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Trends in the upper tropospheric humidity and ice saturation from HIRS satellite measurements in the period 1979-2020

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Major objectives:

- Creation of a long-term UTHi dataset based on satellite data to use them in climate studies.
- Analysis of Upper Tropospheric Humidity trends with respect to ice (UTHi), focusing in the mean values as well as in the upper tail of the data.

Data used:

- Brightness temperatures in multiple channels (Channels 6 and 12; T_6 and T_{12}) from the High-Resolution Infrared Radiation Sounder instrument (HIRS) onboard the NOAA and METOP satellites ($NOAA_{6,7,8,9,10,11,12,14,15,16,17}$ and $METOP_{02,01}$).
- Data are provided as points which are then gridded with a resolution of 2.5x2.5° between 60° S- 60°N .

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Approach used:

The retrieval of the UTHi is performed using a second-order equation developed by Gierens and Eleftheratos, 2019.

$$UTHi\% = \frac{\exp(a + b \times T_{12} + c \times T_{12}^2)}{a' + b' \times T_6}$$

where

T_6: Brightness temperature in channel 6

T_{12}: Brightness temperature in channel 12

a, b, c, a', b': Fit coefficients

a'	b'
0.236	-0.036

	λ (µm)	a	b (1/K)	c (1/K^2)
UTHi	6.7	47.69	-0.2846	3.522 ×10-4
	6.5	50.05	-0.3109	4.063×10-4
UTHw	6.7	43.36	-0.2619	3.266×10-4
	6.5	45.50	-0.2868	4.063×10-4

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Data/bias corrections:

- $T_{6:}$ Channel 6 is in the CO_2 absorption band, therefore T_6 data contains biases due to the increase of the [CO_2] according to Shi *et al.,* 2016. Therefore, T_6 values contain a negative trend that needs to be adjusted proportionally to the increase of the [CO_2].

- $T_{12:}$ The HIRS instrument was updated in 1999 (transition from version $HIRS_2$ to $HIRS_3$ accompanied by a wavelength change. Thus the instrument is sensing a different layer which created inconsistencies (bias of about 7 K) in the T_{12} dataset.
    - This bias is mainly corrected with the second-order retrieval algorithm.
    - Complete homogeneity is achieved with a further bias reduction applied in the numerator of the UTHi derivation algorithm.

