



Compound Hydrometeorological Extremes: Drivers, Mechanisms and Methods

Wei Zhang^{1*}, Ming Luo^{2,3*}, Si Gao^{4,5}, Weilin Chen⁶, Vittal Hari⁷ and Abdou Khouakhi⁸

¹Department of Plants, Soils and Climate, Utah State University, Logan, UT, United States, ²School of Geography and Planning, Sun Yat-sen University, Guangzhou, China, ³Guangdong Key Laboratory for Urbanization and Geo-simulation, Guangdong Provincial Engineering Research Center for Public Security and Disaster, Guangzhou, China, ⁴School of Atmospheric Sciences, Sun Yat-sen University, Zhuhai, China, ⁵Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, China, ⁶Joint International Research Laboratory of Climate and Environment Change, Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing, China, ⁷UFZ-Helmholtz Centre for Environmental Research, Leipzig, Germany, ⁸Centre for Environmental and Agricultural Informatics, School of Water, Energy and Environment, Cranfield University, Cranfield, United Kingdom

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(HCMR), Greece

*Correspondence:

Wei Zhang
w.zhang@usu.edu
Ming Luo
luom38@mail.sysu.edu.cn

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Compound extremes pose immense challenges and hazards to communities, and this is particularly true for compound hydrometeorological extremes associated with deadly floods, surges, droughts, and heat waves. To mitigate and better adapt to compound hydrometeorological extremes, we need to better understand the state of knowledge of such extremes. Here we review the current advances in understanding compound hydrometeorological extremes: compound heat wave and drought (hot-dry), compound heat stress and extreme precipitation (hot-wet), cold-wet, cold-dry and compound flooding. We focus on the drivers of these extremes and methods used to investigate and quantify their associated risk. Overall, hot-dry compound extremes are tied to subtropical highs, blocking highs, atmospheric stagnation events, and planetary wave patterns, which are modulated by atmosphere-land feedbacks. Compared with hot-dry compound extremes, hot-wet events are less examined in the literature with most works focusing on case studies. The cold-wet compound events are commonly associated with snowfall and cold frontal systems. Although cold-dry events have been found to decrease, their underlying mechanisms require further investigation. Compound flooding encompasses storm surge and high rainfall, storm surge and sea level rise, storm surge and riverine flooding, and coastal and riverine flooding. Overall, there is a growing risk of compound flooding in the future due to changes in sea level rise, storm intensity, storm precipitation, and land-use-land-cover change. To understand processes and interactions underlying compound extremes, numerical models have been used to complement statistical modeling of the dependence between the components of compound extremes. While global climate models can simulate certain types of compound extremes, high-resolution regional models coupled with land and hydrological models are required to simulate the variability of compound extremes and to project changes in the risk of such extremes. In terms of statistical modeling of compound extremes, previous studies have used empirical approach, event coincidence analysis, multivariate distribution, the indicator approach, quantile regression and the Markov Chain

method to understand the dependence, greatly advancing the state of science of compound extremes. Overall, the selection of methods depends on the type of compound extremes of interests and relevant variables.

Keywords: compound hydrometeorological extremes, hot-dry, hot-wet, storm surge, tropical cyclones, floods/droughts, cold-dry, cold-wet

INTRODUCTION

Extreme weather and climate events can have devastating consequences on human societies and the environment (Troy et al., 2015; Zscheischler et al., 2020b). A combination of extreme events can exacerbate the damages by cascading individual natural hazard (AghaKouchak et al., 2018), leading to compound events. Compound extremes events are defined as “1) two or more extreme events occurring simultaneously or successively, 2) combinations of extreme events with underlying conditions that amplify the impact of the events, or 3) combinations of events that are not themselves extremes but lead to an extreme event or impact when combined. The contributing events can be of similar (clustered multiple events) or different type(s)” (Seneviratne et al., 2012). Recently, a more general definition of compound extremes has been developed as “A compound event is an extreme impact that depends on multiple statistically dependent variables or events” (Leonard et al., 2014). Under this definition, compound events may be interpreted as extreme impacts that *depend* on multiple variables or events.

Over the past several years, major efforts have been devoted to advancing the science of compound extremes, evidenced by several review articles in the literature (Leonard et al., 2014; Hao et al., 2018; Zscheischler et al., 2018; AghaKouchak et al., 2020; Raymond et al., 2020a; Zscheischler et al., 2020a). For example, compound events have been organized into four themes: preconditioned, multivariate, temporally compounding, spatially compounding, and temporal connections (Zscheischler et al., 2020a). This structuring of compound events facilitates the unravelling of their physical mechanisms and societal impacts, marking a big step in scientific advancements. As a global investigation of compound extremes, Ridder et al. (2020) identified twenty-seven pairs of compound events (e.g., extreme precipitation and temperatures) that provide the first spatial estimates of their occurrences at the global scale.

Compound hydrometeorological extremes are the most deadly and dangerous compound events in terms of damages and impacts (Martius et al., 2016; Hao et al., 2018; Sedlmeier et al., 2018; Li et al., 2020a). Overall, compound hydrometeorological extremes may be subdivided into five categories: hot-dry (Mazdiyasni and AghaKouchak, 2015; Schumacher et al., 2019; Tavakol et al., 2020a), hot-wet (Fischer and Knutti, 2013; Russo et al., 2017; Tavakol and Rahmani, 2019a), cold-wet (Bisci et al., 2012; Hao et al., 2018; Hochman et al., 2019; De Luca et al., 2020), cold-dry (Dabhi et al., 2018; Wu Y. et al., 2021), and compound flood (e.g., storm surge and rainfall) (Wahl et al., 2015; Moftakhari et al., 2017a). First, compound hot and dry (or heat wave and drought) events have been evaluated globally

