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Supplementary Materials for

Atmospheric rivers drive flood damages in the western United States

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The PDF file includes:

Other Supplementary Material for this manuscript includes the following:

(available at advances.sciencemag.org/cgi/content/full/5/12/eaax4631/DC1)

Data S1 (Microsoft Excel format).

Supplementary Text

Effects of AR intensity and insured exposure to risk

In an analysis of collocated same-day or following-day, same-latitude, AR effects, the number of claims, claims paid, and insured losses increased with AR intensity (table S3). Mean values over all 102,270 latitude days (14,610 days by seven latitude bands) are given in the first column of the upper half of the table. On a typical day, in a given latitude band, over the 40-year sample period, 0.6 claims were filed, and 0.5 claims were paid, and mean losses were $13,442. Conditional mean values of claims, claims paid, and insured losses for latitude-days with no AR activity (96,502 latitude days, of a total of 102,270) were lower, as expected (column 2). In the remaining 5,768 latitude days with AR activity (column 3), the effects of ARs on claims and losses are revealed: claims increased by a factor of 12.5, claims paid by a factor of 12.7. Mean insured losses increased from $7,400 per latitude-day on the 96,502 latitude-days with no AR activity to $116,000 per latitude-day on the 5,768 latitude-days with AR activity, a 16-fold increase, statistically significant with $p = 5.7 \times 10^{-10}$ on a Welch two-sided *t*-test. The fact that the ratio of losses with and without AR activity is higher than the ratio of claims with and without AR activity indicates that ARs increased the average insured loss per claim. Latitude-days are used in this analysis to capture same-day or following-day, same-latitude effects. Initially claims compared to AR intensity were limited to the same coastal grid cell as AR landfall. This approach was rejected in favor of the latitude-day formulation because the grid-cell-days excluded some data from the west of the Sierra Nevada range in California and some coastal data from northern California, Oregon, and Washington. It should be noted that the spatially collocated analysis, while conceptually intuitive suffers certain drawbacks, namely it fails to capture spatial lags. AR impacts extend well beyond the area of AR landfall (fig. S4), *e.g.*

impacts in Arizona in particular are associated with ARs that make landfall in Baja California. For these reasons the impact ratios found in these analyses are conservative estimates of AR impacts. However, more complex analyses designed to account for these factors did not significantly alter qualitative nature of the results.

Increased AR intensity, as measured by maximum IVT over the seven coastal grid cells from 32.5°N to 47.5°N, resulted in exponential increases in insured losses. This is revealed by dividing the sample of all latitude-days with AR activity by increments of 250 kg m^{-1} s^{-1}. As IVT increases from 250 kg m^{-1} s^{-1} to 500 to 750 to 1000 kg m^{-1} s^{-1}, insured loss ratios increase from 15.8 to 47.9 to 178 to 625, respectively. All of these differences relative to the absence of AR conditions are statistically significant with $p < 0.0001$. Modest increases in IVT led to disproportionate increases in claims and insured losses. Increases in precipitation associated with ARs are amplified in terms of increased hydrologic flooding (*9 Konrad 2017*), and further amplified in terms of insured losses; this may be due to the high concentrations of properties at risk in certain areas prone to hydrologic flooding.

In specific locations AR impacts are even more pronounced (table S4). The variation in AR impacts by latitude may be accounted for by two factors: differences in vulnerability (*e.g.* number of NFIP policies) at different latitudes, and differences in AR intensity. The 37.5°N latitude band had the greatest average AR-related losses ($272,000): there was a 183-fold increase in insured losses, from $18,000 on days with no AR activity to $3.3 million on days with IVT > 750 kg m^{-1} s^{-1}. ARs are known to cause significant damages along the Russian River in Sonoma County, California (4); the lower reach of the Russian River falls into the 37.5°N coastal grid cell. Other latitude bands also exhibited significant increases in loss during AR events with IVT > 750 kg m^{-1} s^{-1}, ranging from a 17-fold increase at 40°N to a 334-fold increase at 47.5°N. Events with peak IVT > 1000 kg m^{-1} s^{-1} were relatively infrequent at all latitudes so comparisons of losses at the top end of the distribution are highly imprecise.

In southern California (32.5°N, 35°N) the ratios of losses on days with IVT > 500 kg m^{-1} s^{-1}) to non-AR days are 56.7 and 59.2 respectively. In the Bay Area (37.5°N, a latitude band which includes Monterey to the south, Sonoma County and the lower reach of the Russian River to the north, and Sacramento to the east) the ratio is 51.0. Significantly lower ratios of 10.9 and 20.2 are observed in northern California and southern Oregon (40°N, 42.5°N) where the annual mean numbers of policies are much lower (3,800 at 42.5°N compared to 100,000 at 37.5°N). Higher ratios, 61.1 and 72.3 are observed in northern Oregon and Washington, areas with moderate exposure to flood risk as measured by mean annual number of NFIP policies.