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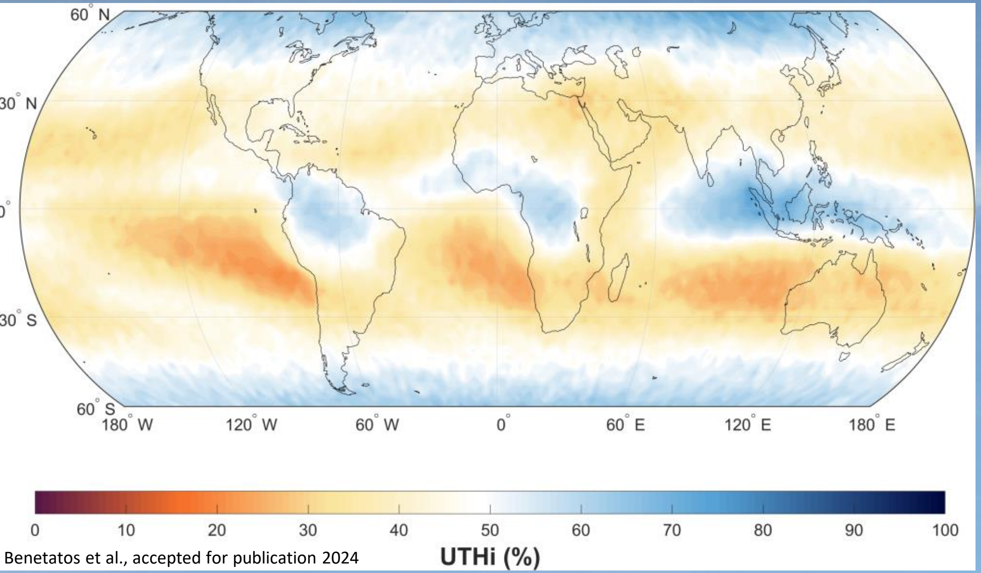
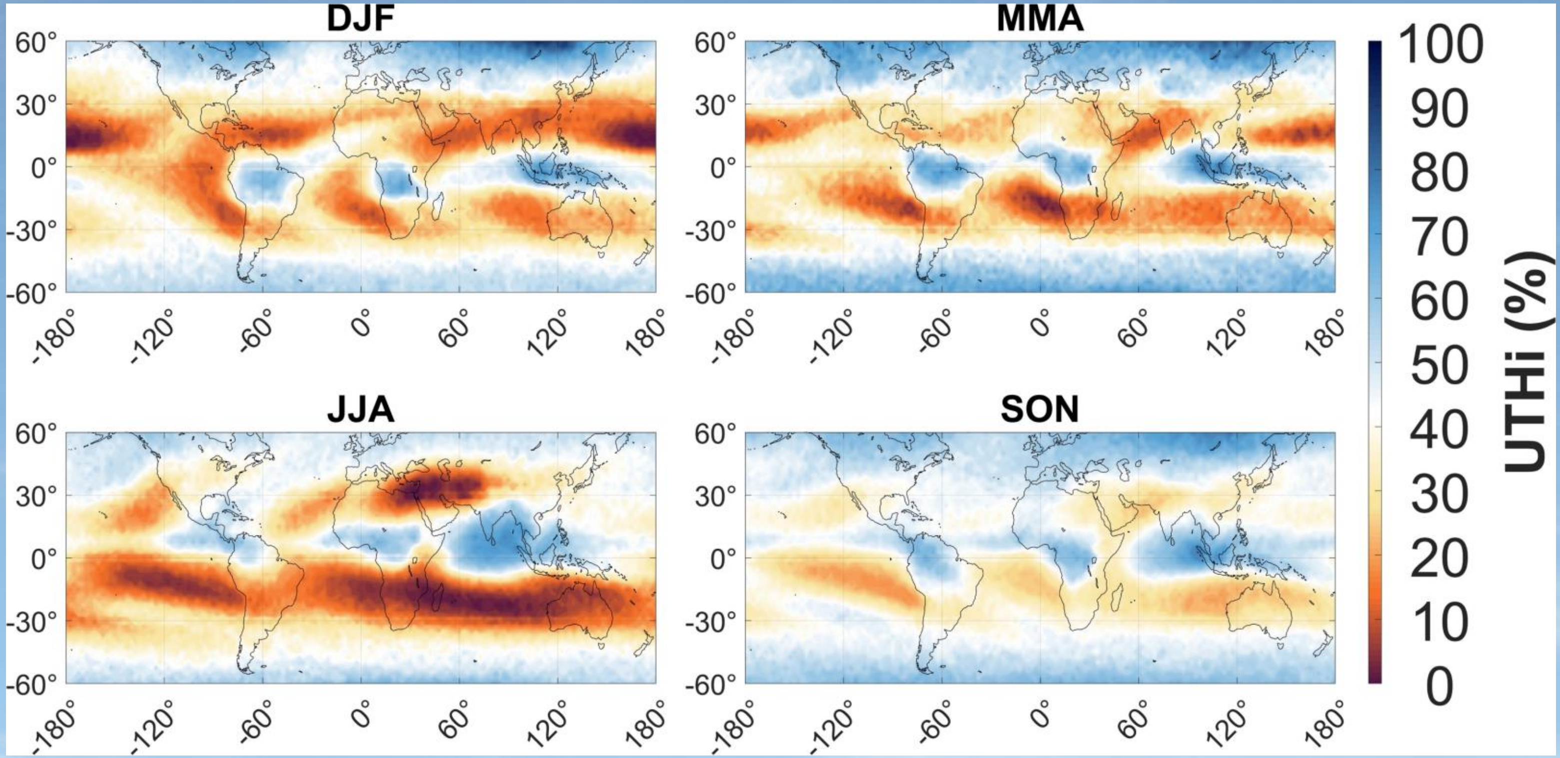
After the application of the previous corrections UTHi is calculated in a 2.5° × 2.5° data grid for 60°S-60°N on a daily, monthly, and decadal temporal scale.



