An Investigation of the Pineapple Express Phenomenon via Bivariate Extreme Value Theory

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1 Goals

I **Regional climate model assessment:** examine and model tail dependence between observed precipitation and WRF model output

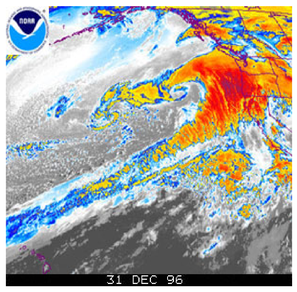
II **Connect precipitation extremes to synoptic-scale processes** via a daily "PE Index"

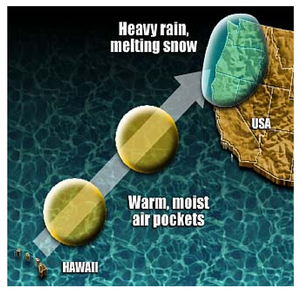
III **Estimate future tail behavior** of western US precipitation

IV **Simulate** future observational extreme precipitation, given regional climate model output

2 Background

- Pineapple Express: the informal name for a storm caused by a stream of moisture (Atmospheric River) extending from near Hawaii to the West Coast of North America
- Produces extreme winter precipitation and flooding events in California and the Pacific Northwest
- Dettinger (2011): "Extremes [of PE events] change notably" under A2 scenario in most climate models





- Extreme Value Theory result: for r.v. X and high threshold u, the exceedances of u approximately follow a Generalized Pareto distribution (GPD):

$$\mathbb{P}(X > x | X > u) \approx \left(1 + \xi \frac{x-u}{\psi_u}\right)^{-1/\xi}$$

- Dependence: for $\mathbf{Z} = (Z_1, Z_2)^T$ a bivariate random vector with unit Fréchet margins $F_Z(z) = \exp\{-z^{-1}\}$, define

$$R = Z_1 + Z_2 \text{ and } W = Z_1/R$$

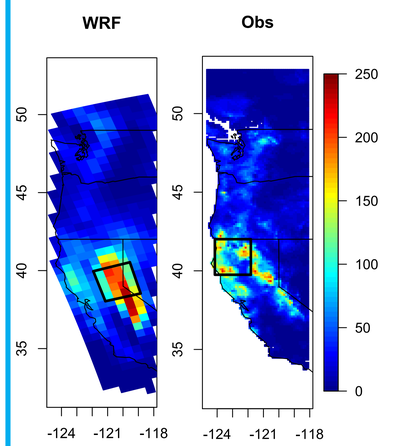
- Tail dependence characterized by a probability measure $H(w)$: called *angular measure*
- Much different than correlation!

3 Data

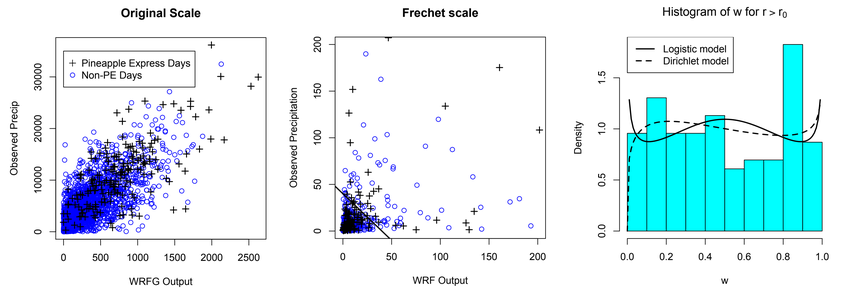
- Daily precipitation output from WRF regional climate model driven by both NCEP reanalysis and CCSM global model
- Gridded observational precipitation data from Surface Water Modeling group at U. of Washington
- Future scenario (A2) precipitation from WRF model driven by CCSM global climate model
- North Pacific daily mean sea level pressure (SLP) fields from NCEP reanalysis and CCSM model
- Winter + November (NDJF) days from 1981-1999 (current) and 2041-2070 (future)

4 Assessing Tail Dependence Between WRF Output and Observations

- For each day t, find the 200×200 km area with the maximum total precipitation from WRF and obs
- Original data → estimate marginals via **GPD** → **Fréchet** → **pseudo-polar** → $H(w)$ to exceedances of $r = r_0$



Precipitation from WRF output (left) and Obs (right) on January 1, 1997. Footprints captured for X_t^{NC} and Y_t^C shown by black lines.



