On the Role of Global Warming on the Frequency of Record-Temperature Events

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Empirics: Philadelphia temperature *(why Philadelphia?)*

- annual pattern & long-term trends
- daily temperature distribution

Tutorial: Evolution of record temperature events

- magnitude of successive records
- time between successive records

Comparison with Philadelphia data

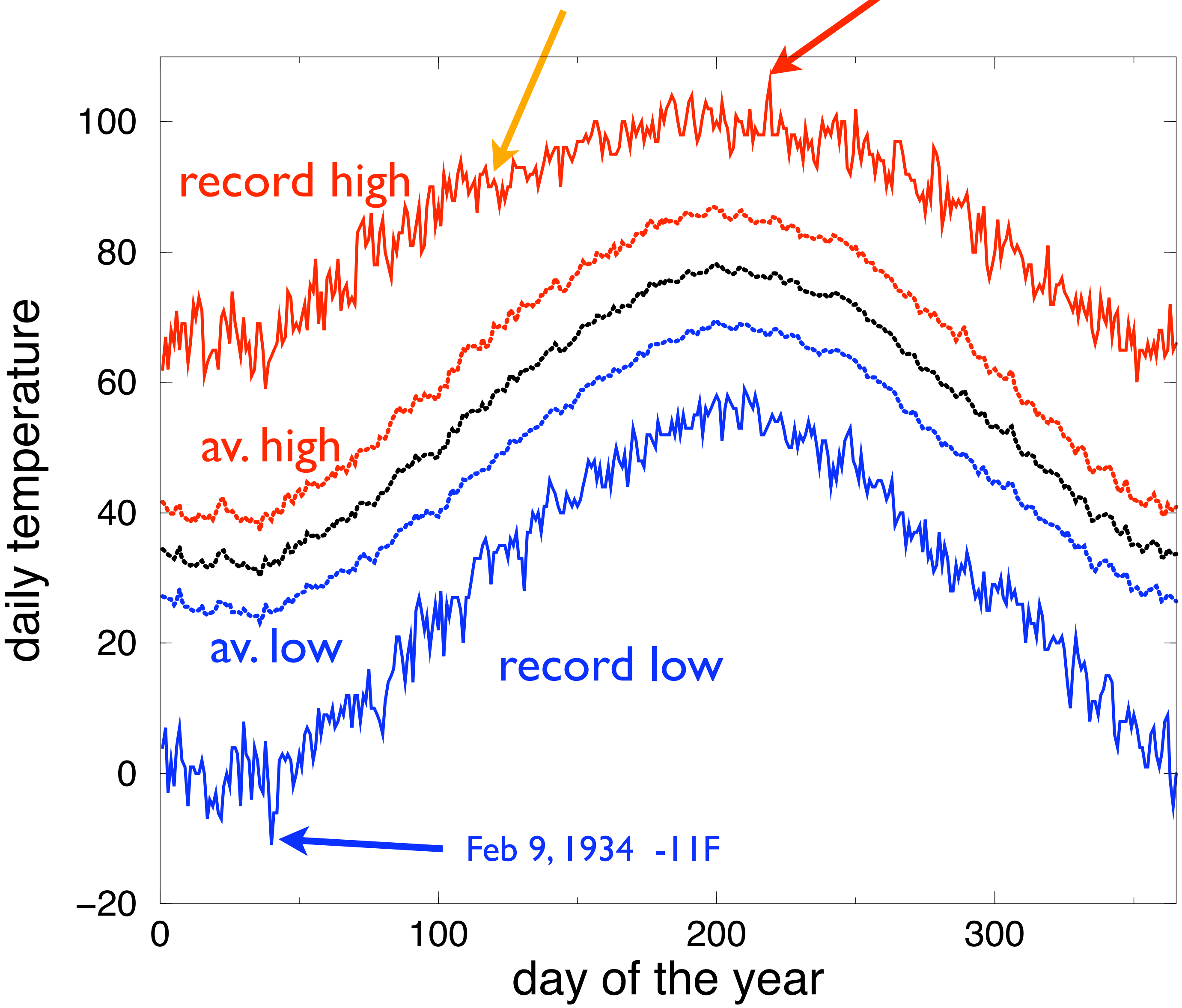
- *role (or non-role) of global warming*

Summary & Outlook

- role of inter-day temperature correlations
- seasonal effects
- asymmetry between high & low temperatures

