Об оценках трендов экстремальных и суб-экстремальных температур в свободной атмосфере методом квантильной регрессии

On the long period trend estimates for the upper-air extreme and sub-extreme temperatures by use of quantile regression

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Climate change:
not only changes in average state are crucial!

- **Among the most essential manifestations of climate change and global warming processes, of especial interest are:**
  - **changes in climate extremes and sub-extremes,**
  - **long period changes in climate variability,**
  - **and changes in frequency and intensity of natural hazards related to meteorology and climate.**
- **All these issues are of growing interest to various categories of customers because of their essential and possibly severe negative societal, economic, and ecological impacts**

More detailed study of the climate trends is needed

- **The traditional studies of climate trends are most often based on estimation of climate trends in average values of climate variables (such as monthly or seasonal average values of temperature, air pressure, precipitation, wind speed, etc.).**
- **For traditional studies, OLS (Ordinary Least Squares) Regression is used in most cases**
- **OLS estimates:**
  - do not provide detailed information on changes in distributions, rather than in average values only,
  - are not sufficient to answer the questions about changes in distribution's left and right "tails", in extremes and near extreme values, as well as in measures of variability.
- **To provide effective climate services, a more detailed study of evolutional changes in whole distributions of climate variables is needed!**

Problems of OLS regression in climate series study

- Violation of homoscedasticity in climatological time series:

$$y_i = x_i \beta + \varepsilon_i$$

$$\varepsilon : E(\varepsilon) = 0, \\ E(\varepsilon' \varepsilon) = \sigma^2 I$$

  - What to do?
    - Use statistical tests to detect heteroscedasticity
    - Use non-parametric techniques
    - Study, if the high frequency variability is really changing in interdecadal scale – heteroscedasticity is the reality of climate time series!

Answer by Quantile Regression

- First introduced in 1978: *Koenker, R., Bassett, G., "Regression quantiles," Econometrica, 46 (1978), 33-50*
- Used mainly in demography, other social sciences, in econometry, in biometry, etc.
- Is provided by several contemporary software product, including SAS, STATA commercial software By Python libraries and by R-project FREE software
- Very few publications on environmental sciences*
- Very few usage in Russia
- Provides regression of any quantile of Y between 0 and 1, while OLS presumes regression only of average of Y's
- Quantile Regression estimates are robust, the results are less sensitive to outliers in Y than OLS estimates
- Quantile regression adds one more dimension to those existing in trends analysis (horizontal, vertical trend distribution, length of series, etc). This is quantile value, which expands between 0 and 1.
- This enables to see the detailed structure of climate trends, unlike OLS instrument for trend analysis (OLS provides "generalized" trend, details of trend are hidden by OLS)

Some notes on Quantile Regression approach

Quantile Regression:

$$F(y) = \text{Prob}\,(Y \le y)$$

$$Q(\tau) = \inf\{y : F(y) \ge \tau\}$$

$$0 < \tau < 1$$

$$\hat{\xi} = \arg\min_{\xi \in R}\Big[\sum_{i: y_i \ge \xi} \tau\,|y_i - \xi| + \sum_{i: y_i < \xi} (1-\tau)\,|y_i - \xi|\Big]$$

$$\min_{\xi \in R} \sum^{n} |y_i - \xi|$$

$$\min_{\beta \in R^p}\Big[\sum_{i \in \{i: y_i \ge x_i'\beta\}} \tau |y_i - x_i'\beta| + \sum_{i \in \{i: y_i < x_i'\beta\}} (1-\tau)|y_i - x_i'\beta|\Big]$$

Can be solved as LP simplex optimization problem

OLS Regression:

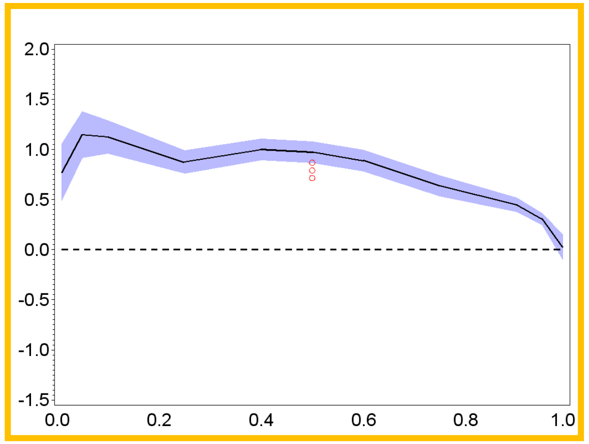
$$\hat{\mu} = \text{argmin}_{\mu \in R} \sum_{i=1}^{n} (y_i - \mu)^2$$

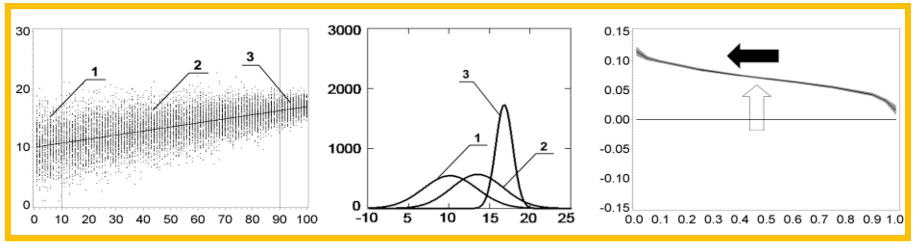
$$E(Y|X = x) = x'\beta$$

$$\hat{\beta} = \text{argmin}_{\beta \in R^p} \sum_{i=1}^{n} (y_i - x_i'\beta)^2$$

Can be solved analytically

The dependency of Predictant Y (depended variable) in our case - trend values, on quantile values is called **PROCESS DIAGRAM**





Our previous experience in QR for climatology

- **We have certain experience in application of QR to climatology:**
  - **A. Timofeev and A. M. Sterin, Using the Quantile Regression Method to Analyze Changes in Climate Characteristics, Meteorol. Gidrol., No. 5 (2010) [Russ. Meteorol. Hydrol., No. 5, 35 (2010)].**
  - **M. Sterin and A. A. Timofeev. Estimation of Surface Air Temperature Trends in Russia Using the Quantile Regression Method. ISSN 1068-3739, Russian Meteorology and Hydrology, 2016, Vol. 41, No. 6, pp. 388–397. Allerton Press, Inc., 2016.Original Russian Text A.M. Sterin, A.A. Timofeev, 2016, published in Meteorologiya i Gidrologiya, 2016, No. 6, pp. 17–30**
- **Our previous studies of QR trends in extremes and sub-extremes are related to surface meteorological variables, namely, they are concentrated on extremes and sub-extremes of surface air temperature. At the same time, it is essential to make similar QR-based studies of the trends for upper-air temperature.**

Quantile Regression (QR) for trend analysis of Upper-air data

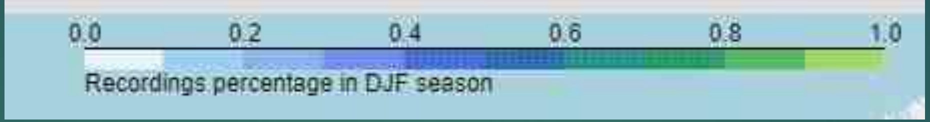
- **Objectives:**
- **What are QR-based features of more detailed structure of climate trends (vertical-quantile sections!)?**
- **Are the radiosonde data sufficient for robust and reliable estimates of climate trends by QR?**
  - **Amount of Data**
  - **Quality of Data**
- **Do QR results support our understanding of such processes as: of evident(?) tropospheric warming and of evident(!) lower stratospheric cooling ?**
- **What details+ can be resulting from QR?**
- **What are the geographical and seasonal patterns of QR trends in the free atmosphere (if any discovered)?**

