4.1 LONG ALPINE BAROMETRIC TIME SERIES IN DIFFERENT ALTITUDES AS A MEASURE FOR 19th/20th CENTURY WARMING

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1. INTRODUCTION

The reality of a considerable warming of the surface near atmosphere since mid 19th century is a widely accepted fact among climatologists. There are still some doubts about the ability of science to isolate a true climate signal from statistically noisy time series, influenced by a number of non climatic factors. Although the authors are convinced that it is in fact possible to remove most of the inhomogeneities from temperature time series - an independent proof for the reality of the temperature increase during the last more than 100 years would be a strong additional argument.
Long-term series of air pressure from mountain observatories - together with low level series - have the potential to provide such evidence. The barometric height equation describes the dependence of mean (virtual) temperature of an air column on the logarithmic ratio of air pressure at the upper and lower ends of the column. For the transformation of temperature into virtual temperature there is an additional need for vapor pressure series.
A relative increase of high level versus low level air pressure would be a „non thermometric" measure for a temperature increase. And it would be a measure for increasing temperatures not only in the thin layer where the thermometers of the meteorological surface network are installed, but for considerable parts of the lower troposphere - remote from a number of biasing effects which are often in connection with changes of the local surrounding of the measuring sites.

2. DATA

Among other climate elements the ALOCLIM data set (compare paper 4.2 of this conference volume) provides carefully homogenized time series of air temperature, air pressure and vapor pressure of some 20 locations in the eastern part of the Alps. A detailed description of the homogenization procedure will be published next year in the series „Österreichische Beiträge zu Meteorologie und Geophysik".
For the purpose in question - calculating air temperatures from air pressure series - a subset of station series had to be chosen that provides maximum possible relative heights in order to increase the climate signal. Table 1 shows the topographic parameters of that ALOCLIM subset.

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Table 1. Stations in the eastern Alps with homogenized long-term air pressure, vapor pressure and air temperature series

coordinates		x	y	z	regional subgroups					
Stations		east	north	(m)	west	east	north	south	high	low
Wien	VIE	16.35	48.22	209		X				X
Kremsmünster	KRE	14.13	48.05	389		X	X			X
München	MUN	11.55	48.13	535	X		X			X
Salzburg	SAL	13.00	47.80	450	X		X			X
Graz	GRA	15.45	47.08	377				X		X
Klagenfurt	KLA	14.33	46.65	459				X		X
Innsbruck	INN	11.38	47.27	609	X					X
Zürich	ZUR	8.57	47.38	569	X					X
Säntis	SNT	9.35	47.25	2500					X	
Sonnblick	SON	12.95	47.05	3111					X	
Villacher Alpe	VIA	13.67	46.60	2160					X	
Zugspitze	ZUG	10.98	47.42	2962					X	

Sorry the map has gone lost (it is present in the conference proceedings volume)

Figure 1. Area of investigation with topography and station network
Dots: Low level stations (209 to 609 m asl),
Triangles: High level stations (2160 to 3111 m asl
Topography: white...below 1000m, light grey...1000-2000m, dark grey...above 2000m

Figure 1 sketches the area of investigation. It is the eastern part of the Alps, ranging from approximately 9 to 16 deg E and from 46 to 48 deg N. Eight stations are located in altitudes from 209 to 609 m asl. - the „low level subgroup", four stations (the „high level subgroup“) are located on mountain tops from 2160 to 3111 m asl.

The longest homogenized low level temperature series in the region begins in 1767, pressure series in 1822 and vapor pressure series in 1840. The mountain observatories are younger, starting in 1851 (VIA), 1864 (SNT), 1887 (SON) and 1901 (ZUG). This limits the length of the analysis to the 110 years from 1887 (the year when three of the four high alpine observatories were in operation already) to 1996.

The absolute necessity to use only carefully homogenized data in climate time series analysis is shown in Figure 2 at the example of the detected inhomogeneities in air pressure series.

Figure 2. Detected inhomogeneities in ALOCLIM air pressure series (original minus adjusted annual mean series)

3. **REGIONAL DIFFERENCES**

The aim of the study is to compare measured and calculated mean air temperatures of a mean air column between the low level and the high level subgroup. A precondition for the existence of such an „east alpine standard air column“ (EASAC) is the non existence of horizontal significantly different climate variations in the area. A subdivision of the low level group into the subgroups West, East, South and North (see Table 1) should clarify that.

