Rock fall- weather relationships: Their chaotic nature and probabilistic ways forward

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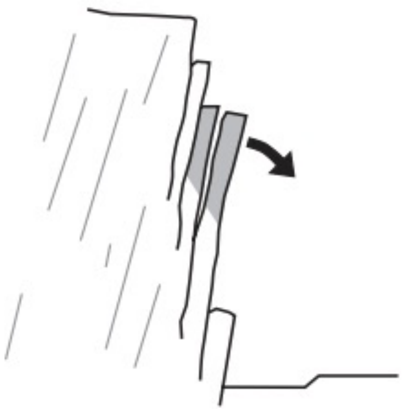
Rock fall processes

Different mechanisms

Fig. 1 *Example of different rock fall detachment mechanisms.*

Rock fall processes

Rock falls, topples, and slides



Detachment

- Triggers
- Precursory factors
- Progressive failure
- Different mechanisms

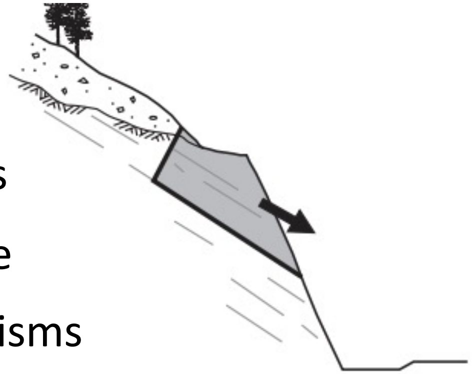


Fig. 2 *Some rock fall and slide detachment mechanisms (after Wyllie and Mah 2012).*

Causes of 308 Rockfalls on Highways in California

Cause of Rockfall	Percentage of Total[a]
Rain	30
Freeze–thaw	21
Fractured rock	12
Wind	12
Snowmelt	8
Channeled runoff	7
Adverse planar fracture	5
Burrowing animals	2
Differential erosion	1
Tree roots	0.6
Springs or seeps	0.6
Wild animals	0.3
Truck vibrations	0.3
Soil decomposition	0.3

[a]May not sum due to rounding.
Source: McCauley et al. 1985.

Triggering Factors of Slope Failures in Yosemite National Park

Triggering Factor	Number	Percent
Rainfall	78	51.0
Rainfall and snow	15	9.8
Freeze–thaw	18	11.8
Earthquakes	21	13.7
Blasting and construction	12	7.8
Lightning, wind storms, spring runoff	9	5.9

Source: Guzzetti et al. 2003.

Table. 1 *Causes and triggering factors for rock slope failures (Higgins and Andrew 2012).*

Seasonal rock fall – weather correlations are well known as well:

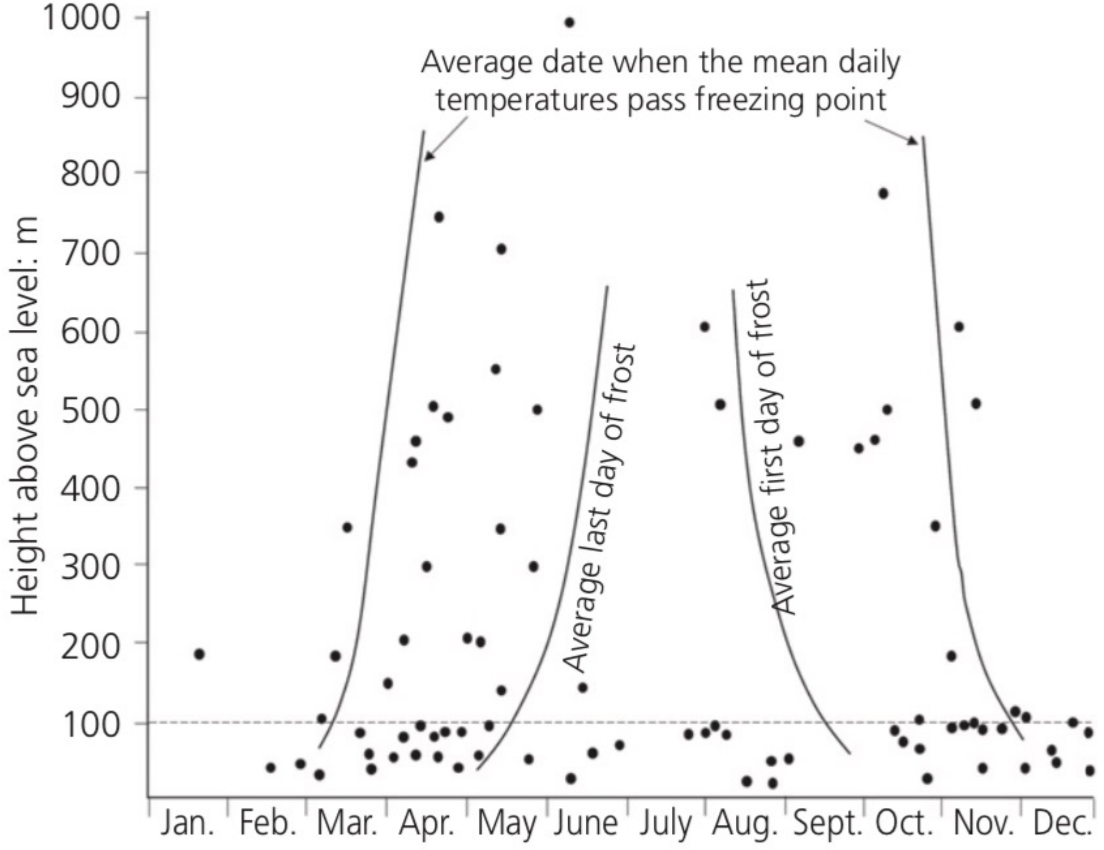


***Fig. 3** Rock fall trends by month and altitude of detachment zone (Bjerrum and Jørstad, 1968).*

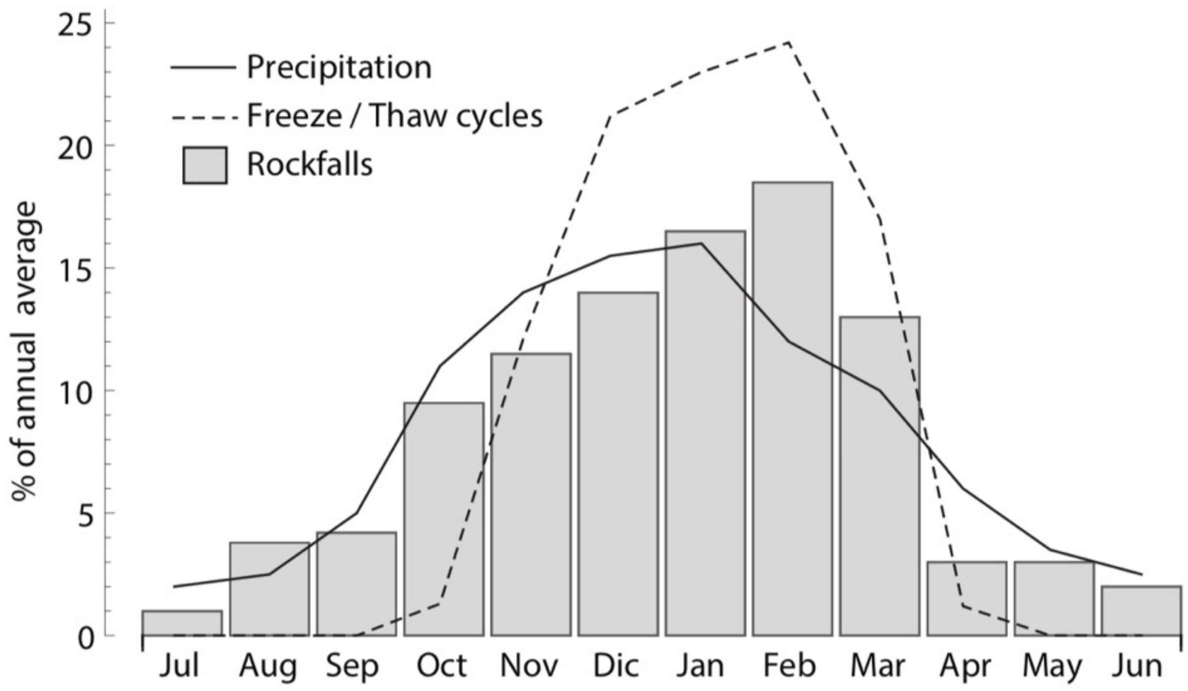


***Fig. 4** Rock fall trends with month and weather indicators along a rail corridor in Canada (after Macciotta et al. 2015).*

Can we know the timing for the next rock fall occurrence based on weather?

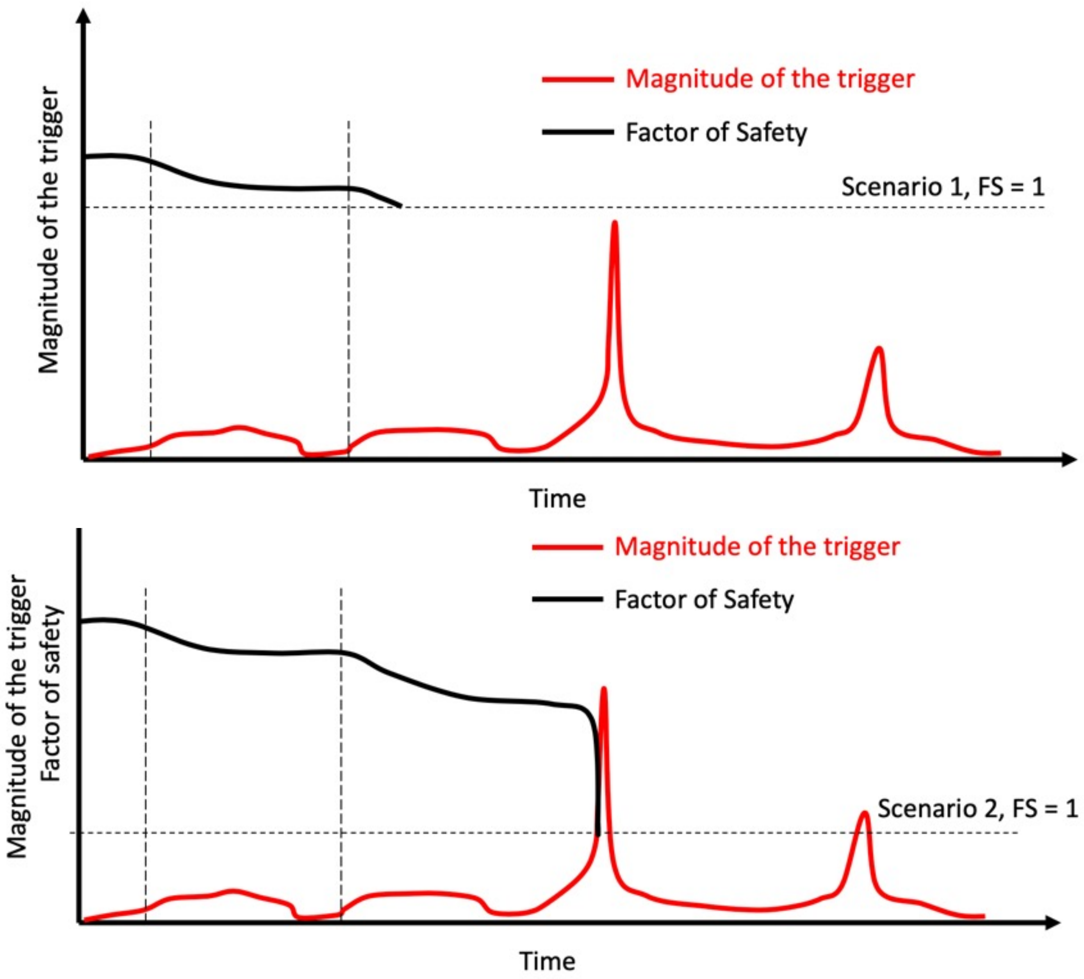


***Fig. 5** Rock block instability illustrated as FoS and magnitude of potential triggers*

- Iterative nonlinear systems are those in which the current state depends on the previous state(s).
- These systems are capable of showing unpredictable behavior arising from simple, deterministic descriptions.
- The phenomenon (rock fall) is determined by its past states, but in practice, small uncertainties and knowledge gaps introduce calculation errors that become amplified with longer forward modeling and prediction

$$X_{i+1} = F(X_i)$$

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Random nature of rock fall occurrences