Quantile Regression (QR) for trend analysis of Upper-air data

- **Input Data:**
- **Data of AEROSTAS data set on temperature (once daily observations for 0 UTC) on the standard pressure levels (up to 30 hPa) primarily from 900+ radiosonde stations over the Globe**
- **Period:**
  - **1979 -2018 for Russian stations**
  - **1984 -2018 for non-Russian stations**
- **Data operations:**
  - **Complex Quality check (flagging values)**
  - **Selection of stations that provide two conditions:**
    - **Condition 1. For a certain year and selected station - amount of correct values of temperature (flagged by 1) at 50 hPa level for a winter season DJF is >=40 (of 90 values max possible)**
    - **Condition 2. For a certain station – amount of years that meet Condition 1, is not less than 30**
  - **The amount of station over the Globe that meet Conditions 1 and 2, is 363. These stations were selected eventually for the calculations and analysis!**

Quantile Regression (QR) for trend analysis of Upper-air data

Spatial distribution of stations meeting criteria, for DJF:

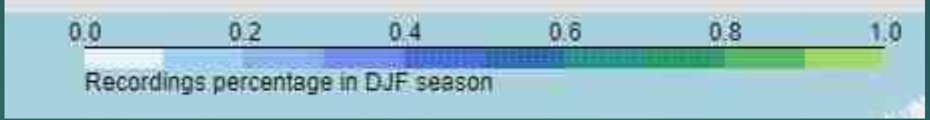


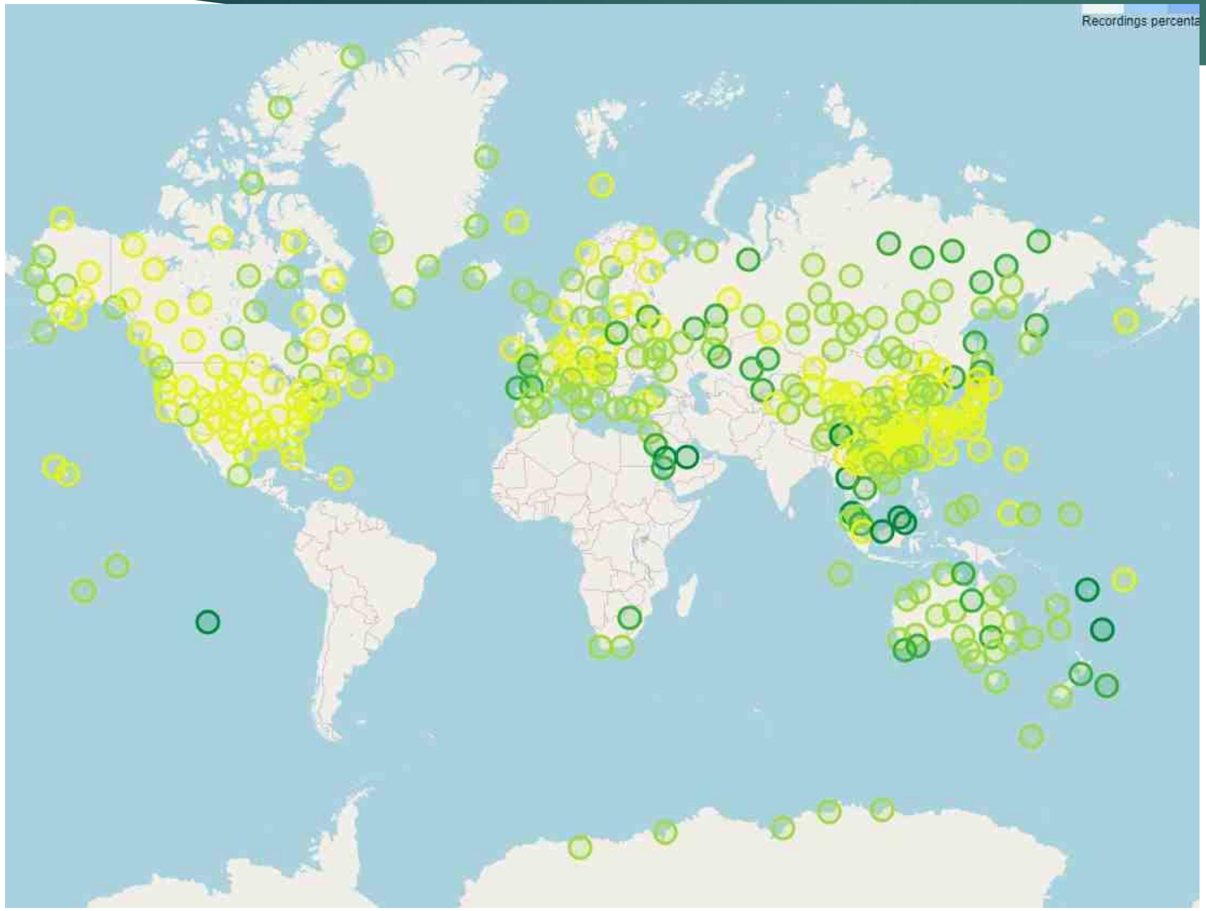
850 hPa

500 hPa

Quantile Regression (QR) for trend analysis of Upper-air data

Spatial distribution of stations meeting criteria, for DJF:



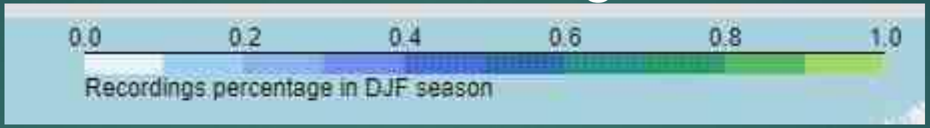


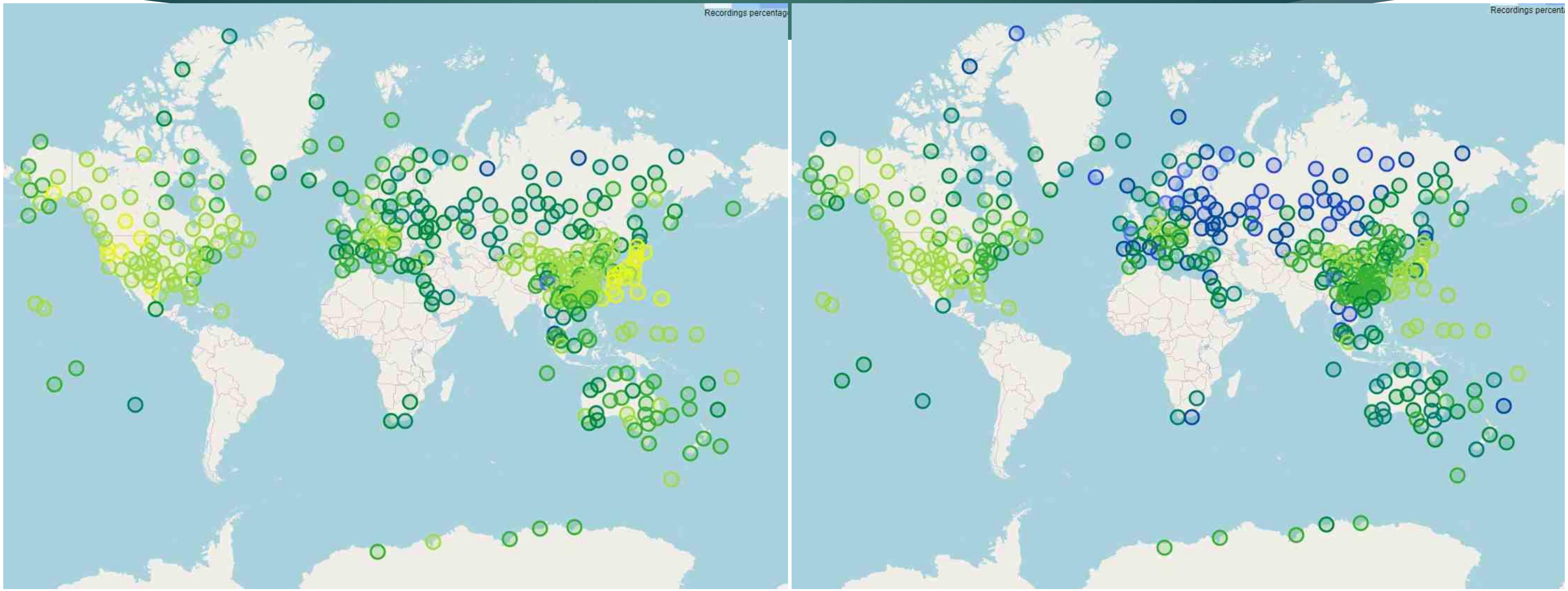
200 hPa

100 hPa

Quantile Regression (QR) for trend analysis of Upper-air data

Spatial distribution of stations meeting criteria, for DJF:





50 hPa

30 hPa

Quantile Regression (QR) for trend analysis of Upper-air data

- **Calculations of QR trends in temperature for each value of quantile τ for a set of quantile values between 0.0 and 1.0**

- **To be more correct, QR calculations were for quantile τ values 0.05 to 0.95 by 0.01 (Very dense scale (!), but it is needed for better visualization!)**
- **In the QR calculations, the optimization problem was solved by the simplex method.**

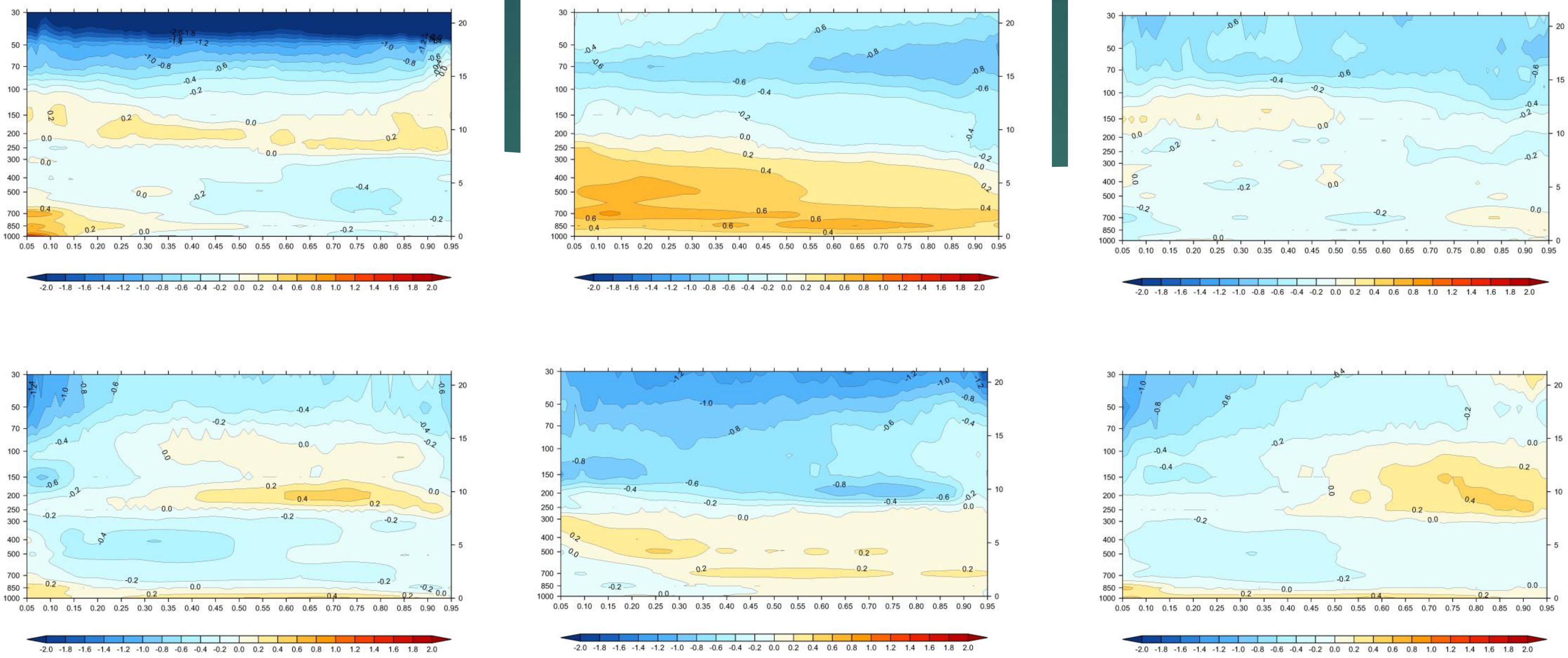
- **The estimates of confidence intervals were calculated by resampling using bootstrap with 200 iterations. The confidence level was selected as 0.05.**

Quantile Regression (QR) for trend analysis of Upper-air data

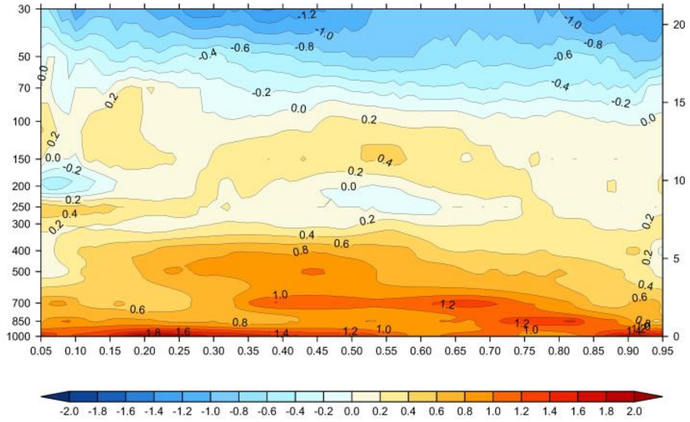
- **Further analysis for each of the selected stations and for each of the four seasons (DJF, MAM, JJA and SON)**
- **Visualizations:**
  - **Process diagrams for selected pressure levels**
  - **Quantile-Vertical sections of trends for each station (X axis – values of τ, Y axis – values of pressure)**

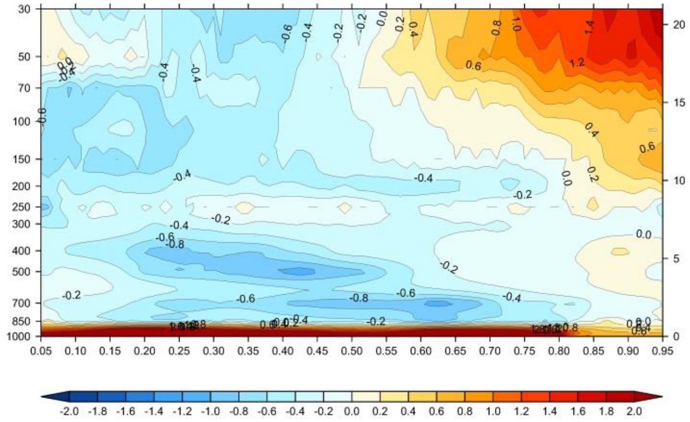
  In visualizations, the trend value units in the process-diagrams are deg.C/ year, and in Quantile-Vertical sections they are deg.C/decade
- **Selected stations over the Globe are grouped by LAT-LONG sectors**
- **Assessment of results (at this paper for northern polar and temperate latitudes)**