Figure 3 shows smoothed time series of the different climate elements for the four horizontal and the two vertical subgroups. As the calculation of mean column temperature in moist air affords virtual temperature, also vapor pressure and virtual temperature are shown.

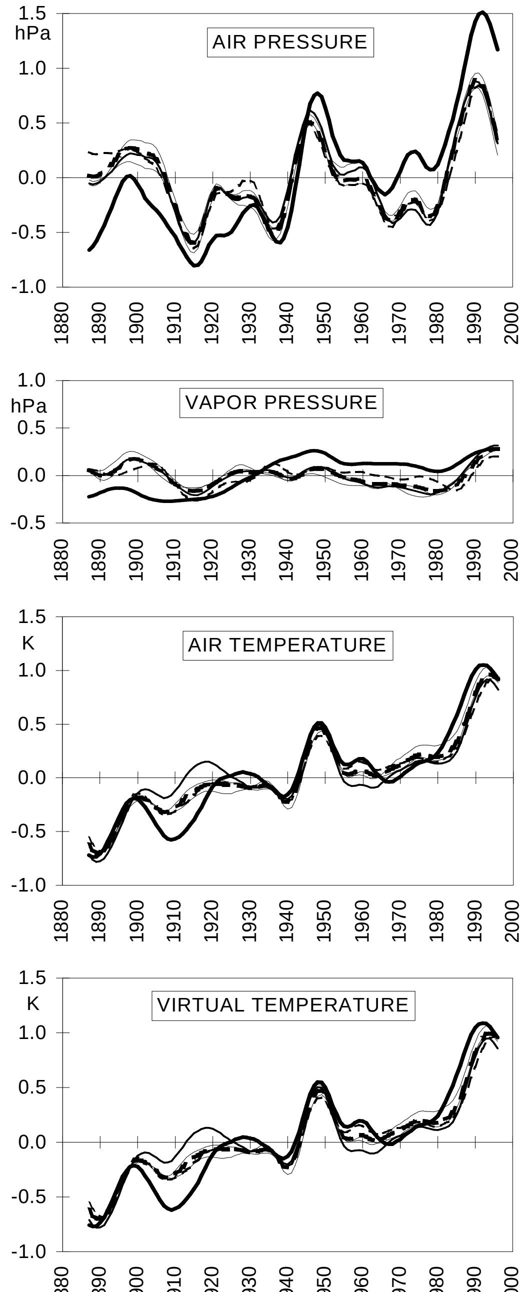

Figure 3. Long term variability of air pressure, vapor pressure, air temperature and virtual temperature in sub-regions of the investigation area

All relative to 1887-1996 averages, high frequent variations suppressed by 21yrs. Gauss low pass filter

bold: high level subgroup, bold broken: low level subgroup, medium: north, medium broken: south,

thin: west, thin broken: east

All curves are deviations from the 110 years average 1887-1996. Virtual temperature (T_V) was calculated from temperature (T), air pressure (p) and vapor pressure (e) according to:

$$T_V = T + 0.378*T*e/p$$

The time series of the virtual temperature excess in Figure 4 show that the transition to virtual temperature does not cause any biasing of the original temperature series. The long term trends and variations of the virtual temperature excess keep within a range less than 0.1 K. This causes the high similarity of the temperature and the virtual temperature series in Figure 3. To be physically strict we will proceed with virtual temperatures but it must be kept in mind, that all results for virtual temperature are highly similar to temperature itself.

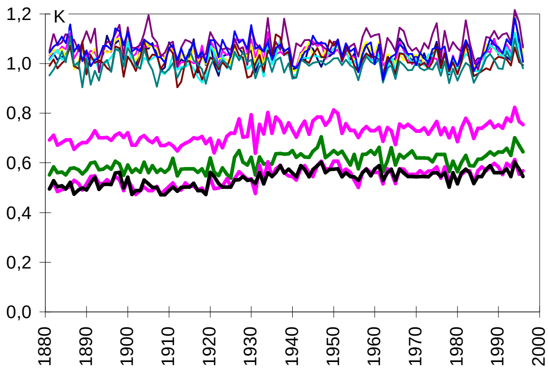

Figure 4. Time series of the virtual temperature excess in the area of investigation
bold: high level series, thin: low level series

