The Stability of the Sunspot Number

Reconstructions and lessons from the last 30 Years

F.Clette, L. Wauters, L. Lefèvre

SIDC - SILSO

Observatoire Royal de Belgique

Chapters

- Detailed “mechanics” of the SSN calculation
- The network: statistics of stations and observations
- Trends in personal k coefficients over the last 31 years (1981-2012)
- The Zürich-SIDC transition: extension to the last 60 years (1949-2012)
- Interpretation: lessons and future steps

Revisiting the base code

- Required for porting to new server and compiler (Linux Ubuntu, f77 to gfortran)
  - Almost completed: double calculation since Sept. 2012, release: mid-2013
  - Redefinition of the data pipeline: new archives, new output files (new values, rms dispersions!)
- Inverse engineering:
  - Full documentation of the algorithms
  - Bug fixes

A new refurbished WDC

- Nov. 2012: WDC-Sunspot officially integrated in the new World Data System:
  - Replaces and merges WDC and FAGS
  - Coordinated by ICSU: management committee, supervision by scientific Unions
  - All earlier data centers must re-register and qualify
- Many changes in preparation:
  - New data products (broader scope)
  - New dedicated and expanded Web site
  - Stronger identity: new name and logo !

SILSO

WDC – Sunspot Index and Long-term Solar Observations

SSN calculation: 4 steps

Step 1

Data elimination: outliers at 2 σ_k

Monthly mean k: first approximation (k, σ_k)

↓

Step 2

Daily average SSN R: first approximation (R, σ_R)

LO data elimination at 1 σ_R

↓

Step 3

Data elimination: outliers at 1 σ_k

Monthly mean k: final (k, σ_k)

↓

Step 4

Iteration: elimination at 1 σ_R

Daily average SSN R_i: final value (R_i, σ_{Ri})

Step 1: monthly k: first approximation

- Preliminary exclusion of days when no k can be calculated:
  - W_{LO} or W_{sta} missing or = 0

- **Station k substitution**:
  - Condition: more than 80% of original observations dropped
  - Monthly mean k calculation is entirely bypassed:
    k replaced by the mean k of previous year
  - ➡ ***Only step where past k are used in the calculation ("memory" effect)***
  - Bug and possible past undocumented changes (tests and 80% threshold)
  - Limited occurrence:
    - One station over ~80 every 2-3 months
    - Mainly during solar cycle minima: up to 10 stations/month (limited impact: low R_i values)

Step 1: monthly k: first approximation

- First elimination of outliers:
  - (daily k – monthly average k) > 2 σ_k
- Bad values are flagged:
  - Not used in subsequent steps of the calculation

- *Possible alternate method:*
  - *Problem: less data will be eliminated for stations with large σ_k compared to better stations with low σ_k*
  - *Alternate solution: define a unique σ_k based on all stations and applied to all stations:*
    - *Low quality stations will have a higher data rejection rate*
    - *High lower*

➡ May lead to the entire elimination of part of the stations, each month.

Step 2: LO data elimination

- LO compared to the daily network average R (first approximation)
- If bad LO value (W_{LO} - R > 1 σ_R) for one day, all daily k coefficients dropped for all stations

➡ ***Only step where the network provides a feedback on the pilot station***

- *Possible alternate solution:*
  - *Replacing W_{LO} by R (network average)*
  - *Preserves daily k values in months with few usable observations*

Step 3: Final monthly k coefficients

- Second elimination of outliers:
  - Applied to values remaining after steps 1 & 2
  - (daily k – monthly average k) > 1 σ_k
- Values excluded at this step are not flagged:
  - Still used in the last step of the calculation (R_i determination)

Step 3: Final monthly k coefficients

- Final k coefficients:
  - used for the final R_i calculation (step 4)
  - Monthly average of **$k = (W_{LO} * 0.6) / W_{sta}$**
  - Average only over days where both W_{LO} and W_{sta} are not out of bound (1 σ_k) or = 0.
  - Monthly mean k coefficients are only calculated and used for the current month
- Not saved (no k « memory » !):
  - Archived monthly & yearly k coefficients calculated after the R_i calculation
  - Monthly average of **$k = R_i / W_{sta}$**
  - Average calculated from a larger number of days (all days where $W_{sta} > 0$ and not beyond 2 σ_k)

Step 4: final R_i determination

- Iterative elimination based on daily average R and dispersion σ_R
- Criteria: iterations stop when
    - $\sigma_R < 10\%$
    - < 5 stations left
    - no station was eliminated in previous iteration (prevents endless loops)
  - *Typically: 1 to 3 iterations (~15% rejection per iteration)*
- Bug and undocumented past modifications:
  - Wrong combination of tests: too few iterations
  - Past option: at each iteration, reduction of the elimination threshold: 3, 2, 1 σ_R (currently 1 σ_R fixed)
  - Limited impact:
    - Difference limited to 1 unit of daily SSN
    - One day over 2-3 months

Step 4: alternate R_i calculation

- When? After R_i iteration, case with similar number of null and non-null values: **20% < N(W_{sta}=0) < 80%**
- Alternate calculation:
  - All null values are ignored
  - Simple daily average: all available data without elimination
- Assumption:
  - if more than 20% of stations observed a sunspot, the sunspot is confirmed for the day
  - Null observations are due to lower quality of one station or the limited lifetime of the spot over the 24h time interval

➡ ***Essential to avoid statistical "erasing" of short-lived solitary sunspots in periods of deep minima.***

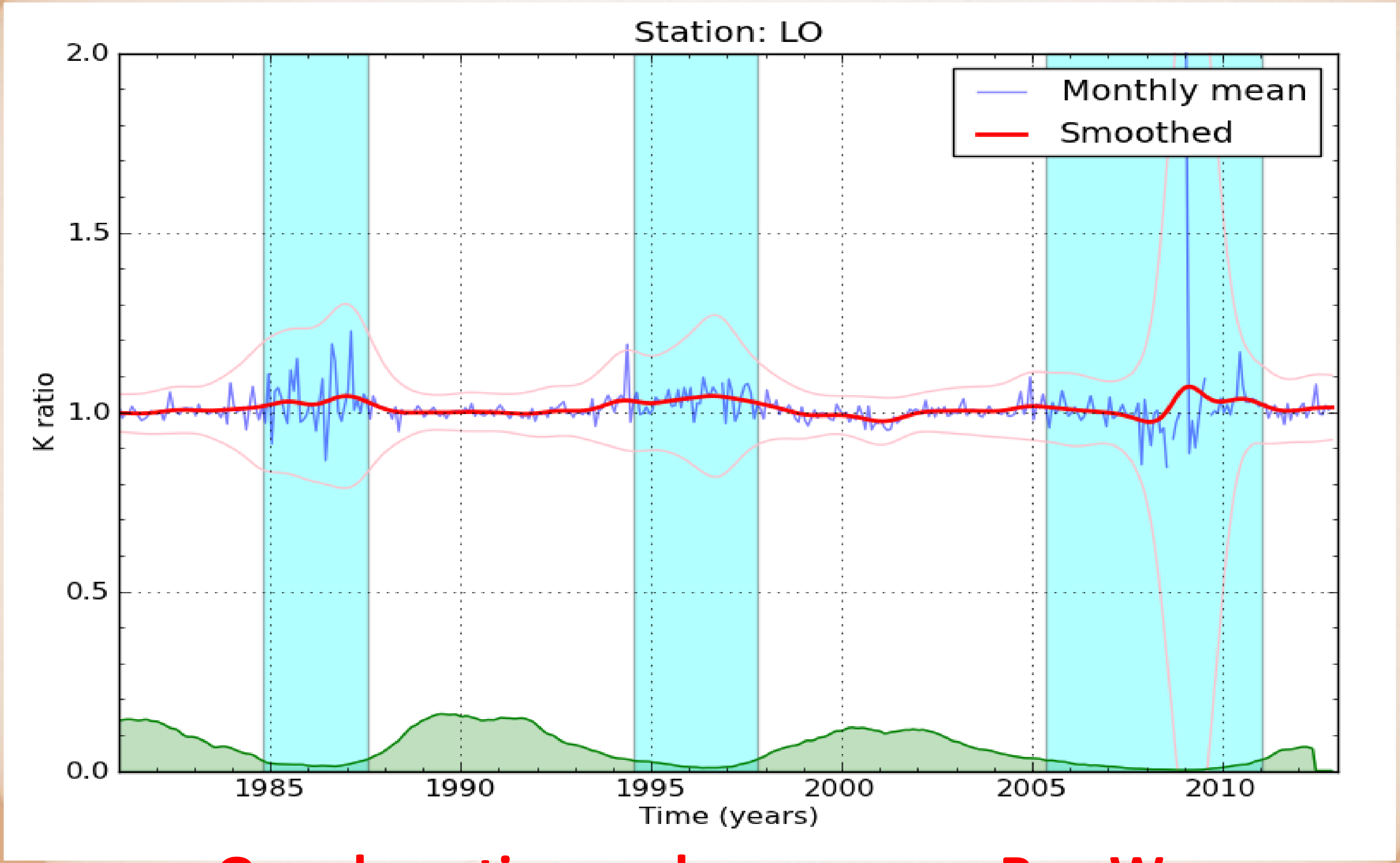
Step 4: alternate R_i calculation

- Impact:
  - When the normal calculation would have given a 0, replaced by a value of 7 (11*0.6)
  - Mainly when $N(W_{sta}=0) < 50\%$ (< 30% of cases when mix of 0 and >0 values)
  - Only in periods of cycle minima: many days with 1 or 0 sunspots
  - Maximum occurrence: 2-3 days/month ***(transition days when a solitary spot appears or vanishes)***
  - **No significant impact on the global SSN scaling**

➡ ***Main cause of inconsistencies in the hemispheric SSN calculation:***

- Decoupled calculations for the total, North and South calculations
- Different sets of input values after elimination
- Problem only in the North/South SSNs

W_{LO} versus R_i



Over long timescales (> 1month) **$R_i \equiv W_{LO}$**

Method: overall properties

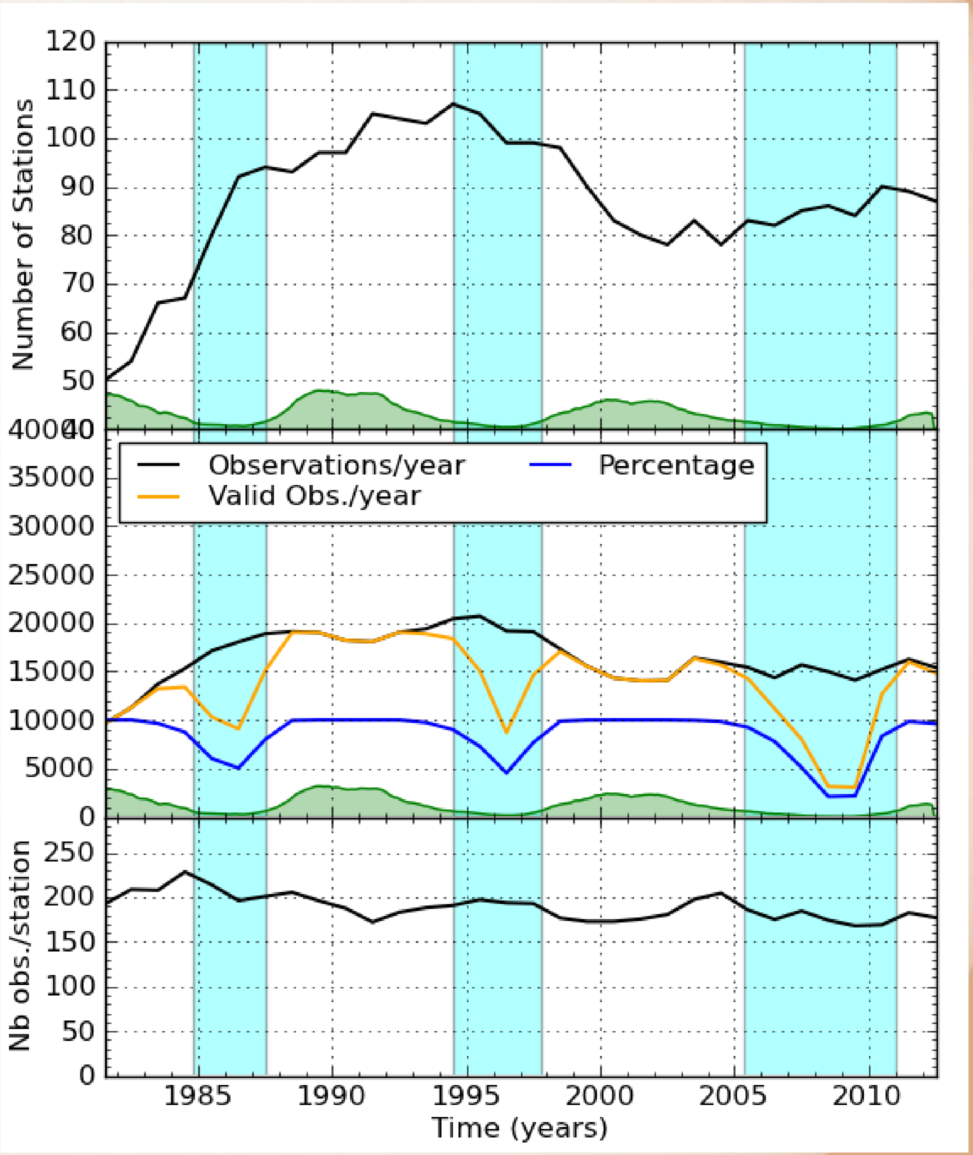
- Method largely equivalent to the Zürich manual calculation:
  - SSN is very close to the raw Wolf number of the primary station
  - Use of the network for filling gaps (average monthly k calculation ensures proper scaling)
- Main differences:
  - Elimination of outliers in daily W values from primary station
  - Better statistics (expanded network)
  - Reduction of the daily dispersion
  - Method stabilized in a program
  - **New primary station: Locarno**
- At timescales > 1 month, the R_i SSN is largely equal to W_{LO}

➡ ***The bulk of collected data was never used to track and define the long-term scaling stability of the LO-based SSN (self-consistent absolute calibration)***

SILSO network: history in numbers

- Number of stations: 3 eras
  - 1981-1995 increase: Koeckelenbergh's recruiting
  - 1995-2002 decline:
  - 2002-2012 stabilization
  - **80 to 110 contributing stations at any given time**
- Number of observations:
  - Follows number of stations
  - Dips during minima (spotless days)

    when R_i < 20
- Observations/station/year:
  - Slight peak around 1985
  - Stable in the range 175-200 days/year (48-55%)
  - **~ 10-35 valid obs./day**

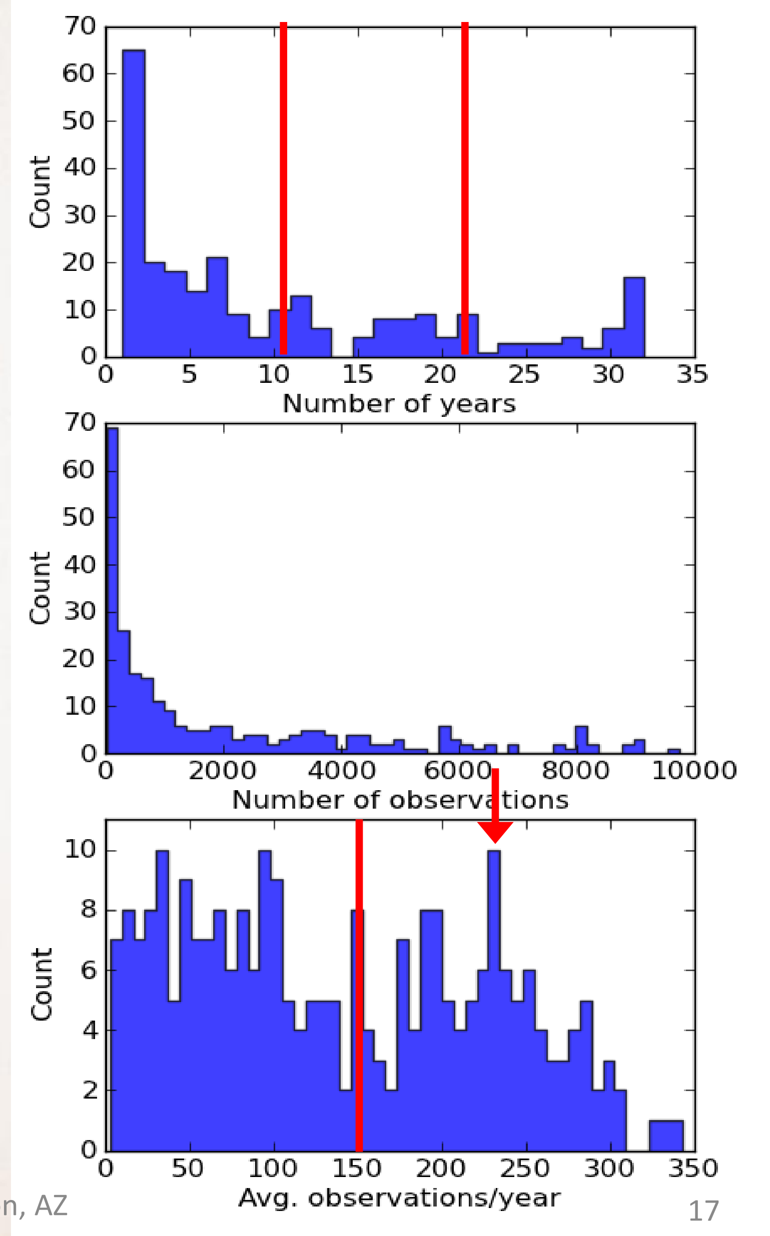


SILSO network: statistics of contributions

- **267 stations**
- **440 432 individual observations**
- > 50% of short participations:
  < 8 years (< 1000 obs.)
- 103 stations with D ≥ 11 years
- 36 stations with D ≥ 22 years:

➡ *Prime information about long-term drifts !*

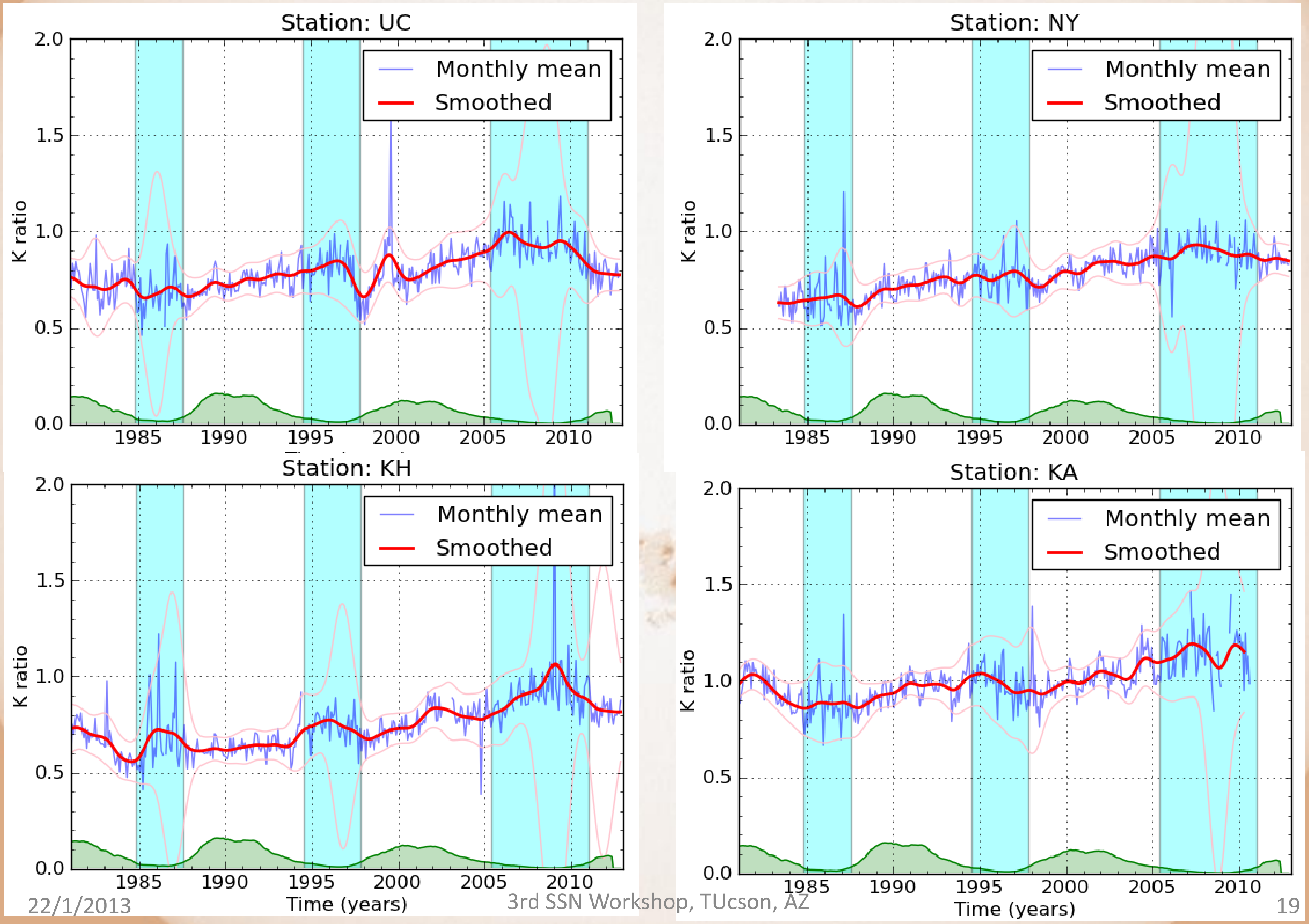
- Average number of observation/year:
  a bimodal distribution
  - Low rates (<150/year):
    - Limited availability of the observer
    - Stations with < 10 days/year:
      - Short participations (partial year)
      - 2 or more widely spaced periods
  - 240/year peak: assiduous stations
    - Rate determined mostly by the weather
    - Sun observable 2 days out of 3 (66%)
  - A few stations > 340 days/year ! (93% coverage): e.g Egypt, Saudi Arabia, Australia



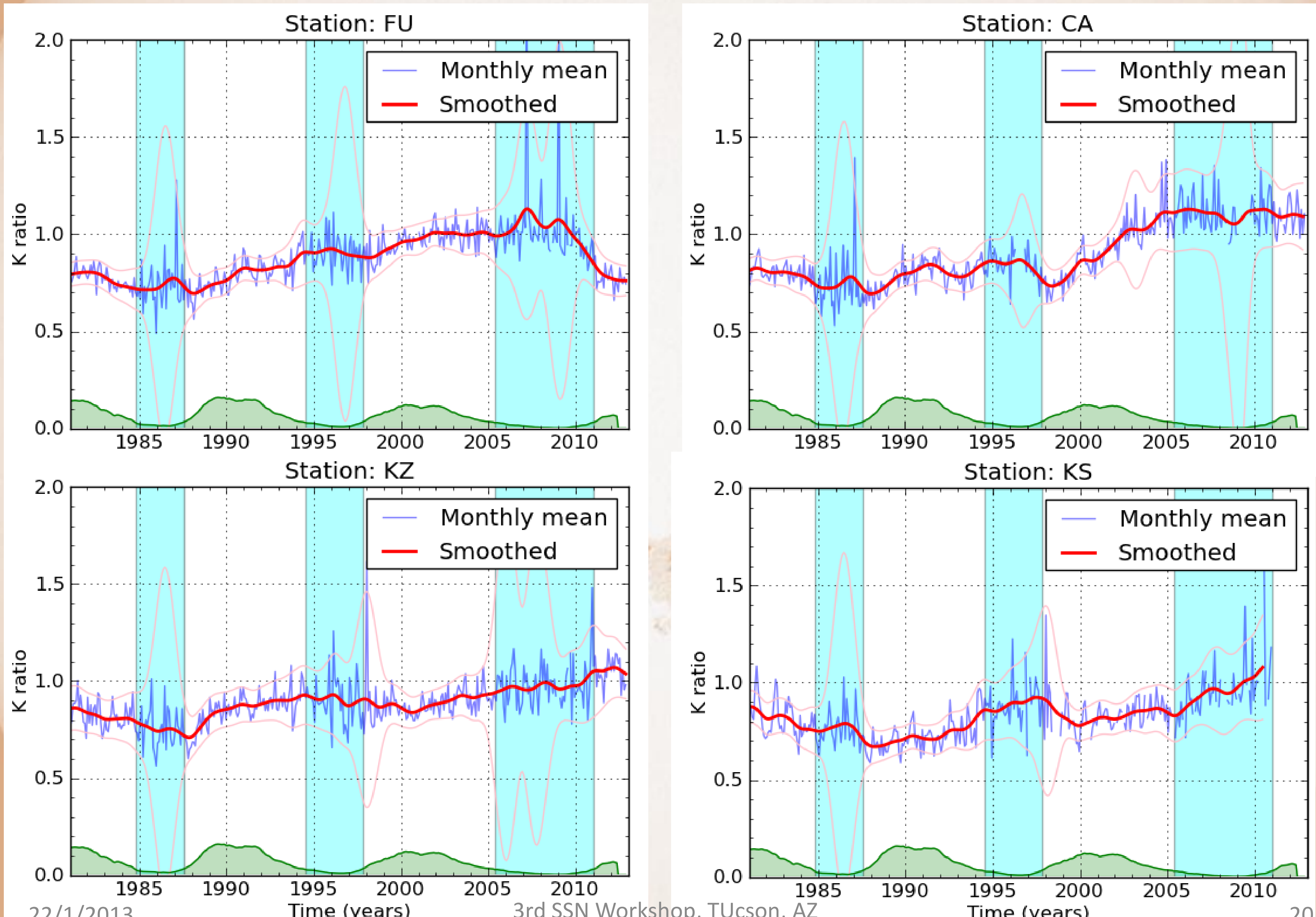
K personal coefficients 1981-2012

- **Alternate definition**:
  - Regular k: $k_r = R_i / W_{sta}$ (with $R_i \approx W_{LO} * 0.6$)
  - Here: **$k = W_{sta} / R_i * 0.6$** (thus, $k \approx W_{sta} / W_{LO}$)
- Easier interpretation:
  - k = 1 if raw number W_{sta} = raw number W_{LO} of pilot station
  - k increases as the station counts more spots relative to the pilot station
- Direct conversion: $k_r = 0.6 / k$

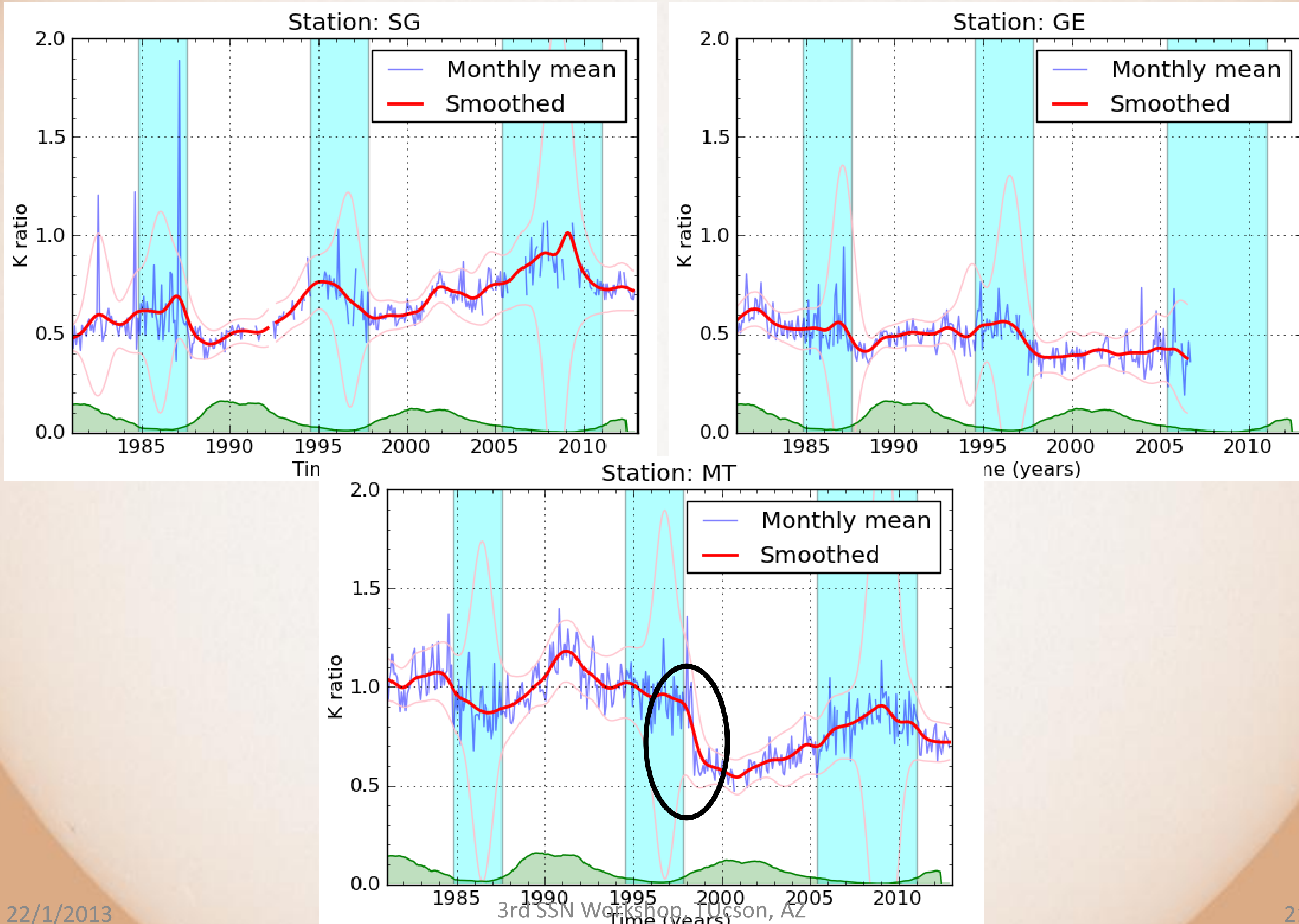
“Best” stations



“Good” stations



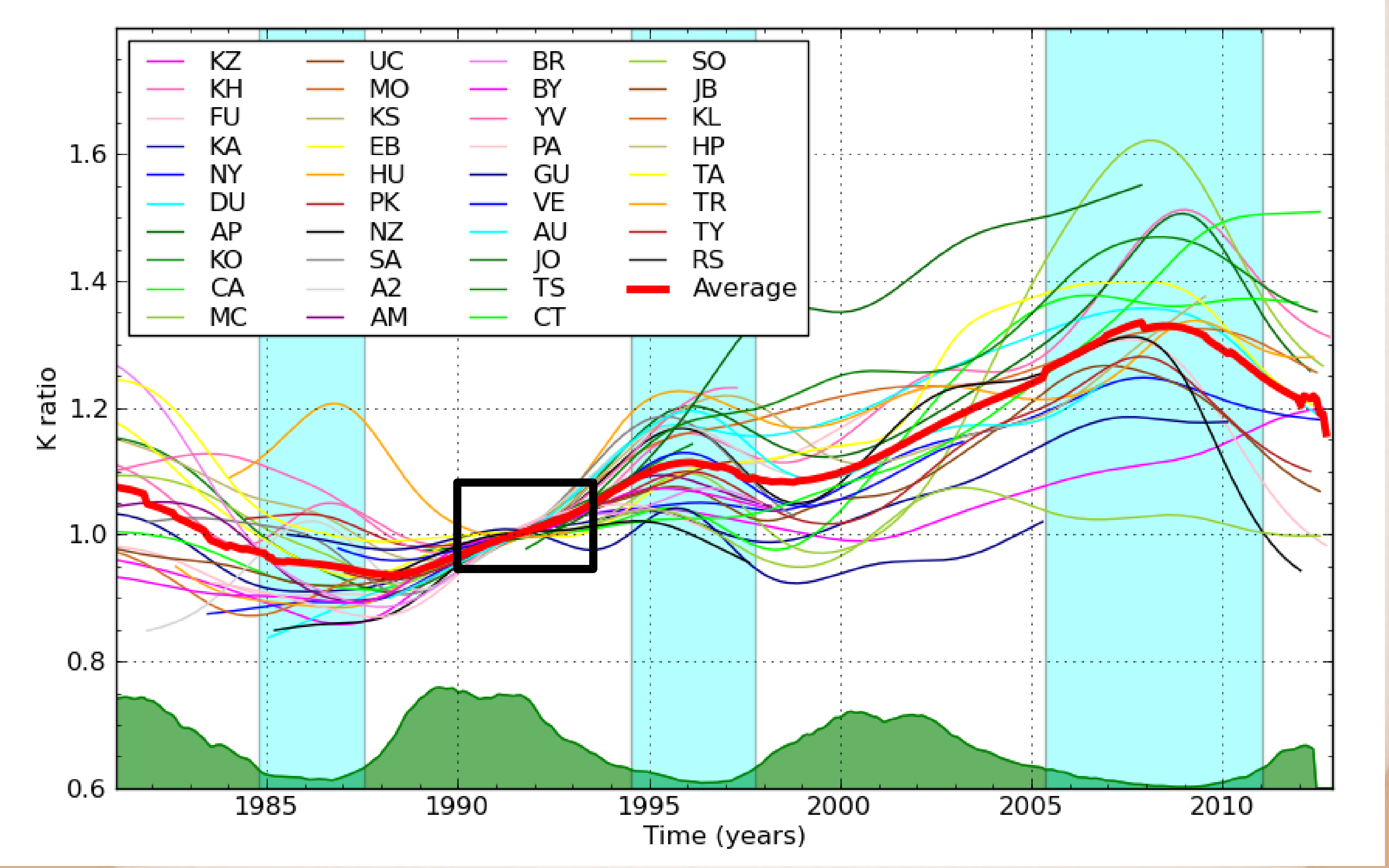
“Fair” and “Bad” stations



Average network k: first estimate

- Normalization to unity over interval 1990-1993:
  - Interval with maximum number of stations
  - "Plateau" in the average network k
  - ➡ **All stations set to same scale before averaging** (same weight)
- Smoothing:
  - **Window function: Gaussian with σ = 5 months**
    - FWHM= 12 months (close to Zürich 13-month « boxcar »)
    - Best rejection of random monthly fluctuations
- Station selection: only "good" stations
    - Long duration (> 20 years, no gaps)
    - Low dispersion
    - No obvious defect (jump)
  - ***Little dependency of average k profile on the selection***

