Debris flows in southeast Australia linked to drought, wildfire, and the El Niño–Southern Oscillation

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ABSTRACT

Between 2003 and 2013, drought, large wildfires, and record-breaking rainfall contributed to debris flows in southeast Australia that appear to be unprecedented in spatial extent and density in historical records. Here, we used a debris-flow inventory from this period of dry and wet extremes to examine the processes and climatic controls underlying the regionwide debris-flow response. Results reveal shallow landslides and surface runoff as two distinct initiation mechanisms, linked to different geologic settings and contrasting hydroclimatic conditions. Landslide-generated debris flows occurred in sandy soils, independent of past fires, and were tightly controlled by extreme rainfall causing saturation and mass failure during La Niña periods. In contrast, runoff-generated debris flows occurred in clay-rich soils from short and intense rainstorms after wildfires in dry conditions, often associated with El Niño. Thus, it appears that both ends of the wet and dry climate extremes produce the same general geomorphic response, debris flows, but in different areas and by different initiation processes. Debris-flow activity is therefore at a maximum when amplitude and frequency of climate oscillations are large. Debris flows in southeast Australia are likely to become more frequent and widespread as wildfire activity and rainfall intensity are predicted to increase.

INTRODUCTION

Studies show evidence of tight coupling among climate variability, wildfire activity, and the geomorphic processes contributing to denudation (Riley et al., 2015; Meyer et al., 2001). Rainfall extremes can be particularly important because they control the frequency of threshold-driven processes such as landslides and debris flows (Coe et al., 2014). In densely vegetated landscapes, droughts promote wildfires, which removes vegetation and alters soil properties, lowering the rainfall threshold for debris flows (Staley et al., 2017). Thus, with the potential for both wet and dry extremes to promote debris flows, it is likely that phenomena such as the El Niño–Southern Oscillation (ENSO) and anthropogenic climate change, which give rise to these extremes (Guerreiro et al., 2018; Cai et al., 2015), are important controls on landscape change.

In southeast Australia, the series of climatic events at the start of the 21st century produced both exceptionally dry and wet conditions (Freund et al., 2017). During this period, debris flows occurred regularly in forested and relatively stable postorogenic mountain ranges, with incidences of both runoff-generated debris flows from short and intense rainfall on burned areas, and landslide-generated debris flows from extended periods of heavy rainfall and saturated conditions (both types described in Meyer et al., 2001). In terms of their density, spatial extent, and impact, there are no historical records of such frequent and extensive debris-flow activity. The socioeconomic costs were significant and included disruptions to water supply, a human fatality, and damage to infrastructure costing >US$60 million.

In this study, we compiled a regional debris-flow inventory from this period (A.D. 2003–2013) of unusually large climate oscillations to gain new insights into the role of wildfire and extreme rainfall in controlling geomorphic responses of headwater catchments in southeast Australia. With its uniquely productive and flammable forests (Cameron et al., 2009), large rainfall variability (van Dijk et al., 2013), and postorogenic, nonglaciated mountain ranges, this landscape setting is particularly suited for investigating links among climate, vegetation disturbance, and erosion processes.

The specific aims were to (1) examine associations among ENSO, extreme rainfall, wildfire activity, and frequency of debris flows, (2) determine how diverse geologic settings contribute to contrasting debris-flow initiation mechanisms, and (3) evaluate the implications of climate variability for debris-flow frequency.

STUDY AREA: DISSECTED UPLANDS OF SOUTHEAST AUSTRALIA

The study was set in the temperate and montane forests of southeast Australia along the southern part of the Great Dividing Range, which is a complex of plateaus, ridges, and dissected uplands consisting of marine sedimentary rocks, plutonic outcrops, and volcanic lithologies (Fig. 1A). The climate is temperate, with warm, dry summers and cool, wet winters. High-rainfall areas (1500–2000 mm yr⁻¹) along the mountain range and south of the divide support tall temperate forests with fire return intervals of 80–150 yr (Cheal, 2010). Drier areas (500–1000 mm yr⁻¹), typically in rain shadows and at lower elevations, support dry open eucalyptus forests and woodlands, which have fire return intervals of 10–50 yr (Cheal, 2010). The timing of debris flows across the full study area was examined in relation to regional hydroclimate and wildfire data between 2003 and 2013, when climate fluctuations were large (van Dijk et al., 2013; Freund et al., 2017).