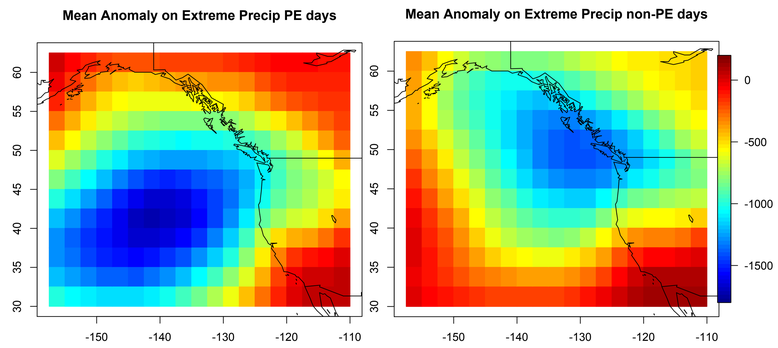
Resulting points (x_t^{NC}, y_t^C). PE days identified by Dettinger et al. (2011).

Left: Fréchet-scaled (z_t^{NC}, z_t^C) with the line $r_t = r_0 = 40$ shown. Right: histogram of $w_t = z_t^{NC}/r_t$ of points for which $r_t > r_0$, with fitted parametric models for H added.

+ *Largest* events from WRF correspond to *largest* events in observed record: tail dependence!

— Not all 'extreme' events associated with Pineapple Express: aim to connect to synoptic-scale processes

5 Building a Daily Pineapple Express Precipitation Index



Mean SLP anomalies (Pa) for largest 130 observed precipitation events, partitioned into PE and non-PE events.

- Two extreme precipitation regimes?
- Define the PE index for day t as the projection of the day t SLP anomaly onto the mean anomaly for extreme PE events
- Measures the similarity between the day t SLP pattern to the pattern shown at far left, as well as its strength
- Find tail dependence between the index and PE-driven precipitation

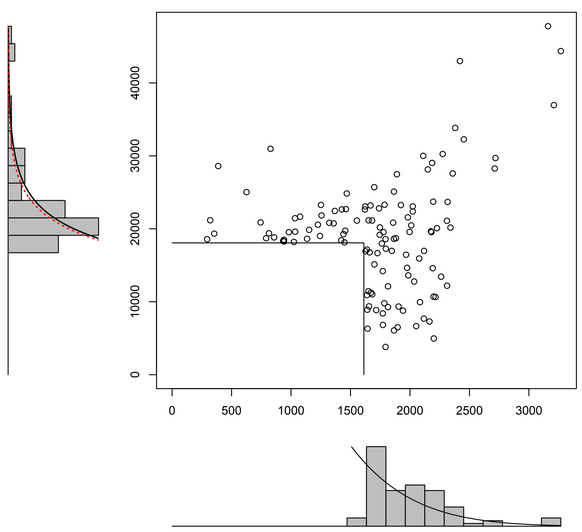
6 Future Pacific Region Extreme Winter Precipitation Observations

- Borrow other NARCCAP models to estimate GPD parameters of future precipitation output:

for RCM i ($i = 1, ..., 5$), GCM j ($j = 1, ..., 4$), run r ($r = 1$ current, $r = 2$ future):

$$\begin{pmatrix}\psi_{ijr}\\ \xi_{ijr}\end{pmatrix} = \begin{pmatrix}\mu_\psi\\ \mu_\xi\end{pmatrix} + \begin{pmatrix}\alpha_{i\psi}\\ \alpha_{i\xi}\end{pmatrix} + \begin{pmatrix}\beta_{j\psi}\\ \beta_{j\xi}\end{pmatrix} + \begin{pmatrix}\gamma_\psi\\ \gamma_\xi\end{pmatrix} \mathbf{1}_{\{r=2\}}(r) + \epsilon_{ijr} \qquad \epsilon_{ijr} \overset{ind}{\sim} N(\mathbf{0}, \Omega_{ijr}^{MLE})$$