Average network k: all “good” stations



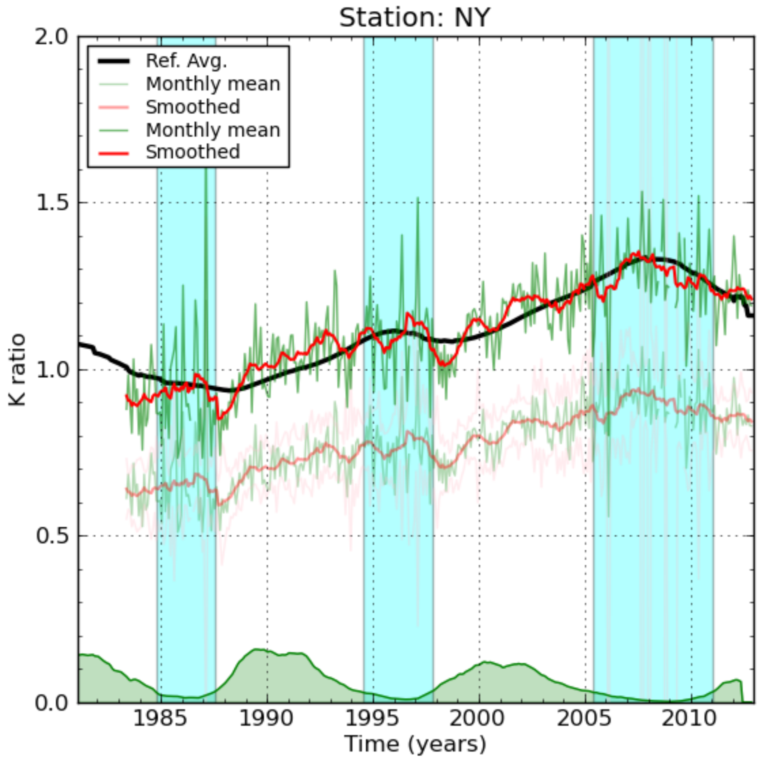
Average network k: least-square fit

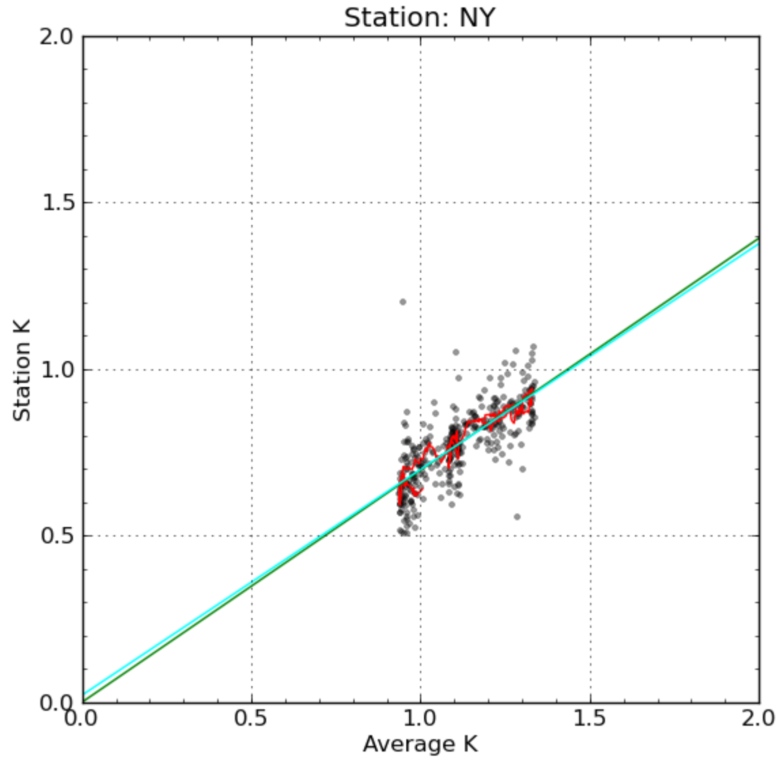
- Least-square normalization over entire 1981-2012 interval
  - Reference: average k profile from first estimate
- Quantitative test of match between the station k variation and the average network k variation: double linear regression:
  1. L-S scaling factor: y= a' x (assumes strict proportionality)
  2. Full linear regression: y= a x +b

  ➡ 2 measures of linear correlation:
    - Linear correlation coefficient R
    - Intercept b close to 0, a ≈ a'

Least-square fits: examples

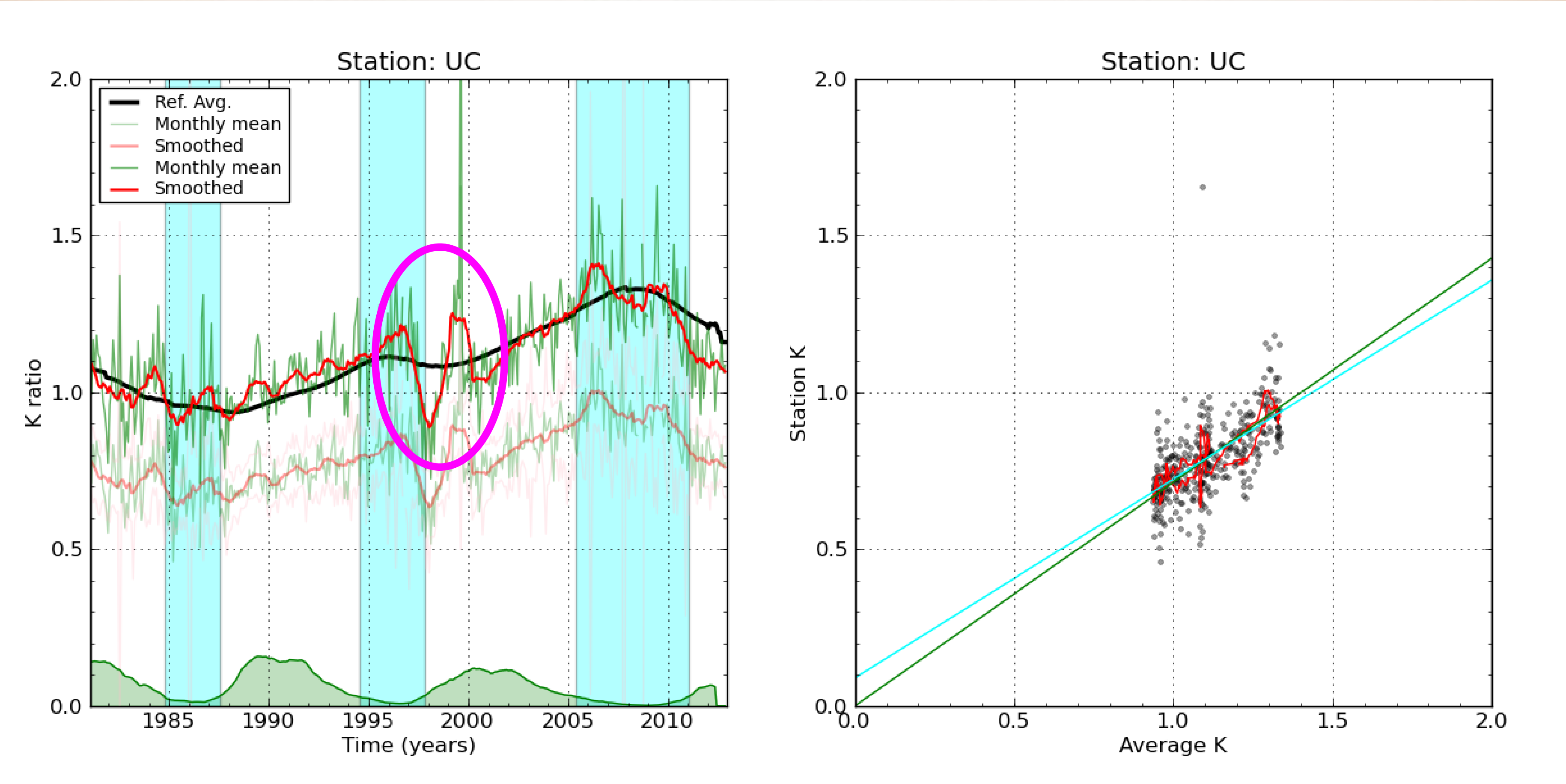
- NY : perfect correlation





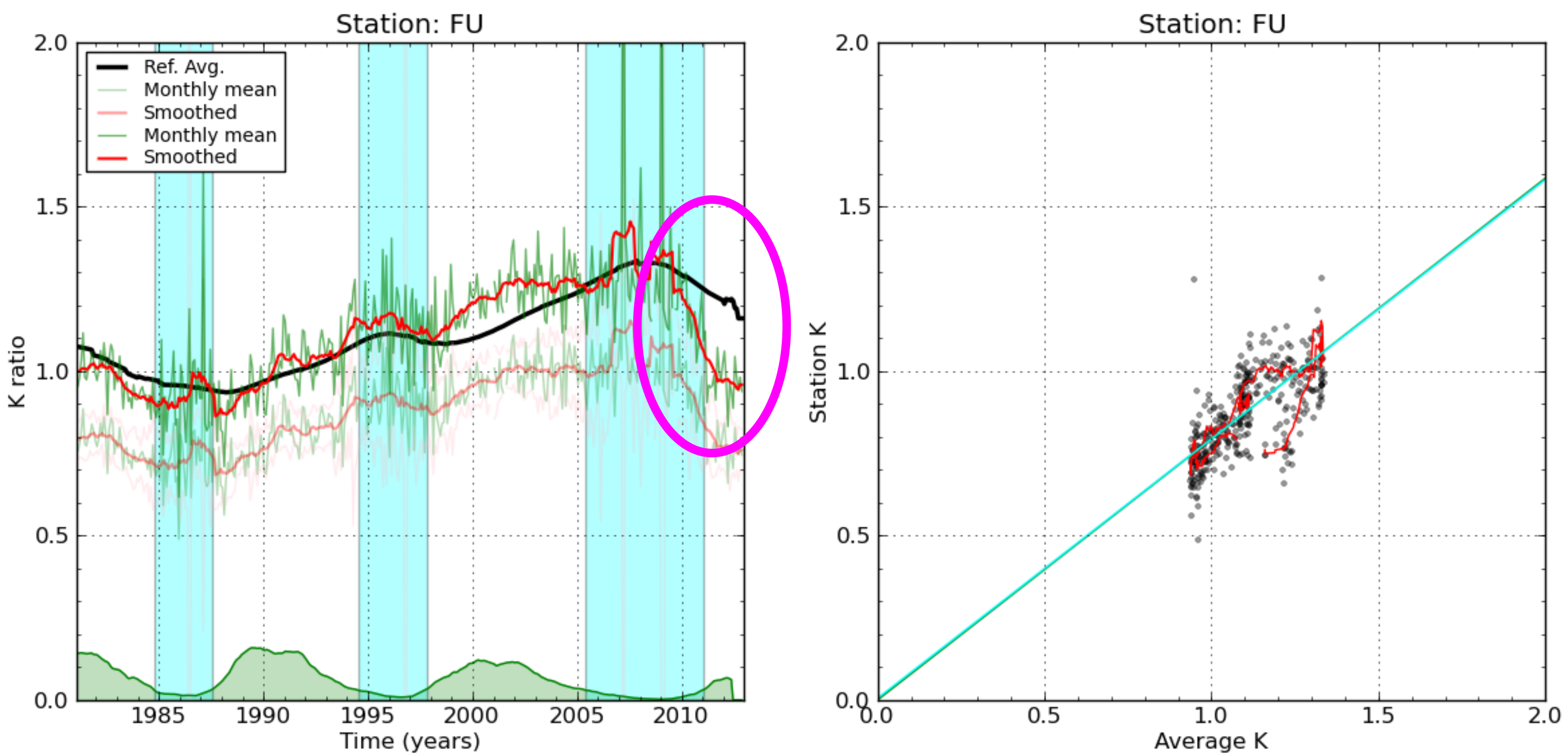
Least-square fits: examples

- Uccle (ROB): example of a good fit



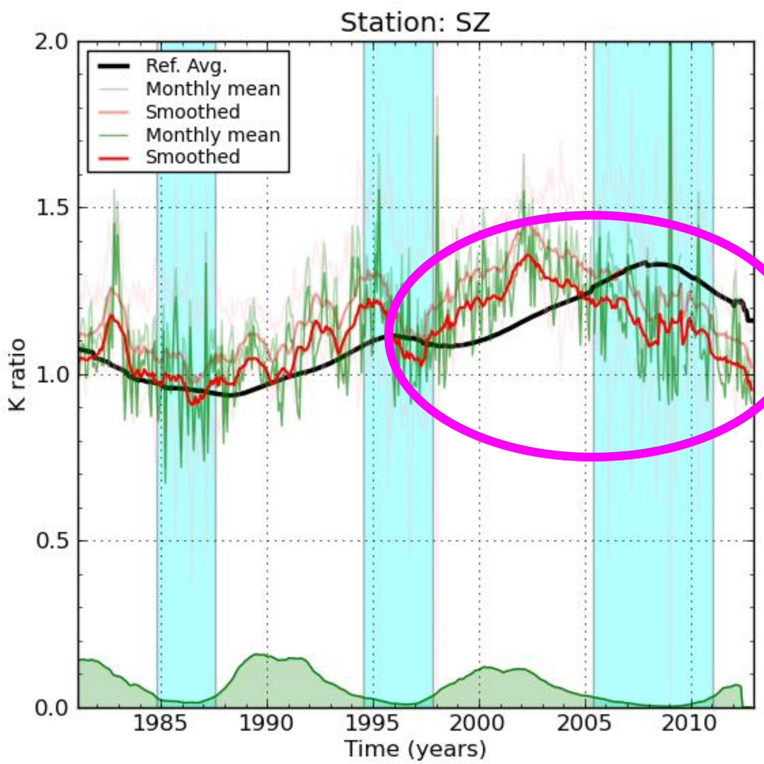
Least-square fits: examples

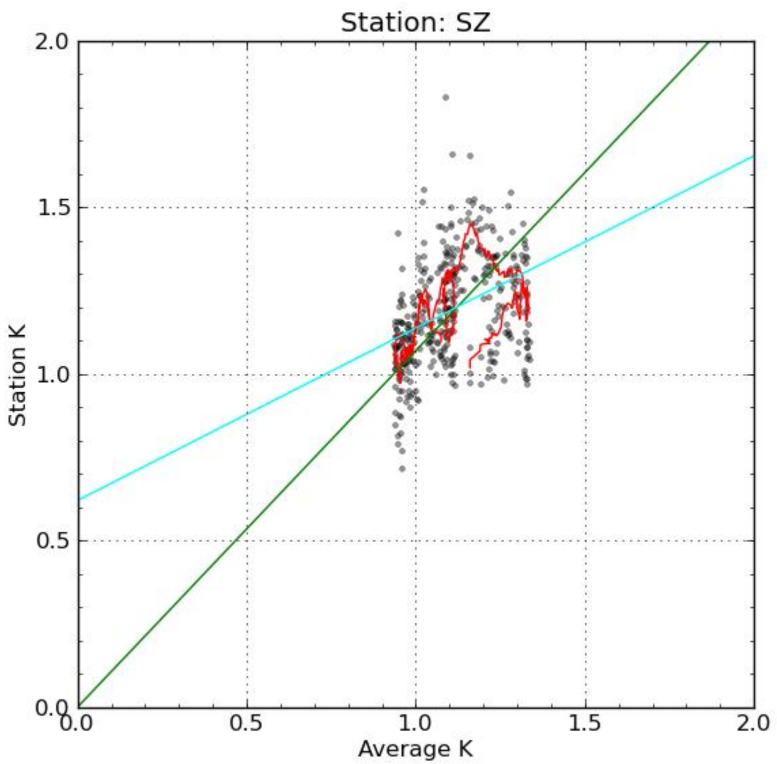
- FU Fujimori : drop after 2008, still a good fit



