, New South Wales and Queensland commencing January 18, 2020 ($1.6B). An earlier hailstorm event on November 17, 2019 was associated with losses of $166M and an East Coast Low Storm in February with losses of $957M[1]. Though the bushfires and associated smoke impacts were deadly there was not another disaster that resulted in ten or more deaths. Based on the suggested scale it would rate as a level III compound event. Since 1966/67 the highest rated compound disaster would be a magnitude V.

1 Values as at 11/9/2020

Further research

The methodology utilised for this study could be used to analyse similar datasets on a regional or global scale.

REFERENCES

AGHAKOUCHAK, A., CHIANG, F., HUNING, L. S., LOVE, C. A., MALLAKPOUR, I., MAZDIYASNI, O., MOFTAKHARI, H., PAPALEXIOU, S. M., RAGNO, E. & SADEGH, M. 2020. Climate Extremes and Compound Hazards in a Warming World. *Annual Review of Earth and Planetary Sciences,* 48.

AGHAKOUCHAK, A., HUNING, L. S., CHIANG, F., SADEGH, M., VAHEDIFARD, F., MAZDIYASNI, O., MOFTAKHARI, H. & MALLAKPOUR, I. 2018. How do natural hazards cascade to cause disasters? : Nature Publishing Group.

ALEXANDER, D. 2018. A magnitude scale for cascading disasters. *International journal of disaster risk reduction,* 30**,** 180-185.

AUSTRALIAN GOVERNMENT DEPARTMENT OF HOME AFFAIRS. 2018. Profiling Australia's Vulnerability: the interconnected causes and cascading effects of systemic disaster risk. Available: https://www.aidr.org.au/media/6682/national-resilience-taskforce-profiling-australias-vulnerability.pdf [Accessed 15/4/2020].

AUSTRALIAN GOVERNMENT PRODUCTIVITY COMMISSION 2014. Natural Disaster Funding Arrangements. Canberra, Australia: Australian Government Productivity Commission.

AUSTRALIAN INSTITUTE FOR DISASTER RESILIENCE. n.d-a. Bushfire - Black Saturday. Available: https://knowledge.aidr.org.au/resources/bushfire-black-saturday-victoria-2009/ [Accessed 7/4/2020].

AUSTRALIAN INSTITUTE FOR DISASTER RESILIENCE. n.d-b. Health - south-eastern Australia heatwave. Available: https://knowledge.aidr.org.au/resources/health-heatwave-south-eastern-australia-2009/ [Accessed 7/4/2020].

BALDWIN, J. W., DESSY, J. B., VECCHI, G. A. & OPPENHEIMER, M. 2019. Temporally compound heat wave events and global warming: An emerging hazard. *Earth's Future,* 7**,** 411-427.

BEVACQUA, E., MARAUN, D., VOUSDOUKAS, M. I., VOUKOUVALAS, E., VRAC, M., MENTASCHI, L. & WIDMANN, M. 2019. Higher probability of compound flooding from precipitation and storm surge in Europe under anthropogenic climate change. *Science advances,* 5**,** eaaw5531.

BORCHERS ARRIAGADA, N., PALMER, A. J., BOWMAN, D. M., MORGAN, G. G., JALALUDIN, B. B. & JOHNSTON, F. H. 2020. Unprecedented smoke-related health burden associated with the 2019–20 bushfires in eastern Australia. *Medical Journal of Australia*.

BULOKE SHIRE. 2011. 2011 Flood Recovery Evaluation. Available: https://aidrmed.s3.ap-southeast-2.amazonaws.com/prod/evaluations/e75b8fb1-6106-4367-9bb7-a9d14dc69e1e/Nov%2014%202012%20-%20Item%203.2.7%20-%202011%20Flood%20Recovery%20Evaluation.pdf [Accessed 19/5/2020].

BURNS, G., ADAMS, L. & BUCKLEY, G. 2017. Independent Review of the Extreme Weather Event South Australia 28 September - 5 October 2016.