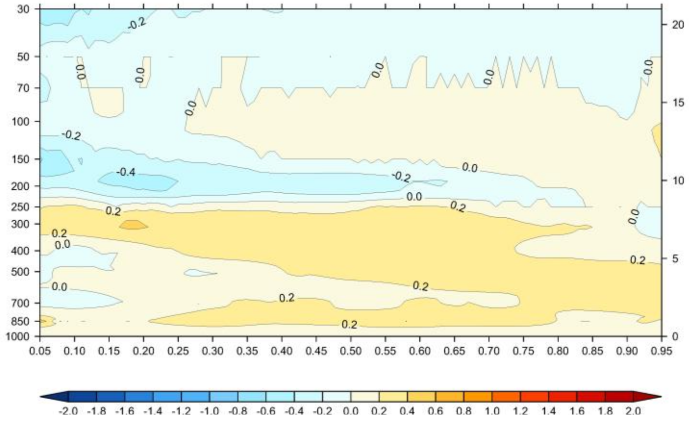
20 N – 60 N 15 W- 60 E DJF

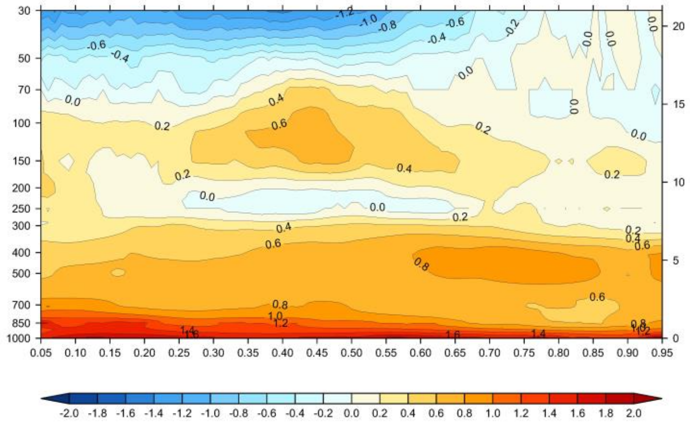


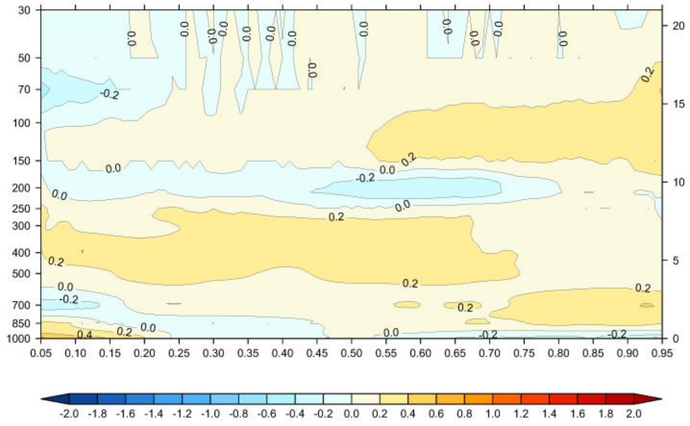
20 N – 60 N 15 W- 170 W DJF

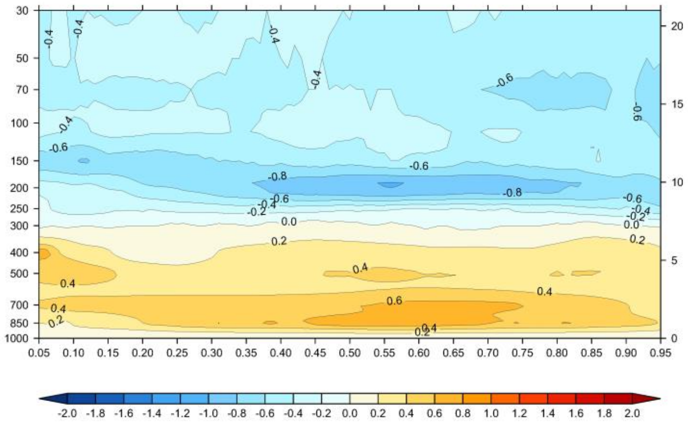




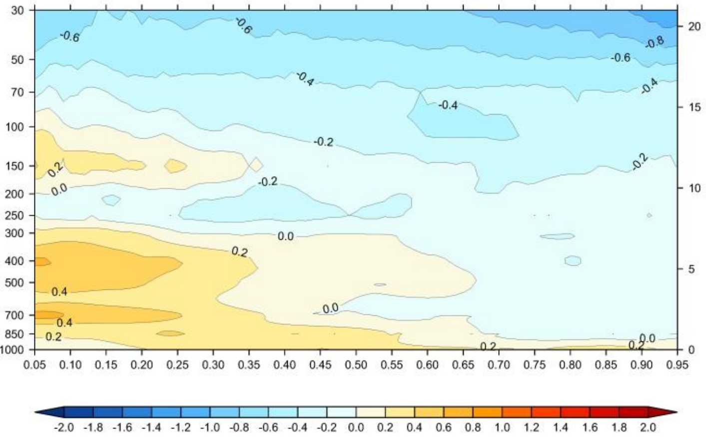


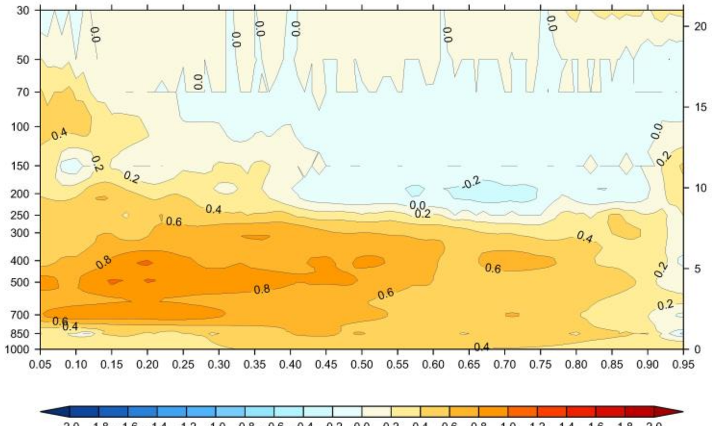


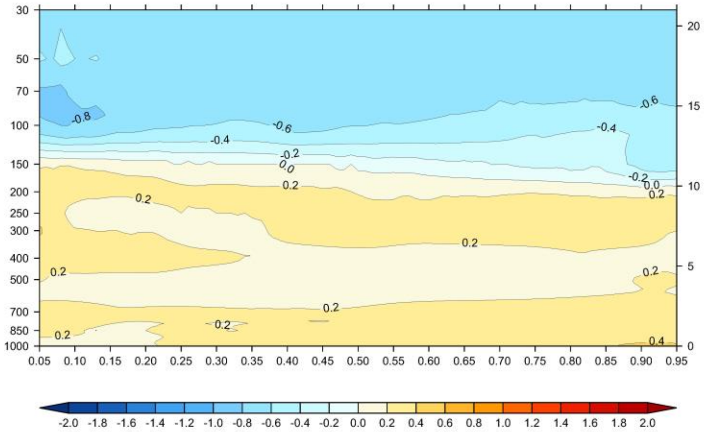


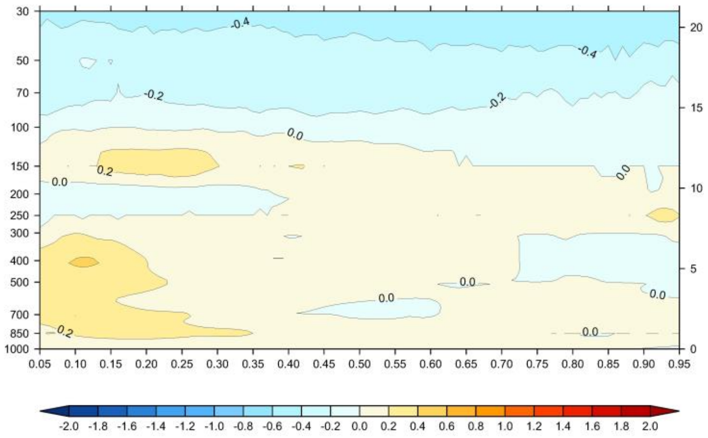