Least-square fits: examples

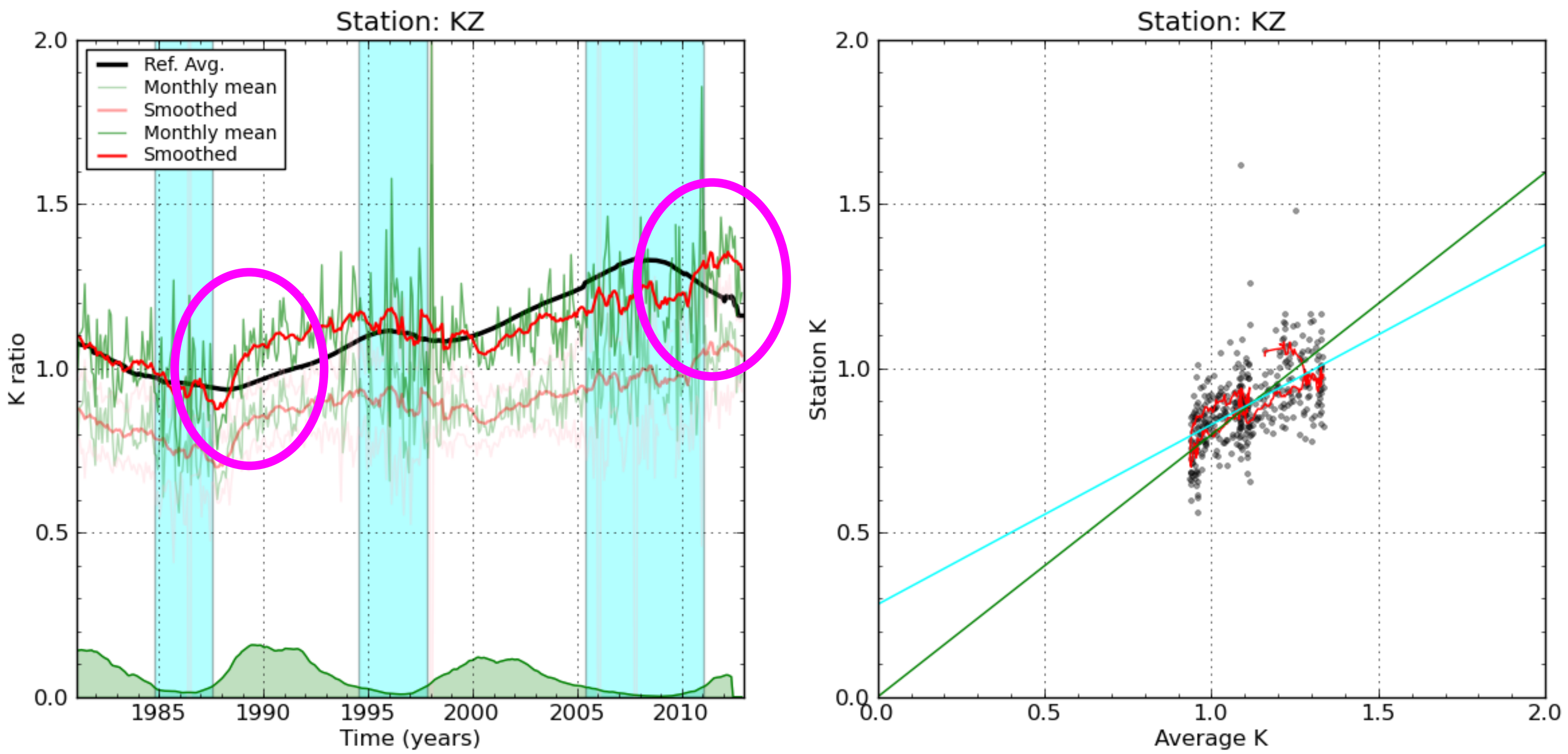
- SZ: partial fit





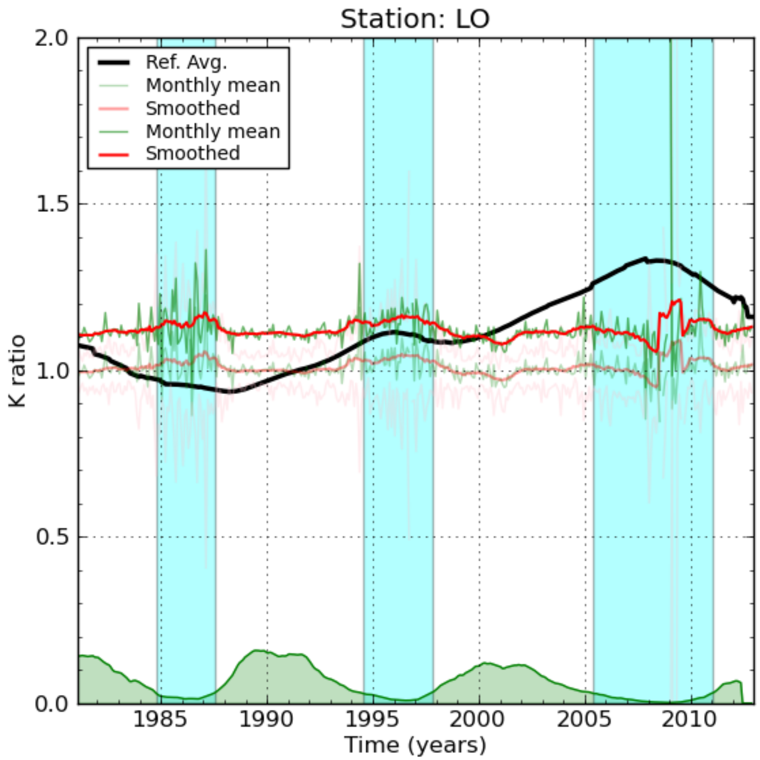
Least-square fits: examples

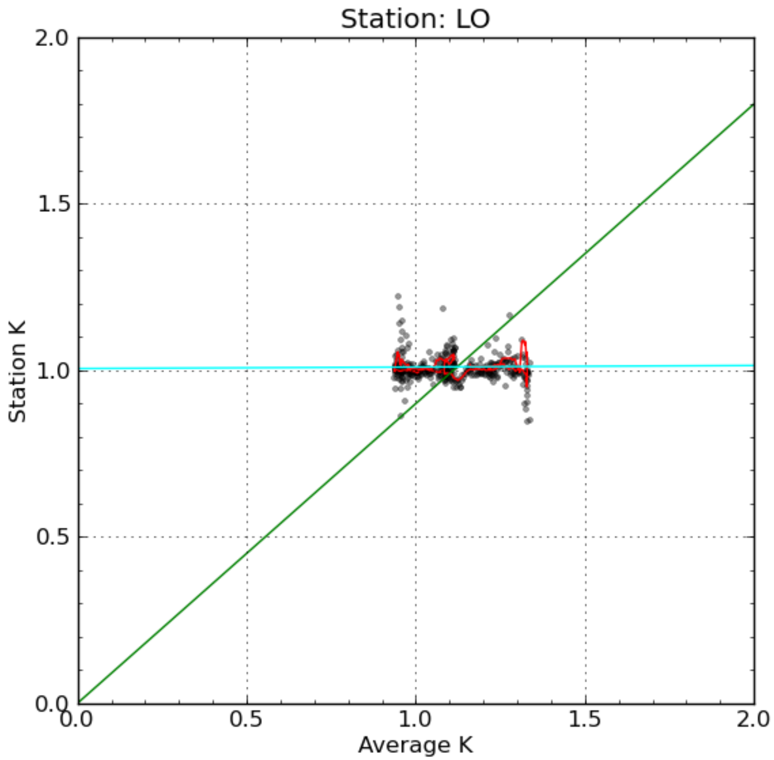
- KZ Kanzelhöhe: high linear correlation but low slope (not proportional)



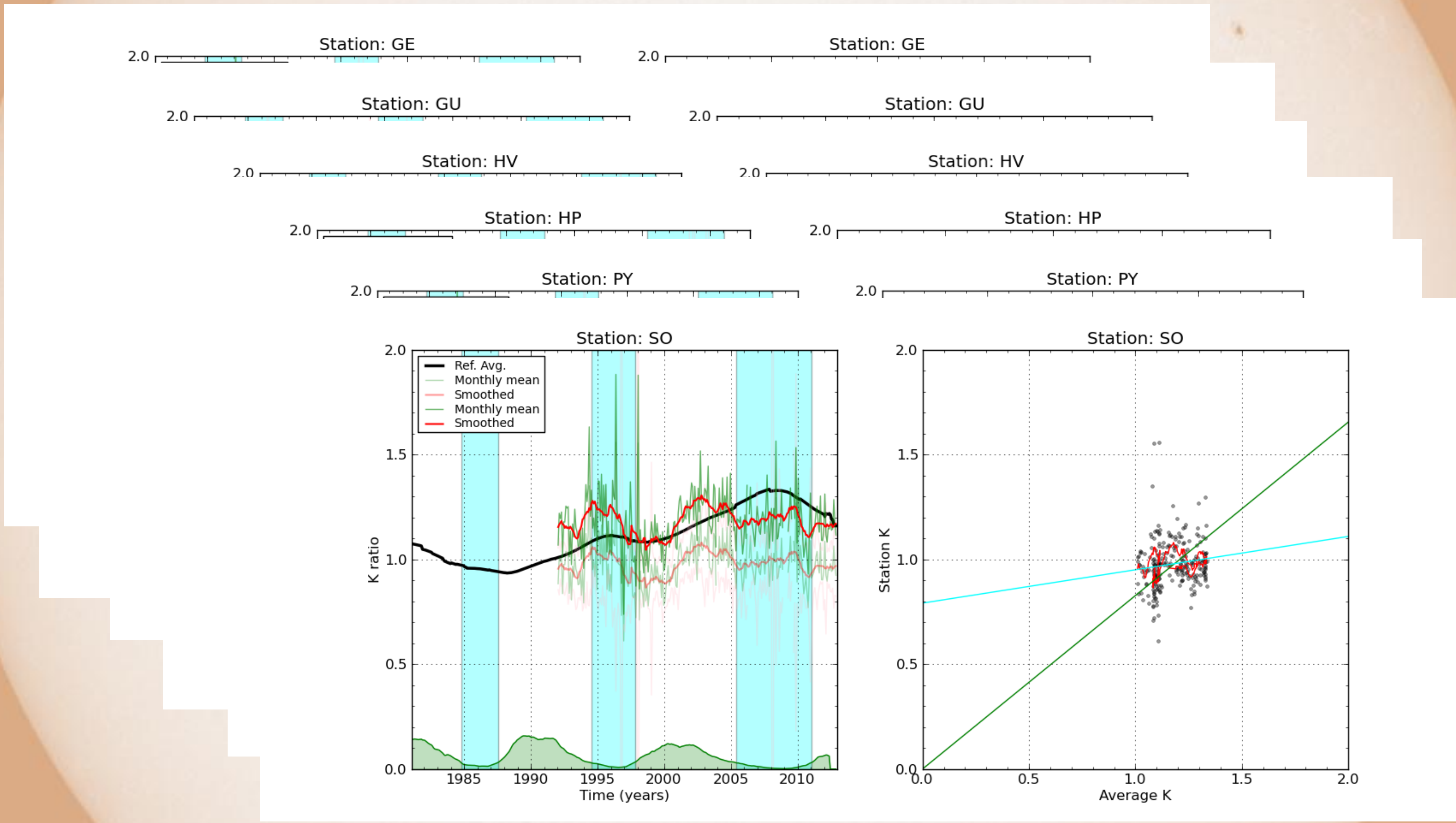
Least-square fits: examples

- LO Locarno: incompatible with the network average
- Average scaling ratio (1.10)
- Similar network k values at both ends



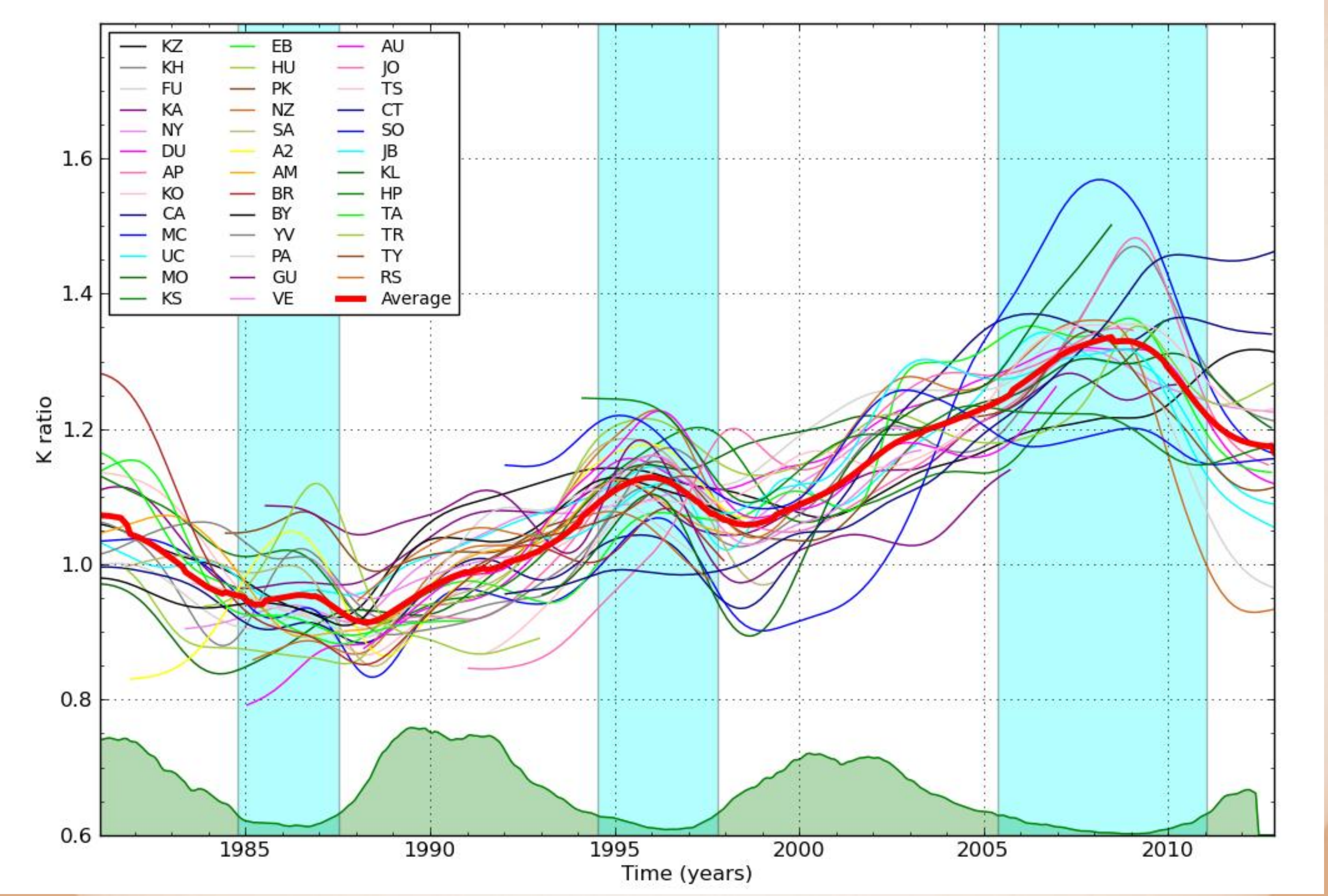


A few other flat profiles



Only 8 stations suggesting a constant ratio with Locarno

Average network k: l-s over 38 “master” stations



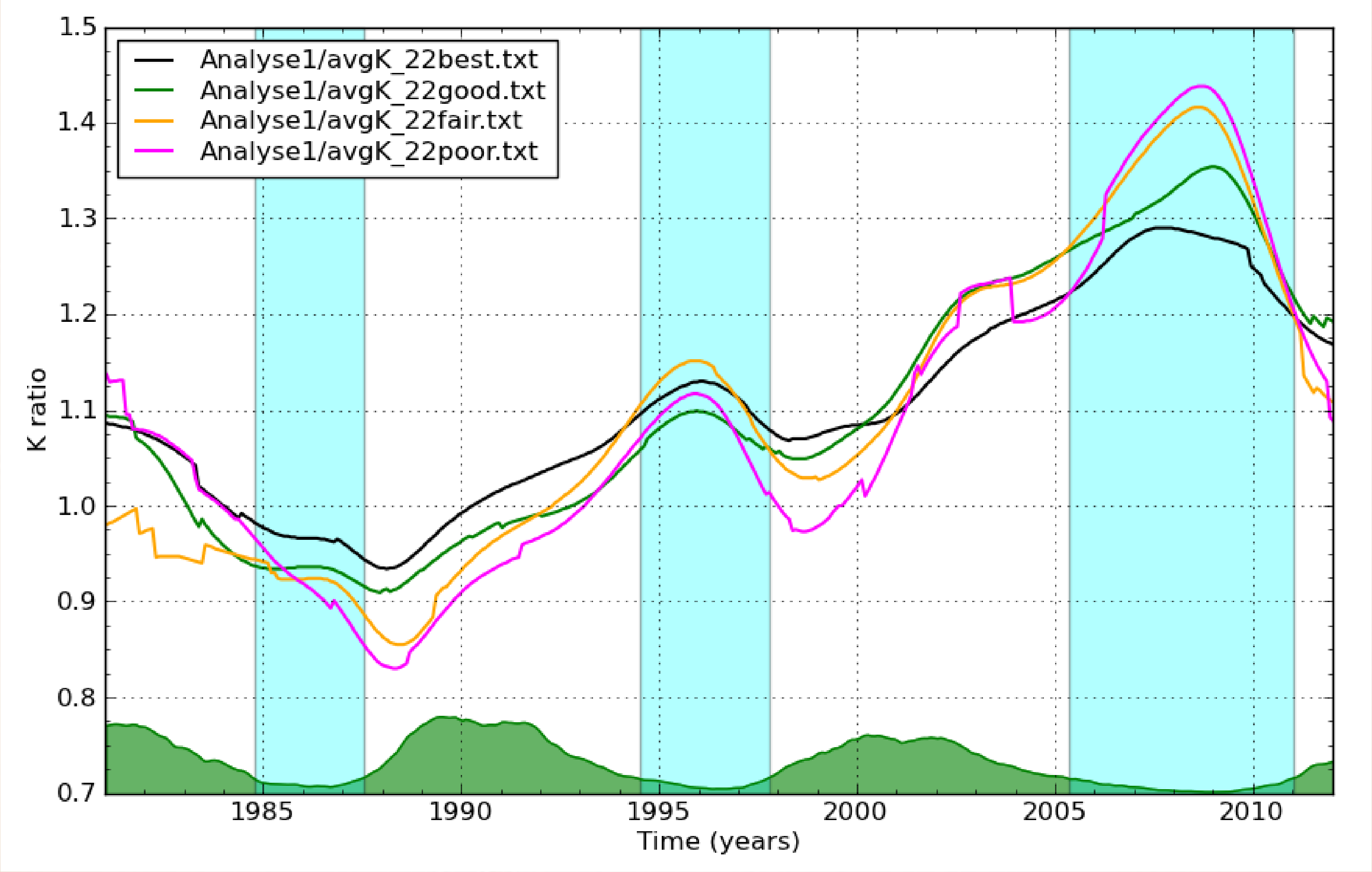
Variable LO trend over the last 31 years