COATES, L., HAYNES, K., O'BRIEN, J., MCANENEY, J. & DE OLIVEIRA, F. D. 2014. Exploring 167 years of vulnerability: an examination of extreme heat events in Australia 1844–2010. *Environmental Science & Policy,* 42**,** 33-44.

COATES, L., HAYNES, K., RADFORD, D., D'ARCY, R., SMITH, C., VAN DEN HONERT, R. & GISSING, A. 2017. An analysis of human fatalities from cyclones, earthquakes and severe storms in Australia. Available: https://www.bnhcrc.com.au/publications/biblio/bnh-3568 [Accessed 22/5/2020].

COLLINS, M., SUTHERLAND, M., BOUWER, L., CHEONG, S.-M., FRÖLICHER, T., JACOT DES COMBES, H., KOLL ROXY, M., LOSADA, I., MCINNES, K., RATTER, B., RIVERA-ARRIAGA, E., SUSANTO, R. D., SWINGEDOUW, D., TIBIG, L., [H.-O. PÖRTNER, D.C. ROBERTS, V. M.-D., P. ZHAI, M. TIGNOR, E. POLOCZANSKA, K. MINTENBECK, A. ALEGRÍA, M. NICOLAI, A. OKEM, & J. PETZOLD, B. R., N.M. WEYER (EDS.)]. IN PRESS. 2019. Extremes, Abrupt Changes and Managing Risk. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

CROMPTON, R. P., MCANENEY, K. J., CHEN, K., PIELKE JR, R. A. & HAYNES, K. 2010. Influence of location, population, and climate on building damage and fatalities due to Australian bushfire: 1925–2009. *Weather, Climate, and Society,* 2**,** 300-310.

CUTTER, S. L. 2018. Compound, cascading, or complex disasters: what's in a name? *Environment: science and policy for sustainable development,* 60**,** 16-25.

DE RUITER, M., COUASNON, A., VAN DEN HOMBERG, M., DANIELL, J., GILL, J. & WARD, P. How can we better understand the risk and impacts of consecutive disasters in developing countries? Geophysical Research Abstracts, 2019a.

DE RUITER, M. C., COUASNON, A., VAN DEN HOMBERG, M. J., DANIELL, J. E., GILL, J. C. & WARD, P. J. 2019b. Why we can no longer ignore consecutive disasters. *Earth's Future*.

DOWDY, A. J. 2017. Climatological Variability of Fire Weather in Australia. *Journal of Applied Meteorology and Climatology*, 1-36.

DOWDY, A. J., QI, L., JONES, D., RAMSAY, H., FAWCETT, R. & KULESHOV, Y. 2012. Tropical Cyclone Climatology of the South Pacific Ocean and Its Relationship to El Niño–Southern Oscillation. *Journal of Climate,* 25**,** 6108-6122.

FEMA. 2018. 2017 Hurricane Season FEMA After-Action Report. Available: https://www.fema.gov/media-library-data/1531743865541-d16794d43d3082544435e1471da07880/2017FEMAHurricaneAAR.pdf [Accessed 6/4/2020].

GALLINA, V., TORRESAN, S., CRITTO, A., SPEROTTO, A., GLADE, T. & MARCOMINI, A. 2016. A review of multi-risk methodologies for natural hazards: Consequences and challenges for a climate change impact assessment. *Journal of environmental management,* 168**,** 123-132.

GANGULI, P. & MERZ, B. 2019. Trends in Compound Flooding in Northwestern Europe During 1901–2014. *Geophysical Research Letters,* 46**,** 10810-10820.

GILL, J. C. & MALAMUD, B. D. 2014. Reviewing and visualizing the interactions of natural hazards. *Reviews of Geophysics,* 52**,** 680-722.

GISSING, A. 2020. 2019/2020 Australian bushfire season. *Risk frontiers Newsletter,* 19.