Spatial and temporal concentration of losses

As described in the main text, flood damages were highly concentrated in space and time. Total insured losses over the 11 western states for the 40-year sample period amounted to $1.7 billion, or $43 million per year (in total damage terms, using the 30-fold NWS-NFIP inflation factor, this is equivalent to $51 billion over 40 years). The top 20 counties (5% of 414 counties) accounted for 69% of total insured losses (Table 2). With the exceptions of Washoe NV and Maricopa AZ, all of the top counties are located in the coastal states of California, Oregon and Washington, and are mainly coastal counties. Proportions of insured losses associated with AR conditions (peak IVT > 250 kg m^{-1} s^{-1} at one of nine coastal grid cells from 27.5°N to 47.5°N on the day of or the day preceding losses) are over 95% for almost all counties in northern California, Oregon, and Washington (see also Fig 2).

Total insured losses in Sonoma county, the top county, were significantly higher than those of the next highest county, Los Angeles, at $172 million and $106 million, respectively. The proportion of insured losses associated with AR conditions was 0.998, consistent with earlier results (*4*): almost all insured losses in Sonoma county occurred during AR events. Slightly lower proportions of total damages caused by ARs are observed in southern California (Los Angeles, San Diego, Orange, and Riverside) and the interior Southwest (Maricopa Arizona). In Arizona this may have been due to non-AR monsoon flooding in the late summer flood season (*41 Cavazos 2008*). In southern California, it is not clear if this was due to significant non-AR flood events (monsoon-related flash floods, cut-off low pressure systems, or coastal flooding due to decaying tropical storms) or to high population densities, coverage levels, and overall risk exposure. Areas with especially high population densities may be susceptible to more random local flooding not related to extreme precipitation events. An interesting outlier among the top 20 counties is Cowlitz Washington, for which only 60% of insured losses were associated with ARs. Cowlitz County is the site of Mount St. Helens, whose eruption in 1980 left the region prone to flood damages from debris flows.

Just as a small number of extreme ARs were responsible for a significant proportion of total damages, the vast majority of high loss days occurred during ARs (fig. S6). Over the 1978–2017 sample there were only 32 days, comprising 16 separate events, on which insured losses exceeded $10m. These 32 days (0.2% of days in the sample period) accounted for 52.3% of total insured losses, and of them only six occurred in the absence of AR conditions on the day of or the day preceding damages. Three of these six days occurred during the extreme flooding event in Colorado of September 11–13, 2013, caused by a slow-moving cold front clashing with warm humid monsoonal air from the south. Understanding extreme loss events is the key to understanding flood damages in the western U.S., and almost all of these extreme loss events were associated with atmospheric rivers.

Spatial distribution of losses

Spatially, there were clear differences in AR impacts by location, by land-falling latitude in particular (fig. S4). ARs that made landfall in Baja California at 27.5°N produced losses in Arizona, New Mexico, and southern Nevada, consistent with similar observations in the hydro-climatology with respect to inland penetration (*16 Rutz 2014*). ARs that made landfall at 30°N, in Baja California Norte, were most significantly connected to losses in Arizona, New Mexico, southern Nevada, southern California, and as far north as the San Francisco Bay Area and the San Joaquin Valley. ARs making landfall at 35°N and 37.5°N were most strongly connected to losses in central and northern California. ARs making landfall to the south at 32.5°N and to the north at 40°N had less strong effects. ARs making landfall at 42.5°N and 45°N showed strong connections to losses in the Pacific Northwest, where deep inland penetration was also notable. ARs making landfall at 47.5°N had little effect on losses in the U.S. though may have caused damages in British Columbia, an area for which no loss data was available.

These results (fig. S4) demonstrate the wide spatial extent of regions affected by ARs that make landfall at different latitudes. Significant impacts were observed across many basins for ARs at all latitudes. Topography also has an effect in determining the spatial distribution of damages. ARs that made landfall at or south of 32.5°N were able to penetrate the transverse ranges of Southern California which are oriented east-west, and the gap between the Sierra San Pedro Martír in Baja California and the Sierra Nevada in California. North of 32.5°N, land-falling ARs were not able to penetrate the Sierra Nevada range, although damages were observed in Washoe County Nevada, fed by the Truckee River with its source in the Sierra Nevada range. To the north, there was some inland penetration through the Columbia Gorge associated with ARs that made landfall at 42.5°N and 45°N. Damages correlated with ARs making landfall at 47.5°N were fairly localized to western Washington, although, given the mean orientation at landfall, these ARs likely caused significant damages in British Columbia. These results suggest the importance of AR orientation at landfall relative to local topography in causing damages.

