Atmospheric Rivers drive flood damages in the western US

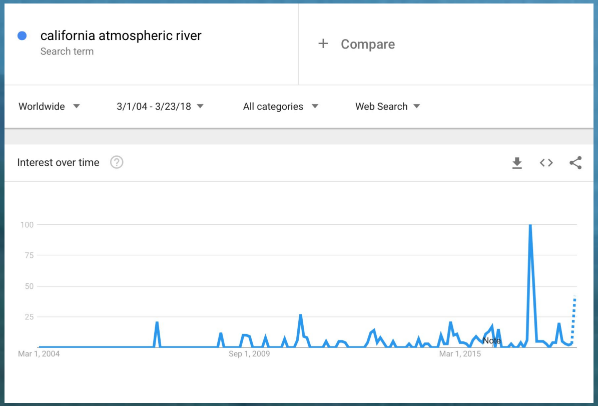
Tom Corringham, Sasha Gershunov, Dan Cayan
UCSD & Scripps Institution of Oceanography

Climate & Hydrology Literature

- Bao, *et al*. 2006
- Browning and Pardoe 1973
- Carlson 1980
- Dettinger 2004, 2011, 2011
- Dettinger *et al*. 2011
- Dirmeyer and Kinter 2009
- Gimeno 2013
- Guan *et al*. 2010, 2012, 2013
- Jiang and Deng, 2011
- Knippertz and Wernli 2010
- Knippertz *et al*. 2013
- Lackmann and Gyakum 1999
- Lavers *et al*. 2011, 2012, 2013
- Lavers and Villarini 2013
- Matrosov 2013
- Neiman *et al*. 2008, 2011
- Newell *et al*. 1992
- Ralph *et al*. 2004, 2005, 2006, 2010, 2011, 2013, 2013
- Ralph and Dettinger 2011
- Ulbrich *et al*. 2008
- Waliser *et al*. 2012
- Wick *et al*. 2013
- Zhu and Newell 1998

Popular Press

- Sacramento Bee
- Los Angeles Times
- New York Times
- Fox News



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WEATHER · 1 day ago

What is an atmospheric river? Powerful storm to drench California

By Zoe Szathmary | Fox News

A powerful atmospheric river brought rain to California this week. (REUTERS/Gene Blevins)

California residents, brace yourselves: an atmospheric river could continue to bring rain to multiple parts of the state this week.

March 23, 2018

Economics Literature

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- ARkStorm estimates costs of a 1000-year AR event
  - *e.g*. Porter, *et al.* 2011
- Cost estimates of specific storm events
  - *e.g*. Perry 2005, DWR ACE California's Flood Future 2013
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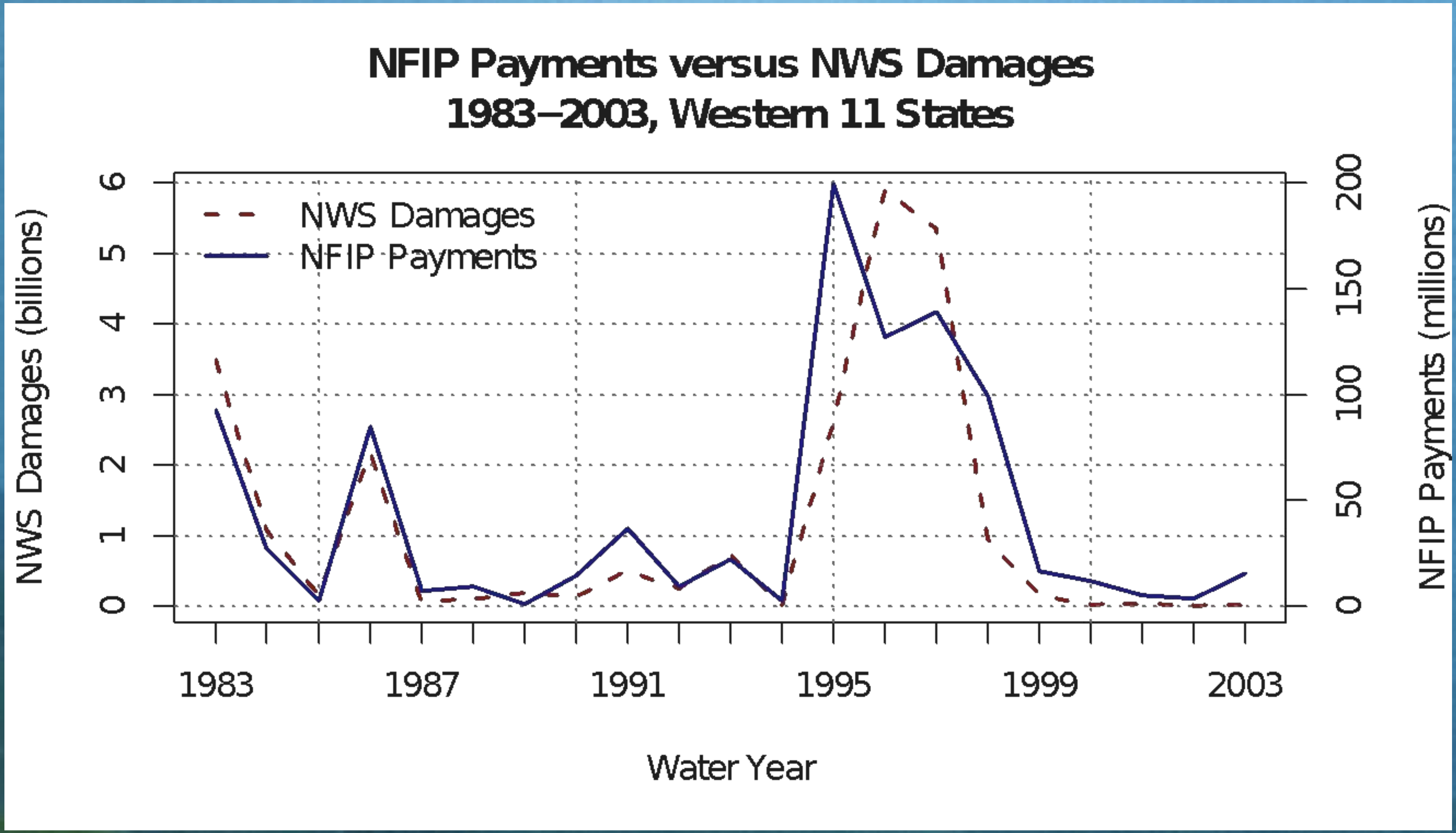
Insured losses accounted for 1/30 of total damages



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Questions

- How much did AR events cost?
- What fraction of flood losses were due to ARs?
- What were the characteristics of damaging events?
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- Will costs increase with climate change?