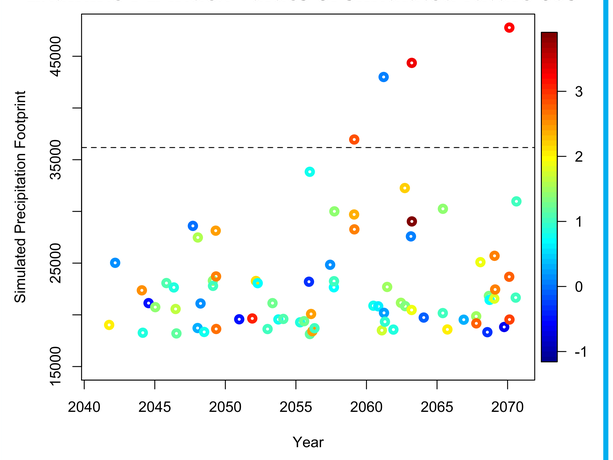
- $\hat{\beta}_{4\xi} = 0.150 \Rightarrow$ NCEP-driven RCM runs produce *heavier tail* of precipitation than GCM-driven runs
- $\hat{\gamma}_\xi = 0.057$: evidence for heavier-tailed precipitation in A2 scenario (100-year event becomes 36.3-year event!)
- Provides an estimate of the upper tail distribution future NCEP-driven WRF output
- Poisson process result and Dirichlet model for the angular measure fitted in (4) allow for simulation of observations, given output from future run of WRF-CCSM (right)
- Evidence not only for changes in location and scale, but ***shape*** of tail as well



Simulated observations of precipitation footprint (y-axis) from future run of WRF-CCSM output (x-axis). Marginal tail histograms added, as well as estimated Generalized Pareto tail densities (solid lines). Red dashed line corresponds to estimated GP tail of observations in current climate. WRF-CCSM is estimated to have a bounded tail, while observations are heavy-tailed.

7 Future PE Precipitation

- Examine PE index values of simulated future obs



Large simulated future precipitation observations, from one realization, with PE index z-scores colored in. Horizontal line corresponds to largest observed event in current climate.

- Future PE index values: increase in the occurrence of large PE index scores (frequency)
- Dependence with observed precipitation also increases: future PE events produce more extreme precipitation than in current climate (intensity)

8 Summary of Results

- Bivariate approach: quantifies uncertainty about climate model representation of extreme events
- Different climate models produce different west coast precipitation tail behavior
- PE index: connects extreme precipitation to short-lived, synoptic-scale patterns
- Evidence for heavier-tailed western US precipitation under A2 scenario
- Future run of WRF-CCSM indicates increased frequency and intensity of extreme precipitation events produced by PE (also found by Leung et al., 2011 and Dettinger, 2011)
- Extensions: Improvement of PE index, conditioning on PE index as well as RCM output to simulate observations

References

Weller, G., Cooley, D., and Sain, S. (2011). An Investigation of the Pineapple Express Phenomenon via Bivariate Extreme Value Theory. *Submitted.*

Dettinger, M. (2011). Climate change, atmospheric rivers, and floods in California - a multimodel analysis of storm frequency and magnitude changes. *JAWRA Journal of the American Water Resources Association*, 47(3):514-523.

Dettinger, M., Ralph, F., Das, T., Neiman, P., and Cayan, D. (2011). Atmospheric rivers, floods and the water resources of California. *Water*, 3(2):445-478.

Leung, L., Correia, J., and Qian, Y. (2011). Regional climate change scenarios for North America simulated by WRF driven by two global climate models. In *Proceedings of the Ninety-first American Meteorological Society Annual Meeting*, Seattle, WA USA.

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