Philadelphia Climate

annual temperature pattern



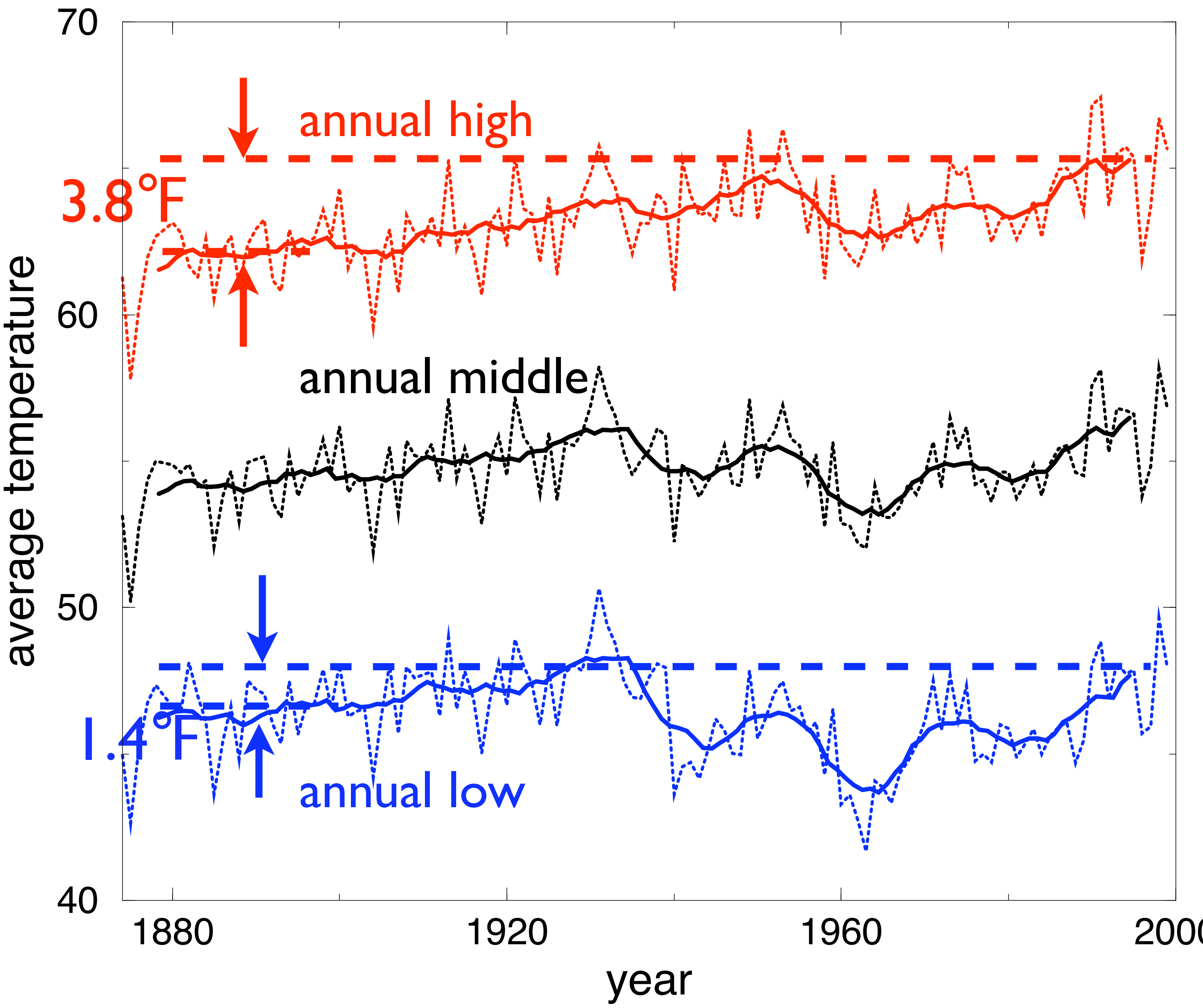
Apr 22, 1985 90F
Temple U. colloquium

Aug 7, 1918 106F

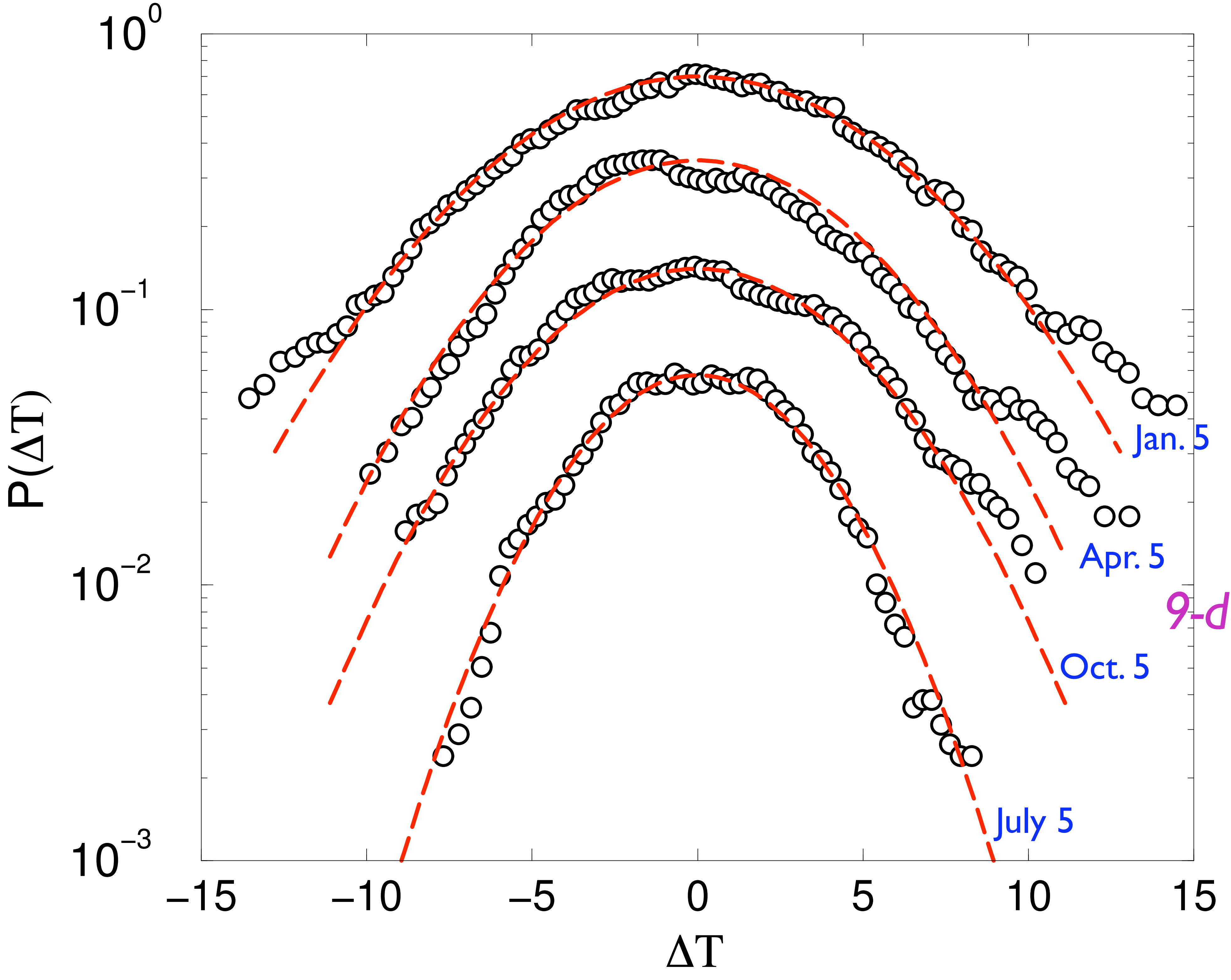
Feb 9, 1934 -11F

long-term temperature trends

IPCC 2001: global warming 0.6°F over past century



Daily Temperature Distribution

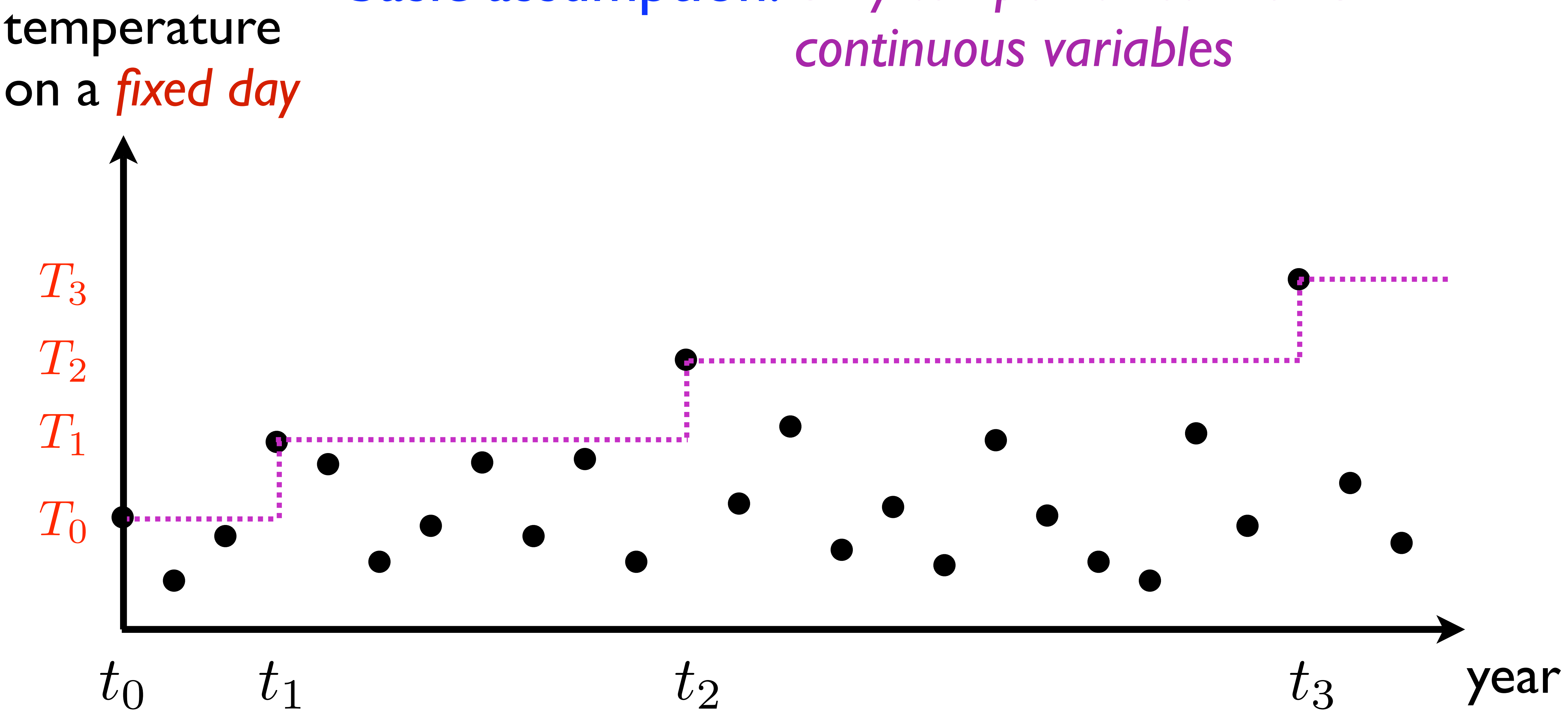


9-day averages

Tutorial: Evolution of Temperature Records

(Arnold et al., *Records*, 1998)

basic assumption: *daily temperatures are iid continuous variables*



Goal: compute $T_k, \mathcal{P}_k(T)$ $\underbrace{t_k, p_k(t)}_{\textit{distribution independent!}}$

Disclaimers

record temperatures → most data discarded

data from a single station only

no control for possible urban heat island effect

only 126 years of data---climatologically puny

unknown data quality and accuracy:

- only daily high & low are reported
- reported accuracy of 1°F

few records → asymptotic analysis questionable

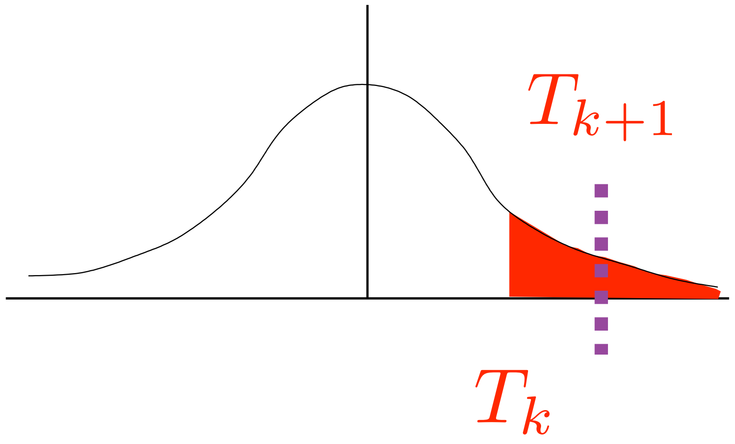
.....