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Top Events

	Number	Start Date	Number of Days	Crossing Latitude	Crossing Region	Max IVT	Claims	Insured Losses (millions)	Total Damage (billions)
1	2796	1/4/95	11	32.5	S. California	922.47	4621	122.6	3.677
2	3482	12/29/05	5	40	N. California	780.84	2547	115.0	3.449
3	2912	12/29/96	8	35	C. Coast	1215.73	3249	99.8	2.993
4	2859	2/5/96	4	45	N. Oregon	684.56	2554	95.0	2.850
5	2265	2/15/86	5	47.5	Washington	825.94	1966	63.1	1.893
6	2804	3/7/95	5	42.5	S. Oregon	883.79	2293	57.7	1.730
7	2987	2/1/98	3	37.5	Bay Area	751.30	2362	45.2	1.357
8	3534	11/1/06	7	40	N. California	996.58	1070	33.1	0.993
9	2073	1/25/83	5	37.5	Bay Area	968.56	1427	32.7	0.981
10	2079	2/25/83	7	37.5	Bay Area	613.87	1713	27.1	0.814
11	2007	1/3/82	3	40	N. California	480.87	1341	26.4	0.792
12	1887	2/12/80	9	30	Baja Norte	677.02	1926	26.2	0.786
13	2264	2/11/86	5	40	N. California	859.92	817	23.0	0.690
14	2543	11/21/90	5	47.5	Washington	899.02	886	21.7	0.652
15	2988	2/4/98	5	40	N. California	849.31	1529	17.0	0.509
16	2843	11/27/95	5	45	N. Oregon	749.63	676	15.2	0.457
17	3420	1/6/05	6	30	Baja Norte	606.81	606	13.4	0.403
18	1888	2/16/80	3	42.5	S. Oregon	771.20	937	11.1	0.332
19	2991	2/20/98	4	42.5	S. Oregon	518.49	1067	10.3	0.310
20	2488	1/5/90	5	47.5	Washington	984.71	303	9.0	0.270

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- Average cost $28m (median $0)
- 53% of events caused zero insured losses
- Conditional on insured loss > 0
  - Average cost $60m (median $1.8m)

- Maximum cost estimated at $1b to $3.5b
- 22 days accounted for 50% of losses over 30 years

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All were associated with Atmospheric Rivers

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AR Significance in Top Counties

	County	State	Insured Losses (millions)	AR Insured Losses (millions)	AR Proportion	Claims	Total Damages (billions)
1	Sonoma	CA	159.490	158.421	0.9933	6089	4.478
2	Los Angeles	CA	91.276	76.798	0.8414	7443	2.563
3	Marin	CA	69.063	68.218	0.9878	2807	1.939
4	Sacramento	CA	52.160	51.052	0.9788	3273	1.464
5	Napa	CA	42.327	42.215	0.9974	1295	1.188
6	Monterey	CA	41.903	41.592	0.9926	1192	1.177
7	Lewis	WA	41.722	40.439	0.9693	1080	1.171
8	King	WA	39.742	38.807	0.9765	1845	1.116
9	Washoe	NV	39.032	38.917	0.9971	572	1.096
10	Clackamas	OR	26.733	25.825	0.9660	606	0.751
11	Snohomish	WA	26.519	25.940	0.9782	1146	0.745
12	Placer	CA	25.586	25.228	0.9860	534	0.718
13	Orange	CA	24.624	21.812	0.8858	3169	0.691
14	Santa Clara	CA	23.541	22.843	0.9704	1253	0.661
15	Maricopa	AZ	20.847	13.716	0.6580	1829	0.585
16	San Diego	CA	19.723	17.436	0.8841	1416	0.554
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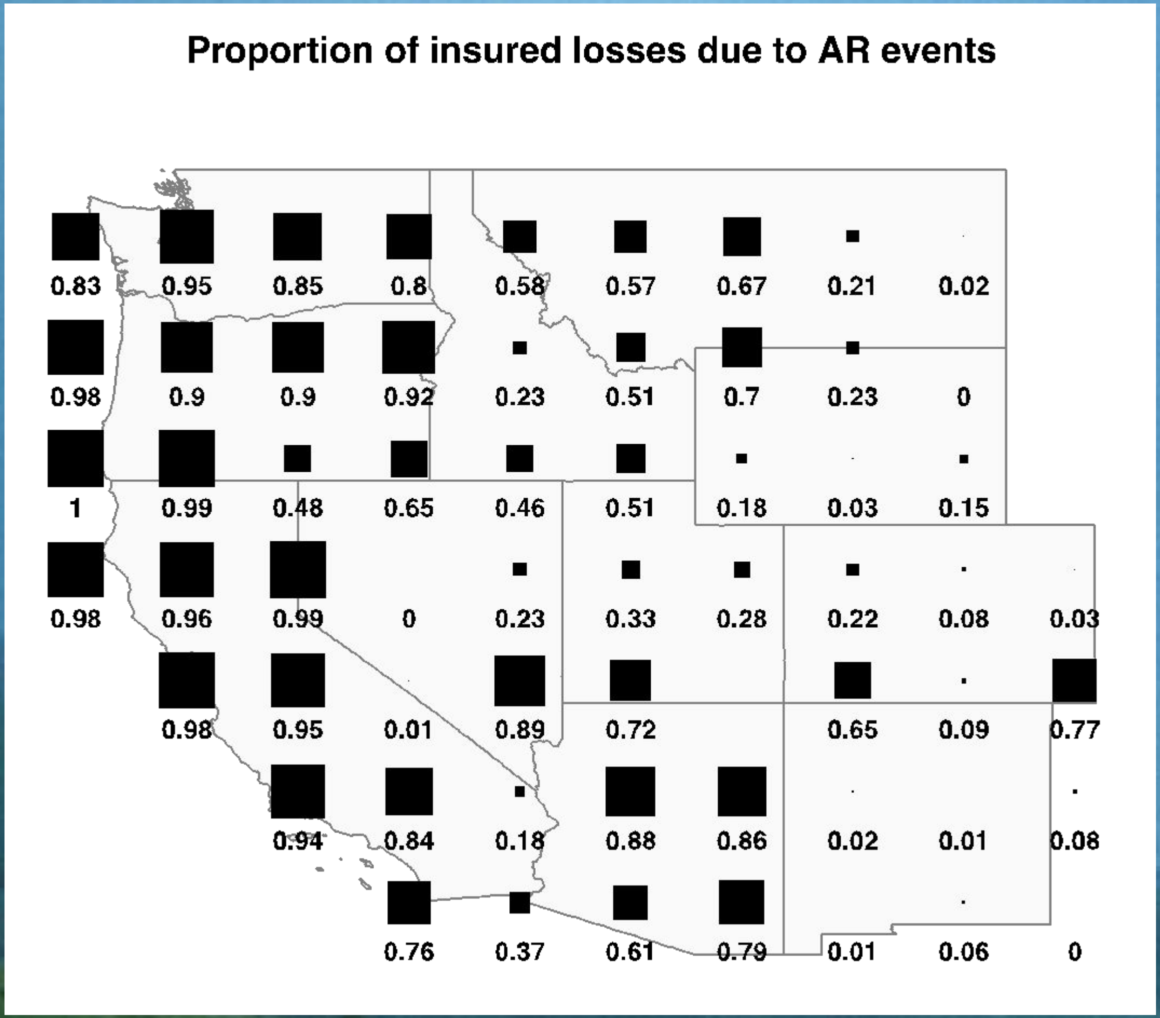
What fraction of losses were due to ARs?