- Consistent drift of most stations relative to LO
- Only a few stations have a constant "flat" k:
  - None among the best stations
  - Mostly with time coverage < 20 years
  - Some with known problem of k decline:
    e.g. GE (elderly observer, age 60 to 90)

➡ **Extracted trend is robust**:

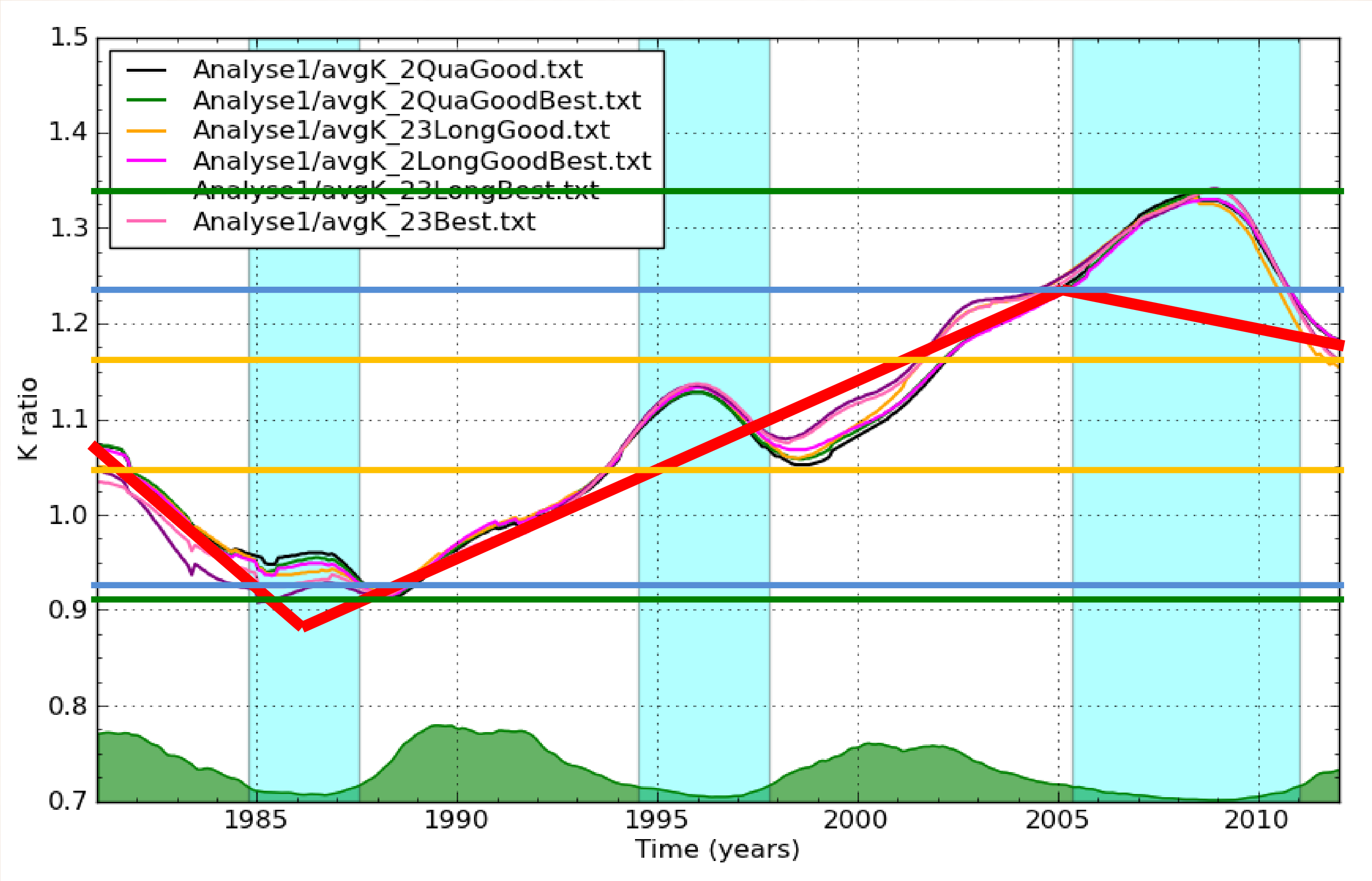
  - Almost Identical for separate non-overlapping subsets of stations.

Network k for distinct subsets



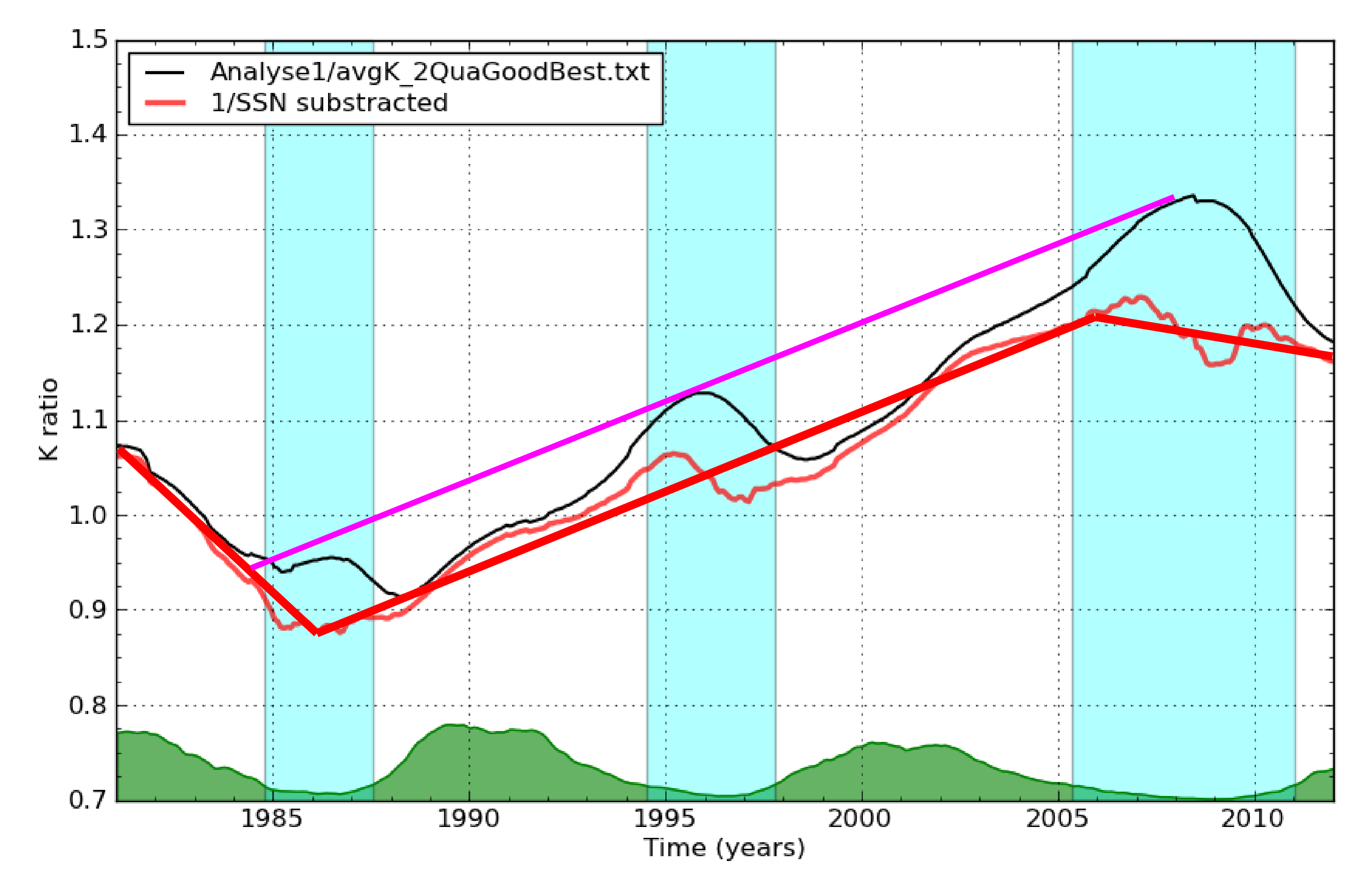
- Amplitude of the variation tends to increase as quality decreases („peaks" associated with minima)

Best network k reconstructions



- 3 successive linear trends: down – up –down
- P-P amplitude: 45% Effective : 30% Start-end: 10%
- 3 "bumps" matching the solar minima: solar cycle modulation

Linear and cycle components: a simple trial



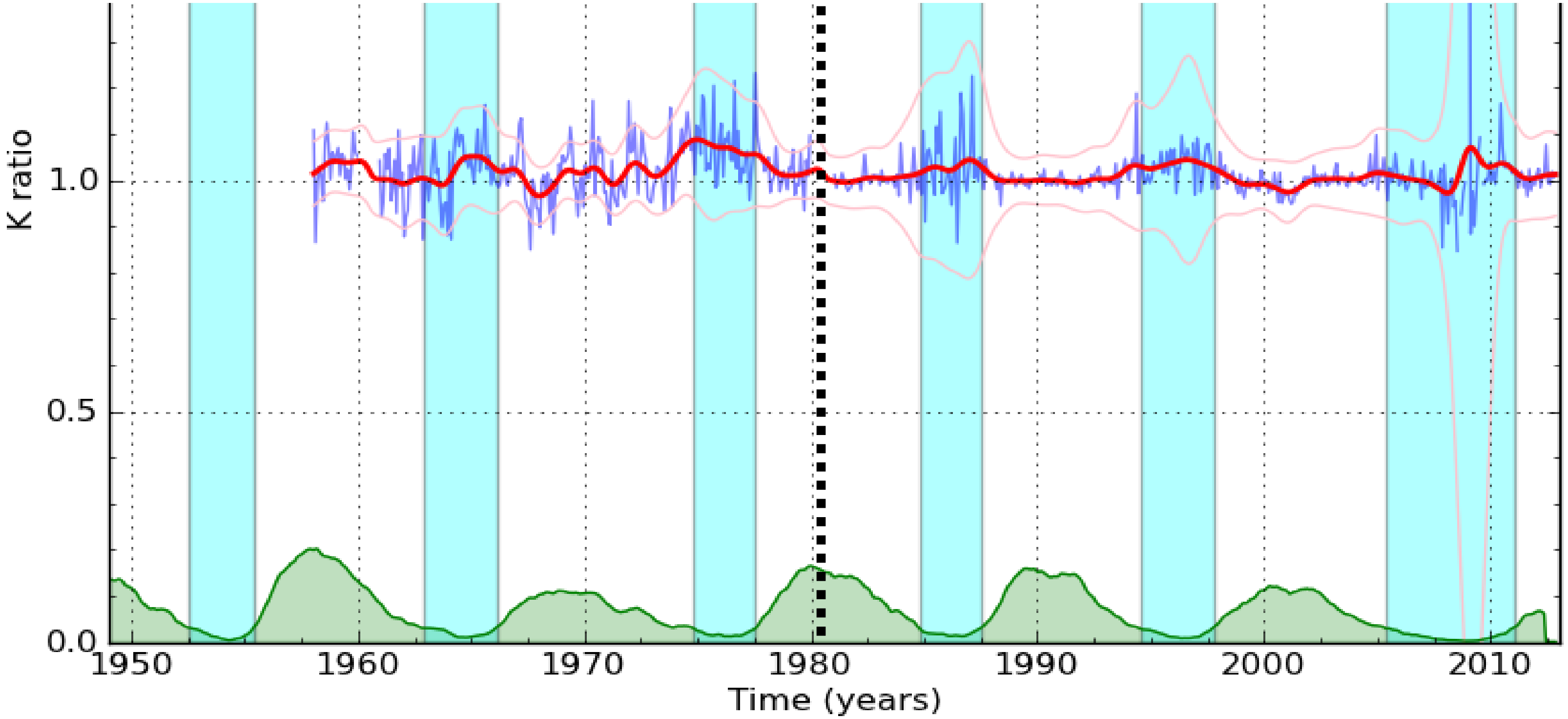
- Subtraction of a 1/SSN modulation: “bumps” can be strongly eliminated
- Amplitude of the modulation: ~ 10 %

Extension before 1981

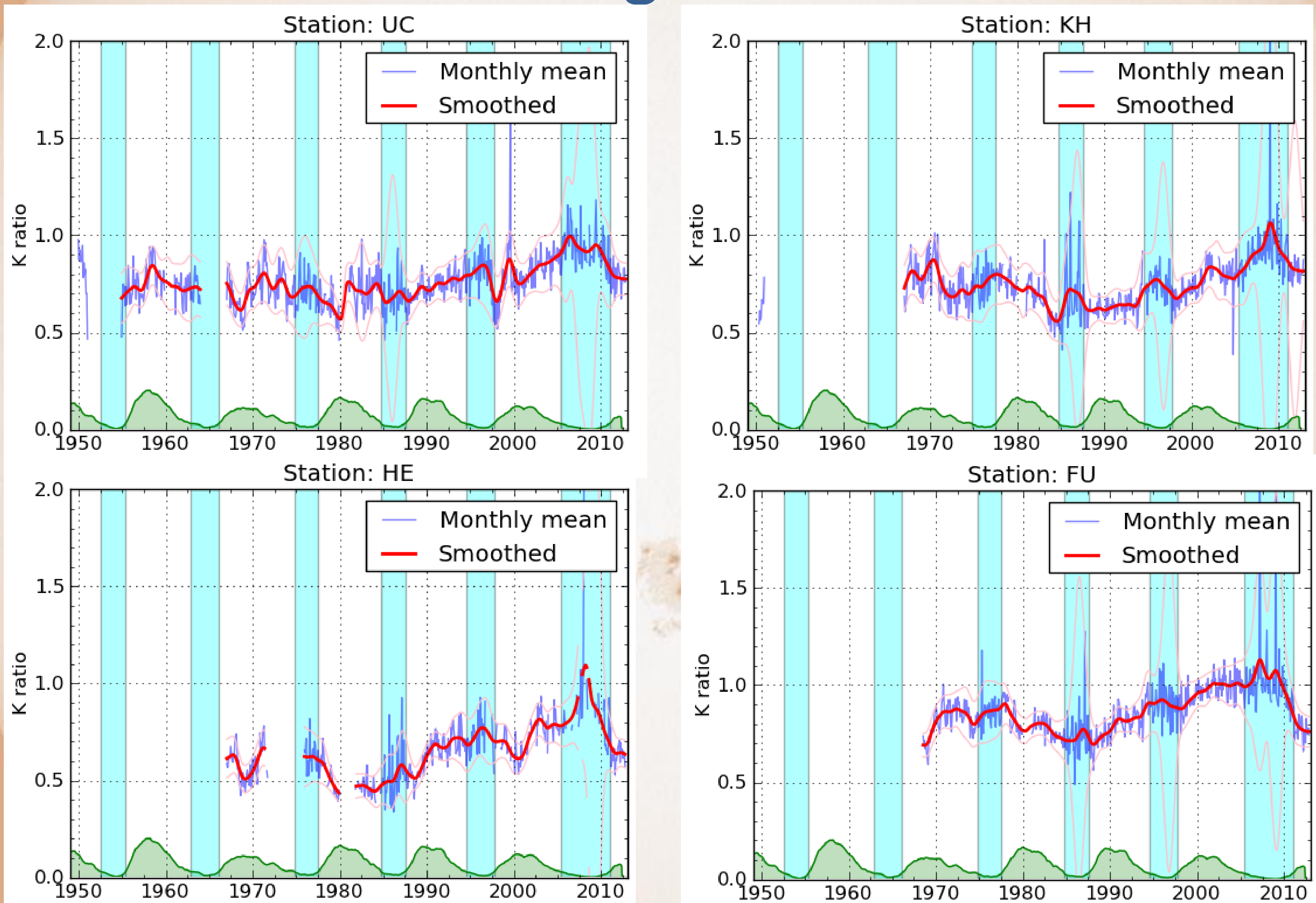
- New questions:
  - **Did Locarno drift relative to Zürich also before 1981?**
  - **Is there a calibration jump at the 1980-81 transition between Zürich and Brussels?**
- Available data:
  - Paper files from Locarno (raw observing reports)
  - Smaller number of stations: 26
    - Only subset of stations observing both before and after 1981
    - Many unusable for k calibration over the entire period
    - Good coverage of the 1970-1990 period (transition diagnostic!)
  - Imported in the global SILSO database *(cf. L. Wauters)*
  - 9 missing years over 30: 1951-54, 1960, 1964-66, 1980 (paper files lost?)
  - Full Locarno data set since 1958
  - **Major issue: raw Zürich reports are missing !**