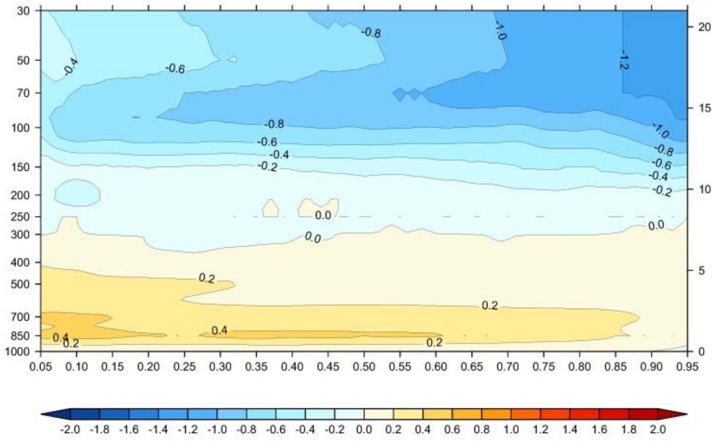
20 N – 60 N 15 W- 170 W JJA

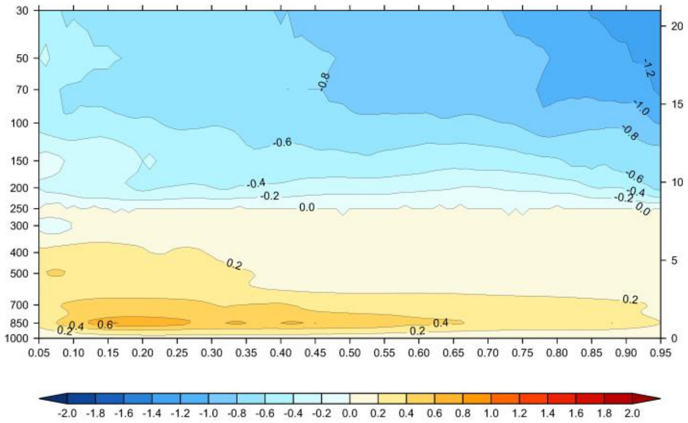




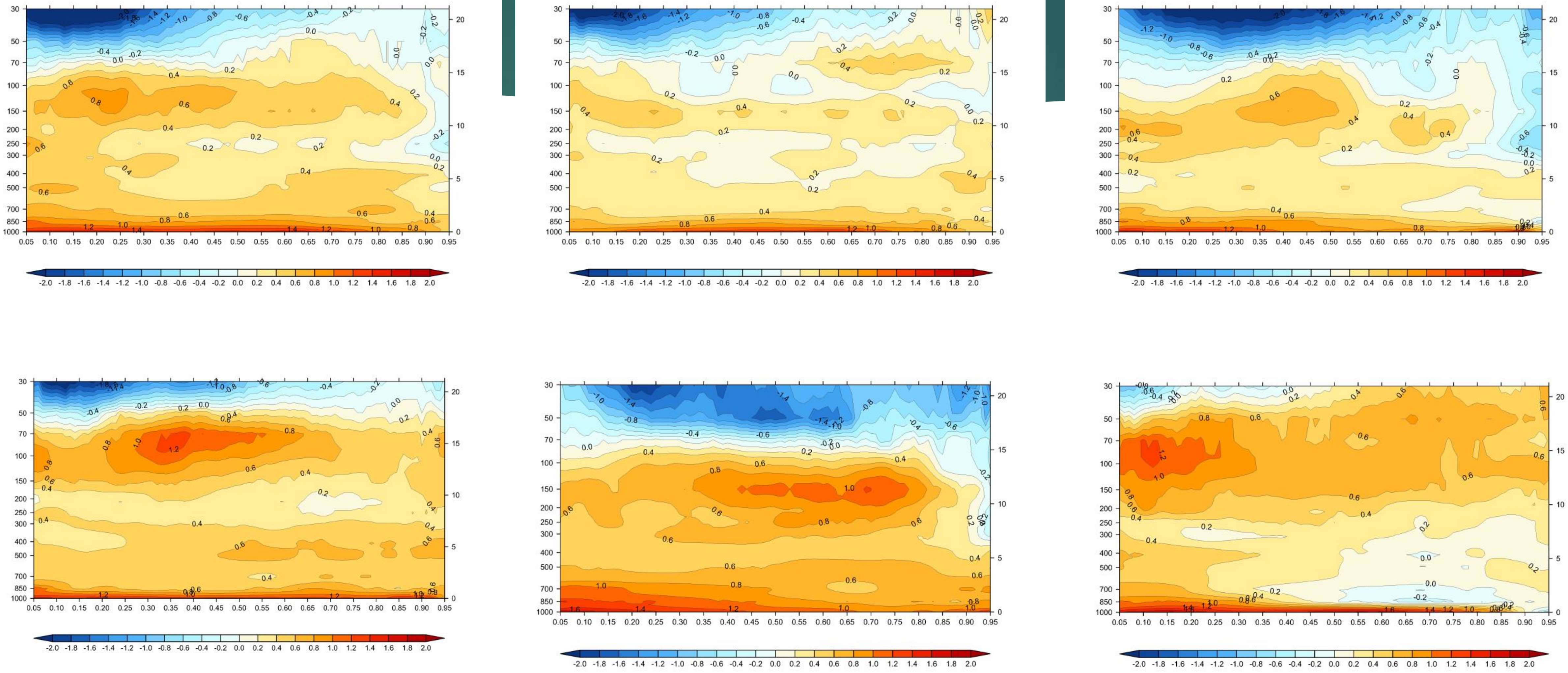




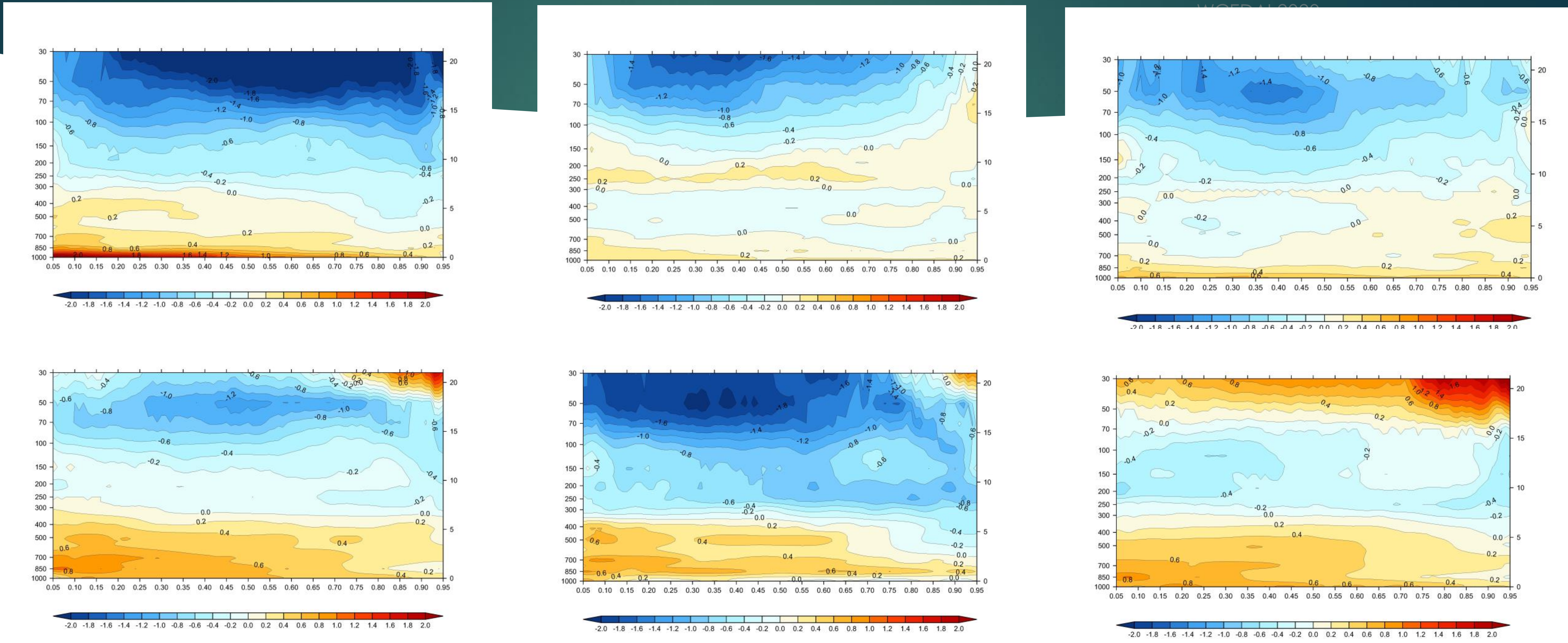




60 N – 90 N 15 W- 170 W DJF

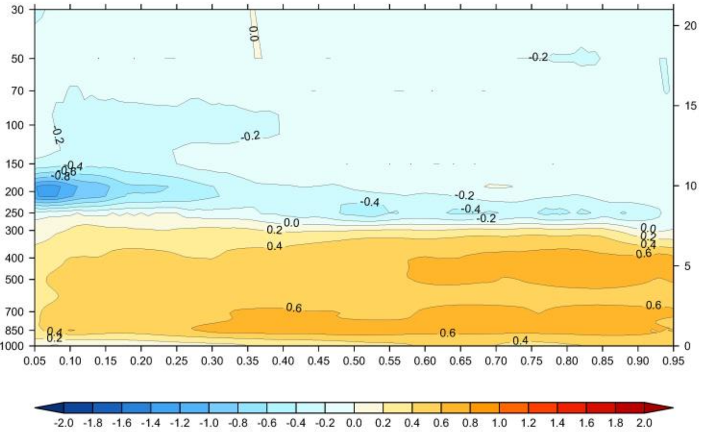


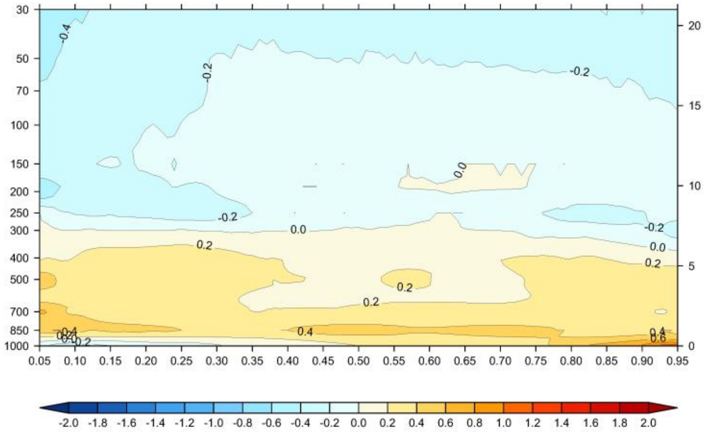
60 N – 90 N 15 W- 60 E   DJF

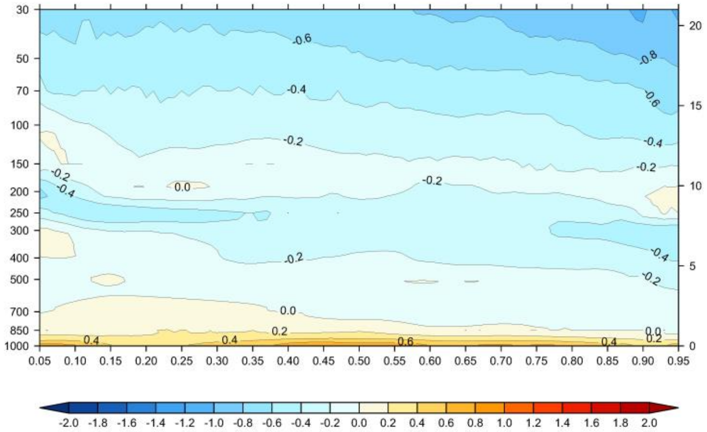


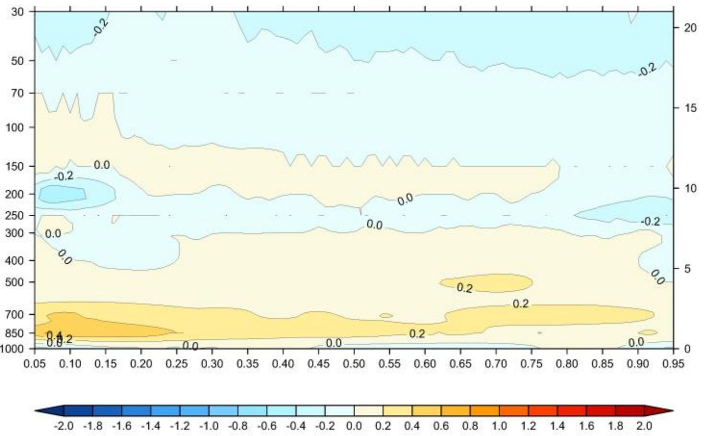