One common mathematical expression is the Logistic difference equation:

$$X_{i+1} = kX_i(1 - X_i)$$

- Xi is the value of variable X at time i and k is a growth factor.
- Values between 0 and 1 for k values between 0 and 4 and initial X between 0 and 1.
- Depending on the value of k, the solution of the equation can tend to a fixed value, jump between defined values (2, 4, 8…2n values), or behave in a chaotic manner. The chaotic behavior is observed for values of 3.57 < k < 4

k = 1.1 and X_1 = 0.5 $X_{i+1} = 1.1\, X_i\,(1 - X_i)$

k = 3 and X_1 = 0.5 $X_{i+1} = 3\, X_i\,(1 - X_i)$

k = 3.95 and X_1 = 0.5 $X_{i+1} = 3.95\, X_i\,(1 - X_i)$

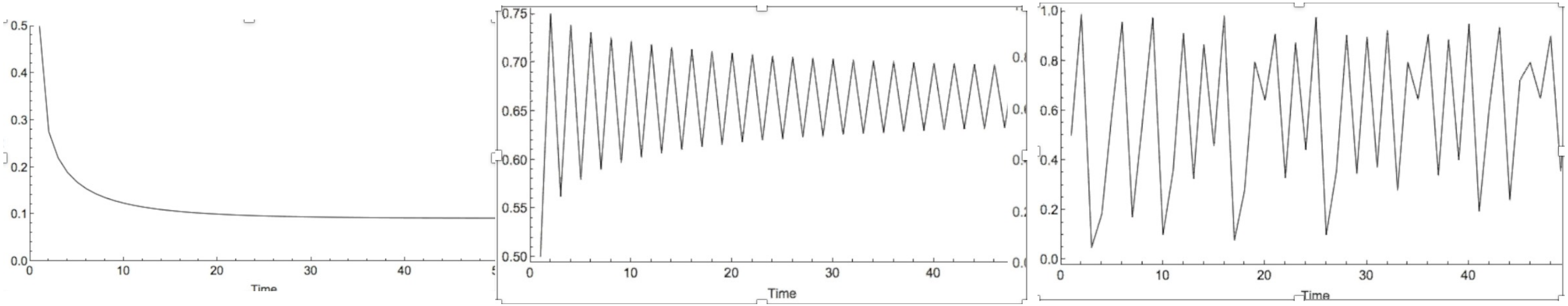

Fig. 6 *Logistic difference equation behavior for different input parameters*

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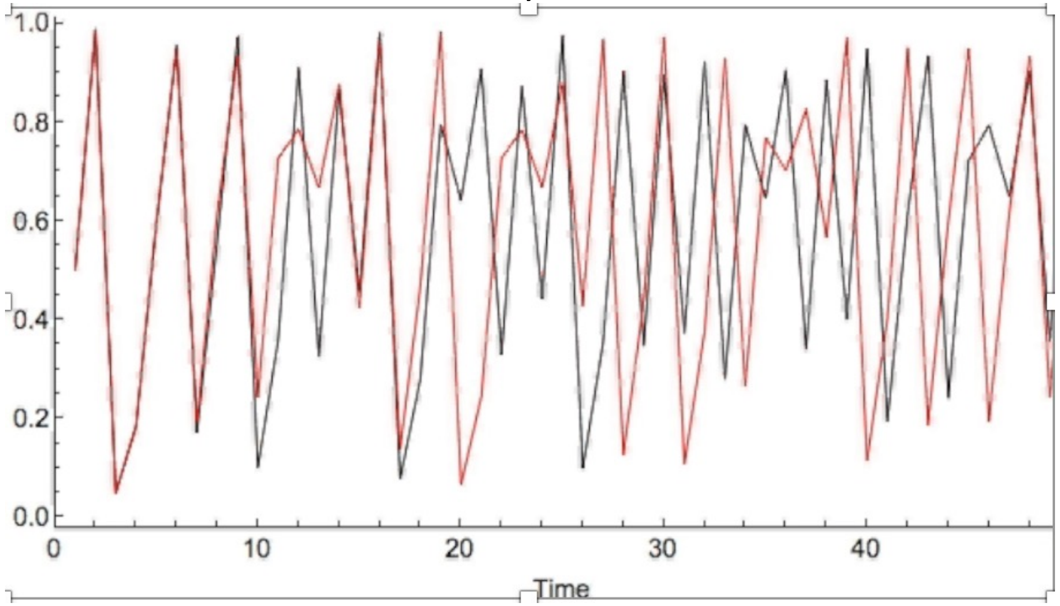
Random nature of rock fall occurrences

Importantly, "rounding error" compounds:

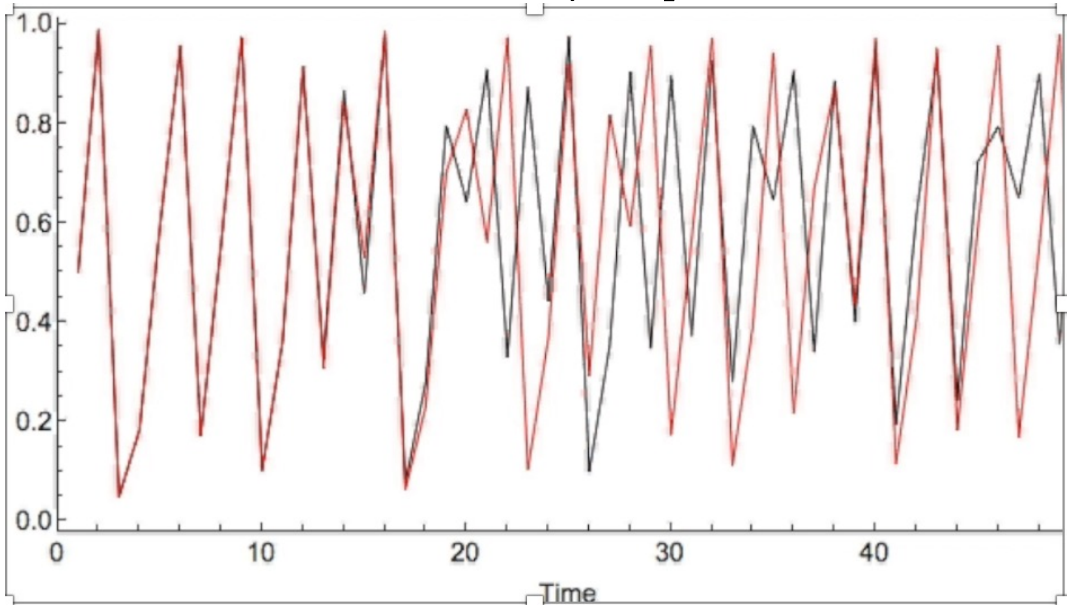
Sensitivity to k



$k = 3.95$ and $X_1 = 0.5$ $\quad X_{i+1} = 3\, X_i\, (1 - X_i)$

$k = 3.949$ and $X_1 = 0.5$ $\quad X_{i+1} = 3\, X_i\, (1 - X_i)$

Sensitivity to X_1



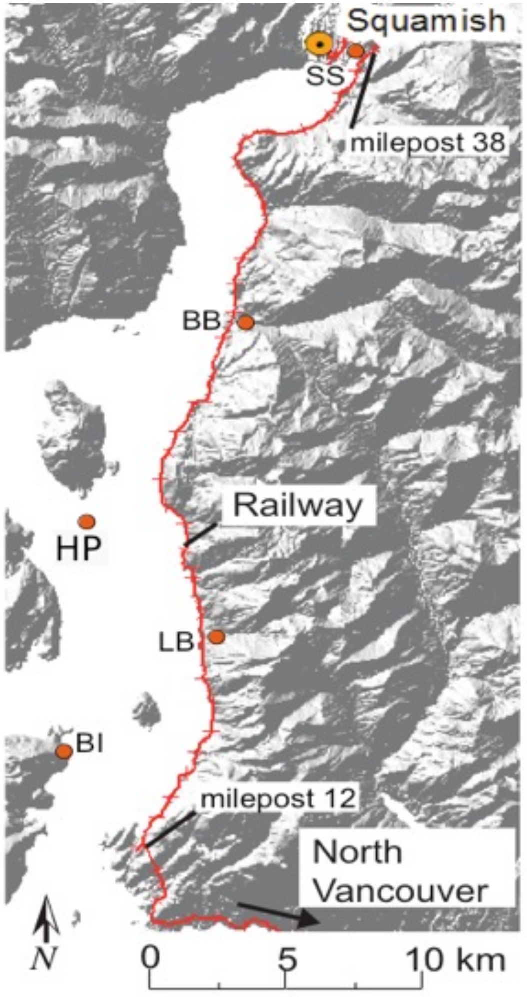
$k = 3.95$ and $X_1 = 0.5$ $\quad X_{i+1} = 3\, X_i\, (1 - X_i)$

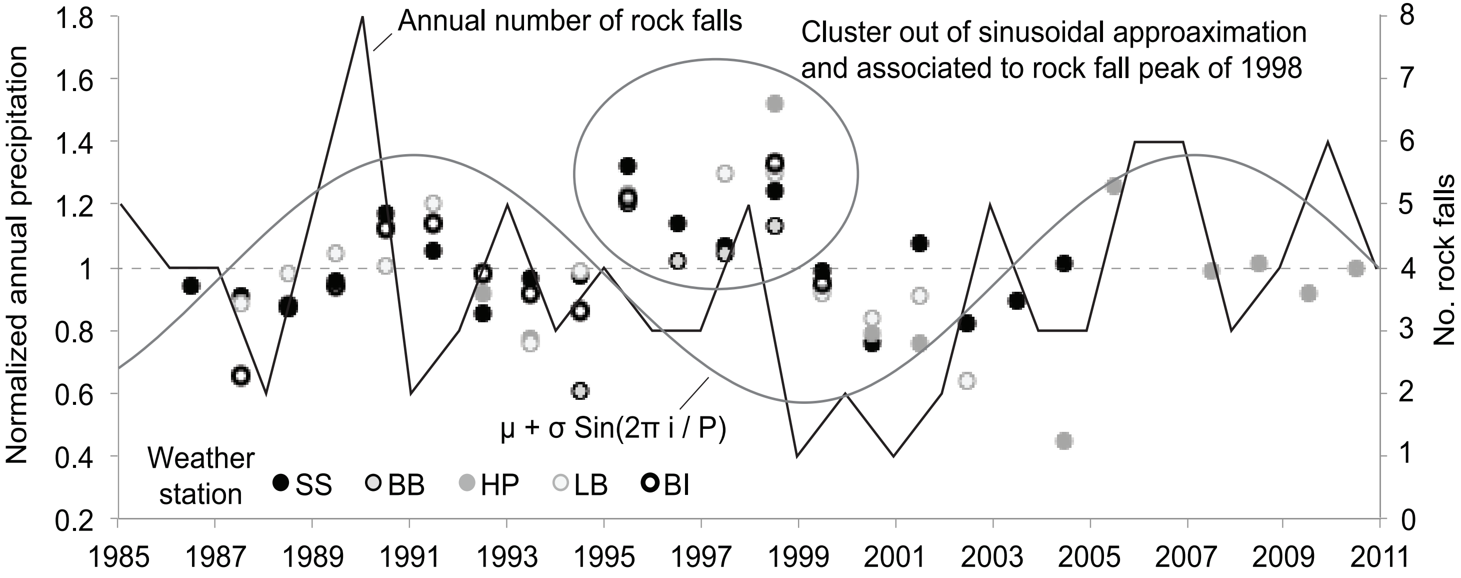
$k = 3.95$ and $X_1 = 0.499$ $\quad X_{i+1} = 3\, X_i\, (1 - X_i)$

Fig. 7 *Logistic difference equation behavior – sensitivity in the chaotic regime*

Random nature of rock fall occurrences

Plausibility tested along railway line between North Vancouver and Squamish





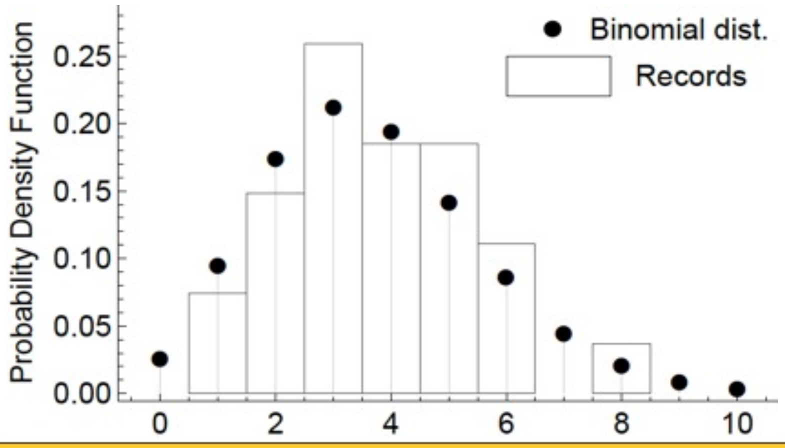


***Fig. 8** Location, annual rock fall occurrences, annual precipitation, and statistical distribution of rock falls along a railway line between North Vancouver and Squamish (After Macciotta and Hendry, 2017).*

Random nature of rock fall occurrences

Used binomial distribution fit and logistic difference equation to simulate 10,000 years of annual rock fall data. Results were compared against the 27-year rock fall database to evaluate which simulation was a better fit.