Locarno: two distinct statistics

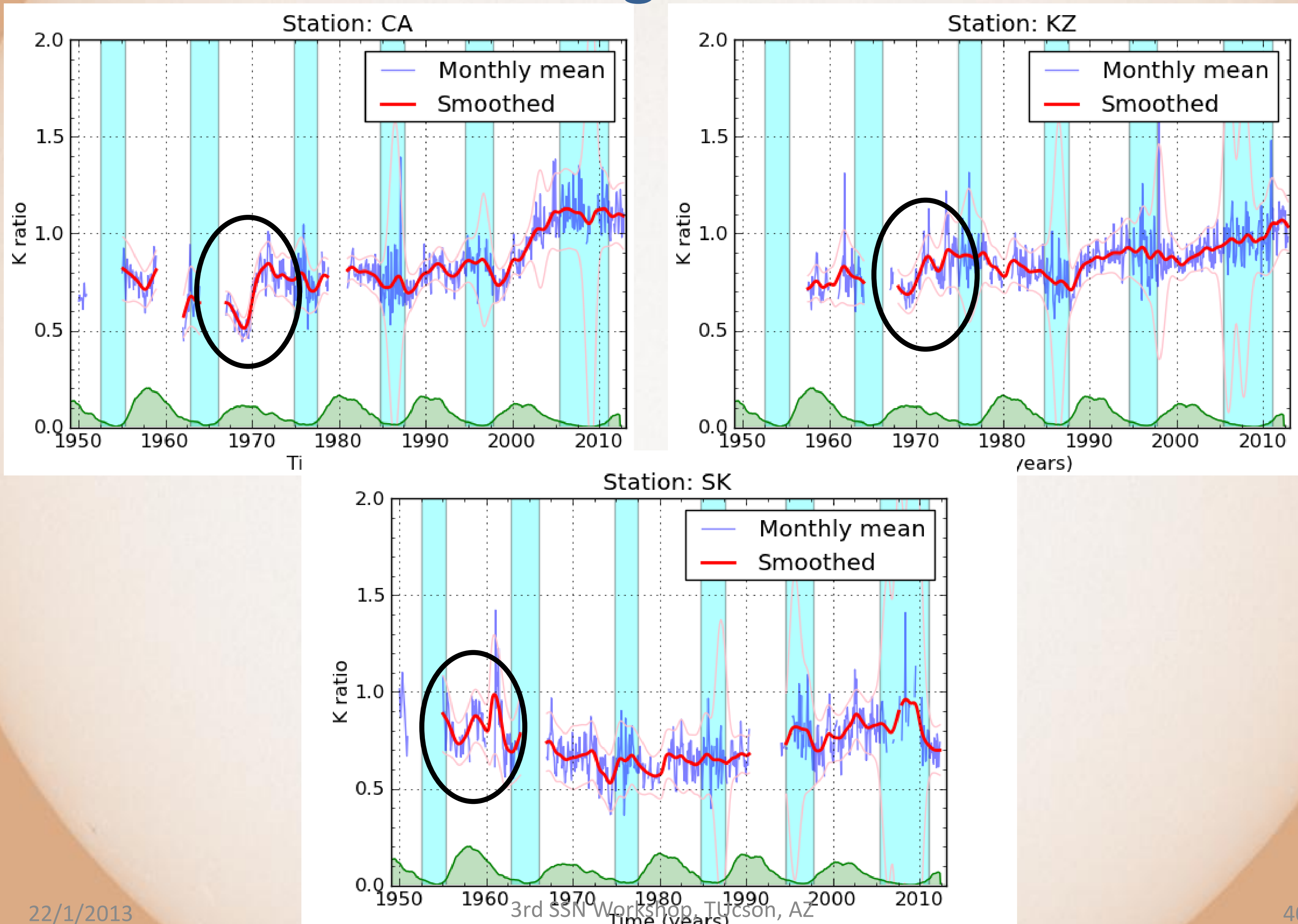
- After 1980: very low dispersion ($R_i \equiv W_{LO}$)
- Before 1980, larger dispersion:
  - Indication that Locarno was only a secondary station (< 25% of daily values used as substitute for Zürich?)
  - Still, k_{LO} is consistent with a constant value over 22 years (1958-1980).



The longest series

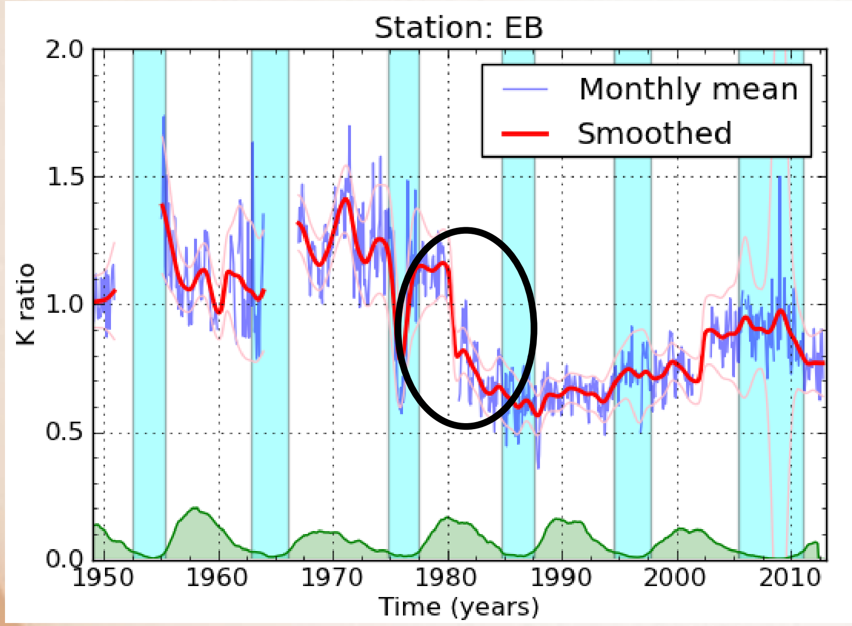


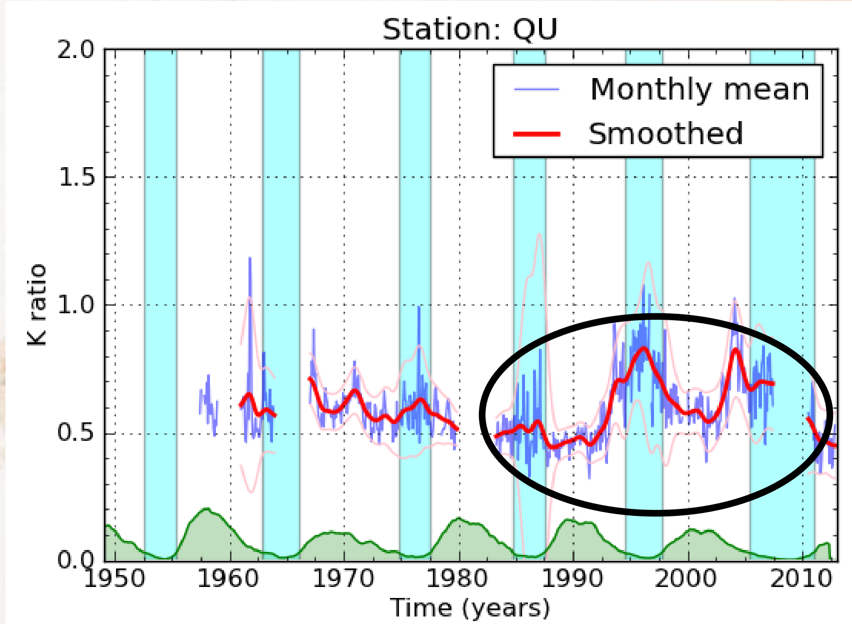
The longest series



The longest series: stations with defects

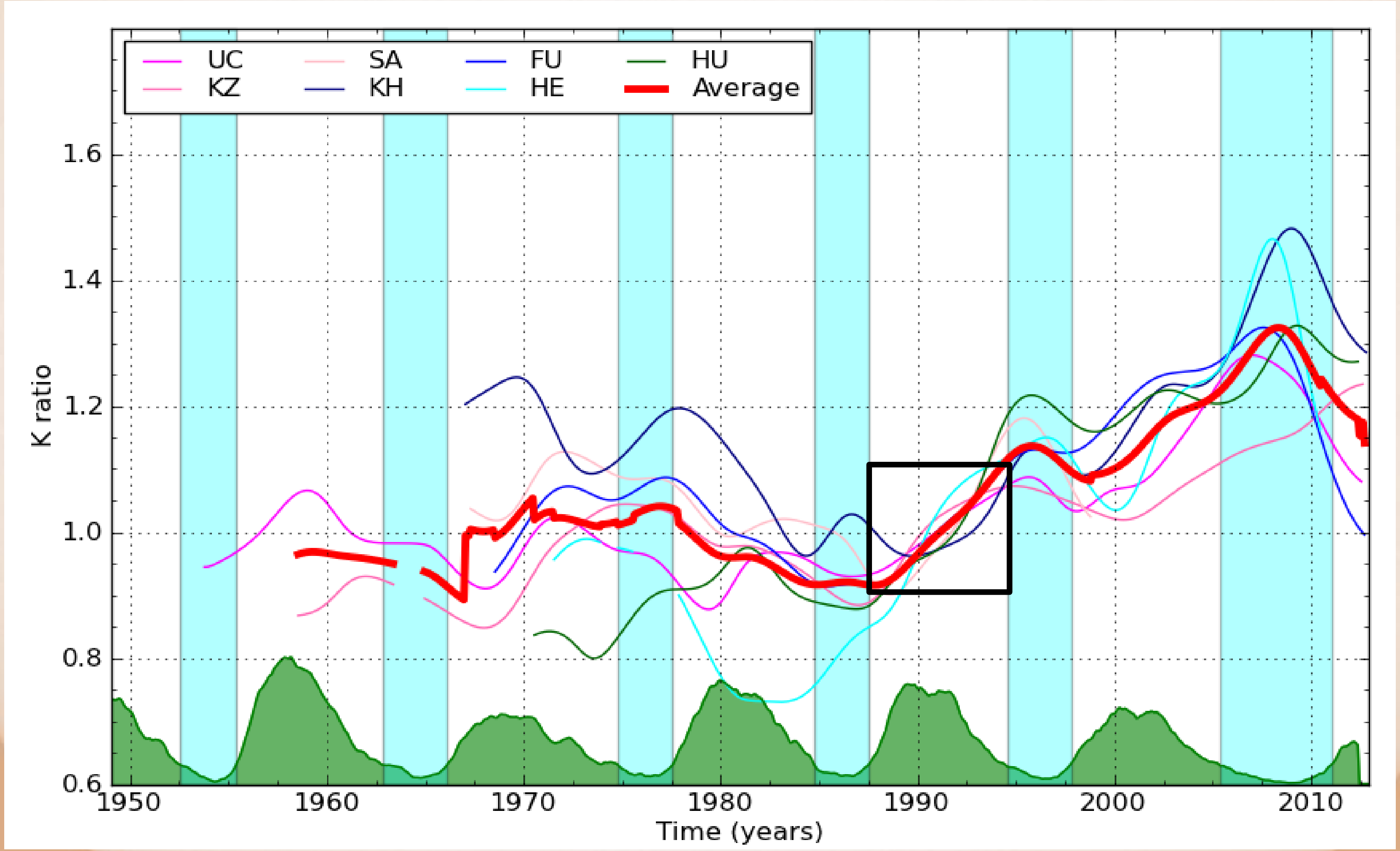
- EB: usable only after 1980
- QU: only usable before 1980
- Entirely dropped in this first analysis:





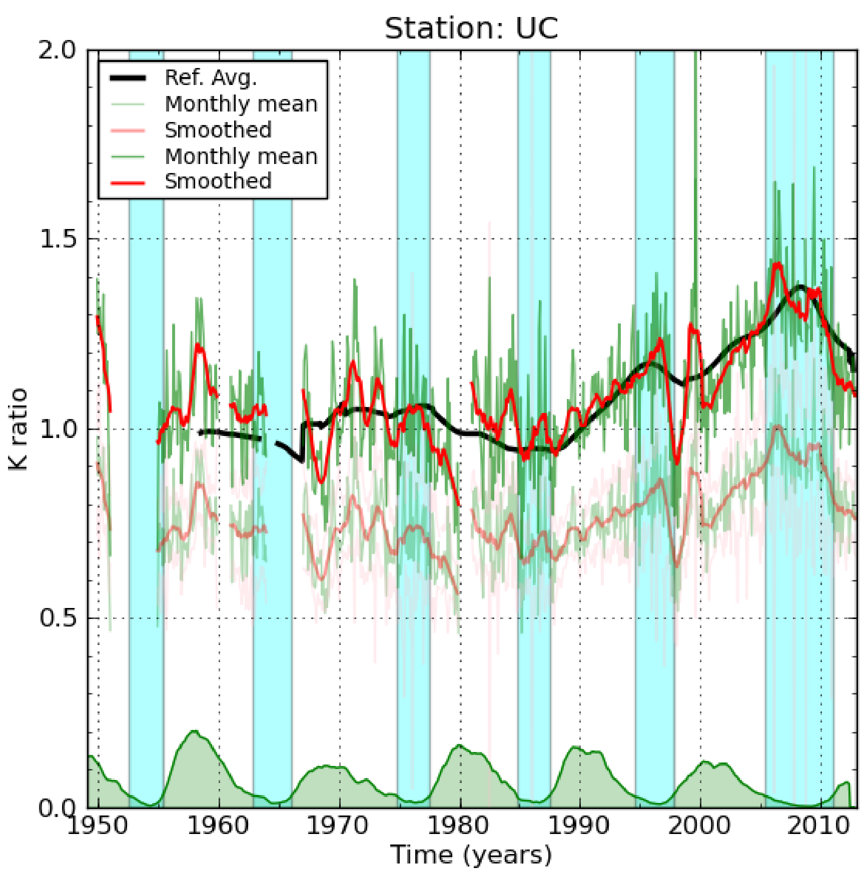
Average network k: first approximation

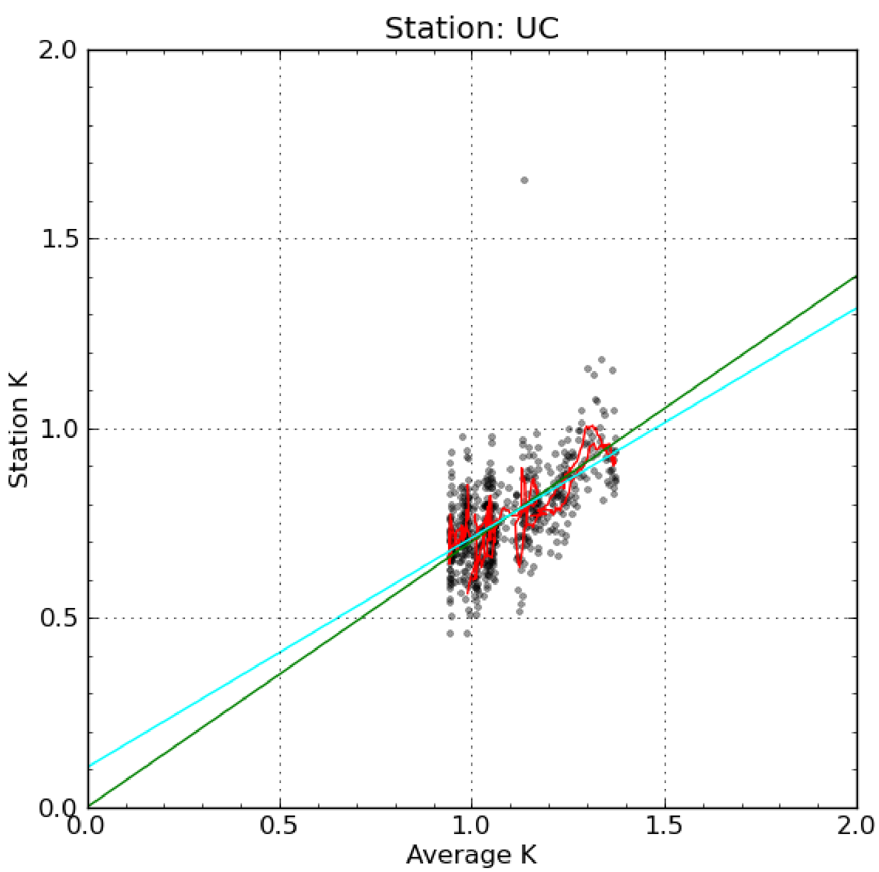
- Normalization: interval 1987 – 1995 (cycle 22)