Features: is it enough convincing to attribute to increasing SSW frequencies and amplitudes?

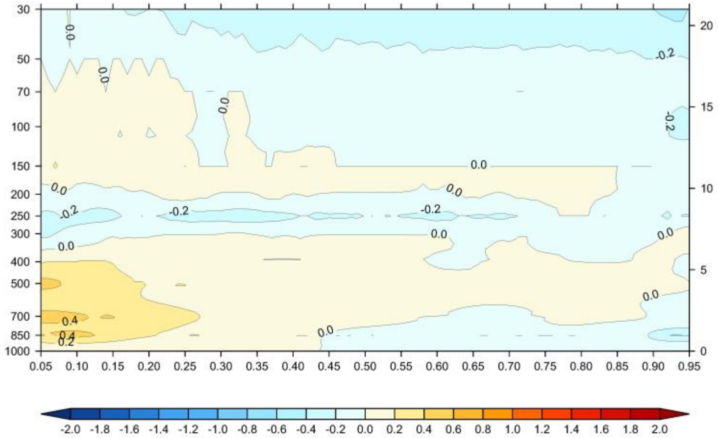
60 N – 90 N 15 W- 170 W JJA

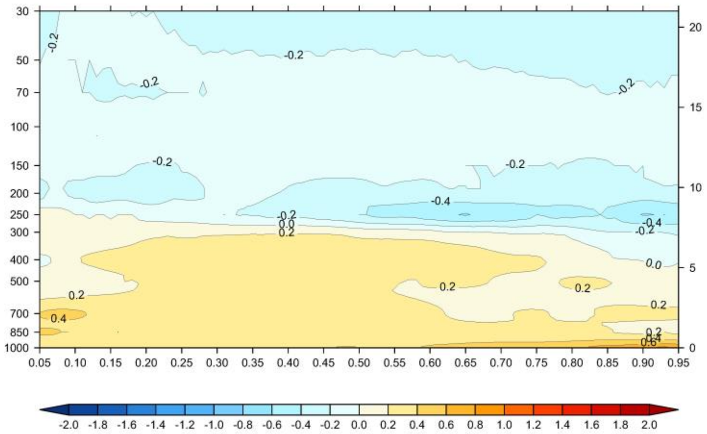






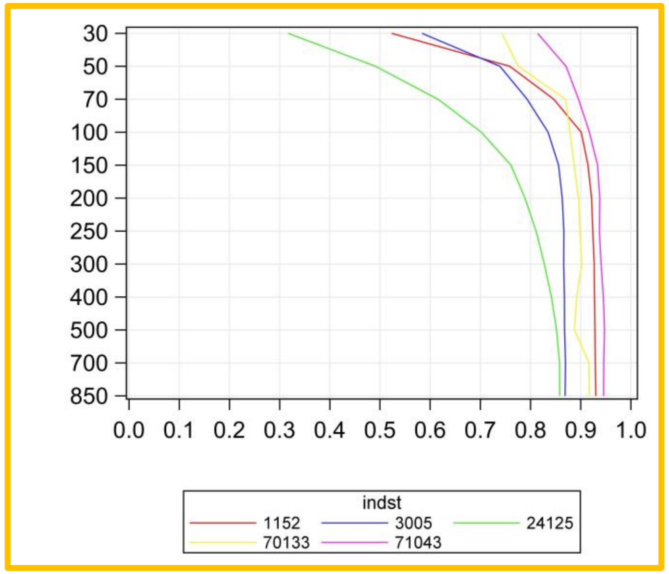






Case study – comparing quantile-vertical sections - for 5 northern stations, winter (DJF)

- The unequal amount of observations along vertical profile - does matter!