The clear result of the analysis of regional differences is that there are none in respect to the horizontal component (at least according to the long term aspect which is the interesting one in this study). The smoothed air pressure series show maximum deviations among the four horizontal subgroups of 0.3hPa, those of vapor pressure are even closer together. 90 years of the period of investigation are characterized by very close temperature time series (maximum differences 0.25 K), only the first two decades of 20th century differ stronger. The northern sub-region was 0.5 K relatively warmer than the one south of the main ridge of the Alps.
The clear result according to the horizontal component allows the calculation of low level means of all three elements which are highly representative for the whole area of investigation.
It is not subject of this study but it should not be failed to notice that there is a stunning general similarity of temperature and air pressure series. As the process of homogenization has been carried out strictly separate for each climate element, a potential import of information from one element to another is out of question. The similarities are real and will be subject of discussion in another study.
For temperature and virtual temperature also the high and the low level subgroups are as similar as the horizontal ones. Therefore there won't be any troubles concerning the calculation of vertical means.
For air pressure and vapor pressure the situation is different. Both show also high similarity at time scales from 20 to 50 years. But throughout the complete investigation period both have an increasing long term trend of the high level versus the low level group.
The relative increase of high level versus low level air pressure is the one that is of special interest for our study. It is this effect that can be expected as the result of a warming of the alpine air. It will be discussed quantitatively in the following chapter.

4. AIR PRESSURE AND TEMPERATURE IN THE „EAST ALPINE STANDARD AIR COLUMN“ (EASAC)

As any horizontal regional differences are far from significance, it is possible to define an „east alpine standard air column“ which can be assumed representative for the studied region. To obtain as much vertical potential as possible the high level group was reduced to the three highest observatories Säntis (2500m), Zugspitze (2962m) and Sonnblick (3111m). Because of the strong similarity within the high alpine subgroup this caused no loss of information. For the low level group all eight stations were averaged, for the high level group the three mentioned ones.
Regression analysis of the long term annual means of the 11 pressure series resulted in the following equation:

$$p(z) = 1019.3*e^{-0.000124z}$$

with z being the altitude in m, p the air pressure in hPa and 1019.3 hPa the extrapolated sea level pressure in the region.
The performance of the regression formula is very high. It explains more than 99% of the vertical distribution of p.
For further proceeding we need the vertical extension of EASAC. Mean air pressure time series at the upper and the lower edge of EASAC were averaged linearly - therefore the corresponding altitudes had to be calculated as „barometric mean heights“ according to the above formula. This resulted in the following boundaries of EASAC: It reaches from z_0=449m to z_1=2855m and has a vertical extension of 2406m.
Figure 5 shows the time series of mean column temperature and of the difference of lower boundary minus higher boundary air pressure. The temperature increase is accompanied by a decreasing air pressure

extension of the air column. This is qualitatively the true effect - the warming air causes a reduction of air density and thereby a relative decrease of lower boundary in relation to higher boundary air pressure.

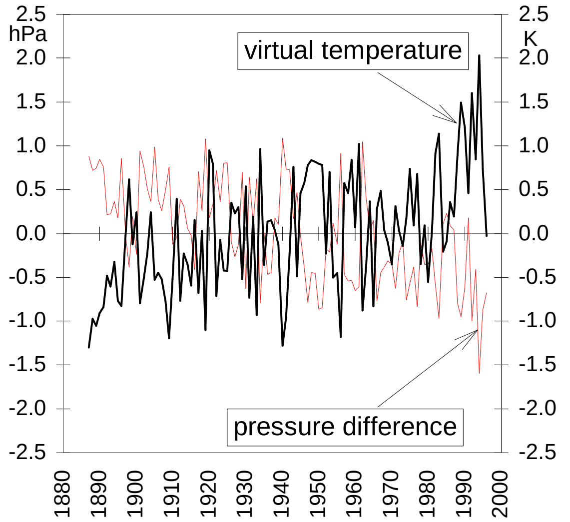

Figure 5. Time series of air pressure difference (low level mean minus high level mean) and mean virtual air temperature of „East alpine standard air column“ (449m to 2855m barometric height extension)

From barometric height equation the following formula for mean (virtual) column temperature can be derived:

$T_{V,mean} = \Delta z * g / R * \ln(p_1/p_0)$

with:

$\Delta z = 2406m$, $g = 9.811\ kgm/s^2$
and $R = 287\ J\ kg^{-1}\ K^{-1}$

Applied on EASAC - air pressure series for p_0 and p_1 this equation produces a calculated virtual mean column temperature series, obtained without thermometric measurements and valid not only for surface near level, but for a 2400m thick layer of the lower troposphere.
This has been the aim of the study and Figure 6 compares this calculated mean column temperature with the measured temperature (obtained as the mean of the high level and the low level group).
The result of the comparison is surprisingly good. Although derived by two totally independent procedures and based on independently homogenized climate elements, the two time series of thermometrically and barometrically measured mean EASAC temperatures show a high degree of correlation.