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- **89%** of flood damages in the western 11 states are caused by atmospheric river events

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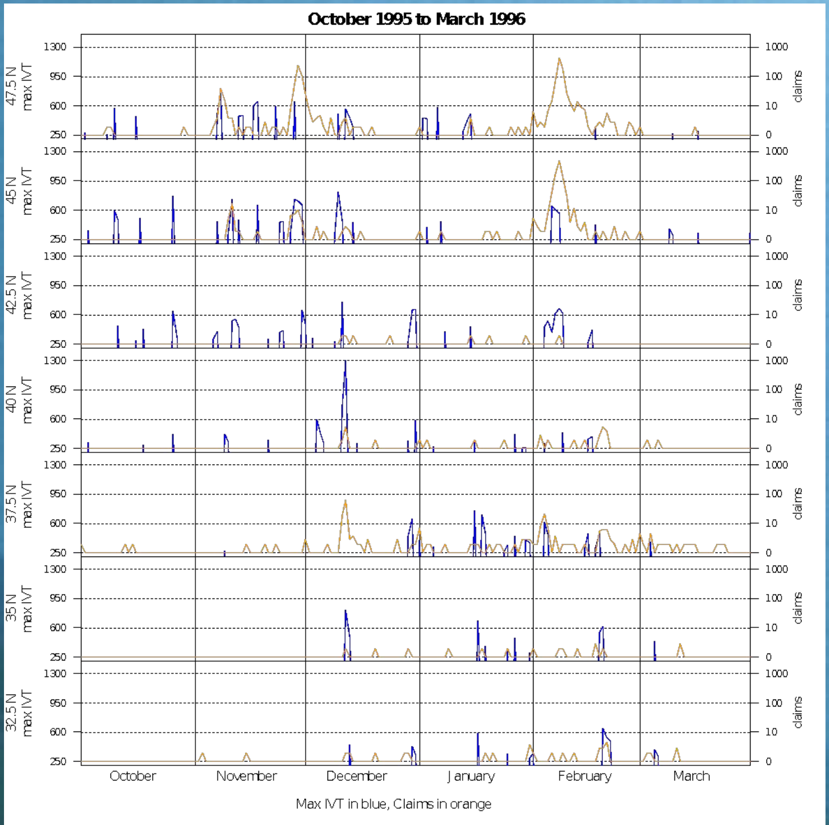
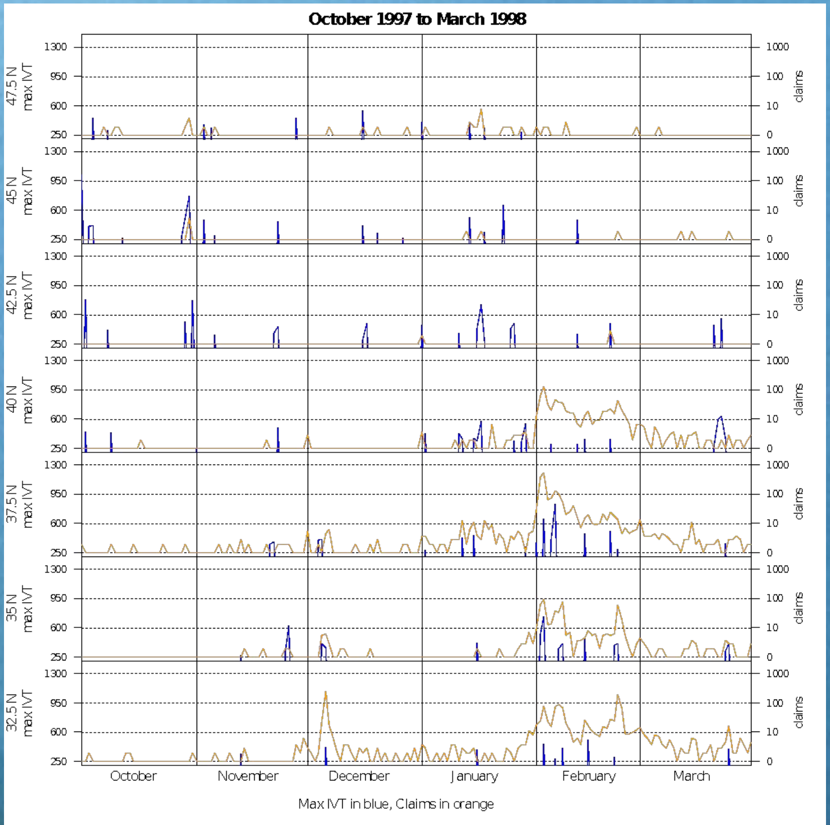
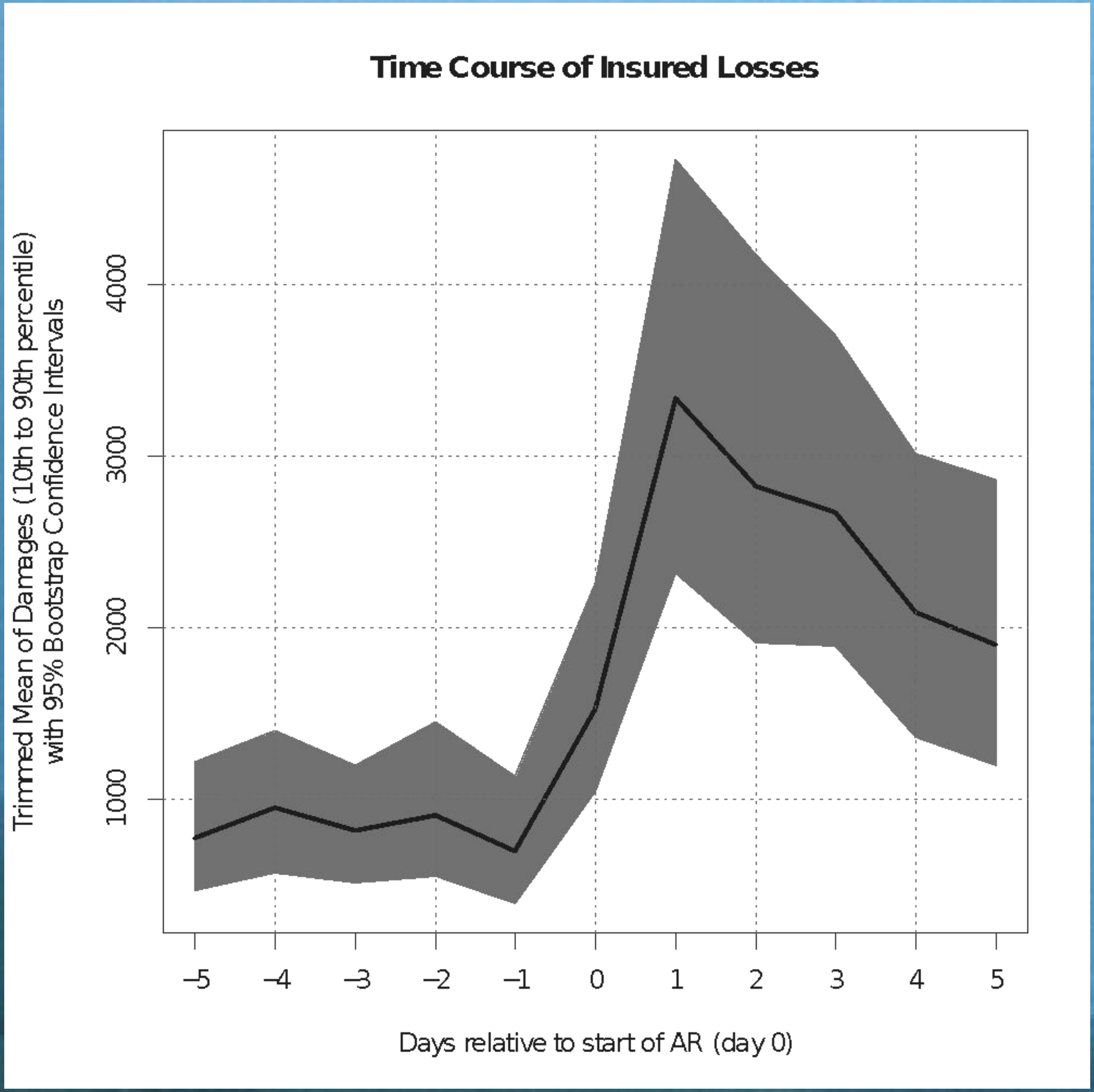
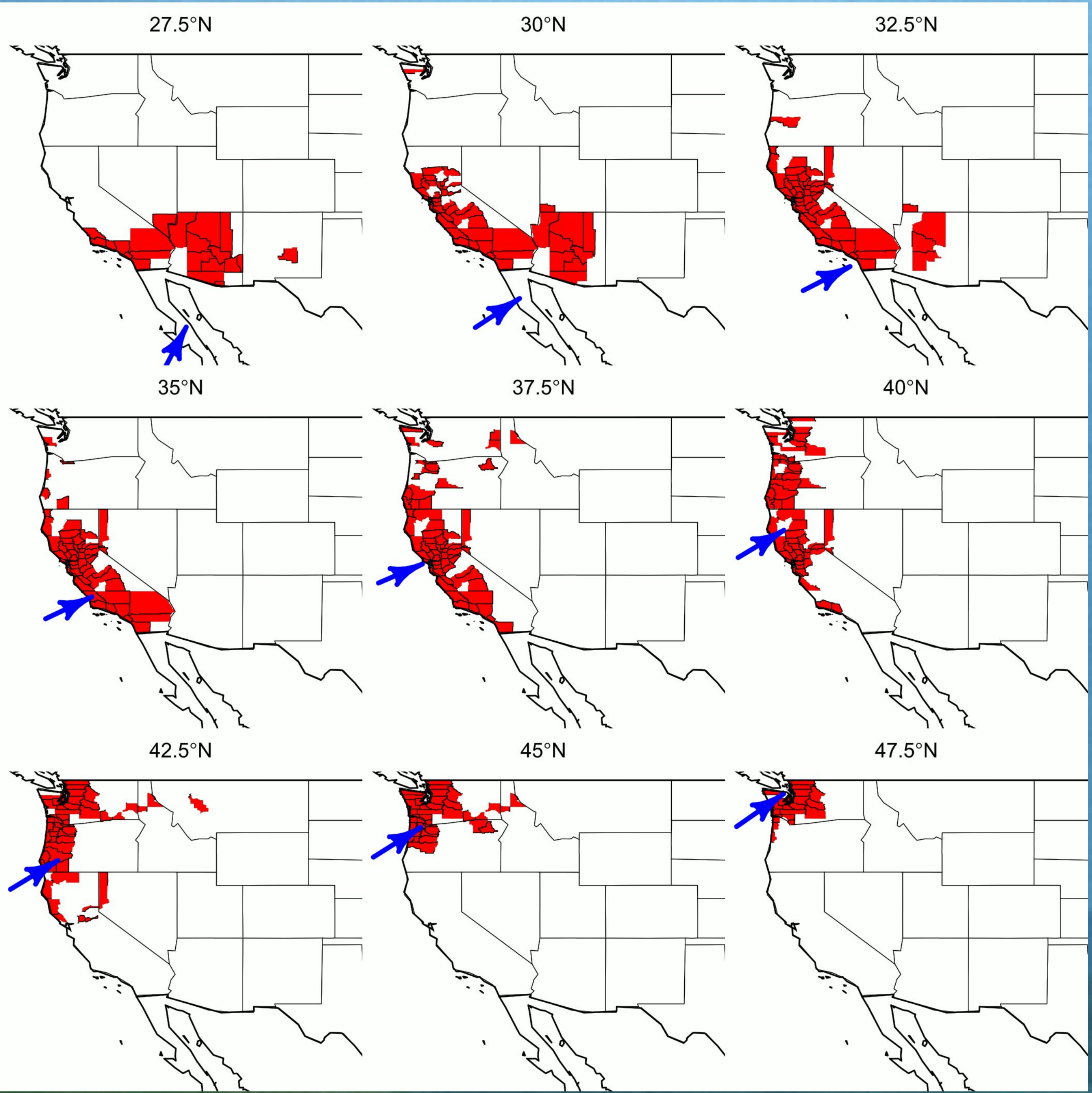
Time Series of IVT and Claims