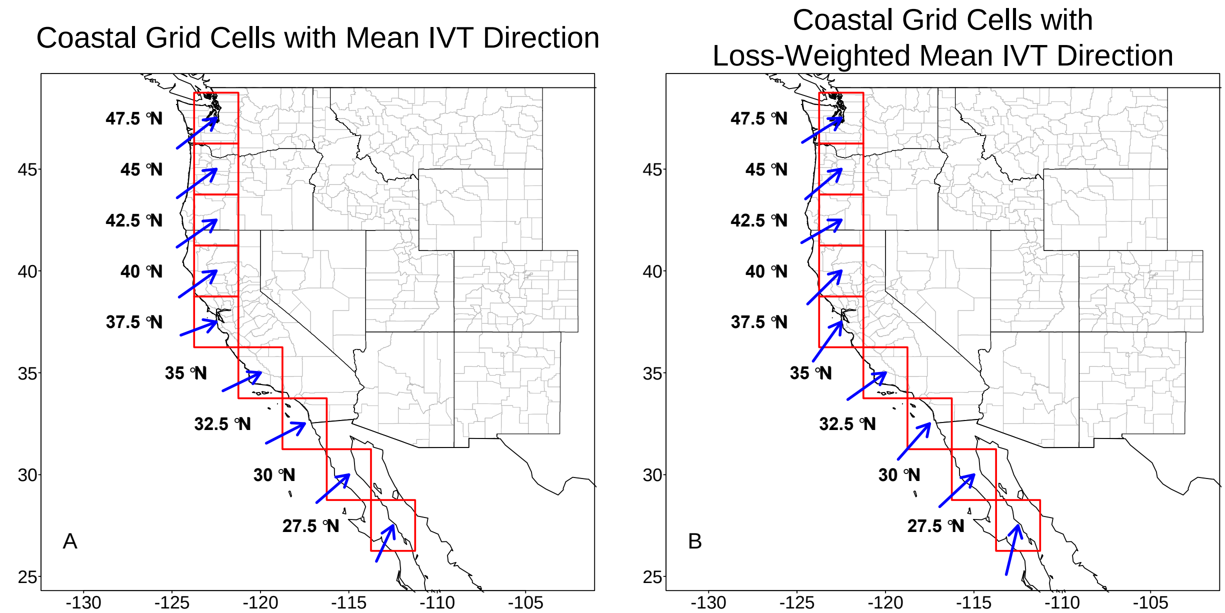

Fig. S1. Coastal grid cells. G17 coastal grid cells from 27.5°N to 47.5°N are outlined in red. Losses are considered over the 11 western states (414 counties, with boundaries indicated in grey). Mean IVT direction is indicated by the blue arrows in panel A (mean IVT intensities are not shown). Mean IVT direction weighted by losses over the 11 western states in indicated by the blue arrows in panel B (loss-weighted intensities are not shown). A more southerly, south to north, direction is observed at latitudes south of 37.5°N, particularly at 37.5°N, for the loss-weighted IVT directions, indicating that more southerly ARs are more damaging than average ARs at these latitudes.