Evolution of *Typical* Record Temperature

$$p(T) \equiv \text{daily temperature distribution}$$

$$T_0 = \int_0^\infty T\, p(T)\, dT$$

$$T_{k+1} = \frac{\displaystyle\int_{T_k}^\infty T\, p(T)\, dT}{\displaystyle\int_{T_k}^\infty p(T)\, dT}$$



Record Temperature Distributions

prob. temperature > T

$$p_>(T) \equiv \int_T^\infty p(T')\,dT'$$

prob. temperature < T

$$p_<(T) = 1 - p_>(T)$$

probability distribution of k^{th} record

$$\begin{aligned}
\mathcal{P}_k(T) \quad &= \quad \left(\int_0^T \overset{\substack{\text{previous record T' < T} \\ \downarrow}}{\mathcal{P}_{k-1}(T')} \sum_{n=0}^{\infty} \overset{\substack{\text{next n temperatures < T'} \\ \downarrow}}{[\,p_<(T')\,]^n}\, dT'\right) \overset{\substack{\text{last temperature = T} \\ \downarrow}}{p(T)}\,, \\
&= \quad \left(\int_0^T \frac{\mathcal{P}_{k-1}(T')}{p_>(T')}\, dT'\right) p(T)\,.
\end{aligned}$$

Record Time Evolution

$q_n(T_k) \equiv$ prob. $(k+1)^{\text{st}}$ record n years after k^{th} at T_k

$$= \underset{\substack{\uparrow \\ \text{n-1 non-records}}}{p_<(T_k)^{n-1}}\, \underset{\substack{\uparrow \\ \text{record}}}{p_>(T_k)}$$

expected time between k^{th} and $(k+1)^{\text{st}}$ records at T_k:

$$t_{k+1} - t_k = \sum_{n=1}^{\infty} n\, p_<^{n-1}\, p_> = \frac{1}{p_>(T_k)}$$

finite for given T_k

waiting time distribution for k^{th} record: averaged over T_k

$$Q_n(k) \equiv \int_0^\infty \mathcal{P}_k(T)\, q_n(T)\, dT$$

$$= \int_0^\infty \mathcal{P}_k(T)\, p_<(T)^{n-1}\, p_>(T)\, dT$$

in general

infinite

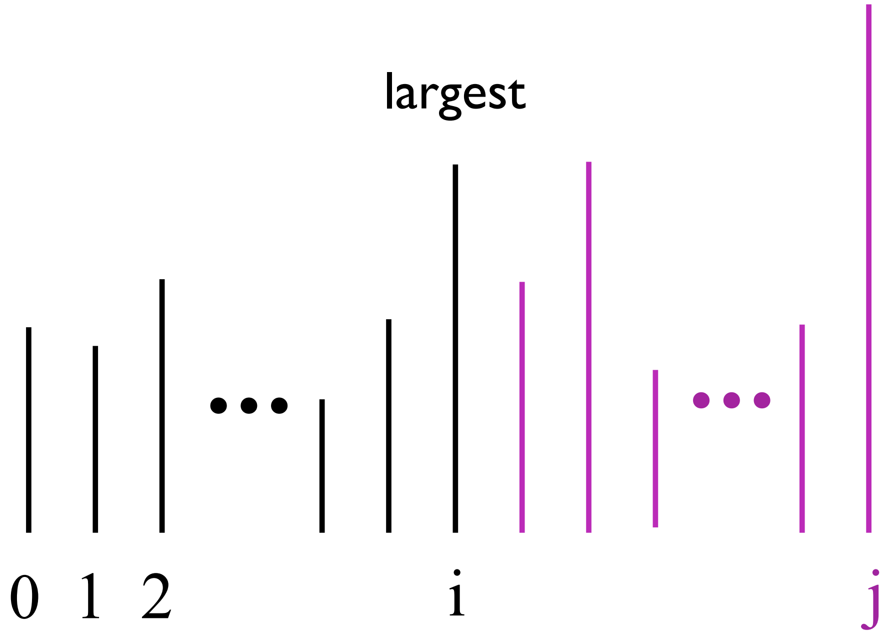
waiting time

Record Time Statistics

(Glick 1978; Sibani et al 1997, Krug & Jain 05, Majumdar)

define $$\sigma_i = \begin{cases} 1 & \text{if record in } i^{\text{th}} \text{ year} \\ 0 & \text{otherwise} \end{cases}$$

then $$\langle \sigma_i \rangle = \frac{1}{i+1} \qquad \langle \sigma_i \sigma_j \rangle = \langle \sigma_i \rangle \langle \sigma_j \rangle$$



therefore $$\langle n(t) \rangle = \sum_{i=1}^{t} \langle \sigma_i \rangle \sim \ln t \qquad P(n) = \frac{(\ln t)^n}{n!} e^{-\ln t}$$

probability that current record is broken in ith year:

$$= \frac{1}{i(i+1)} \to \text{time until next record} = \infty$$

Records with Gaussian Temperature Distribution

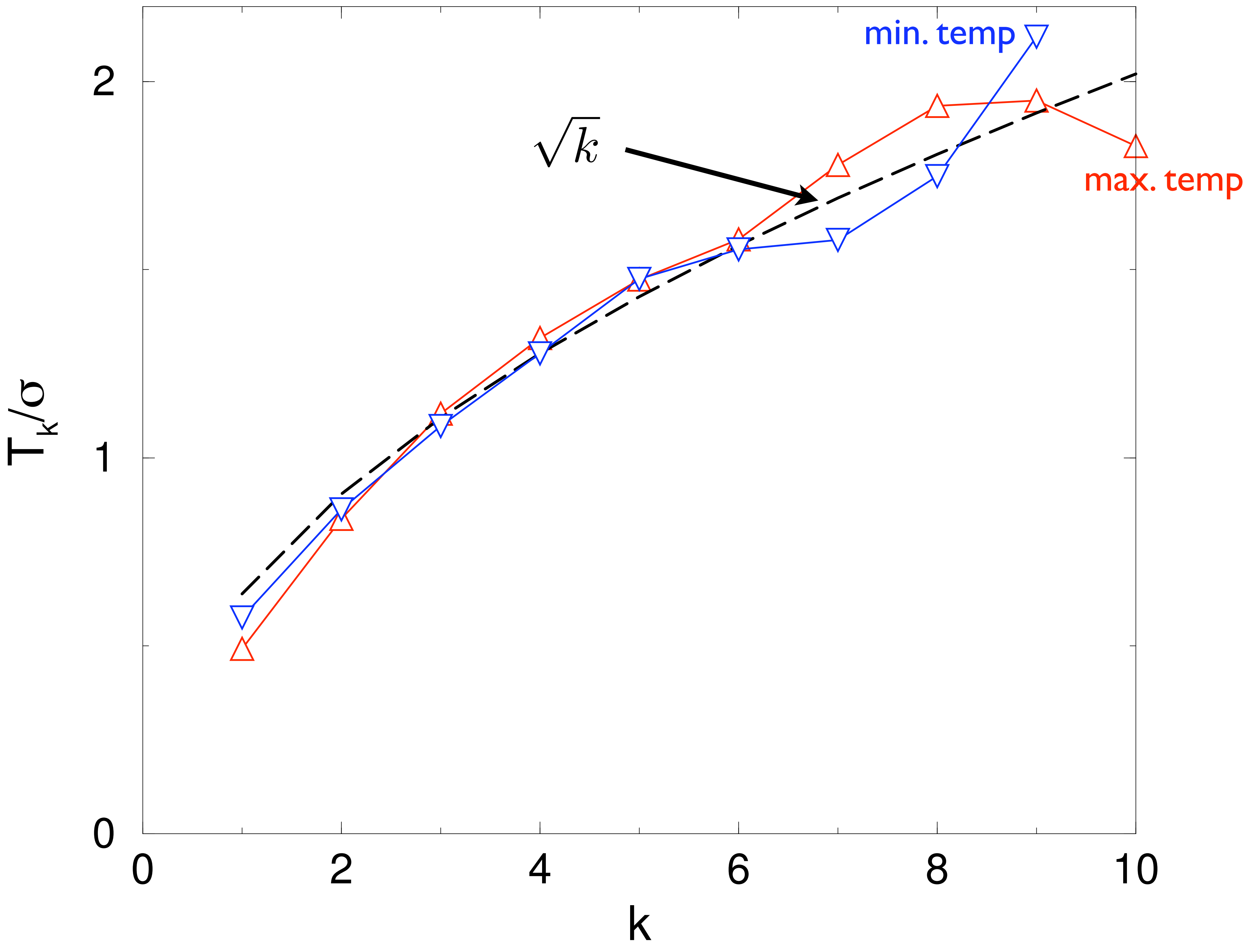
$$p(T) = \frac{1}{\sqrt{2\pi\sigma^2}}\, e^{-T^2/2\sigma^2} \qquad T_{k+1} = \frac{\int_{T_k}^{\infty} T\, p(T)\, dT}{\int_{T_k}^{\infty} p(T)\, dT}$$