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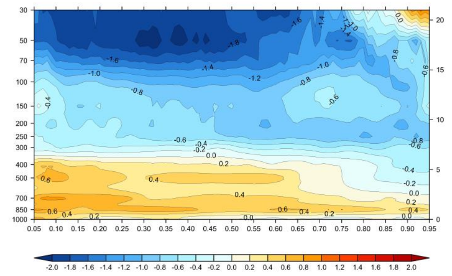

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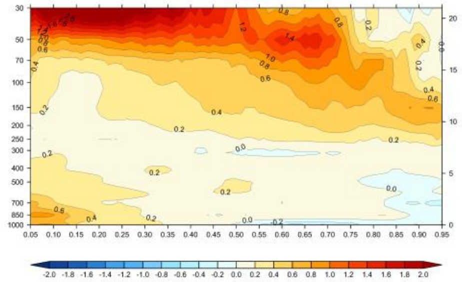

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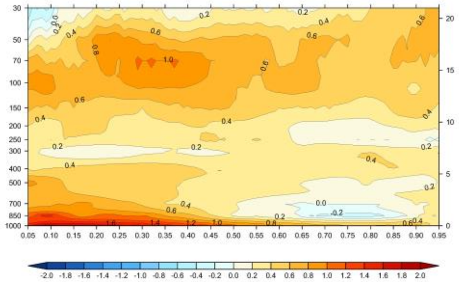

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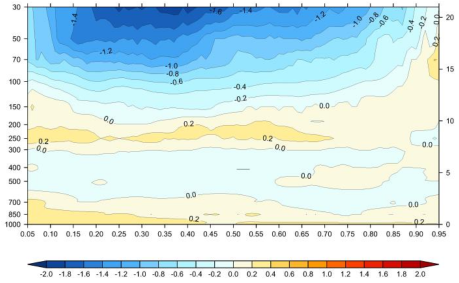

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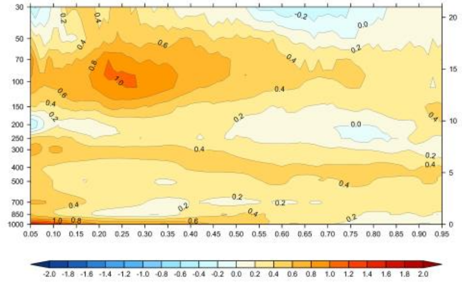


1152 : Bodo Vi : 67.3 14.4 : Norway
3005 : Lerwick : 60.1 -1.2 : United Kingdom
24125 : Olenek: 68.5 112.4 :Russia
70133 : Kotzebue Wien Memorial airport : 66.9 -162.6 : United States
71043 : Norman Wells N. W. t. : 65.3 -126.8 : Canada

Some concluding notes - troposphere

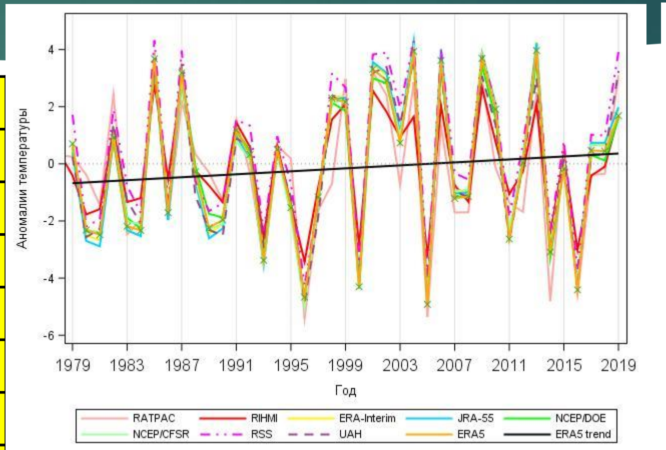
- **For UA radiosonde data, the application of Quantile Regression technique helps to extend the understanding of detailed patterns of temperature climate trends.**
- **Tropospheric warming is one of the features that could be outlined.**
- **Like the surface temperature QR trends, the tropospheric temperature QR**

  trends are positive, and they are larger for small values of quantile τ (closer to 0.0) than for large quantile values (close to 1.0)
- **This is valid, at least, for winter seasons for troposphere in northern polar and northern temperate latitudes:**
- **The coolest temperatures ("left tail" of distributions) are increasing more rapidly, than the warmest ("right tail" of distributions).**

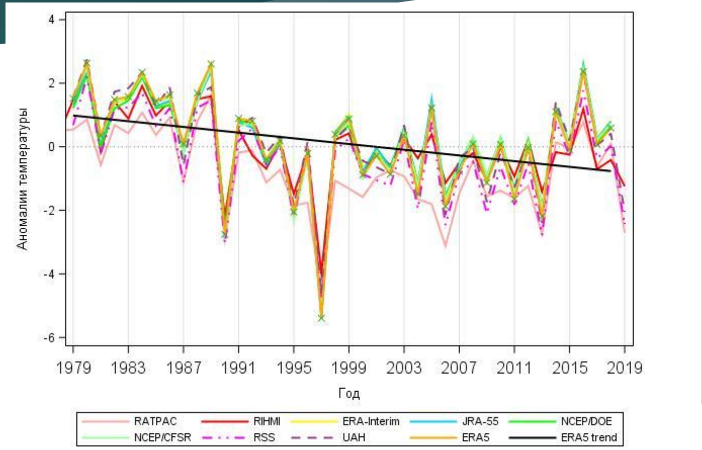
Lower Stratosphere, 60N-90N. Period 1979-2018

OLS trends for seasons and for the year

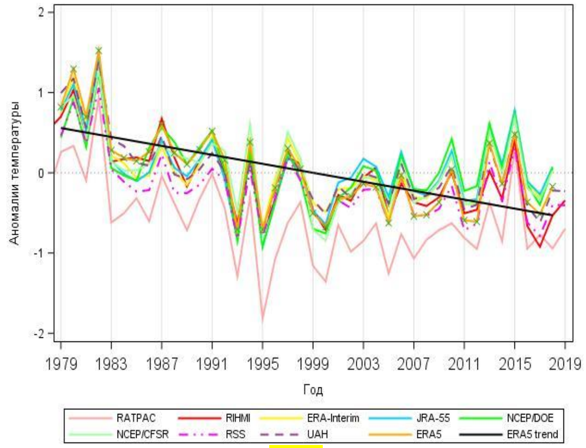
	DJF	MAM	JJA	SON	YEAR
RATPAC	-0.21±0.32	-0.37±0.17	-0.20±0.06	-0.15±0.07	-0.24±0.10
RIHMI	0.04±0.24	-0.43±0.15	-0.27±0.05	-0.23±0.05	-0.23±0.07
Era-Interim	0.41±0.34	-0.32±0.21	-0.15±0.06	-0.08±0.07	-0.04±0.09
ERA5	0.26±0.34	-0.45±0.21	-0.27±0.06	-0.23±0.07	-0.18±0.10
JRA-55	0.44±0.35	-0.32±0.21	-0.12±0.06	-0.05±0.07	-0.02±0.11
NCEP/DOE	0.19±0.34	-0.32±0.20	-0.11±0.06	-0.25±0.07	-0.12±0.10
NCEP/CFSR	0.28±0.36	-0.36±0.21	-0.17±0.06	-0.12±0.07	-0.09±0.10
RSS	0.24±0.34	-0.42±0.20	-0.20±0.05	-0.19±0.07	-0.14±0.09
UAH	0.24±0.33	-0.45±0.20	-0.23±0.05	-0.25±0.07	-0.19±0.09



