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The Little Ice Age: Thermal and Wetness Indices for Central Europe

The kinds of evidence used to reconstruct past weather and climate can be divided into two classes: for those generated through natural manifestations of climatic change and analyzed by scientific disciplines, the term *field data* is appropriate; for the body of man-made climatic data in the form of written and illustrated documents buried in archives, libraries, and museums we use the term *documentary data*. Only recently has it been shown that documentary sources of information about past climates are not equally reliable. Much material which purports to record historical events is gravely misleading. Almost all compilations of weather descriptions, printings, and manuscripts include events which are non-contemporary. Often observations have been copied (or miscopied) from other sources, sometimes even without giving a reference.[1]

We distinguish *two groups of documentary data* in Table 1. The first group includes instrumental *measurements* and several types of non-instrumental *observations* for which individual *weather factors* (temperature, precipitation, wind, etc.) are specified. We include among the measurements only those which are found in archives and libraries. Most of them were made by private individuals before networks were created by national weather services.

The second group, *documentary proxy data*, summarizes a variety of information which reflects the combined effect of several weather factors, during a period of several months. Like the field data of the scientist, documentary proxy data can be calibrated with instrumental measurements and used to estimate specific meteorological variables.

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1 Martin J. Ingram and David J. Underhill, "Historical Climatology," *Nature*, CCLXXVI (1978), 329–334; *idem*, "The Use of Documentary Sources for the Study of Past Climate," paper given at the Conference on Climate and History (Univ. of East Anglia, 1979), 59–91.

Table 1 A Taxonomy of Data Used to Reconstruct Past Weather and Climate

ORIGIN INDIVIDUAL WEATHER FACTORS	FIELD DATA	DOCUMENTARY DATA (archives, libraries, museums)
specified		*Measurements, observations* — Chronicles, annals, etc. — Non instrumental diaries — Measurements taken prior to the creation of national networks
nonspecified	— Pollen — Tree rings — Isotopes — Moraines — Varves etc.	*Documentary proxy data* — Phenological observations — Wine and grain harvest dates from administrative sources (paraphenological data) — Quantity and quality of wine produced — Illustrated sources of glaciers

The first part of this article presents three types of documentary proxy data (phenological observations, grain harvest dates, and vine yields) and shows how they are interpreted, calibrated, and cross-dated to non-instrumental observations. In the second part a quantification of the whole body of observations—specified and unspecified—is provided in the form of an index for both temperature and precipitation with a time resolution of a month. It is then demonstrated to what extent such a great body of highly detailed information may modify the periodization of the little ice age in Central Europe.[2]

A data bank of documentary weather evidence (CLIMHIST) has been compiled following a systematic search for evidence in the major libraries and archives of Switzerland. The search revealed more than 27,000 records, mainly from places on the plateau. The records include monthly means of the Basel temperatures (from

2 Phenology is the science which relates periodic biological phenomena (crop growth, migration of animals, etc.) to weather and climate. The stages of development of a certain species (burgeoning, flowering, ripening, etc.) are called phenophases.

1755); several series of rainfall measurements (from 1708); summaries of more than 70,000 daily observations from weather diaries; some 3,000 observations of snow-cover and snowfalls on the alpine pastures; almost 3,000 phenological observations; and reports on the conditions of crops and cattle, the quality of harvests, and the occurrence of diseases.

A numerical code assigned to the descriptive observations facilitated the management of the data by computer. The printout has the form of a weather chronology in readable form. It contains information about the weather and its impact upon the hydro-, bio-, and anthroposphere from 1525 to 1825 with time intervals from ten days up to entire seasons.[3]

CONVERTING DOCUMENTARY PHENOLOGICAL MATERIAL INTO CLIMATIC DATA Occasional phenological observations of crops or trees are contained in many chronicles and annals. They have never been used as climatic evidence, probably because they were too erratic and could not easily be interpreted. Given that the fluctuations of phenophases are in good agreement over distances of several hundred kilometers, the Swiss evidence, which is presented below, may also be conclusive for the climate in great parts of Central Europe.[4]

In most cases single phenological observations describe the growth pattern of outstanding years. Plants are known to be living instruments which show in their growth response the composite effect of temperature, rainfall, sunshine, and radiation. In most cases temperature is the dominant variable. Hence a reference to the growth calendar of plants was the most objective way

3 Pfister, "Klimageschichte der Schweiz 1525–1825," in preparation. The CLIMHIST data bank (compiled by Pfister) is stored on disks and could easily be included in a larger international data bank. *Idem*, "The Reconstruction of Past Climate: The Example of the Swiss Historical Weather Documentation," paper given at the Conference on Climate and History (Univ. of East Anglia, 1979), 134.

4 Helmut Lieth (ed.), *Phenology and Seasonality Modelling* (New York, 1974), preface; John A. Kington, "An Application of Phenological Data to Historical Climatology," *Weather*, XXIX (1974), 320–328; Fritz Schnelle, "Temperaturverhältnisse und Pflanzenentwicklung in der Zeit von 1731 bis 1740 in Mittel-und Westeuropa," *Meteorologische Rundschau*, XI (1959), 58–63; *idem*, "Hundert Jahre phänologische Beobachtungen im Rhein-Main Gebiet 1841–1939, 1867–1947. Ein Beitrag zur Klimageschichte des Rhein-Main Gebiets," *Meteorologische Rundschau*, II (1950), 150–156; Max Bider, "Untersuchungen an einer 67-jährigen Reihe von Beobachtungen der Kirschblüte bei Liestal (Basel-Landschaft)," *Wetter und Leben*, XII (1960), 36–50.

of documenting the coldness or the warmth of a particular season before the thermometer was invented. It implied that the reader, who was supposed to be familiar with agriculture, could compare it to the "normal" pace of vegetative growth. Whether the historian of climate can decode this material and convert it into valid climatic data depends entirely on the quality of the evidence which can be found. Two conditions must be met in order to be able to decode the phenological information.

First, phenological series of sufficient length (fifteen to twenty years at least) are required for a period which is fully documented by meteorological measurement (temperature, precipitation, and duration of sunshine). Such a series allows for quantification of the relationship between the growth pattern of a certain species and the environmental factors. Although modern phenology seeks to "explain" biological processes in terms of environmental parameters, the historian of climate, who uses phenology as a substitute for meteorological measurement, has to take temperature as the dependent variable and the phenological observations as the independent variable. The study must also include ecological theory and may not be restricted to statistical manipulations.[5]

In many countries a considerable body of observations has already been collected. In Switzerland in particular a few series have survived from the eighteenth century but, surprisingly, more recent observations are difficult to find because regular network observations were not begun until three decades ago. The only record which is both sufficient in length and also covered by a full set of meteorological measurements has been maintained by the observers of three meteorological stations in the Canton of Schaffhausen (northern Switzerland) from the end of the nineteenth century until about 1950. These records were used to

5 Lieth, *Phenology*, 3–19. In particular, attitude and exposure of the place on which the plant grows have to be taken into account. Norbert Becker, "Phänologische Beobachtungenan Reben und ihre praktische Anwendung zur Gütekartierung von Weinbergslagen," *Weinwissenschaft*, XXIV (1969), 142, has found that for the vine flower an increase in altitude of 10 m corresponds to a delay of 0.36 days, if the other factors are held constant. Richard Volz, "Phänologische Karte von Frühling, Sommer and Herbst als Hilfsmittel für eine Klimatische Gliederung des Kantons Bern," *Jahrbuch der Geographischen Gesellschaft Bern*, LII (1975/6), 46–52, has found that for apple bloom the mean delay between the earliest appearance (south) and the latest appearance (east) is 4.5 days. For the wheat harvest no clear pattern has emerged.

calibrate the body of historical evidence contained in the CLIMHIST data bank (see Table 2).[6]

Second, because phenological observations are only conclusive in the form of deviations from a mean, we need to determine whether the means have changed from those of the past and whether such changes were the result of the changing climate or the introduction of new varieties. The results are discussed in Figure 1.

When we compare recent and historical means it is surprising to find that they differ only by one or two days, which does not affect the kind of rough estimates which we have given.[7] Table 2 displays the calibration of phenophases at the most conclusive meteorological statistics.

