International Training Course on Cryosphere Observation, Monitoring, and Research along the Belt and Road

Climatic and Environmental Records in Cryospheric Regions

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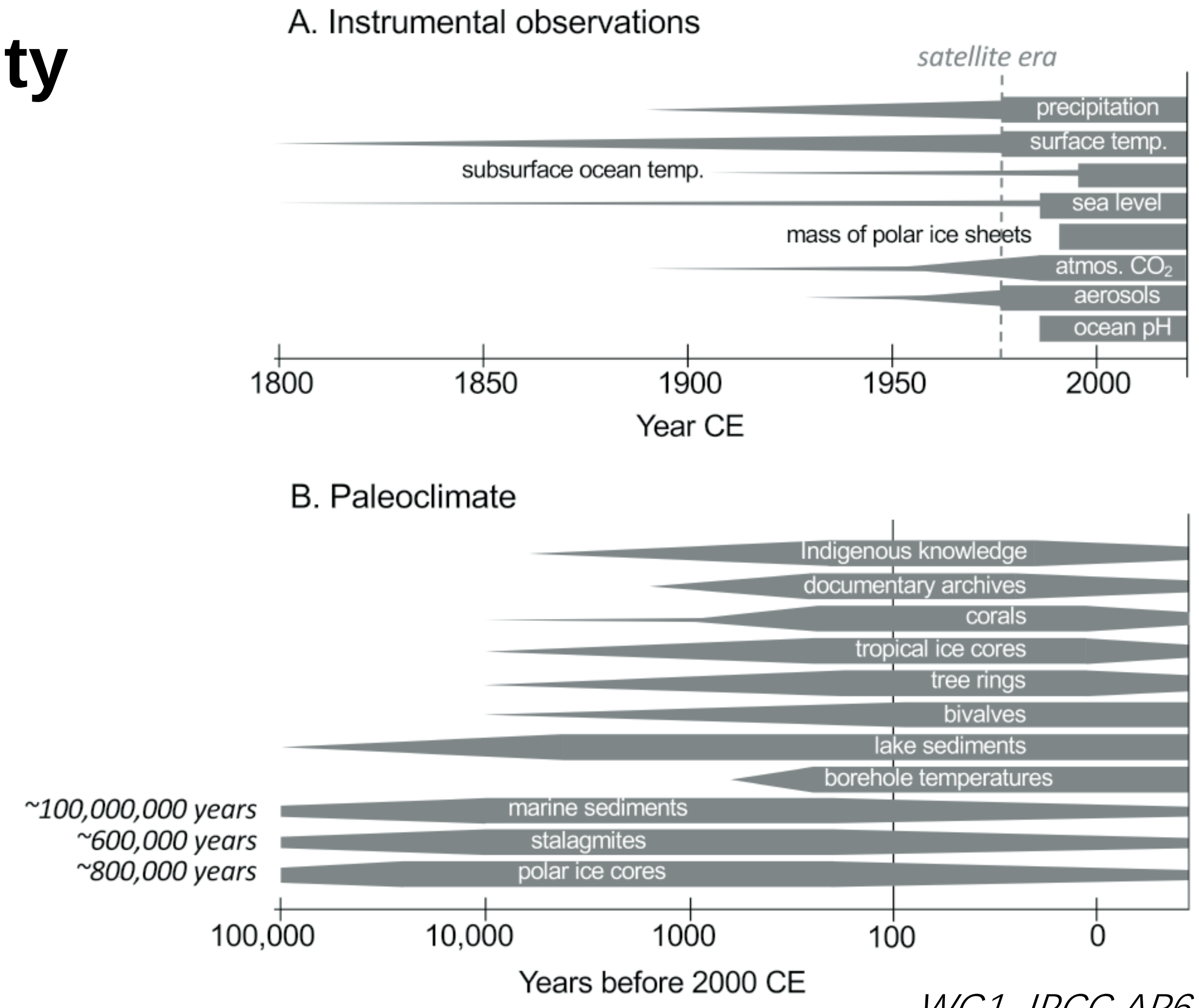
Outline

1. **Introduction: values of cryospheric archives**
2. Dating is crucially important
3. Proxies in ice cores
4. Main findings of ice cores building to our knowledge
5. Other media of proxies in cryospheric regions
6. Gaps and prospective: e.g., MPT, TP, warming levels

Cryosphere provides high-quality paleoclimate archives

Schematic of temporal coverage of:
(a) selected instrumental climate observations and
(b) selected paleoclimate archives. *The satellite era began in 1979 CE.*

The width of the taper gives an indication of the amount of available records.

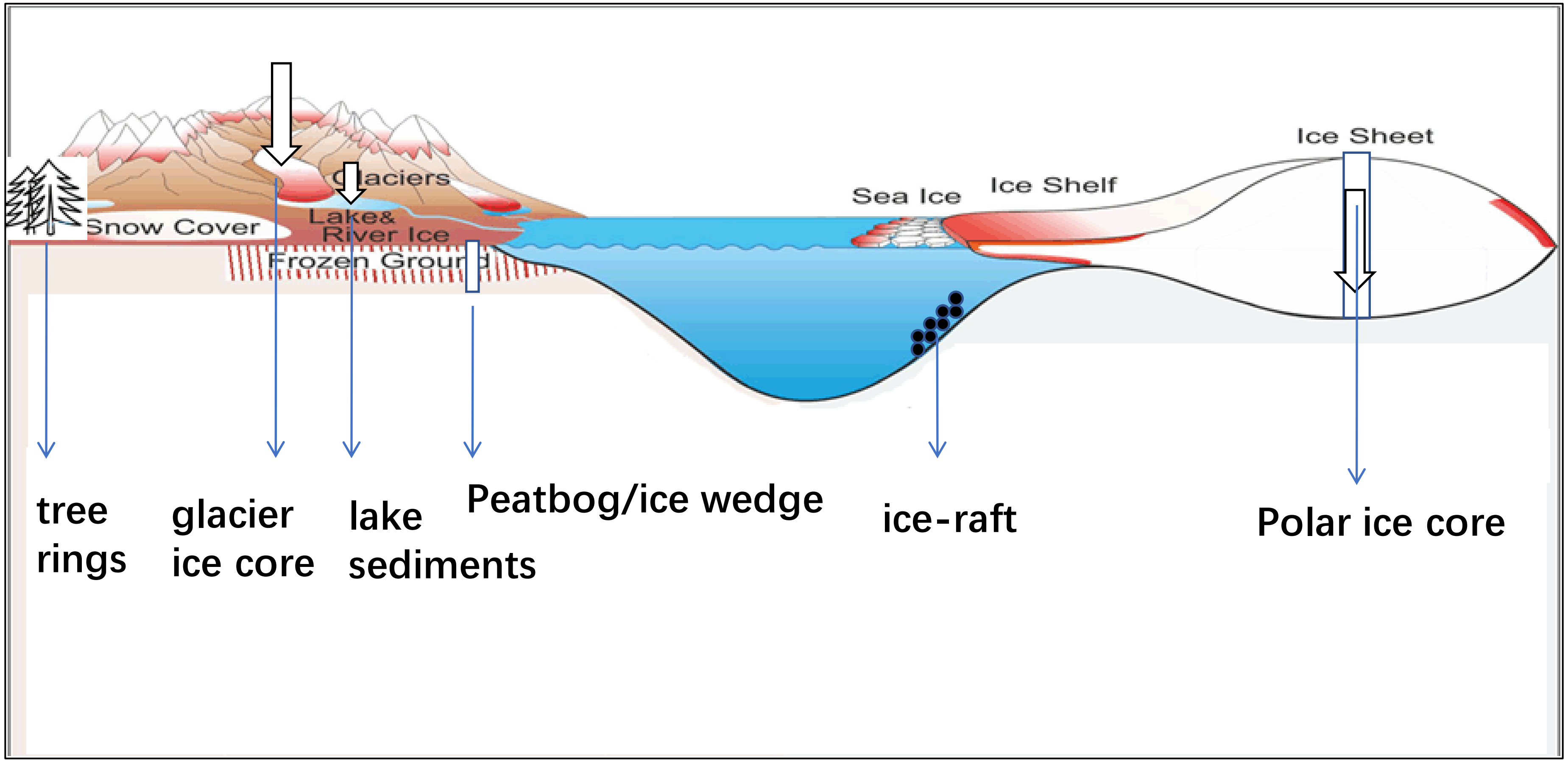


WG1, IPCC AR6

器测资料(A)和古气候档案(B)所涵盖的时间尺度示意

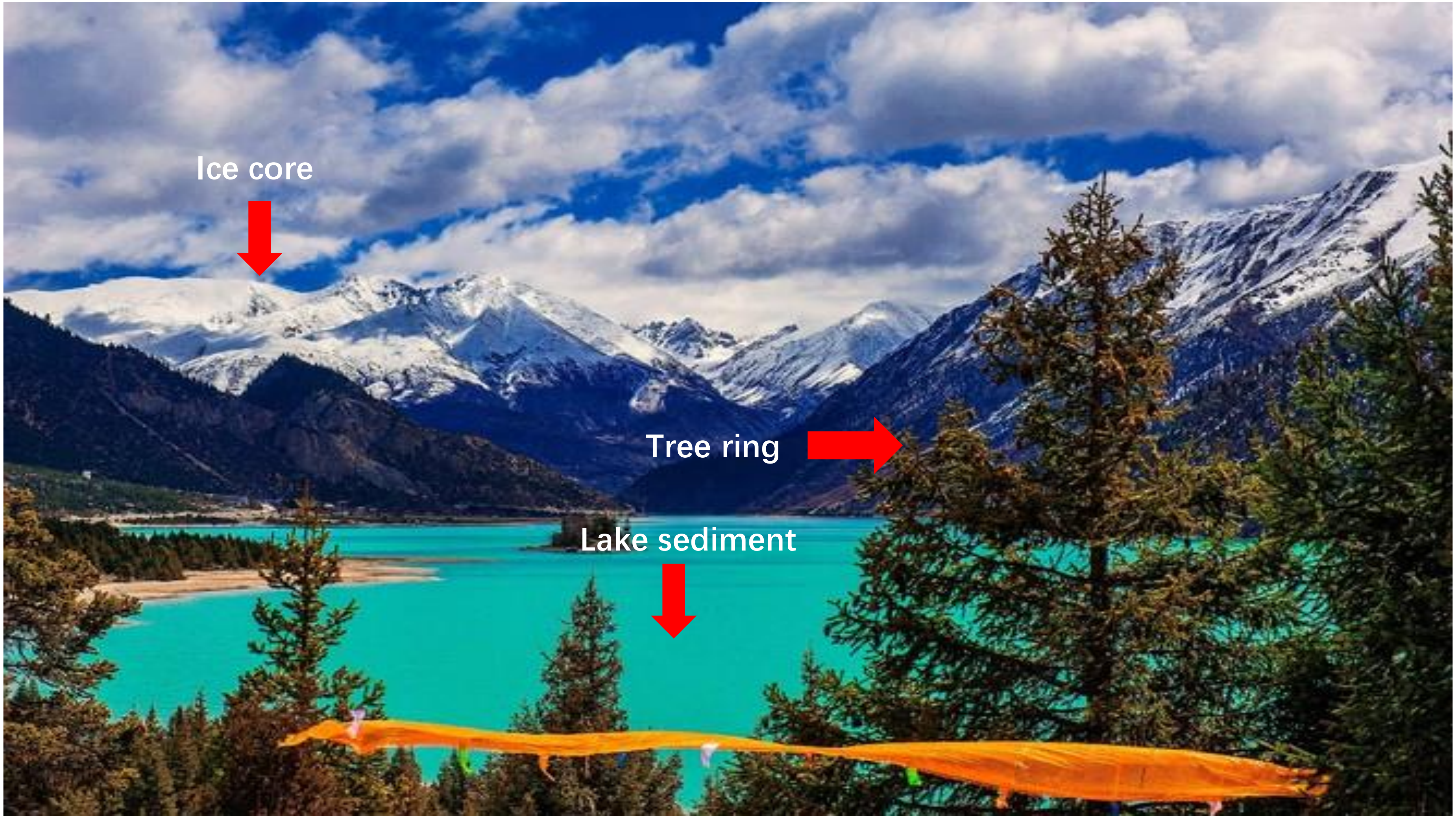
(横条的宽度代表数据丰富度)

Schematic illustration of available media over cryospheric regions for paleo-environment reconstruction



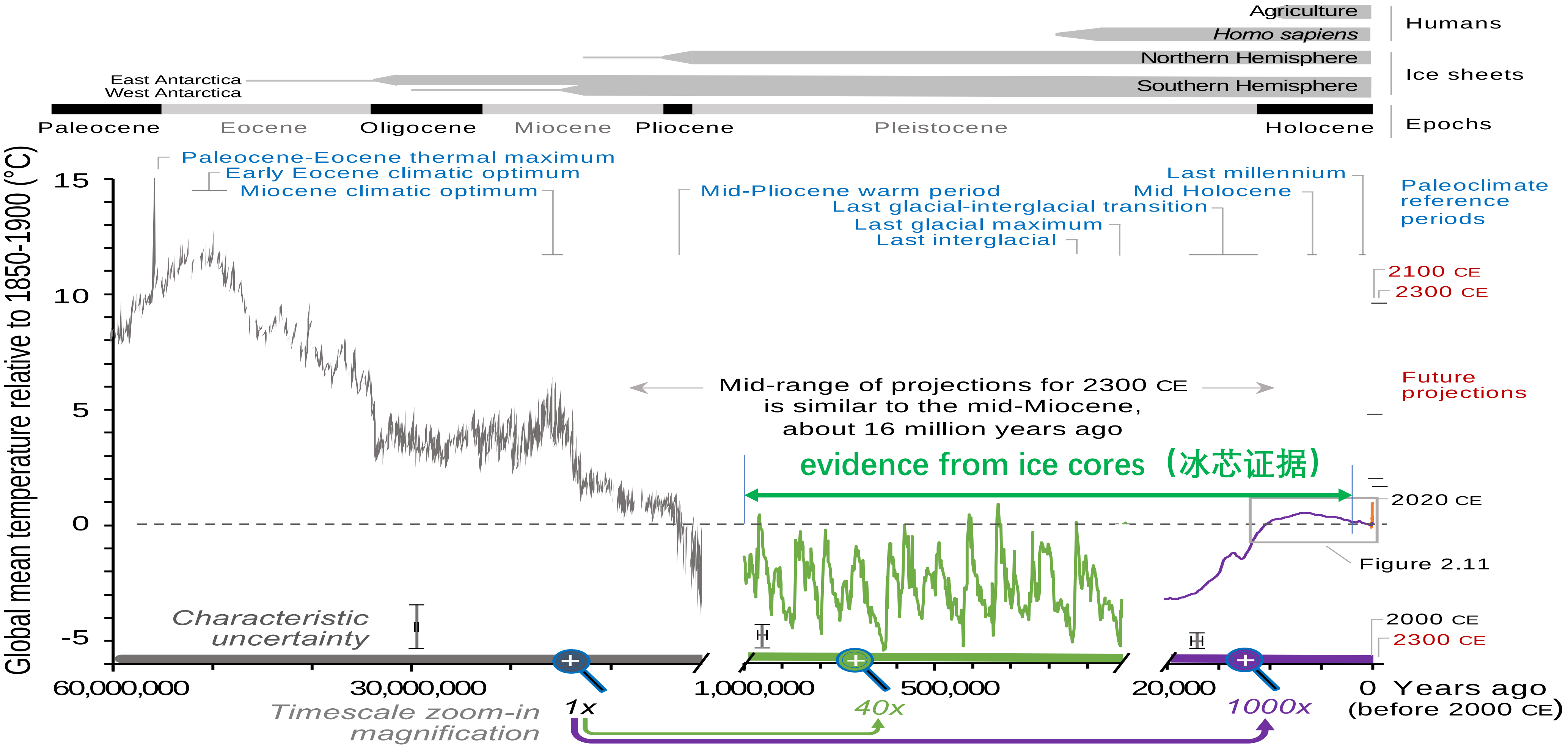
(background picture: IPCC AR5)

Some cases, multiple opportunities in one region *— good for validation*



Background, Basong Lake (Tibet)

Ice core records build on our detailed knowledge on climate since mid-Pleistocene



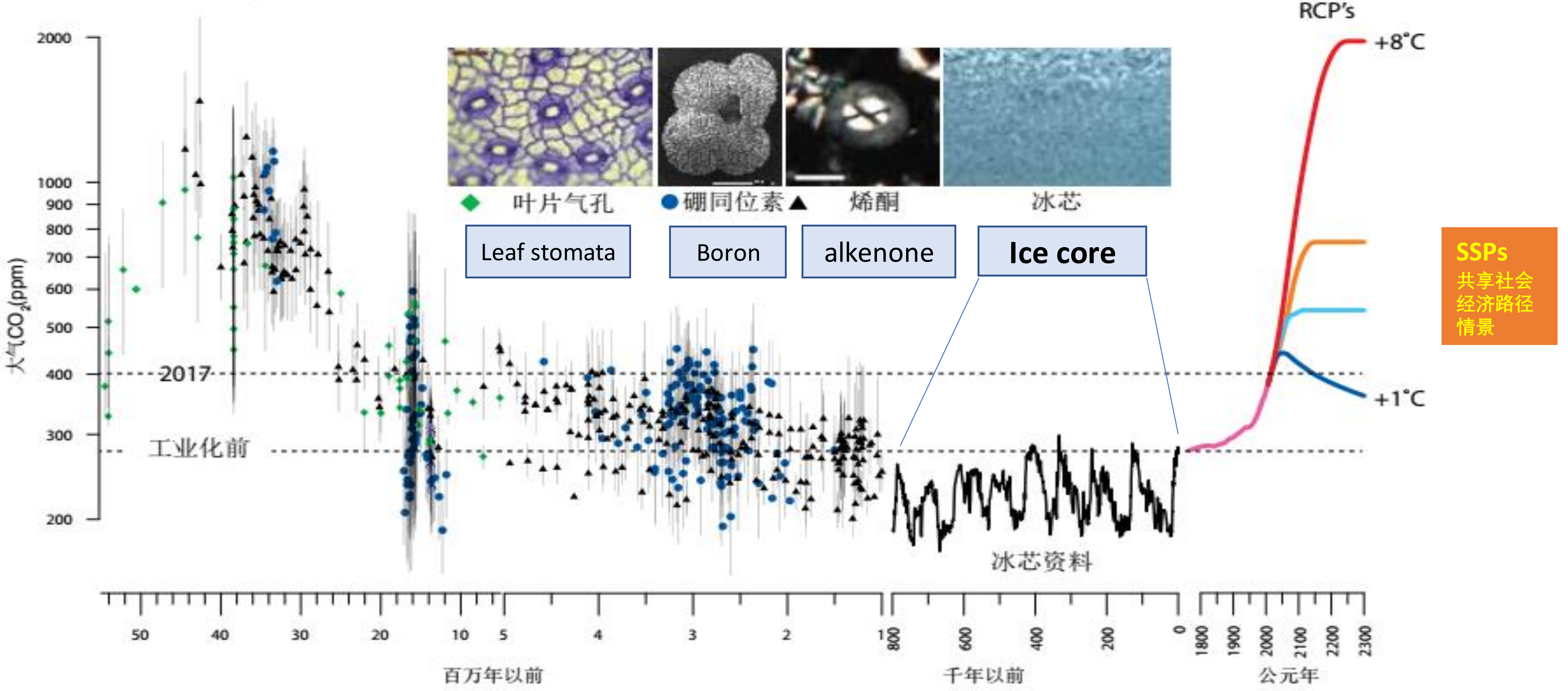
Global temperature evolution over past 60 million years with future projections

(IPCC AR6,2021)

- 硼同位素(蓝色圆圈)、烯酮(黑色三角形)和叶片气孔(绿色菱形)重建过去5500万年（老第三纪始新世）以来的大气CO_2浓度。
- 过去80万年系南极冰芯记录
- Keeling曲线 --- 1953-2016 (粉红)
- 预估2100年四种排放情景下的温升：RCP8.5(红)、6.0(橙)、4.5(浅蓝)和、2.6(蓝）和 SSPs情景

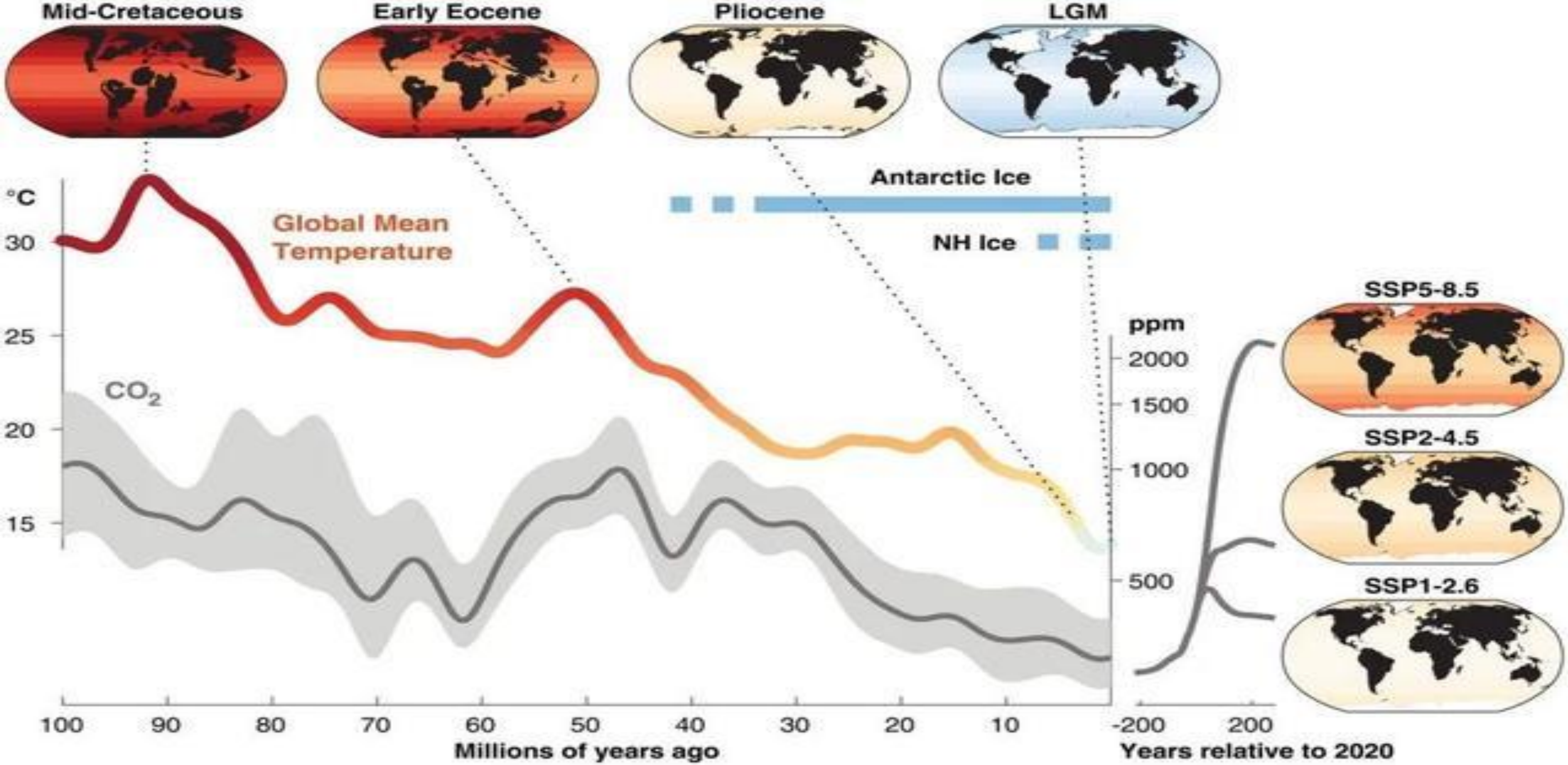
据秦大河

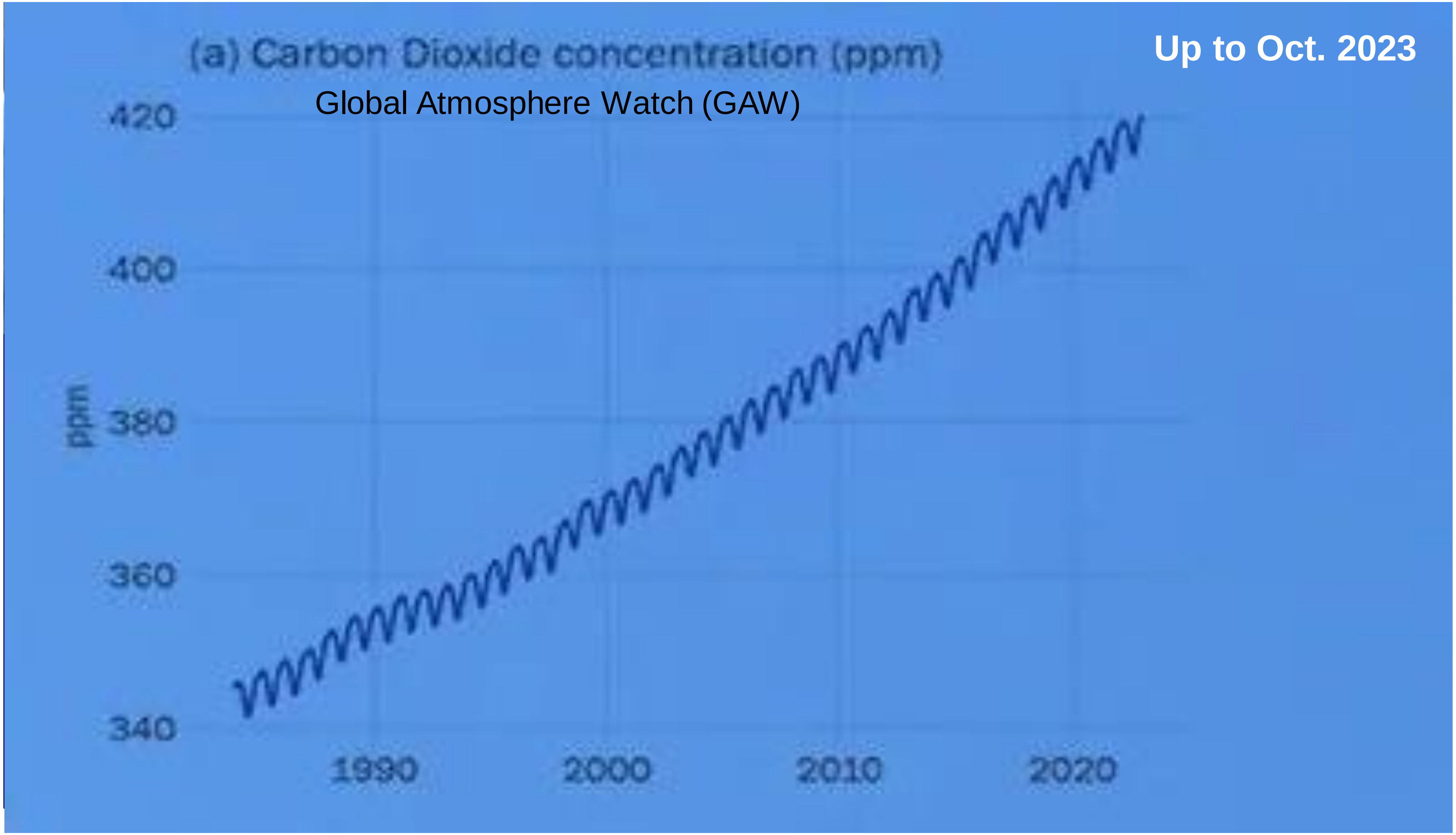
WMO GHGs Report (Oct 2017)