Mean UTHi for 1979-2020

Mean UTHi per season for 1979-2020



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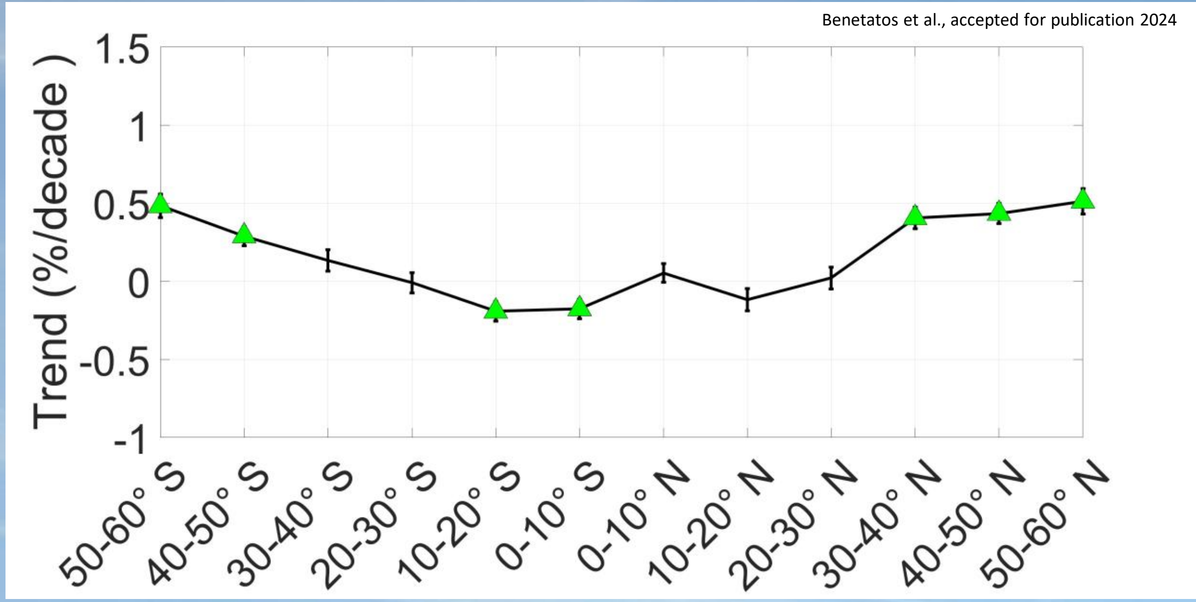
Trend analysis results on mean UTHi anomalies values:

- Small negative trend in the tropics (30 °N – 30 °S).
- Positive trends in the mid latitudes.
- Trends increasing with latitude.

Mean UTHi anomalies

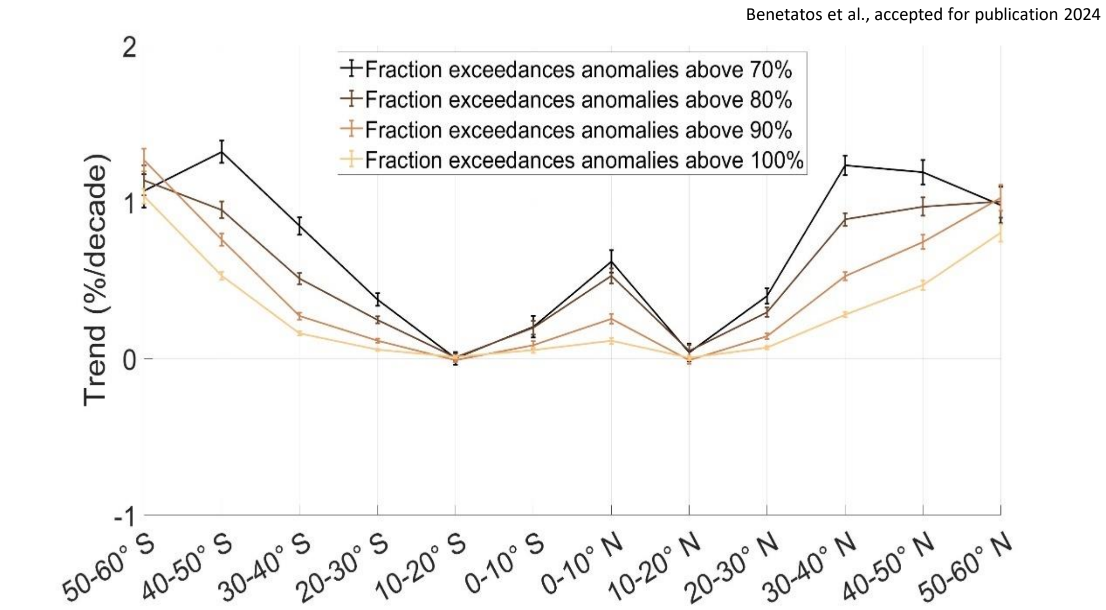


Trend analysis applied on the monthly mean UTHi anomalies. Trends are calculated for the period between 1979-2020.

Trend analysis results on UTHi threshold exceedances anomalies values:

- Small positive or no trends in the tropics.
- Positive trends in the mid latitudes.
- Trends increasing with latitude.

Exceedances anomalies



Trend analysis applied on the monthly mean fraction exceedances anomalies of UTHi above 70%, 80%, 90% and 100%. Trends are calculated for the period between 1979-2020.