THE EXTREMES OF INDIVIDUAL PHENOPHASES

Sweet cherry flower. Based upon the longest known phenological record (from the ninth to the nineteenth century) which relates to a variety of cherry tree in Japan, Arakawa has demonstrated the close correlation between spring temperatures and flowering. We can deduce from Table 2 that his conclusion agrees with the result obtained from the analysis of the Unter-Hallau series. Temperatures in March seem to be far more important than in April.[8]

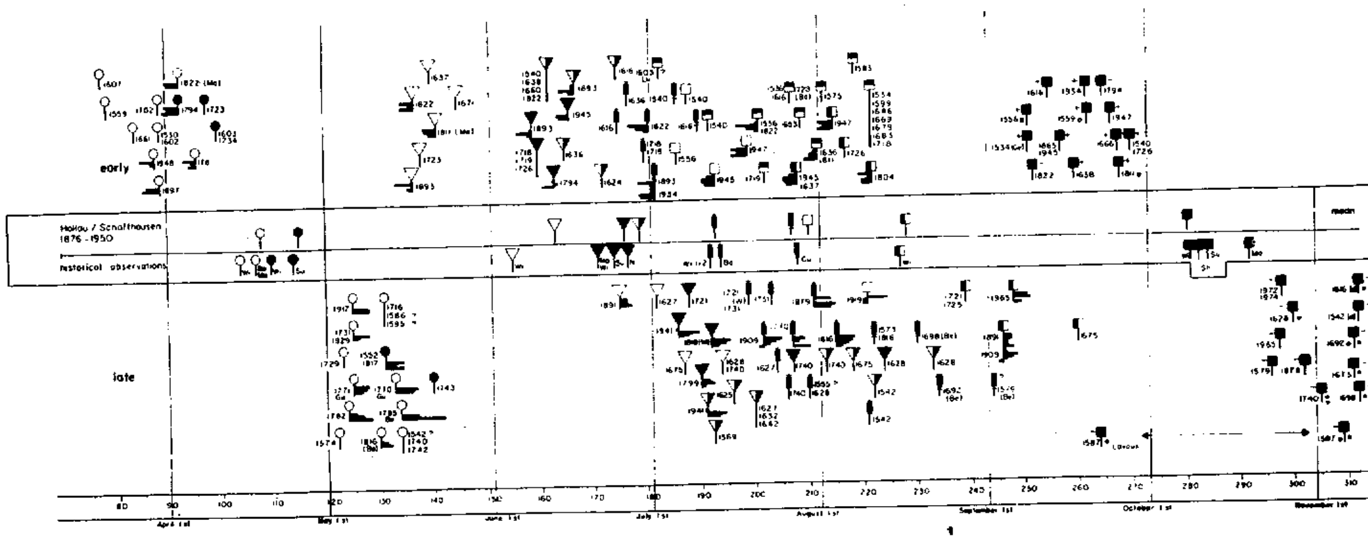
If the cherry flower were advanced by more than two weeks, we may conclude that either February and March had been much

6 Richard J. Hopp, "Plant Phenology Observation Networks," in Lieth, *Phenology*, 25–43, for a survey of the historical series and an exhaustive bibliography. From 1611 to 1644 the beginning of the rye harvest is reported in the "Chronicle of Abraham Künzli," unpub. ms., Stadtbibliothek, Winterthur Ms. Q 72. For 1721 to 1738, Pfister, "Zum Klima des Raumes Zürich im späten 17. und frühen 18. Jahrhundert," *Vierteljahrsschrift der Naturforschenden Gesellschaft Zürich*, CXXII (1977), 447–471. For 1760 to 1802, *idem*, *Agrarkonjunktur und Witterungsverlauf im westlichen Schweizer Mittelland* (Bern, 1975), 73–78. For the nineteenth and twentieth centuries, *idem*, "Local Phenological Time Series from the Canton of Schaffhausen (Switzerland) and their Application for the Interpretation of Historical Records," unpub. ms.

7 An exception is the events of the Winterthur series (1721–1738), which are considerably more advanced than the recent means, and may be attributed to the high frequency of early springs in the 1720s.

8 H. Arakawa, "Twelve Centuries of Blooming Dates of the Cherry Blossoms at the City of Kyoto and its own Vicinity," *Geofisica pura e applicata*, XXX (1955), 36–50. The results for Unter-Hallau agree well with those of Bider, "Untersuchungen," 9–10.

Fig. 1 Extremes of Vegetative Development, 1525–1825 in the Swiss Lowlands (400–500 m).[a]

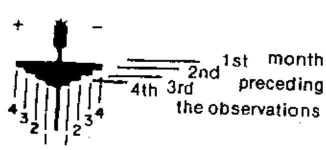


Legend for Fig. 1

- sweet cherry 1st flower
- vine 1st flower
- vine last flower
- spelt start of harvest
- grapes Red Burgundy change colour
- vine start of harvest
- mean of several series
- sweet cherry full flower
- vine full flower
- rye start of harvest
- grapes Early Burgundy change colour
- first grape ripened (Early Burgundy)
- quality of vine: + good, − poor
- snowfall
- frost

Temperature Index:

deviation from mean 1901 - 60 (°C)



Historical series and single observations outside the altitude range 400 - 500 m

Ba	Basel	256m	
Ba	Batterkinden BE	473m	1718 - 70
Be	Bern	540m	1780 - 1827
Ge	Geneve	375m	
Gu	Gurzelen BE	591m	1766 - 84
Ma	Maschlins GR	534m	1792 - 1818
N	Neuchatel	447m	1701 - 50
Sh	Schaffhausen	403m	1616 - 70
Su	Sutz BE	463m	1785 - 1803
Wi 1	Winterthur	443m	1611 - 44
Wi 2	Winterthur	443m	1721 - 38

a Figure 1 provides a survey of means, maxima, and minima of selected phenological events, both modern and historical. The dates have been converted to days of the year and are shown on the x-axis. Symbols are used to express the different phenophases. Within the frame, which divides the graph into an upper and a lower part, the means are represented; the recent ones have been taken from the Schaffhausen series, and the historical ones from various records, which are listed in the legend. The earliest single events, which are contained in the historical and the recent record, are plotted above the frame, whereas the latest ones are plotted below.

Because the date of phenological events is also affected by altitude, the documentation refers mainly to phenophases observed at altitudes from 400 to 500 m (events outside this range are marked with letters in parentheses). Differences in exposure were not considered. Whenever an event occurred after the beginning of the thermometrical measurement in Basel (1755), horizontal bars are drawn, which represent the deviations of temperature from the 1901 to 1960 average (positive to the left, negative to the right) during the preceding months. Thus observations which are calibrated with measured temperatures can easily be compared with data from the pre-meteorological period.
SOURCE: CLIMHIST data bank.

Table 2 Selected Phenophases at the Meteorological Station of Unter-Hallau (alt. 430 m) in Northern Switzerland and Their Response to Temperature

PHENOPHASE	N	MEAN DATE	DETERMINED BY TEMPERATURES IN				
				PARTIAL R^2		PARTIAL R^2	TOTAL R^2
Sweet cherry flower	54	April 16 (day 106)	March	48	April	12	60
Vine first flower	61	June 9 (day 160)	May	59			59
Rye start of harvest	45	July 12 (day 193)	May	18	June	29	47
Wine harvest (variety Red Burgundy)	70	Oct 7 (day 280)	April to June	54	July to Sept	9	63

N = number of observations
R^2 = proportion of total variance explained by the mean temperature of the listed months.
SOURCE: Pfister, "Local Phenological Time Series."

above average (1822, 1897, 1794) or that January had been extraordinarily warm and February and March had been somewhat above average (1948). For 1607, when the cherry blossom appeared four weeks too early, Renward Cysat reported that there was no winter at all. The ground was never frozen or covered with snow, the sun shone most of the time, the vegetation did not come to a standstill, and people were wearing summer clothes. We may estimate that during this "year without a winter" January and February may both have been as warm as March, on average, which has never been the case from 1755 to the present. The cherry blossomed nearly as early in 1602 and 1603. However, Cysat reports considerable delays in the spring vegetation in 1600, 1601, and 1608, which suggests that outstanding weather patterns prevailed in spring during that first decade of the seventeenth century.[9]

A delay of flowering by three weeks or more suggests that the March-April period may have been at least 5° too cold. An extreme case was March 1785, which was 8° below the mean. The delays in 1716, 1740, 1770, and 1817 can be attributed more to an unusually cold April.[10]

9 Renward Cysat (ed. Joseph Schmid), *Collectanea pro Chronica Lucernensi et Helvetiae* (Luzern, 1969), I, Pt. 2, 907, 908, 945.

10 Bider, Max Schüepp, and Hans von Rudloff, "Die Reduktion der 200 jährigen Basler Temperaturreihe," *Archiv für Meteorologie, Geophysik und Bioklimatologie*, IX (1959), 360–412. Examples for 1716 and 1740 are contained in the CLIMHIST data bank.

Vine flower. We should consider only the observations which were carried out in an open vineyard. Plants which are sheltered by the wall of a house will flower considerably earlier. Differences in varieties, however, can be neglected. Although the first flower is advanced or delayed mainly according to temperature in May (see Table 2), an early flower may also follow a very warm April, as was the case in 1811 and 1893 and, according to descriptive evidence, in 1723. The times of the full bloom and the last flower vary with temperatures in both May and June. In all those years, for which an early flowering was reported (e.g. 1636–1638, 1660, and 1718), the wine harvests throughout Central and Western Europe were also very advanced. Thus if the evidence suggests that the vine flowering ended in the first half of June, the advance of the wine harvest should be credited mainly to the warmth of spring.[11]

Extreme delays (1542, 1627, 1628, 1632, 1642, 1675, and 1740) were much more frequent and much more pronounced than extreme advances.