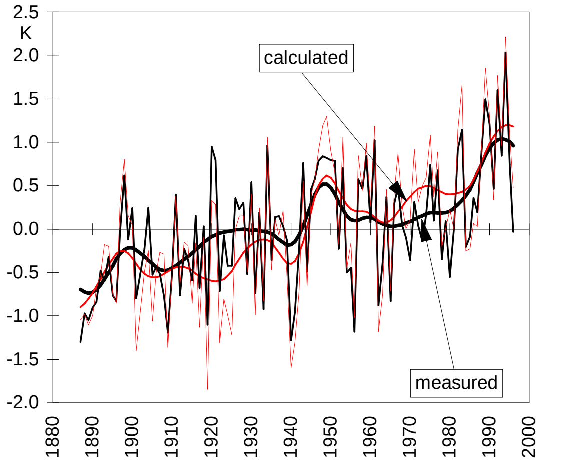

Figure 6. Time series of the virtual temperature calculated from air pressure at the upper and lower boundary of the „East alpine standard air column“ (thin) and of the directly measured mean virtual temperature of the column (bold)
Single years 1887-1996 and 21 yrs. smoothed (as in Fig.3), all relative to 1887-1998 avarages

Calculation has successfully reproduced the 110 years temperature increase of 1.8 K, It follows to a high degree the smoothed form of the measured curve and also the high frequent correlation is good, as can be seen in Figure 7.

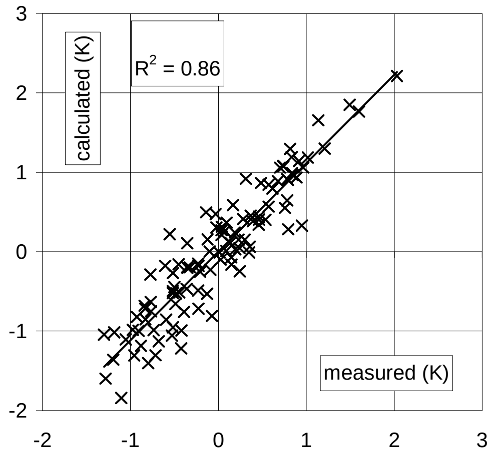

Figure 7. Correlogram of calculated versus measured mean virtual column temperature in the eastern Alps

The year to year measured minus calculated temperature differences are shown in Figure 7. The differences are balanced, the long term mean is 0.0 K. Therefore the long term trend is not biased. The square mean difference is 0.32 K which may be due to some remaining inhomogeneities in the temperature and/or the pressure series. As it is not clear which of the two climate elements is biased (most probably both), this remaining differences may not be called „error of calculation“. They reflect more the level of remaining inhomogeneities which has to be accepted when two independently homogenized measured climate elements are compared with theoretical physical laws.

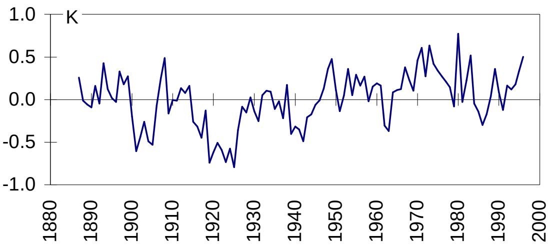

Fig. 7. Difference time series of calculated minus measured (virtual) air temperature of „East alpine standard air column“

1.5. CONCLUSIONS

The study of alpine high and low level climate time series of air temperature, air pressure and vapor pressure was able to demonstrate that:

- It is not convenient to analyse climate time series without careful homogenization. They always are biased by non climatological noise which at least equals the real climate signal, in the case of air pressure exceeds it by a factor of two to five.
- Homogenizing is possible - not only for temperature but also for air pressure and vapor pressure. In the case of air pressure a climate signal of only 1 hPa per 110 years could successfully be isolated.
- Applying the principle of relative air pressure - barometric height equation allows to calculate mean air column (virtual) temperature time series which are highly correlated to directly measured air temperature series.
- Thereby the directly measured warming of +1.8K since the 1880s in the eastern Alps could be confirmed by an independent and non thermometric measure - air pressure.

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