GISSING, A., EBURN, M. & MCANENEY, J. 2018. Planning and capability requirement for catastrophic and cascading disasters - literature review. Melbourne: Bushfire and Natural Hazards Cooperative Research Centre.

GLASSER, R. 2019. Preparing for the Era of Disasters. Available: https://s3-ap-southeast-2.amazonaws.com/ad-aspi/2019-03/SR%20135%20Preparing%20for%20the%20Era%20of%20Disasters.pdf?DWvHu1e1M0UMbiuK5_A8qhOlZJr1z0qD [Accessed 6/4/2020].

HAO, Z., SINGH, V. P. & HAO, F. 2018. Compound extremes in hydroclimatology: a review. *Water,* 10**,** 718.

HAYNES, K., COATES, L., VAN DEN HONERT, R., GISSING, A., BIRD, D., DIMER DE OLIVEIRA, F., RADFORD, D., D'ARCY, R. & SMITH, C. 2017. Exploring the circumstances surrounding flood fatalities in Australia - 1900-2015 and the implications for policy and practice. *Environmental Science and Policy.,* 76**,** 165-176.

HERNANDEZ, A., LEAMING, W. & MURPHY, Z. 2017. Sin Luz Life Without Power. *Washington Post* [Online]. Available: https://www.washingtonpost.com/graphics/2017/national/puerto-rico-life-without-power/ [Accessed 6/4/2020].

INSURANCE COUNCIL OF AUSTRALIA. 2020. ICA DATAGLOBE. Available: https://www.icadataglobe.com/access-raw-hazard-datasets [Accessed 5/4/2020].

KHANAL, S., RIDDER, N., TERINK, W. & HURK, B. V. D. 2019. Storm surge and extreme river discharge: A compound event analysis using ensemble impact modelling. *Frontiers in Earth Science,* 7**,** 224.

KISHORE, N., MARQUÉS, D., MAHMUD, A., KIANG, M. V., RODRIGUEZ, I., FULLER, A., EBNER, P., SORENSEN, C., RACY, F. & LEMERY, J. 2018. Mortality in puerto rico after hurricane maria. *New England journal of medicine,* 379**,** 162-170.

LEONARD, M., WESTRA, S., PHATAK, A., LAMBERT, M., VAN DEN HURK, B., MCINNES, K., RISBEY, J., SCHUSTER, S., JAKOB, D. & STAFFORD-SMITH, M. 2014. A compound event framework for understanding extreme impacts. *Wiley Interdisciplinary Reviews: Climate Change,* 5**,** 113-128.

MATTHEWS, T., WILBY, R. L. & MURPHY, C. 2019. An emerging tropical cyclone–deadly heat compound hazard. *Nature Climate Change,* 9**,** 602-606.

MCANENEY, J., MCANENEY, D., MUSULIN, R., WALKER, G. & CROMPTON, R. 2015. Government-sponsored Natural Disaster Insurance Pools: A view from down-under. *International Journal of Disaster Risk Reduction*.

MCANENEY, J., SANDERCOCK, B., CROMPTON, R., MORTLOCK, T., MUSULIN, R., PIELKE, R. & GISSING, A. 2019. Normalised insurance losses from Australian natural disasters: 1966–2017. *Environmental Hazards***,** 1-20.

PESCAROLI, G. & ALEXANDER, D. 2015. A definition of cascading disasters and cascading effects: Going beyond the "toppling dominos" metaphor. *Planet@ Risk,* 3.

PESCAROLI, G. & ALEXANDER, D. 2018. Understanding compound, interconnected, interacting, and cascading risks: a holistic framework. *Risk analysis,* 38**,** 2245-2257.

PESCAROLI, G., TURNER, S., GOULD, T., ALEXANDER, D. & WICKS, R. 2017. Cascading Effects and Escalations in Wide Area Power Failures: A Summary for Emergency Planners.