$$T_0 = 0 \qquad T_1 = \sqrt{\frac{2}{\pi}}\,\sigma$$

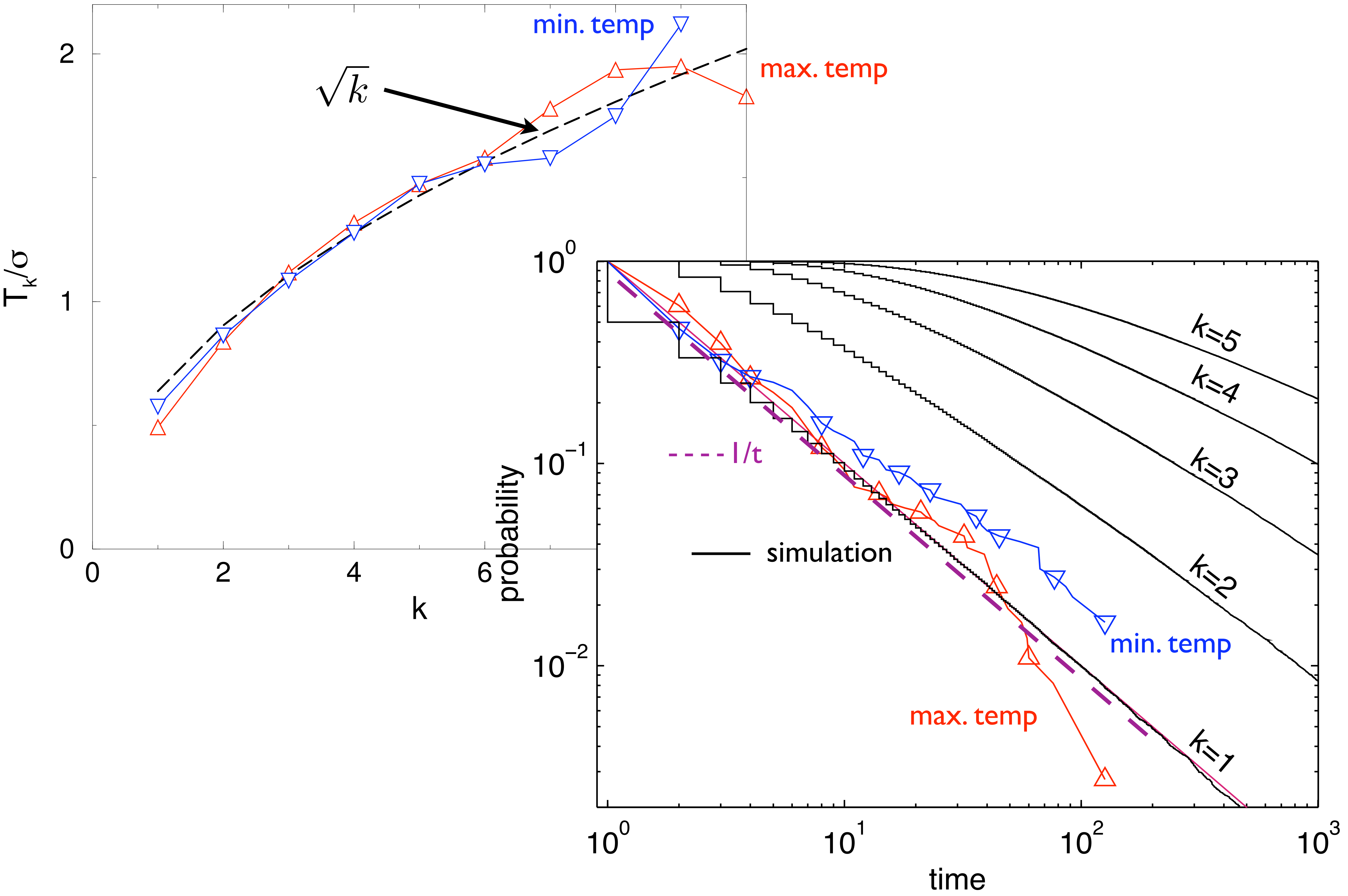
$$\begin{aligned} T_{k+1} &= \frac{\int_{T_k}^{\infty} \frac{1}{\sqrt{2\pi\sigma^2}}\, T\, e^{-T^2/2\sigma^2}\, dT}{\int_{T_k}^{\infty} \frac{1}{\sqrt{2\pi\sigma^2}}\, e^{-T^2/2\sigma^2}\, dT} \\ &= \frac{T_1\, e^{-T_k^2/2\sigma^2}}{\mathrm{erfc}\left(T_k/\sqrt{2\sigma^2}\right)} \\ &\sim T_k\left(1 + \frac{\sigma^2}{T_k^2}\right) \qquad k \to \infty \end{aligned}$$

$$\frac{\partial T}{\partial k} \sim \frac{\sigma^2}{T} \qquad \to \qquad T_k \sim \sqrt{2k\sigma^2}$$

Philadelphia Record Temperature Values . . .



. . . and Record Times



Records If Global Warming Is Occurring

assume daily temperature distribution

$$p(T;t) = \begin{cases} e^{-(T-vt)} & T > vt \\ 0 & T < vt \end{cases}$$

as a soluble example only

exceedance probability

$$\begin{aligned} p_>(T_k; t_k + j) &= \int_{T_k}^{\infty} e^{-[T-v(t_k+j)]}\, dT \\ &= e^{-(T_k - vt_k)}\, e^{jv} \end{aligned}$$

prob of record at year n

$$\begin{aligned} q_n(T_k) &\equiv p_>(T_k)\, p_<(T_k)^{n-1} \\ &\to e^{nv}\, X \prod_{j=1}^{n-1} (1 - e^{jv}\, X) \end{aligned}$$