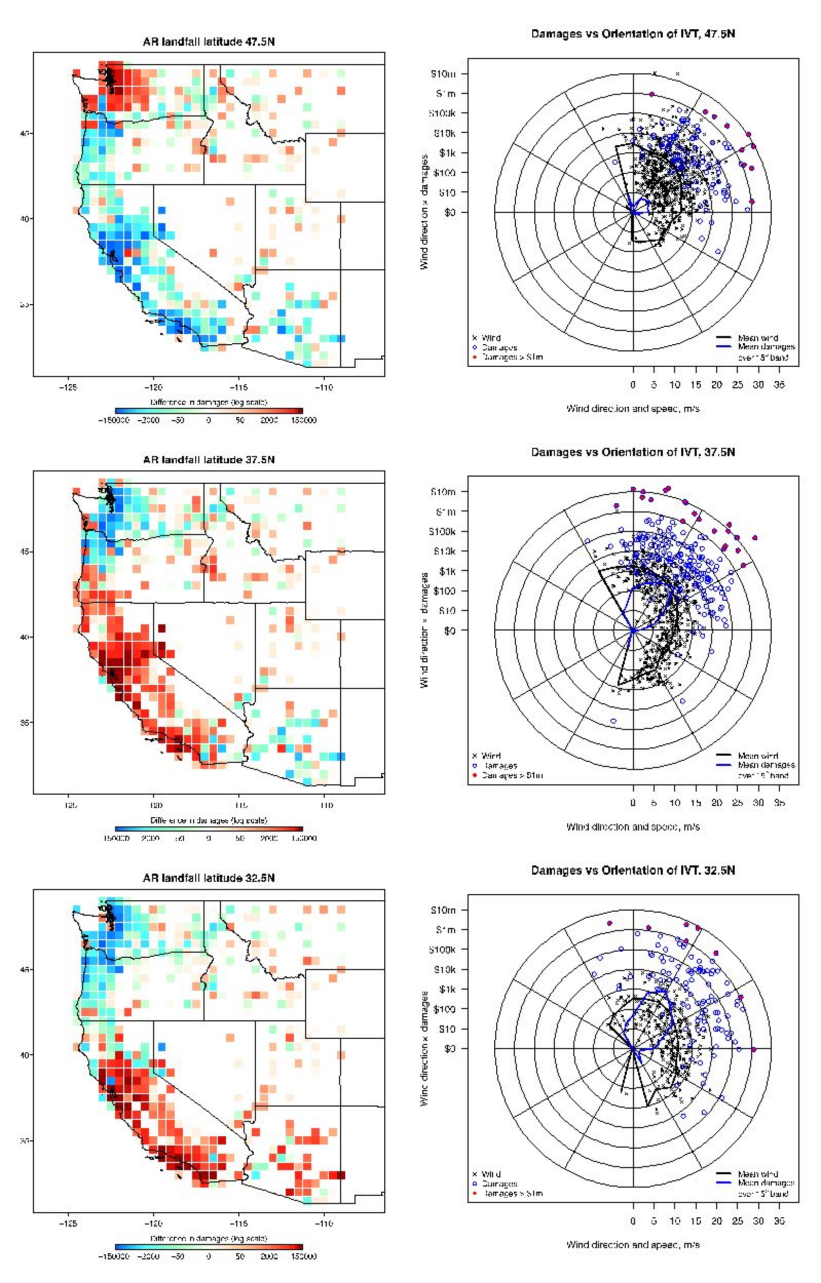




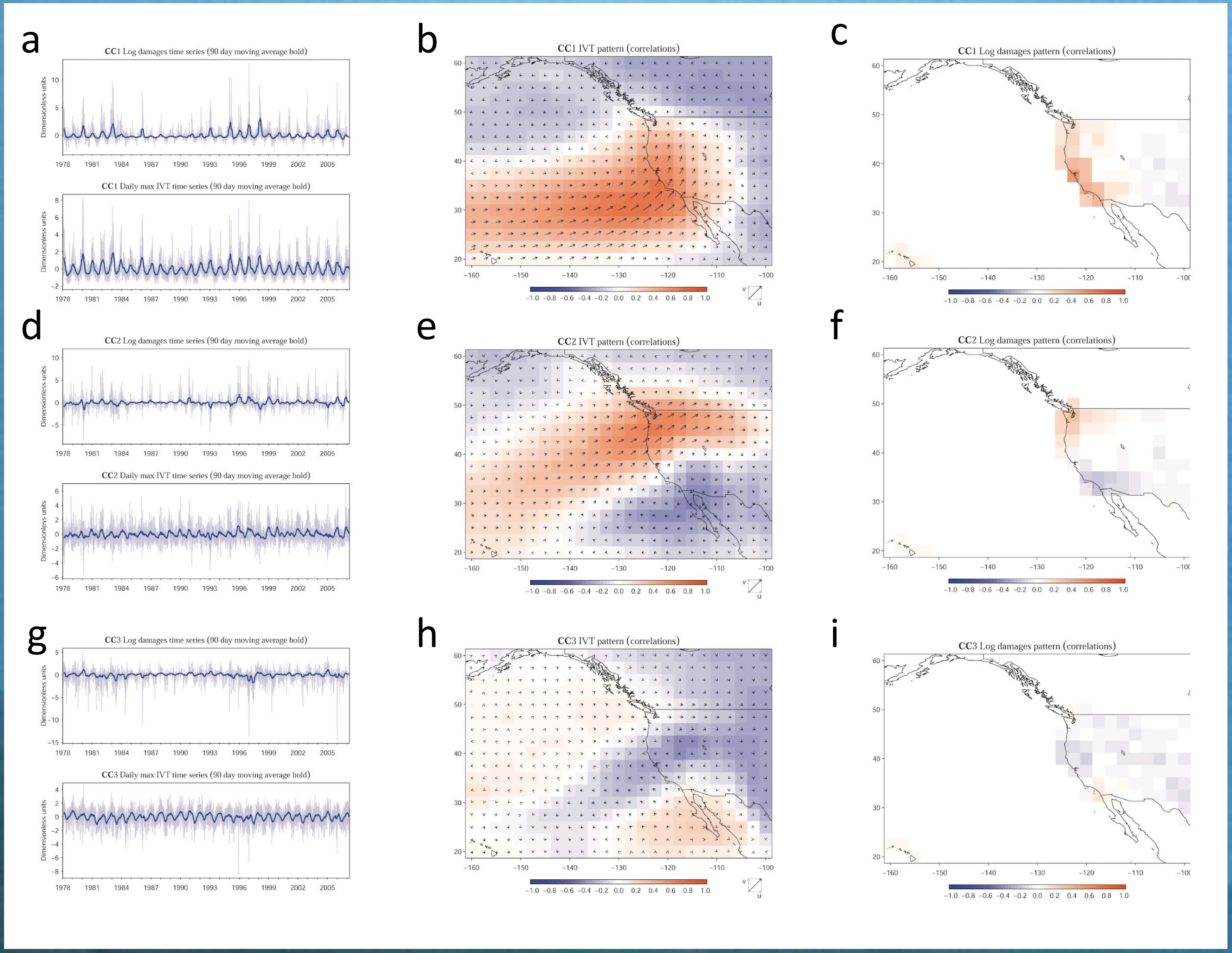

Time Course of Insured Losses
Trimmed Mean of Damages (10th to 90th percentile)
with 95% Bootstrap Confidence Intervals
1000
2000
3000
4000
−5
−4
−3
−2
−1
0
1
2
3
4
5
Days relative to start of AR (day 0)



27.5°N
30°N
32.5°N
35°N
37.5°N
40°N
42.5°N
45°N
47.5°N



AR landfall latitude 47.5N
Difference in damages (log scale)
Damages vs Orientation of IVT, 47.5N
Wind direction × damages
Wind direction and speed, m/s
× Wind
○ Damages
● Damages > $1m
Mean wind
Mean damages
over 15° band
AR landfall latitude 37.5N
Damages vs Orientation of IVT, 37.5N
AR landfall latitude 32.5N
Damages vs Orientation of IVT, 32.5N


a
CC1 Log damages time series (90 day moving average bold)
CC1 Daily max IVT time series (90 day moving average bold)
b
CC1 IVT pattern (correlations)
c
CC1 Log damages pattern (correlations)
d
CC2 Log damages time series (90 day moving average bold)
CC2 Daily max IVT time series (90 day moving average bold)
e
CC2 IVT pattern (correlations)
f
CC2 Log damages pattern (correlations)
g
CC3 Log damages time series (90 day moving average bold)
CC3 Daily max IVT time series (90 day moving average bold)
h
CC3 IVT pattern (correlations)
i
CC3 Log damages pattern (correlations)
Dimensionless units

Characteristics of damaging events

- Multi-day events
- Affected multiple latitude bands
- Strong south-westerly component
- Orientation effects varied by latitude

- A small number of extreme events account for a large proportion of total damages

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Questions

- How much did AR events cost?
- What fraction of losses were due to ARs?
- What were the characteristics of damaging events?
- **What were the key drivers of damages?**

- Will costs increase with climate change?