POSCHLOD, B., ZSCHEISCHLER, J., SILLMANN, J., WOOD, R. R. & LUDWIG, R. 2020. Climate change effects on hydrometeorological compound events over southern Norway. *Weather and Climate Extremes***,** 100253.

QUIGLEY, M., ATTANAYAKE, J., KING, A. & PRIDEAUX, F. 2019. A multi-hazards earth science perspective on the COVID-19 pandemic: the potential for concurrent and cascading crises.

RISBEY, J. S., POOK, M. J., MCINTOSH, P. C., WHEELER, M. C. & HENDON, H. H. 2009. On the remote drivers of rainfall variability in Australia. *Monthly Weather Review,* 137**,** 3233-3253.

SADEGH, M., MOFTAKHARI, H., GUPTA, H. V., RAGNO, E., MAZDIYASNI, O., SANDERS, B., MATTHEW, R. & AGHAKOUCHAK, A. 2018. Multihazard scenarios for analysis of compound extreme events. *Geophysical Research Letters,* 45**,** 5470-5480.

SENEVIRATNE, S., NICHOLLS, N., REICHSTEIN, M., SORTEBERG, A., VERA, C. & ZHANG, X. 2012. Changes in Climate Extremes and their Impacts on the Natural Physical Environment *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. IPCC (Cambridge, UK and New York, USA)*.

SHIMIZU, M. & CLARK, A. L. 2015. Interconnected risks, cascading disasters and disaster management policy: a gap analysis. *Planet@ Risk,* 3.

SUTANTO, S. J., VITOLO, C., DI NAPOLI, C., D'ANDREA, M. & VAN LANEN, H. A. 2020. Heatwaves, droughts, and fires: exploring compound and cascading dry hazards at the pan-European scale. *Environment international,* 134**,** 105276.

SWISS RE. 2018a. At USD 144 billion, global insured losses from disaster events in 2017 were the highest ever, sigma study says. Available: https://www.swissre.com/media/news-releases/2018/nr20180410_sigma_global_insured_loses_highest_ever.html [Accessed 6/4/2020].

SWISS RE. 2018b. Sigma - Natural catastrophes and man-made disasters in 2017: a year of record-breaking losses. Available: https://www.swissre.com/dam/jcr:1b3e94c3-ac4e-4585-aa6f-4d482d8f46cc/sigma1_2018_en.pdf [Accessed 6/4/2020].

SWISS RE. 2019a. Global catastrophes caused USD 56 billion insured losses in 2019, estimates Swiss Re Institute. Available: https://www.swissre.com/media/news-releases/nr-20191219-global-catastrophes-estimate.html [Accessed 6/4/2020].

SWISS RE. 2019b. Sigma Natural catastrophes and man-made disasters in 2018: "secondary" perils on the frontline. Available: https://www.swissre.com/dam/jcr:c37eb0e4-c0b9-4a9f-9954-3d0bb4339bfd/sigma2_2019_en.pdf [Accessed 6/4/2020].

UNITED NATIONS 2015. Sendai Framework for Disaster Risk Reduction 2015-2030. Geneva, Switzerland: UNISDR.

WUEBBLES, D. J., FAHEY, D. W. & HIBBARD, K. A. 2017. Climate science special report: fourth national climate assessment, volume I.

YE, L., SHI, K., XIN, Z., WANG, C. & ZHANG, C. 2019. Compound Droughts and Heat Waves in China. *Sustainability,* 11**,** 3270.

ZSCHEISCHLER, J., VAN DEN HURK, B., WARD, P. J. & WESTRA, S. 2020. Multivariate extremes and compound events. *Climate Extremes and Their Implications for Impact and Risk Assessment.* Elsevier.

ZSCHEISCHLER, J., WESTRA, S., VAN DEN HURK, B. J., SENEVIRATNE, S. I., WARD, P. J., PITMAN, A., AGHAKOUCHAK, A., BRESCH, D. N., LEONARD, M. & WAHL, T. 2018. Future climate risk from compound events. *Nature Climate Change,* 8**,** 469.