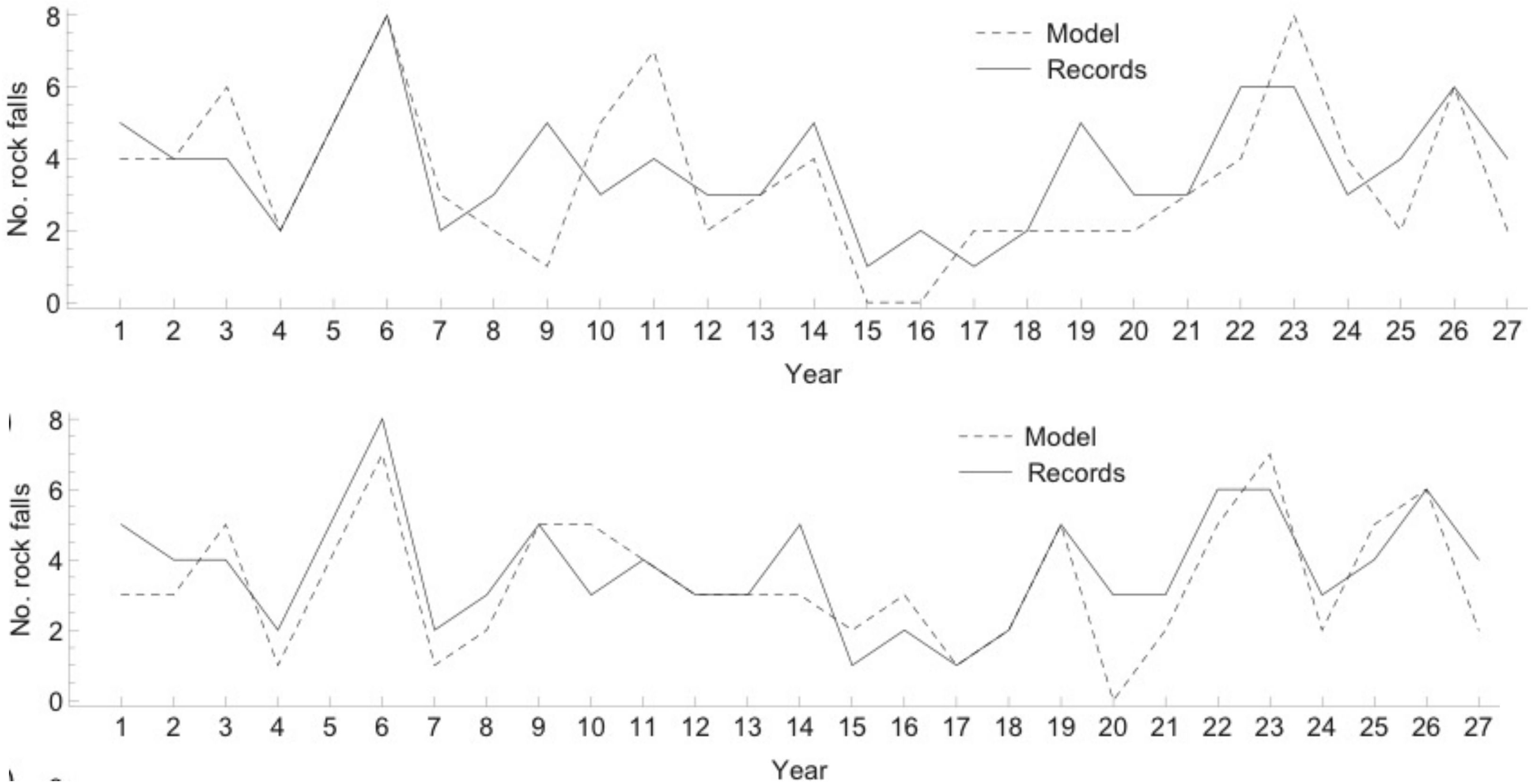


Fig. 9 *Results of 27-year synthetic data from random binomial simulation and from Logistic difference equation (After Macciotta and Hendry, 2017).*

Binomial distribution best correlation: 0.67

Follows general trend

Does not correlate much when smaller periods (3 to 5 years) are analyzed.

Iterative, nonlinear approach had a best correlation of 0.79

Follows general trend and correlates better with smaller periods (3 to 5 years).

Random nature of rock fall occurrences

- Implication is that prediction becomes unachievable at a practicable budget

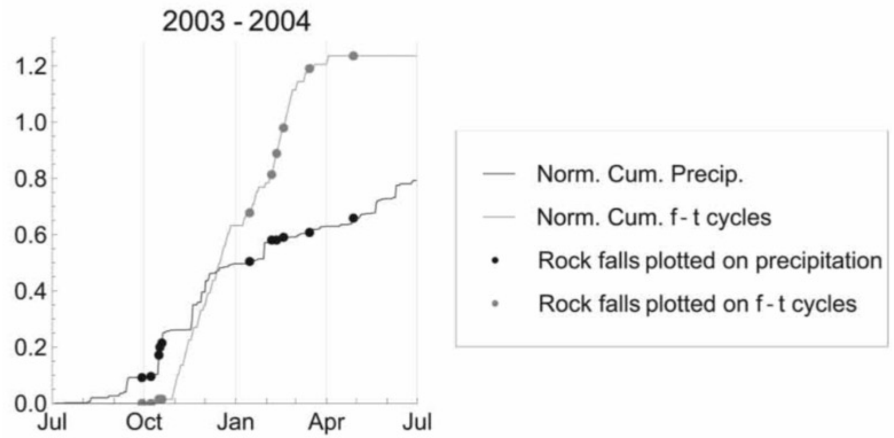
- Rock fall are commonly treated stochastically

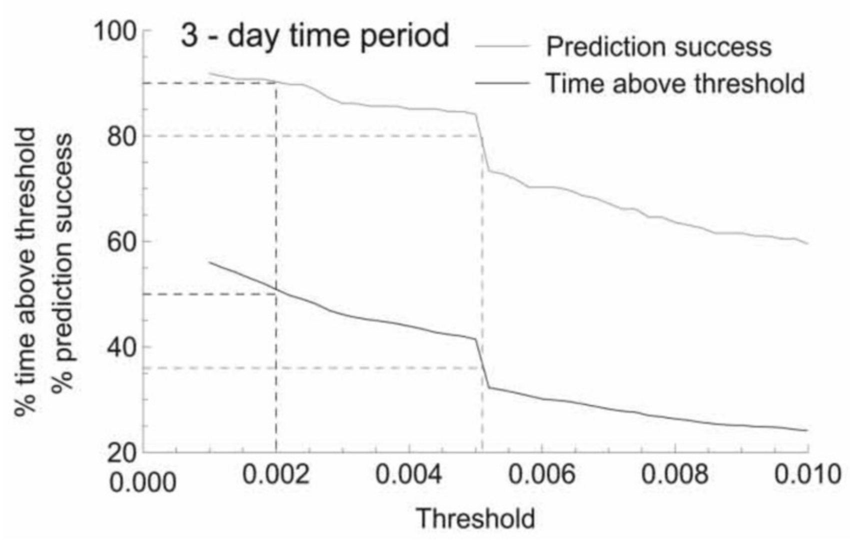
- The way forward is an Informed Probabilistic Approach for risk management
  - Considers non-linear behavior
  - Accounts for weather trends