- 通过烯酮、硼同位素、植物化石叶片气孔资料、冰芯记录、GAW实测和情景预估，获得新生代（约6000万年以来）古大气CO_2浓度，以及现代及未来大气CO_2浓度。
- 预估未来全球CO_2浓度将高于1750年，联系气候敏感度和地球系统模式，据监测气候系统，提高和和改善气候-冰盖-地球系统模式，提高对未来的预估能力。

Thus we know exactly how much human emissions exceed natural variation




(a) Carbon Dioxide concentration (ppm)
Up to Oct. 2023
Global Atmosphere Watch (GAW)
ppm
420
400
380
360
340
1990
2000
2010
2020

Content

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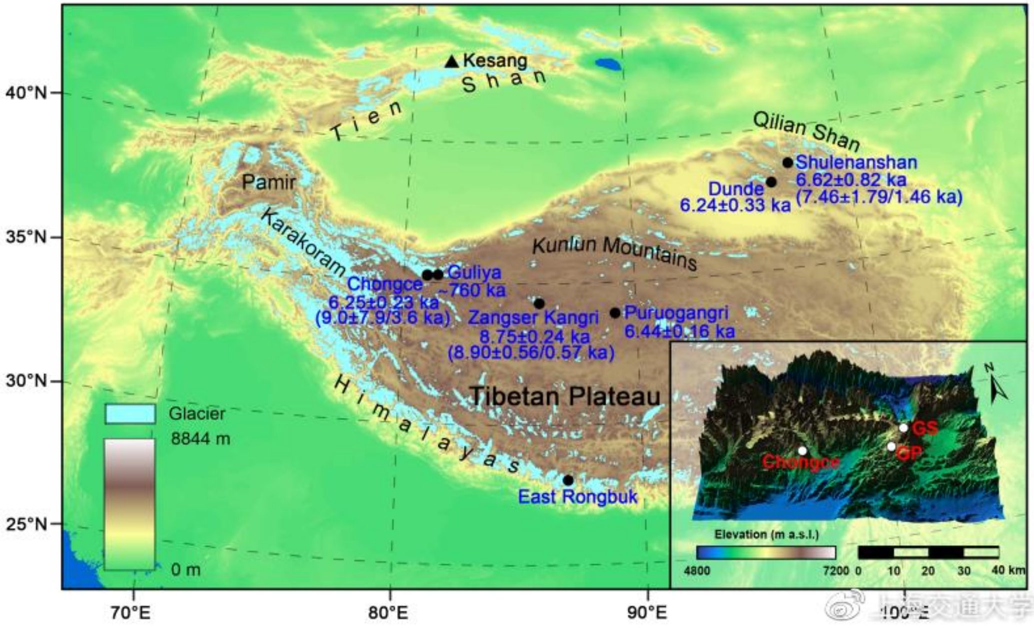
Strong debate on ice age over high mountains



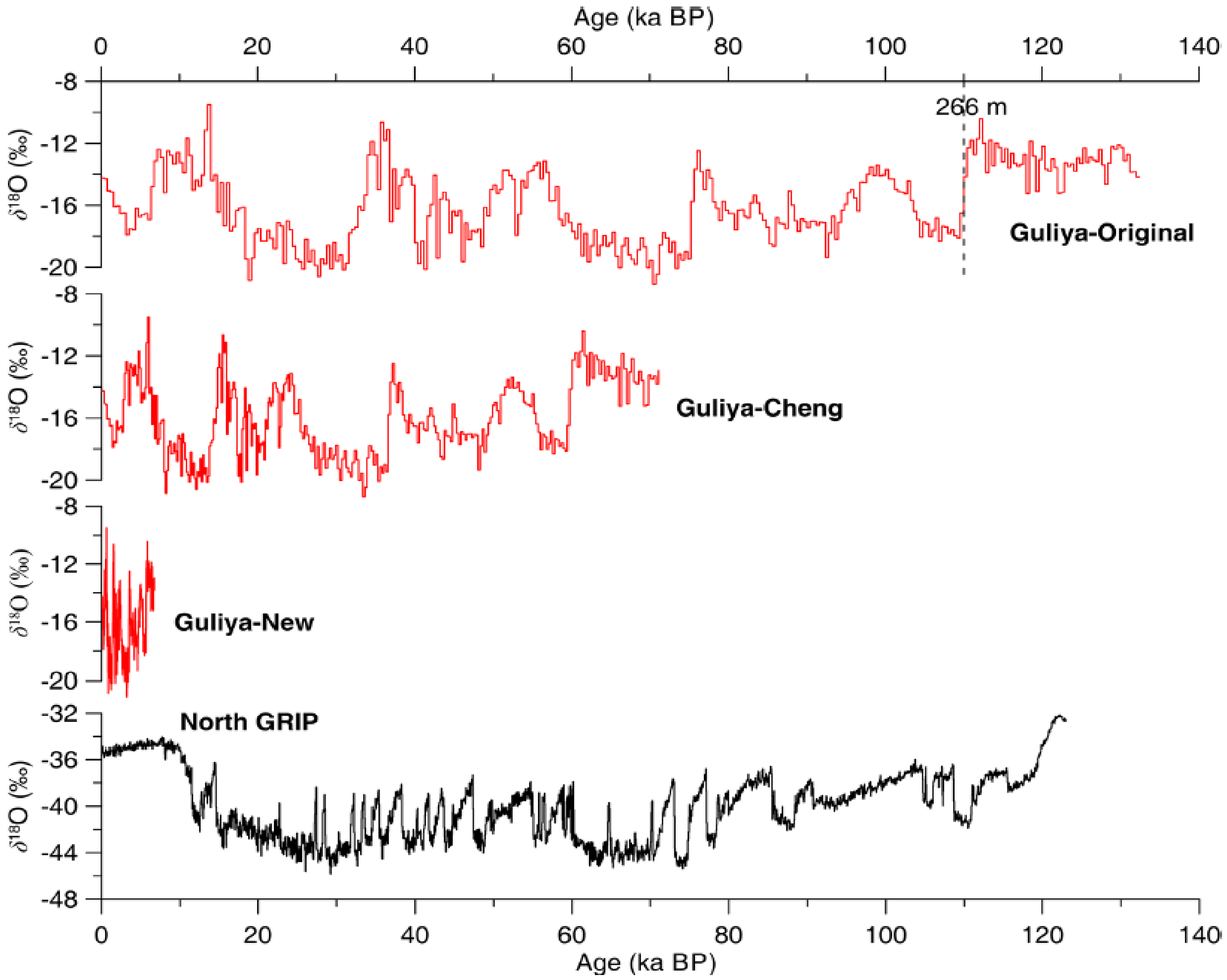


Figure 4. The $\delta^{18}O$ profiles of the Guliya and North Greenland Ice Core Project (GRIP) ice cores. The Guliya-Original profile is plotted on its original chronology (Thompson et al., 1997). The Guliya-Cheng profile is the original Guliya record linearly compressed by a factor of 2, as suggested in Cheng et al. (2012). The Guliya-New profile is the original Guliya record further compressed linearly so that the high $\delta^{18}O$ values fall within the warm Holocene.

(Hou et al., 2019)

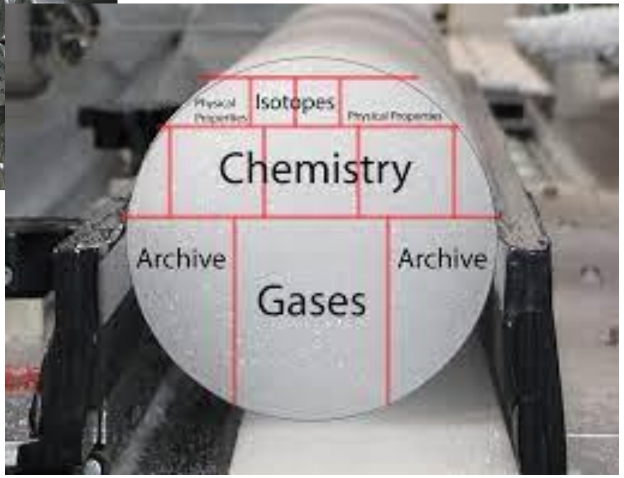
Dating methods of ice core

— annual cycles of physical/chemical features
— reference layers
— cosmogenic radionuclides
— modelling by flow law
— orbital tuning
— paleo-analogy
— multiple methods combination
— new technologies

Drilling

Cold storage

Cut plan

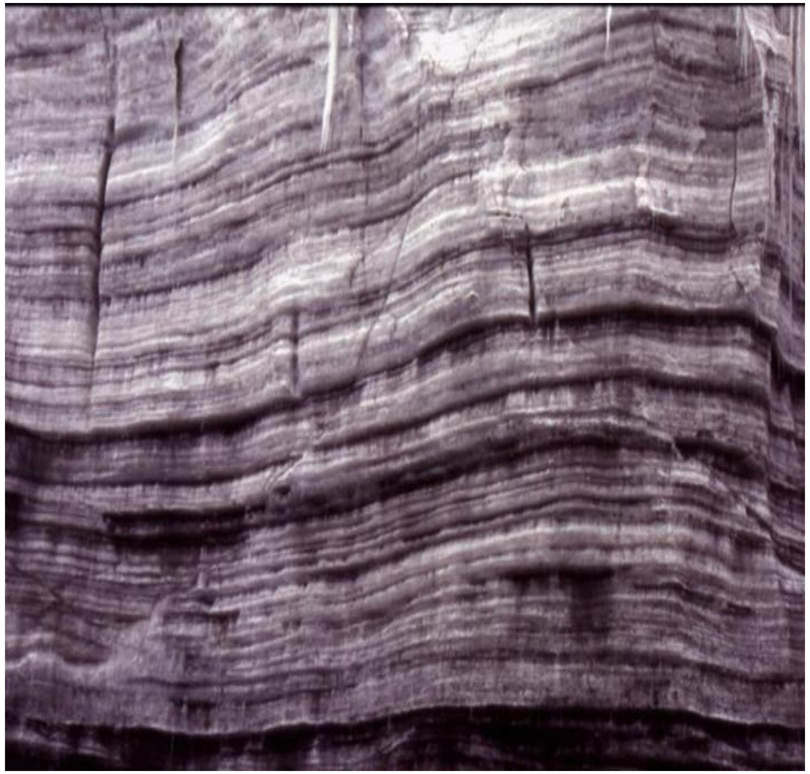


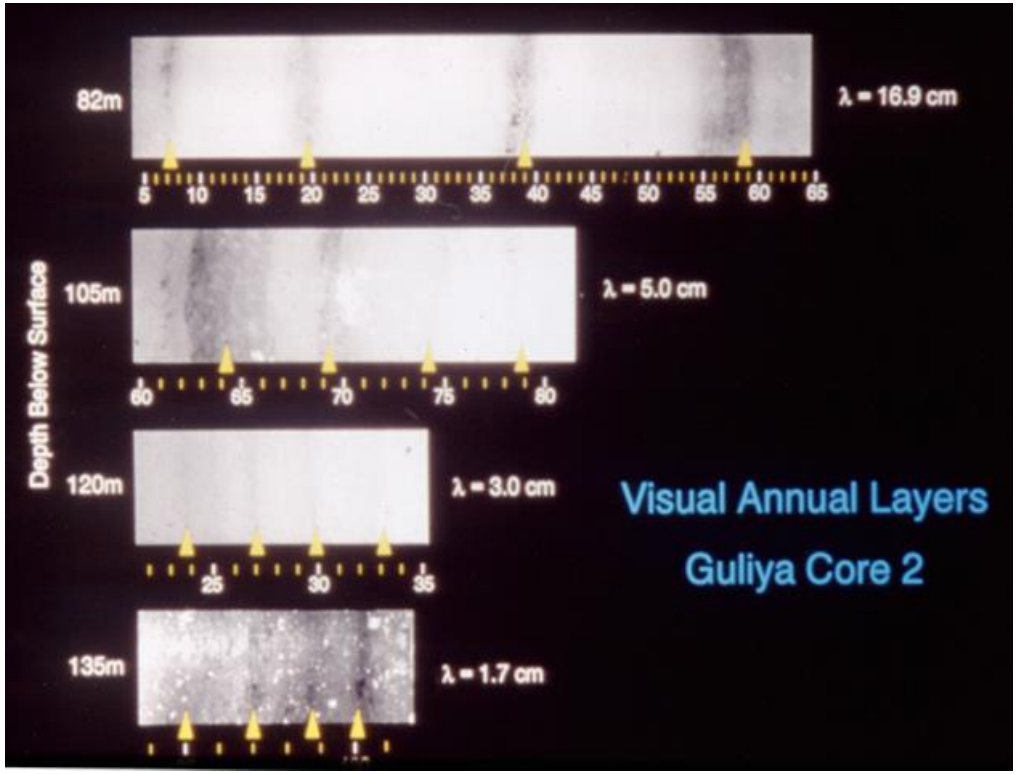
Analyses

Procedure from field to lab (simplified)

- annual cycles of physical/chemical features

- **annual cycles of physical/chemical features**

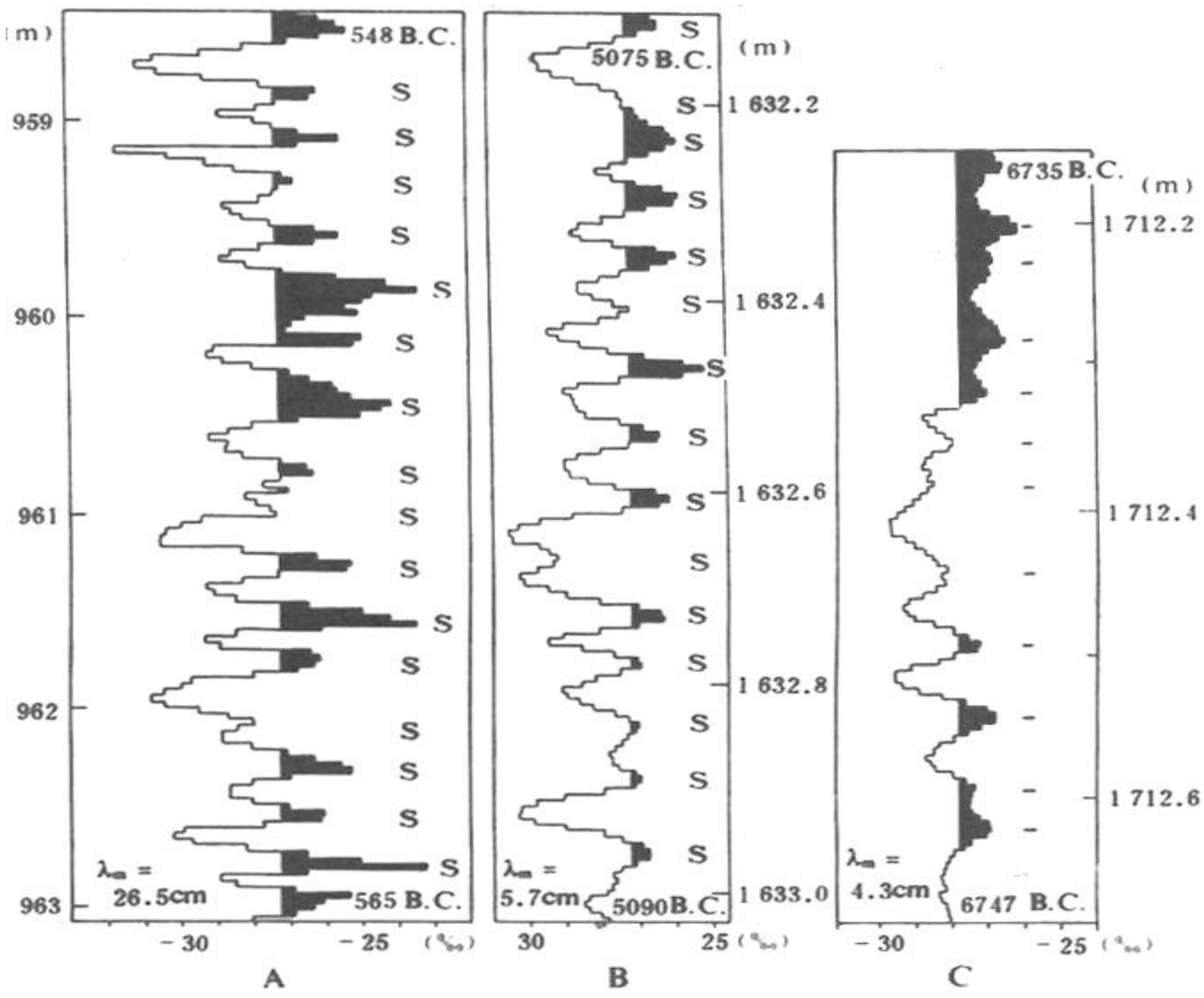




Regular dust deposition of central Asia forms winter/spring dust layers in glacier, offering annual signals for ice core dating

- **annual cycles of physical/chemical parameters**

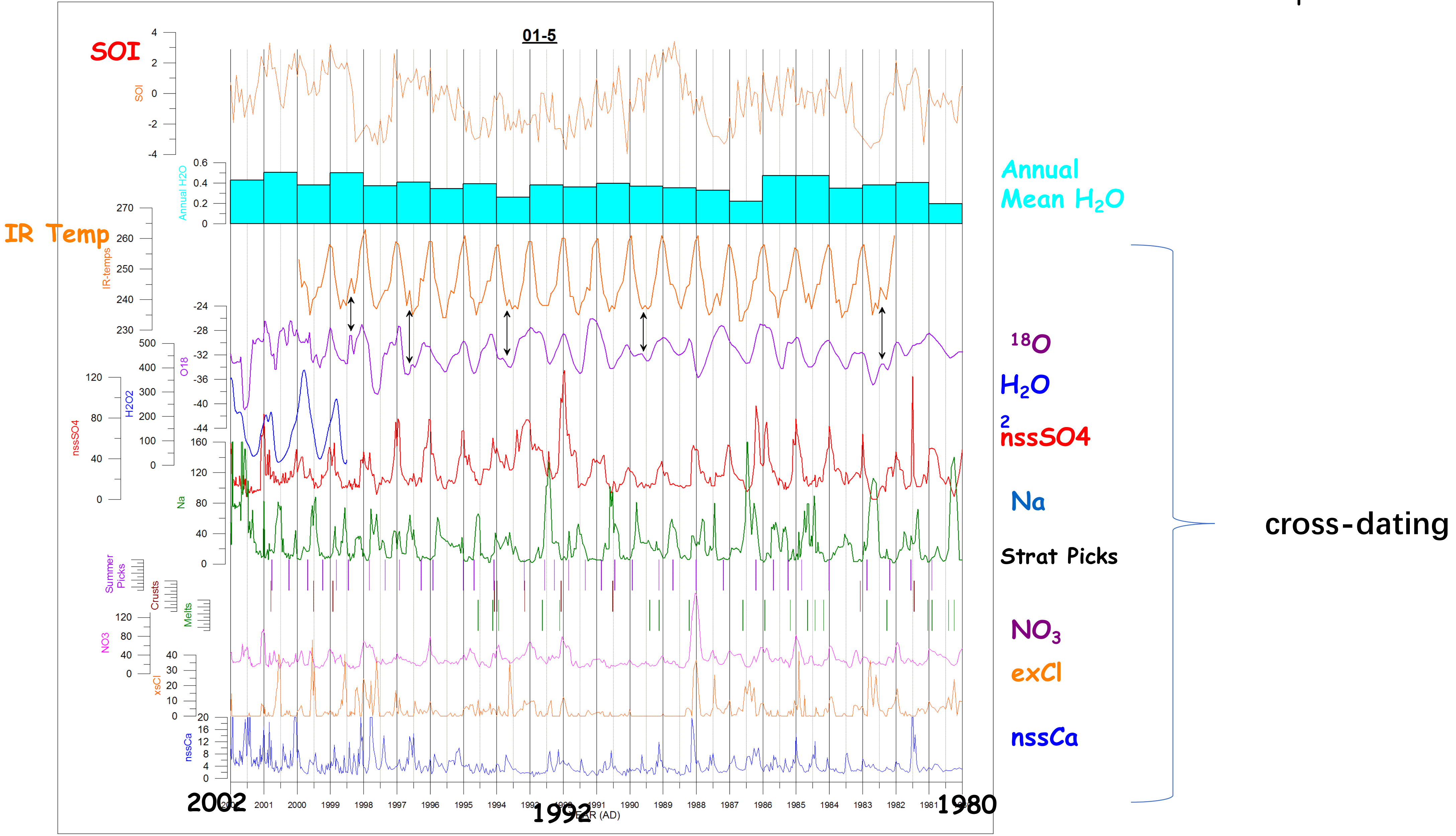
When physical layers are not visible, chemical layers are reliable reference for dating



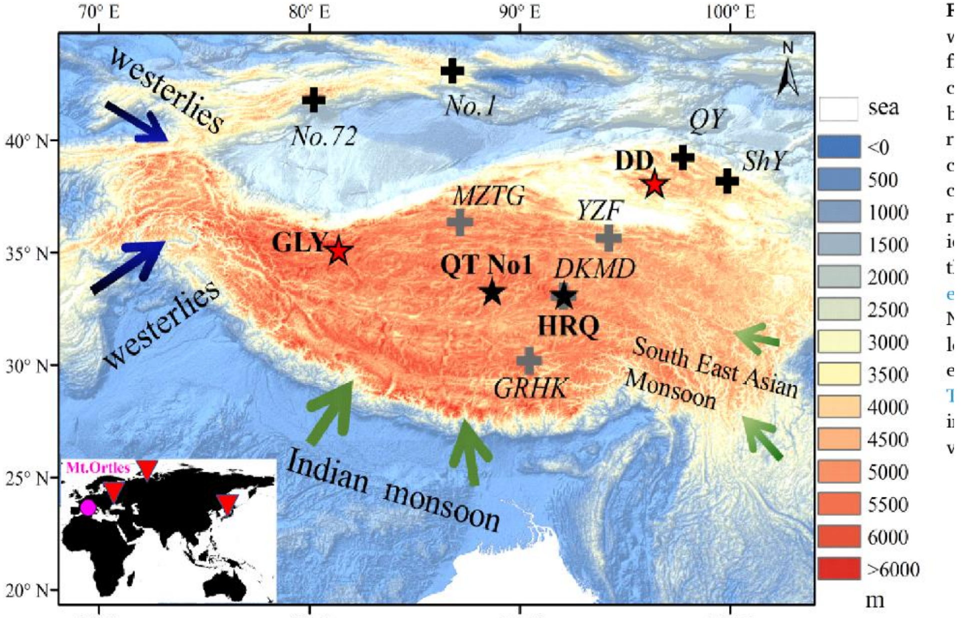
Annual signals of $\delta^{18}O$ in Dye-3 ice core, Greenland