At four debris-flow sites, channel heads (Fig. DR1 in the GSA Data Repository) were mapped to examine the role of fire and rainfall in causing debris flows. Channel heads associated with runoff-generated debris flows (Fig. 1E) were mapped in the Beechworth and Kilmore-Murrundindi fires (300 and 3300 km², respectively), 1 yr after the fires ignited in February 2009 (Fig. 1B). The rock types at these sites were mainly marine sediments (mudstone) and metamorphic derivatives (schist and gneiss). Soils are typically clay

GSA Data Repository item 2019183, methods for debris flow mapping, hydroclimatic analyses, rainfall and fire severity analysis, and general additive models, with Figures DR1–DR7, Tables DR1–DR4, and file ‘Mapping_Data.xlsx’ that contains data on the location of mapped channel heads, is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.


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loams. Channel heads associated with landslide-generated debris flows (Fig. 1D) were mapped in The Grampians and at Wilsons Promontory (Fig. 1C), which were subject to heavy rainfall (100 < $P_{34}$ [24 h precipitation] < 300 mm) in 2011 (January and March, respectively). A wildfire in The Grampians occurred in January 2006 (Mount Lubra fire, 1300 km$^2$). At Wilsons Promontory, a wildfire occurred in March 2005 (Tidal River fire, 60 km$^2$) and in February 2009 (Black Saturday fire, 110 km$^2$). The Grampians is a cuesta landscape consisting of marine sedimentary rocks (mainly sandstone), and Wilsons Promontory is granitic. Both sites have coarse-textured loamy sands. See the Data Repository (Table DR1) for details on site attributes.

**METHODS**

A regionwide debris-flow inventory was assembled from aerial imagery, reports from catchment managers, and the Australian Landslide Database (https://researchdata.ands.org.au/landslide-search/). Each debris flow was examined by imagery to discriminate between landslide and runoff as debris-flow triggers (Figs. 1D and 1E). A monthly time series of the two debris-flow types was compiled and compared with metrics showing the timing and areal extent of heavy rainfall ($P_{34}$,150 mm) and large wildfires (burn area >100 km$^2$) and analyzed alongside the Southern Oscillation index (SOI) and soil moisture from the Australian Water Resources Assessment Landscape model (AWRA-L; www.bom.gov.au/water/landscape) and a daily water-balance model (Smith et al., 2015).

Channel heads were mapped using 15-cm-resolution aerial imagery. Debris-flow fans were mapped first, and then the channel heads of the contributing drainage network were located. For runoff-generated debris flows, the channel head was defined as a channel with minimum depth of 20 cm over at least 5 m of channel length, which is based on field surveys (Nymann et al., 2011) and aligned with definitions elsewhere (e.g., Hyde et al., 2014). For landslide-generated debris flows, the channel head is the headscarp. Channel heads were compiled into 1 × 1 km grids of channel head density (km$^{-2}$) and paired with grids of mean burn severity (difference normalized burn ratio [dNBR]), area with gradient >0.3, and total rainfall during the debris-flow–triggering storms.

The impact of each factor on channel head density was determined from partial dependencies, calculated using generalized additive models (GAMs; Wood, 2017; see Data Repository here).

Contrasting initiation mechanisms of landslide- and runoff-generated debris flows were examined in relation to landform and process domains by plotting channel heads alongside the slope-area curve. Slope-area curves were obtained for drainage areas ($A_{m}$<10$^4$ m$^2$, from flow paths originating at 400–500 points randomly located along ridges in eight catchments where debris flows occurred. The valley head, which marks the upstream limit of the fluvial drainage network, was identified from the cumulative areas distribution (CAD; Fig. DR7). The lower limit of hillslopes was determined from the inflection point in the slope-area curve. Slope-area data below the hillslope domain were fitted with an equation (Stock and Dietrich, 2003, their equation 5) that represents the nonlinear transition from hillslope to fluvial domains. Debris-flow domains were identified from the second derivative of this equation (Stock and Dietrich, 2003).