Variable	Loss	Prob(Loss > 0)	Loss | Loss > 0
Intercept	2.283***	-0.152*	4.43***
	(0.058)	(0.076)	(0.05)
Policies	0.509***	0.619***	0.164***
	(0.063)	(0.087)	(0.042)
Wind *u*	0.161	0.146	0.135*
	(0.083)	(0.108)	(0.059)
Wind *v*	0.077	0.09	0.109
	(0.079)	(0.105)	(0.061)
Wind Speed	0.612***	0.671***	0.119
	(0.135)	(0.178)	(0.097)
IWV	0.687***	0.82***	0.235***
	(0.088)	(0.117)	(0.062)
IVT	0.124	-0.016	0.207**
	(0.116)	(0.15)	(0.078)
Soil	0.418***	0.477***	0.264***
	(0.105)	(0.139)	(0.079)
Snow	0.54***	0.621***	0.069
	(0.099)	(0.127)	(0.07)
Adjusted R-Squared	0.4278		0.2997
AIC		1081.4	
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$			

Damage Function

Variable	Model1	Model2	Model3	Model4	Model5	Model6
Intercept	2.283***	2.283***	2.283***	2.283***	2.283***	2.283***
	(0.071)	(0.069)	(0.068)	(0.061)	(0.059)	(0.059)
Policies	0.906***				0.568***	0.562***
	(0.071)				(0.061)	(0.061)
IVT		1.097***			0.842***	
		(0.069)			(0.061)	
Soil			1.153***		0.928***	
			(0.068)		(0.061)	
IVT * Soil				1.512***		1.372***
				(0.061)		(0.061)
Adjusted R Squared	0.1272	0.1872	0.2069	0.3566	0.3899	0.4023

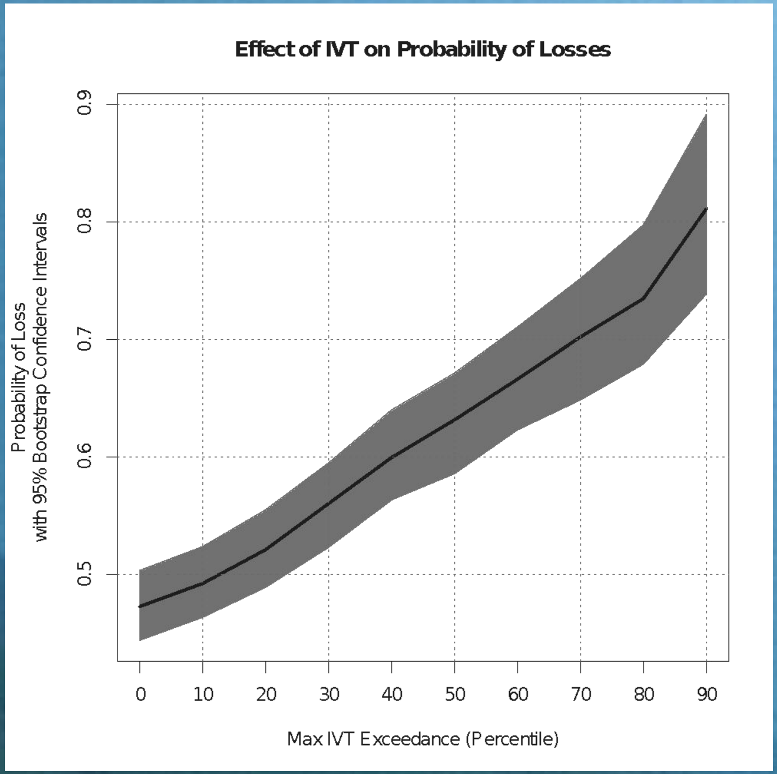
$*$ $p < 0.05$, $**$ $p < 0.01$, $***$ $p < 0.001$