and regionally (Feng et al., 2020), including Europe (Ionita et al., 2017; Liu et al., 2020), China (Chen L. et al., 2019; Kong et al., 2020; Xu et al., 2021; Yu and Zhai, 2020), Australia (Cowan et al., 2014; Herold et al., 2016), northern hemisphere (Vogel et al., 2019), the United States (Mazdiyasni and AghaKouchak, 2015; Hao et al., 2020c; Tavakol et al., 2020a), southern Africa (Hao Y. et al., 2020) and at the global scale (Zscheischler and Seneviratne, 2017; Feng et al., 2020; Wu et al., 2021). Overall, this type of compound extreme is manifested by drought, heat and aridity events in which there are usually low soil moisture, high temperature and high vapor pressure deficit (Zhou et al., 2019). Second, compound hot and wet extremes have been reported across the globe, including hot-humid events (Fischer and Knutti, 2013; Li et al., 2020; Poppick and McKinnon, 2020; Yuan et al., 2020; Luo and Lau, 2021). The main driver of this compound is that heat stress is associated with high humidity, which is conducive to precipitation. In order to better quantify the future change of precipitation extremes, dew point temperature may be used (Zhang et al., 2019b), highlighting the role of humidity in formulating the compound hot and wet extremes. For example, extreme heat stress events are followed by flooding in the central United States (Zhang and Villarini, 2020). Third, compound cold-wet extreme events were documented over the Mediterranean (Bisci et al., 2012; Hao et al., 2018; Hochman et al., 2019; De Luca et al., 2020), associated with snowfall and cold frontal systems. Fourth, compound cold-dry events have been reported across China (Miao et al., 2016; Zhou and Liu, 2018), Europe (Potopová et al., 2021) and the globe (Dabhi et al., 2018; Wu Y. et al., 2021). Fifth, compound flooding arising from storm surge and rainfall has received attention (Wahl et al., 2015; Moftakhari et al., 2017a; Paprotny et al., 2018; Bevacqua et al., 2019; Marsooli et al., 2019; Bevacqua et al., 2020; Couasnon et al., 2020; Gori et al., 2020a, 2020b). Compound floods include storm surge and heavy rainfall, storm surge and sea level rise, storm surge and high discharge, and sea level rise and river flow. Compound flooding in the coastal regions may be caused by tropical cyclones and other weather systems (e.g., frontal systems, atmospheric rivers and low-pressure systems). Associated with strong wind and torrential precipitation (Khroukhi et al., 2017; Rios Gaona et al., 2018; Zhang et al., 2018), tropical cyclones play a central role in causing compound flooding (Wahl et al., 2015; Gori et al., 2020a, 2020b). **Table 1** summarizes compound hot and dry, hot and wet, cold and dry, cold and wet and compound flooding, which fall into the four categories documented in (Zscheischler et al., 2020) (i.e., preconditioned, multivariate, temporally compounding and spatially compounding).

Despite substantial progress in understanding compound extremes, there is still no review summarizing the drivers,

TABLE 1 | Types of compound hydrometeorological extremes under the four categories documented in (Zscheischler et al., 2020). “X” represents that the compound extreme type falls into a category based on literature.

Types	Preconditioned	Multivariate	Temporally compounding	Spatially compounding
Hot and Dry	Tavakol et al. (2020a)	Wu et al. (2020)	Zhang and Villarini (2020)	Alizadeh et al. (2020)
Hot and Wet	Wang et al. (2019b)	Soneja et al. (2016)		
Cold and Dry	Miao et al. (2016)	Dabhi et al. (2018)	Hsiao et al. (2021)	
Cold and Wet	Hochman et al. (2019)	De Luca et al. (2020)		
Compound Flooding	Ridder et al. (2018)	Xu et al. (2018)		

mechanisms, and methods employed for their evaluation. A previous review article by Hao et al. (2018) did summarize advancements in the study of compound hydrometeorological extremes, but the present work, in contrast, focuses on physical mechanisms and drivers. Here, we review the status of recent scientific advancements and suggest potential future directions for studying compound extremes and extremes in general. We additionally assess recent advancements in understanding compound hydrometeorological extremes in terms of their fundamental drivers, underpinning mechanisms, and methods employed.

COMPOUND HOT AND DRY EXTREMES

Compound hot and dry extreme is among the first investigated compound hydrometeorological extremes in the literature (Chang and Wallace, 1987; Easterling et al., 2000; Ciais et al., 2005). Back to the 1980s, drought and heat wave in Kansas City have been identified to occur together, associated with circulation patterns and moisture conditions (Chang and Wallace, 1987). This type of compound is featured by two variables: temperature and precipitation, which are closely associated with one another due to the well-known thermodynamic relationship (Held and Soden, 2006). The land-atmospheric feedbacks are commonly used to interpret this compound mechanism (Miralles et al., 2019).

Overall, there are two physical mechanisms used to explain compound hot and dry extremes in the literature. The first concept is that there are persistent atmospheric circulation patterns which are responsible for both drought and heat waves (Vautard et al., 2007; Rowell, 2009; Mueller and Seneviratne, 2012; Quesada et al., 2012; Schneidereit et al., 2012; Seager and Hoerling, 2014). The large-scale circulation patterns related to drought or heat wave consist of blocking highs (Schneidereit et al., 2012; Horton et al., 2014; Dong et al., 2018; Luo et al., 2020; Luo and Lau, 2020), atmospheric stagnation events (Horton et al., 2014), planetary wave patterns (Teng et al., 2013; Screen and Simmonds, 2014; Mann et al., 2017) and subtropical highs (Luo and Lau, 2017; Zhang Y. et al., 2019; Li et al., 2019; Liu et al., 2019; Kong et al., 2020). For example, blocking highs and ridge patterns sit on the atmosphere for a long period of time, increasing temperature and evapotranspiration and suppressing precipitation (Matsueda, 2011; Schneidereit et al., 2012; Hoskins and Woollings, 2015; Dong et al., 2018; Schumacher et al., 2019).

Moreover, atmospheric stagnation events not only influence temperature and precipitation—because of lack of convection and atmospheric movement and transport (Tressol et al., 2008; Zou et al., 2020)—but they can also deprive the air quality (Kerr and Waugh, 2018; Toro et al., 2019; Zou et al., 2020). Subtropical high/anticyclonic patterns are known as a strong high-pressure system that drives drought and heat waves over East Asia and North America, responsible for the compound hot-dry extreme.

In addition to large-scale circulation patterns, atmosphere-land feedbacks are also responsible for the compound heat waves and droughts (Lansu et al., 2020, 2020; Zhou et al., 2021). Overall, dry soil and plants tend to reduce evaporation, leading to dry atmospheric condition and suppressed precipitation, thereby resulting in meteorological droughts (Dickinson, 1995; Seneviratne et al., 2006). On the other hand, the reduced evapotranspiration can also be associated with more solar radiation and sensible heat that increase temperatures on the earth surface, leading to or magnifying the heat wave. The atmosphere-land feedback is known as a fundamental mechanism for interpreting compound heat wave and drought. For example, the severity of atmospheric aridity is dramatically decreased if the feedback from soil to atmosphere state does not exist (Zhou et al., 2019). Moreover, surface albedo change induced by drought conditions may also be coupled with heat waves (Eltahir, 1998). However, the impacts of albedo on the land-atmosphere coupling may be limited and secondary (Teuling and Seneviratne, 2008).

