Design in a changing climate

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a discussion

- Return levels
- Mitigation
- Compromise between safety and cost
- Statistics – climate models

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Communication is essential for risk management

- clear
- intuitive
- simple --- but not too simple!

Fort Collins

***The 2012-2050 10% probability warmest winter has a minimum temperature* of 12^o F**

***The 2050-2090 10% probability warmest winter has a minimum temperature* of 16^o F**

***The statistical uncertainty is* $\pm\, 4^o$ F**

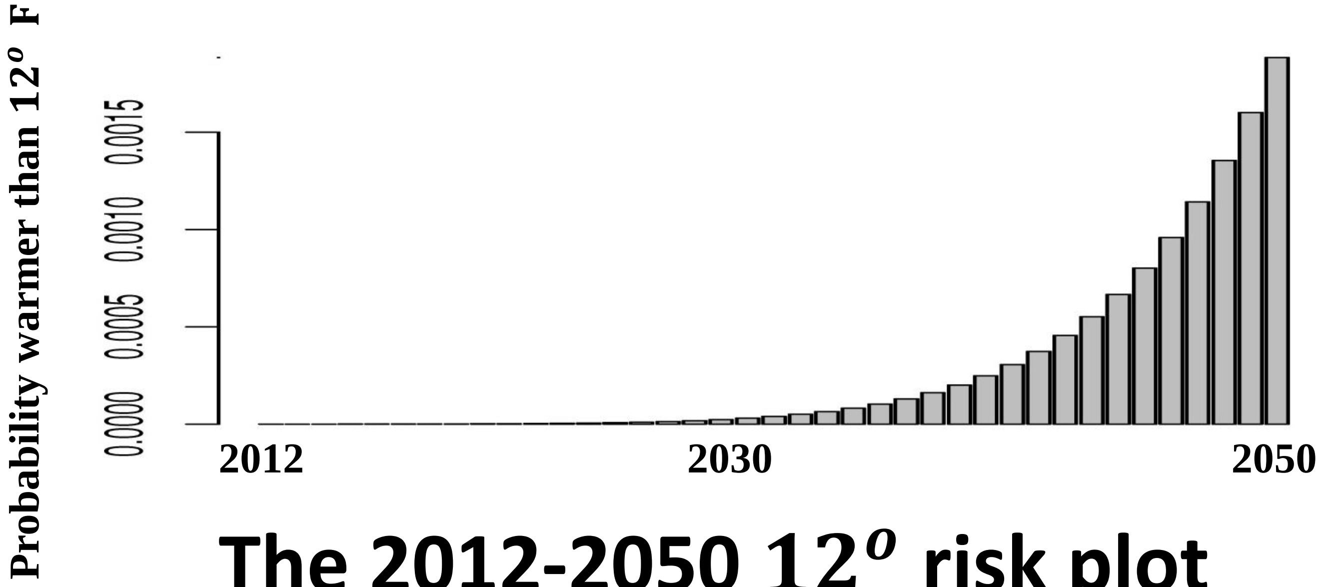
The 2020-2060 1% probability flood exceeds 3.5 m

The 2015-2040 5% probability windstorm has windspeeds exceeding 37 m/s

The 2012-2111 73,3% (=$(1 - e^{-1})$%) probability largest rainfall is 20 cm

Current practise!