overestimate of record time

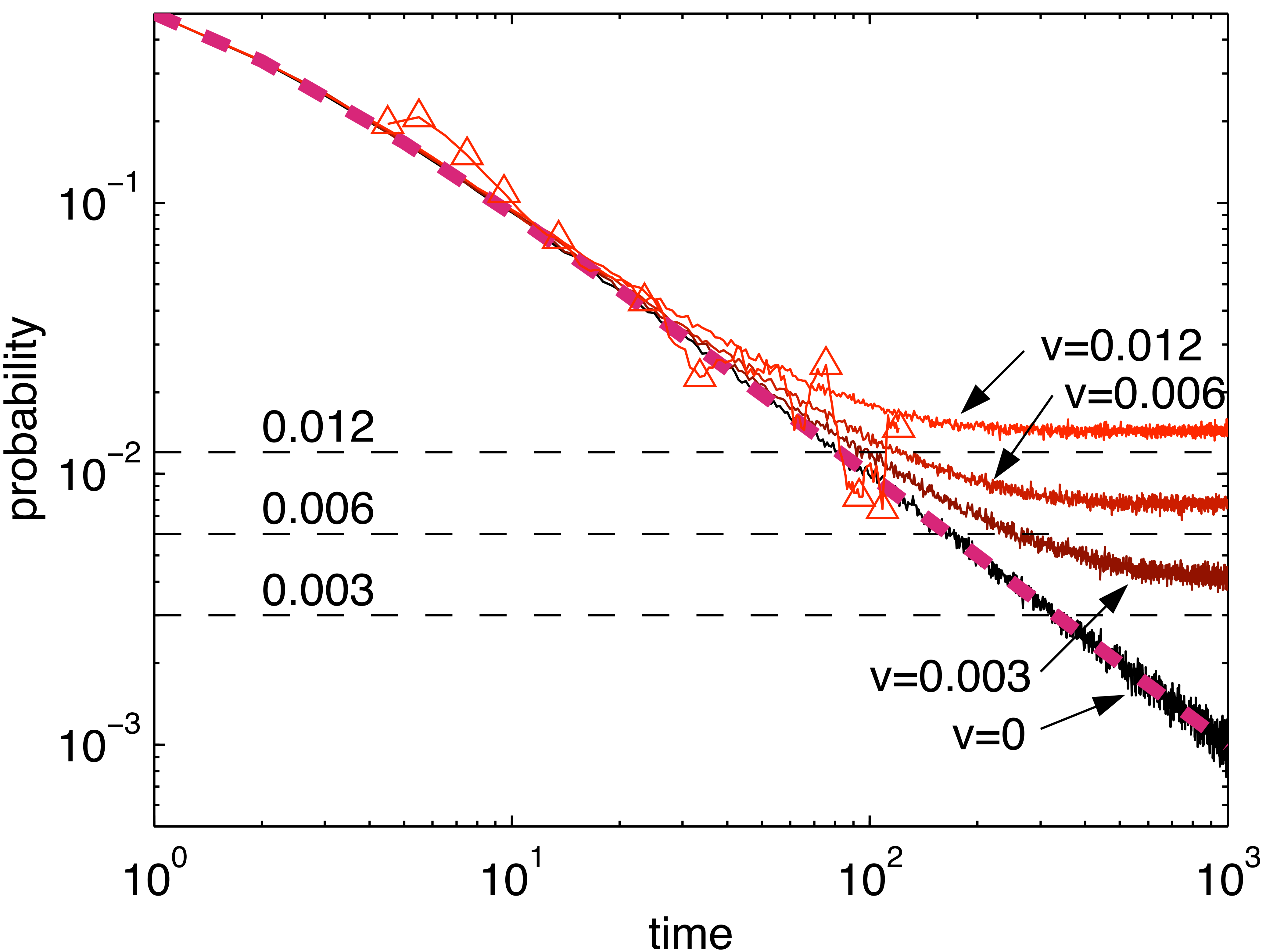
$$e^{jv} X = 1 \quad \to \quad (t_{k+1} - t_k)v = T_k - vt_k$$

$$\to t_k \sim \frac{k}{v}$$

records ultimately occur at constant rate

(Ballerini & Resnick, 85; Borokov, 99)

Frequency of Record High Temperatures



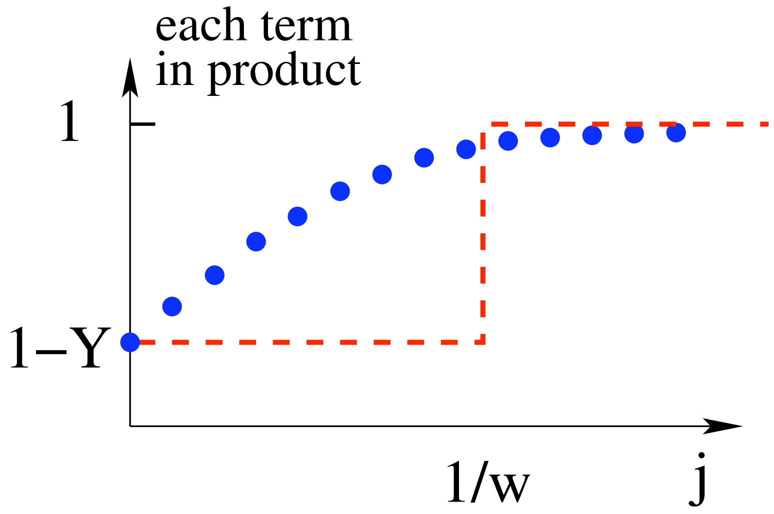
Global Cooling *(low temperature records in warming)*

$$q_n(T_k) \equiv p_>(T_k)\, p_<(T_k)^{n-1}$$

with $w = |v| > 0$

$$\rightarrow e^{-nw}\, Y \prod_{j=1}^{n-1} (1 - e^{-jw}\, Y)$$

$$Y = e^{-(T_k + w t_k)}$$



$$q_n(T_k) \sim \begin{cases} (1-Y)^n\, e^{-nw}\, Y & n < n* \sim w^{-1} \\ (1-Y)^{1/w}\, e^{-nw}\, Y & n > n* \end{cases}$$

$$\rightarrow t_{k+1} - t_k \sim e^{[T_k + w t_k]} \qquad (e^{T_k} \text{ for } w = 0)$$

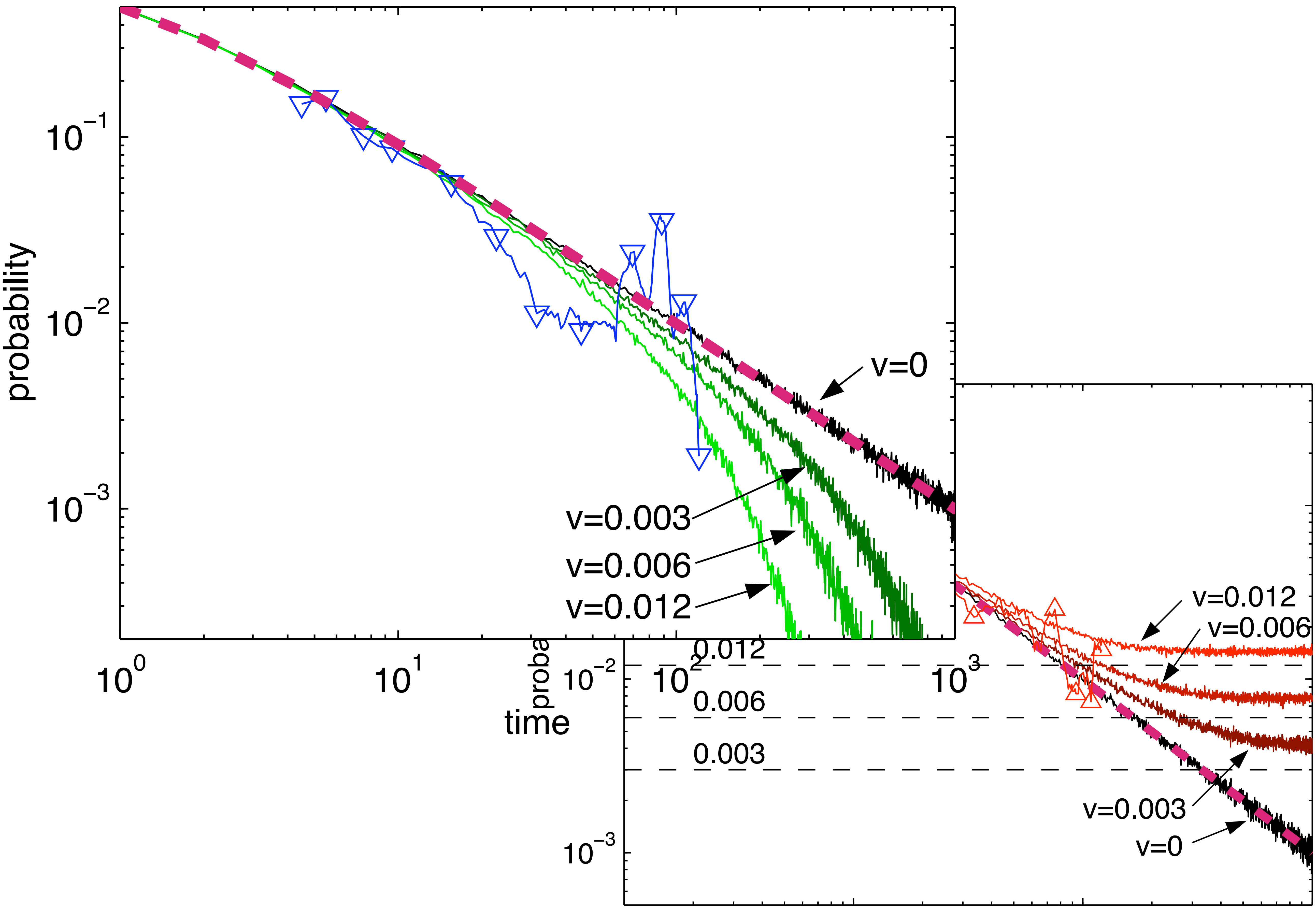
continuum limit: $\dfrac{\partial t}{\partial k} \sim e^{k + wt}$