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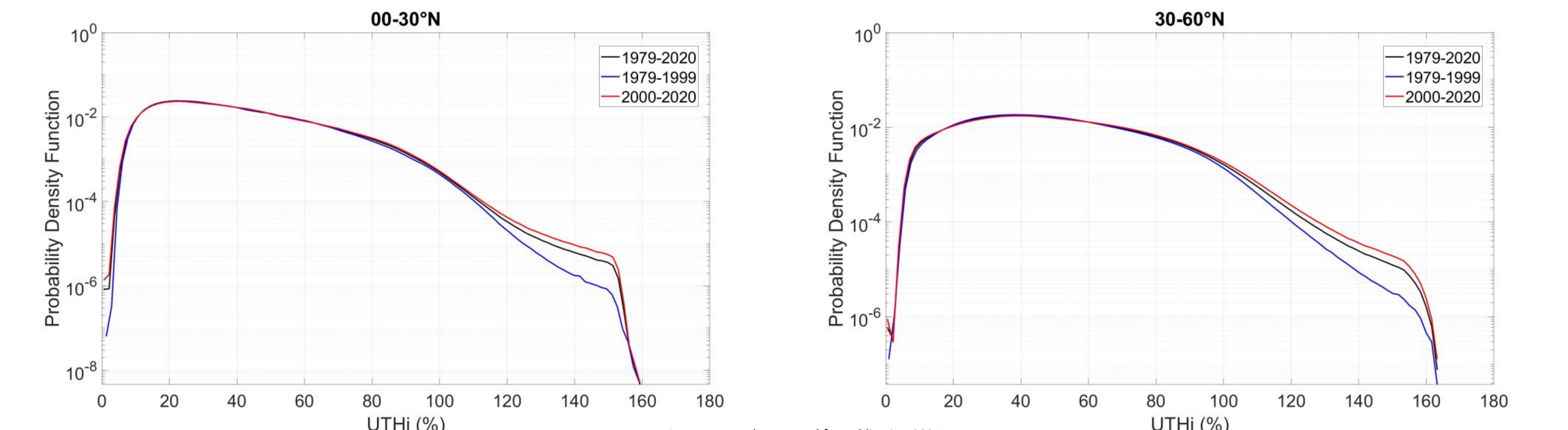
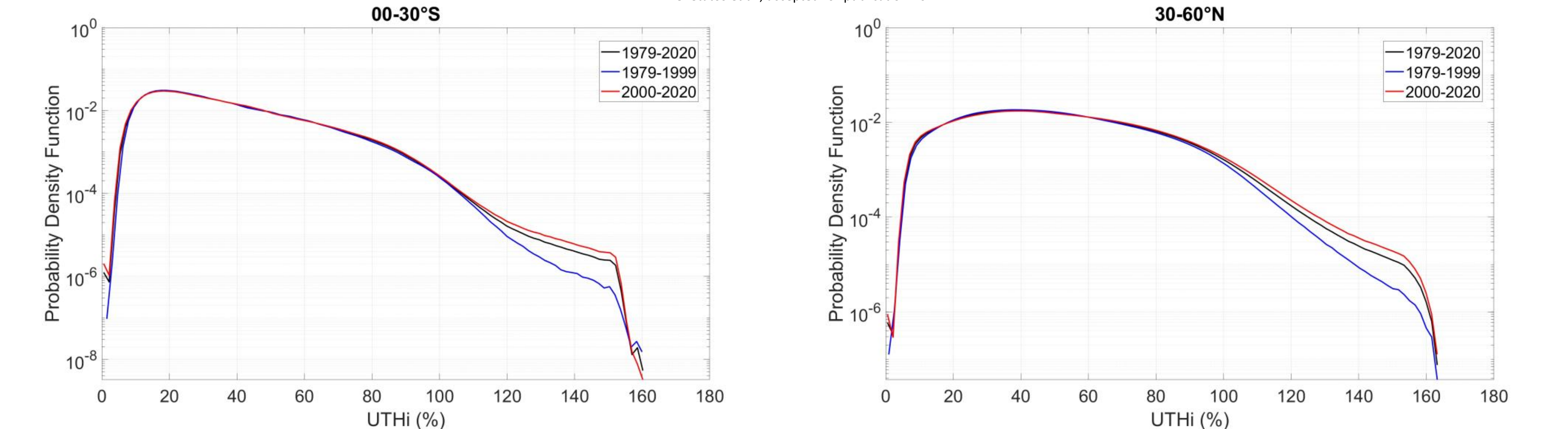
Probability density functions of UTHi



Benetatos et al., accepted for publication 2024



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Comparison of our results with other similar studies:

Wright, Sobel and Galewsky, 2010

In this study the authors compare the zonal mean relative humidity response between two model simulations. One with 1979 concentrations of greenhouses gases and one with doubled CO_2.

They report:

- A distinctive pattern dependent on latitude, where the relative humidity of upper troposphere is decreased in tropics by 1-2%. ✓
- A reversal of the trend in the middle latitudes ✓
- Increase of relative humidity in high latitudes by about 6-7%. They also note that the negative trends in the tropics are slightly larger in the Southern hemisphere. ✓

Irvine and Shine, 2015

In this study the authors compare the change in the frequency of Ice Supersaturated Regions (ISSRs) from the 1979-2005 (historical) period to mid-21st century and until the end of it with the help of global climate models.