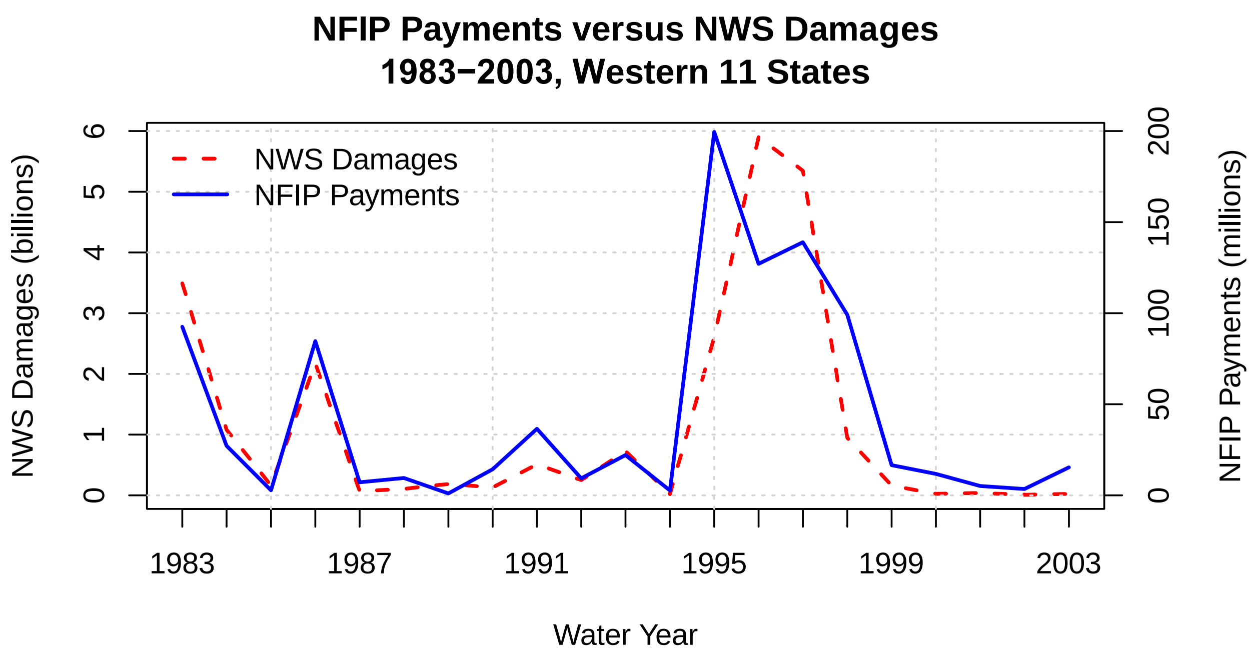

Fig. S2. NFIP payments versus NWS damages. Annual aggregates of NWS damage estimates (dashed red line) and NFIP insured losses (solid blue line) reveal strong coherence (Pearson correlation of 0.8). On average over the 40-year time period, NFIP insured losses accounted for approximately 3.3% of total reported NWS damages. In the comparison of 1983–2003 annual NFIP losses to NWS annual damages over the 11 western states, some discrepancies are observed in the years with significant damages, *e.g*. 1995 and 1996. The high value of NFIP payments relative to NWS payments in 1995 appear to be due to a single event, January 9, 1995, with losses concentrated in Sonoma County with damages primarily occurring in the residential communities along the lower Russian River. The high value of NWS payments relative to NFIP payments in 1996 appears to be due to extreme losses reported by the NWS in Oregon associated with the Willamette Valley flood which caused high non-residential damages. These discrepancies highlight the need for the collection of more comprehensive flood impact data.

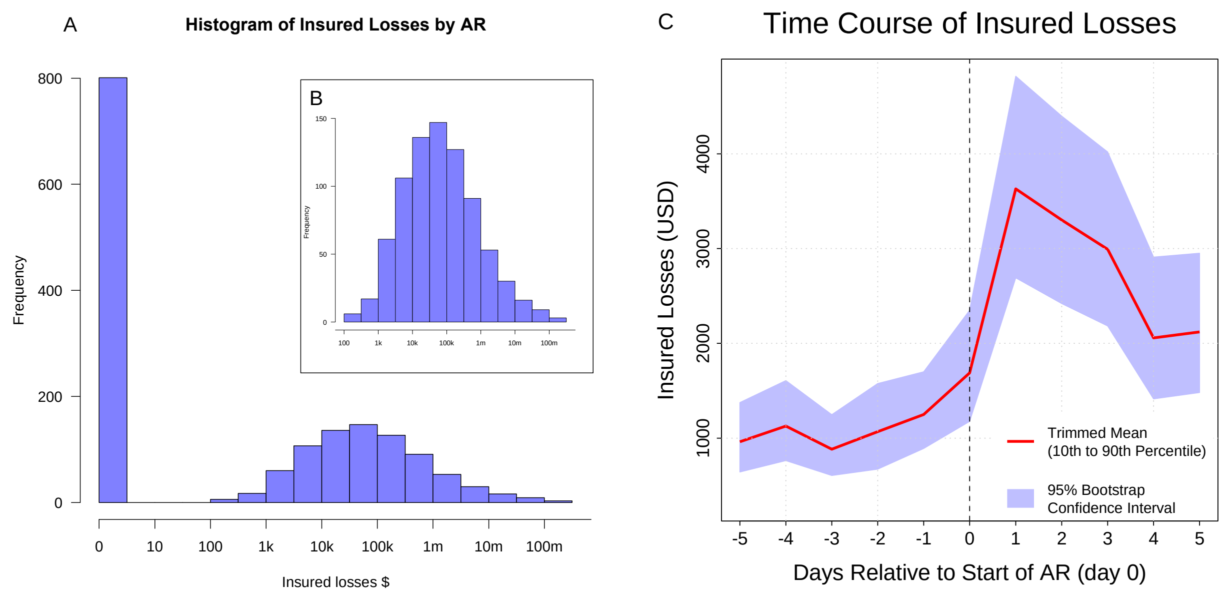

Fig. S3. Distribution and time course of insured losses. The distribution of insured losses by AR reveals that half of all events cause zero insured losses (A). The remaining half appear roughly log normal but with some evidence of right skew indicating the importance of extreme flood damage events in the distribution (B). The trimmed means of NFIP insured losses per day of event, from 5 days ahead to 5 days post-landfall show the time course of a typical event (C). 95% confidence intervals are bootstrapped with 1000 replicates. A trimmed mean, mean of values from the 10th to 90th percentile, is used to exclude extreme values which masked the key temporal pattern. For a typical event, peak damages occurred one day after initial landfall as precipitation caused by ARs takes time to accumulate and run off through stream channels to cause losses. An 80% increase in damages relative to baseline is observed on the day of landfall; a 300% increase relative to baseline is seen on the day after landfall, with mean losses then gradually returning to baseline over several days.