Fort Collins
high yearly minimum temperature

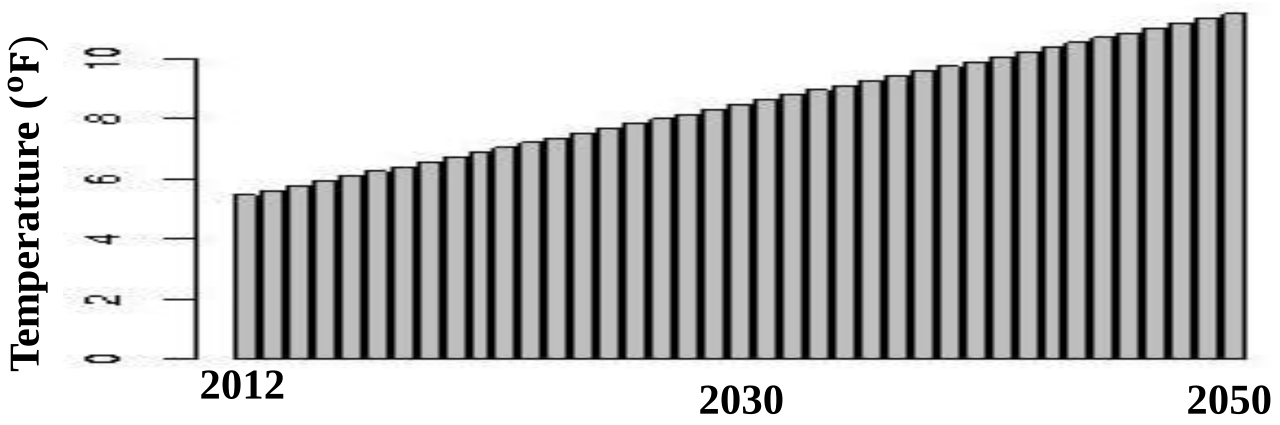


The 2012-2050 12^o risk plot

(Remember: "The 2010-2050 10% probability "warmest winter" has a minimum temperature of 12^o F")

Statistical uncertainty → Color bands?

Fort Collins
high yearly minimum temperatures



2012-2050 10/49% risk temperature plot

Statistical uncertainty → Color bands?

Current practice

(thinks of a stationary climate with independence between years)

the 1000-year return level flood is the flood level $\boldsymbol{u}$ which on the average is exceeded once every thousand year - briefly: "**the 1000-year flood**"

= $(\mathbf{1}-\boldsymbol{F})^{-\mathbf{1}}\,(\mathbf{1}/\mathbf{1000})$, with F the d. f. of the maximum flood in a year ≈ $\boldsymbol{P}$**(1000-year max>u)**≈ $\mathbf{1}-\boldsymbol{e}^{-\mathbf{1}}$

= $\boldsymbol{e}^{-\boldsymbol{\theta}}$ **if dependency.**
Different in changing climate!

Very useful and convenient indeed: One number gives you two things at once. E.g. it follows that if you design dykes to resist the 1000-year flood, then the probability of a catastrophe during 100 years is ***1-*** $\boldsymbol{e}^{-\mathbf{0.1}} \approx \mathbf{0.1}$.

but

This doesn't make sense in a changing climate!

Current practice

(thinks of a stationary climate with independence between years)

the 35 m/s wind storm return period is the number of years it on the average takes between the occurrence of two storms with wind speeds exceeding 35 m/s

Variation around mean?
Different in a changing climate!

=$\mathbf{1}/(\mathbf{1}-$***F(35))*** = *with* F the d. f. of the maximal wind speed in a year.