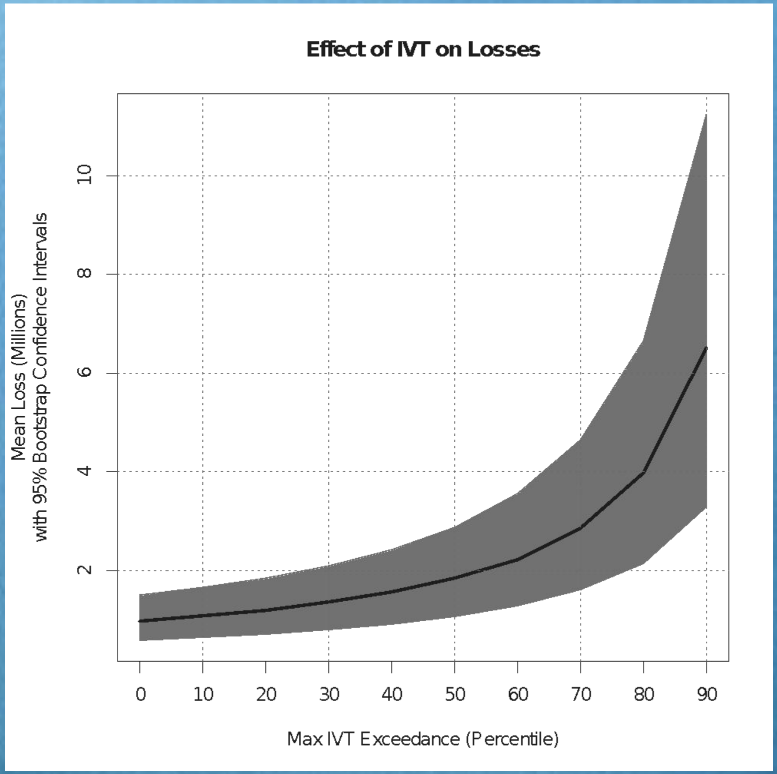
Damage Function

Latitude	27.5	30	32.5	35	37.5	40	42.5	45	47.5
Intercept	-5.41874*	-11.6970	2.5462	-7.2858	-15.5681***	-8.1227***	-19.0669***	-3.3502***	-10.3252***
	(2.19166)	(6.0399)	(1.6269)	(3.5782)	(2.8386)	(1.6176)	(2.8901)	(0.8233)	(1.7053)
Policies								0.00001495***	0.00001059***
								(0.00000354)	(0.00000258)
Max IVT							0.0088***		
							(0.0024)		
Max IWV	0.08435*	0.1992		0.2654**	0.1605*		0.3621***		0.1699***
	(0.03985)	(0.1155)		(0.0952)	(0.0772)		(0.0935)		(0.0532)
Max Wind Speed	0.63020***				0.5415***	0.5896***			0.2103***
	(0.11170)				(0.0966)	(0.0886)			(0.0563)
Zonal Wind u				0.6303**			0.3210		0.1972***
				(0.2037)			(0.1718)		(0.0744)
Meridional Wind v		0.2799		0.2575					
		(0.1808)		(0.1301)					
Snow Depth		18.7574**			16.0505***		15.1015***		
		(5.9012)			(3.1547)		(3.0062)		
Soil Moisture				6.4539*		8.1839***			5.9539***
				(2.8936)		(2.1886)			(1.0981)
IVT * Snow								0.02355***	
								(0.0027)	
IVT * Soil			0.0177***						
			(0.0044)						
Degrees of Freedom	138	41	27	29	117	111	105	171	333
Adjusted R2	0.1817	0.2226	0.3514	0.5261	0.4738	0.4609	0.5035	0.3918	0.3723

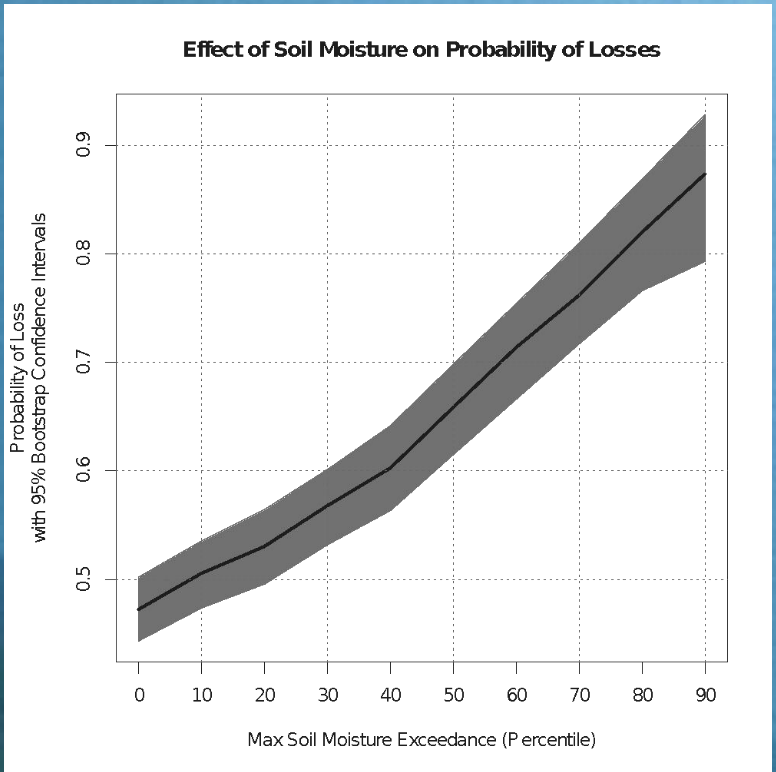
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

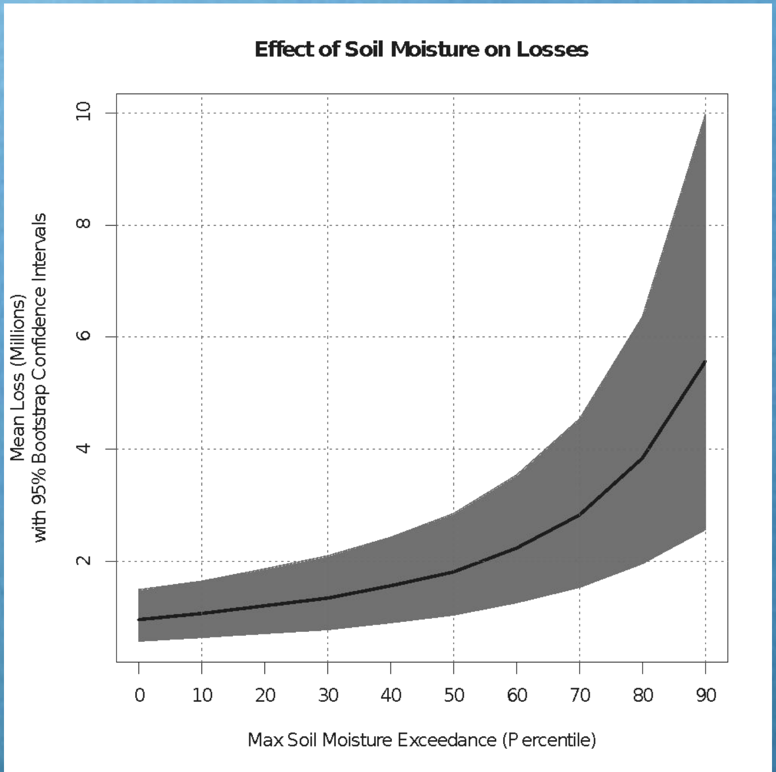
Damage Function





Damage Function





Conclusions

- How much did AR events cost? **Up to $1 – 3b**
- What fraction of losses were due to ARs? **89%**
- What were the characteristics of damaging events?
  - **Multi-day, spatially distributed, south-westerly flow**
- What were the key drivers of damages?
  - **Risk exposure, AR intensity, antecedent moisture levels**

- Will costs increase with climate change?
  - **Costs increase exponentially with AR intensity**
  - **Costs increase exponentially with antecedent soil moisture and snowpack**