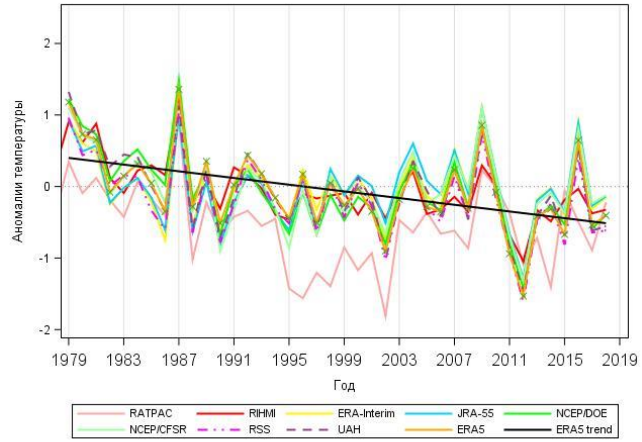
DJF



MAM

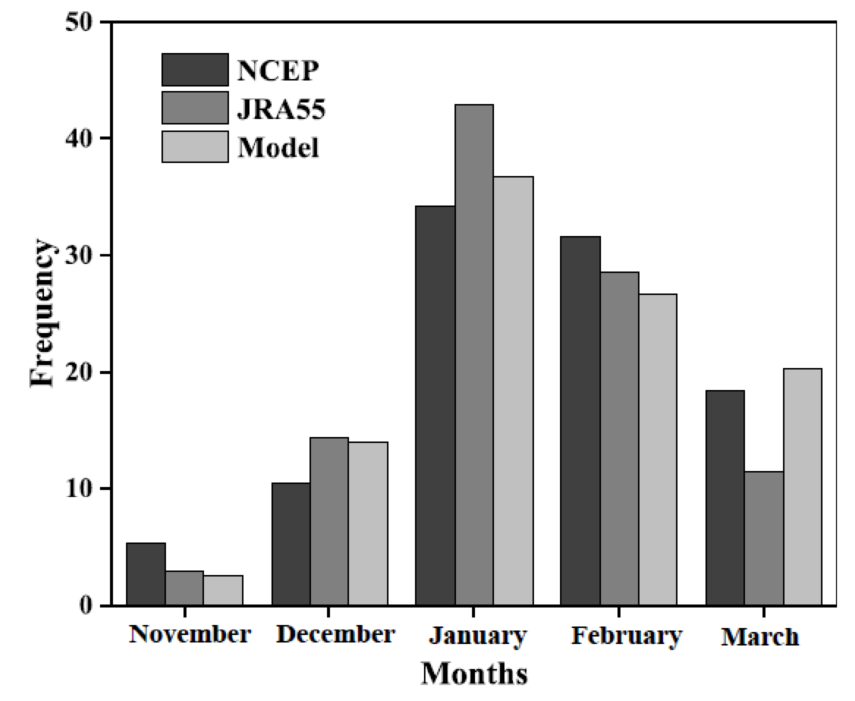


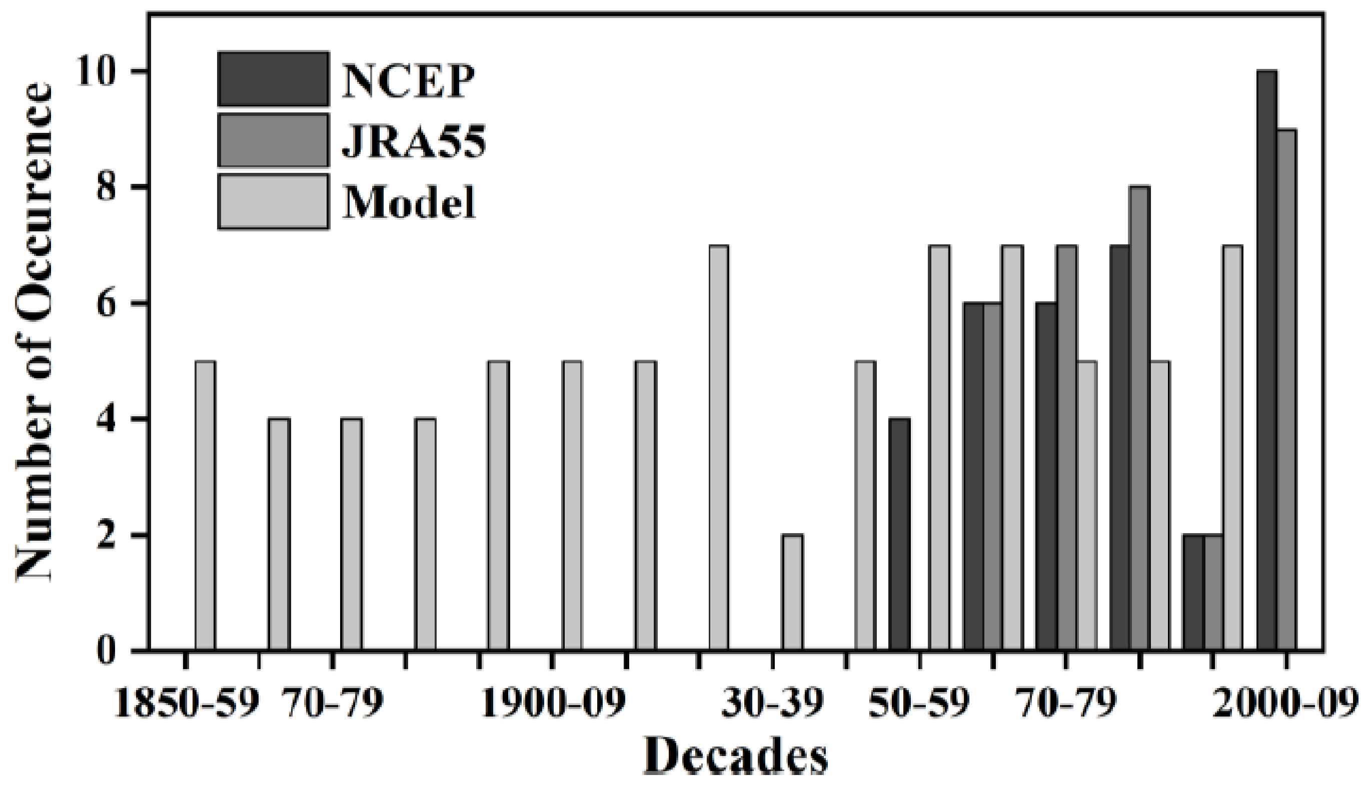
JJA



SON

SSW frequency and amplitudes changes: manifestation in QR T trends





Source: Can Cao et al. Statistical Characteristics ofMajor Sudden Stratospheric Warming Events in CESM1-WACCM: A Comparison with the JRA55 and NCEP/NCAR Reanalyses/ Atmosphere 2019, 10, 519; doi:10.3390/atmos10090519

Some concluding notes – lower stratosphere

- Lower stratosphere temperature for the northern stations:
  - OLS regression demonstrates that cooling for DJF is not reliably detected,
  - Based on most data sources, winter OLS trends are positive but not significant statistically
- Lower stratosphere temperature QR trends:
- Data quality and data amount can be considered as critical factor for the estimates of QR T trends, especially for the lower stratosphere T QR trends
- Insufficient amount of lower stratosphere data and differences between the data amount along the vertical profile can lead to artefacts and to physically unexplainable results
- WE saw several unexplainable results!
- Sudden Stratospheric Warming (SSW) is the physical factor that possibly could be the explanation of results: the frequency and amplitudes of SSW in winter months is increasing
- QR trends for the Upper Air Data is really a Big Data problem!

Thank you!

- **Questions?**
- **Comments?**