Start of cereal harvest. Today the decision to begin the harvest is made by an individual and, therefore, is affected by economic and social factors as well as purely climatic ones. But, while the three field system was in use (i.e. until the early nineteenth century) agreement was reached jointly by the farmers of a village. In the eastern part of Switzerland, where spelt and rye were grown, the latter was harvested about two weeks earlier on averge. The maturity of rye is controlled by temperatures in June and, to a lesser extent, by those in May (see Table 2). Again the very early rye harvests (1616, 1636, 1718, 1719, and 1822) as well as the earliest spelt harvest (1540) were clearly connected to very early wine harvests.

11 Hermann Trenkle, "Die Verwendung phänologisch-klimatologischer Beobachtungen bei der Gütebewertung von Weinbergslagen," *Weinwissenschaft*, XXIV (1969), 327–338. The significance of temperatures in May for an early flowering is also emphasized by Ernst Peyer and Werner Koblet, "Der Einfluss der Temperatur und der Sonnenstunden auf den Blütezeitpunkt der Reben," *Schweiz. Zeitschrift für Obst-und Weinbau*, CXII (1966), 250–255; W. Hofäcker, *Einfluss von Umweltfaktoren auf Ertrag und Mostqualität der Rebe* (Hohenheim, 1974); Becker, "Oekologische Kriterien für die Abgrenzung des Rebgeländes in den nördlichen Weinbaugebieten," *Weinwissenschaft*, XXXII (1977), 77–102. Emmanuel Le Roy Ladurie and Micheline Baulant, "Grape Harvests from the Fifteenth through the Nineteenth Centuries," in this issue, provides a main series composed from 102 local series of wine harvest dates.

Delayed harvests of rye and spelt reflect temperatures from May to July. Those in 1816 and 1879 were affected by extremely low temperatures, which were the lowest ever recorded in Basel during that period. Again the most deferred cereal harvests agree almost completely with the latest vintages of the little ice age (1542, 1879, 1740, 1816, 1698, 1555, 1628, and 1573).[12]

Maturation of grapes and date of the vintage. Chronicles from vine-growing regions frequently reported the date on which the coloration of grapes was observed for the first time or gave the date on which the first grape reached maturity. In interpreting this evidence we have to differentiate between early and late varieties.[13]

Wine harvest dates have been taken as good proxies for mean temperatures during the period between April and September, and may give a general idea of the spring-summer temperatures for the last 500 years. If, however, we want to crossdate wine harvest dates with more detailed qualitative information and use them to estimate the temperature patterns of a particular season or month, a more sophisticated model is needed. A multivariate statistical analysis of the Unter-Hallau series has revealed that wine harvest dates are more closely correlated with temperatures from April to June than with those from July to September (see Table 2).[14]

Several authors have shown that the growth of the grapes after fructification includes a phase of standstill of up to three weeks in duration which, in locations with favorable climatic conditions, occurs in August; this could explain the non significant correlation for this month. The low impact of temperatures in April and September may reflect the fact that growth is not

12 *Ibid.*

13 According to Figure 1 the coloration of the Early Burgundy grape, which was very widespread in the past, sets in fifteen days earlier than that of the Red Burgundy (Pinot Noir) grape. According to Trenkle, "Weinbergslagen," the mean date for the Müller Thurgau grape is Oct. 6, and for the Riesling is Oct. 29, to mention the extremes.

14 Marcel Garnier, "Contribution de la phénologie à l'étude des variations climatiques," *La Meteorologie,* XL (1955), 291–300; Le Roy Ladurie (trans. Barbara Bray), *Times of Feast, Times of Famine: A History of Climate Since the Year 1000* (Garden City, 1971), 50; Le Roy Ladurie and Baulant, "Grape Harvests." Correlations with the monthly mean temperatures: June (−.59), significance 0.001; May (−.54), significance 0.001; July (−.34), significance 0.03; September, April, and August were not significant.

activated as long as temperatures are below 10°. The duration of daylight, which plays an important role, could also account for the importance of temperatures in early summer.[15]

It is not surprising that the very late wine harvest dates show almost no temporal dispersion. If the grapes failed to reach maturity, which was not unusual in the Swiss vineyards during the little ice age, the harvest decision was triggered by early frosts and snowfalls. Thus these dates are not really conclusive for the rank order of the coldest spring-summer seasons.

Instead of focusing upon the analysis of certain phenophases, the whole pattern of phenophases from spring to autumn may be examined. From Figure 1 two types of phenophases can clearly be distinguished.[16]

1. *All phenophases advanced*
   - Documented with temperature measurements: 1781, 1794, 1811, 1822, 1893, 1934, and 1945.
   - Cases from the pre-meteorological period: 1540, 1559, 1599 (evidence not entirely reliable), 1603, 1604, 1637, and 1719.[17]
   - Temperature pattern: (derived from the Basel series) two or all of the spring months and June above the 1901–1960 average; July, average or above.
2. *All phenophases delayed*
   - Documented with temperature measurements: 1770, 1816, 1817, 1879, 1891, and 1909.
   - Cases from the pre-meteorological period: 1542, 1573, 1627, 1628, 1716, and 1740.
   - Temperature pattern derived from the Basel series: at least four months from March to July below the 1901–1960 average.

15 Peyer and Koblet, "Blütezeitpunkt"; G. Alleweldt, "Der Einfluss des Klimas auf Ertrag und Mostqualität der Reben," *Rebe und Wein,* XX (1967), 312–317; Pierre Basler, "Beeinflussung von Leistungsmerkmalen der Weinrebe (Vitis vinifera L.) in der Ostschweiz durch Klimafaktoren und Erträge sowie Versuch einer Qualitätsprognose, *Weinwissenschaft,* forthcoming.

16 The list is not exhaustive. The evidence not represented in Figure 1 is contained in the CLIMHIST documentation.

17 In 1540 the vine was possibly retarded by extreme drought and high temperatures in July and August, as happened in 1947: *Bericht über den Weinbau des Kantons Schaffhausen* (Schaffhausen, 1947), 6; Becker, "Oekologische Kriterien," 89.

Major changes in the intervals between phenophases may also be indicative of a significant deviation from the mean temperature. A shortening always indicates that temperatures during the interval have been above average. In 1934, when May was almost 2° above the mean, the interval between the first sweet cherry flower and the first vine flower (fifty-four days on average) was only twenty-eight days. Similar cases (twenty-nine days in 1726 and thirty-two days in 1731) are supported with descriptive evidence. A drastic shortening of the interval between the first vine flower and the start of the rye harvest, about two weeks compared with thirty-three days on average, occurred in 1616. The rye reached maturity even six days earlier than in 1822, which was the hottest June since 1755 (4° above the 1901–1960 average). This early date suggests that the heatwave in June 1616, which is impressively described in the sources, was the most severe since at least 1525.

Major delays between phenophases indicate that temperatures during the interval were below average. In 1916, when the mean duration of vine flowering in the vineyards of the Canton of Zurich was twenty-seven days instead of nineteen days, on average, June was 3° below the 1901–1960 mean. In 1628 and 1740 the first vine flowers in the vineyards of Schaffhausen appeared around July 10. But, although the duration of flowering was average in 1740, which suggests a July temperature around the mean, it was extended some thirty-five days in 1628 (see Fig. 1). This late flowering points to an extreme cold spell, which is consistent with the high number of snowfalls on the alpine pastures reported from the same summer.[18]

RYE HARVEST DATES AND THEIR CLIMATOLOGICAL SIGNIFICANCE

It has been shown that the phenological observations of the chroniclers and early amateurs can be used as a yardstick to measure the thermal deficit or excess of the most extreme seasons of the little ice age. But even if we were to compile many documents of this type, we could never hope to bring together a continuous and homogeneous record.

However, the series of wine harvest dates collected by Le Roy Ladurie is a model. His series was obtained from purely administrative documents, which were kept regularly year after year. Le Roy Ladurie made a similar attempt with cereal harvest dates for the south of France, but discarded this evidence, perhaps because the series was too rough and short.[19]

I have discovered in several Swiss archives a new type of climatic evidence which can be obtained by extracting tithe figures from county accounts. With these figures it is possible to draw up a long, continuous, and homogeneous series of valid proxies for grain harvest dates. Such a series enables us to make temperature estimates for the May-June period and to support our estimates with descriptions of particularly hot and cold spells from weather diaries.