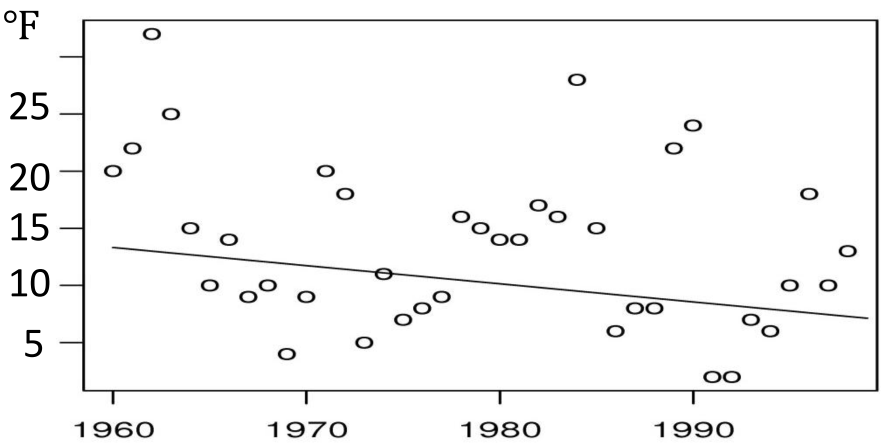
Fort Collins

~~the 2020 12^{o} highest minimum winter temperature return period~~

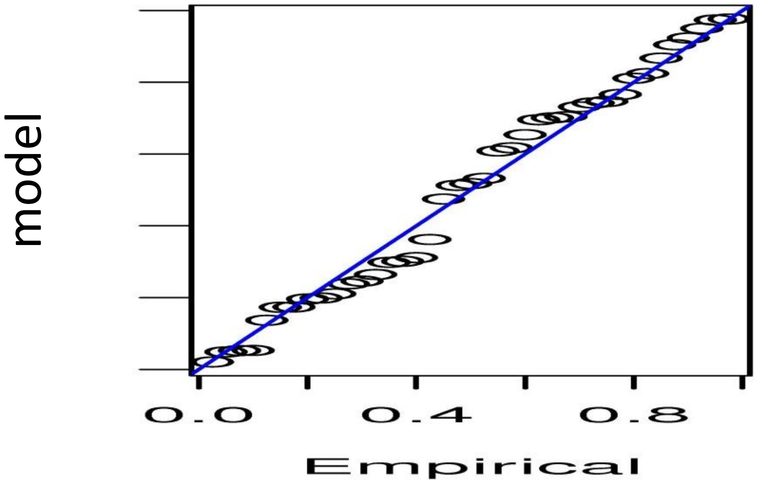
- Intrinsically stationary concept
- Depends on what happens after design life
- Means different things in different nonstationary scenarios
- Doesn't describe variation around mean

\+ One doesn't have to specify a probability, just a level

Fort Collins: standard data analysis (R package: extRemes)



neg. yearly minimum temperatures



$$X \sim \exp(-(1+\gamma\frac{x-\mu_t}{\sigma})^{-1/\gamma})$$

$$\mu_t = \alpha + \beta t$$

$$\hat{\alpha} = 334$$
$$\hat{\beta} = -0.15$$
$$\hat{\sigma} = 5.6$$
$$\gamma = -0.052$$

$\sum =$

-80.4	4.28e-02	5.69	-1.284
0.0428	-2.25e-05	-0.00283	0.000640
5.69	-2.83e-03	0.242	0.0283
-1.28	6.40e-04	0.0283	0.00333

Estimation

$$P = P(y;\theta) = P(y;\alpha,\beta,\sigma,\gamma)$$

$= P($**2012-2050 warmest winter has a minimum temperature > y**$)$

$$= 1 - (1-\exp\{-(1+\gamma\frac{-y-\mu_{2012}}{\sigma})^{-\frac{1}{\gamma}}\}) \cdot \ \dots \ \cdot (1-\exp\{-(1+\gamma\frac{-y-\mu_{2050}}{\sigma})^{-\frac{1}{\gamma}}\})$$

solve $\mathrm{P}(y;\hat{\theta}) = 1/10$ for y

→ $\hat{y}_{1/10} =$ ***the 2012-2050 10% probability warmest winter minimum temperature*** **(= 12^o F)**

Delta method

$$\boldsymbol{P(y;\theta)}$$

$$= \mathbf{1} - (\mathbf{1} - \exp\{-(\mathbf{1} + \boldsymbol{\gamma}\frac{-\boldsymbol{y} - \boldsymbol{\mu}_{\mathbf{2012}}}{\boldsymbol{\sigma}})^{-\frac{1}{\gamma}}\}) \cdot \ \dots \ \cdot (\mathbf{1} - \exp\{-(\mathbf{1} + \boldsymbol{\gamma}\frac{-\boldsymbol{y} - \boldsymbol{\mu}_{\mathbf{2050}}}{\boldsymbol{\sigma}})^{-\frac{1}{\gamma}}\})$$