**RESULTS**

There were at least 21 debris-flow clusters identified in the study area, which occurred in 11 periods between 2003 and 2013 (Fig. 1A). Debris flows were associated with two distinct processes: (1) runoff-generated debris flows after wildfire in dry conditions (Figs. 2A and 2E), and (2) landslide-generated debris flows during the wet period in 2010–2012, when large areas were subject to $P_{34}$ >150 mm (Figs. 2A and 2B). The two processes were related to ENSO modes, with wildfire and extreme rainfall more likely to occur in El Niño and La Niña conditions, respectively (Fisher-exact test; $p = 0.49$, odds ratio = 9). Approximately 85% of the area impacted by large wildfires occurred when SOI < 0, while 75% of the area impacted by $P_{34}$ >150 mm occurred when SOI > 0 (Fig. DR2). The study period comprises some of the lowest and highest soil moisture records on record (in the 5th and 95th percentiles, respectively), when evaluated against the median of the soil moisture reconstruction between 1911 and 2017 (Fig. 2D).

There were 139, 179, 445, and 125 channel heads at The Grampians, Wilsons Promontory, Kilmore-Murrundindi, and Beechworth, respectively (Table DR1, Figs. DR3–DR6). Post-European records at these study sites reveal no periods of debris-flow activity equivalent in spatial extent or density. Wildfire affected the density of debris flows caused by runoff, but not those caused by landslides (Fig. 3A). For landslide-generated debris flows, the partial dependency increased with daily rainfall ($P_{34}$) for the full range of $P_{34}$ in the observations. For runoff-generated debris flows, there was a dependence on the maximum

![Image](https://researchdata.ands.org.au/landslide-search/)
Figure 2. A: Periods of runoff- and landslide-generated debris flows (RGDF and LGDF, respectively) in temperate forests of southeast Australia. Blue and red shading show where 5 mo running average of standardized Southern Oscillation index (SOI) in panel E is >1 (La Niña) or <−1 (El Niño). B: Area subject to daily rainfall totals (P_{day}) >150 mm. C: Annual area burned by wildfires >100 km^2. D: Spatially averaged long-term (A.D. 1911–2016) deciles of soil water content (10–100 cm) from Australian Water Resource Assessment Landscape model (AWRA-L, www.bom.gov.au/water/landscape) (0 is median; ±0.25 are lower/upper quartiles) and 5 mo running average (black line). E: Monthly values of standardized SOI from the Climate Analysis Section, NCAR, Boulder, USA (Trenberth, 1984; https://climatedataguide.ucar.edu/climate-data/southern-oscillation-indices-signal-noise-and-tahitidarwin-slp-soil) and 5 mo running average (black line).

For landslide-generated debris flows (Figs. 4A and 4B), channel heads were concentrated within the hillslope domain, and they were similarly distributed with respect to slope and area. For runoff-generated debris flows (Figs. 4C and 4D), the channel heads were centered at larger drainage areas (~10^4 m^2) compared to the landslides (~10^3 m^2), and they were more variable with respect to slope and area.

DISCUSSION

The debris flows in this study occurred during some of the driest and wettest conditions on record, based on hydroclimatic reconstruction from meteorological measurements dating back to 1911 (Fig. 2D). The hydroclimatic conditions are also extraordinary in the longer term. Freund et al. (2017), for instance, showed that the extent and severity of the Millennium Drought (2001–2009) were unprecedented over the past 400 yr, and that the 2010–2011 period (Fig. 2B) was amongst the wettest summer periods in the past several centuries. Extreme rainfall and the drought in southeast Australia have both been linked to ENSO, with La Niña and El Niño modes being associated with wet and dry extremes, respectively (van Dijk et al., 2013; Mariani et al., 2016).