They report:

- Change of such regions is regional rather than globally uniform. ✓
- In the tropics, they report a strong decrease in the CISS frequency of 3.3 percentage points by the mid-century and of 8.8 points by the end of the century. X
- In the northern hemisphere midlatitudes there is a small increase in the frequency of the CISS regions of around 0.7 and 0.9 percentage points until the mid-21st century and the end of it respectively. ✓
- In the northern polar region, they report an increase in the CISS frequency of 1.7 percentage points by mid-century and 4.9 by the end of the century. ✓

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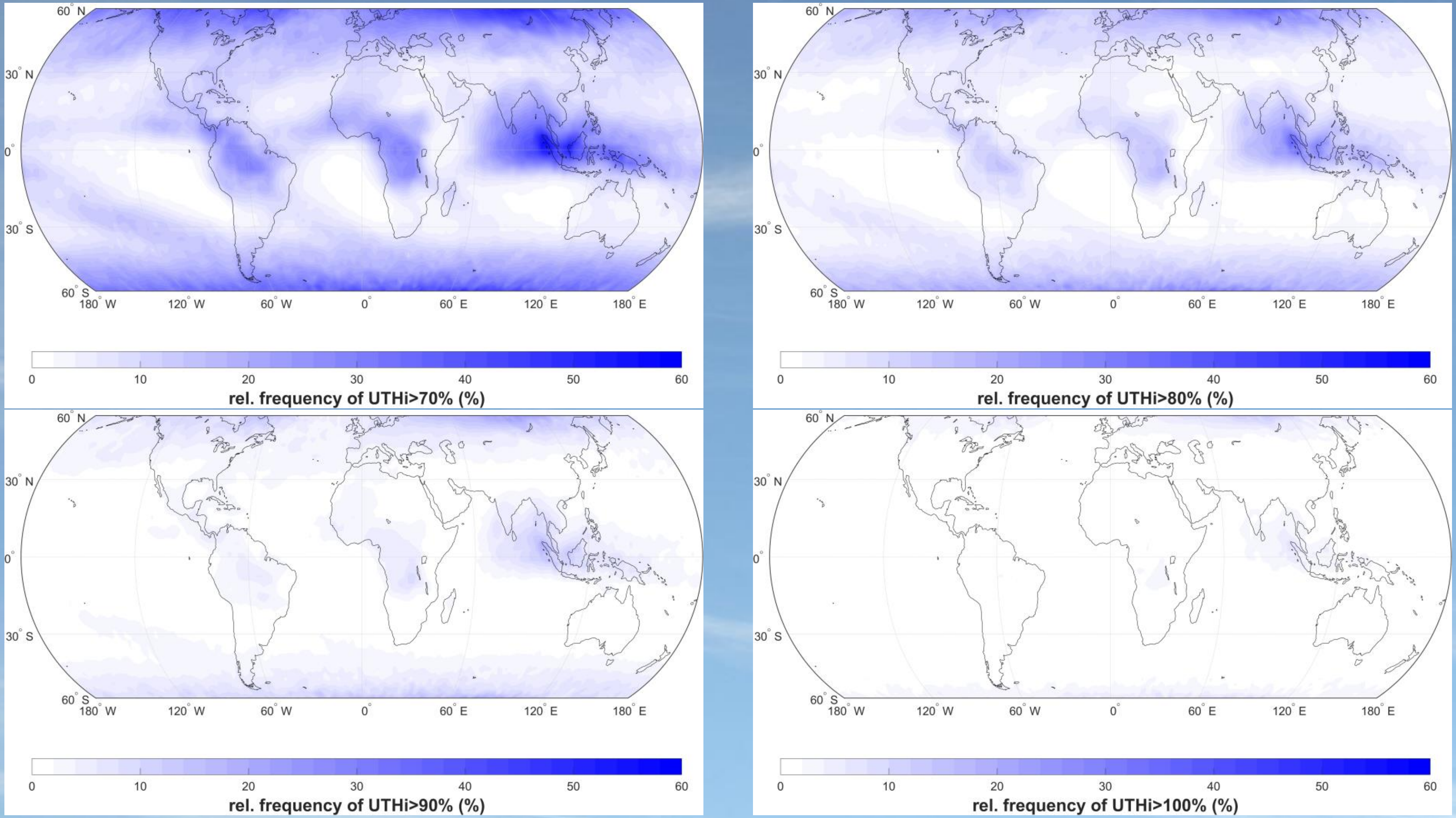
Mean frequency of UTHi exceedances for 1979-2020

70%

80%

90%

100%



What’s next? →

- Spatial distribution of UTHi exceedances and exceedances trends
- Seasonal variability maps of UTHi exceedances

Benetatos et al., In preparation, 2024

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To sum up:

- We have produced an homogeneous time series of UTH from HIRS satellite measurements. This is the result of the 2nd-order retrieval (Gierens and Eleftheratos, 2019), which was necessary to make the $HIRS_{2/3-4}$ data consistent not only in the bulk, but also in the upper tail of the distribution, together with the T_6 correction and a final bias correction following the breakpoint analysis to correct apparent jumps around the year 2000.