$$\underbrace{(1 - e^{-wt})}_{<0} = w(e^k - 1)$$

$$\approx wt$$

no solution for $t_k > \dfrac{1}{w}$

Frequency of Record Low Temperatures



Summary & Outlook

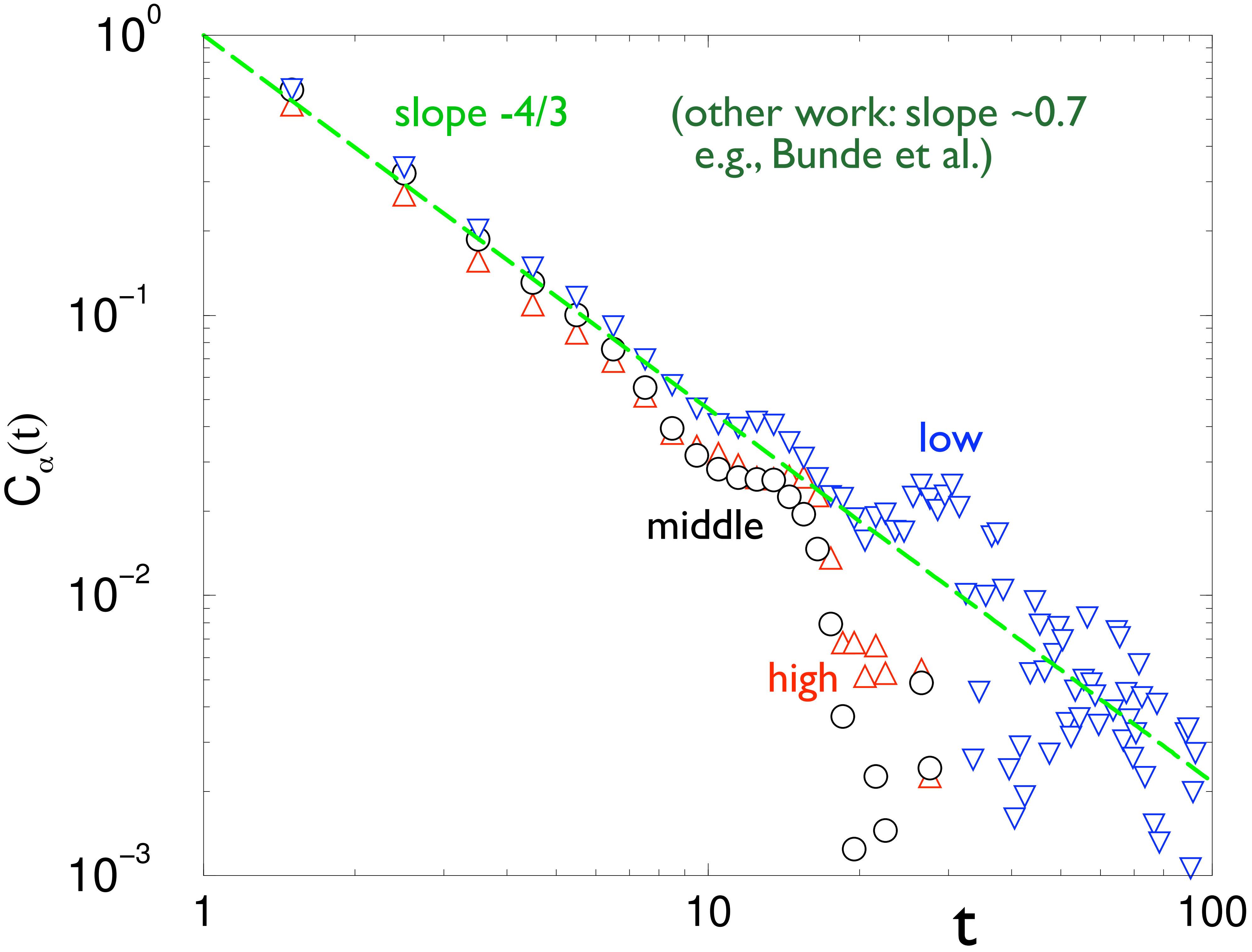
Record temperature and time statistics are obtainable from basic extreme value considerations

Current global warming rate does not yet seem to significantly affect record temperature statistics

Inter-day temperature correlations also do not affect record temperature statistics

Inter-day Temperature Correlations

$$C_\alpha(t) = \frac{1}{365}\sum_{i=1}^{365}\frac{\langle T_i T_{i+t}\rangle - \langle T_i\rangle\langle T_{i+t}\rangle}{\langle T_i^2\rangle - \langle T_i\rangle^2} \quad \alpha = \text{low, middle, high}$$



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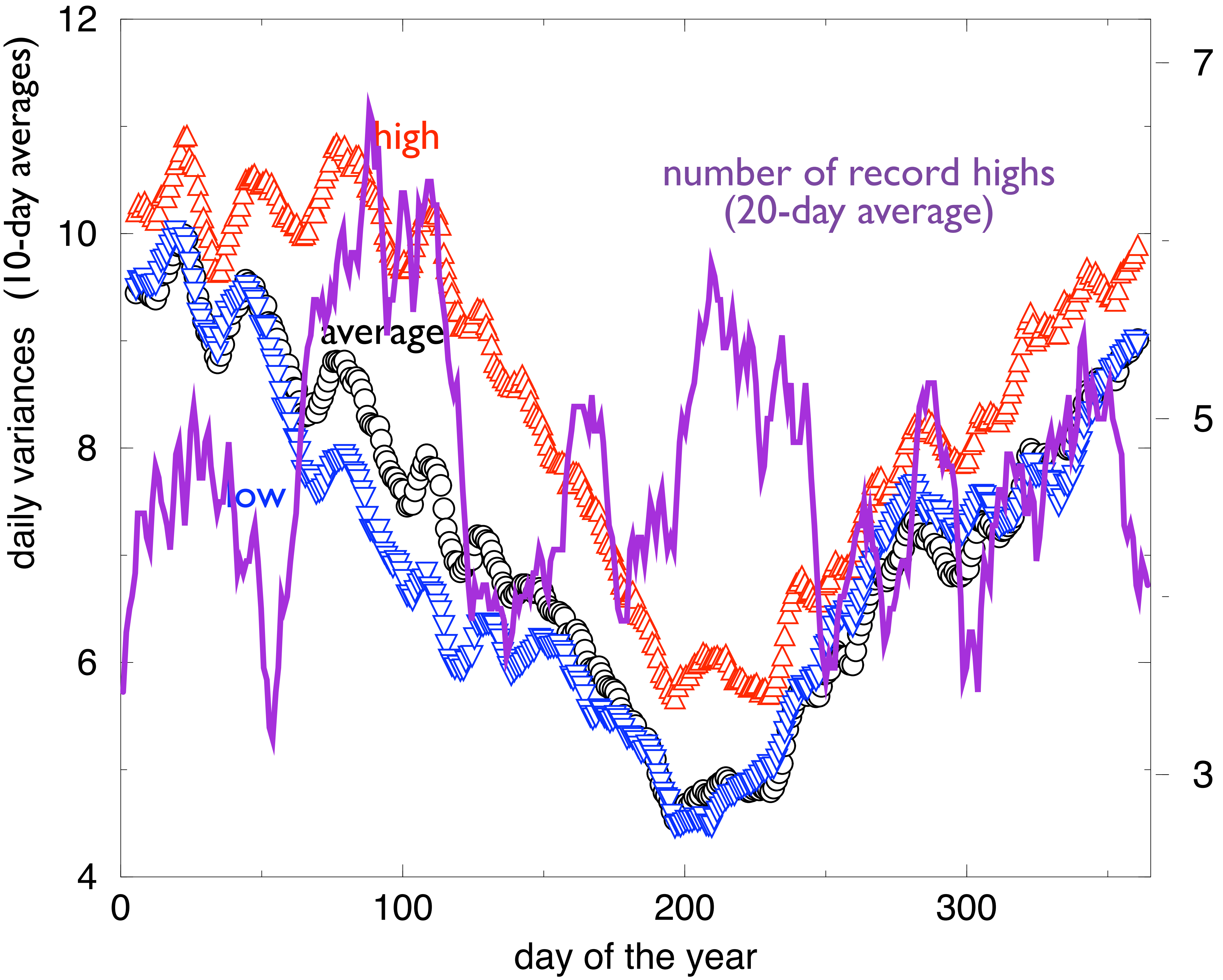
Open issues:

- Difference between high & low records
  - *1705 record highs; 1346 record lows*
- Seasonal effects
  - *more record highs in spring*

Seasonal Variance & Record Numbers



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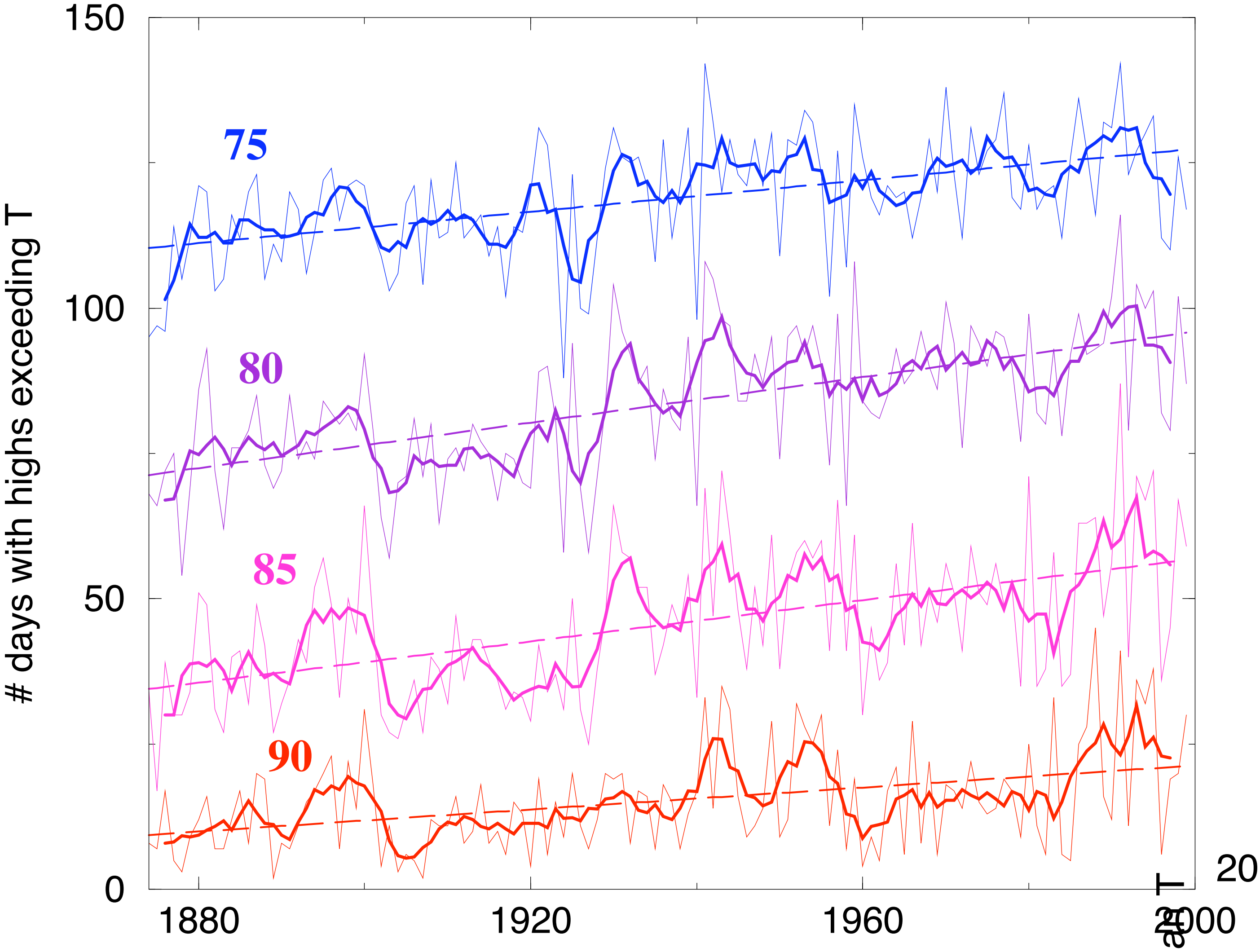
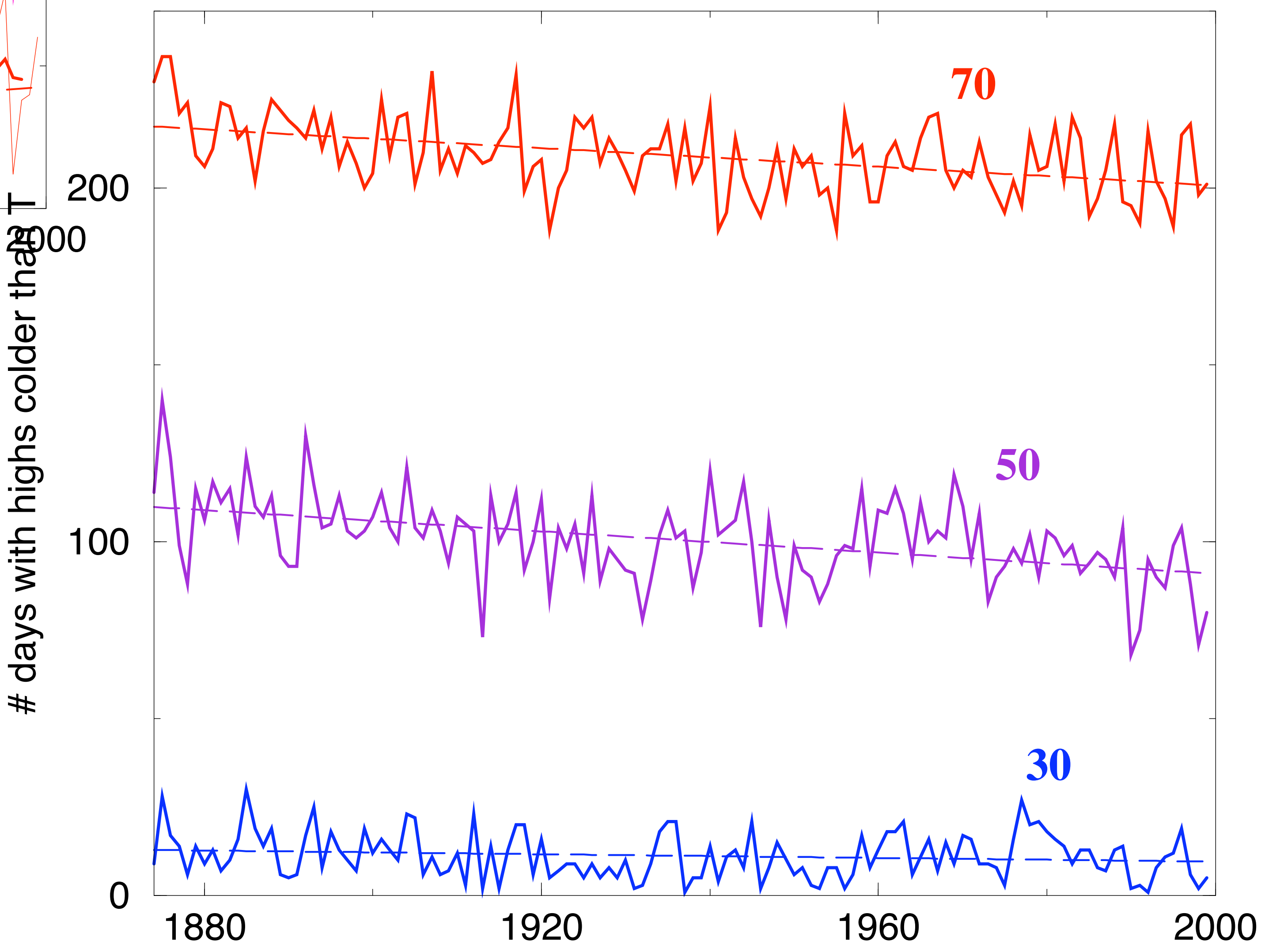
- Day/night asymmetry

more hot days....



and fewer cold days....