The evaporation and transpiration on land play a central role in the land-atmosphere feedback, which is influenced by changes in radiation and temperature, shapes cloud feedback and water vapor variability, and acts as a bridge between water and carbon cycles through its connection to photosynthesis. In other words, evapotranspiration modulates the surface energy partitioning by affecting key meteorological variables including air temperature and precipitation. Observing evaporation is still quite challenging and the capability of observing evaporation is limited (Wang and Dickinson, 2012). Although some evaporation data have been released over the years, these data are not directly sensed from space or *in situ*. Rather, they are produced by simple physical or statistical models (Fisher et al., 2008; Jung et al., 2010; Miralles et al., 2011; Mu et al., 2011). The evaporation is associated with land conditions and plant physiology during droughts and heat waves, potentially modulating the atmospheric boundary layer state (Betts et al., 1996;

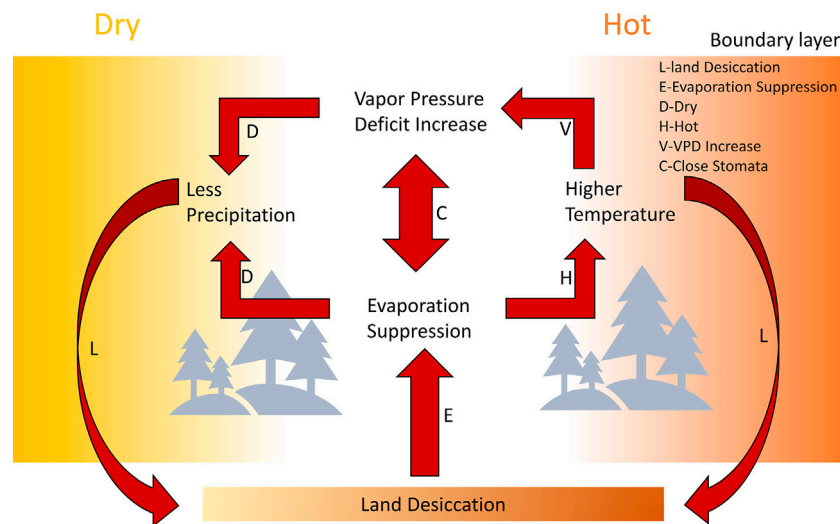


FIGURE 1 | Physical mechanisms of compound hot-dry extremes and land-atmosphere interactions. The physical mechanisms are based on previous studies on compound hot-dry extremes (e.g., Mazdiyasni and AghaKouchak, 2015; Massmann et al., 2019; Miralles et al., 2019; Schumacher et al., 2019; Tavakol et al., 2020a).

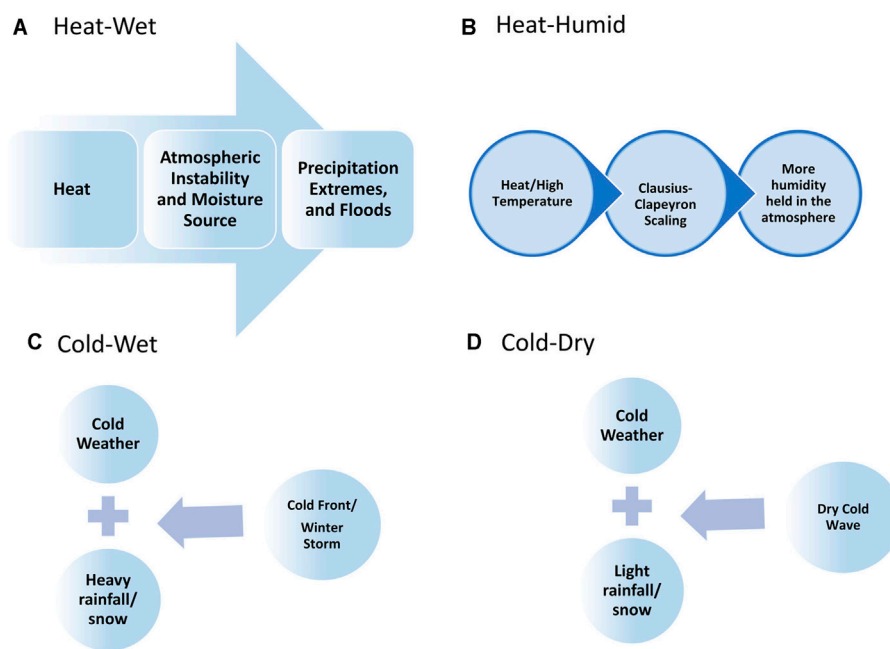


FIGURE 2 | Schematic of compound hydrometeorological extremes: **(A)** heat-wet (Soneja et al., 2016; Wang S. S.-Y. et al., 2019; Imada et al., 2019; Zhang and Villarini, 2020; Chen et al., 2021), **(B)** heat-humid extremes (Fischer and Knutti, 2013; Li et al., 2020; Poppick and McKinnon, 2020; Yuan et al., 2020), **(C)** cold-wet (Bisci et al., 2012; Hao et al., 2018; Hochman et al., 2019; De Luca et al., 2020) and **(D)** cold-dry (Dabhi et al., 2018; Wu Y. et al., 2021; Potopová et al., 2021). The Clausius-Clapeyron scaling represents the water holding capacity of the atmosphere corresponding to air temperature changes (Held and Soden, 2006).

Holtzlag and Ek, 1996; Ek and Holtzlag, 2004). Under increased vapor pressure deficit (VPD), plants tend to close the stomata to avoid water loss (**Figure 1**), thereby reducing evapotranspiration (Rigden and Salvucci, 2017; Massmann et al., 2019). Compound hot extremes consist of both

daytime and nighttime heat extremes (Wang et al., 2020). The spatially compound dry events have been identified to cause damages to agriculture (Singh et al., 2021). The schematic of compound hot-dry extremes is illustrated from the perspective of land-atmosphere feedbacks (**Figure 1**).

COMPOUND HEAT AND WET EXTREMES

Compared with compound hot and dry extremes, compound heat and wet extremes are less explored in the literature (**Figure 2**). This type of extreme is manifested by flooding and heat wave (Soneja et al., 2016; Wang S. S.-Y. et al., 2019; Imada et al., 2019; Zhang and Villarini, 2020; Chen et al., 2021) and heat wave and humid events (Fischer and Knutti, 2013; Li et al., 2020; Poppick and McKinnon, 2020; Yuan et al., 2020). We will elaborate on these compound extremes in the following discussion.

Flooding/Precipitation and Heat Wave/Stress

This type of compound can be classified into temporal compounding (e.g., occur sequentially) (Raymond et al., 2020a; Zscheischler et al., 2020a). The compound flooding and heat waves are featured by heat waves followed by floods or vice versa. The understanding of this compound extreme is still limited and previous research has mainly focused on case studies. No theories have been proposed to formulate these compounds. There are compound summer heat and precipitation extremes reported over central Europe (Beniston, 2009; Sedlmeier et al., 2018), Spain (Morán-Tejeda et al., 2013) and China (Hao et al., 2013; Wu S. et al., 2021; Wang P. et al., 2021). Moreover, floods that follow heat waves have been identified across the central United States (Zhang and Villarini, 2020), and this compound is manifested by the fact that heat stress may set the stage for extreme precipitation and flooding due to increasing sensible heat flux and moisture convergence under extreme heat stress. Similarly, the floods followed by elevated heat have also been identified across China during 1961–2018, exhibiting an increasing trend (Chen et al., 2021). Western Japan experienced catastrophic floods followed by a record-breaking heatwave during early July 2018 (Wang S. S.-Y. et al., 2019; Imada et al., 2019) and this catastrophic compound event caused an estimated 10 billion USD in damage. Based on climate projections, this type of compound will be more frequent under global warming (Wang S. S.-Y. et al., 2019). Currently, the compound flooding and heat waves are still under investigation, and further understanding of their drivers and mechanisms is required in the near future.