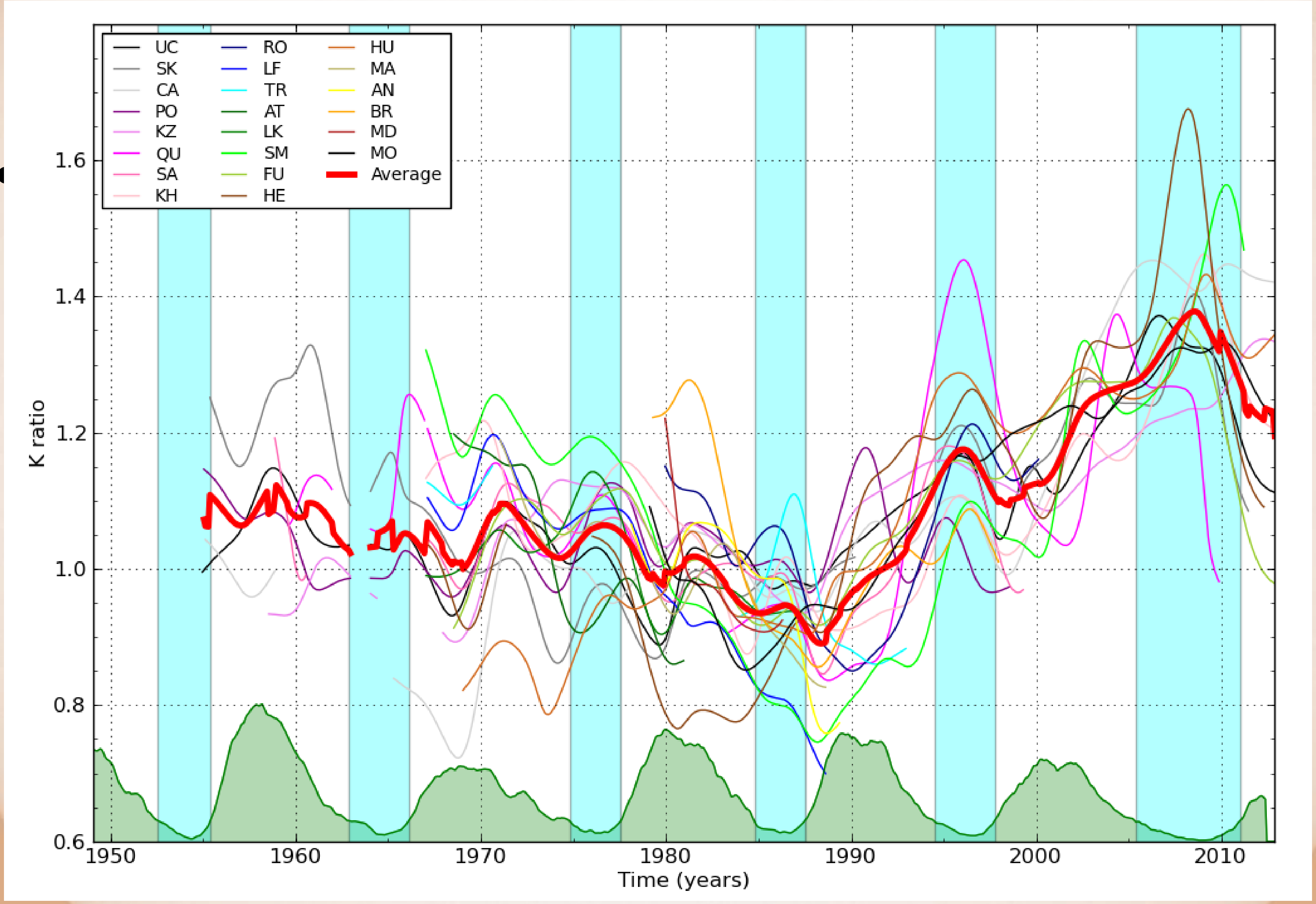
Least-square fit

- UC Uccle: good fit to average

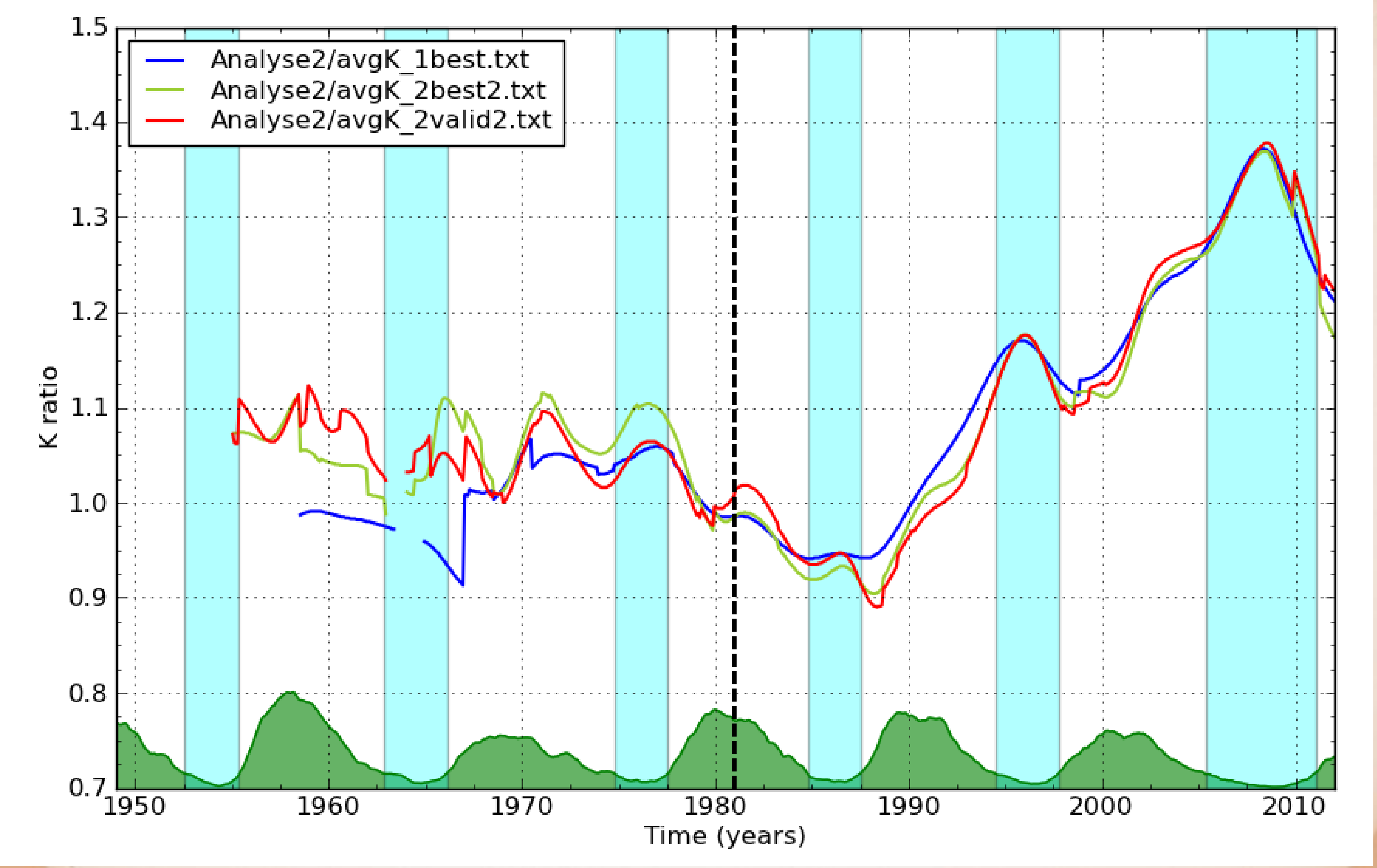




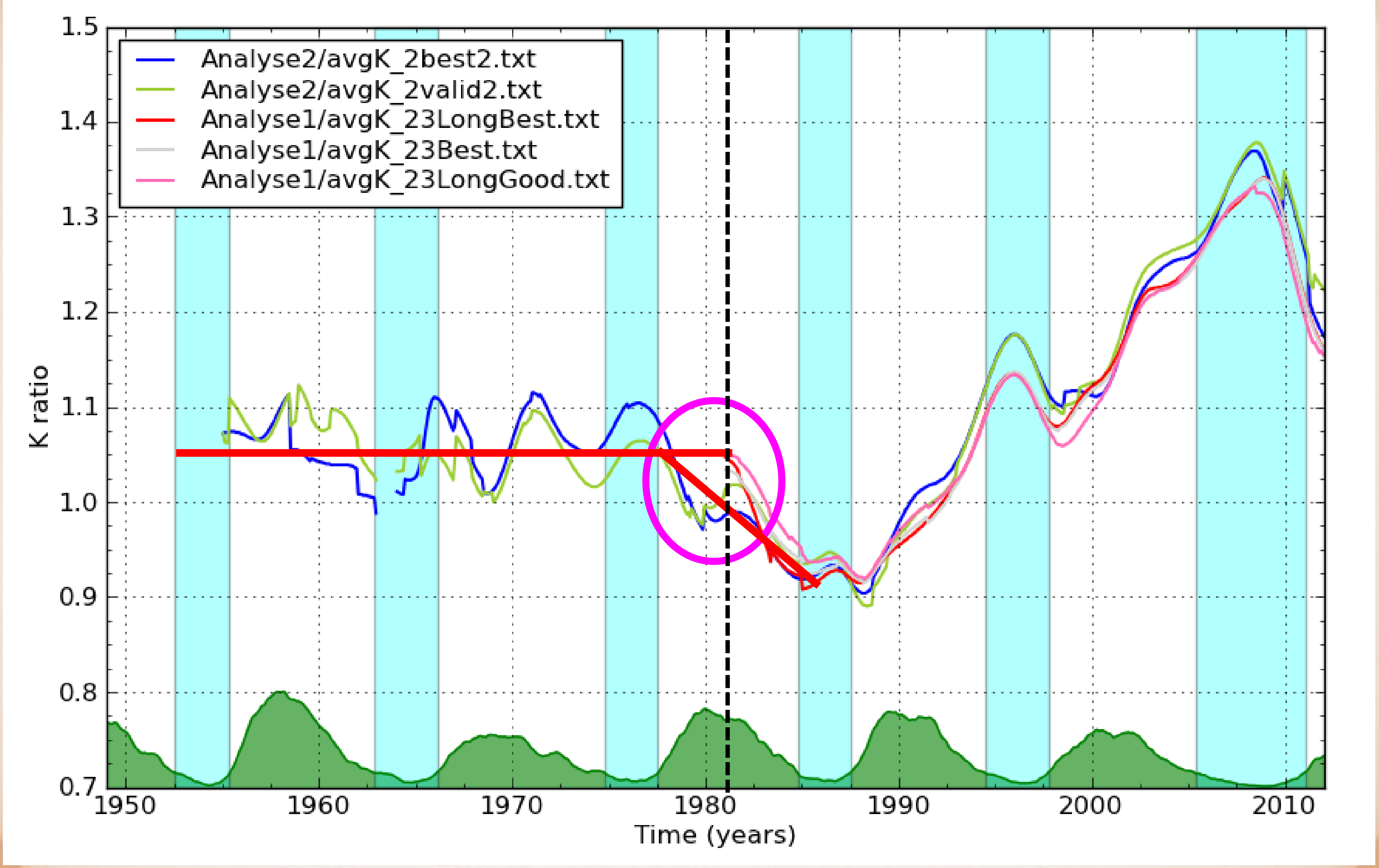
Average network k: l-s fit (22 stations)



Average network k: consistent trends



Pre & post-1980 consistency



- 10% inaccuracy (underestimate) over 1977-1980 ?
- Overall scale before 1980 seems ~5% too high

1949-1980 versus 1981-2012

- The extended average k profile is consistent with the full SILSO network statistics over the common period 1981-2012.
- **No significant jump occurs in 1980-81**:
  - An equal number of stations report a slight upward or downward step (when there is one).
- The flat average k profile before 1981 indicates the **absence of drift in the final period of the Zürich SSN**.
  - Possible drift starting already in 1977

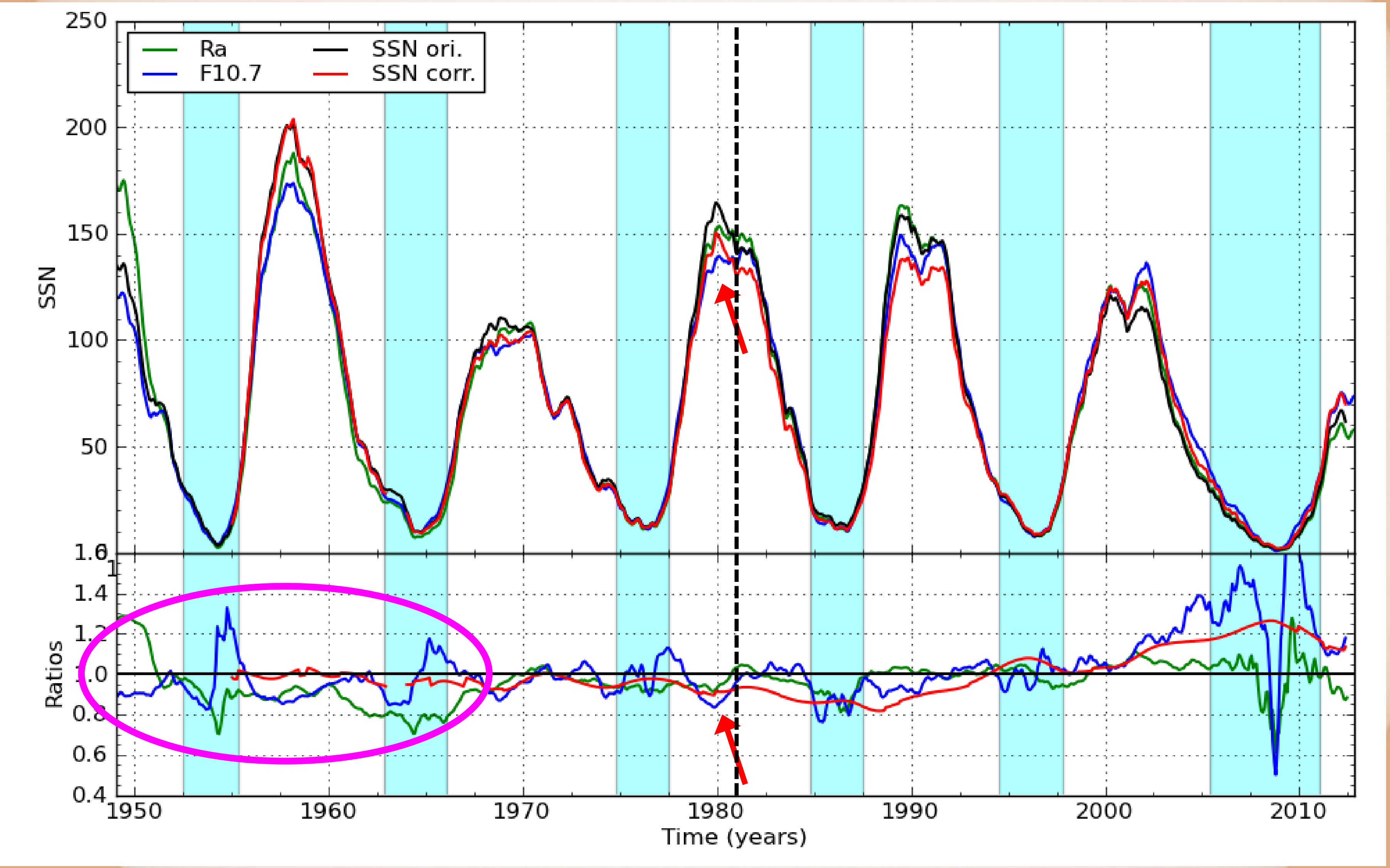
LO scaling variations: new questions

- Tentative interpretation of LO trends:
  - Before 1980, LO was tied to its reference, Zürich *(How?)*
  - After 1980, LO lost its earlier reference and suffered from drifts.
  - Possible factors: 3 phases:
    - **1980- 1987** (cycle 21-22 minimum): tendency to overcount
    - **1987- 2008**: slow linear degradation of count (Cortesi's eyesight ? Local seeing conditions? Instrument ageing?)
    - **2008 – 2012**: "restoration" of initial scaling (Cagnotti's effect?)
  - Solar cycle modulation:
    - **Second-order effect of the sunspot weighting ?**
- ➡ New diagnostics for the Locarno team:
  - Guided by the sign of trends and specific dates