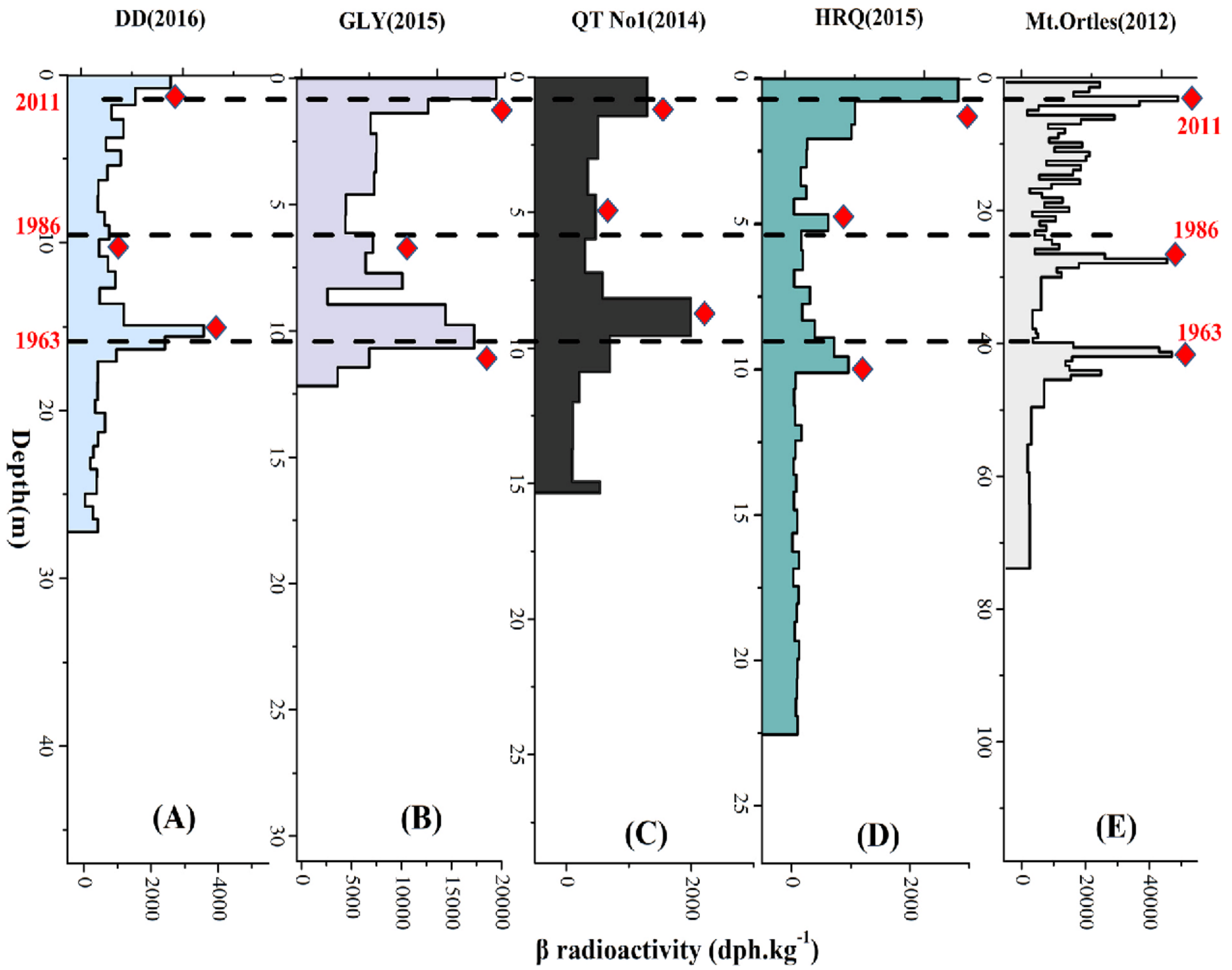
High resolution (sub-annual), multi-parameter, multi-disciplinary

ITASE West Antarctic Example



● reference layers: *nuclear bomb tests*



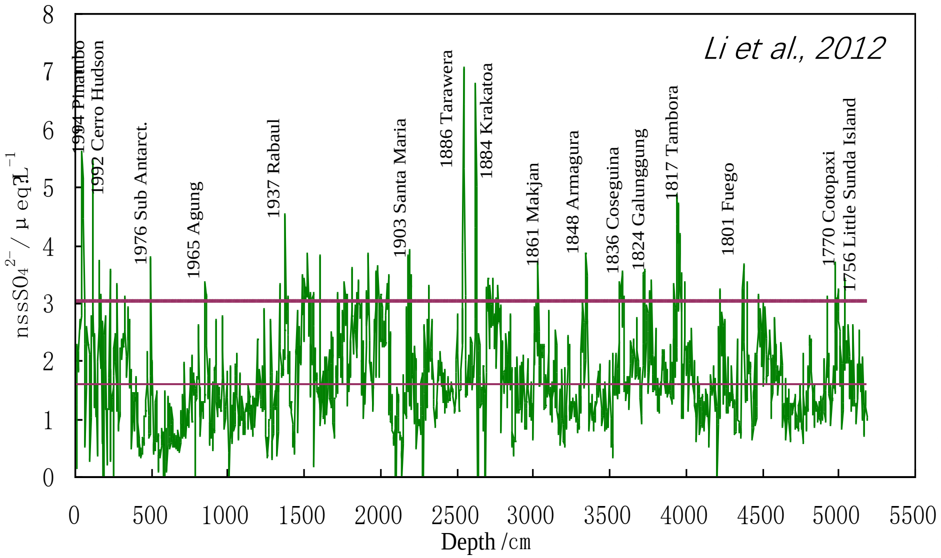


Major nuclear bomb tests and nuclear power plant incidents release large amounts of radionuclides. Investigates beta (β) activities of radionuclides from ice cores give a reliable reference year.

Deji et al., 2022

- **reference layers:** *Volcano eruption events*

The injection of sulfur into the stratosphere by explosive volcanic eruptions eventually deposit to polar ice sheet/cap, serve as reference years for the last approximately 1000 years. Large eruption events such as Tambora, Agung, Pinatubo.



Singular Value of non-sea-salt (nss)SO_4^{2-} (usually $\geq 2\sigma$) considered as indicator of volcano events;

nss SO_4^{2-} = SO_4^{2-} (sample) - [(SO_4^{2-}/Na^+) (sea water) × Na^+ (sample)]

There is 1-2 years' lag of recorded year in the ice to the eruption years, since there is long-distance transport to polar regions from low-middle latitudinal volcanic eruptions

cosmogenic radionuclides

Ways of deposit into ice：

1. Precipitation condensation nucleus
2. Stored in air bubbles

Origins：

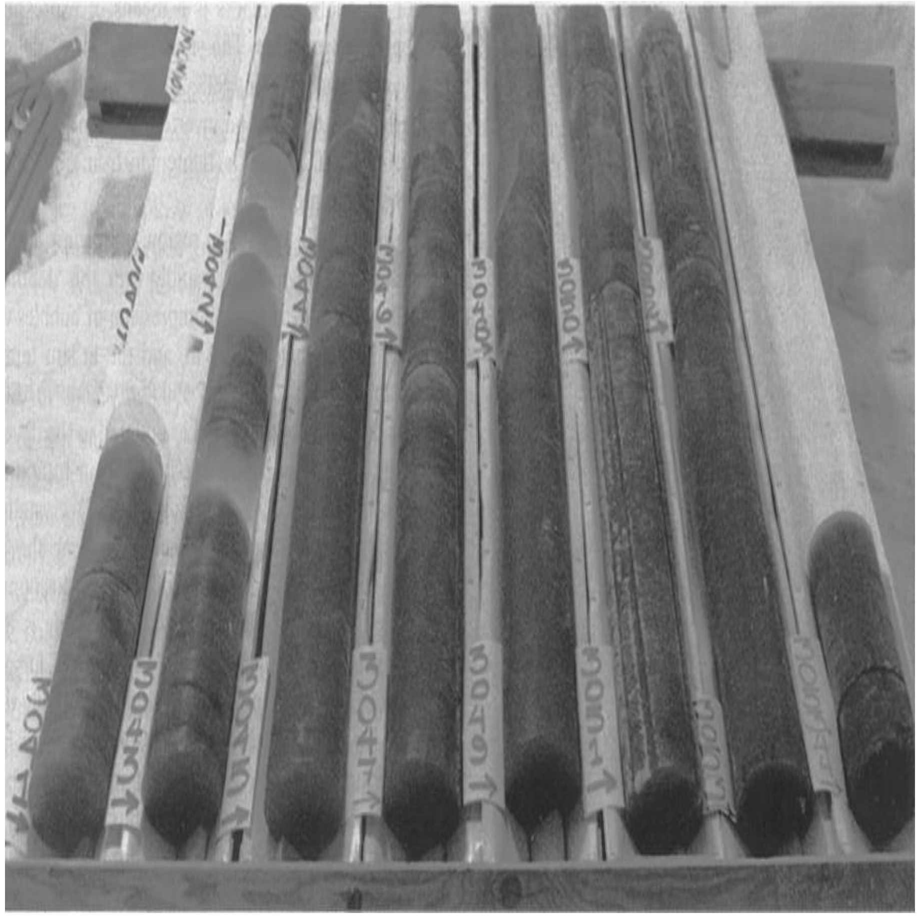
cosmogenic radionuclides ： ^{12}S, ^{37}Al, ^{14}C, ^{10}Be, ^{81}Kr;

nuclear test： ^{3}H, ^{137}Cs, ^{90}Sr

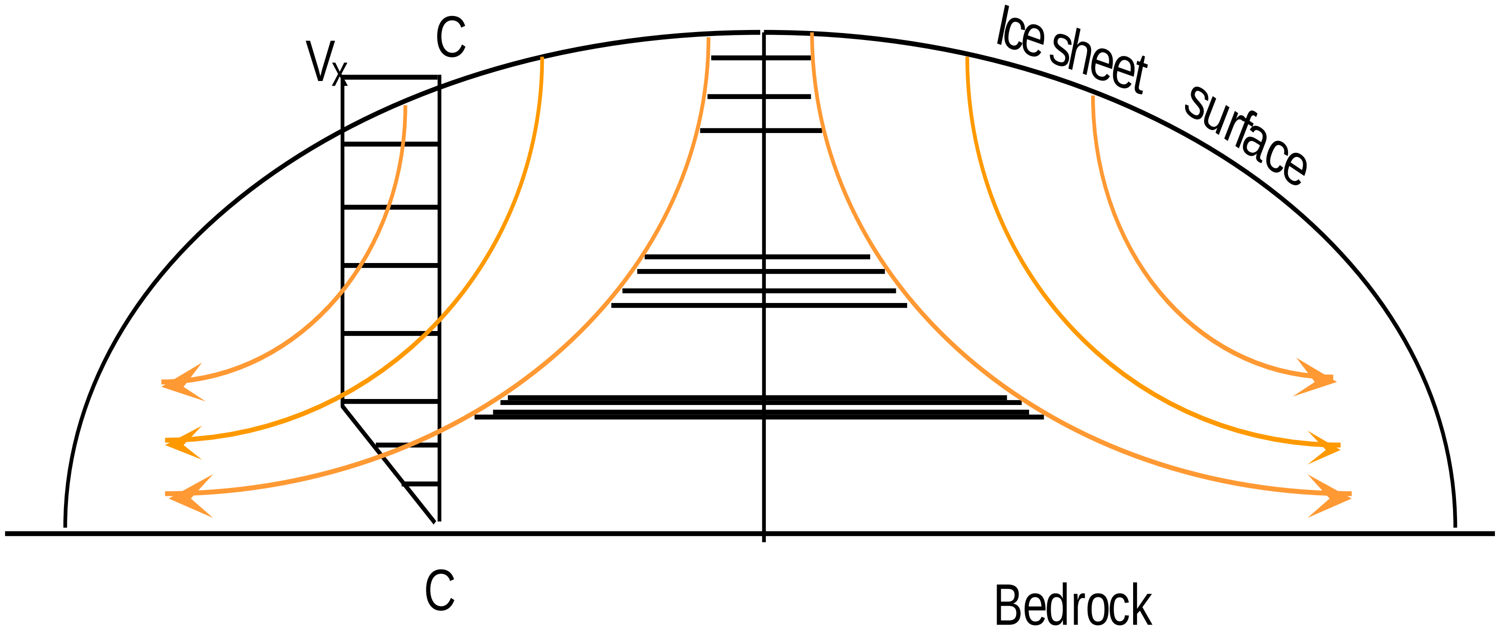
others： ^{210}Pb

Mostly used are: ^{210}Pb, ^{10}Be, ^{36}Cl

（require large ice volume）



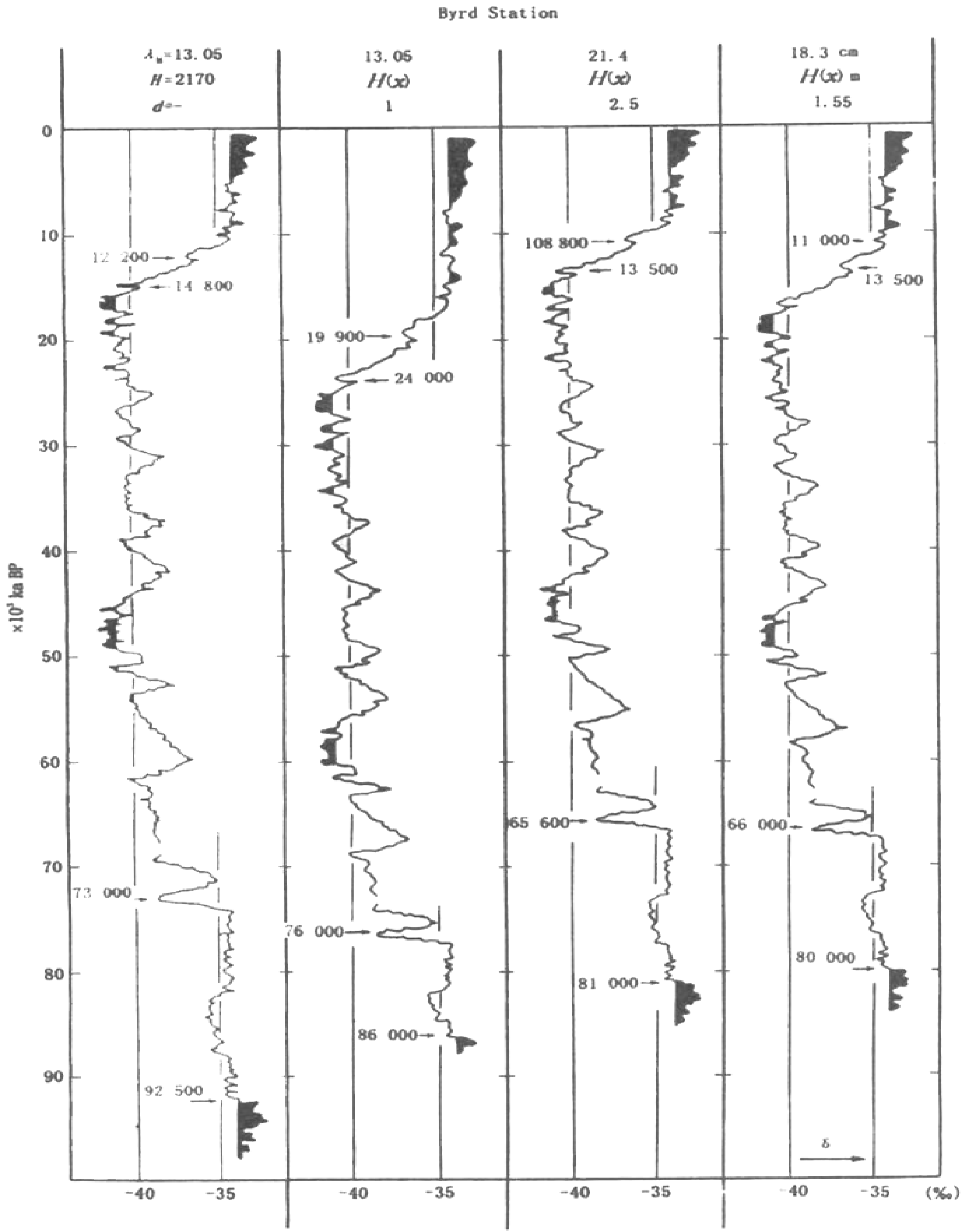
Ice flow law



$$t = -(h/c)\ln(1-y/h)$$

H-ice thickness, c-accumulation rate, y-meters above bedrock

Age profile along the depths can be roughly estimated according to flow law, such as Nye law

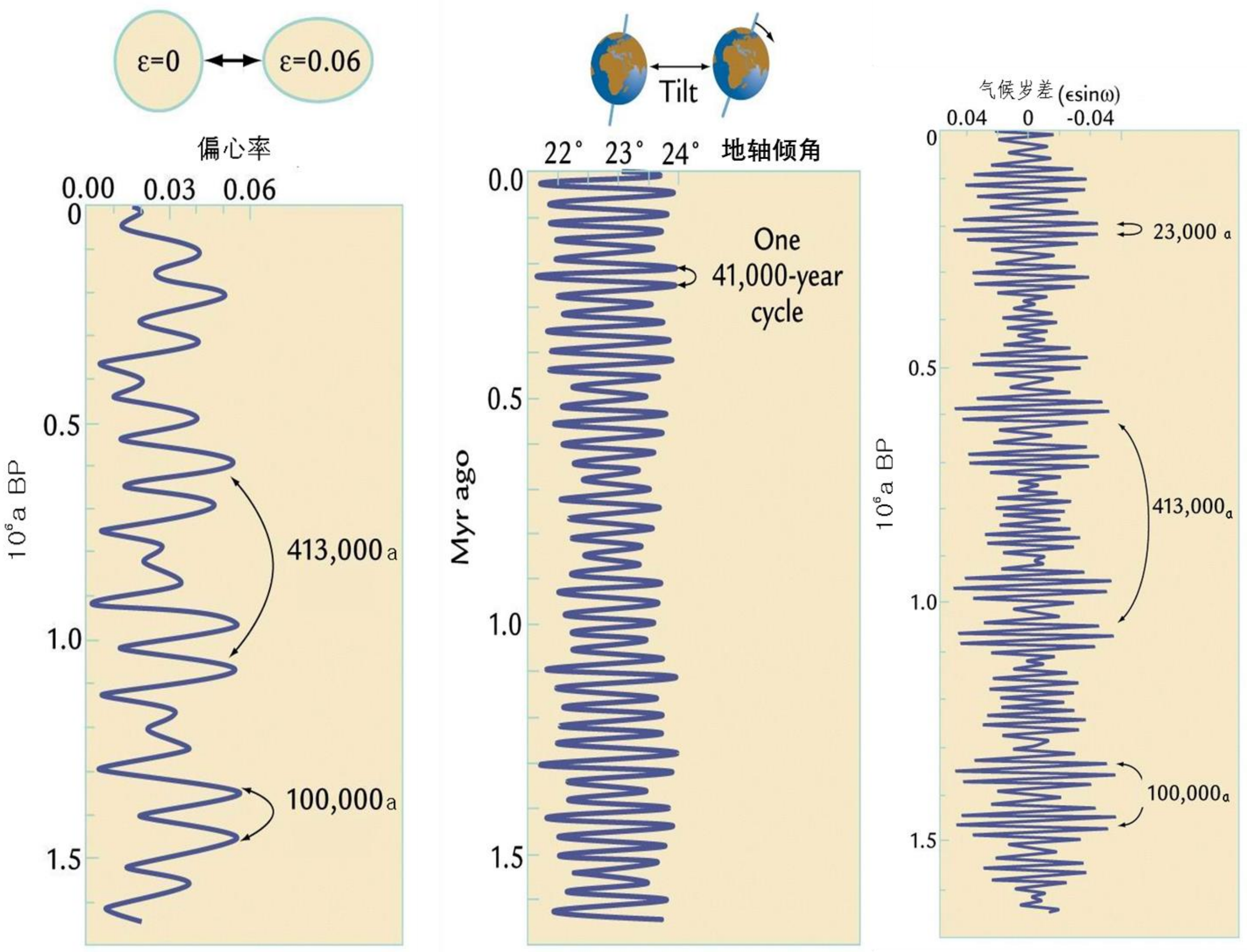


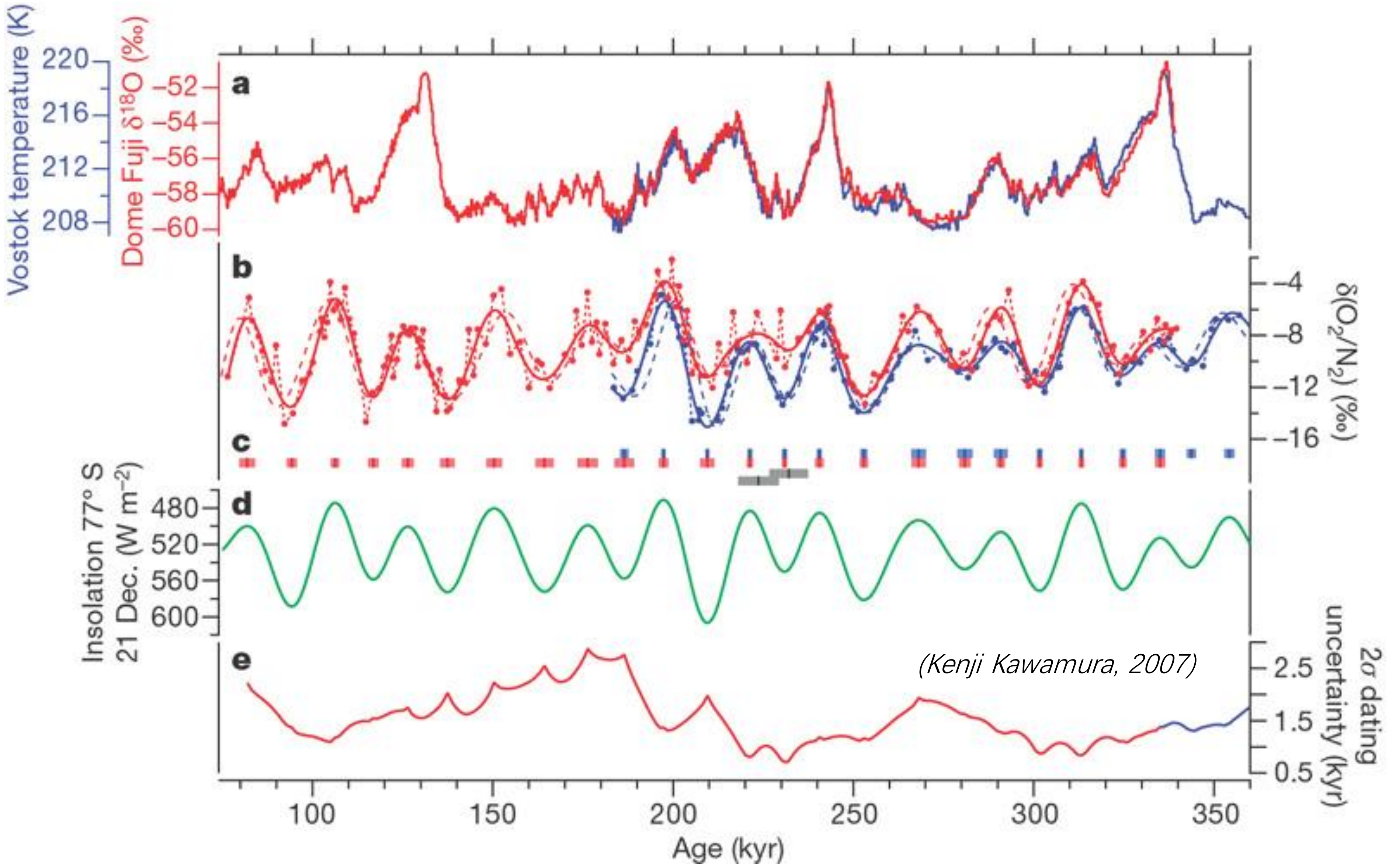
Dating results of Bryd ice core (Antarctica) by combining $\delta^{18}O$ profile and ice flow modelling.