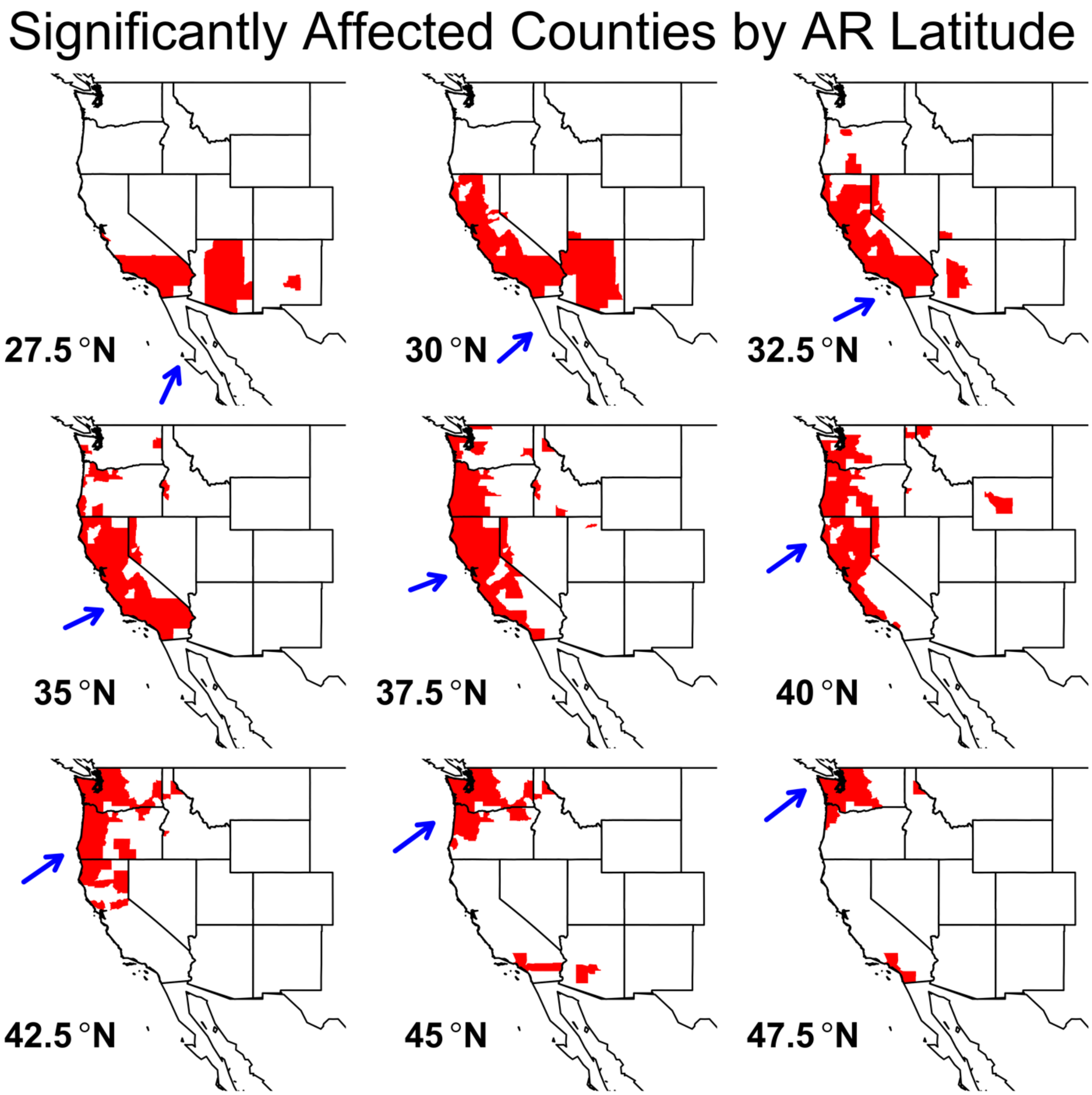

Fig. S4. Spatial footprints of ARs. The spatial footprints of AR impacts by latitude at landfall cover wide areas, where the correlation is calculated between the adjusted logarithm of insured losses [log(x + 1)] and daily IVT, above a threshold of 250 kg m^{-1} s^{-1} for each latitude band and each county; counties with correlations significant at the 0.1% level are shaded.