Heat Wave and Humid Event

The combined humidity and temperature extremes have been discussed in the literature and identified by climate models and observations (Fischer and Knutti, 2013) and the joint behavior of temperature and humidity extremes arises from the Clausius-Clapeyron (C-C) relationship. Overall, surface humidity increases as temperatures increase over open water bodies. However, this relationship may not hold over land due to the lack of soil moisture (Fischer and Knutti, 2013). Many factors may influence the risk of such humid heat extremes, including irrigation (Lobell et al., 2008; Krakauer et al., 2020), external forcing that contains both natural (e.g., volcanic eruption) and anthropogenic (e.g., greenhouse gases) sources (Fischer and

Knutti, 2013; Russo et al., 2017; Lutsko, 2021), and urbanization (Oleson et al., 2015; Luo and Lau, 2018; Wang Y. et al., 2019).

While the heat and humid events have been projected to increase under global warming (Russo et al., 2017; Byrne and O’Gorman, 2018; Chen X. et al., 2019; Tavakol and Rahmani, 2019b; Wang P. et al., 2021), the combination of heat and relative humidity in the future is still uncertain (Byrne and O’Gorman, 2018). We commonly use wet bulb temperature or apparent temperature to quantify the compound heat-humid events (Russo et al., 2017), although the wet bulb temperature exhibits nonlinear relationship between temperature and relative humidity which is magnified by an increase in temperature (Coffel et al., 2019).

COMPOUND COLD-DRY AND COLD-WET EXTREMES

Cold-wet compound extreme events have been reported over the Mediterranean (Bisci et al., 2012; Hao et al., 2018; Hochman et al., 2019; De Luca et al., 2020). The wintertime cold-wet compound events are commonly associated with snowfall and cold frontal systems. For example, the polar air outbreak associated with a cold front tends to cause heavy snowfall and rainfall. In contrast, compound cold-dry events have been found in China (Miao et al., 2016; Zhou and Liu, 2018), Europe (Potopová et al., 2021) and the globe (Dabhi et al., 2018; Wu Y. et al., 2021). Compound cold/dry and cold/wet extremes have decreased over the vast majority of the world, and are projected to be less frequent using CMIP6 model projection (Wu Y. et al., 2021).

COMPOUND FLOODING

Rising attention has been paid to compound flooding that arises from storm surge and rainfall (Wahl et al., 2015; Moftakhari et al., 2017a; Paprotny et al., 2018; Bevacqua et al., 2019; Marsooli et al., 2019; Bevacqua et al., 2020; Couasnon et al., 2020; Gori et al., 2020a, 2020b). Compound flooding includes storm surge and high rainfall, storm surge and mean sea level rise, storm surge and riverine flooding, and coastal and riverine flooding. Tropical cyclones, atmospheric rivers and extratropical cyclones play a central role in causing the compound flooding (Wahl et al., 2015; Gori et al., 2020a, 2020b) because these storms associated with strong wind are responsible for storm surge and heavy precipitation (Khouakhi and Villarini 2016a; Khouakhi et al., 2017; Rios Gaona et al., 2018; Zhang et al., 2018, 2019a; 2021) in the coastal regions (**Figure 3**). Tropical cyclones have been projected to intensify under climate change, thereby probably leading to higher storm surge (Knutson et al., 2010, 2015; Bhatia et al., 2019). Meanwhile, rainfall caused by tropical cyclones has also been projected to increase in the future (Knutson et al., 2010; Wright et al., 2015; Scoccimarro et al., 2017; Liu et al., 2018). The changes in the intensity of tropical cyclones in concert with the increase in rainfall suggest a higher future risk of compound extremes caused by storms.

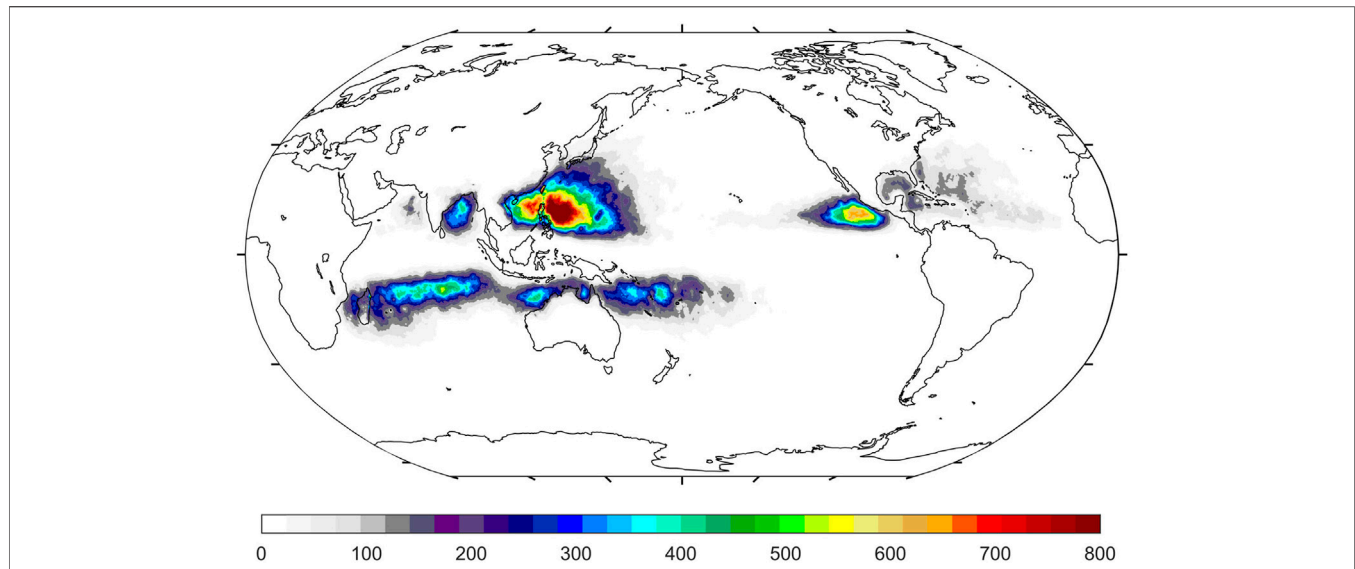


FIGURE 3 | Annual average tropical cyclone precipitation (unit: mm/year) in observations based on the International Best Track Archive for Climate Stewardship (IBTrACS; Knapp et al., 2010) dataset and the Multi-Source Weighted-Ensemble Precipitation Version 2 (MSWEP v2, Beck et al., 2017a; 2017b) precipitation data.