Tithes paid in kind are known to be a fair guide to the size of grain harvests. They were influenced by several variables, notably the percentage tithed of the harvest, the acreage under cultivation, and the yield per acre. Yields per acre are known to be a function of the quantity and quality of labor input, the amount of fertilizer applied, and the meteorological conditions. But as Slicher van Bath has cautioned, the relationship between plant growth and weather patterns is more complicated than is assumed; in the case of wheat and winter grains in the temperate zone, the weather patterns affecting growth fall into eight different phases and extend over a twelve-month period.[20]

An element of the tithe accounts that has turned out to be sensitive to climate is the date of the tithe auction. Before the early nineteenth century the right to collect tithes from certain areas was sold by auction to tithe-farmers, who carried out the work of tithe collection for provincial governors and were entitled to keep a small proportion of the revenue for themselves.[21]

18 Bider et al., "Basler Temperaturreihe"; CLIMHIST documentation.

19 Le Roy Ladurie, *History of Climate*, 50, 271.

20 Francois Jeanneret and Philippe Vautier, *Kartierung der Klimaeignung für die Landwirtschaft in der Schweiz* (Bern, 1977); Pfister, *Agrarkonjunktur*, 111–121, for the past; Bernhard Stauffer and Alfred Lüthi, "Wirtschaftsgeschichtliche Quellen im Dienste der Klimaforschung," *Geographica Helvetica*, XXX (1975), 49–56, provided a significant correlation between a tithe curve from the Canton of Argovia (northern Switzerland) and the changing ratio of oxygen in an ice core from Camp Century, Greenland. B. H. Slicher van Bath, "Agriculture in the Vital Revolution," *Cambridge Economic History of Europe* (Cambridge, 1977), V, 42–132.

21 Pfister, "Climate and Economy in Eighteenth Century Switzerland," *Journal of Interdisciplinary History*, IX (1978), 223–243.

In order to assess the size of the harvest, the fields were inspected by peasants hired by the governor some days prior to the auction, which in turn preceded the beginning of the harvest. In several tithe accounts the date of the auction appears regularly every year, whereas in others it is missing. It can be shown that the dates of inspection and auction were carefully chosen according to the ripeness of the grain. "The tithes in the mountains [at altitudes of 600 to 800 m] have not been inspected yet because the fields are still far from maturity and yields cannot be assessed properly at this time," wrote the governor of the County of Bipp to the Council of Bern on August 8, 1770. But it was risky to delay the auction until the grain was overripe, because the kernels could drop out of the ears, as was reported in 1806. Often the tithe districts, tributary to a corporation or a governor, were situated at different altitudes. Thus appropriate auction dates, up to five in some counties, had to be fixed for each altitude.[22]

The mean dates of the series are essentially a function of altitude. The higher a set of districts was situated, the later the auction took place on average. The mean delay was 4.6 days per 100 m, which corresponds exactly to the figure obtained by Volz from similar modern data.[23]

Tithe auction dates can therefore be used as substitutes for phenological observations in the same way as wine harvest dates. A variety of non-climatic factors must also be taken into account, in particular the time constraints of the governor or his delegate.

Because no dated tithe auction records have survived from the sixteenth century and because tithes were gradually abolished in the nineteenth century in return for a compensation, tithe auction dates cover only a little more than 200 years (1611–1825). The forty-two series which could be brought together varied in length and were in most cases highly correlated.

Those records of sufficient length were aggregated into a main series. Within the interval for which there were thermometrical measurements the residuals were compared with the May and June deviations of the temperatures in May and June from the 1901–1960 average. The timing of the tithe auction allowed an estimation of temperature deviations in the May–June period

22 *Idem*, "Getreide-Erntebeginn und Frühsommertemperaturen im schweizerischen Mittelland seit dem frühen 17. Jahrhundert," *Geographica Helvetica*, XXXIV (1979), 23–35.
23 Volz, "Phänologische Karte," 48.

with a standard error of 0.6°C. An advance or a delay of the auction date by seven days corresponded roughly to a deviation of 1° from the 1901–1960 average in May and June. Cross-dating with descriptive evidence suggests that the proxy underestimates the size of the anomaly.[24]

Tithe auction dates were also highly correlated with the main series of wine harvest dates from Western and Central Europe.[25] Figure 2 compares the mean residuals of tithe auction dates with temperatures in May–June in central England. In general the fluctuations of the tithe curve and the temperature curve in central England are in good agreement.[26] The high frequency of extreme years at the beginning of the series is striking, notably during the intervals 1611–1617 and 1626–1638.

Comparisons with the present, which can be made from two phenological series, are conclusive. Whereas the mean of the early series on the rye harvest from Winterthur (1611–1644) is exactly the same as in the Unter-Hallau series (1888–1950) (see Fig. 1), the standard deviation is nearly twice as large. This reflects an enhanced variability of temperature from spell to spell and from year to year, which, according to Lamb, is characteristic of regimes with frequent blocking, or meridional (north–south) circulation patterns in middle latitudes. As mentioned above, springs and winters from 1600 to 1610 were frequently affected by similar weather patterns.[27]

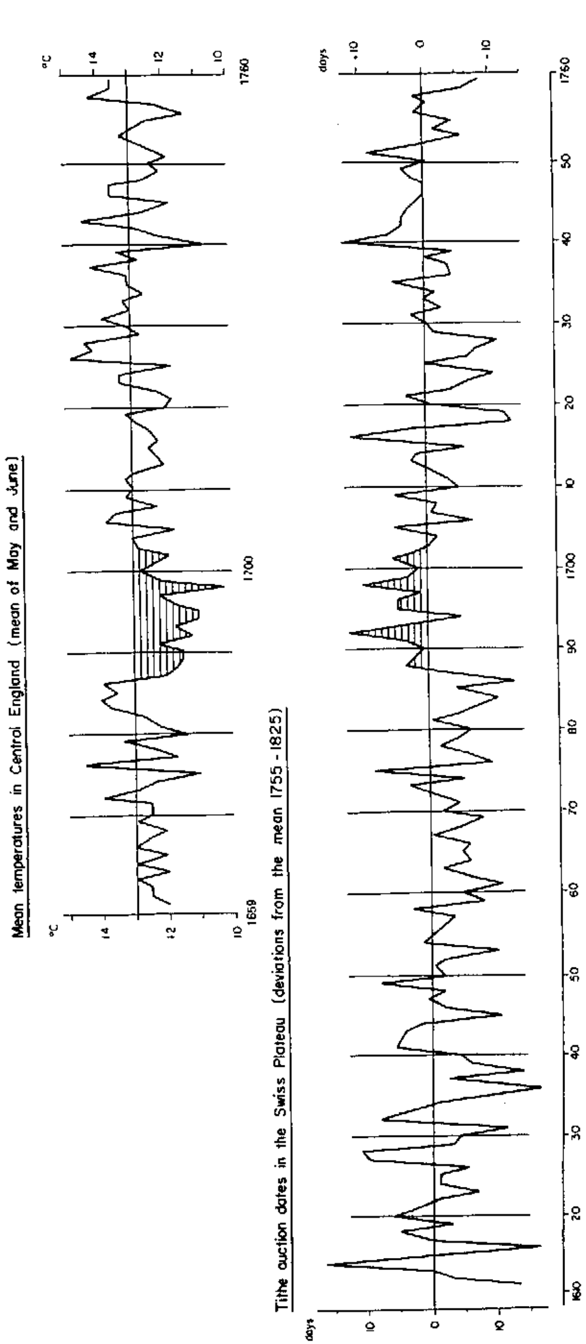
Two major episodes in the climatic history of the seventeenth century, the warm period from 1676 to 1686 and the cold years from 1687 to the turn of the century, are clearly shown in the curve in Figure 2. From the interpretation of the tithe curve and the body of descriptive evidence it may be derived that the sharp contrast between the two periods operated mainly through a

24 The model is as follows: $Y' = 0.056 - (0.13676 * TR)$ where Y' is the estimated deviation of the temperatures in Basel in May-June from the 1901–1960 average, and TR the residual of the aggregated series of tithe auction dates.

$R^2 = .64$ standard error: .6°

Harold Fritts et al., "Past Climate Reconstructed from Tree Rings," in this issue, have observed the same feature in tree-ring structure.
25 Coefficient of correlation r = .7 for 209 paired observations. Significance 0.0001.
26 Coefficient of correlation r = .68 for 95 paired observations. Significance 0.001. Major deviations are revealed in the early 1660s, where the May-June period in Switzerland was warmer than in England.
27 Hubert H. Lamb, *Climate: Present, Past and Future* (London, 1977), II, 465–466.

Fig. 2 Comparison of the Tithe Auction Dates in the Swiss Plateau and Central England Temperatures in Early Summer.