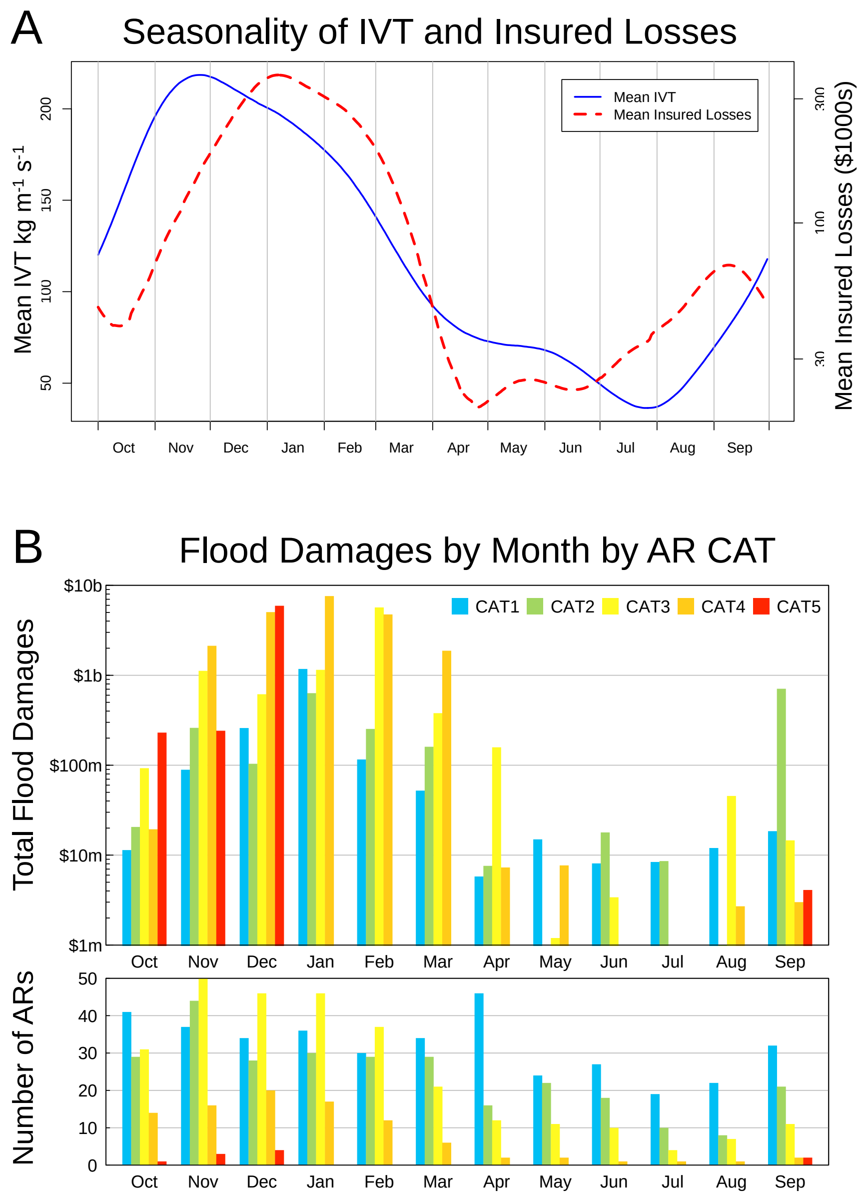

Fig. S5. Seasonality of insured losses. Seasonality of IVT and mean insured losses: daily mean IVT and daily mean insured losses (plotted on a logarithmic scale) by day of water year (excluding February 29th), filtered using a 90-day Gaussian filter, reveal a one-month winter lag between AR activity and insured losses (A). Losses are low relative to IVT in the late spring and early summer, and high relative to IVT in the late summer. Total flood damages by month by AR CAT reveal a peak flood damage season of November through March. Similar, though muted, seasonality is observed in the number of ARs by category over the course of the water year (B).