（λ_h-accumulation，H-ice thickness，d-ice divergence）

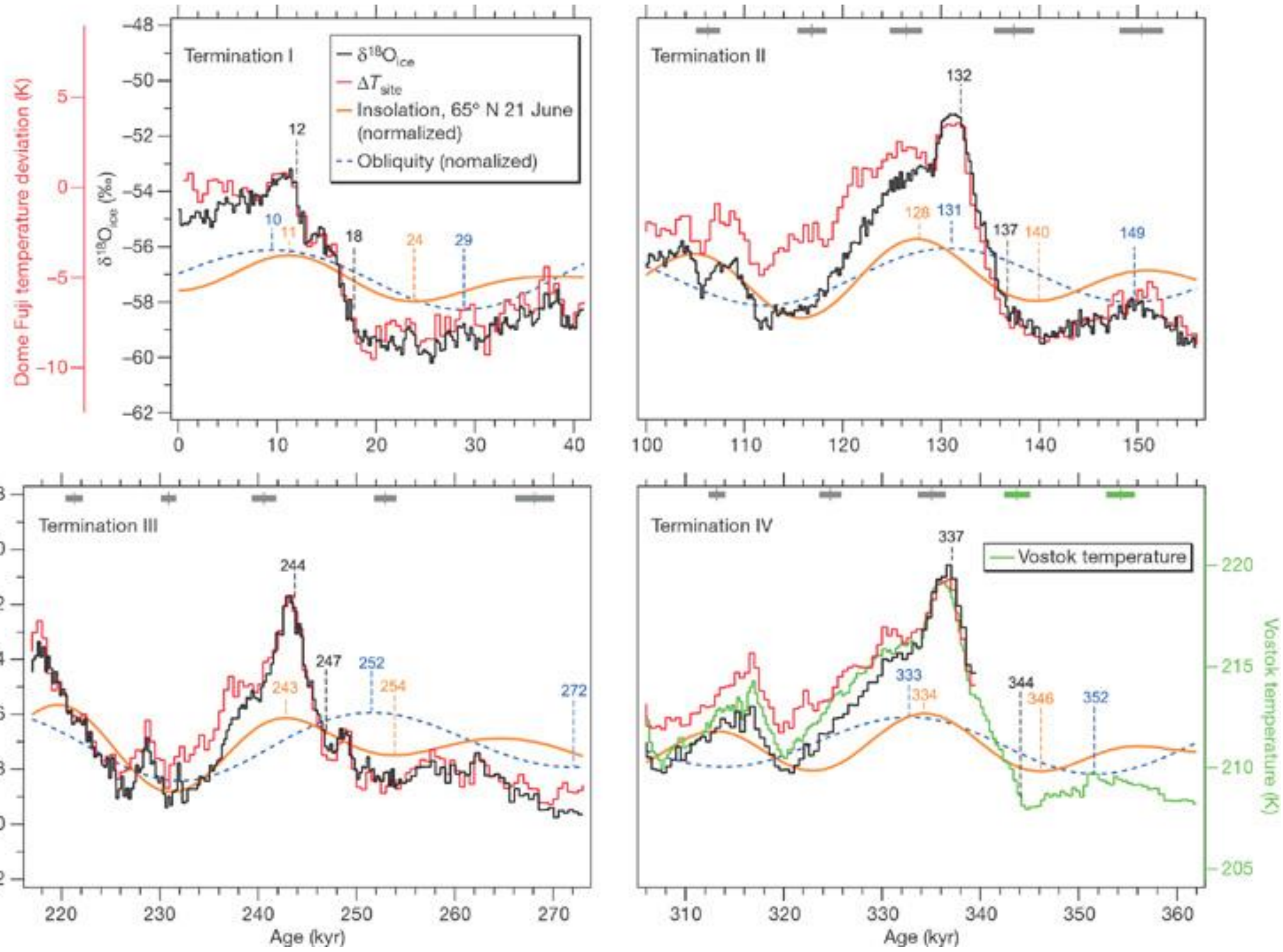
● Orbital tuning (轨道调谐)

Orbital tuning refers to the process of adjusting the time scale of a geologic or climate record so that the observed fluctuations correspond to the Milankovitch cycles (on time scales of 20-100 kyr.) in the Earth's orbital motion.





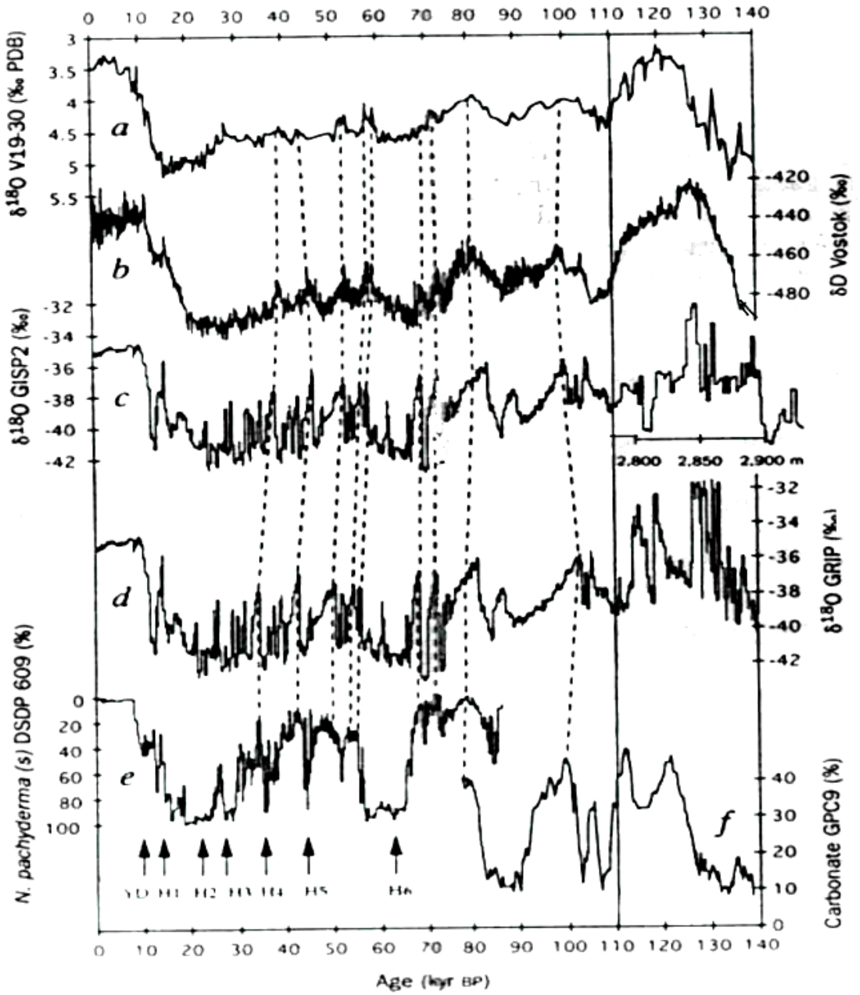
Orbital tuning of the Dome Fuji and Vostok timescales using O_2/N_2 records

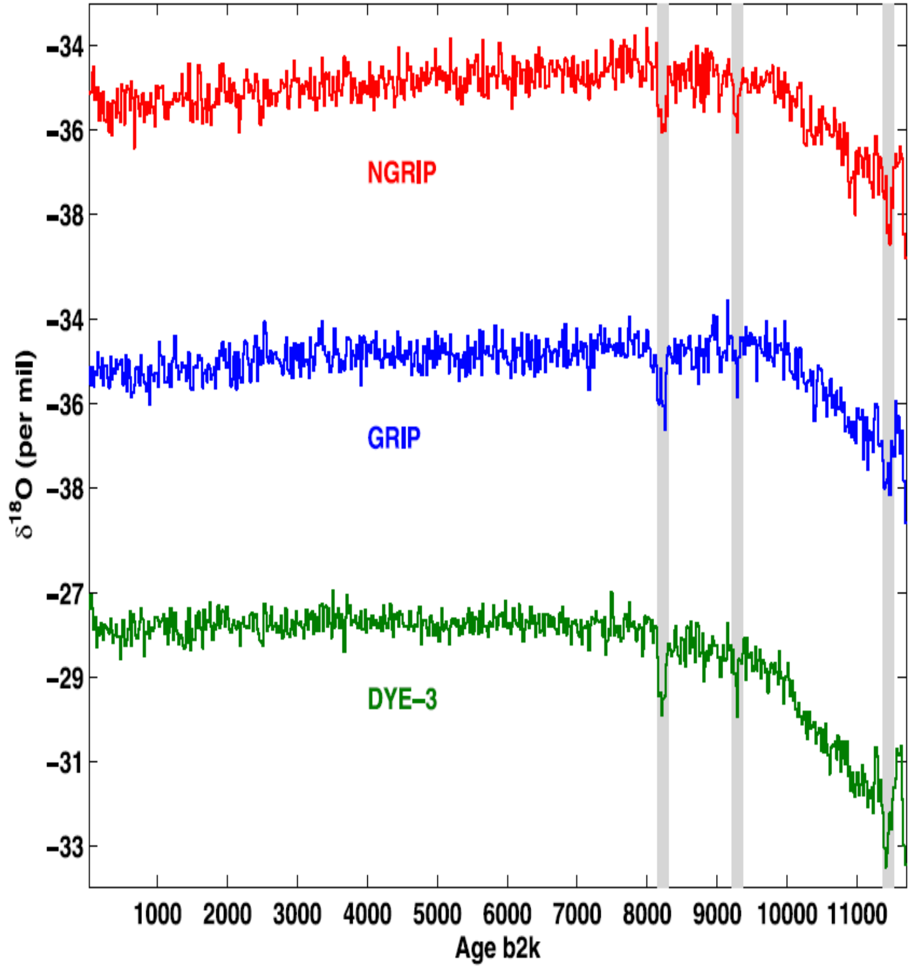


(Kenji Kawamura, 2007)

Comparison of Antarctic parameters with insolation and obliquity around the last four terminations

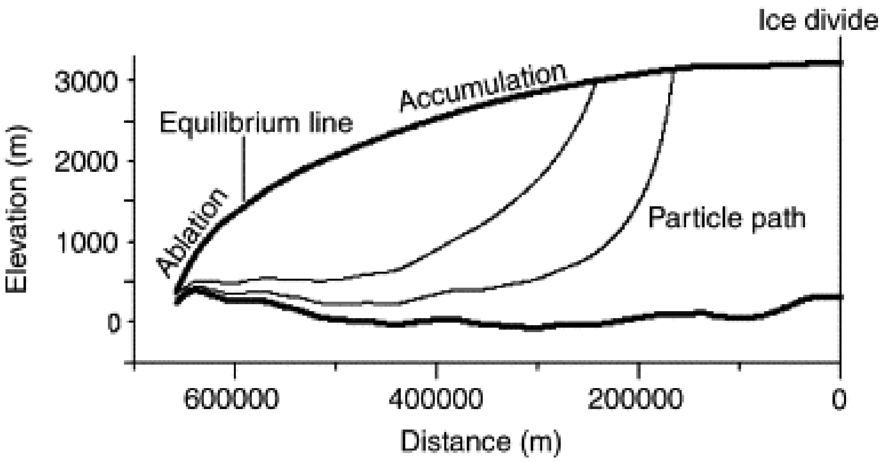
● paleo-analogy (古相似)



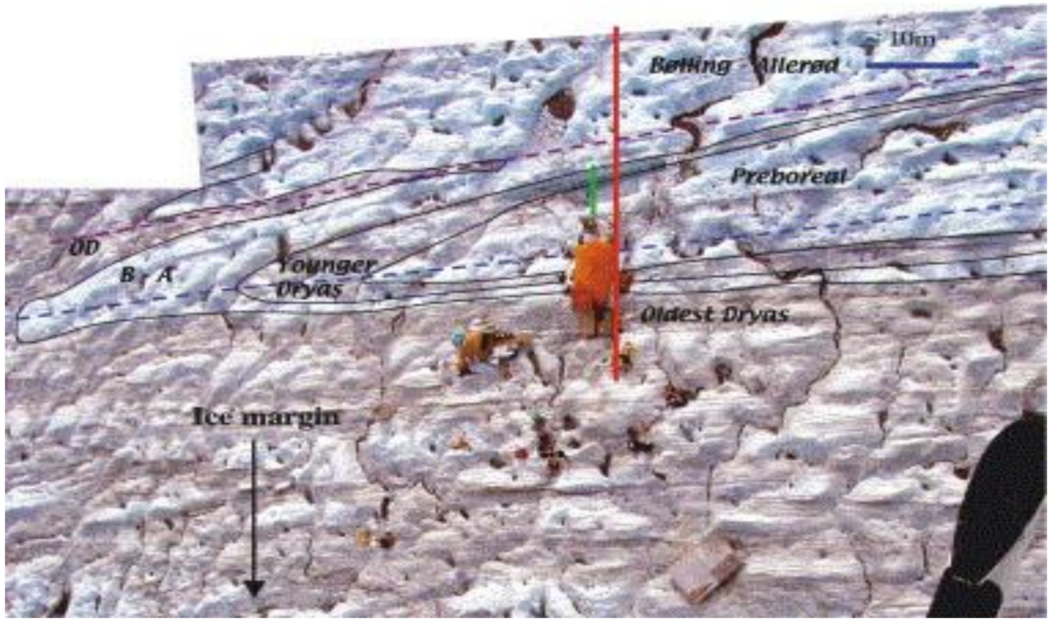


Holocene profiles of δ18O for the DYE-3, GRIP, and NGRIP ice cores on the GICC05 timescale. The **8.2 ka event**, the **9.3 ka event**, and the **11.4 ka** Preboreal Oscillation are indicated by shading. *(Vinther et al., 2006)*

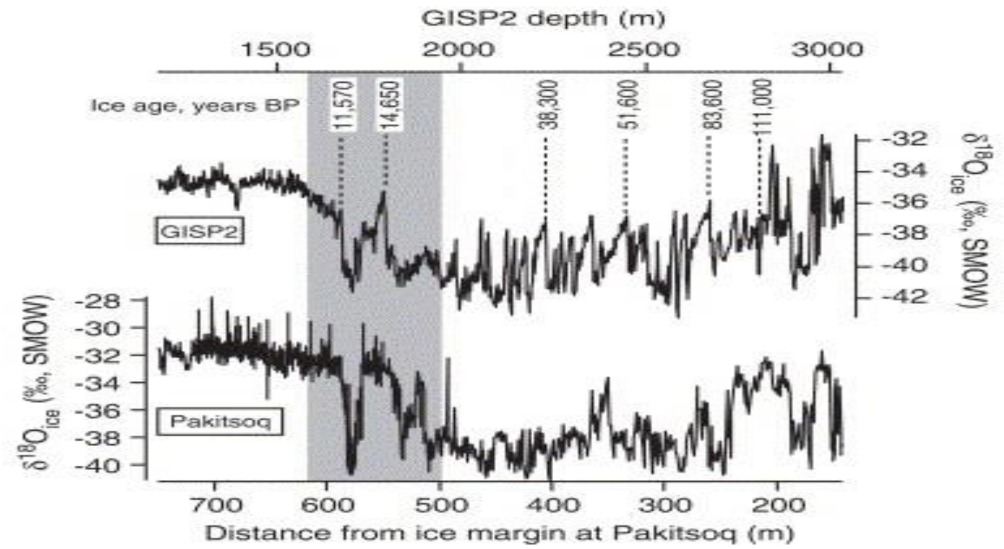
● Horizontal ice dating



Cross-section of an ice sheet, showing particle paths （Reeh et al. (2002).



A view of the sampling site from above, illustrating the folding in the ice at the sampling site in 2004

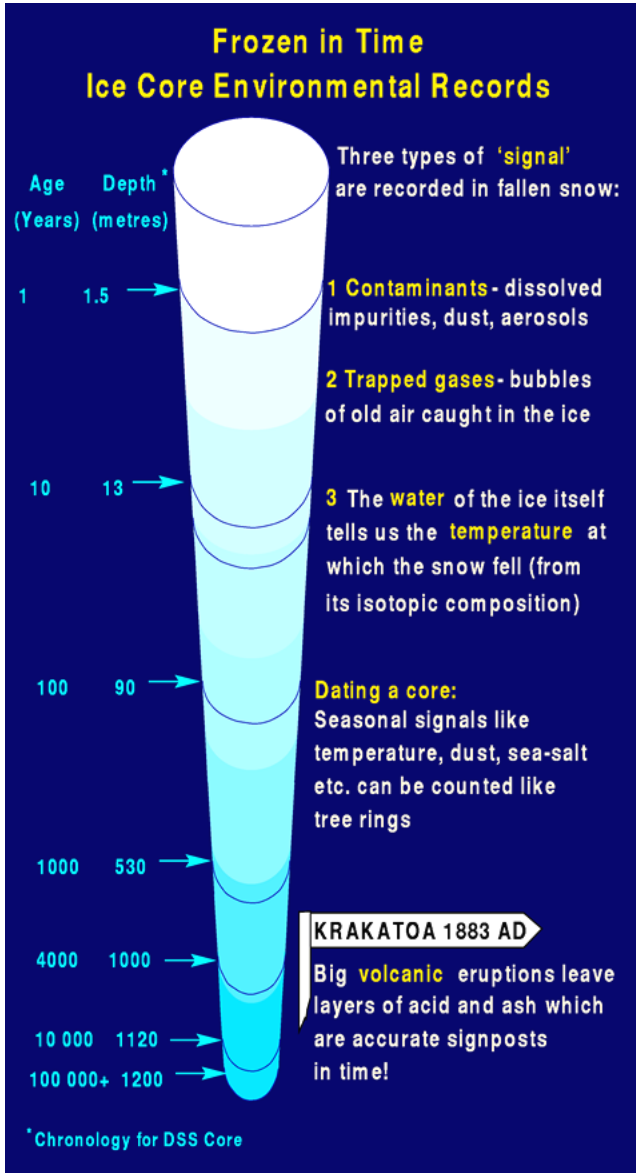


Comparison of a Pakitsoq **ice margin** δ^{18}O record from samples taken along a horizontal profile with **GISP2**.

Pakitsoq data are from Reeh et al. (2002); GISP2 δ^{18}O is from Grootes and Stuiver (1997);

(Petrenko et al., 2006)

- **Summary: cross-dating, using multiple methods and reference**



Cross-dating can reduce errors and uncertainties

upper section: physical/chemical annual signals

middle section: reference layer, gases, flow law, paleo-analogy

bottom section: cosmogenic radionuclides, etc

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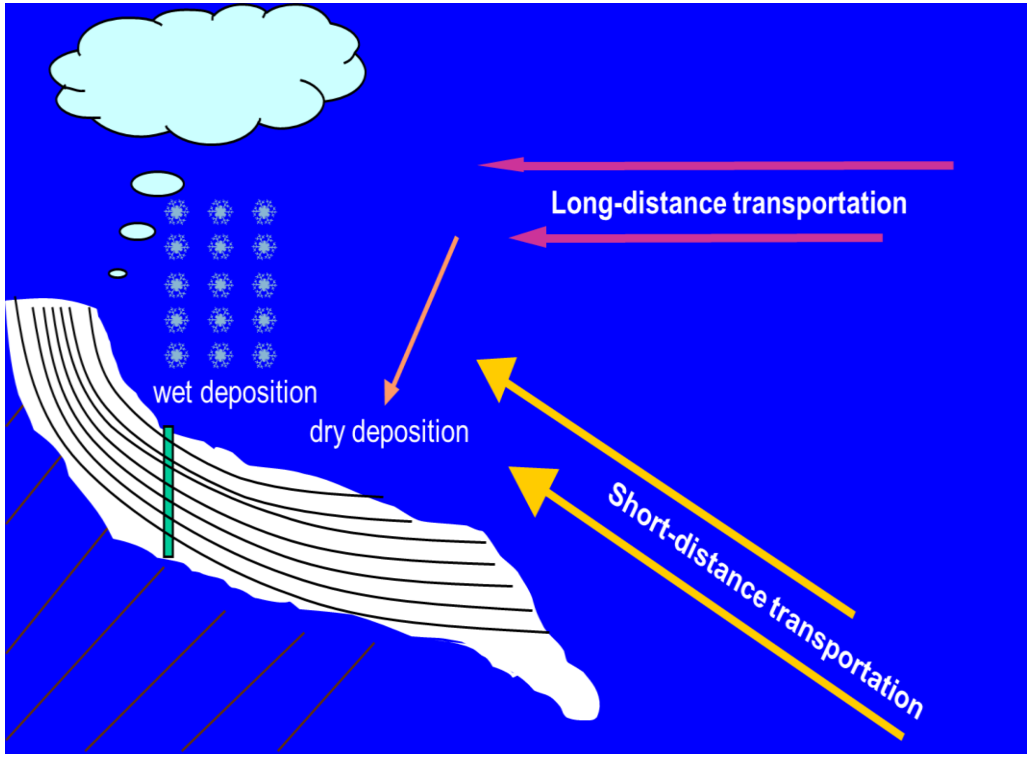
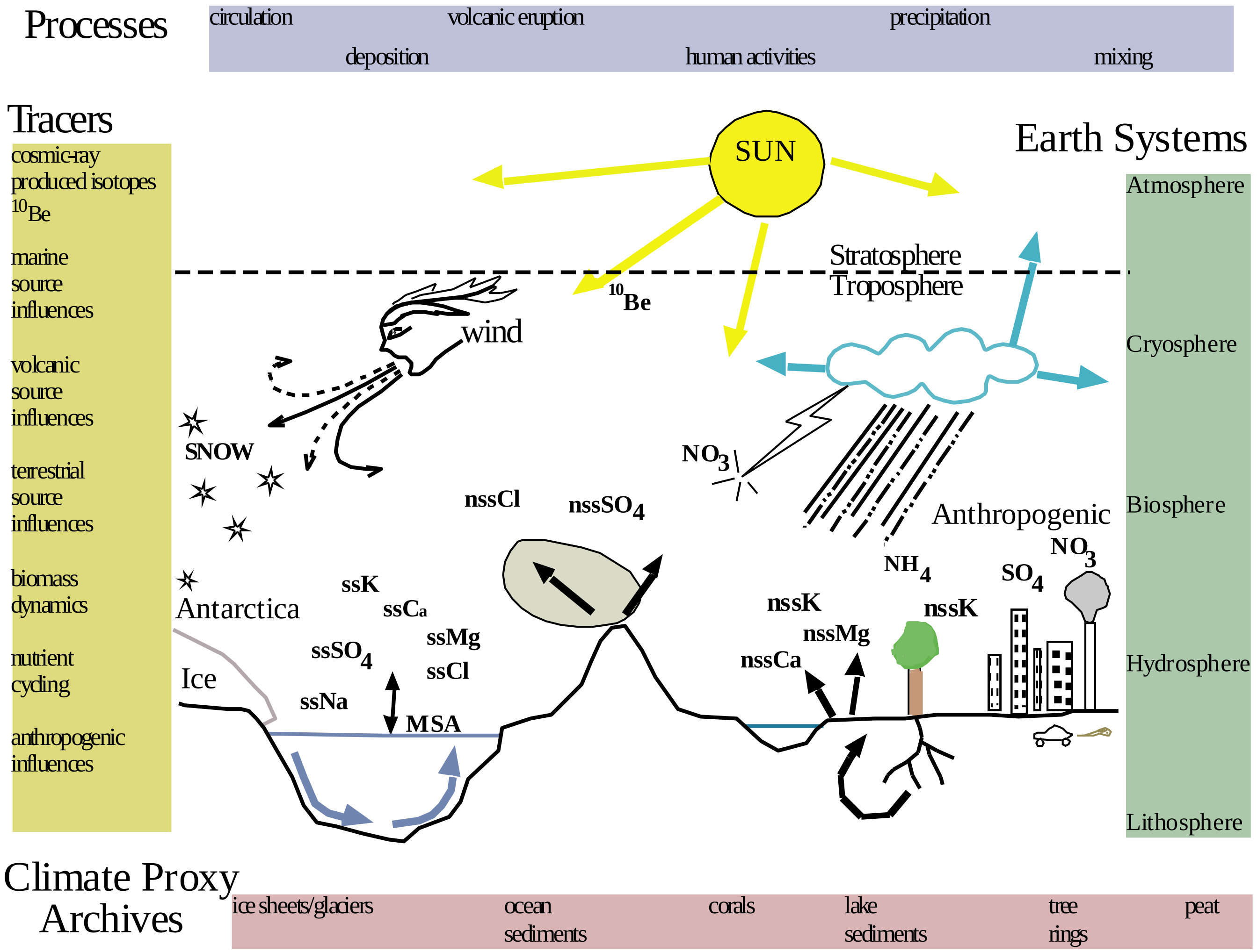
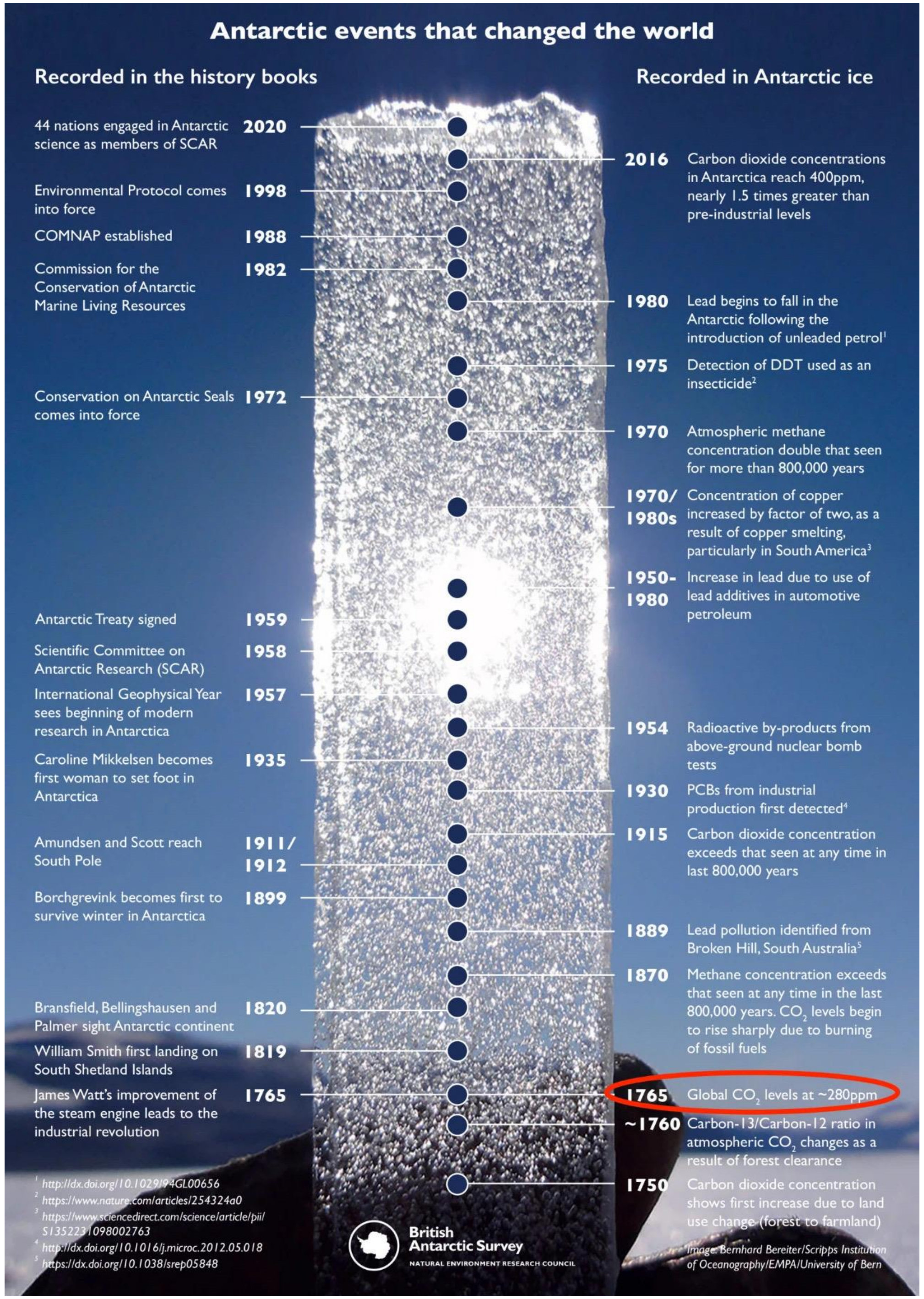
Impurities(杂质) origin in ice cores