Storm Surge and Heavy Rainfall

Storm surge is defined as a rise in sea level during tropical/extratropical cyclones due to strong winds that force the sea water on shore (Lin and Chavas, 2012; Waliser and Guan, 2017; Veatch and Villarini, 2020), leading to coastal flooding (Khouakhi and Villarini, 2016b; Garner et al., 2017; Herdman et al., 2018; Xu et al., 2019). When storm surge is accompanied by heavy rainfall associated with tropical cyclones, the resulting damages would be exacerbated. Strong dependence has been found between extreme rainfall and storm surge in coastal regions (Zheng et al., 2013; Mohanty et al., 2020). Overall, the compound storm surge and heavy rainfall events are associated with tropical cyclones, atmospheric rivers (Lin et al., 2010a), medicanes (Amores et al., 2020; Davolio et al., 2020; Zhang et al., 2020), and extreme extratropical cyclones (Danard et al., 2004; Colle et al., 2015; Mäll et al., 2017; Lin et al., 2019).

This type of compound has also been reported in many parts of the world including the Netherlands (van den Hurk et al., 2015; Ridder et al., 2018), in coastal and estuarine regions of Australia (Wu et al., 2018), Morocco (Zellou and Rahali, 2019), the United States (Lin et al., 2010b; Gori et al., 2020a), China (Xu et al., 2018; Fang et al., 2021), Britain (Svensson and Jones, 2002, 2004), and Europe in general (Bevacqua et al., 2019). In particular, the catastrophic impacts of the compound storm surge and heavy precipitation are marked in urban watershed (Joyce et al., 2018).

The risk of compound flooding resulting from storm surge and heavy rainfall has been increasing in major coastal cities of the United States (Wahl et al., 2015). The risk of compound storm surge and heavy rainfall is projected to increase in the future (Karim and Mimura, 2008; Bevacqua et al., 2019; Bates et al., 2020; Hsiao et al., 2021). However, there are still large uncertainties in quantifying changes in the risk of compound flooding due to the insufficient skill of climate models in

simulating extreme precipitation caused by storms (Zhang et al., 2019a; Roberts et al., 2020; Vannière et al., 2020). Alternatively, previous efforts have been made to develop parametric tropical cyclone rainfall models (Marks and DeMaria, 2003; Lonfat et al., 2007; Langousis and Veneziano, 2009; Zhu et al., 2013; Emanuel, 2017; Brackins and Kalyanapu, 2020; Xi et al., 2020). The parametric tropical cyclone rainfall models are listed in **Table 2**, including R-CLIPER (Marks and DeMaria, 2003; Tuleya et al., 2007), IPET (IPET 2006), PHRaM (Lonfat et al., 2007), MSR (Langousis and Veneziano, 2009), RMS (Grieser and Jewson, 2012) and TCRM (Zhu et al., 2013; Emanuel, 2017; Xi et al., 2020). The parametric models are very useful to quantify the future risk of tropical cyclone rainfall and coastal flooding (Zheng et al., 2014; Geoghegan et al., 2018).

Storm surge caused by tropical/extratropical cyclones will be exacerbated by the rise of sea level, magnifying the coastal flood hazards (Little et al., 2015; Haigh et al., 2016; Muis et al., 2016; Voudoukas et al., 2018; Marsooli et al., 2019). Indeed, sea level rise can greatly increase the risk of coastal flooding caused by storm surge (McInnes et al., 2003; Karim and Mimura, 2008; Hallegatte et al., 2011; Tebaldi et al., 2012; Zhang et al., 2013; Arns et al., 2015).

Storm Surge and Riverine Floods

While storm surge can be compounded with extreme rainfall, it is also dangerous when storm surge is in concert with riverine flooding. Many studies have analyzed the co-occurrence of storm surge and riverine/fluviial floods (Kew et al., 2013; Klerk et al., 2015; Khanal et al., 2019), including simulations using global coupled river-coast flood model (Ikeuchi et al., 2017). The effect of compound storm surge and riverine flooding has also been examined using remote sensing technologies in western coastal Louisiana (Ramsey et al., 2011), in a tidal river in Rhode Island

TABLE 2 | Parametric models for tropical cyclone rainfall.

Parametric models	Short name	References
Rain-Climatology and Persistence	R-CLIPER	Marks and DeMaria, 2003, Tuleya et al. (2007)
Interagency Performance Evaluation Task Force	IPET	IPET, (2006)
Parametric Hurricane Rainfall Model	PHRaM	Lonfat et al. (2007)
Modified Smith for Rainfall	MSR	Langousis and Veneziano, (2009)
Risk Management Solutions, LTD.	RMS	Grieser and Jewson, (2012)
Tropical cyclone rainfall model	TCRM	Zhu et al. (2013), Emanuel. (2017)

(Teng et al., 2017), the Rhine–Meuse Delta (Klerk et al., 2015), the United Kingdom (Hendry et al., 2019), the Netherlands (Khanal et al., 2019), the USA (Dietrich et al., 2010; Couasnon et al., 2018) and Italy (Bevacqua et al., 2017). In addition to regional scale analysis of this compound extreme, some studies have examined the dependence of storm surge and extreme discharge at the global scale (Ward et al., 2018). The compound flooding is caused by the interactions between physical drivers from oceanographic, hydrological, and meteorological processes in coastal areas, leading to highly complex interplays (Couasnon et al., 2020). Overall, the compound flooding is based on their drivers, including storm surge, precipitation, and river discharges. While many compound flood events are associated with tropical cyclones, some are related to typical synoptic weather systems (Couasnon et al., 2020).

Statistical methods and coupled modeling have been used to quantify the compound storm surge and riverine flood (Dietrich et al., 2010). For example, a global river routing model forced by global hydrological models and bounded downstream by a global tide and surge model has been used to assess the effect of storm surge on riverine flood (Eilander et al., 2020). Hydrologic and hydrodynamic models are combined to assess compound flooding caused by the 2016 tropical storm Matthew (Zhang and Najafi, 2020). In addition, joint probabilities and copula have been widely used to examine the compounds (Czajkowski et al., 2013; Petroliagkis et al., 2016; Couasnon et al., 2018).

Sea Level Rise and Coastal Flooding

Sea level rise may reduce the gap between high tidal datum and flood stage, increasing the frequency of coastal flooding (Andersen and Shepherd, 2013; Kriebel and Geiman, 2014; Schindelegger et al., 2018). When riverine and coastal floods occur back-to-back, their impacts would be stronger than they happen in isolation (Ward et al., 2018, 2018). Overall, sea level rise can double the frequency of coastal flooding in the next few decades (Mousavi et al., 2011; Woodruff et al., 2013; Karegar et al., 2017; Vitousek et al., 2017). For example, due to sea level rise, there is increased coastal flooding in California (Heberger et al., 2011; Garcia and Loáiciga, 2014), Mekong Delta (Takagi et al., 2015), Italian coastal plains (Rinaldo et al., 2008; Antonioli et al., 2017), Mediterranean (Reimann et al., 2018), the US East Coast (Ezer and Atkinson, 2014; Dahl et al., 2017), Miami Beach, Florida (Wdowski et al., 2016), Latin America (Reguero et al., 2015), China (Fang et al., 2016). Sea level rise is found to be compounded with fluvial flooding using a bivariate flood hazard assessment (Moftakhari et al., 2017a). Sea level rise can influence

cyclonic storm surge floods in Bangladesh (Karim and Mimura, 2008). Future sea level rise can not only increase the probability of infrastructure failure, but it can also increase the compounding flood drivers (Moftakhari et al., 2017a). Climate change will increase the potential to cause higher frequency and magnitude of coastal flooding due to hurricane intensification and sea level rise (Figure 4) (Mousavi et al., 2011).