$$= 1 - \exp\{\boldsymbol{\varphi}(\boldsymbol{x};\boldsymbol{\theta})\}$$

$\hat{\boldsymbol{y}}_{\mathbf{1/10}}$ **solves** $\boldsymbol{\varphi}(\boldsymbol{y};\hat{\boldsymbol{\theta}}) =$ **log(1-1/10) for** $\boldsymbol{y}$

$$\boldsymbol{\nabla\varphi} = \left[\frac{\partial\boldsymbol{\varphi}}{\partial\boldsymbol{\theta}}\right] = \left[\frac{\partial\boldsymbol{\varphi}}{\partial\boldsymbol{\alpha}}, \frac{\partial\boldsymbol{\varphi}}{\partial\boldsymbol{\beta}}, \frac{\partial\boldsymbol{\varphi}}{\partial\boldsymbol{\sigma}}, \frac{\partial\boldsymbol{\varphi}}{\partial\boldsymbol{\gamma}}\right]$$

$$\boldsymbol{V_{\varphi}} = [\boldsymbol{\nabla\varphi^T}\textstyle\sum\boldsymbol{\nabla\varphi^T}]_{\hat{\boldsymbol{y}}_{\mathbf{1/10}}} / \frac{\partial\boldsymbol{\varphi}}{\partial\boldsymbol{x}}\Big|_{\hat{\boldsymbol{y}}_{\mathbf{1/10}}}$$

← compute with Maple

→ confidence interval for $\boldsymbol{y}_{\mathbf{1/10}}$

Parametric bootstrap

- simulate $\varepsilon_{1960}, \dots, \varepsilon_{1999}$ from $\exp(-(1+\hat{\gamma}x)^{-1/\hat{\gamma}})$
- compute $y_{1960} = -(\hat{\mu}_{1960} + \hat{\sigma} \cdot \varepsilon_{1960})$, …, $y_{1999} = -(\hat{\mu}_{1999} + \hat{\sigma} \cdot \varepsilon_{1999})$
- estimate the 2012-2050 10% probability warmest winter minimum temperature from $y_{1960}, \dots, y_{1999}$

Repeat many times, and use resulting sample of estimates to compute confidence interval for the 2012-2050 10% probability warmest winter minimum temperature

Olsen, J.R., Lambert, J.H. and Haimes, Y.Y. (1998). Risk of Extreme Events Under Nonstationary Conditions. *Risk Analysis,* **18**, *497-510.*

Definition of return period	**Formula**
Inverse of the probability of failure within the year t. (Expected observations of identical years before failure.)	$\frac{\mathbf{1}}{\mathbf{1}-\boldsymbol{F_t(u)}}$
Expected waiting time before failure at the beginning of the design life of a project.	$\sum_{1}^{\infty} \mathbf{kF_1(u) \cdot \ldots \cdot F_{k-1}(u)(1-F_k(u))}$
Expected waiting time before failure starting at any year t during the project life.	$\sum_{1}^{\infty} \mathbf{kF_1(u) \cdot \ldots \cdot F_{k+t-2}(u)(1-F_{k+t-1}(u))}$

F_k(u) = probability of no failure in year k

Vogel, R.M., Yaindl, C. and Walter, M. (2011). Nonstationaitry: Flood magnification and recurrence reduction factors in the United states. *J. Amer. Water Resources Ass.* **47,** 464-474.

"… Nonstationarity in floods can result from a variety of anthropogenic processes including changes in land use, climate, and water use … A decadal flood magnification factor is defined as the ratio of the T-year flood in a decade to the T-year flood today. Using historical flood data across the United States we obtain flood magnification factors in excess of 2-5 for many regions of the United States … Similarly, we compute recurrence reduction factors which indicate that what is now considered the 100-year flood, may become much more common in many watersheds."