Dry and wet deposition: main processes





(Modified from Oeschger)



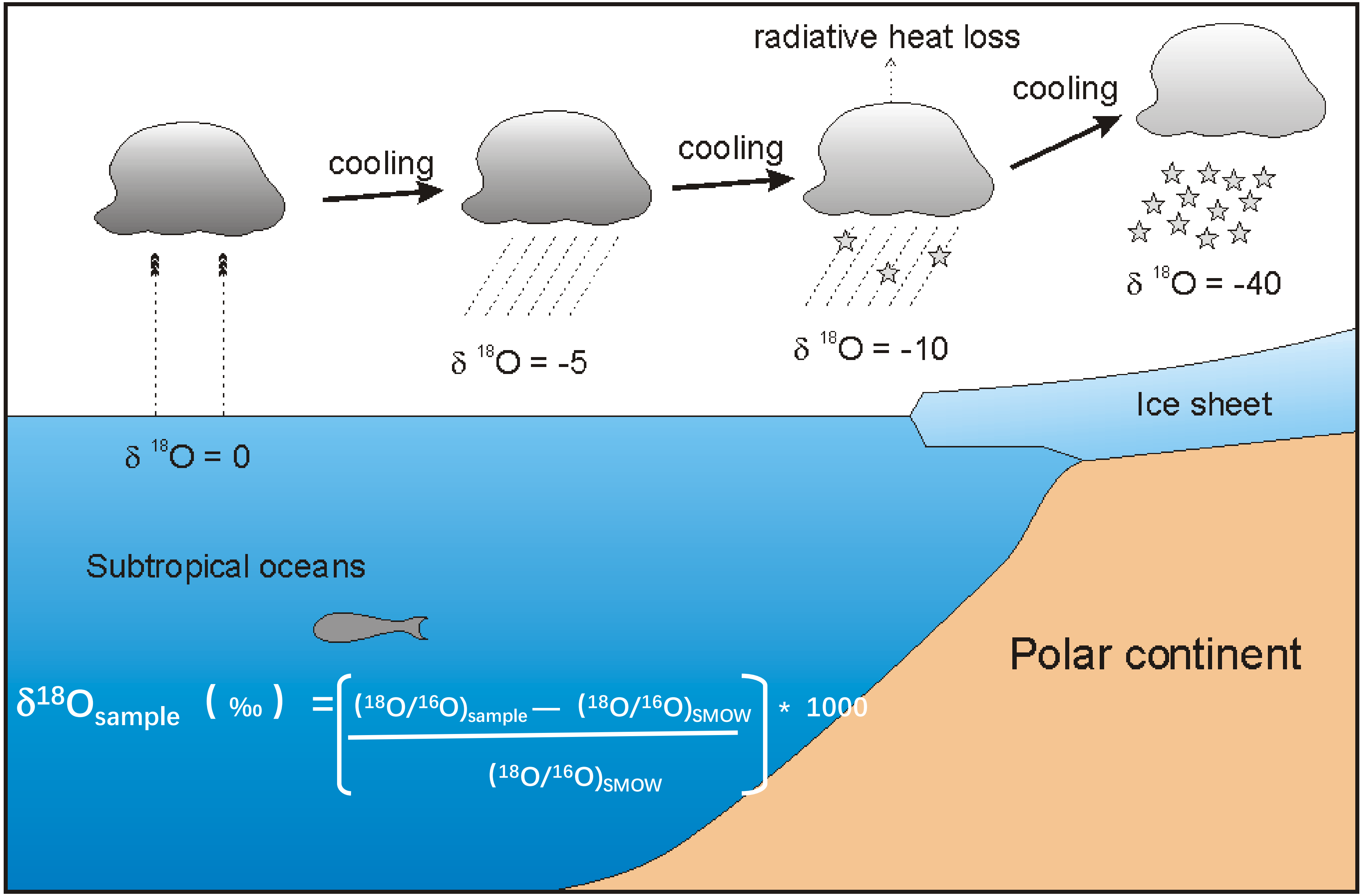
Ice Core data
A shopping list

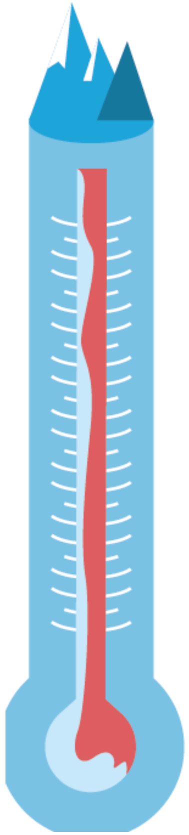
- The ice: ^{18}O , ^{17}O , ^{16}O, ^{1}H og ^{2}D
- Continental dust, volcanic ash, micrometheorites and biological materiale
- Ions: Cl^-, NO_3^-, SO_4^{2-}, F^-, H^+, Na^+, K^+, NH_4^+, Mg^{2+}, Ca^{2+}
- Gas in air bubbles: CO_2, CH_4, O_2, N_2, SF_6.
- Radioactive isotopes: ^{10}Be, ^{36}Cl, ^{210}Pb, ^{32}Si, ^{14}C, ^{137}Cs, ^{90}Sr.
- DNA
- Ice Properties
- Bore hole logging: temperature, geometry

climatic and environmental proxies in ice cores

Main climate parameters	**proxies**
Temperature	$\delta^{18}O$， δD， melt-layers
Precipitation	Accumulation rate, ^{36}Cl etc
Atmospheric circulation	Sea salts, continental dust, etc
Environmental events	
volcanoes	tephra， ECM， SO_4^{2-} etc
Solar events	^{10}Be etc
Sea ice extent	Sea salts， MSA, IPSO25
desertification	Dust particles、continental crust elements
Biomass burning	Levoglucosan and Surfactants、soot、black carbon、K+
Ice sheet elevation	Total gas content
Human activities	metals， POPs， NH_4^+、SO_4^{2-}, GHGs, etc

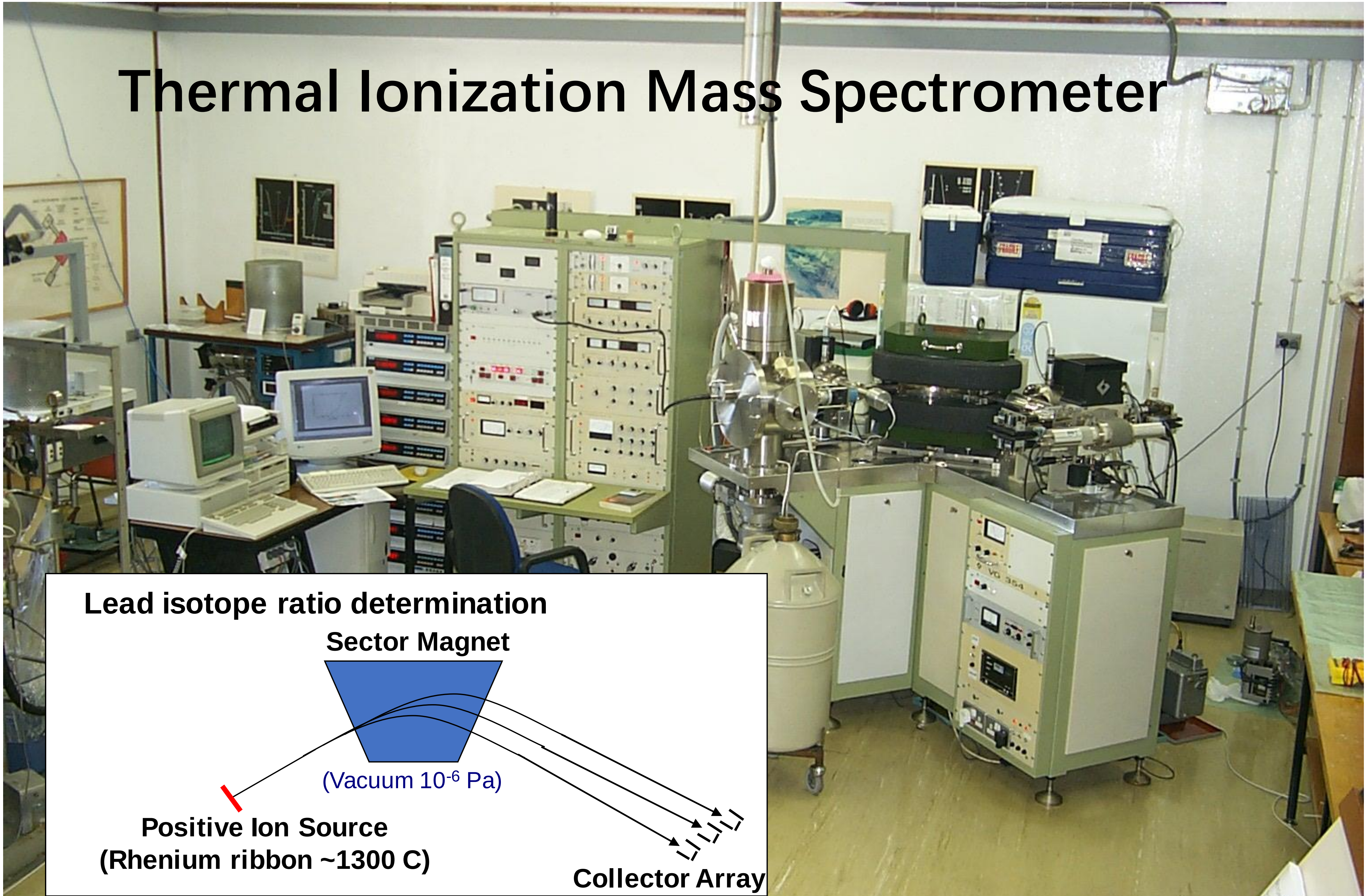
● Proxy of temperature (T)





$\delta^{18}O$, δD

Thermal Ionization Mass Spectrometer



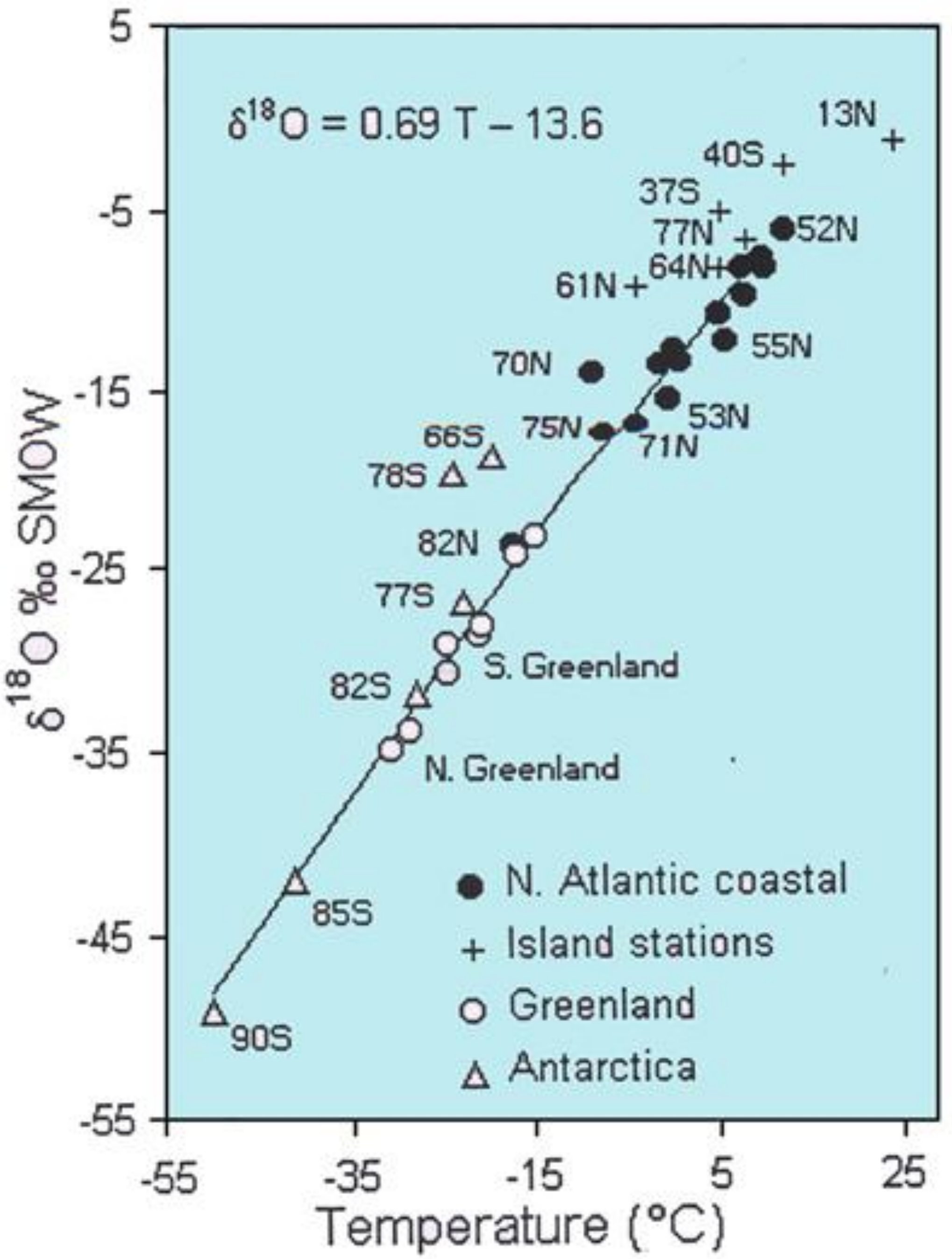
The relationship between δ and T:

Theoretically, the level of the δ value is related to the condensation temperature when cloud form precipitation. However, it is very difficult to accurately know the condensation temperature in cloud. Besides, the snowfall process itself is very complex. But, since temperature is the most important factor controlling stable isotopes in precipitation, and it is easy for us to know the annual average temperature of the precipitation location, therefore, **Dansgaard (1964) developed the empirical relationship between $\delta^{18}O$ in precipitation and the annual average temperature (T)**.

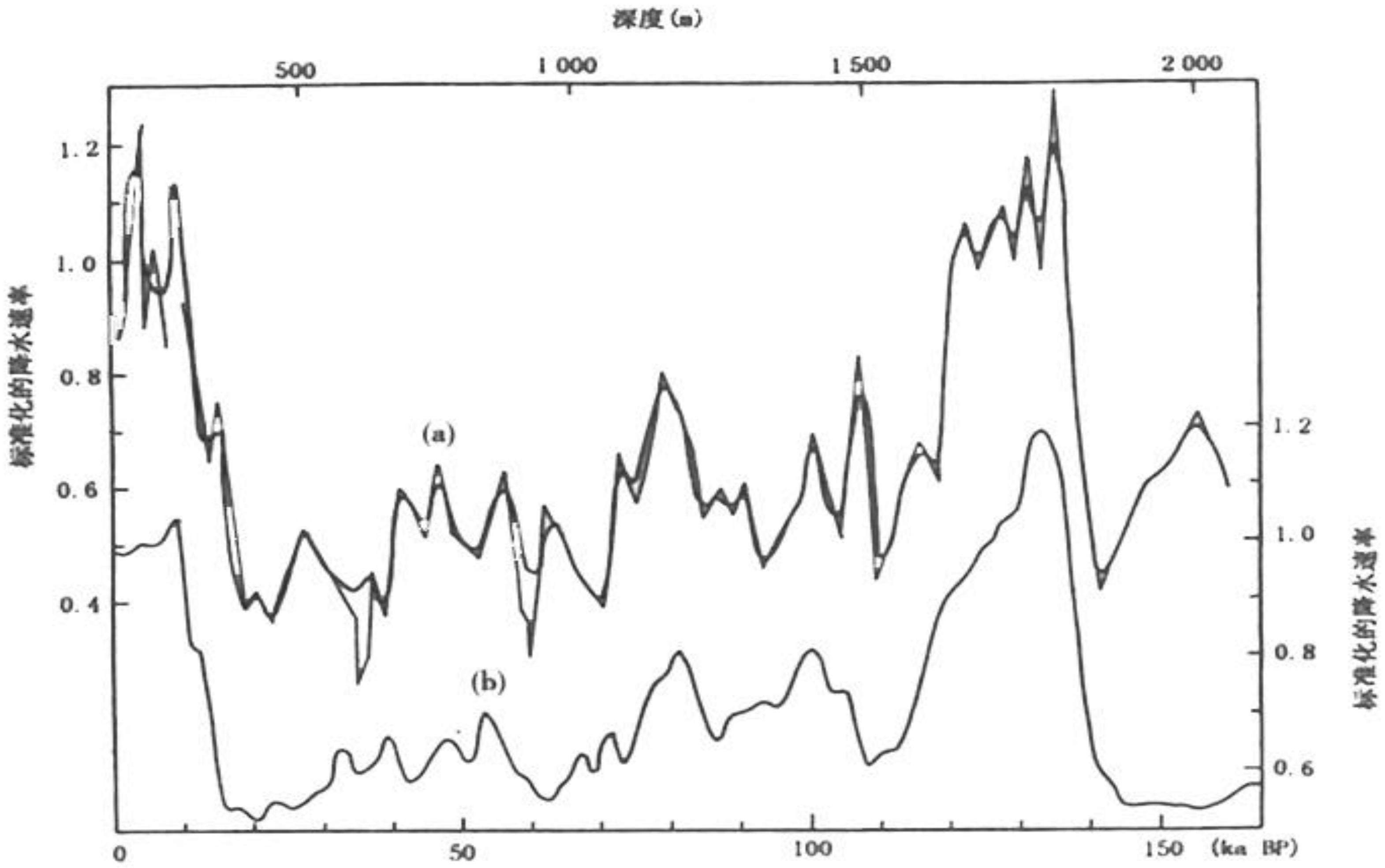
δ值与温度的关系：

理论上讲，δ值的高低与云团形成降水时的凝结温度有关，但很难准确知道某次降雪过程中云团的凝结温度，况且，降雪过程本身也十分复杂；

但，因为温度是控制降水中稳定同位素最重要的因素，而我们很容易得知降水地点的年平均温度，因此，Dansgaard(1964)年得出了降水中$\delta^{18}O$与年平均温度之间的经验关系。

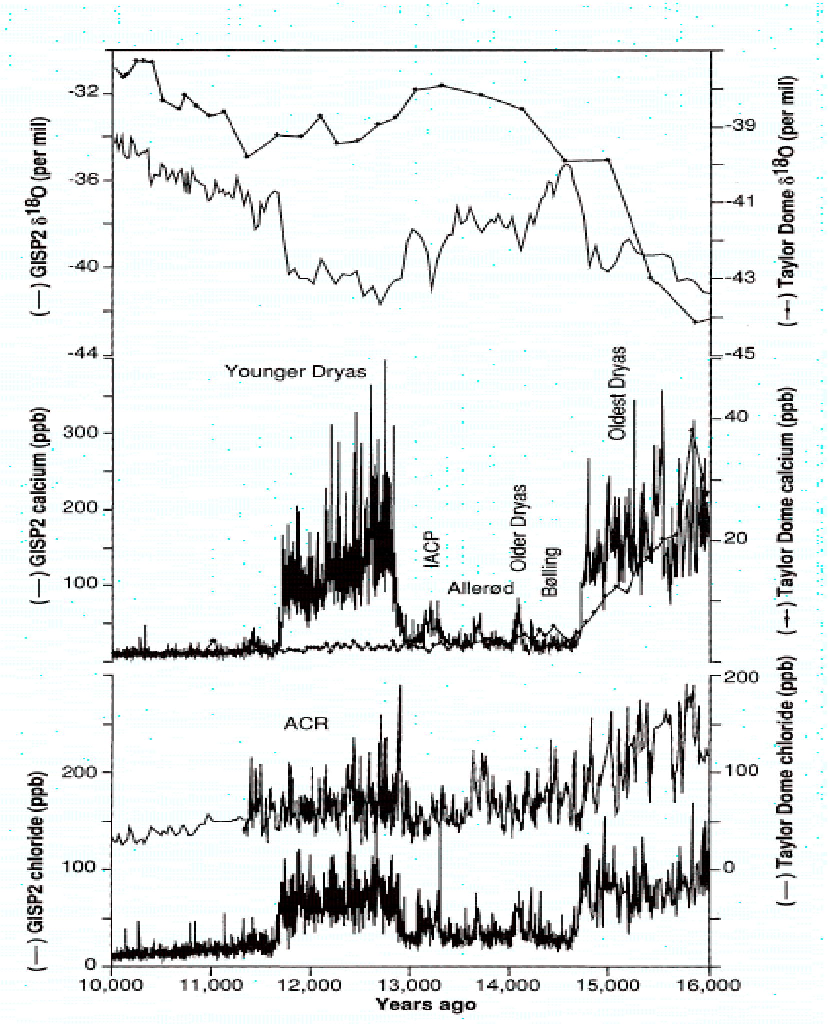


● **Proxy of precipitation (p)**

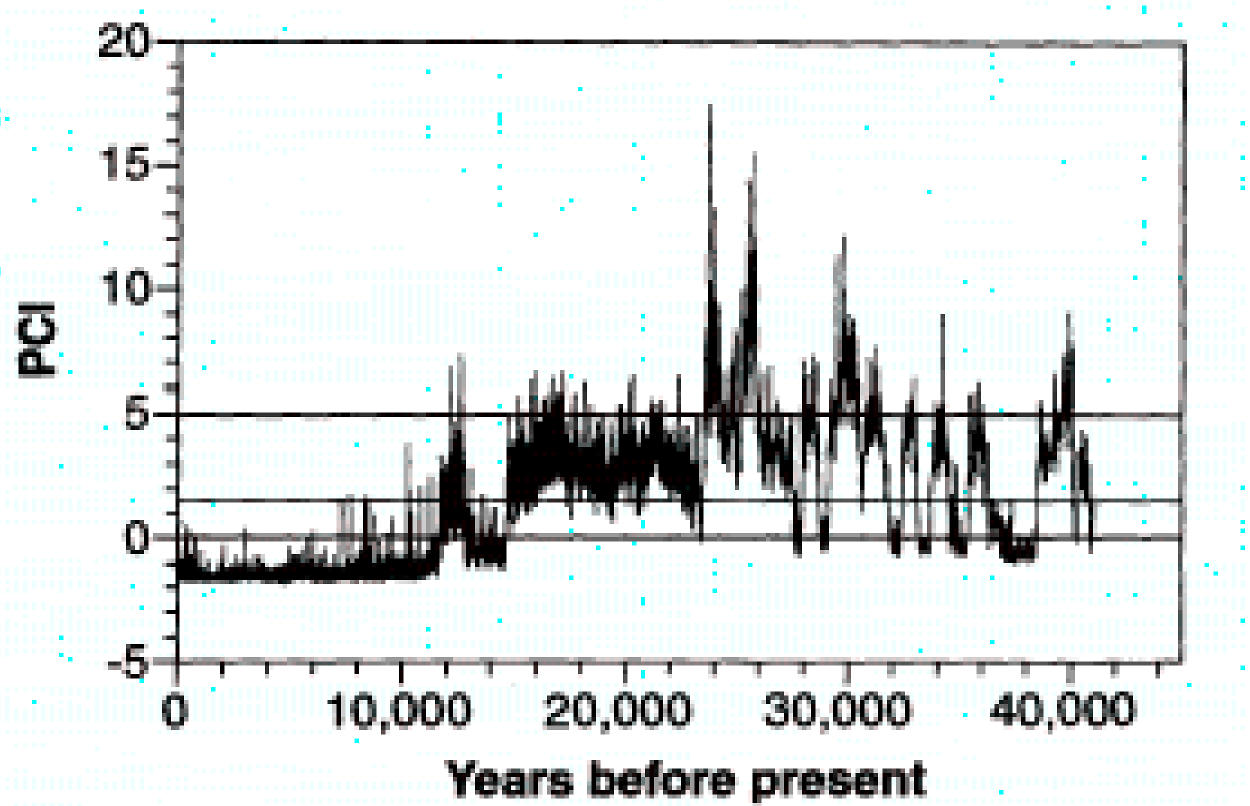


Precipitation (accumulation rate) at Vostok reconstructed by (a) ^{10}Be, (b) $\delta^{18}O$

● Proxy of atmospheric circulation strength *(continental Ca, Al; marine Na, Cl)*