- Long term and short term forecasting of rock fall probability -> rock fall risk and the expected risk variability in time

Proposed way forward

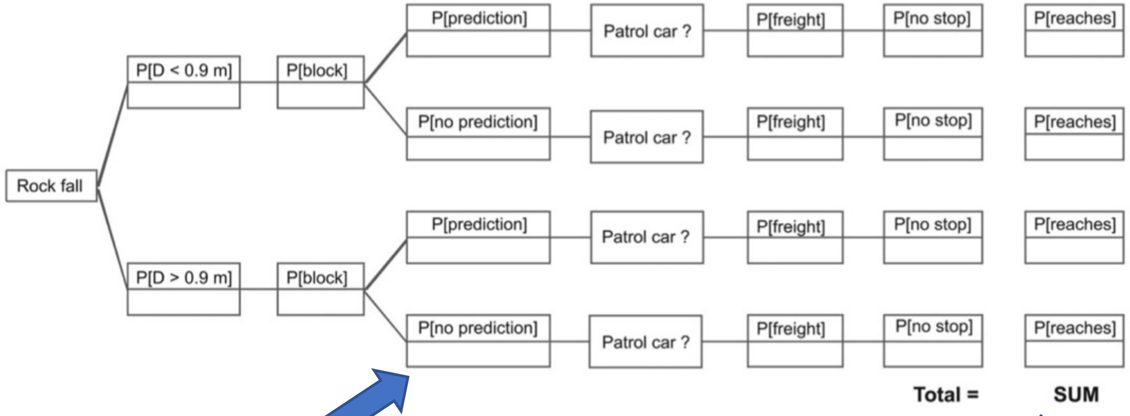
In the short term:





90% prediction success
Threshold at 0.002
Hazard time 50% (183 days/year)

80% prediction success
Threshold at 0.0051
Hazard time 36% (131 days/year)



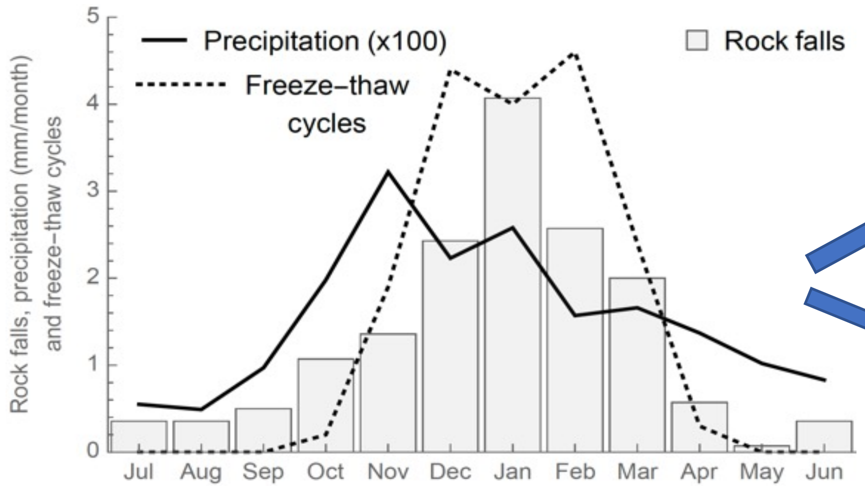
Weather-based criteria for periods of higher rock fall hazard - Squamish 124-157		3-day cumulative precipitation	
		≤ 2 mm	> 2 mm
a) Has there been a freeze-thaw cycle within 3 days?	No	Non-hazardous period	Hazardous period
	Yes	Hazardous period	Hazardous period
b) Within 2 first weeks of spring thaw?	No	Non-hazardous period	
	Yes	Hazardous period	

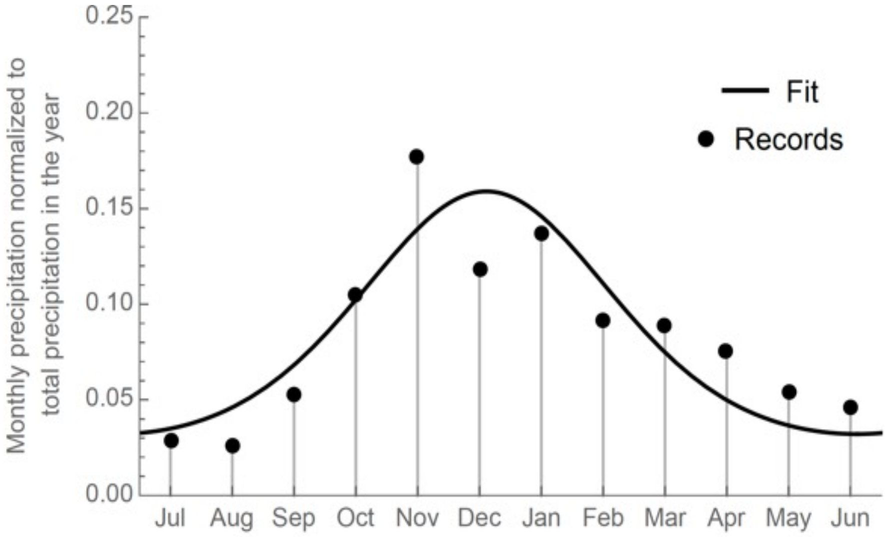
Notes:
90% of rock falls occur within hazardous periods
10% of rock falls occur within non-hazardous periods
An average of 50% of the time within a year is under a hazardous period warning

Fig. 10 *From rock fall – weather relationship to risk-based operational strategies (After Macciotta et al., 2017).*