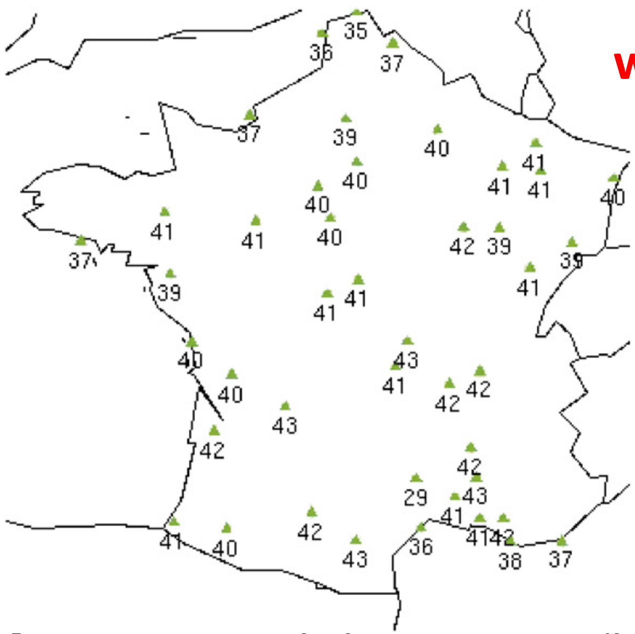
Based on linear normal model for logarithms of annual maximum instantaneous peak streamflow

Laurent, C. and Parey, S. (2007). Estimation of 100-year-return-period temperatures in France in a non-stationary climate: Results from observations and IPCC scenarios. *Global and Planetary Change* **57**, 177–188

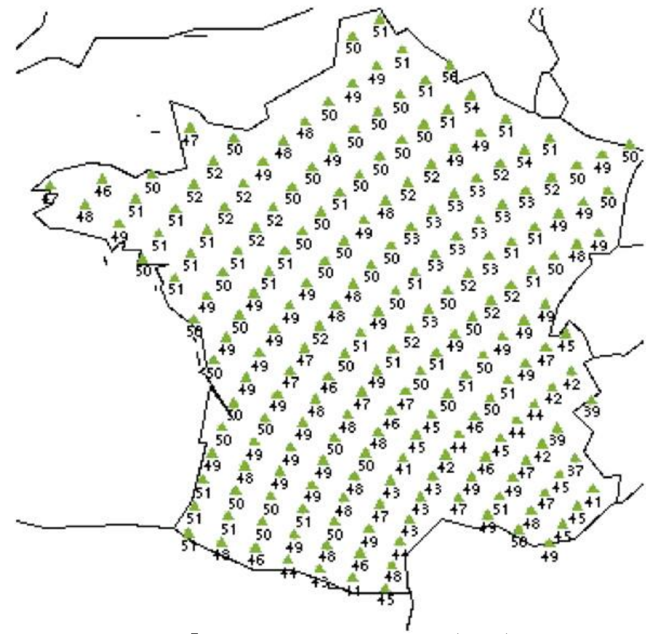
100- year return period: the value of u which solves

$$(1 - F_1(u)) + \ldots + (1 - F_{100}(u)) = 1$$

?
which year



100-year-return-period temperatures (in °C) estimated from a non-stationary extrapolation of measurements from 1960 to 2003



100-year-return-period temperatures (°C) estimated from a stationary extrapolation of ARPEGE–Climat temperatures from 2070 to 2100 (A2 scenario).

French dams and Dutch dikes: 10,000 year return levels

10,000 years ago, there were few humans and little civilization on earth. 10,000 year from now, our world will be completely and utterly different in ways we cannot even imagine now.

Common codes: 100 year return levels

From 1912 to 2011 we have passed from a largely non-industrialized world to a post-industrial world. There has been two world wars, the Soviet Union has appeared and vanished, and China is rising to become the major superpower. Also 100 years from now the world will be completely different. But hopefully some major engineering structures will survive 100 years and more.

However interpretations like the following do make sense

The probability that an individual dam will fail next year is 1/10,000. There are (perhaps?) 650 dams in France, so "on the average" 650 x 100/10.000 = 6.5 dams will fail during the next 100 years -- but non-stationarity and dependence makes reality more complex than this.

We (Rick and I) need help with

- *ideas*
- *feedback*
- *references*
- *data sets*
- *experiences about accuracy of confidence intervals*