Coastal and Riverine Floods

Riverine and coastal floods characterized by the simultaneous or successive occurrence of high sea levels and high river flows can be life threatening and cause infrastructures damage (Nadal et al., 2010; Ganguli et al., 2020; Khanam et al., 2021). This type of flooding was remarkable during hurricane Harvey in Houston-Galveston Bay (Valle-Levinson et al., 2020; Huang et al., 2021b). For example, around 600 million people in coastal regions may be exposed to this type of compound flood by 2,100 (Kulp and Strauss, 2019). Over the years, the location in a river system where riverine and coastal flood drivers can contribute to the water level has been defined as the transition zone (Bilskie and Hagen, 2018). For example, the 2016 Louisiana flood was caused by excessive rainfall and coastal floods (Wang et al., 2016).

NUMERICAL MODELING

Climate models have been used to quantify compound extremes and their distributions (Sherwood, 2018; Raymond et al., 2020b; Xu et al., 2021; Yuan et al., 2020). Given the five types of compound extremes (Table 1), it is still quite challenging to represent the extremes in numerical models (Table 3). Due to the key role of land-atmosphere feedbacks in shaping the compound dry-hot events, fully-coupled models are desirable for performing simulations (Fischer et al., 2007; Stéfanon et al., 2014; Keune et al., 2016; Sillmann et al., 2017). Current numerical models have been used to simulate the compound extremes, including large eddy simulators (Cioni and Hohenegger, 2017), column models (Van Heerwaarden et al., 2010; Miralles et al., 2014), regional climate models and global climate models (Vautard et al., 2013; Chung et al., 2014; Stegehuis et al., 2015). While regional climate models are extremely useful in resolving land conditions (Fischer et al., 2007; Stéfanon et al., 2014; Keune et al., 2016; Sillmann et al., 2017), global climate models are commonly used to assess changes in land conditions on extreme weather (e.g., drought and heat wave) (Hauser et al., 2016; Kala et al., 2016; Rasmijn et al., 2018). The models in the Coupled Model

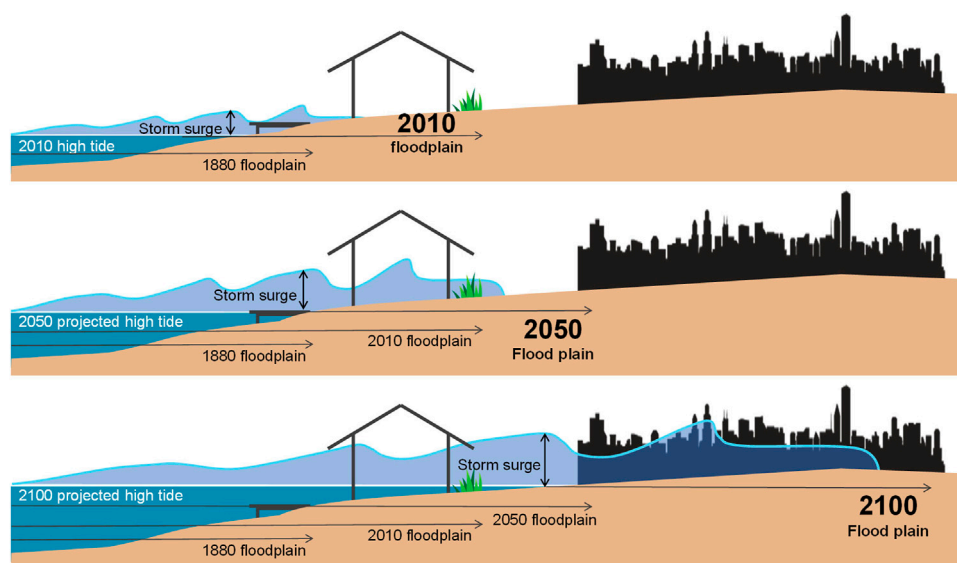


FIGURE 4 | Schematic illustrating the risk of coastal flooding under the present and future climates (Andersen and Shepherd, 2013; Kriebel and Geiman, 2014; Moftakhari et al., 2017a; Schindelegger et al., 2018).

TABLE 3 | Numerical models for studying compound extremes.

Numerical models	References	Description
Single column models	Van Heerwaarden et al., 2010 Miralles et al., 2014	A mechanistic model of the soil-water-atmosphere column
Large eddy simulators	Cioni and Hohenegger (2017)	A very high-resolution regional model (<1,000 m)
Regional climate models	Vautard et al. (2013) Chung et al. (2014) Stegehuis et al. (2015)	A high-resolution model that can simulate atmosphere-land interactions
Global climate models	Hauser et al. (2016) Kala et al. (2016) Rasmijn et al. (2018)	A model the simulates the global climate with a lower spatial resolution
Storm surge models coupled with wave model (SLOSH, ADCRIC) and hydrological models	Sebastian et al. (2014) Yin et al. (2016)	A coupled system that simulates storm surge, sea level rise, river discharge and stream flow

Intercomparison Project Phase 6 (CMIP6) exhibit some skill in simulating the co-occurrence of hot and dry compound events in North America and Europe (Ridder et al., 2021). Because the numerical models' outputs are limited by the climatological biases, univariate and multivariate bias correction methods have been used to correct the biases, and thus improving the performance and usability of the models (Maraun, 2016; Vezzoli et al., 2017; Vrac, 2018; Zscheischler et al., 2018; François et al., 2020). While univariate bias correction operates well in a single variable, multivariate bias correction methods aim to reduce biases that depend on multiple variables, which is an important feature of compound extreme events. Climate model evaluation is usually univariate without considering the multivariate nature of multiple hazards, it is thus important to evaluate the biases in the dependence between the contributing variables in climate models (Vezzoli et al., 2017). However, rare studies have evaluated the climate model multivariate representation of hazard indicators (Bevacqua et al., 2019; Villalobos-Herrera et al., 2021; Zscheischler et al., 2021).

Regional climate models also take initial and boundary conditions from the output of global climate models and can resolve small-scale processes, thereby perform well in simulating single events simulations (Fischer et al., 2007; Stéfanon et al., 2014; Keune et al., 2016; Sillmann et al., 2017). Therefore, regional climate models depend heavily on the simulation of global climate models, which are commonly used to simulate a longer simulation (e.g., years or decades) with a coarser spatial resolution ($\sim 1-2^\circ$) (Orlowsky and Seneviratne, 2013; Cook et al., 2020; Ridder et al., 2020, 2021; Ukkola et al., 2020; Vogel et al., 2020; Su et al., 2021).