SOURCES: Temperature: Gordon Manley, "Central England Temperatures," *Quarterly Journal of the Royal Meteorological Society*, C (1974), Table 1. Tithe auction dates: Pfister; "Getreide-Erntebeginn und Frühsommertemperaturen," *Geographica Helvetica*, XXXIV (1979), Graph 4 (revised).

change in the prevailing weather in May. This month was repeatedly sunny, warm, and dry from 1676 to 1686. Then suddenly it became dull, chilly, and wet for more than a decade. These cold spells did not always extend over all of the summer months, as we might conclude from the prevailing interpretation of the wine harvest dates. Similarly temperatures in May (and sometimes June) retarded the vegetation during the 1740s. In both cases the interpretation of the retreats and advances of the two Grindelwald glaciers, by far the best documented in the historical past, pose contradictions as long as the wine harvest dates are taken as indicators of the quality of the summer months.[28]

FLUCTUATIONS OF VINE YIELDS AND MIDSUMMER TEMPERATURES

As an indicator of climate the grapevine has three major advantages:

1. The plant remains the same for twenty to fifty years. No annual planting is required.

2. The entire length of the growing season from March/April to October is needed to bring the grapes to maturity.

3. Harvest date, yield per acre and wine quality can be used as climatic proxy evidence for three different periods of the growing season: late spring/early summer, midsummer, and late summer/early autumn.

In comparison with the date of the harvest quantity and quality of wine have not often been utilized for the reconstruction of past climates, probably because reliable data from the preinstrumental period are difficult to find and because their interpretation is controversial.

Wine quality. Weger and Rima have found a cyclical quality in a bisecular series of wine yields from the estate of Johannisberg in the Rineland, which could be related to the fluctuations of sunspots. Wright has shown that the good and bad wine years in Luxemburg from the seventeenth century varied according to the warmth of summers in central England. Further back in time is the well-known wine chronicle for southern Germany by

28 Bruno Messerli et al., "Die Schwankungen des Unteren Grindelwaldgletschers seit dem Mittelalter. Ein interdisziplinärer Beitrag zur Klimageschichte," *Zeitschrift für Gletscherkunde und Glazialgeologie*, XI (1975), 12–50, 78.

Müller, which lists contemporary opinions on the size and the quality of the harvest from 1 A.D. to 1950.[29]

Wine quality is generally a function of aggregate temperatures in summer and early autumn. But, when comparing temperatures with Oechsle ratings, we must remember that quantity interferes somewhat with quality, i.e. the higher the yields per acre the lower the sugar content will be under the same climatic conditions. For this reason the use of standardized Oechsle ratings (°Oe at kg/m²) is recommended. Basler has found very high correlations in different wine growing regions of eastern Switzerland (R^2 of .92 to .95) between the temperatures at noon above 12° to 15°C aggregated from June to the date of the harvest. The correlation with August, however, was found to be significantly lower than for the other months.[30]

In the past the qualities were described in such terms as mediocre, excellent, and bad. Although we cannot be sure that the absolute standards of taste have not changed over the centuries, comparisons have shown that these subjective estimates of quality do agree rather well with the Oechsle ratings. Unfortunately most wine chronicles are non-contemporary for most of the period covered; the famous work of Müller is, for instance, not entirely based on verified sources and should be used with great care. In addition, Weise points out the large variance from one vineyard to another and recommends against analyses of isolated series.[31]

29 Nilolaus Weger, "Weinernten und Sonnenflecken," *Berichte des Deutschen Wetterdienstes in der US-Zone,* 38 (1952), 229–237; Alessandro Rima, "Considerazioni su una serie agraria bisecolare; la produzione di vino nel Rheingau (1719–1950)," *Geofisica e Meteorologia,* XII (1963), 25–31; Peter Wright, "Wine Harvests in Luxembourg and the Biennial Oscillations in European Summers," *Weather,* XXIII (1968), 300–304; Karl Müller, *Geschichte des Badischen Weinbaus* (Lahr, 1953).

30 At the beginning of the nineteenth century Ferdinand Oechsle from Pforzheim invented an instrument to weigh the sugar content of wines. The degrees Oechsle (°Oe) indicate the specific weight of the grape juice (SWJ): SWJ = °Oe + 1000. The sugar content in grams equals about twice the Oechsle rating. A wine of 80° therefore has a specific weight of 1080 g and a sugar content of 160 g. Basler, "Beeinflussung"; Becker, "Oekologische Kriterien," 80; Hofäcker, *Einfluss von Umweltfaktoren,* 36–38; Müller, *Weinbaus,* 241; N. E. Davis, "An Optimum Summer Weather Index," *Weather,* XXIII (1968), 305–318; Rudolf Weise, "Ueber die Rebe als Klima Kriterium," *Berichte des Deutschen Wetterdienstes in der US-Zone,* 12 (1950), 121–123.

31 Wright, "Luxembourg," 302; Edmond Guyot and Charles Godet, "Le climat et la vigne," *Bulletin de la Société des Sciences Naturelles de Neuchâtel,* LX (1935), 218. Weise, "Rebe als Klima Kriterium," 123.

Wine quantity. Yields per acre are not only affected by climate but, in the long term, also by a change in varieties, manuring, cutting, and the technique of cultivation. Climatic factors, together with diseases, may only help to explain the short-term fluctuations from year to year. Detailed analyses of yield series have been made in order to determine the weight of the different components which may affect the size of the harvests.[32]

Based on a period of sixty-two years (1871–1932) for which the mean yield per acre in the Canton of Vaud (western Switzerland) was available, Guyot and Godet found that temperatures in July and August significantly affected yields. If these months were hot and sunny and at the same time the plants could find enough water in the soil, a plentiful yield could have been expected. If cold and wet spells occurred in June and early July, they affected the flowering. Similar conditions in July and August affected the growth of the grapes as well over very large areas. The obvious damage caused by late frost and hail, however, varied considerably from one vineyard to another and was less significant, as can be seen from an analysis of the yield series of several wine growing regions. In addition, widespread and heavy damage by frost, such as occurred in 1709 and 1740, was always reported by a great number of weather chroniclers and vine growers and can therefore be considered in the interpretation. Also the burgeons that were killed by late frost were often replaced by supplementary burgeons. We may therefore conclude that a careful analysis of several series of wine yields from rather distant areas may well reveal fluctuations of temperatures in the summer months.[33]

32 Hans Schwarzenbach, *Die Produktivitätsentwicklung im schweizerischen Weinbau* (Bern, 1963), 11; Bernard Primault, "Le climat et la viticulture," *International Journal of Biometeorology,* XIII (1969), 7–24.

33 Guyot and Godet, "Le climat et la vigne," 209–223; Guyot, "Calcul de coefficients de corrélation entre le rendement du vignoble neuchâtelois, la température et la durée d'insolation," *Bulletin de la Société des Sciences Naturelles de Neuchâtel,* LXV (1940), 5–15; Koblet, "Fruchtansatz bei Reben in Abhängigkeit von Triebbehandlung und Klimafaktoren," *Weinwissenschaft,* XXI (1966), 297–323; Primault, "Climat et viticulture," 17. Müller, *Weinbaus,* 244, points to the fact the several diseases, in particular infection with the peronospora fungus, was only observed in wet summers. Weger, "Weinernten und Sonnenflecken," 234. The burgeons survive temperatures of −3.5°C unless they are dry; wet burgeons are killed at −1.5°C, especially through hoarfrost. The plant also stands

In contrast to grain harvests, which are increasingly well documented through tithes, little is known historically about wine production. This is probably because the annual fluctuations in grain harvest yields are more conclusive for a historian, who is concerned with demography, agrarian legislation, and the social impact of subsistence crises. Although wine was also an important staple food, substitute beverages were readily available.[34]

In what follows I outline and discuss the climatological significance of the evidence drawn from several Swiss archives.[35]

In most counties of the two protestant states of Bern and Zürich, which were either situated in vine-growing areas or had inherited possessions from ancient religious orders, a part of the governors' revenues was paid in wine. In some cases the nature of the payments was not specified in the sources; more frequently, we know that they came from vineyards which were cultivated by individual vine-growers in return for a third or half of the yield. The governor in his turn took the other half or two thirds of the harvest. This suggests that those revenues directly reflected variations in yields. A sample of several local series was taken from each major vine-growing region on the Swiss plateau. Subsequently, four regional series and a main series were aggregated from these data.[36]

Occasionally, the size of the individual vineyards, from which the payment came, was specified in a source, which allows computation of yields per acre. The longest series of that kind (1538–1838) could be drawn from the account books of the ancient foundation of Fraumünster in Zürich. From the data for which the size of the vineyard was specified in the source, a series of mean yields per acre was computed.

extreme winter temperatures up to −20°C when the cold spell sets in early enough. Primault, "Climat et viticulture," 9; Alfred Schellenberg, *Weinbau* (Frauenfeld, 1966), 94ff.

34 Joseph Goy and Le Roy Ladurie (eds.), *Les fluctuations du produit de la dîme. Communications et travaux* (Paris, 1972). A considerable number of new tithe series from many European countries were presented at the conference on "Prestations paysannes, dîmes, rente foncière et mouvement de la production agricole" (Paris, 1977).