Postwildfire surface runoff, which regularly caused runoff-generated debris flows in landscapes with clay-rich soils (Figs. 1A and 2A), did not appear to be a debris-flow trigger in landscapes comprising sandy soils (Fig. 1C), despite wildfire (Fig. 1B) and rainstorms with 30 min intensities (>25 mm h^{-1}) that are known to trigger runoff-generated debris flows (Table DR4). The debris flows in areas with sandy soils were instead triggered by landslides, primarily during wet La Niña conditions in 2010–2011 (Fig. 2A). Conversely, the sites with clay-rich soils that produced runoff-generated debris flows did not produce landslides during the 11 yr period despite being subject to rainfall with daily totals >150 mm (Figs. 1A and 1C). Thus, the two debris-flow types appear to operate in distinct geologic settings, and the fire dependency switches on or off depending on debris-flow type.

The apparent geologic control on dominant debris-flow types, which has been noted elsewhere (e.g., the western United States; Larsen et al., 2006), may be linked to landscape and to soil texture. Clay-rich soils tend to be more cohesive and less prone to landslides than sandy soils. In contrast, sandy soils may be less vulnerable to runoff-generated debris flows because coarse-textured soils promote preferential flow and high infiltration rates compared to less porous clay-rich soils (Cawson et al., 2016). Low susceptibility of sandy soils to runoff-generated debris flows may have led Shakesby et al. (2007) to conclude that fire is of relatively minor importance to the long-term geomorphology of southeast Australia. Our results, however, suggest fire may be an important geomorphic agent in geologies that produce clay-rich soils. With landslides showing no dependence on past wildfire (Fig. 3B), our results also point to an important contrast between conifers and eucalyptus in terms of the geomorphic legacy of wildfire. With rapid vegetation recovery in eucalyptus forests, it seems that root decay and reduced soil cohesion, leading to more landsliding, as observed in the conifer forest of the United States (e.g., Meyer et al., 2001), is not an important feature of burned catchments in the southeast Australian region.
With channel heads concentrated in unchanneled colluvium (drainage area \(\sim 10^3\) m\(^2\)), the landslide-generated debris flows (Figs. 4A and 4B) closely resemble those in the Colorado Front Range (Rengers et al., 2016). The tight clustering of channel heads indicates a process controlled by slope thresholds. For runoff-generated debris flows (Figs. 4C and 4D), the loosely distributed channel heads indicate weaker dependence on slope and stronger dependence on properties that govern runoff production, which are variable in burned areas (Van der Sant et al., 2018; Moody et al., 2013). In The Grampians (Fig. 4B), the strong curvature in the slope-area relation (Table DR1) indicates a landscape shaped by pore-pressure–sensitive landsliding (Tucker and Bras, 1998). At sites with runoff-generated debris flows (Figs. 4C and 4D), the slope-area curve lacks a distinct landslide process domain. This is also true for Wilson Promontory (Fig. 4A), despite the apparent susceptibility of this landscape to mass failure. Considering these results, and observations by Meyer et al. (2001) that granitic rock types can produce both types of debris flows, it is likely that runoff-generated debris flows also occur in Wilsons Promontory, but with higher rainfall thresholds. Similarly, landslides are known to occur in clay-rich soils (Rutherford et al., 1994), and their absence from the record may be due to higher rainfall thresholds in these soils.

CONCLUSIONS
In southeast Australia, both dry and wet ENSO modes produce a regionwide increase in debris flows triggered by two contrasting processes. One type of debris flow is caused by surface runoff after wildfire, often associated with El Niño. The other is caused by landslides during extended periods of heavy rainfall, more likely during La Niña. Debris-flow frequency in southeast Australia is therefore at a maximum when climate oscillations are large. Hourly rainfall intensities are increasing in southeast Australia (Guerreiro et al., 2018). Daily rainfall extremes are projected to increase (Grose et al., 2015). When such changes occur alongside increases in wildfire frequency and intensification of ENSO (Cai et al., 2015), debris flows will become more frequent and widespread. However, the magnitude of change, and implications for sediment delivery, would depend not just on the external climate forcing, but also the rate of change in southeast Australia’s major climatic regions: Climate of the Past, v. 13, p. 1751–1770, https://doi.org/10.5194/cp-13-1751-2017.


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