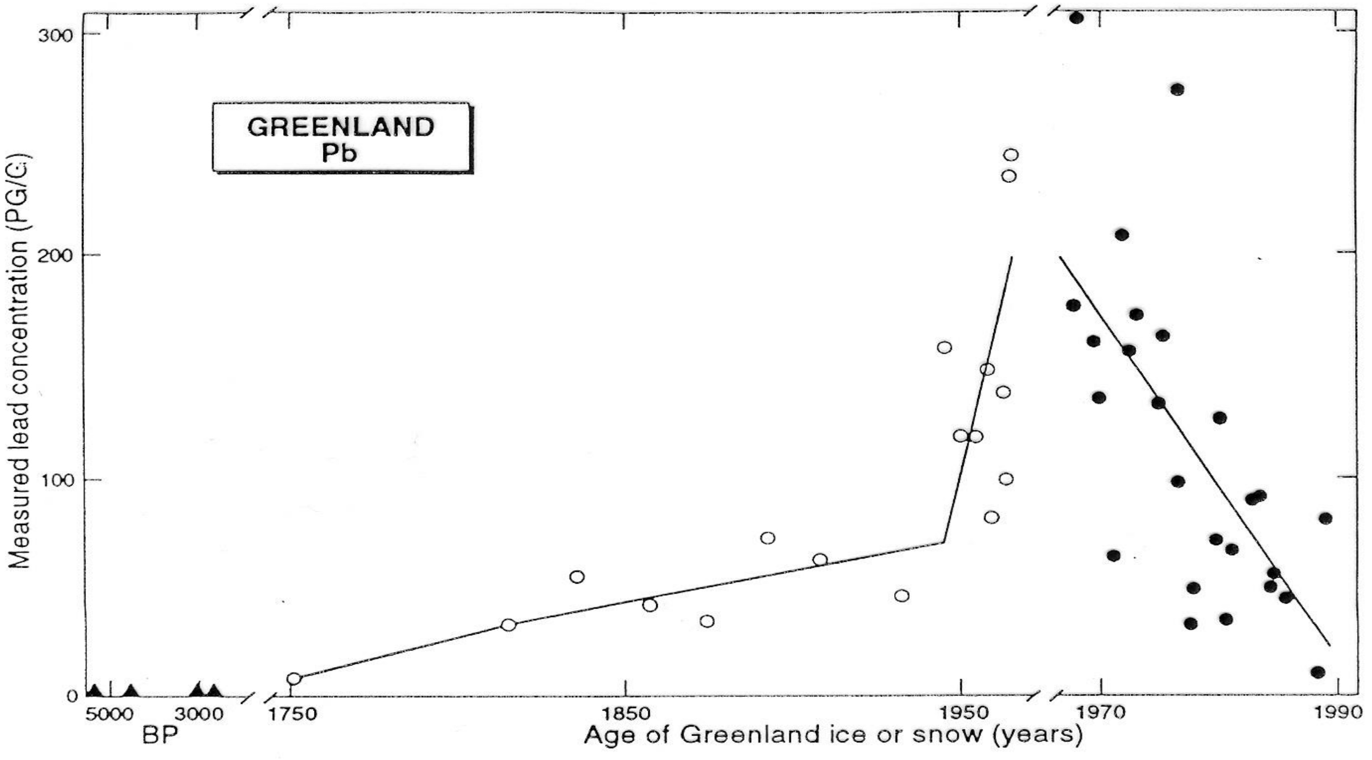
Stronger dust load during YD/ACR than Holocene revealed in polar ice cores



(Mayewski et al., 1994, Science, 263)

Polar circulation index (PCI) reconstructed through sea salts records in GISP2 ice core

- **Proxy of human being's pollution**



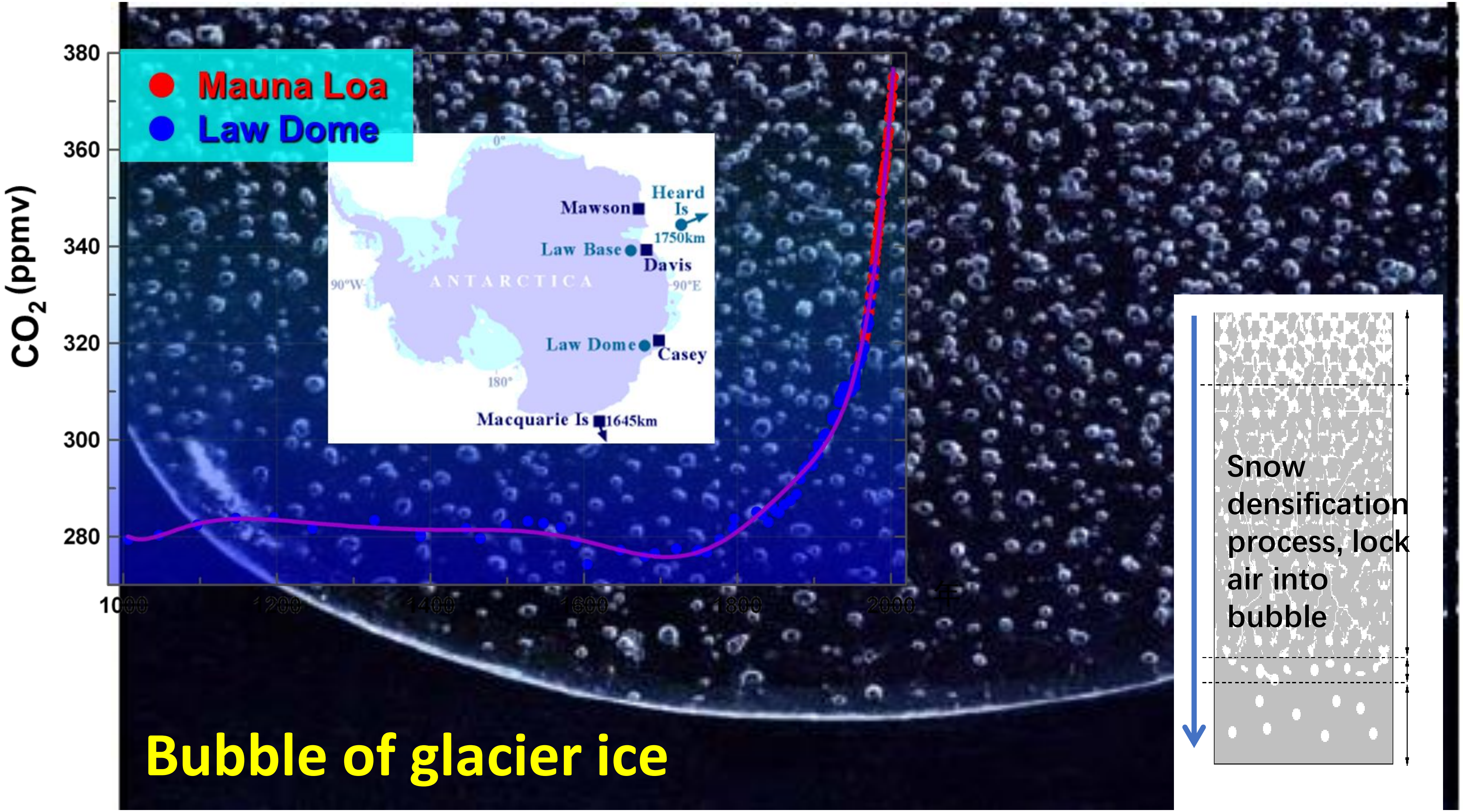
changes in Pb concentration in Greenland ice and snow. From Murozimi et al (1969); Ng and Patterson (1981) and Boutron et al (1991).

- From the 1750s to 1950s:
  ~20 fold increase
- In the 1960s:
  ~100 fold increase
  massive use of Pb additives
- After the 1970s:
  sharp decrease
  phase-out of leaded gasoline
- Direct response to human activities

Large-scale Pb pollution in the Northern Hemisphere since the Industrial Revolution

Source: S. Hong

- Direct record of ancient air



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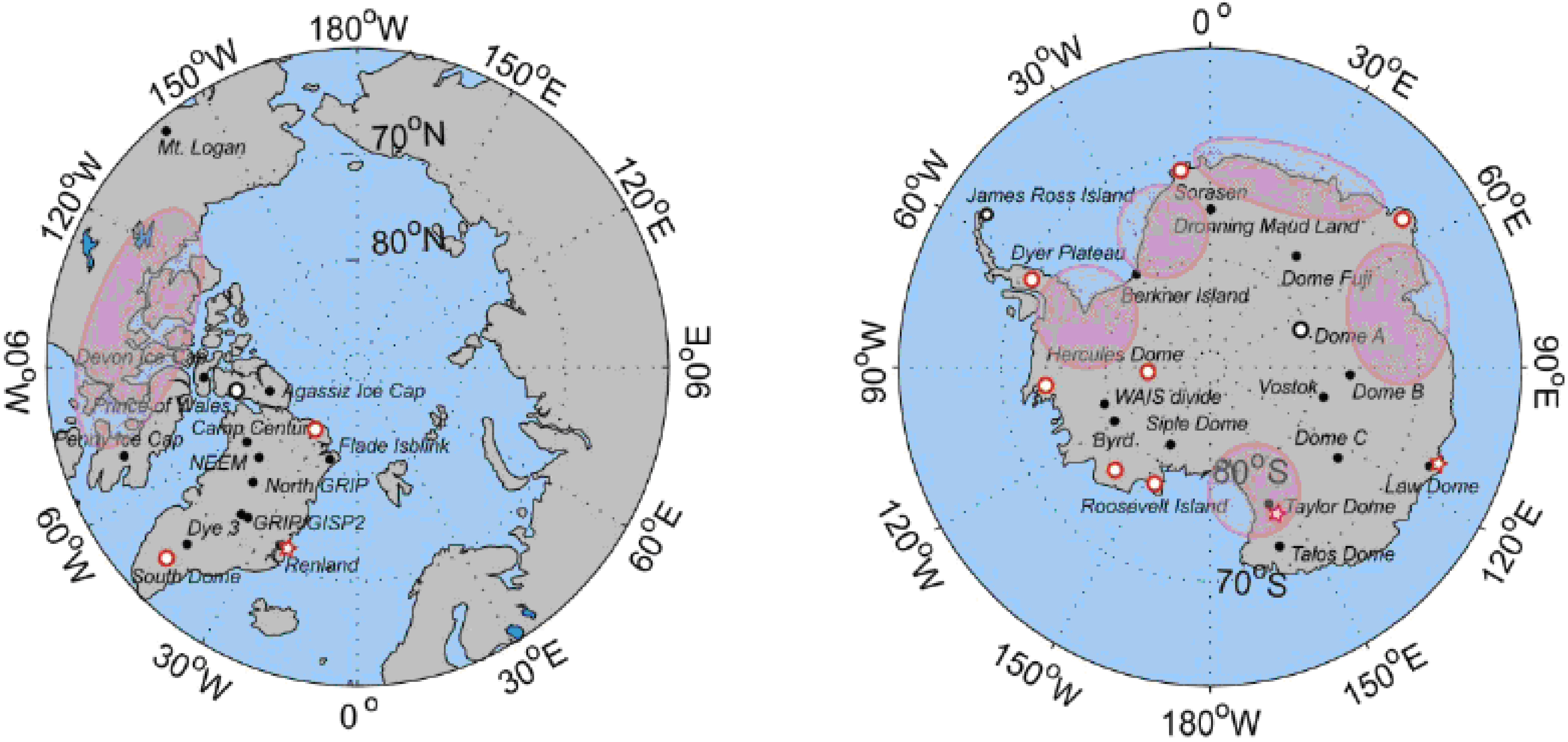
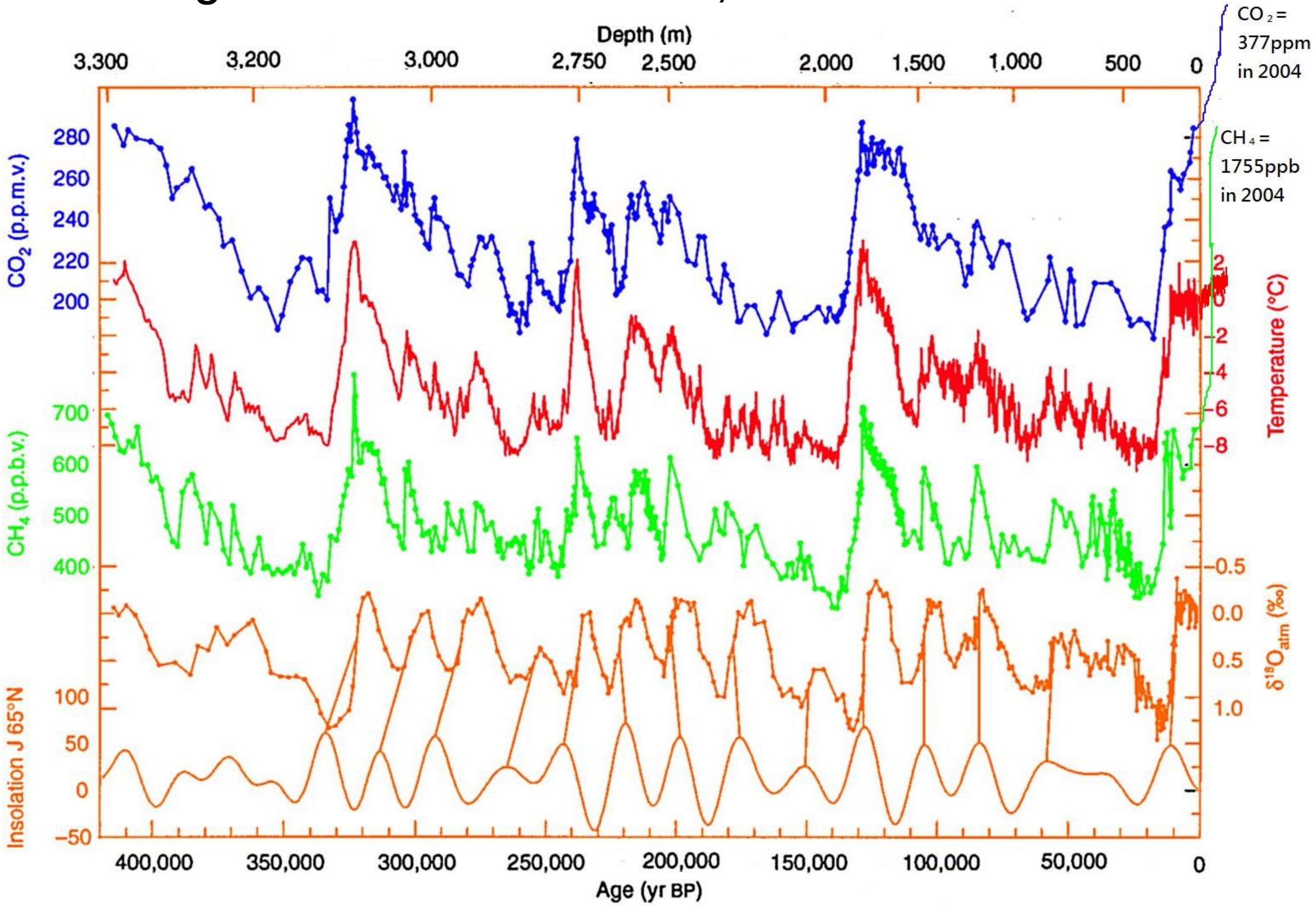


Distribution of ice cores in polar ice sheet

（black dots：finished；white dots：ongoing；red dots：planning）

- **Long-term climate evolution, much more detailed than before**

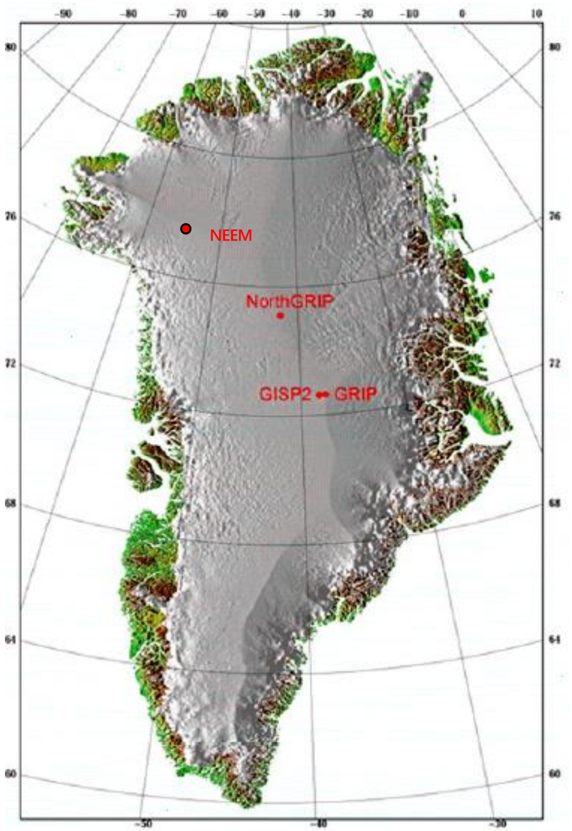


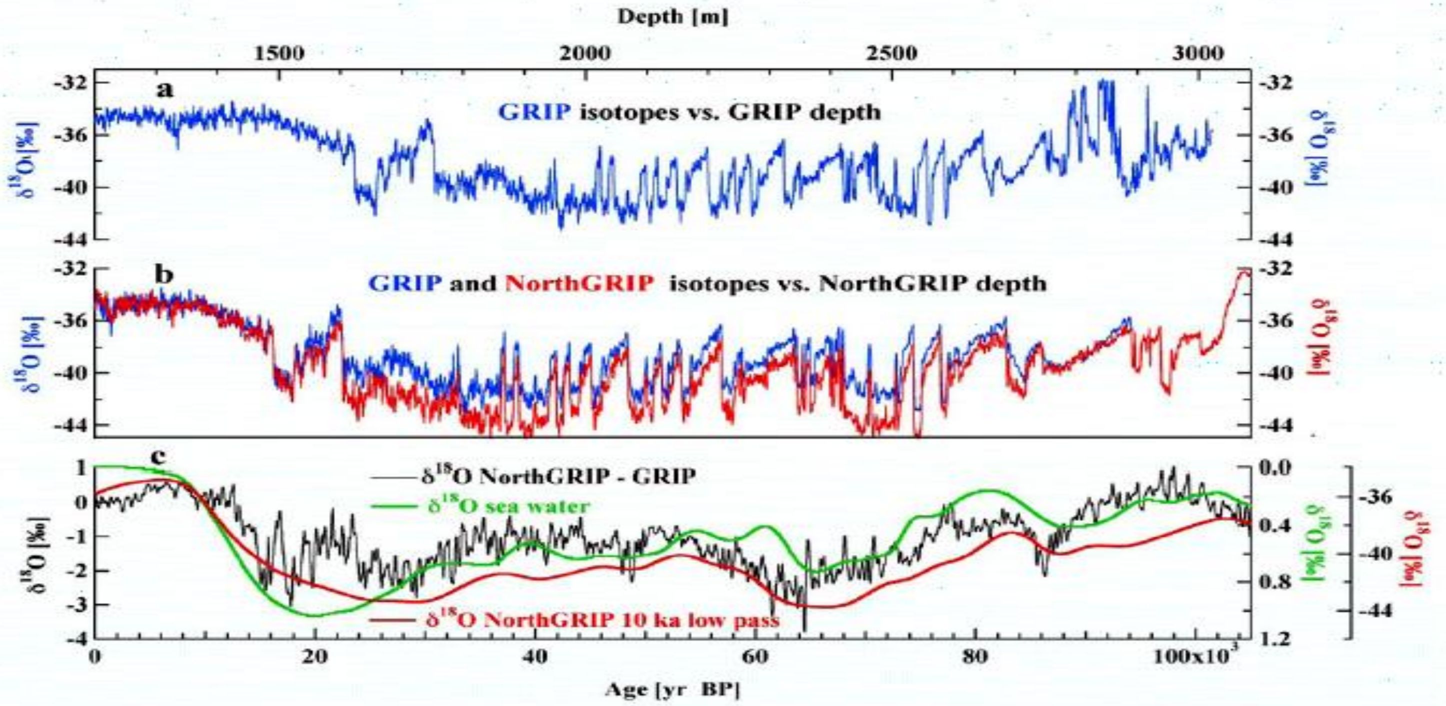
420,000 years of ice core data from Vostok, Antarctica research station.

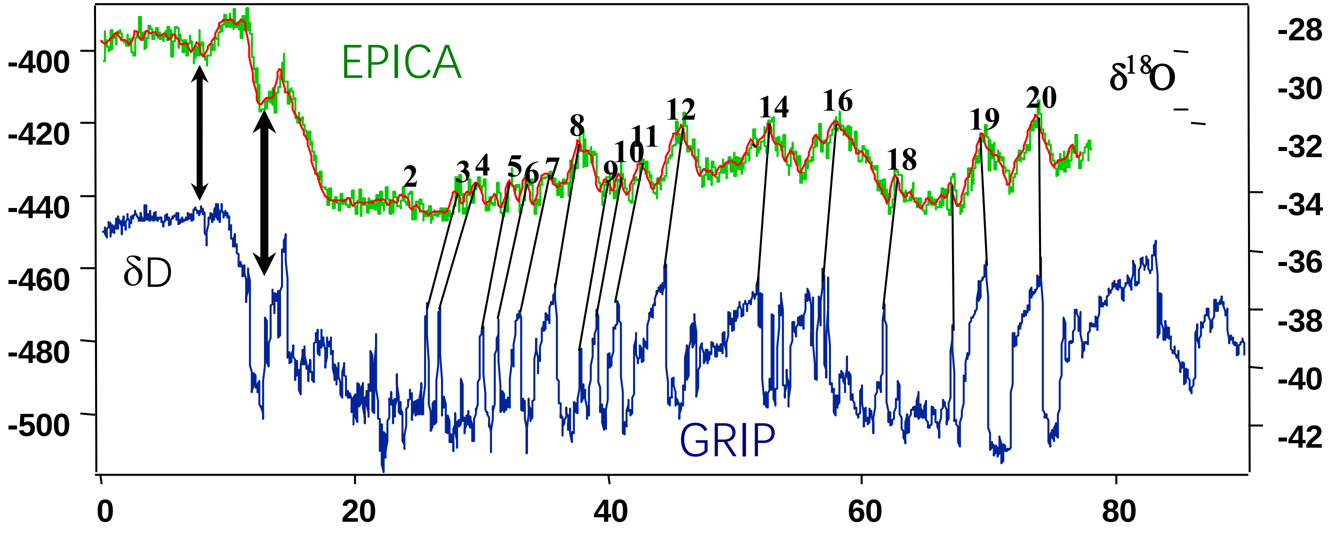
Current period is at right. From bottom to top: * Solar variation at 65°N due to en:Milankovitch cycles (connected to 18O). * 18O isotope of oxygen. * Levels of methane (CH4). * Relative temperature. * Levels of carbon dioxide (CO2). From top to bottom: * Levels of carbon dioxide (CO2). * Relative temperature. * Levels of methane (CH4). * 18O isotope of oxygen. * Solar variation at 65°N due to en:Milankovitch cycles (connected to 18O).

Wikimedia Commons.