35 Pfister, "Die Fluktuationen der Weinproduktion im Schweizer Mittelland vom 16. bis ins frühe 19. Jahrhundert," *Schweizer Zeitschrift für Geschichte*, XL (1980), forthcoming.

36 *Ibid.* The main series was composed from the residuals of the local series, which could all fairly be described through linear trends. It was assumed that those trends included mainly changes in the surface cultivated and long term changes in yields per acre.

A comparison of the main series of yields, for which the size of the vineyards was not known, with the series of mean yields per acre produced a highly significant correlation coefficient of 0.85. Thus, we may conclude that the former series for the most part reflects fluctuations of yields per acre. Also, it turned out that the residuals of the regional series were significantly correlated among each other as well as with the individual series of yields per acre. This is consistent with the observations of Müller and Weise, who noted that in Germany years of plenty and years of dearth mainly agreed, even between rather distant vine-growing regions.[37]

The Basel series was again used for the comparison of the wine yields with the temperatures of the individual months. A stepwise regression analysis yielded that July had the greatest weight, with r = .43, which is consistent with the result obtained from recent data, where r was .46. Taken together, the temperature of the three summer months could explain 46 percent of the variance in the yield curve. The hypothesis that wine years from the historical past are valid indicators of summer temperatures was also confirmed through the significant correlations with the tithe auction dates and the wine harvest dates.[38]

The trends of the curve in Figure 3 reflect the major phases of the little ice age: the long term drop over the six decades from 1530 to 1600 took, after 1560, the form of clusters of bad years, which become increasingly long, frequent, and pronounced. Among the thirteen years from 1585 to 1597 all except one (1593) provided yields below the long term trend; in the worst cases (1588 and 1589) the grapes collected in some vineyards hardly filled a hat. This patch of cold wet summers also saw quick and far-reaching advances of the alpine glaciers during the 1590s. Another cluster of bad wine years (1618–1629) preceded a wave of glacial activity after 1630.

From 1630 the curve climbs steadily up to the turning point in 1687, which introduces the barren 1690s. During the first two

37 Coefficient of correlation r = .85 for 266 paired values. Significance 0.00001. A correlation matrix is provided by Pfister, "Weinproduktion." Müller, *Weinbaus*, 240; Weise, "Rebe als Klima Kriterium," 122.

38 Guyot and Godet, "Le climat et la vigne." Vine yields correlated with tithe auction dates: coefficient of correlation r = .49 for 187 paired values. Significance .0001. Vine yields correlated with Swiss wine harvest dates: coefficient of correlation r = .36 for 187 paired values. Signifiance .001.

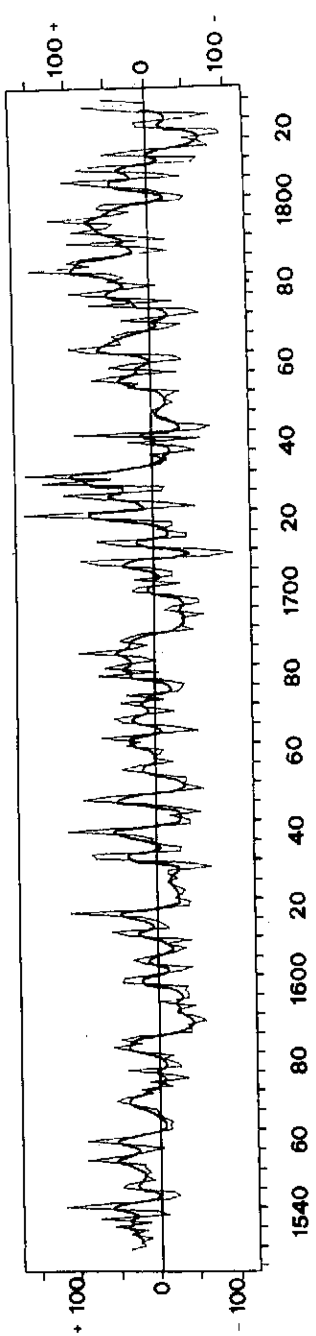


Fig. 3 Fluctuations in Wine Yields at the Swiss Plateau, 1530–1825[a]

SOURCE: Pfister, "Flukuationen."

a Average of 14 local series from the major vine-growing regions, represented as deviations from the mean (%).
The bold line marks a five-year running mean.

decades of the eighteenth century the trend was uneven. Suddenly, from 1719 to 1729 the vine became exuberant. From Lake Geneva to the Rhineland wine casks overflowed; the glaciers, after a secondary peak around 1720, retreated. In the following five decades a change to moderate slumps and peaks becomes observable and can clearly be connected to minor episodes of glacial history. The abundance of wine around 1780, comparable to that of the 1720s, was also witnessed in the vineyards of France and Germany. From 1794 the curve descends to its lowest point in 1816, the year without a summer. Again, in the following years, quick and far-reaching glacial advances occurred.[39]

Although the fluctuations of vine yields and wine harvest dates were roughly parallel, some inconsistencies should not be overlooked. Sometimes, notably in the second half of the 1580s and of the 1620s, the slump in vine yields was more marked than the delay of wine harvests. Given the presumption that wine harvest dates were strongly responsive to temperatures in spring and early summer, whereas vine yields were chiefly indicators of temperatures in midsummer, in both periods midsummers may have been notably colder than springs and early summers. For 1588, 1589, 1622, and 1625, where the differences were most striking, this pattern can be supported by descriptive evidence.[40]

The wine boom of the 1720s and the 1780s, however, was not accompanied by a proportionate advance of wine harvest dates. Three tropical summers occurred in both decades (1723, 1727, and 1729, 1781, 1783, and 1788). They were all very warm with frequent thunderstorms, which stimulated the yields of wine far beyond normal. The wine boom of those years may also be explained by the fact that the previous summers were warm. According to experts in vine-growing, warmth increases the number of flowers in a following spring.[41]

Thus wine yields, like tithe auction dates, not only support the evidence of the wine harvest dates; if they are properly mar-

39 Rima, "Produzione di vino nel Rheingau," 26; Tisowksy, "Häcker und Bauern in den Weinbaugemeinden am Schwanberg," *Frankfurter Geographische Hefte, XXXI* (1957), 50; Heinz J. Zumbühl, *Die Schwankungen der Grindelwald-Gletscher inden historischen Bild- und Schriftquellen des 12. -19. Jahrhunderts* (Zürich, 1980); Le Roy Ladurie, *History of Climate*, 207.

40 See CLIMHIST data bank.

41 Müller, *Weinbaus*, 240.

shalled and studied in their ecological context, they may give us more detailed knowledge of the character of past summers. Such knowledge may then help to explain some of the inconsistencies which still exist between the evidence from glacial and from proxy data.

In addition, the analysis of wine yield series may also be conclusive for the economic history of the vine-growing regions of Central Europe. The evidence suggests that wine-growers lived through the parallel coincidence of good and poor yields, a common economic experience, which was closely tied to climatic history.

THE COMPILATION OF INDICES Climatic history may be analyzed in two ways. The first approach relates field data to a complex of climatic variables, and traces their fluctuations back in time. Although the time resolution of some data may be high, it is always restricted to a specific season or interval. In addition, most field data and historical proxy data respond to a complex of meteorological variables, chiefly rainfall and temperatures, which are difficult to disentangle. Also, the response is in most cases a function of the weather patterns during several months.

The second approach, which should rather be called weather history, analyzes different kinds of descriptive evidence, very accurately dated and related to specific meteorological events, which can only occasionally be used to estimate temperature or rainfall. One form of analysis of this fragmentary type of information is to transform the material into a numerical index prior to interpreting it in terms of standard meteorological variables. Indices of wetness and winter severity were first derived by Brooks and Easton in the 1920s. After 1960 this work was refined by Lamb, who computed decadal indices via compilations from chronicles, annals, diaries, and similar sources.[42]

The present approach attempts to bridge the gap between climatic history and weather history by cross-dating different kinds of field data (such as tree ring densities and glacial advances) and documentary proxy data (such as phenological observations, paraphenological data, and wine yields) with the large number of descriptive records in the CLIMHIST data bank, in order to obtain rough estimates of temperature and wetness for individual months. Two types of indices are derived, a weighted and an unweighted one. For the construction of a *weighted thermal index* and a *weighted wetness index*, which are described in more detail elsewhere, weight factors ranging from +3 to −3 have been applied. In order to derive the thermal index proxy data were used to assess the magnitude of a temperature deviation from the long term mean, whereas the exact timing of the corresponding warm or cold weather spell was obtained from descriptive evidence. The wetness index is based upon the number of rainy days counted in weather diaries, and descriptions of floods and droughts given in chronicles and rainfall measurements (from 1708).[43]

