A multifractal analysis of air temperature signals based on the wavelet leaders method

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Hölder regularity
- Hölder exponent
- Spectrum of singularities
- Wavelet leaders method (WLM)

Application to surface air temperature signals
- Data description and first results
- Hölder spaces-based classification and blind test
- Discussion and conclusions
Hölder regularity

1. Hölder regularity
   - Hölder exponent
   - Spectrum of singularities
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2. Application to surface air temperature signals
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Definition

Let $f$ be a signal and $x_0$ a real number. Then $f$ belongs to the Hölder space $C^\alpha(x_0)$ if there exists a polynomial $P_{x_0,\alpha}$ of degree at most $\alpha$, a positive constant $C$ and a neighborhood $V_{x_0}$ of $x_0$ satisfying

$$|f(x) - P_{x_0,\alpha}(x)| \leq C|x - x_0|^{\alpha}$$

for all $x \in V_{x_0}$. 
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for all $x \in V_{x_0}$.

Definition

The Hölder exponent $h(x_0)$ of $f$ at $x_0$ is defined as the supremum of the exponents $\alpha$ such that $f$ belongs to $C^\alpha(x_0)$:

$$h(x_0) = \sup\{\alpha : f \in C^\alpha(x_0)\}.$$
Monofractality

- Hölder exponent changes from point to point: \( f \) multifractal
- Constant Hölder exponent: \( f \) monofractal, i.e. \( f \) is regularly irregular
- Example of a monofractal function: fractional Brownian motion

Fractional Brownian motions with Hölder exponents 0.2, 0.4, 0.6 almost surely.
How to characterize the global regularity of a signal?

**Definition**

The spectrum of singularities of $f$ is the Hausdorff dimension of the set of points sharing the same Hölder exponent:

$$d_f : h \mapsto \dim_{\mathcal{H}}(\{x_0 \in \mathbb{R} : h(x_0) = h\}),$$

where $\dim_{\mathcal{H}}(X)$ denotes the Hausdorff dimension of the set $X$.

Corollary: $f$ is monofractal if and only if its spectrum of singularities is reduced to a single point.
1) Wavelet decomposition of the signal:

\[ f(x) = \sum_{j,k \in \mathbb{Z}} c_{j,k} \psi(2^j x - k) = \sum_{\lambda \in \Lambda} c_{\lambda} \psi_{\lambda} \]

where \( \psi \) is a wavelet and \( c_{j,k} \) is the wavelet coefficient associated to the dyadic interval \( \lambda \) at scale \( j \) and position \( k \):

\[ \lambda = \lambda_{j,k} = [2^{-j} k, 2^{-j} (k + 1)] \]

and

\[ c_{j,k} = 2^j \int_{\mathbb{R}} f(x) \psi(2^j x - k) dx. \]

2) For each \( \lambda \), compute the wavelet leaders

\[ d_{\lambda} = \sup_{\lambda' \subset \lambda} |c_{\lambda'}| \]
3) Remove the null wavelet leaders and compute

\[ S(q,j) = \frac{1}{2^j} \sum_{\lambda \in \Lambda_j} d^q_{\lambda}, \]

where \( \Lambda_j \) is the set of dyadic intervals at scale \( j \).

4) Compute the function \( \tau \) defined as

\[ \tau(q) = \lim_{j \to +\infty} \frac{\log(S(q,j))}{\log 2^{-j}}, \]

which is numerically obtained through the slopes of linear regressions at small scales of \( \log(S(q,j)) \) seen as a function of \( j \).

5) The spectrum of singularities is obtained as

\[ d(h) = \inf_q \{qh - \tau(q)\} + 1. \]
Log($S(q,j)$) for a fractional Brownian motion with Hölder exponent 0.5 with $q$ ranging from -1 to 1.
τ function associated to the previous signal. Linear regression gives a slope of 0.494021.

6) Remark: if τ is a straight line, then f is monofractal, in which case the Hölder exponent of f is the slope of τ.
Remark: if $\tau$ is a straight line, then $f$ is monofractal, in which case the Hölder exponent of $f$ is the slope of $\tau$.

If $f$ is a monofractal signal with Hölder exponent $H$, then $f$ belongs to the uniform Hölder space $C^H$, and a norm in this space is defined by

$$\| f \|_{C^H} = \sup_{j,k} \left\{ \frac{|c_{j,k}|}{2^{jH}} \right\} := N$$
Application to surface air temperature signals

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Analyzed data

- Daily mean temperature data from 1951 to 2003, calculated as average of minimum and maximum daily temperatures
- Weather stations located below 1000 meters of altitude
- 115 stations selected
- Missing data up to 7%, less than 1% for 97 stations
- Values integrated for more stable numerical results (i.e. $x_n$ replaced by $\sum_{j=1}^{n} x_j$.)
Analyzed data (Granada)
Monofractal nature of the signals

\[ \tau \] functions associated to Aachen (green), Шепетивка (blue) and Granada (orange), with respective slopes 1.156, 1.218, 1.323.
Hölder exponents and norms

- $\tau$ linear $\rightarrow$ signals are monofractal
- Mean coefficient of determination : $R^2 = 0.9975 \pm 0.0028$
- Hölder exponents ranging from 1.093 to 1.43
- Norms ranging from 8.23 to 30.45
Distribution of the exponents and norms

Link with climate types?
Köppen-Geiger climate classification

Classification based on maximum and minimum monthly mean temperatures (references fixed at 22°C and 0°C). Stations close to 0.5°C of another type of climate were also associated to this second category. Here, precipitations were not taken into account.
Climate distribution
Distribution of the exponents and norms
Distribution of the exponents and norms
Distribution of the exponents and norms
Maximum matching with Köppen-Geiger classification if

\[
\begin{align*}
H_1 &= 1.186 \\
H_2 &= 1.275 \\
N_1 &= 14.81 \\
N_2 &= 16.18
\end{align*}
\]

Result: 93.9% correctly associated

Remark: without the norm, 89.6% correctly associated.
Results on the map

Stations marked with a brown cross are the ones whose type of climate was erroneously predicted. The others were correctly predicted; green discs stand for Oceanic climate, blue triangles correspond to continental stations and orange diamonds are the Mediterranean ones.
69 other stations

40 years of data between 1951 and 2003
Blind test

Result: 88.4% correctly associated

Remark: without the norm, 84.1% correctly associated.
All the stations

115 stations of reference (diamonds) + 69 stations of the blind test (triangles)

Overall result: 91.8% correctly associated
Discussion of the results

Results

- Oceanic stations ↔ Lowest Hölder exponents
- Continental stations ↔ Intermediate Hölder exponents
- Mediterranean stations ↔ Largest Hölder exponents

Discussion

- On a daily basis, Oceanic climate is more irregular than the Continental weather, which is less regular than Mediterranean climate.
- Explanation could be the North Atlantic Oscillation (NAO), anticyclonic conditions in Southern Europe, ...
Conclusions and future work

Conclusions

- WLM shows surface air temperatures signals are monofractal signals
- Their belonging to functional spaces reflects their temperature-based Köppen-Geiger climate type
- Algorithm and results confirmed through blind tests

Future work

- Checking of the validity of current climatic models
- Analysis of other climate indices (pressure, precipitation,...)
- Generalization to global temperatures
Some references

- European Climate Assesment and Dataset: http://eca.knmi.nl/.


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