Numerical models have also been used to study compound flooding. Ideally, an earth system model that resolves tropical cyclones, waves, ocean circulation, and hydrological cycle can simulate all the processes and interactions at play (Flato, 2011). However, the current generation of earth system models cannot resolve or simplify the processes responsible for the compound flooding (Meehl et al., 2020). To quantify the impacts of sea level rise on storm surge, previous studies have used three methods: numerical simulation of storm surge with sea level rise using the

TABLE 4 | Statistical methods for studying compound extremes.

Statistical methods	References	Description
Empirical Approach	Fischer and Knutti, (2013) Hao et al. (2013) Morán-Tejeda et al. (2013) Miao et al. (2016)	Count the occurrence frequency based on threshold and percentile
Event coincidence analysis	He and Sheffield, (2020) Zhang and Villarini, (2020) Chen et al. (2021)	Examine the coincidence of two events against random occurrence
Multivariate Distribution	Trepanier et al. (2017) Zscheischler and Seneviratne, (2017) Sadegh et al. (2018) Alizadeh et al. (2020) Hao et al. (2020b) Ribeiro et al. (2020a)	Examine the dependence of the two or more extremes using the joint/marginal probability
Indicator Approach	Karl et al. (1996) Gallant and Karoly, (2010) Gallant et al. (2014) Wu et al. (2020)	Combine the components of the compound extreme into an indicator
Quantile Regression	Quesada et al. (2012) Meng and Shen, (2014)	Examine the relationship between predictand and predictor, which are extremes
Markov Chain Model	Steinemann, (2003) Chowdhury et al. (2015) Sedlmeier et al. (2016)	Describe a sequence of events where the present state depends only on the antecedent state
Complex Networks	Boers et al. (2019) Nowack et al. (2020) Sun et al. (2018)	Identify interacting extreme events with a dynamic lead-lag

Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model (Glahn et al., 2009) or the Advanced Circulation (ADCIRC) model (Sebastian et al., 2014; Yin et al., 2016), the simple linear addition method (Kleinosky et al., 2007; Frazier et al., 2010) and Linear addition by expansion method (McInnes et al., 2013). The storm surge model and hydrological model are forced with high-resolution climate model outputs for analyzing the joint occurrence of coastal water levels and river peaks (Ganguli et al., 2020).

STATISTICAL MODELING

Statistical models and observations have been used to investigate compound hydrological extremes. For example, a theoretical framework has been developed to examine compound extremes (Leonard et al., 2014). Recently, much attention has been paid to understand the dependence between multiple relevant variables associated with compound extremes, particularly from a statistical perspective. Overall, the statistical methods employed across the literature consist of empirical approach, event coincidence analysis (ECA), multivariate distribution, the indicator approach, quantile regression and the Markov Chain method (Table 4) (Hao et al., 2018).

Empirical Approach

The empirical approach is performed by counting the simultaneous or sequential frequency/occurrence of the extremes based on the definition (e.g., maxima, threshold or percentile). This approach has been used to examine the

compound temperature and precipitation extremes (Fischer and Knutti, 2013; Hao et al., 2013; Morán-Tejeda et al., 2013; Miao et al., 2016, 1961–2011), air pollution and temperature extremes (Schnell and Prather, 2017), storm surge and rainfall (Wahl et al., 2015). Based on the frequency/occurrence of the compound events, the trend and change point of the time series has been commonly examined to identify temporal change patterns (Dabhi et al., 2021; Feng and Hao, 2020).

Event Coincidence Analysis

Event coincidence analysis (e.g., events synchronization) has been used to formulate and test null hypotheses on the origin of the observed relationship (Donges et al., 2016). In the analysis of temporal compound extremes (e.g., floods that follow heat stress) (Zscheischler et al., 2020a), it is important to test the null hypothesis that whether this lagged association between floods and heat stress is randomly distributed (Zhang and Villarini, 2020). This method has been used to quantify the lagged compound droughts and pluvial floods (He and Sheffield, 2020), the association between precipitation and soil moisture extremes (Sun et al., 2018), and flood-heatwave events (Chen et al., 2021).

Multivariate Distribution

As discussed before, an essential element of the compound extreme is the dependence between different drivers (Leonard et al., 2014). In order to quantify the dependence, multivariate distribution has been widely used in applications (Trepanier et al., 2017; Zscheischler and Seneviratne, 2017). The multivariate distribution has been employed to quantify the joint distribution of temperature and precipitation extremes

(Hawkes, 2008; Tebaldi and Sansó, 2009; Rodrigo, 2015; Zscheischler and Seneviratne, 2017). Different ways have been proposed to construct the multivariate distribution, including parametric distribution, copula, entropy, and nonparametric models.

Copula theory has been employed to characterize the bivariate and trivariate joint distribution and assess complex dependence structures, e.g., in the case of upper tail dependence (Bevacqua et al., 2017; Ribeiro et al., 2020b; Tavakol et al., 2020b). $C(x, y) = P(X \leq x, Y \leq y) = S(U, V; \theta)$, where θ denotes the copula parameter, X and Y are two random variables and U and V denote the marginal distribution and S is the copula. In order to better quantify the dependence, a number of copula families have been developed including extreme-value copula, archimedean copula and elliptical copula (Nelsen, 2007).

The copula models can be used to calculate the joint probability and/or bivariate return periods of compound extremes, thereby quantifying their risk (Sadegh et al., 2018; Alizadeh et al., 2020; Ribeiro et al., 2020a; Hao et al., 2020b). In addition, the copula theory has also been used in multivariate bias correction methods to adjust dependencies among variables in climate models' output (Vezzoli et al., 2017).

The multivariate distribution approach can also quantify the conditional association among different extremes. A common compound extreme (hot-dry event) is characterized by the dependence of high temperatures on precipitation deficit (Alizadeh et al., 2020; Hao et al., 2020b) due to land-atmospheric feedbacks. Different from previous methods in which the extremes were selected prior to analysis, some compound extremes may happen when not all components are defined as extreme. The conditional probability approach can solve this problem (Heffernan and Tawn, 2004; Zhang and Singh, 2007).

Indicator Approach

In defining compound extremes, it is extremely difficult to define a "threshold" for identifying extremes in a multivariate situation (Salvadori et al., 2013). The indicator approach develops an indicator based on the information of multiple variables by formulating a function F , which could be a linear combination or joint distribution of these variables.

Previous studies have developed such indicators for compound extremes (Karl et al., 1996; Gallant and Karoly, 2010; Gallant et al., 2014; Wu et al., 2020). Similar indicators have been developed to characterize drought and flood conditions (Kao and Govindaraju, 2010; Hao and AghaKouchak, 2013; Hao and Singh, 2015; Paprotny et al., 2018; Wang L. et al., 2019).