- Greenland ice core shows very high-resolution changes of climate, abrupt climate events (ACE) during cold stages are firstly revealed



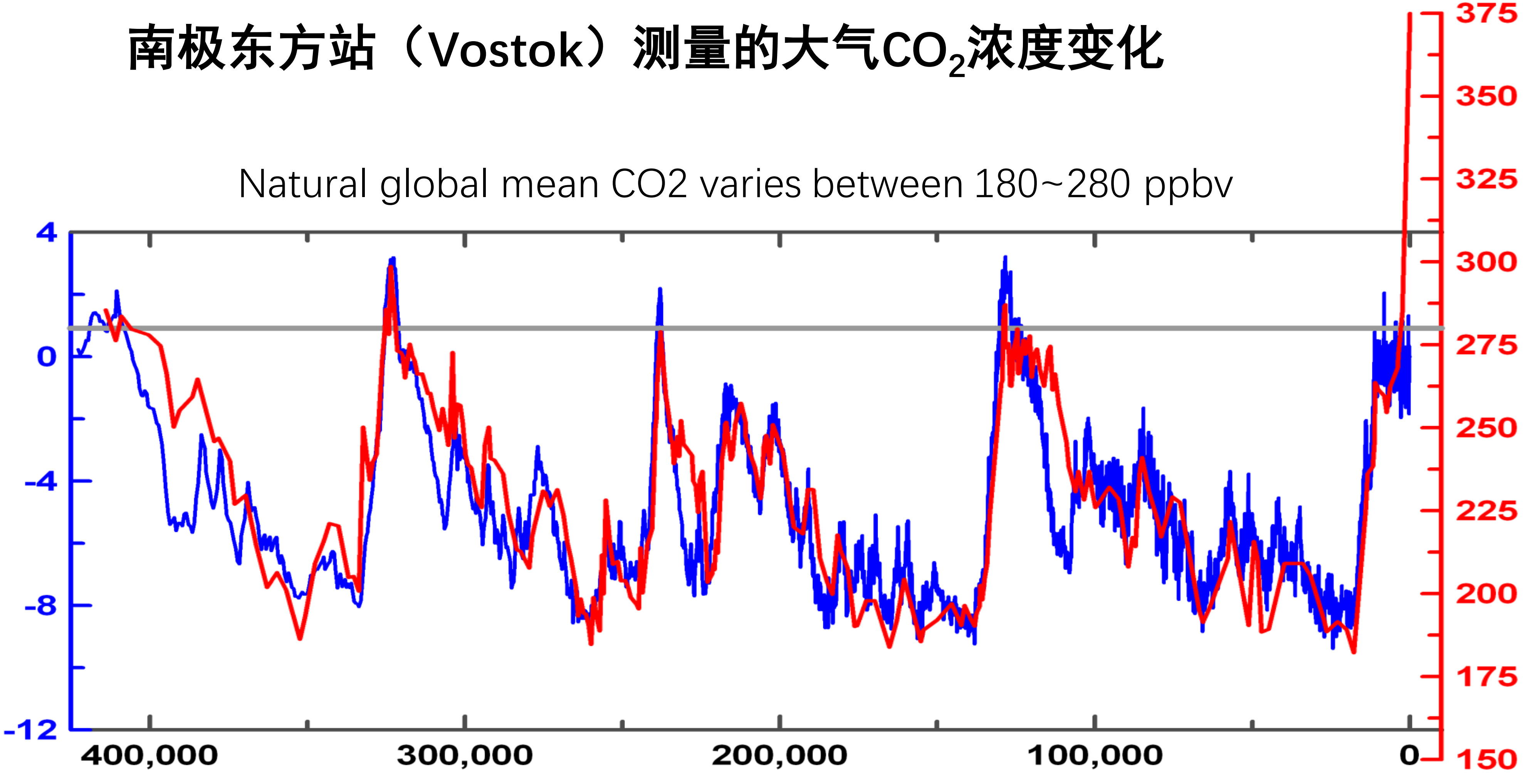




Bi-polar seesaw

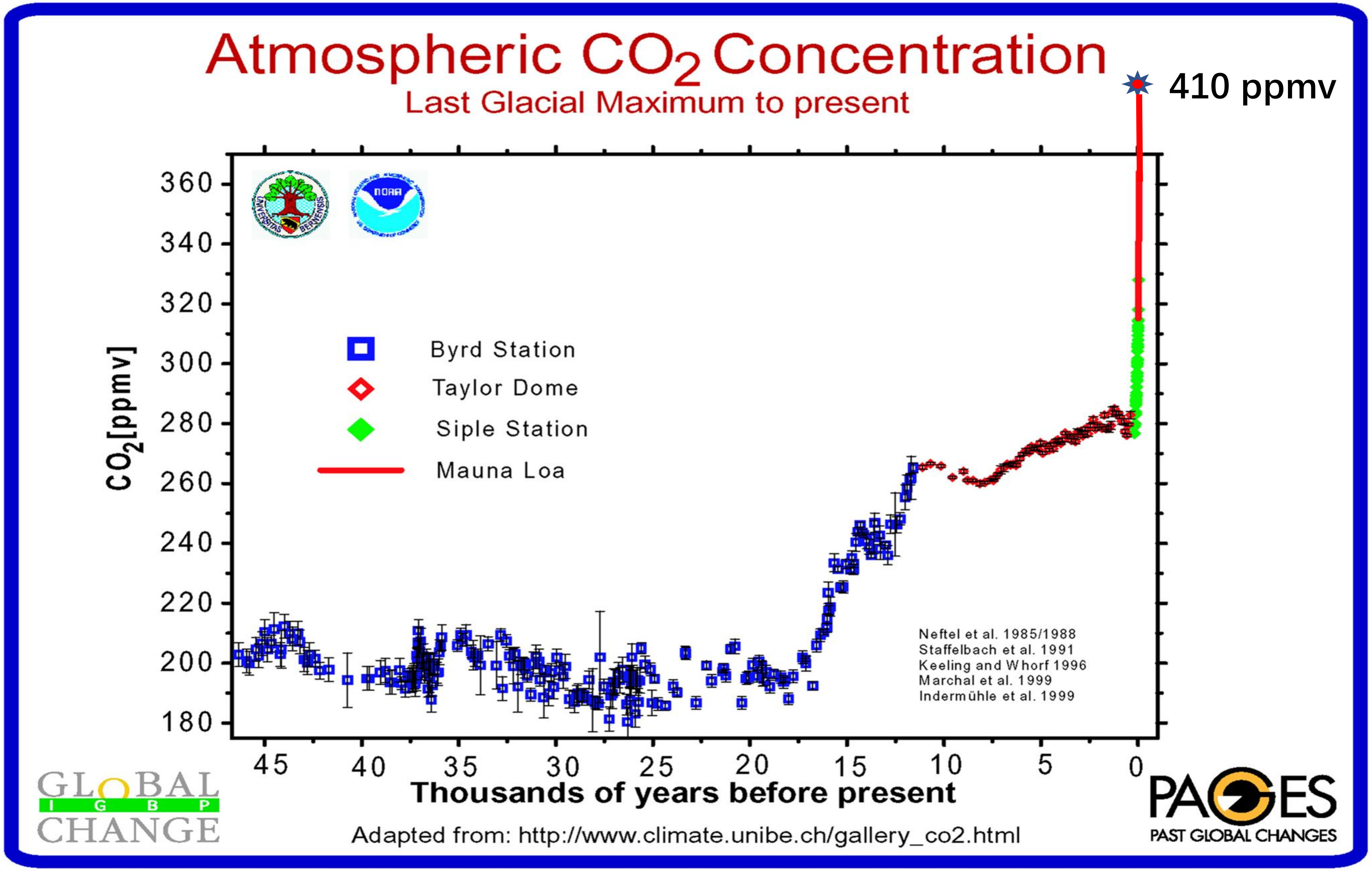
● **Strong evidence for GHGs history (evidence stage-1:** ***glacial-interglacial cycles*****)**

May 2021: 412PPmv



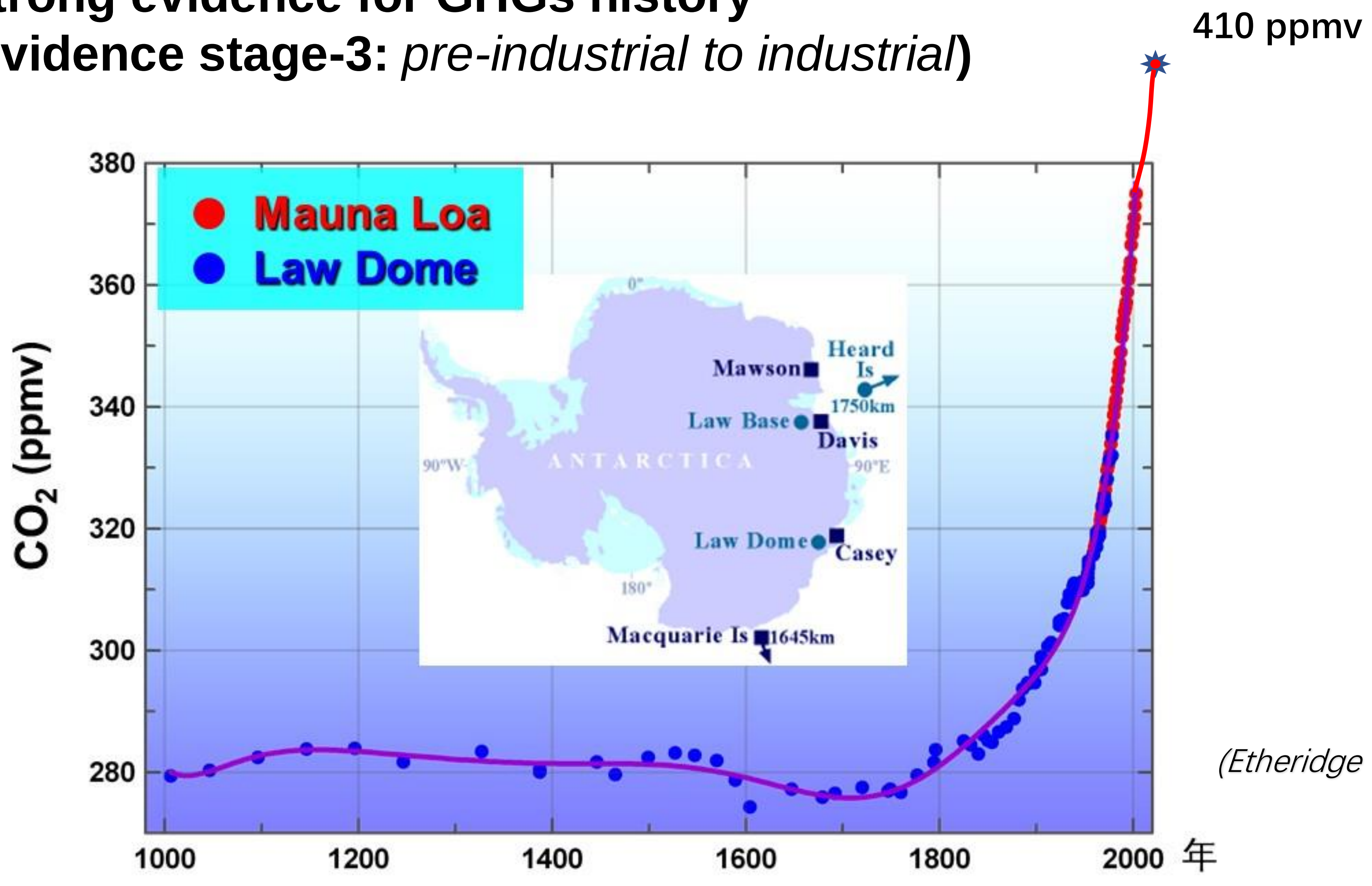
Petit et al., Nature, 1999

- **Strong evidence for GHGs history (evidence stage-2:** ***LGM to Holocene*****)**



3.2

- **Strong evidence for GHGs history (evidence stage-3: *pre-industrial to industrial*)**



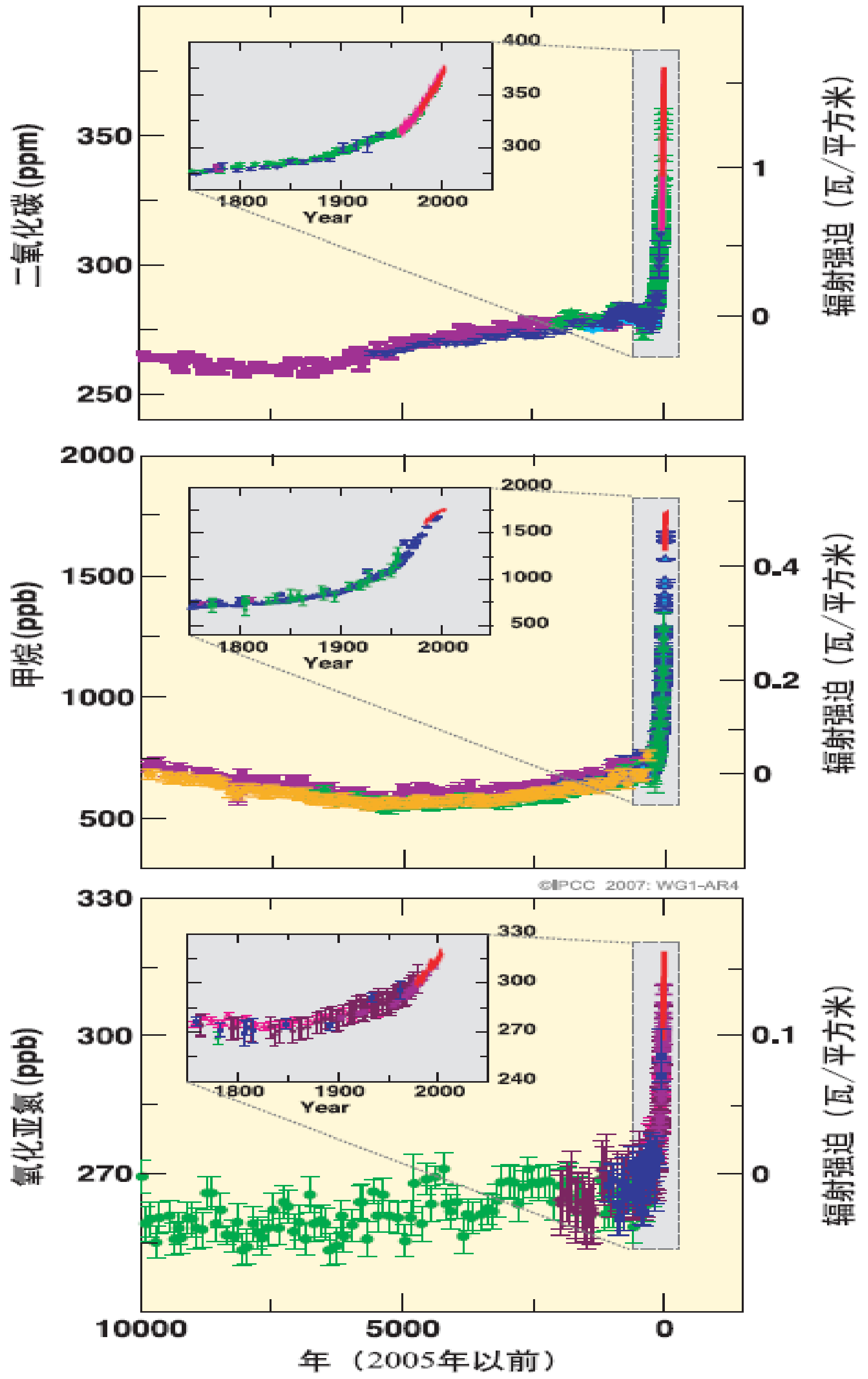
(Etheridge et al., 1998)

High-resolution CO_2 concentration of last 1000 years, recorded in Law Dome ice core

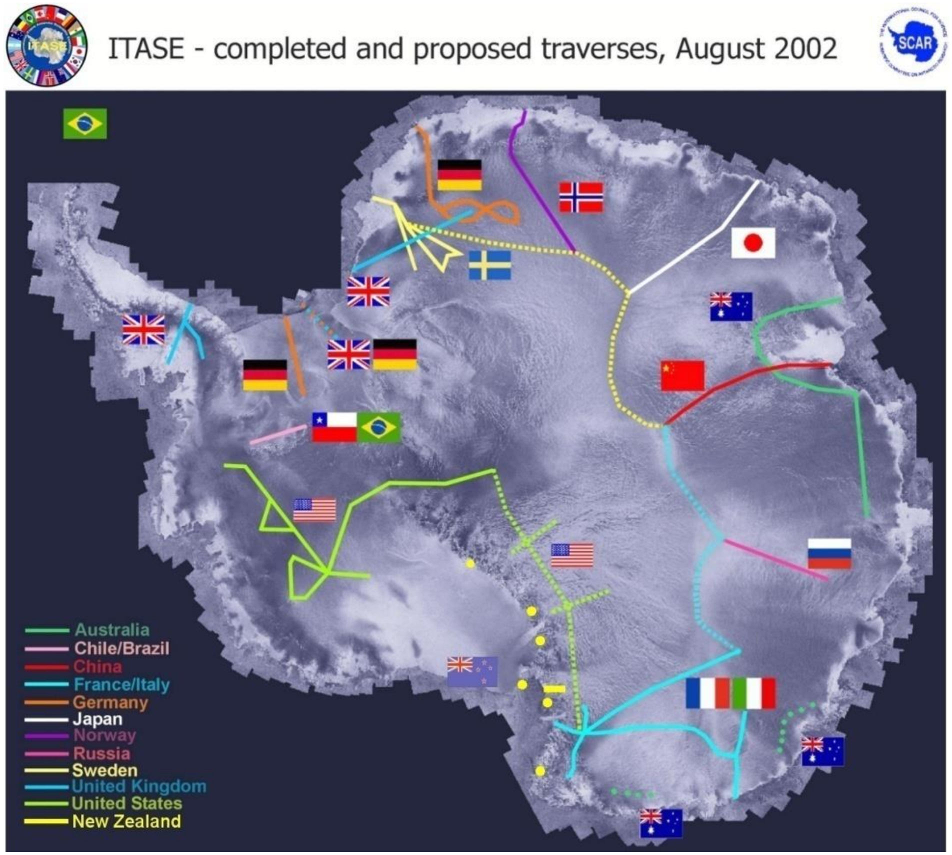
- **Baseline for calculating radiative forcing of human GHGs emission**

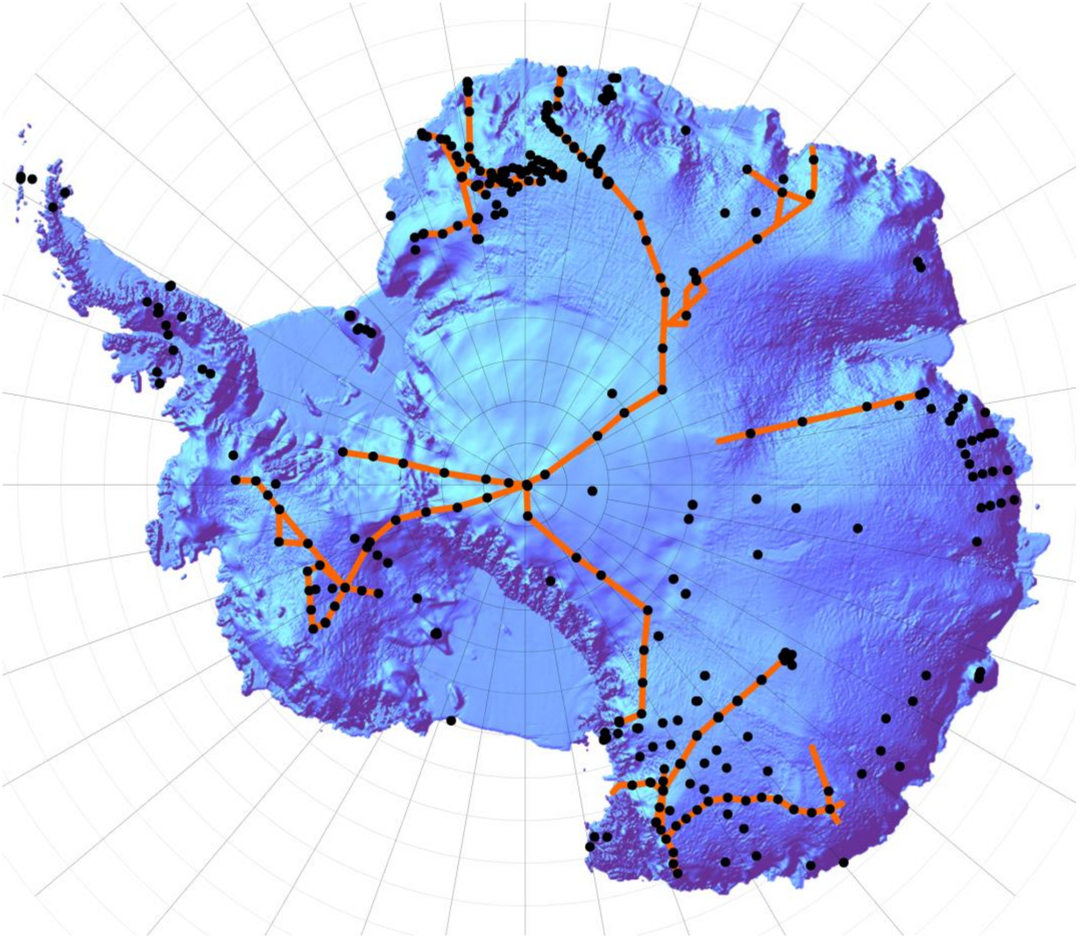
The variations of atmospheric carbon dioxide, methane and nitrous oxide concentrations in the last 10,000 years and since 1750 AD (insert Figures). The measured values shown in the figure are derived from ice cores (symbols of different colors indicate different research results) and atmospheric samples (red line),
and the corresponding radiative forcing values are shown on the right vertical axis of the figure.

最近一万年和公元1750年(嵌入图)以来大气二氧化碳、甲烷和氧化亚氮浓度的变化*(图中所示测量值分别源于冰芯,不同颜色的符号表示不同的研究结果)***和大气样本***(红线)***，所对应的辐射强迫值见图右侧纵坐标**



- **Shallow cores provide plentiful information of decadal\centennial\millennial changes of climate/environment**



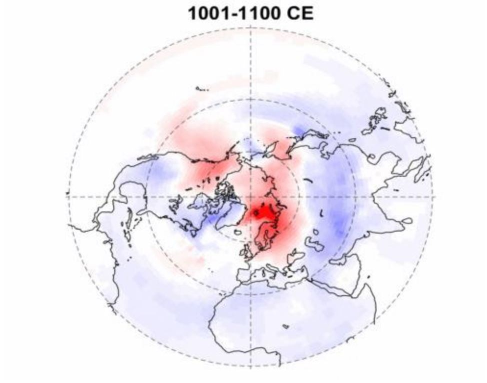


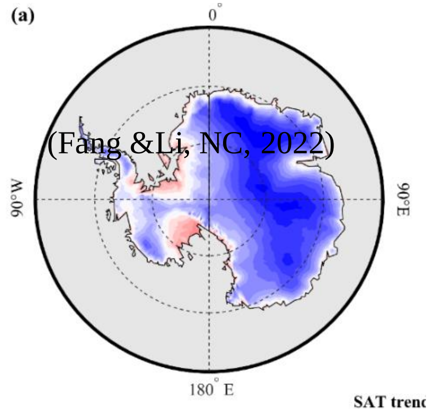
ITASE (International Trans-Antarctica Scientific Expedition)

Traverse Plan

Main insight: changes in recent decades are unprecedented in the last millennia

Temperature

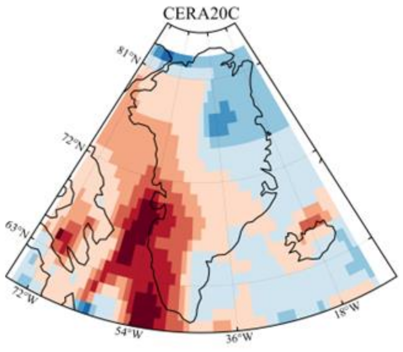


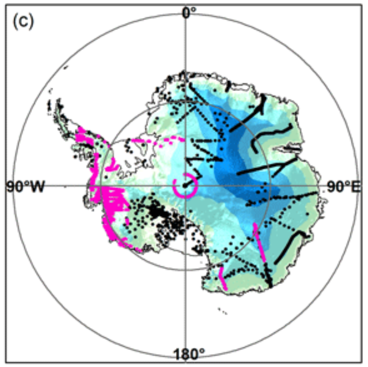


(Fang &Li, NC, 2022)

(Fang et al., 2021)

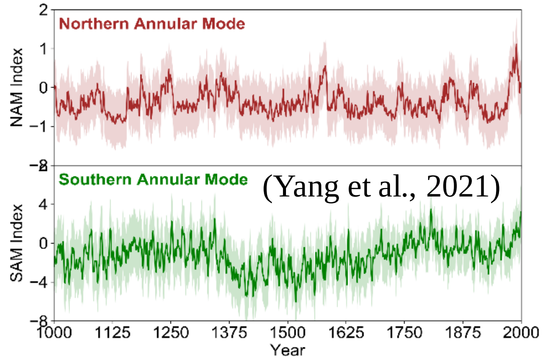
Accumulation rate





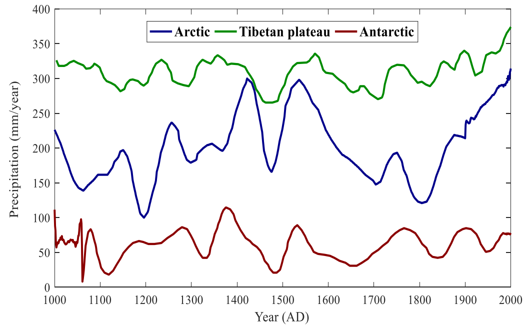
(Wang et al., ESSD, 2021)

Atmospheric circulation



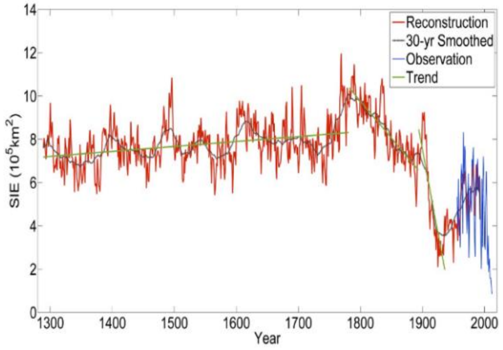
(Yang et al., 2021)

Precipitation

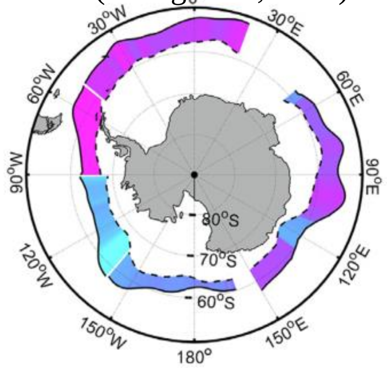


(Fang et al., 2023)

Sea ice extent

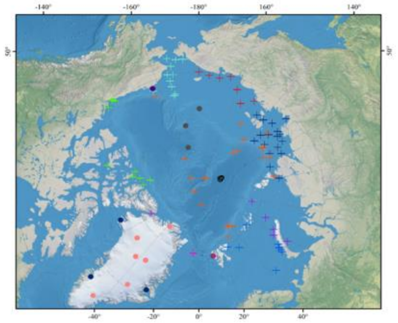


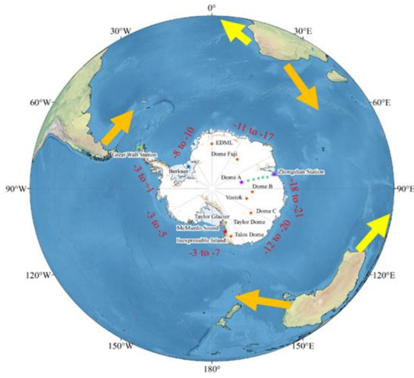
(Zhang et al., 2018)



(Yang et al., SB, 2021)