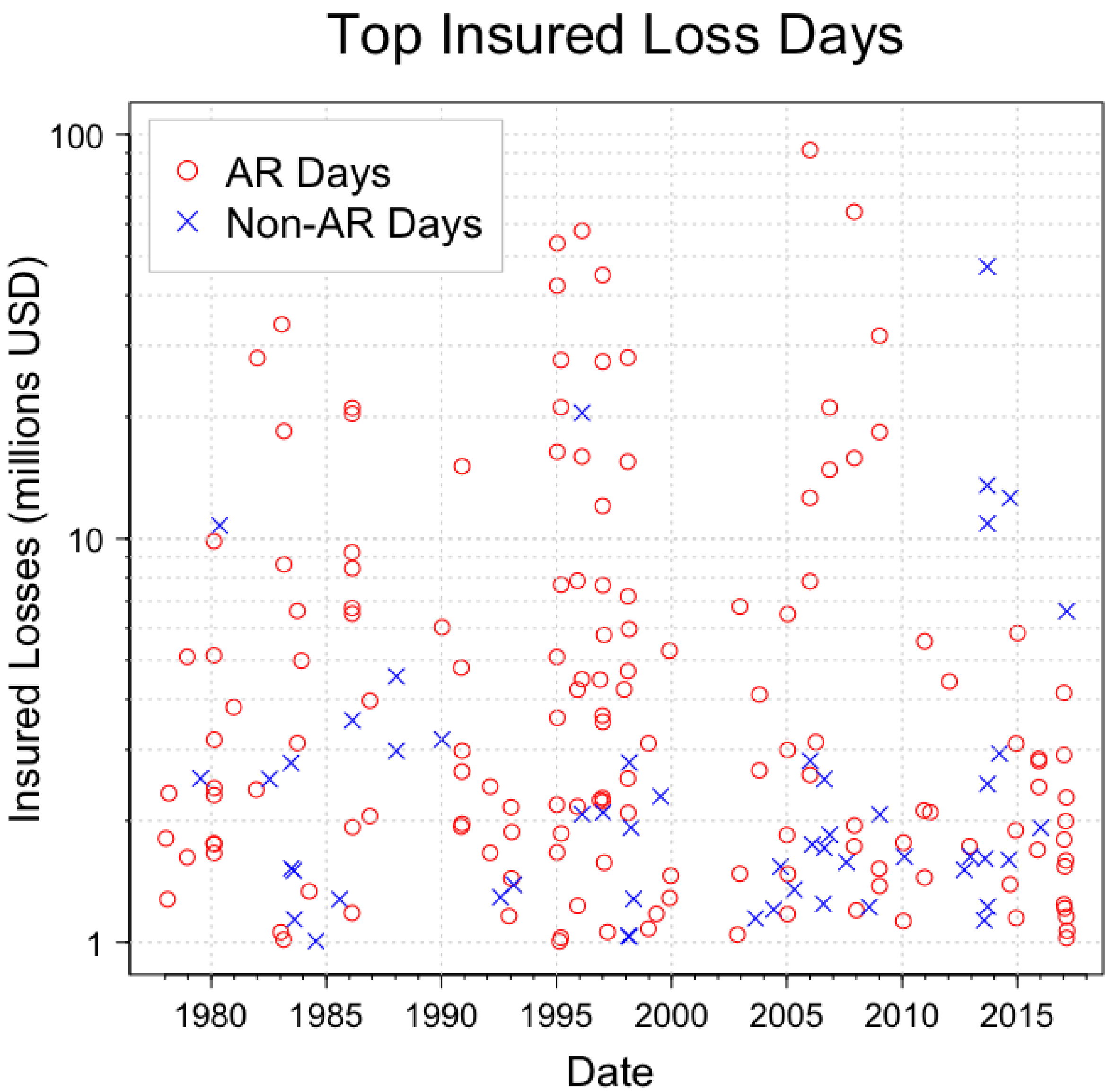

Fig. S6. Days with over $1 million in insured losses. One hundred sixty-eight of 202 days with losses over $1 million and 26 of 32 days with losses over $10 million occurred during ARs. Over the 1978-2017 sample there were only 32 days, comprising 16 separate events, on which insured losses exceeded $10m. These 32 days (of a sample of 14,610 days) accounted for 52.3% of total insured losses, and of them only six occurred in the absence of AR conditions on the day of or the day preceding damages.

Table S1. Damages by AR category by month, in millions of dollars.

	AR CAT	Jul	Aug	Sep	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	Apr	May	Jun
Sum of Damages	**CAT 1**	6	12	17	11	**73**	**106**	**320**	**96**	**36**	4	15	7
	CAT 2	3	1	711*	18	**246**	**217**	**1303**	**255**	**159**	4	0	15
	CAT 3	8	43	7	88	**463**	**571**	**857**	**5646**	**398**	165**	2	8
	CAT 4	0	5	10	26	**1655**	**5125**	**6751**	**4804**	**1875**	3	8	0
	CAT 5	0	0	4	232	**1407**	**5929**	**1327**	**0**	**0**	5	0	0
Mean Damages by AR	**CAT 1**	0	1	1	0	**3**	**4**	**11**	**5**	**1**	0	1	0
	CAT 2	0	0	26*	1	**6**	**8**	**42**	**8**	**5**	0	0	1
	CAT 3	1	6	1	3	**9**	**13**	**22**	**145**	**17**	11**	0	1
	CAT 4	0	3	3	2	**79**	**190**	**260**	**300**	**268**	1	4	0
	CAT 5	0	0	2	77	**281**	**1482**	**664**	**0**	**0**	5	0	0
Number of ARs	**CAT 1**	18	19	25	37	**29**	**28**	**30**	**21**	**26**	36	22	24
	CAT 2	8	10	27	28	**43**	**28**	**31**	**32**	**33**	22	18	17
	CAT 3	6	7	10	34	**52**	**45**	**40**	**39**	**24**	15	17	14
	CAT 4	2	2	4	14	**21**	**27**	**26**	**16**	**7**	2	2	1
	CAT 5	0	0	2	3	**5**	**4**	**2**	**0**	**0**	1	0	0

* Two AR CAT2 storms in September occurred coincident with decaying tropical storms (Octave 1983, Norbert 2014) in Arizona

** One highly damaging CAT3 storm occurred April 1, 2006, in northern California

Damages under $0.5m are rounded down to $0.