- Our homogeneous time series shows that UTH increased in the past 40 years in the midlatitudes but not in the tropics.

    - Estimated trends are about 0.4 to 0.5% per decade in the northern midlatitudes, between 0.1 and 0.5% per decade in the southern midlatitudes, and no or negative trends in the tropics. For the globe, we estimate a near-global trend of about 0.15% per decade which means an overall increase from 1980 to 2020 of about 0.6%.

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References

Gierens, K. and Eleftheratos, K. (2019) ‘On the interpretation of upper-tropospheric humidity based on a second-order retrieval from infrared radiances’, *Atmospheric Chemistry and Physics*, 19(6), pp. 3733–3746. Available at: https://doi.org/10.5194/acp-19-3733-2019.

Irvine, E.A. and Shine, K.P. (2015) ‘Ice supersaturation and the potential for contrail formation in a changing climate’, *Earth System Dynamics*, 6(2), pp. 555–568. Available at: https://doi.org/10.5194/esd-6-555-2015.

Lindau, R. and Venema, V. (2013) ‘*On the multiple breakpoint problem and the number of significant breaks in homogenization of climate records*’, *Quarterly Journal of the Hungarian Meteorological Service*. Bonn.

Shi, L. *et al.* (2016) ‘Algorithm development of temperature and humidity profile retrievals for long-term HIRS observations’, *Remote Sensing*, 8(4). Available at: https://doi.org/10.3390/rs8040280.

Wright, J.S., Sobel, A. and Galewsky, J. (2010) ‘Diagnosis of zonal mean relative humidity changes in a warmer climate’, *Journal of Climate*, 23(17), pp. 4556–4569. Available at: https://doi.org/10.1175/2010JCLI3488.1.

Thank you!!

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Data corrections:

a) Challenge:

Channel 6 is in the CO_2 absorption band, therefore T_6 data contains biases due to the increase of the $[CO_2]$ according to Shi *et al.,* 2016. Therefore, T_6 values contain a negative trend that needs to be adjusted proportionally to the increase of the $[CO_2]$.

Solution:

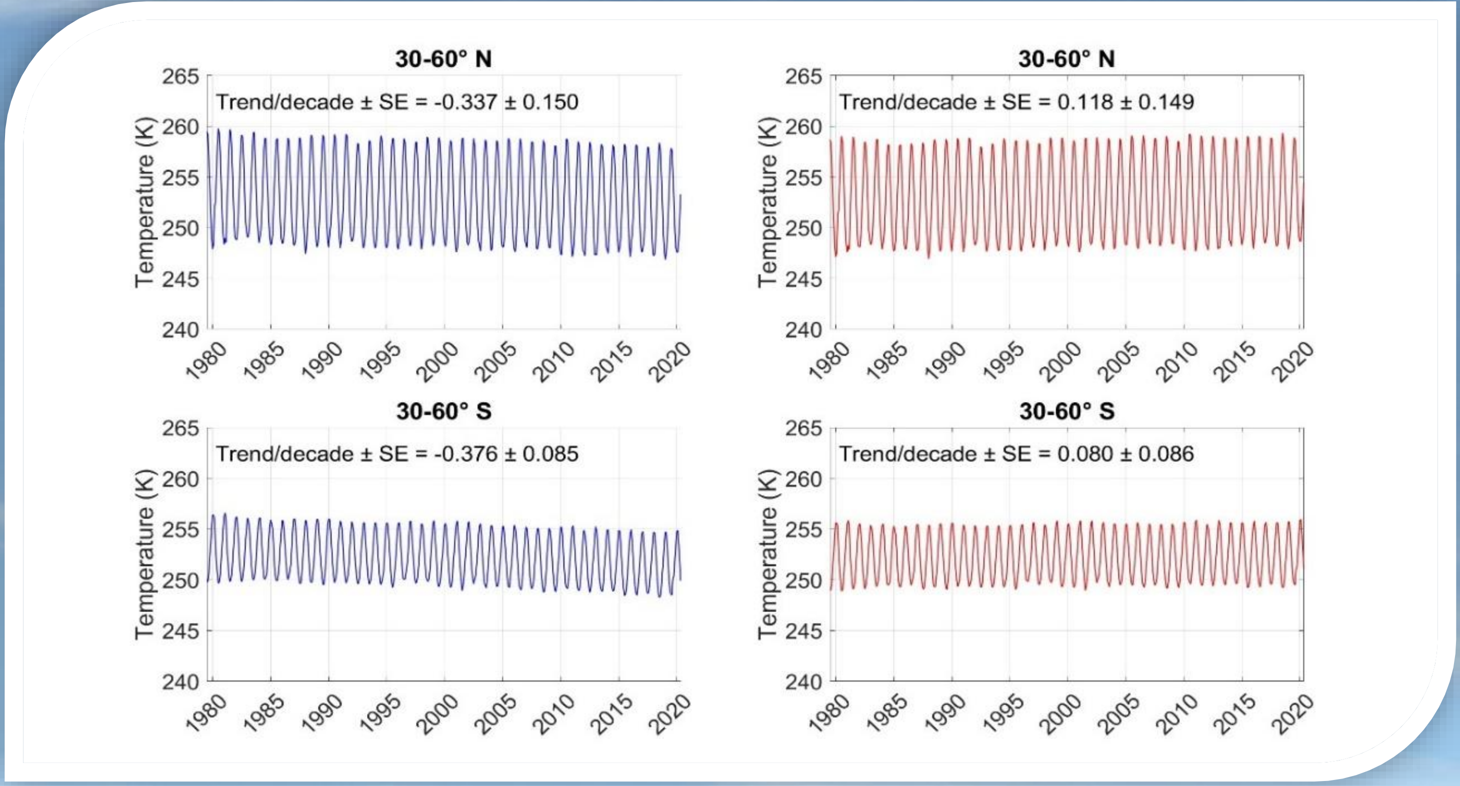
A simple algorithm is applied using a reference value of $[CO_2]$ of 370 ppmv:

$$\frac{\mathrm{d}[T_6]}{d[CO2]} = \frac{-1.98}{410-330} = -0.02475\,\frac{K}{ppmv}$$

$$T_6'(\,m) = T_6(m) + |-0.02475| * ([CO_2(m) - 370])$$

Where:

m: month



T_6 temporal distribution on a monthly scale over 1979-2020 before (left) and after (right) the bias correction due to the $C0_2$ increase for the tropics (a) and the mid-latitudes (b). Trends per decade ± the standard error are included.

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b) **Challenge:**

Identifying the bias:

- We use a multiple-break point approach (Lindau and Venema, 2013) to find breaks in the numerator of the UTHi retrieval equation,
- Maximum external variance between the segment averages is used as a decision criterion,
- Breaks identified around 2000 in all latitudes.

Solution:

Calculating the bias between $HIRS_2$ and $HIRS_3$ numerator values by subtracting the values of $HIRS_3$ from $HIRS_2$.

External variance eq.

$$\frac{1}{n}\sum_{i=1}^{N} n_i(\bar{x_i} - \bar{x})^2$$

	Latitude zone	Difference		Latitude zone	Difference
Northern Hemisphere	55-60°N	-0.0274	Southern Hemisphere	55-60°S	-0.0285
	50-55°N	-0.0344		50-55°S	-0.0214
	45-50°N	-0.0427		45-50°S	-0.0285
	40-45°N	-0.0542		40-45°S	-0.056
	35-40°N	-0.0609		35-40°S	-0.08
	30-35°N	-0.0675		30-35°S	-0.1007
	25-30°N	-0.0924		25-30°S	-0.1065
	20-25°N	-0.1128		20-25°S	-0.1216
	15-20°N	-0.1276		15-20°S	-0.1358
	10-15°N	-0.1235		10-15°S	-0.1319
	5-10°N	-0.0962		5-10°S	-0.1136
	0-5°N	-0.0899		0-5°S	-0.0951