Quantile Regression, Markov chain Model and Complex Networks

The quantile regression enables the quantification of the relationship between the extremes of two variables (i.e., predictand and predictor). The quantile regression is therefore useful to study the compound extremes (e.g., drought and temperature extremes) (Quesada et al., 2012;

Meng and Shen, 2014) and humidity and temperature extremes (Poppick and McKinnon, 2020; Huang et al., 2021), compound cool/dry and cool/wet events (Zhou and Liu, 2018). The Markov Chain model is another method to examine the connections between a sequence of extreme events. Previous works have used this method to examine the temporal change of drought (Steinemann, 2003) and heavy precipitation (Chowdhury et al., 2015; Sedlmeier et al., 2016). Complex networks are a powerful tool to unravel the connections between nodes of the network (Boers et al., 2019; Nowack et al., 2020). Complex networks are capable of driving the casual relationship between two or more variables (Sun et al., 2018). In addition, Bayesian network (Couasnon et al., 2018; Tilloy et al., 2019; Sanuy et al., 2020) and Artificial Neural Network (Kabir et al., 2020; Feng et al., 2021; Huang et al., 2021a) have been used to understand compound extremes (e.g., compound flooding).

CONCLUSION AND DISCUSSION

Compound hydrometeorological extremes (e.g., hot and drought compound) exert profound impacts on agriculture and water irrigation demand (Zampieri et al., 2017; Lu et al., 2018; Ribeiro et al., 2020b; Haqiqi et al., 2021; Vogel et al., 2021). For example, the compound drought and heatwave events may affect socio-ecological systems (Mukherjee et al., 2020), wildfires (Abatzoglou and Williams, 2016; AghaKouchak et al., 2020; Sutanto et al., 2020), air pollution (Tressol et al., 2008; Zhang H. et al., 2017; Wang et al., 2017; Lin et al., 2020), heat-related deaths (D'Ippoliti et al., 2010; Mitchell et al., 2016). Hot and dry weather conditions may lead to outbreaks of extreme fire due to low humidity and dry vegetation (AghaKouchak et al., 2020).

To mitigate and adapt to compound hydrometeorological extremes, we need to better understand the current state of the science of such extremes. Here, we have reviewed the current understanding of hydrometeorological extremes focusing on heat waves and drought (hot-dry events), heat stress and extreme precipitation (hot-wet events), compound flooding, dynamical models, and statistical methods.

Overall, there are two physical mechanisms used to explain compound hot and dry extreme in the literature. The first concept is that there are persistent atmospheric circulation patterns which are responsible for both drought and heat waves, and land-atmosphere feedbacks which are also responsible for the compound heat waves and droughts. Compared with compound hot and dry extremes, compound hot and wet extremes are less visited in the literature with case studies. We have summarized compound flooding events that include storm surge and high rainfall, storm surge and sea level rise, storm surge and riverine flooding, and coastal and riverine flooding. Looking ahead, there is a rising risk of compound flooding in the future because of changes in sea level rise, storm intensity and precipitation, land-use-land-cover change in the future (Slater et al., 2021).

In terms of methods, numerical modeling and statistical methods have been used to investigate compound extremes. Overall, climate

models alone or coupled with land models, hydrological models, hydrodynamic models and wave models are common tools to investigate compound floods by complementing statistical modeling tools. Climate models still lack skill in simulating dynamical compound extremes, although they perform well in simulating some thermodynamic aspects. Overall, the statistical methods consist of empirical approaches, event coincidence analysis, multivariate distributions, the indicator approach, quantile regression and the Markov Chain method. These methods have greatly advanced our understanding of such extremes, providing a quantification of risk associated with the extremes. Over the decades, machine learning algorithms have advanced many research fields in recent years including climate science. However, while machine learning research has been used to examine individual extreme events (e.g. Grazzini et al., 2019; Bruneau et al., 2020; Chattopadhyay et al., 2020), work on compound extremes is still in its infancy. At the time of writing this article, there were hardly any published studies harnessing machine learning or deep learning to better understand compound hydrometeorological extremes. Therefore, machine learning and its recent algorithmic advances can provide an opportunity and a promising avenue to improve our understanding of compound extreme events.

It would be extremely valuable to build prediction systems for compound hydrometeorological extremes. Indeed, a statistical prediction system has been built to predict compound hot-dry extremes (Hao et al., 2019). Building a statistical prediction model for compound extremes requires the identification of predictors and the evaluation of the predictability of the predictors, which are still challenging tasks (Sillmann et al., 2017). Hybrid statistical-dynamical prediction systems which combine statistical modelling with outputs from dynamical climate models would be promising for predicting compound extremes. Specifically, hybrid statistical-dynamical prediction systems train the relationship between predictors and predictands based on statistical modeling and make predictions based on predictors based on dynamical models. Indeed, several hybrid prediction systems have been developed for individual extremes such as tropical cyclones in the western North Pacific and North Atlantic (Murakami et al., 2016; Zhang W. et al., 2017) and more recently for flood prediction in the USA (Slater and Villarini, 2018). Future research may use Subseasonal to Seasonal (S2S) forecasts such as the products of the North American Multi-Model Ensemble (NMME) or the C3S system of the European Centre for Medium-Range Weather Forecasts (ECMWF) and Copernicus to develop an enhanced prediction of compound extremes.

Given the strong impacts of compound extremes on society, the bottom-up approach is used to examine the compound extremes (Culley et al., 2016; Zscheischler et al., 2018), by

identifying the drivers and/or hazards that lead to large impacts. This approach usually begins with a strong impact (e.g., disaster), followed by identifying underlying factors, processes or phenomena shaping the outcome. This includes identifying which factors lead to large impacts. This bottom-up approach has been widely used to study compound weather and climate events. While the bottom-up approach is relevant, the perspective of the present study lies in the physical hazards associated with compound events.

Finally, we have identified several future research directions for compound hydrometeorological extremes, including:

- projecting the risk of compound extremes for different levels of future warming (Zscheischler et al., 2018; Wang et al., 2020);
- evaluating the impacts of the compound extremes on natural and built environments (AghaKouchak et al., 2020; Zhang and Najafi, 2020);
- developing adaptation measures to the changing risk of compound extremes (Weber et al., 2020; Clarke et al., 2021);
- enhancing subseasonal-to-seasonal prediction of these extremes (Zamora et al., 2021; Zou, 2021);
- improving the representation and evaluation of compound extremes in fully-coupled climate models (Ridder et al., 2021; Zscheischler et al., 2021) and developing multivariate bias correction for these models (Vezzoli et al., 2017; Zscheischler et al., 2019);
- applying machine learning to understand these extremes (Wang L. et al., 2021; Zou, 2021).

AUTHOR CONTRIBUTIONS

WZ, SG, and ML designed the research. All the authors contribute to writing and reviewing the manuscript.

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