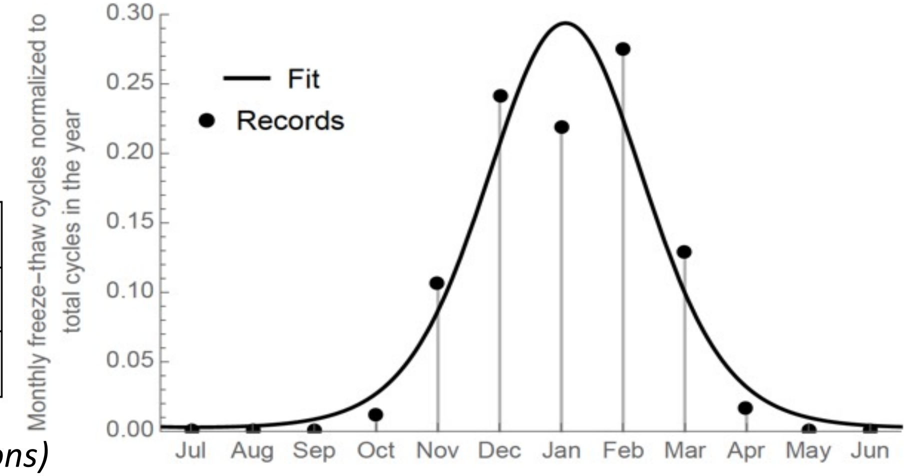
Proposed way forward

Seasonal variation of risk and long term risk variability:





von Mises distribution fit to normalized monthly precipitation



von Mises distribution fit to normalized freeze-thaw cycles

$$M(\mu_0,\kappa) = \frac{1}{2\pi I_0(\kappa)} e^{\kappa\cos(\omega-\mu_0)}, \quad 0 < \omega \leq 2\pi \quad \kappa > 0 \quad 0 \leq \mu\_0 < 2\pi,$$

von Mises	μ_0	κ	Correlation coefficient (r)
Precipitation	2.7 (mid-December)	0.8	0.88
Freeze-thaw cycles	3.2 (mid-January)	2.3	0.95

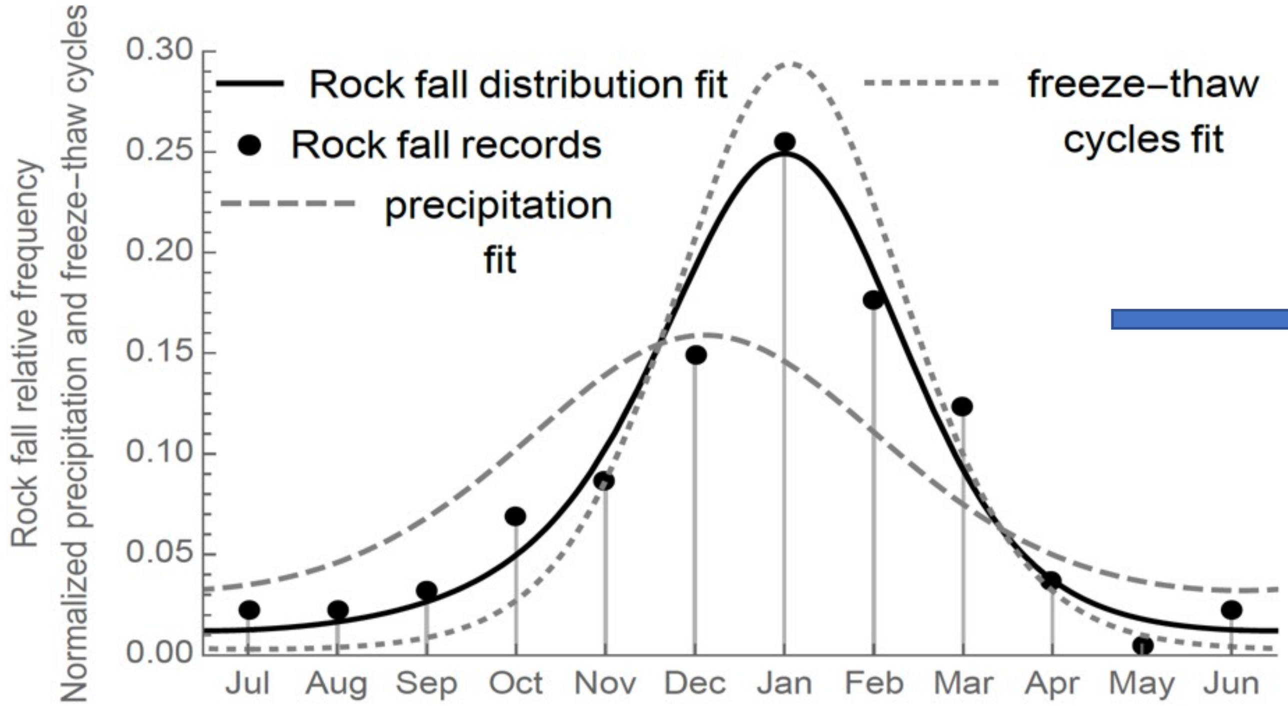
Fig. 11 *Weather data fitted to von Mises distributions (circular distributions) for statistical modeling (After Pratt et al., 2018; Macciotta, 2019).*

Proposed way forward

Using the von Mises distributions for weather:

<u>Mixture distribution:</u> $F_M = \sum_{j=1}^{m} W_j F_j(\omega)$,

von Mises	W_j
Precipitation	0.3
Freeze-thaw cycles	0.7



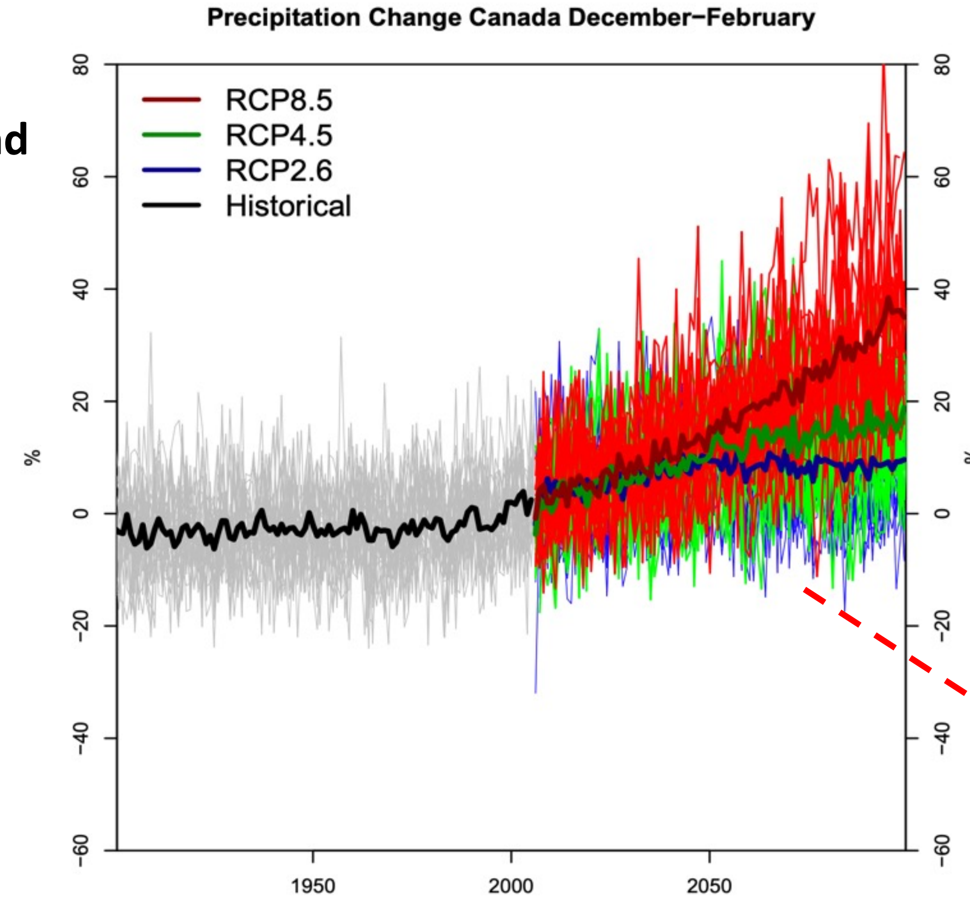
Month	Average daily rock fall probability (θ_i) ($\times 10^{-2}$)
January	0.9
February	1.6
March	1.3
April	0.8
May	0.5
June	0.5
July	0.5
August	0.6
September	1.3
October	2.1
November	1.9
December	1.2

***Fig. 12** Quantified correlation between weather normals and rock fall probability with fitted Mixed von Mises distributions (After Pratt et al., 2018).*

Seasonal variation of risk and long term risk variability:

Climate Change projections (Canada) forecast scenarios of increased precipitation in the Winter months without much changes for the summer months.

Opens a window to forecast rock fall variability due to Climate Change.



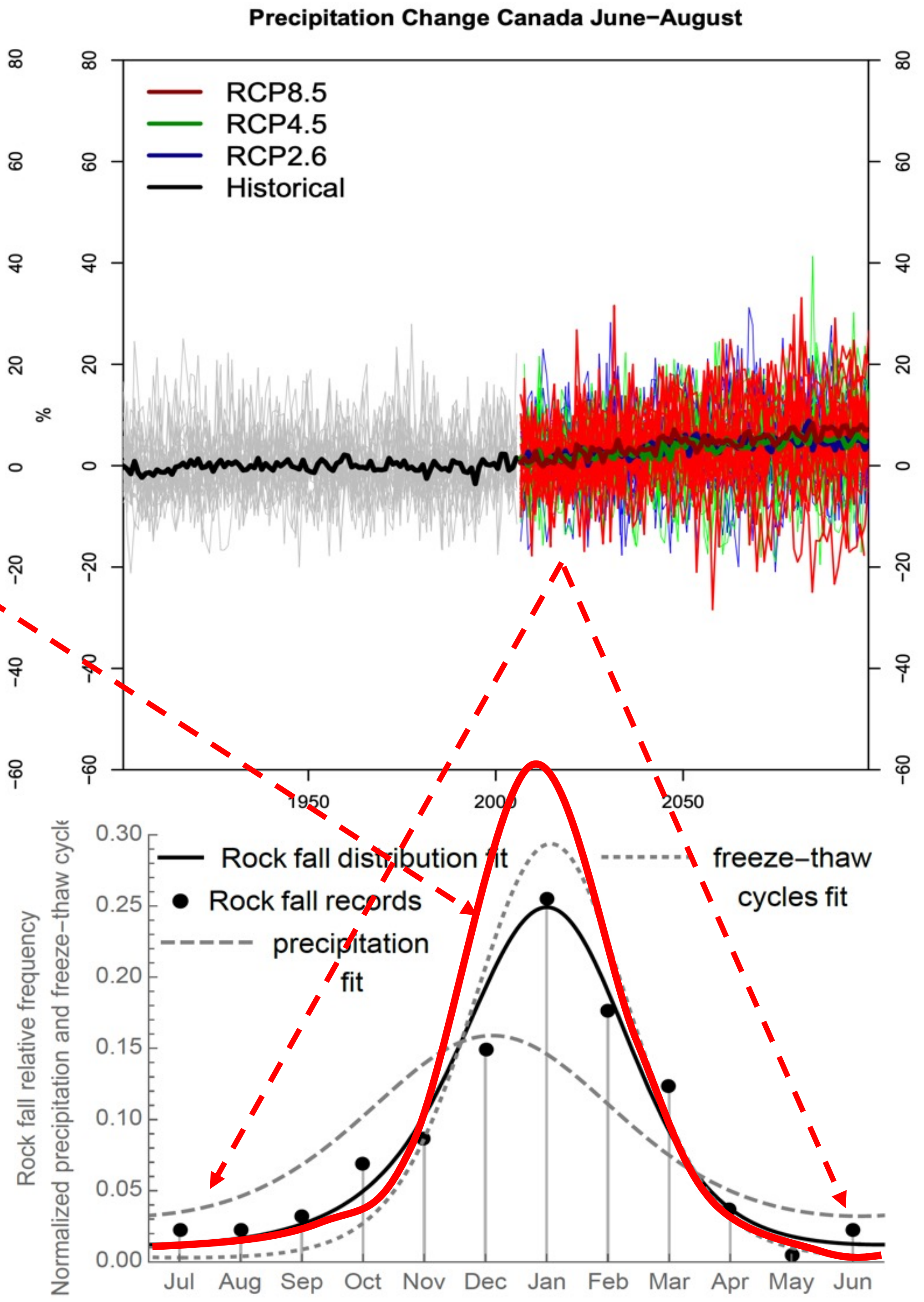


Fig. 13 *Sketch of possible rock fall frequency variations as a consequence of climate change (and possible rock fall risk variability) – insight from quantified rock fall weather relationships.*

Remarks:

- Rock fall behavior appears to follow non-linear patterns, which implies deterministic, **non-predictable** behavior.
- Rock falls are treated stochastically, way forward is an enhanced Informed Probabilistic Approach that considers the non-linear behavior and accounts for weather trends in a quantitative manner.
- Research has been moving forward in this front, providing first steps towards quantification of the relationship between weather and rock fall occurrences (short term) and seasonality (longer term), and time dependent variation of rock fall risk.
- Much work is still required, but recent research has opened a window of opportunity for forecasting rock fall risk variations as a consequence of Climate Change.

THANK YOU!

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