The *unweighted decennial thermal index* in Figure 4 gives the excess number of unmistakably mild months (M) per decade contrasted with months of unmistakably cold character (C), i.e. M–C, for the individual months and the entire seasons of the spring–summer period. Correspondingly the *unweighted wetness index* is W–D, where W is the number of months with evidence of frequent rains and D is the number of months with evidence of drought per decade. In both cases unremarkable months and those without observations score zero. The "difference" index was used despite its known sensitivity to missing data, because the number of spring and summer months without any observation was very small (about 20 out of 300 for each month).[44]

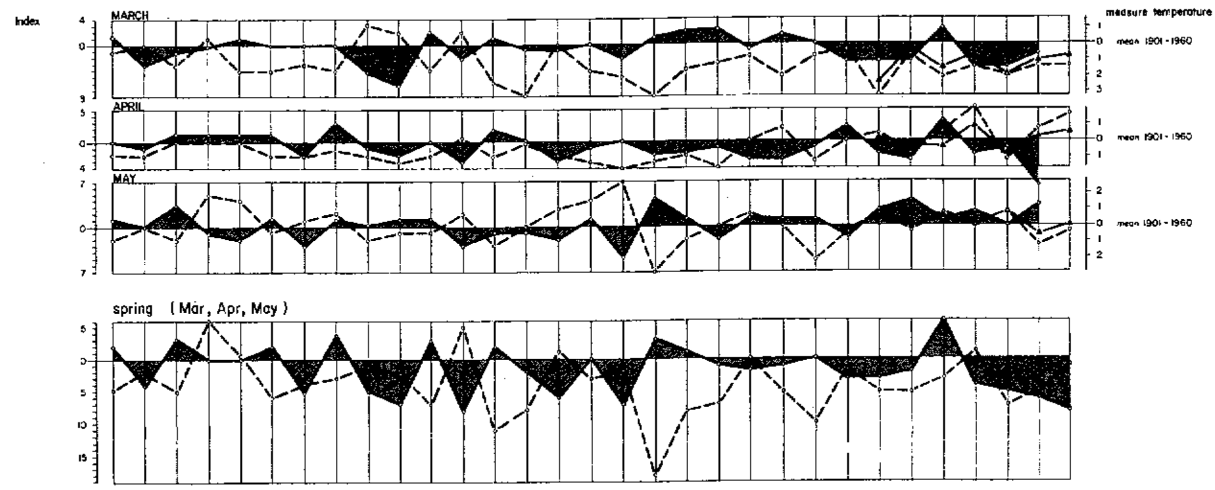
The second step in indexing is to convert the crude index to a meteorological parameter. For the thermal index it was assumed that the unmistakable cases were at least 1°C warmer or colder than the 1901–1960 average. During the last six decades covered with thermometrical measurement, the months were classified according to the same criterion, and the index in Figure 4 was also compared with the measured decennial averages. The figure illustrates that both curves are parallel for all months and that two points of the index represent roughly 1°C.

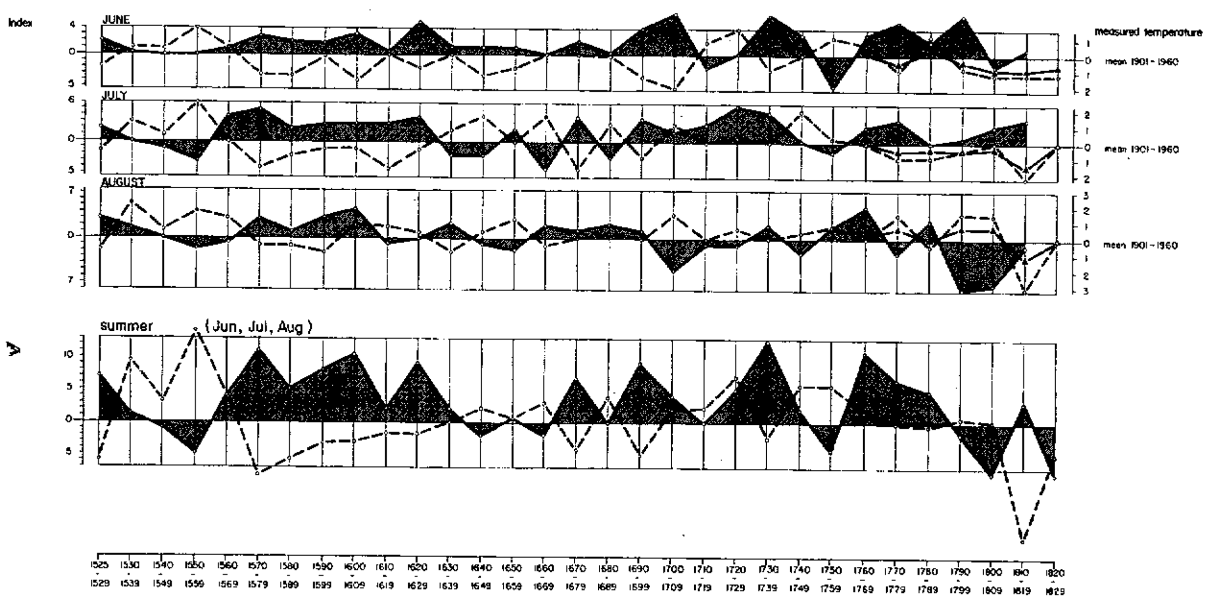
42 C. E. P. Brooks, *Climate through the Ages* (London, 1926); C. Easton, *Les hivers dans l'Europe occidentale* (Leyden, 1928); Lamb, *Climate*, 34–5, 440; Pierre Alexandre, *Le Climat au Moyen Age en Belgique et dans les Regions Voisines (Rhenanie, Nord de la France)* (Liège, 1976).

43 Pfister, "Swiss Historical Weather Documentation"; *idem*, "Die älteste Niederschlagsreihe Mitteleuropas; Zürich 1708–1754," *Meteorologische Rundschau*, XXI (1978), 56–62.
44 Ingram and Underhill, "Use of Documentary Sources," 81.

10-jährige Summe
mild month (m) - cold month (c)
m - c = Index
Für langen Zeitalter; über dem Schnitt 1901-60 (+1), darunter (-1). Monate ohne Angabe (0)

Fig. 4 Decennial Unweighted Thermal and Wetness Index for Spring and Summer (Monthly and Seasonal Values)





thermal index — wetness index — measured temperature
The excess or deficit of wet months is set off with the hatched area

For the wetness index the measured precipitation or the number of rainy days of each month was compared with a histogram of the 1901–1960 precipitation statistics at the same place. Months below the lower quartile range (at least as dry as the fifteen driest months) were classified dry; those above the upper quartile range (at least as wet as the fifteen wettest months) scored wet.[45]

THERMAL AND WETNESS INDICES FOR SPRING AND SUMMER, 1525–1825 Figure 4 displays decennial means of unweighted thermal and wetness indices for each individual spring and summer month and for both seasons. The wetness curve is set off with the tinted area; the broken curve represents the thermal patterns. Although the thermal curve is mainly based upon observations on the plateau, it also represents conditions at higher altitudes, because temperature patterns in spring and summer (but not in autumn and winter) are highly correlated between lowland and upland stations.[46]

The character of the spring months. Of all the months represented March reflects the climatic change of the little ice age most persistently and distinctly. Until 1560 no clear pattern emerges. Then the cooling starts. March remains cold, in many cases a real winter month, for the entire period displayed in the figure (with the noticeable exception of the two warm and dry decades at the beginning of the seventeenth century).

The coldest decade documented with measured evidence (1760–1769) was 2° below the 1901–1960 mean; a similar deviation has been estimated for the 1690s based upon careful observations of snowcover in a weather diary from Zurich. During the 1640s, likewise, March was probably just as cold. This persistent cold, together with the prevailing notion of drought (fifteen decades with an excess of dry months as against eight with an excess of wet months), suggests that this month was frequently dominated by northerly winds and blocking anticyclones. A significant warming in March did not occur before 1900.[47]

45 If all observations are rank ordered from highest to lowest, the 25th percentile corresponds to the lower quartile and the 75th percentile to the upper quartile.

46 Paul Messerli, *Beitrag zur statistischen Analyse klimatologischer Zeitreihen* (Bern, 1980).

47 Bider et al., "Basler Temperaturreihe," Table 1; Pfister, "Klima des Raumes Zürich," passim. Kington, "Historical Daily Synoptic Weather Maps from the 1780s," *Journal of Meteorology*, III (1978), 65–71, presents a synoptic analysis of this extremely cold March in 1785.