Table S2. Effect of antecedent ARs on mean flood damages by AR event.

	Mean Damage ($m)
No AR in past 5 days	22.3
CAT1 or higher in past 5 days	59.3
CAT2 or higher in past 5 days	75.6
CAT3 or higher in past 5 days	82.2
CAT4 or higher in past 5 days	94.8
CAT5 or higher in past 5 days	172.4
No AR in past 10 days	17.4
CAT1 or higher in past 10 days	50.5
CAT2 or higher in past 10 days	60.2
CAT3 or higher in past 10 days	66.1
CAT4 or higher in past 10 days	62.9
CAT5 or higher in past 10 days	123.3

Table S3. Average claims and insured losses per latitude-day by AR intensity (quartiles).

	Overall	No AR: max IVT < 250 kg m^{-1} s^{-1}	max IVT > 250 kg m^{-1} s^{-1} (*)	max IVT > 500 kg m^{-1} s^{-1} (*)	max IVT > 750 kg m^{-1} s^{-1} (*)	max IVT > 1000 kg m^{-1} s^{-1} (*)
Claims	0.6	0.4	5	13.2	42.1	87.7
Claims Paid	0.5	0.3	3.8	10.4	34.2	76.6
Loss (USD)	13,442	7,320	115,853	350,294	1,301,812	4,574,053
n Latitude-Days	102,270	96,502	5,768	1,501	172	15

Ratio of Impacts Relative to No Atmospheric River Activity						
Claims	1.5	1	12.5	33.0	105	219
Claims Paid	1.7	1	12.7	34.7	114	255
Loss (USD)	1.8	1	15.8	47.9	178	625

(*) t-statistics on differences in means > 4 throughout (versus days with no AR activity)

Table S4. Daily average insured losses by latitude band by AR intensity.

	32.5°N	35°N	37.5°N	40°N	42.5°N	45°N	47.5°N
Loss ratio, no AR	1	1	1	1	1	1	1
Loss ratio, all days	1.7	1.7	1.8	1.1	1.5	2.4	2.2
Loss ratio, max IVT > 250 kg m^{-1} s^{-1}	25.0	18.1	15.0	3.4	8.0	19.5	20.3
Loss ratio, max IVT > 500 kg m^{-1} s^{-1}	56.7	59.2	51.0	10.9	20.2	61.1	72.3
Loss ratio, max IVT > 750 kg m^{-1} s^{-1}	0	315.0	183.2	16.9	87.1	176.0	333.6
Loss ratio, max IVT > 1000 kg m^{-1} s^{-1}	no ARs	no ARs	0.9	2.5	291.8	1,521.0	2,421.2
Loss, no AR ($)	3,588	8,358	18,072	6,347	755	4,357	9,777
Loss, all days ($)	6,125	13,963	33,171	7,271	1,099	10,657	21,805
Loss, max IVT > 250 kg m^{-1} s^{-1} ($)	89,576	151,516	271,629	21,860	6,034	85,099	198,337
Loss, max IVT > 500 kg m^{-1} s^{-1} ($)	203,300	494,410	922,208	69,066	15,246	266,027	706,506
Loss, max IVT > 750 kg m^{-1} s^{-1} ($)	0	2,632,913	3,311,091	107,039	65,778	766,961	3,261,447
Loss, max IVT > 1000 kg m^{-1} s^{-1} ($)	no ARs	no ARs	16,005	15,964	220,276	6,626,925	23,672,232
n days, no AR	14,179	14,038	13,740	13,739	13,658	13,470	13,678
n all days	14,610	14,610	14,610	14,610	14,610	14,610	14,610
n days, max IVT > 250 kg m^{-1} s^{-1}	431	572	870	871	952	1140	932
n days, max IVT > 500 kg m^{-1} s^{-1}	81	114	199	221	318	345	223
n days, max IVT > 750 kg m^{-1} s^{-1}	2	9	27	28	44	39	23
n days, max IVT > 1000 kg m^{-1} s^{-1}	0	0	1	3	6	3	2
Number of Policies	46,016	48,219	100,169	13,902	3,756	15,313	20,109