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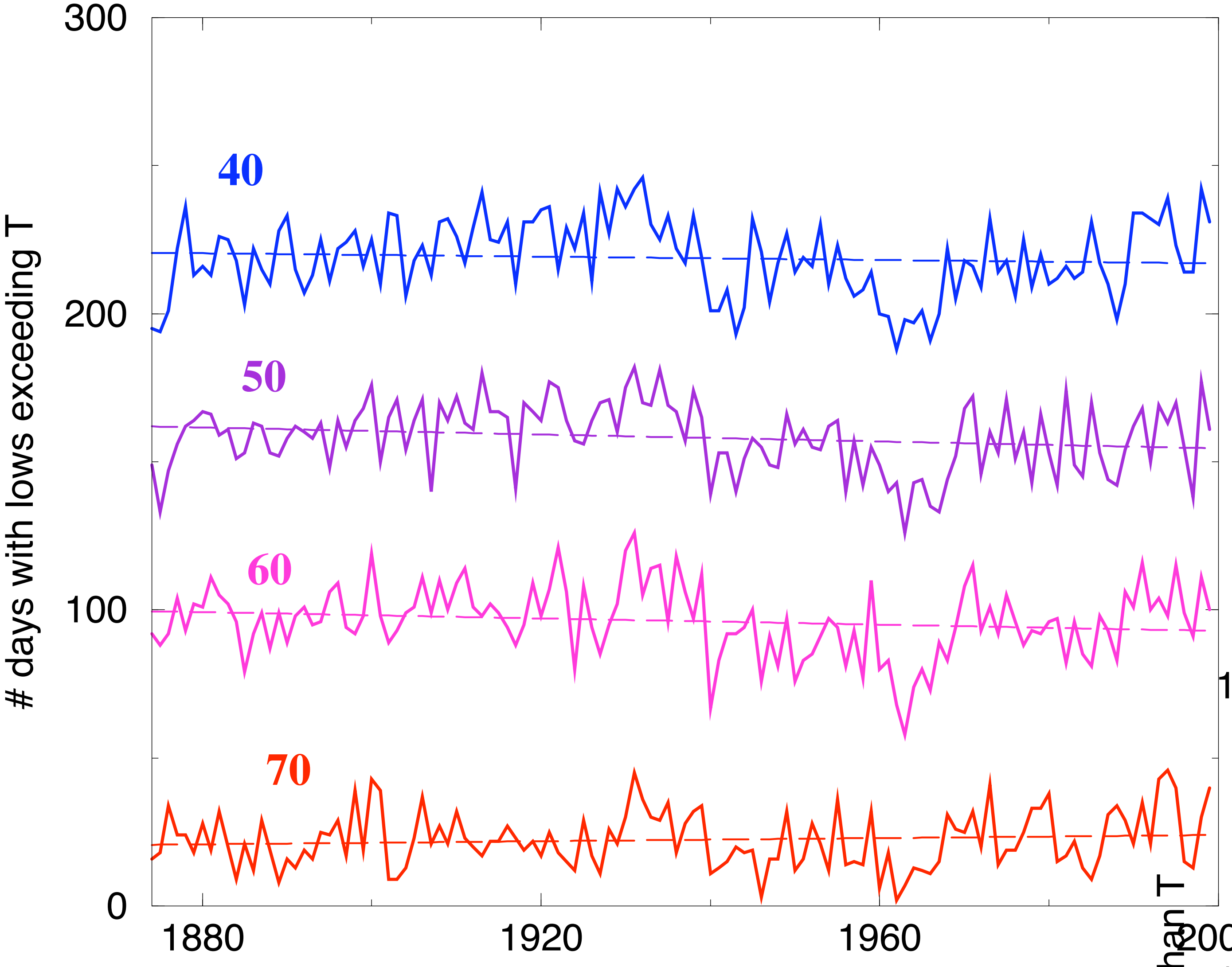

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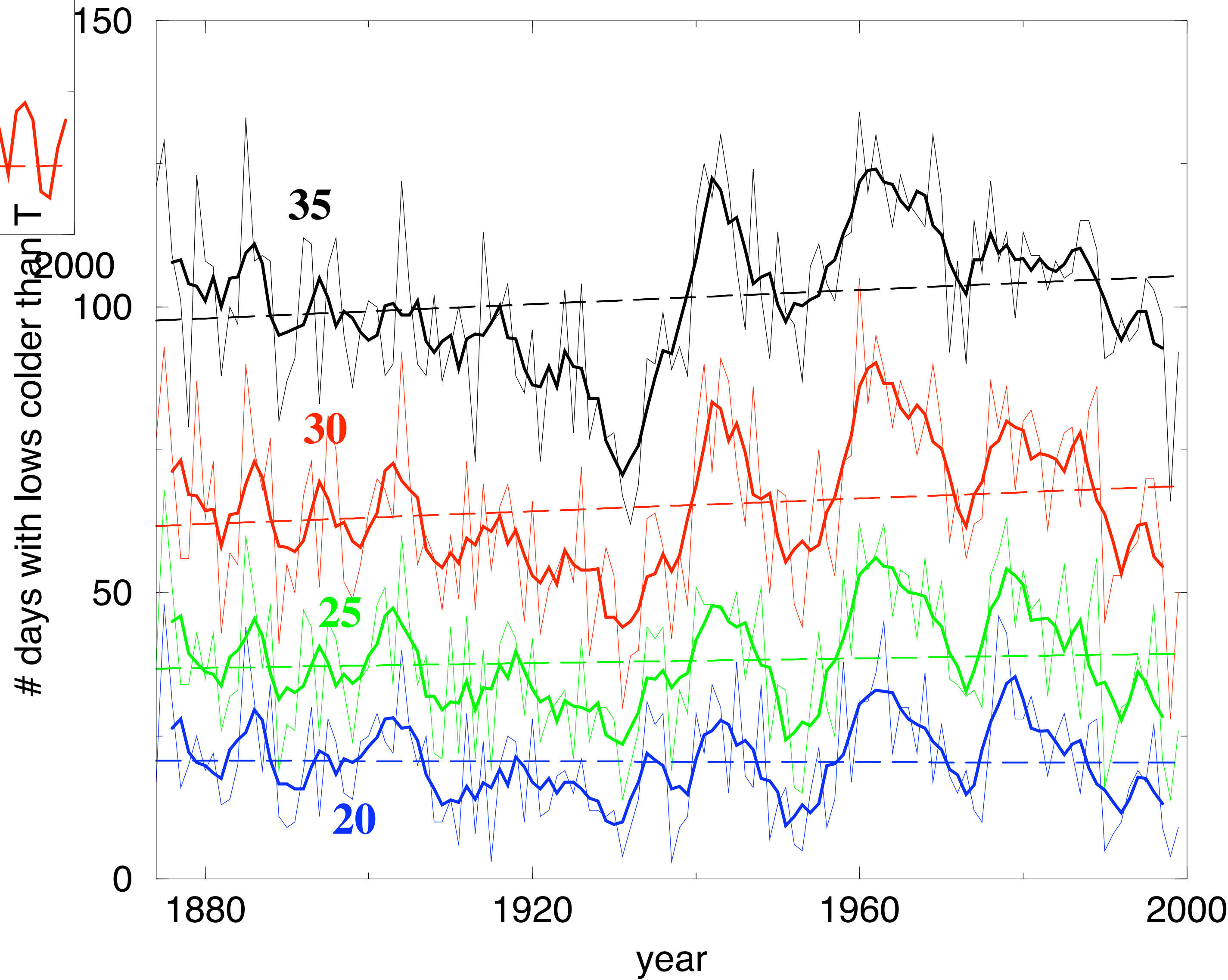

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- Seasonal effects
  - *more record highs in spring*
- Day/night asymmetry
- Role of changing variability
- Serious data collection & model validation

Thank you Newton Institute!

Thank you for participating!

Have a safe trip home!

I HOPE TO SEE YOU AGAIN!