April shows less variation than March. From 1525 to 1720 the thermal index fluctuates slightly below the zero line, which suggests that this period, taken as a whole, was probably somewhat below the 1901–1960 average. After 1740 a warming of April is observable, which is maintained until the end of the little ice age. Although the wet months are more frequent during the sixteenth century, April was rather dry during most of the seventeenth and eighteenth centuries (with the exception of the 1640s, the 1750s, and the 1780s).[48]

May does not reflect a typical little ice age pattern. If we take the period from 1525 to 1825 as a whole, neither temperature nor precipitation seems to have significantly differed from the mean of the present century. After the cold wet decade of the 1540s, there was a net excess of warm and dry months up to the turn of the century, notably during the 1550s and the 1560s. During the first half of the seventeenth century, warm and cold months roughly balance. Then, from the 1660s the curve rises to its highest peak of +7 in the 1680s. At the same time the wetness index goes down to a minimum of −5. In sharp contrast, the 1690s show a drastic slump in the thermal index (−14 points) which is accompanied by a sudden increase in wetness (+9 points). In central England the measured difference between these two decades was 1.8°; in Switzerland it may have been considerably greater. Another marked excess of cold months stands out in the 1740s.

The polarity between the warm period from 1580 to 1690 (with an excess of 12 index points) and the succeeding cold period from 1690 to 1800 (with a deficit of 13 index points) could account to some extent for the delay of the wine harvests in the eighteenth century compared with those in the seventeenth century, given the sensitivity of the growth pattern of grapevines to temperatures in May (see Table 2).[49]

If we look at the composite picture of the three spring months, the dominant impression is one of coldness and drought. Only two decades (the 1550s and the 1630s) had an excess of more than one warm month, whereas twelve decades were −5 or be-

48 Bider et al., "Basler Temperaturreihe," Table 1.

49 Gordon Manley, "Central England Temperatures: Monthly Means 1659 to 1973," *Quarterly Journal of the Royal Meteorological Society*, C (1974), 389–405. Le Roy Ladurie and Baulant, "Grape Harvests"; Anne-Marie Piuz, "Climat, récoltes et vie des hommes à Genève, XVI^{e}-XVIII^{e} siècle," *Annales*, XXIX (1974), 599–618.

low, the coldest being the 1690s (−18), the 1640s (−11), and the 1740s (−10). These tendencies are clearly reflected in the wine harvest dates. An analysis of the Basel temperature series by Messerli has revealed that for the period 1860–1965 springs were .3° warmer than in the preceding period 1755–1860, which is statistically significant.[50]

The character of the summer months. June clearly reflects the climatic change of the sixteenth century. Around 1560 this month, which had been predominantly warm during the preceding two decades, became wet and cool. Most remarkably, this tendency was not interrupted for the next 140 years (except during the 1660s, when both indices were at zero). By contrast, the excess of cold months was always moderate; the maximum (−5) was observed in the 1700s together with the greatest excess in wetness (+7). During the eighteenth and early nineteenth centuries there was an alternation of periods which were warm and dry (1710s, 1720s, and 1750s) with periods which were rather cool and wet (1730s, 1740s, 1760–1800, and 1810s). As a whole, the predominance of wetness prevails.

July presents a very similar picture until 1630: hot and dry midsummers from 1540 to 1560 were followed by an uninterrupted series of seven damp and cool decades. From 1630 to 1670, however, Julys were clearly warmer and drier than Junes. Also during the 1690s the excess of cold and wet months was less pronounced. Again, from 1700 to 1760 the thermal index was above or at the line, whereas wetness was often very pronounced (+6 in the 1730s). After 1760 a second long succession of cool and rainy decades set in which culminated in the 1810s, when the July curve descended to its lowest point (−5). This corresponds to a deviation of minus 1.2° from the 1901–1960 mean. The slumps of 1570–1579, 1610–1619, and 1670–1679 (−4 each) might have been of an order of magnitude of −1°C. On the other hand, the peak of the 1550s (+6) may have been equal to the warmest decennial mean for July (1943–1952), which, in Central Europe, was about 1.2° above average.[51]

August, taken as a whole, was probably no colder and wetter

50 Paul Messerli, *Beitrag*, 24.
51 Bider et al., "Basler Temperaturreihe," Table 1.

than in the present century. In contrast to the preceding months, the warm and dry phase of the mid-sixteenth century was extended to the 1560s, and from 1600 to 1630 late summers were rather warm. Thus the cool and wet pattern of Junes and Julys at the end of the sixteenth century did not include August, except during the three decades from 1570 to 1600. Similarly, the coldest phase of the little ice age, the 1690s, is not reflected in this curve. Again, from 1790 to 1810, the cold and wetness of June and July were counterbalanced by the warmth of August.

A composite curve combines the composite thermal and wetness patterns of the three summer months. The significance of the climatic change which occurred during the sixteenth century is revealed by a comparison of the number of "warm," "cold," "dry," and "wet" summer months from 1525 to 1600:[52]

1525–1569		1570–1600	
warm	*cold*	*warm*	*cold*
48	21	26	44
dry	*wet*	*dry*	*wet*
24	30	11	35

From 1560 to 1630, taken as a whole, summers were persistently cool and wet. Although cooling was most pronounced at the beginning (−8) and diminished afterwards, the excess of wet months was mostly above +5, except from 1610 to 1619. If we allow for a time lag, this pattern is clearly connected to the thrust of the alpine glaciers from the mid-1580s to the turn of the century. From 1630 to 1670 both indices are near zero, which suggests that summers were roughly equal to those of the present century. During the little interglacial, as we might call that episode, most glaciers began to retreat. From 1670 to 1740, and again from 1760 to 1790, there was a clear excess of wet summer months, although the summers were not so frequently cold as during the first phase of the little ice age (1560–1630). This may explain why the dimension of the glacial advances during that time remained limited.

The long-lasting advanced position in the nineteenth century was chiefly triggered by the short-term fluctuation of the 1810s,

52 Pfister, "Swiss Historical Weather Documentation."

the most drastic slump in temperature (−17) contained in the index. Many glaciers, however, were already somewhat advanced when the fluctuation began.[53]

It has been demonstrated that crossdating instrumental data, field data, documentary proxy data, and a body of descriptive data yields a refined picture of the thermal and wetness patterns in spring and summer. What can we conclude from the result?

When we reduce our focus to the level of individual seasons and months only two features persist through the entire period of the little ice age: the cold in March and the cool and wet character of June. If we consider the whole pattern, the little ice age in Central Europe was a period of rather heterogeneous climate. As far as the spring-summer period is concerned, like the big ice age, it crumbles away into a variety of sub-periods, into minor fluctuations, which might be called little interglacial or little little ice age, if the signs of the indices agree in several seasons for more than a decade. On a shorter time scale three periods stand out, in which springs and summers were simultaneously cold: 1570–1600, the 1690s, and the 1810s. This conclusion holds not only for Switzerland, but also for large parts of the European continent and probably for the northern hemisphere as a whole. As we may conclude from a variety of studies, those phases of climatic hardship had, particularly in the marginal regions, severe economic and demographic impacts upon many societies of preindustrial Europe.[54]

53 Le Roy Ladurie, *History of Climate*, 207; Zumbühl, *Grindelwald-Gletscher*; Bruno Messerli et al., "Schwankungen," passim.

54 Tom M. L. Wigley et al., "Geographical Patterns of Climatic Change: 1000 B.C.–1700 A.D.," *Quaternary Research*, forthcoming; Piuz, "Climat, récoltes"; Gustav Utterström, "Climatic Fluctuations and Population Problems in Early Modern History," *Scandinavian Economic History Review*, I (1955), 3–47; Francois Lebrun, *Men and Death in Anjou in the Seventeenth and Eighteenth Centuries* (Paris, 1971); K. Walton, "Climate and Famines in Northeast Scotland," *Scottish Geographical Magazine*, LXVIII (1952), 13–21; John D. Post, *The Last Great Subsistence Crisis in the Western World* (Baltimore, 1977).

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Severe Drought and Recent History

Man's existence throughout history has been plagued by drought. Areas with either moist or dry climates have suffered from drought in normal times or in periods of climatic extremes. Droughts are not isolated events but are part of the large-scale patterns of atmospheric circulations that determine climate in their normal configurations but can lead to drought and flood in their extreme deviations from normal. The configurations of atmospheric flow tend toward certain fixed sizes or wave lengths and thus we have "teleconnections"—a meander of large-scale flow in the atmosphere over one area of the earth's surface tends to be associated with repercussions in other areas. For example, if a deep trough with stormy weather lies over the North Pacific in proper position to be associated with a ridge over land, then the area dominated by the high-pressure ridge will be dry. If the condition is prolonged or oft-repeated and if it catches the natural water supply at a low ebb then drought ensues. These teleconnected events often have positive feedbacks and are synergistic in character.

Over the years these abnormal patterns repeat themselves—not periodically so that we can predict them, but at seemingly random intervals. Some places are more natural targets for drought, although changes in climate can shift the positions of these target areas, but drought remains an enduring problem.

The definition of drought is partly contingent upon its impact on society and on the economy. For the purposes of this article we shall consider drought as an extended period of deficient precipitation relative to normal. According to this definition drought can occur almost anywhere in the world, because the natural variability of precipitation is a reliable statistical characteristic of climate.

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