A rescaled SSN versus other indices

- **SSN multiplied by the average k profile**: good approximation of the SSN produced using the network average as composite pilot station *(cf. L. Wauters' analysis)*
- **Relative k variations only**:
  - No full absolute scaling available yet
  - Current scaling: scaled to LO over 1987-1995
  - Probably within 5 % of final scaling (still significant!)
- Two main indices over last 60 years: R_A and $F_{10.7cm}$
- Smoothing of indices: 13-month tapered "boxcar"
- $F_{10.7}$ proxy for R_i:
  - Exponential formula R2 *(Johnson 2011)*
  - Modified base minimum flux 68.5 sfu instead of 66.5 sfu *(cf. L. Lefèvre)*

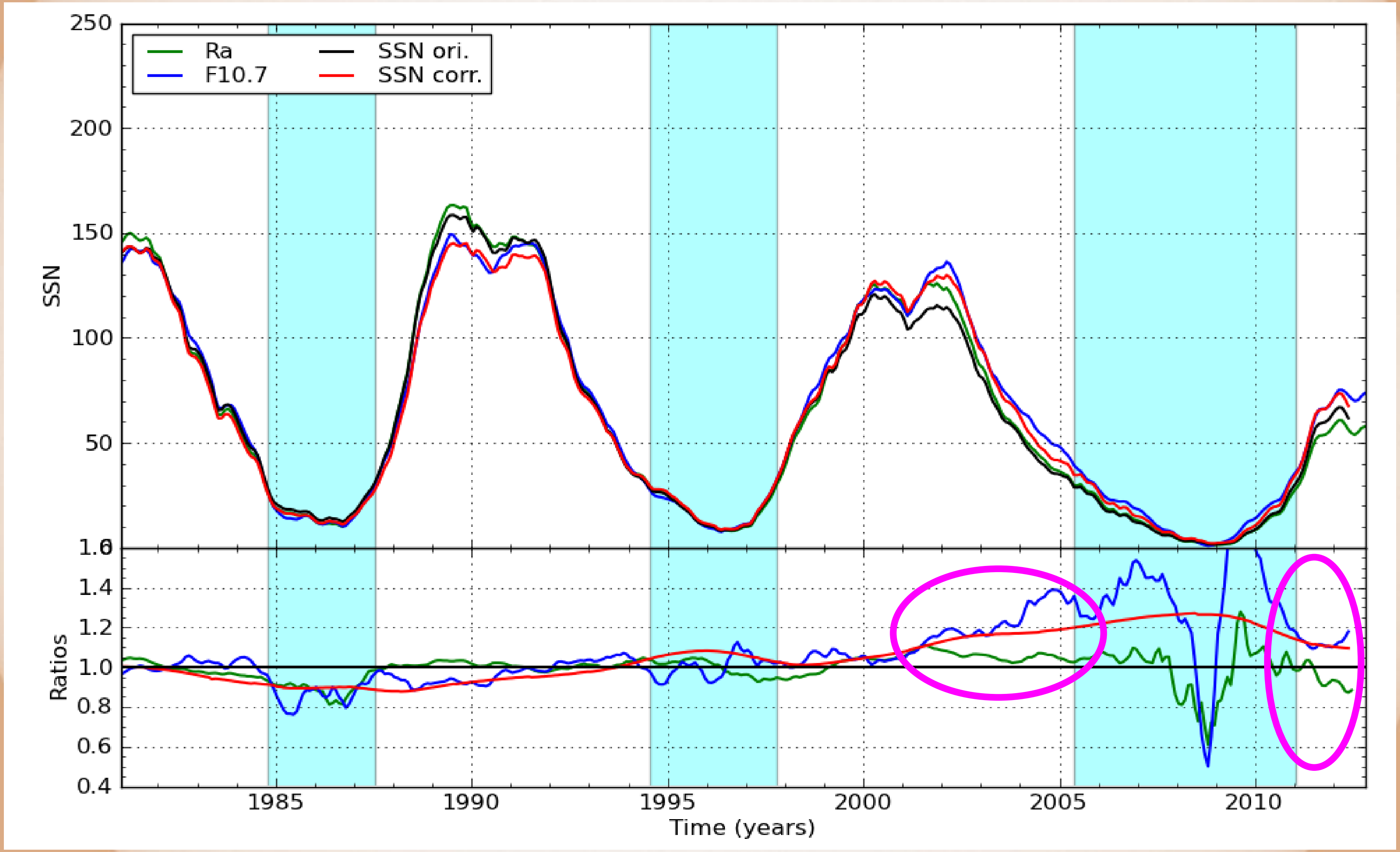
Comparison and ratios for 1949-2012



The Zürich period

- Before 1980:
  - $F_{10.7}$ less accurate before 1962
  - R_A unreliable before 1968 *(cf. Shapley 1949, Hossfield 2002)*
  - All indices very consistent during cycle 20
  - The corrected SSN remains very close to the original R_Z
- Around 1980-81:
  - A divergence of the corrected SSN may start already in 1977.
  - The corrected SSN is consistent with R_A
  - Only anomaly: **the first peak of cycle 21 is missed only by $F_{10.7}$.**

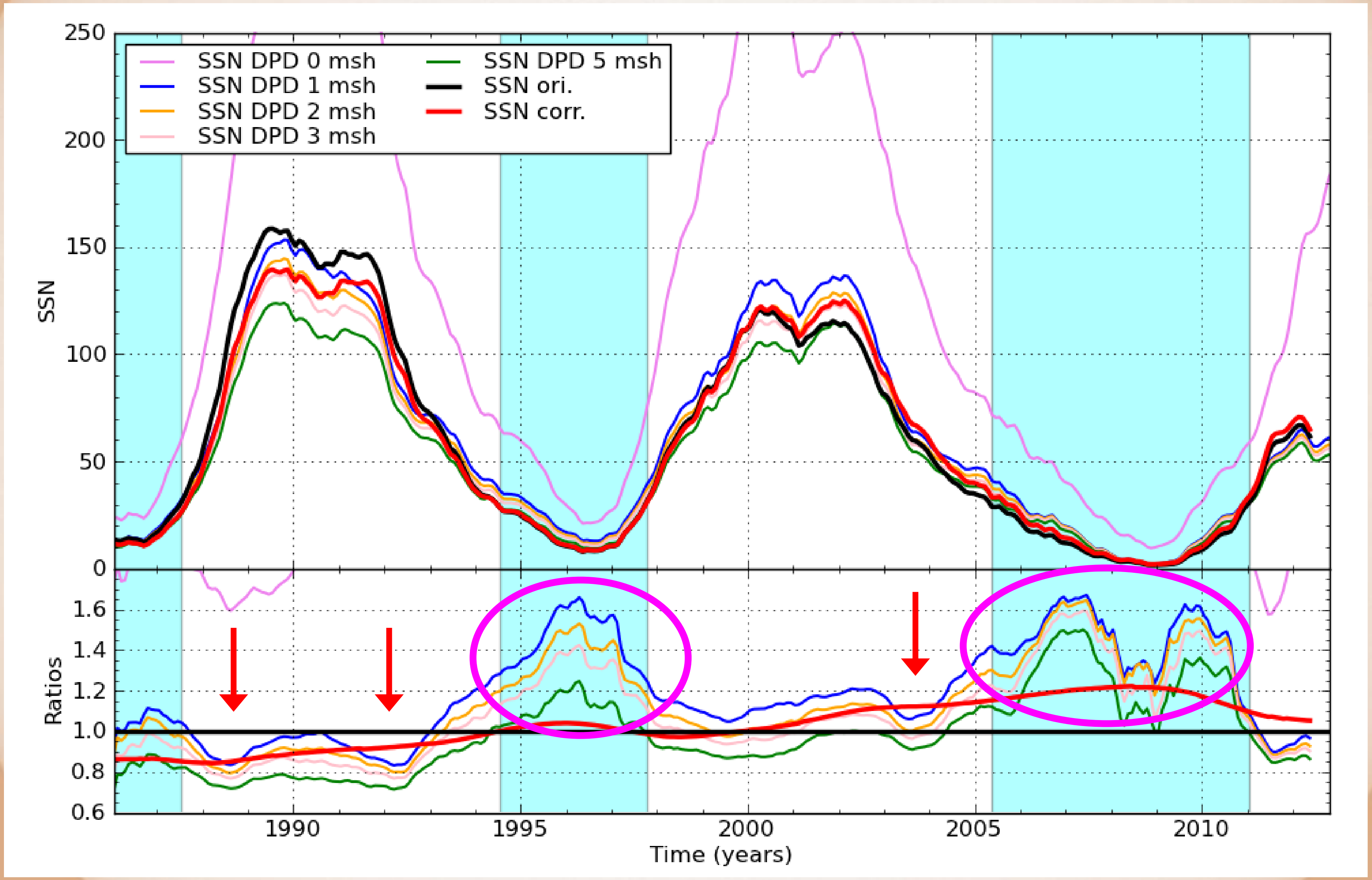
Comparison and ratios for 1981-2012



The SIDC-SILSO period: main changes in SSN

- Lower maximum for cycle 22
- Higher SSN in the second half of cycle 23 and in early cycle 24
- In cycle 22 and 23, the second peak of each maximum is raised: equal or higher than first peak
  - Better match with $F_{10.7}$
- Only minor changes in the minima

Comparison with the DPD SSN



The SIDC-SILSO period: $F_{10.7}$ and R_{DPD}

- The corrected SSN tracks much better the $F_{10.7}$ flux over the interval 1981-2001
- Over cycle 23, only part of the R_i - $F_{10.7}$ divergence is compensated by the corrected SSN

➡ The cycle 23 disagreement is reduced but cannot be explained solely by a LO drift.

- The corrected SSN and $F_{10.7}$ match again in cycle 24
- The corrected SSN tracks better the R_{DPD} SSN over the entire 1981-2012 interval:
  – Best match with the 1 or 2 msh threshold for the smallest observed spots *(~3 arcsec seeing)*

The SIDC-SILSO period: R_A , a special case

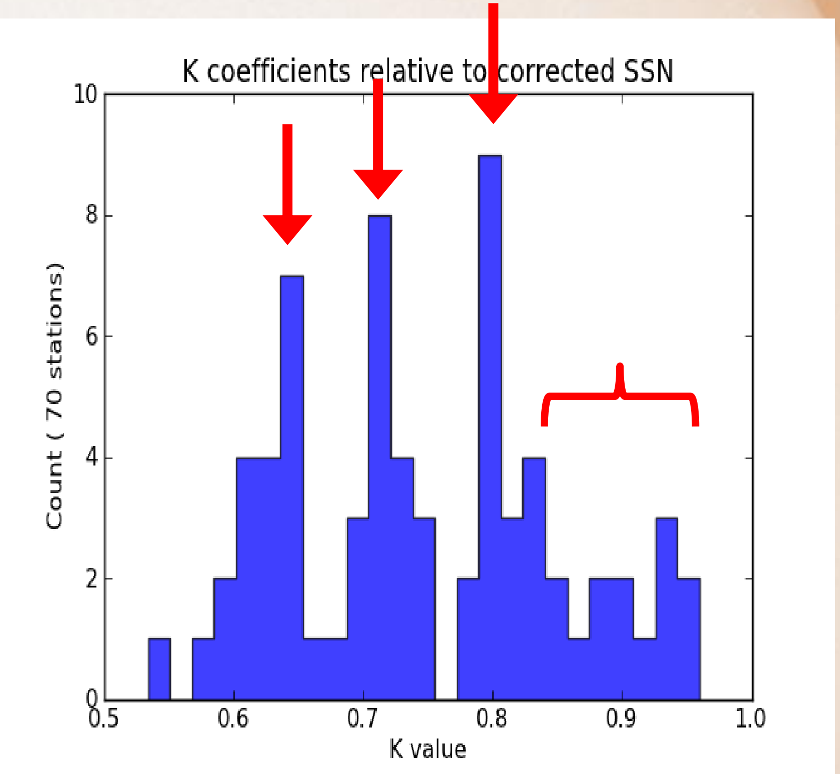
- Between 1987 and 2010, R_A matches better the original uncorrected SSN:
  - Requires further investigation:

    Was there any tuning according to R_i ?
- **Anomaly since last minimum (2008):**

  R_A is lower than all other indices (>10%):
  - Continuous downward trend
  - Larger 20% underestimate relative to the corrected SSN
  - **Must be investigated !** *(can probably be corrected if needed)*

Distribution of “true” k coefficients

- Most SILSO stations scale proportionally to the corrected SSN: k constant over 1981-2012
- k coefficients are more meaningful than the original k relative to LO:
  – “smeared” by LO scaling drift
- **Multimodal distribution: 3 peaks**
  – 0.62: the Wolf scale
  – 0.71 and 0.80: ?
  – 0.8 to 0.95 tail: counts similar to LO (but without sunspot weighting !)
  – All k < 1: none can reach the high LO values
- *NB: The histogram remains the same for any subset of station (sorting by station quality)*
  → *Single peaks do not correspond to good, fair or bad stations.*



- Calls for further investigation: study of common characteristics of stations belonging to each peak (telescope aperture?)

Conclusions: key progresses

- New modern and documented software
- New products and identity: SILSO !
- **First self-consistent determination of scaling variations in the SSN** (without external references)
- **Robust determination of a drift in the Locarno pilot station**
  - 10% solar-cycle modulation: measure of the sunspot weighting effect (vs 15-20%, *Svalgaard 2012*)
- **Significant impact on the correlation between the SSN and other indices**:
  - Cycle 22 & 23 amplitude corrections of 10% or more
  - Better overall agreement with $F_{10.7}$ and the DPD SSN
  - Improvement versus R_A is not systematic
- **Demonstration of the potential of the large SILSO network**:
  - diagnostic tool + correction tool
  - made possible by the cumulative contribution of many “citizen scientists” *(cf. “Galactic Zoo” project by Lintott et al. 2008, Yale Univ.)*
- **All base data available** ➡ **entirely recalculating R_i is possible !**

A key choice: the “reference station”

1. **Locarno after correction:**
   – Requires the full understanding of the causes
2. **Another single pilot station** (UC?):
   – Same risk of an accidental drift
   – Simpler to trace and correct problems if they arise
3. **A composite of several reliable stations**:
   – Better mutual drift control
   – More complex interpretation
   – Higher requirement: multiple permanent dedicated stations
4. **Hybrid solution**: single pilot station + a subset of monitoring stations
   – Keeps the base index calculation simple
   – Checked against the average of the best stations

Next actions: collecting targeted information

- **Involving Locarno** in the understanding of the drift
- **Individual contacts** with different key stations presenting clear defects (Mitaka, Ebro, Kanzelhöhe, etc.):
  - Targeted investigation of past changes
  - ➡ Possible total or partial restoration of time series entirely excluded in the current analysis.
- Searching for the **original Zürich group and spot counts** (1940-1980)
- Individual **feedback to observers** about their bad or good (!) performance:
  - Improving interactivity
  - Highlights in Sunspot Bulletin

Next actions: deriving a correction

- Understanding **the multi-peaked distribution of the new k** coefficients
- Establishing the **absolute scale of the average network k**
- Determining the **optimal smoothing for the average network k** (Fourier analysis)
- Evaluating the **effects of alternate options in the SSN calculation**
- Producing a **new corrected R_i series from 1981** onwards:
  - Internal "private" release for the SSN workshop community
  - Official release with all other corrections of the SSN series ?
  - Exploit the new knowledge of the diagnosed biases to the pre-1980 R_Z series ?

Thank you

CA Catania (IT)
DU Dubois (BE)
EB Ebro (SP)
FU Fujimori (JP)
GE Gerard (BE)
GU Guillery (FR)
HE Helwan (EG)
HP Presov (SK)

HV Kysucke (SK)
KA Kawagushi (JP)
KH Kandilli (TK)
KO Konkoly (H)
KS Kislovodsk (RU)
KZ Kanzelhöhe (A)
LO Locarno (SW)
MT Mitaka (JP)

NY Nijmegen (NL)
PY Pyong Yang (NK)
QU Quezon (PH)
SG Cochabamba (BO)
SO Sobota (SK)
SZ Suzuki (JP)
UC Uccle (BE)