Bias correction algorithm

Bias values=$Num_{HIRS/2(lat)}$-$Num_{HIRS/3-4(lat)}$

$Num_{HIRS/3-4(lat)adj}$=$Num_{HIRS/3-4(lat)}$+ bias values

Num= $a + b \times T_{12} + c \times T_{12}^2$

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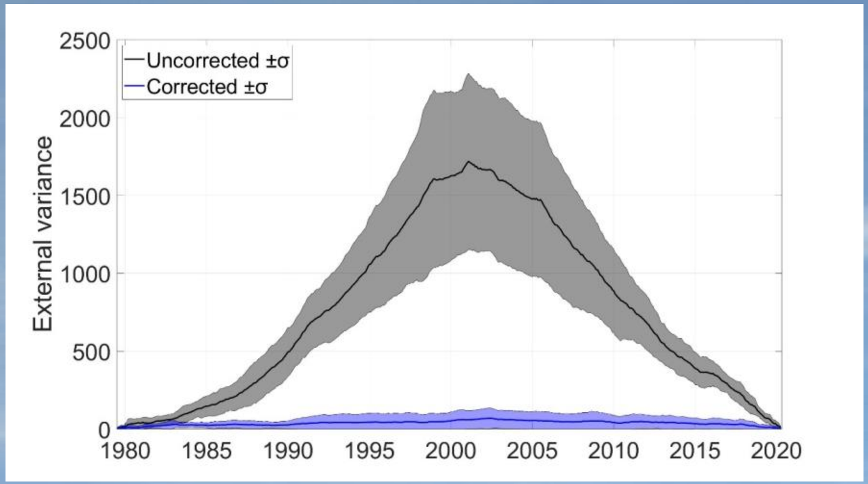
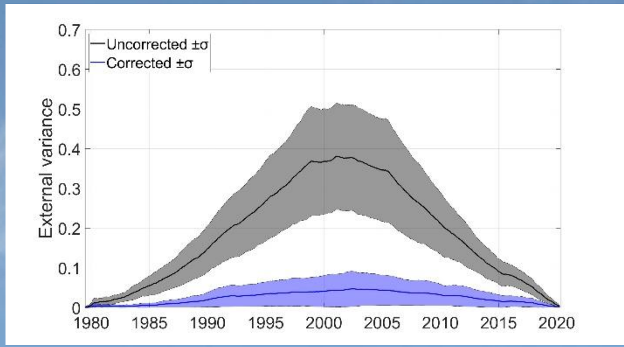
Mean UTHi anomalies



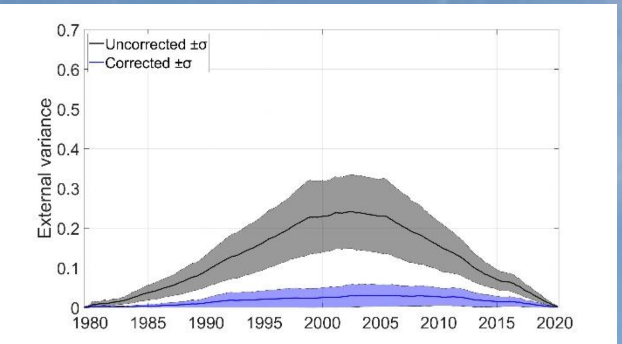
Mean external variance of UTHi anomalies across all latitudes (60°N-60°S) ± the respective standard deviation (shade) before (black) and after (blue) the bias correction. The external variance time series is calculated first for each 10° of latitude and then averaged over all latitudes.

Exceedances anomalies above 70%



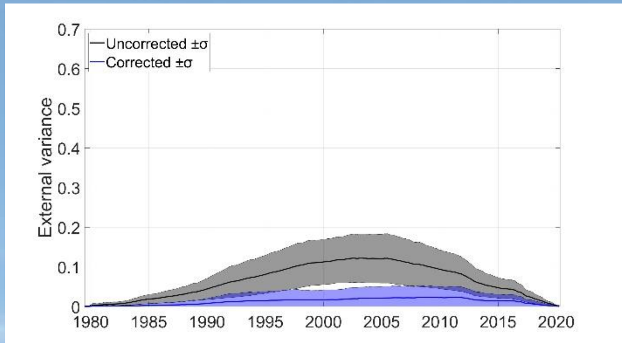
a

Exceedances anomalies above 80%



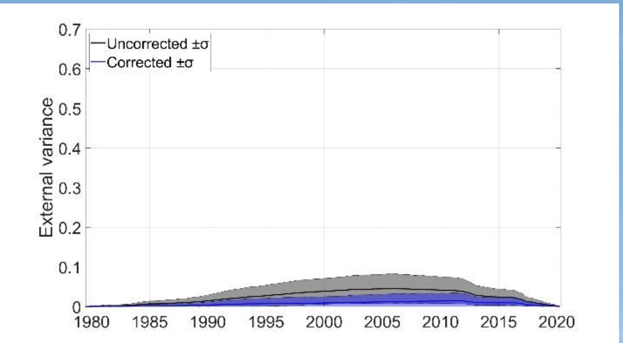
b

Exceedances anomalies above 90%



c

Exceedances anomalies above 100%



d

Mean external variance of the fraction of UTHi exceedances anomalies above 70% (a), 80% (c), 90% (e), 100% (g) and the respective standard deviation before (black) and after (blue) the bias correction between 60°N and 60°S. The external variance is calculated first for each 10° of latitude and then averaged over latitudes.

Interpretation: In the uncorrected data the maximum variance is around the year 2000, which means that there is a break in the numerator. In the corrected data (blue line) there is no break in the timeseries around the year 2000.