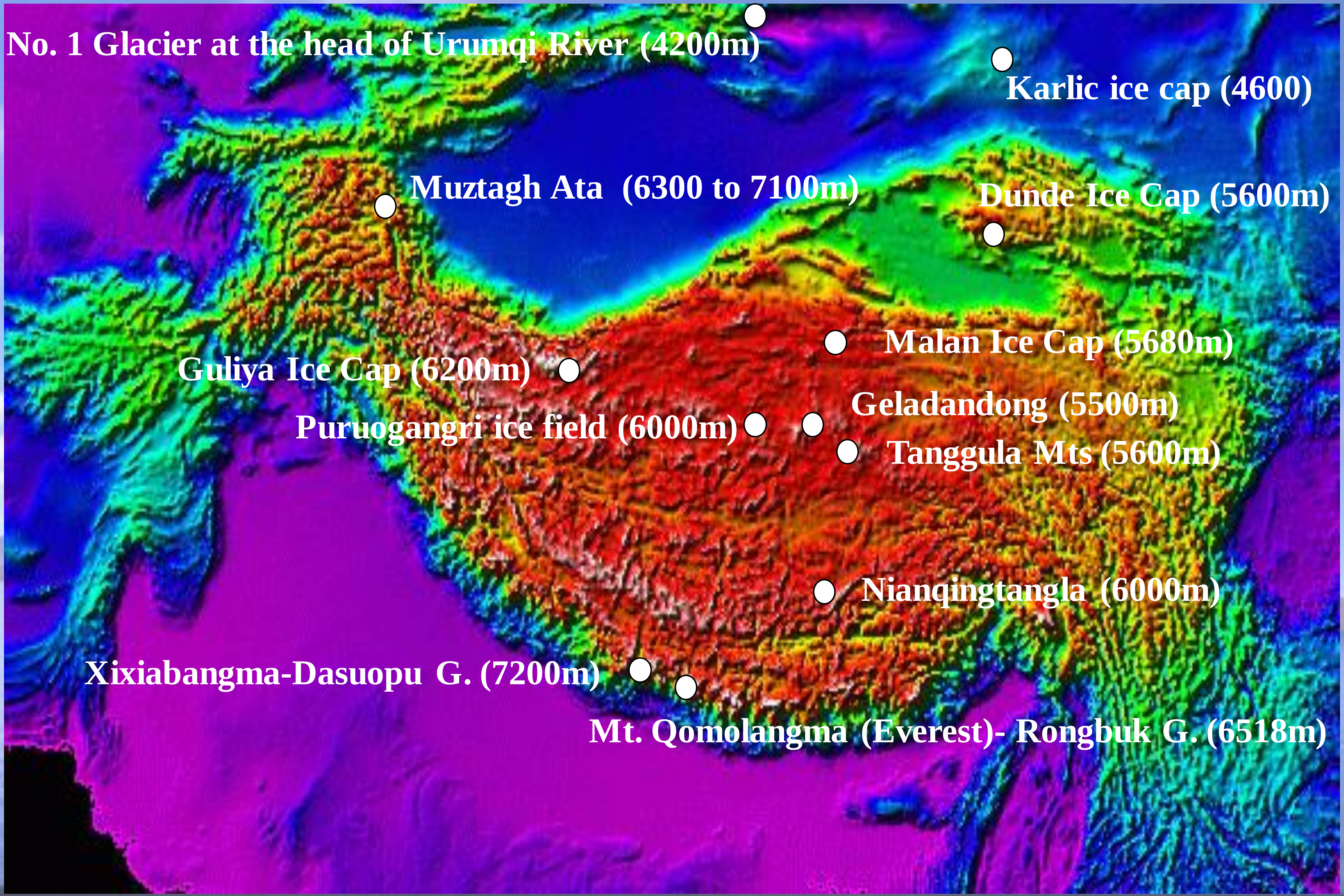
Environmental index



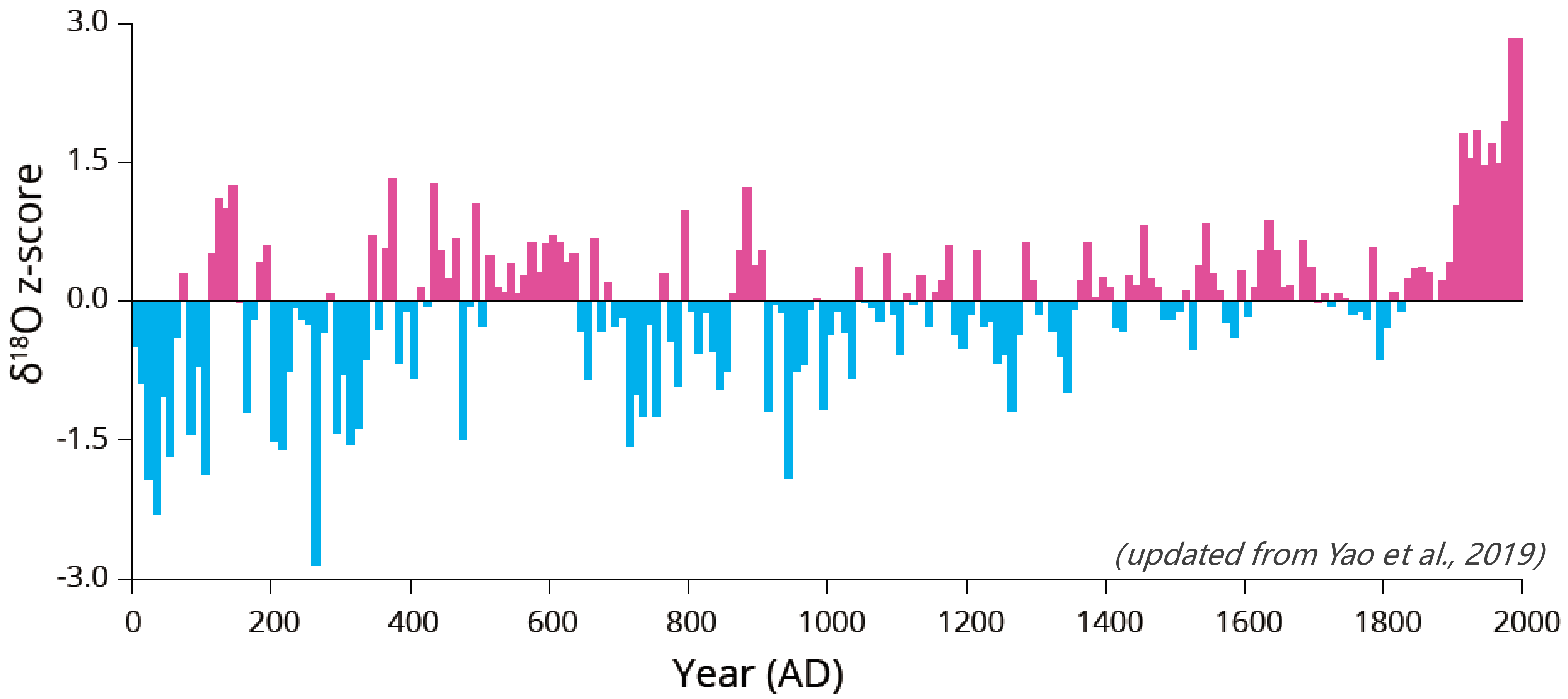


(Du et al., ESSD, 2022)

Ice coring sites over Tibet Plateau



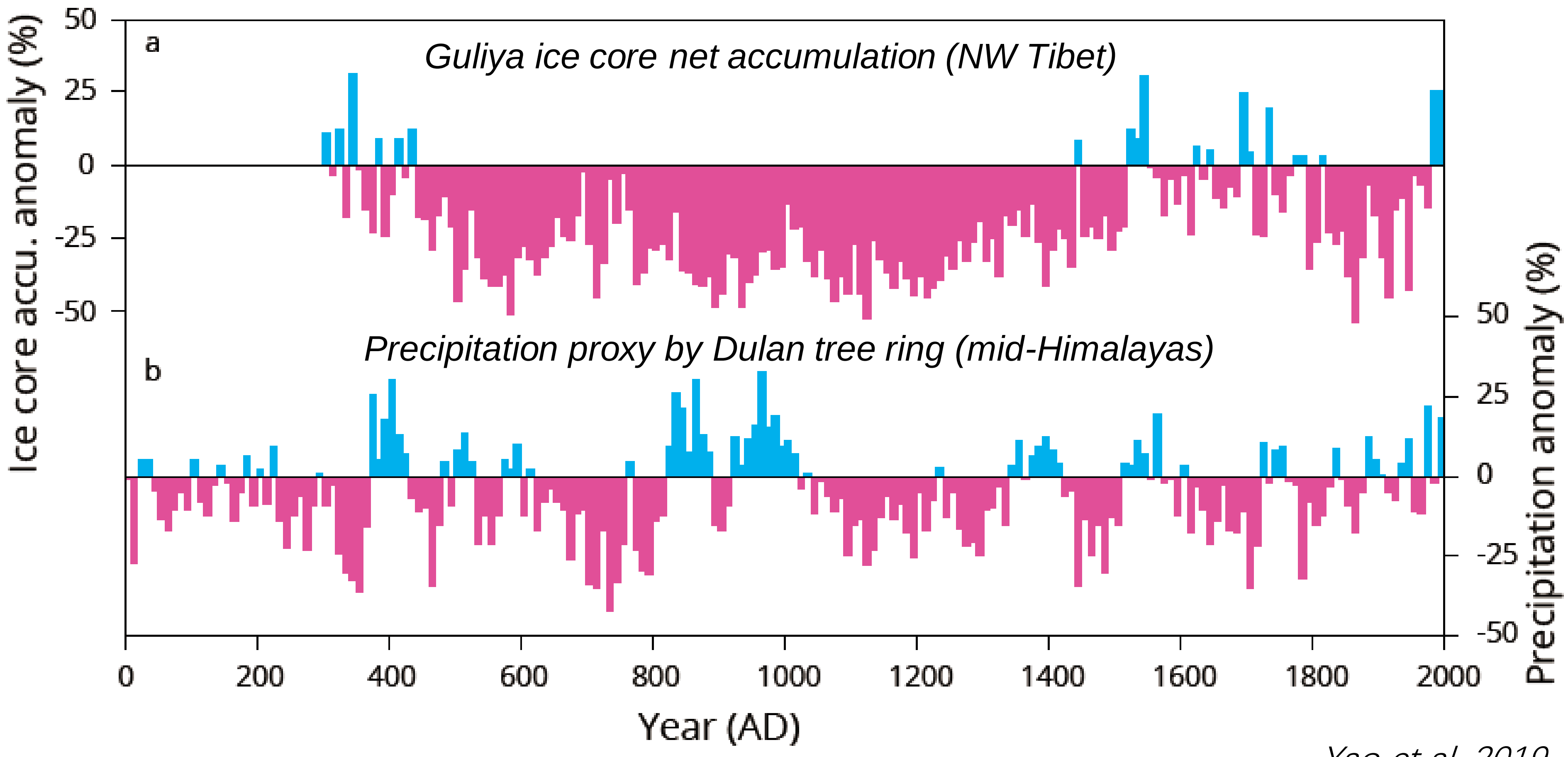
- **Warming started from early 20th century**
- **Warming since 1961 are unprecedented over the last 2000 years**



Temperature variations composited from four Tibetan Plateau ice cores for the past 2000 years

- **Precipitation shows significant spatial heterogeneity in different studies.**

The regional differences in precipitation patterns between the northern and southern parts of the TP that have occurred in the last 500 years, or on even longer time scales, are the result of dominating monsoons and westerlies



Yao et al. 2019

Reconstructed precipitation variations in the TP over the past 2000 years through (a) Guliya ice core net accumulation, and (b) Dulan tree ring

(*Note: The red and blue areas represent dry and wet climates, respectively, with 1961–1990 serving as the base period*)

Outline

1. Introduction: values of cryospheric archives
2. Dating is crucial important
3. Proxies in ice cores
4. Main findings of ice cores building on our knowledge
5. **Other media of proxies in cryospheric regions**
6. Gaps and prospective: e.g., MPT, TP, warming levels

Tree ring over cold regions are valuable proxies for cryospheric changes

Tree rings: rings of different shades of color formed as the speed of cell division activities in the cambium of the trunk phloem varies with the seasons.

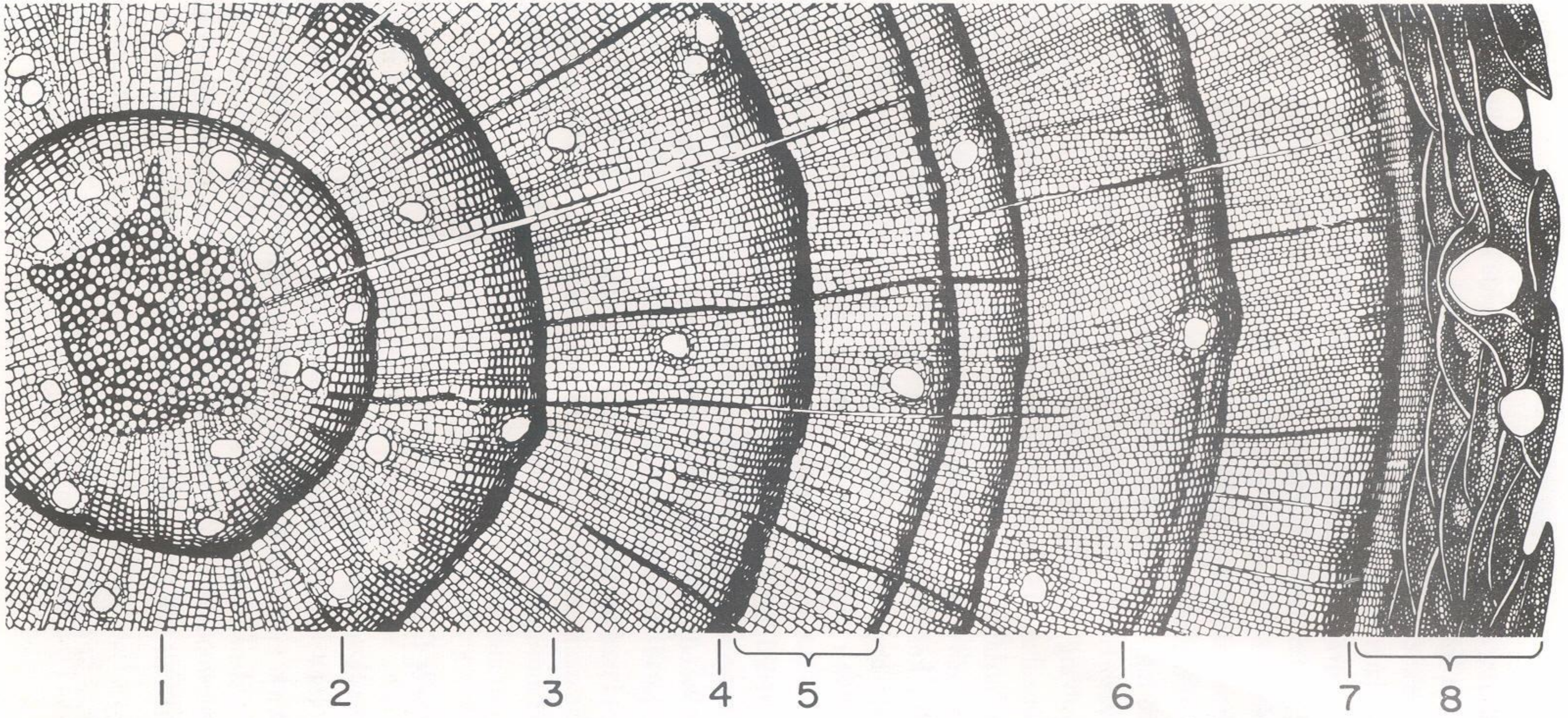
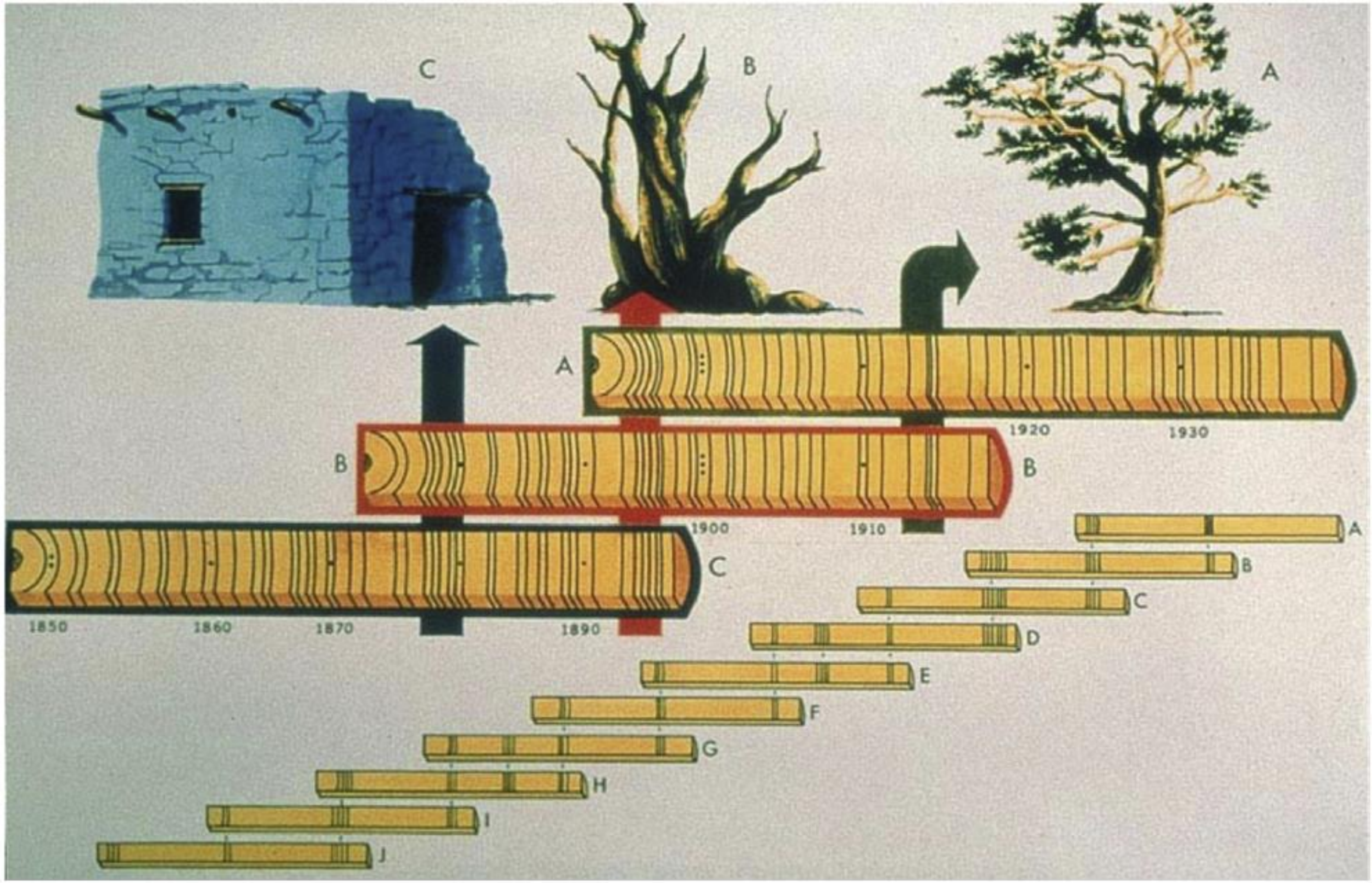


FIG. 3. Cross section of a typical conifer stem showing: (1) pith, (2) resin duct, (3) earlywood cells (light), (4) latewood cells (dark), (5) annual ring, (6) false interannular ring, (7) cambium, and (8) bark.

Fritts, 1976

Cross-dating and extending time series



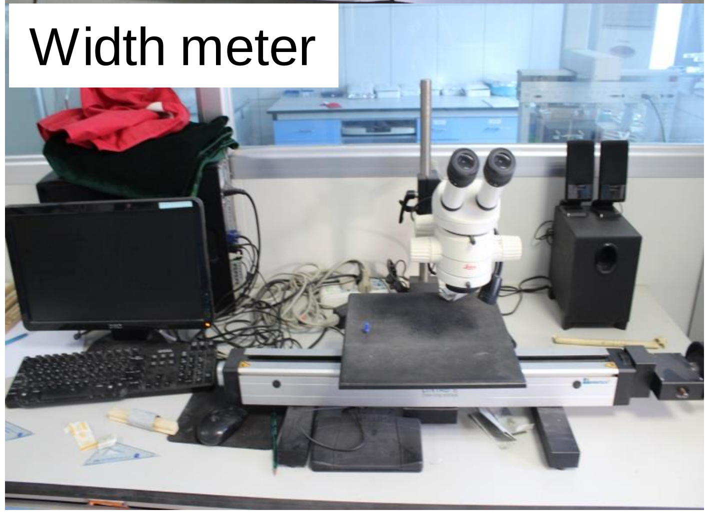
Crossdating method (NOAA)

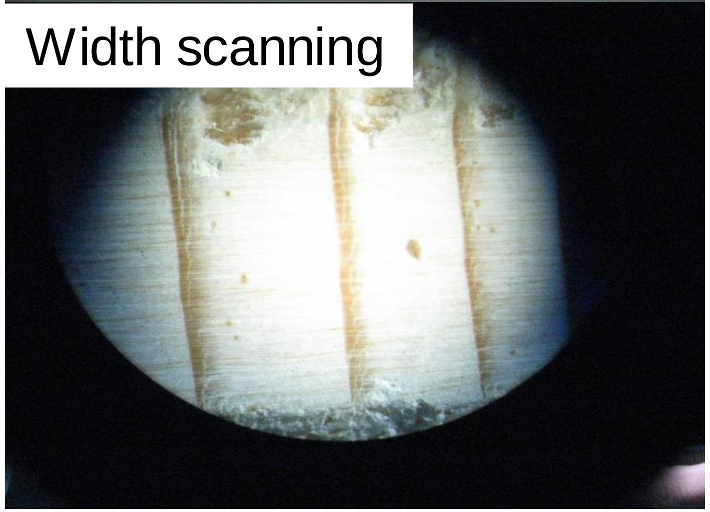
Tree-ring coring

Tree ring measurements in lab

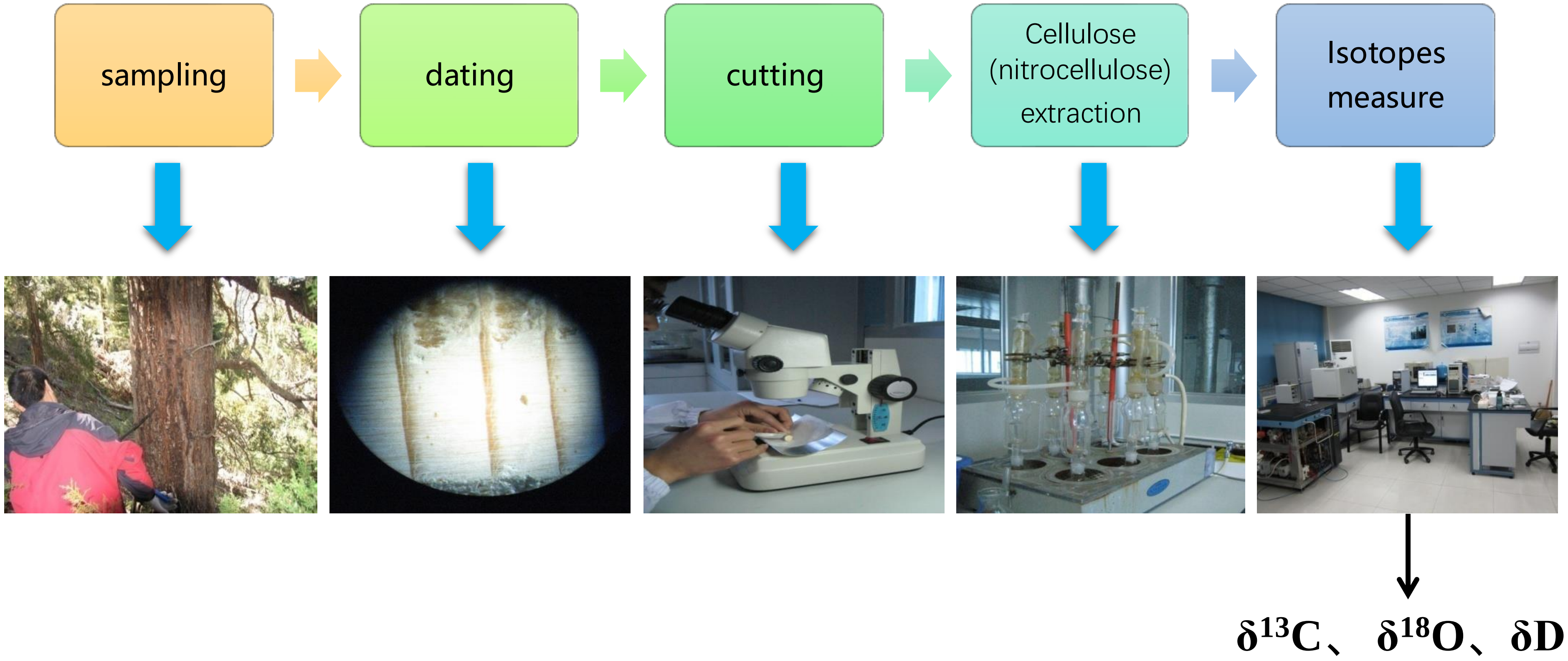

sample


Primary dating


Width meter

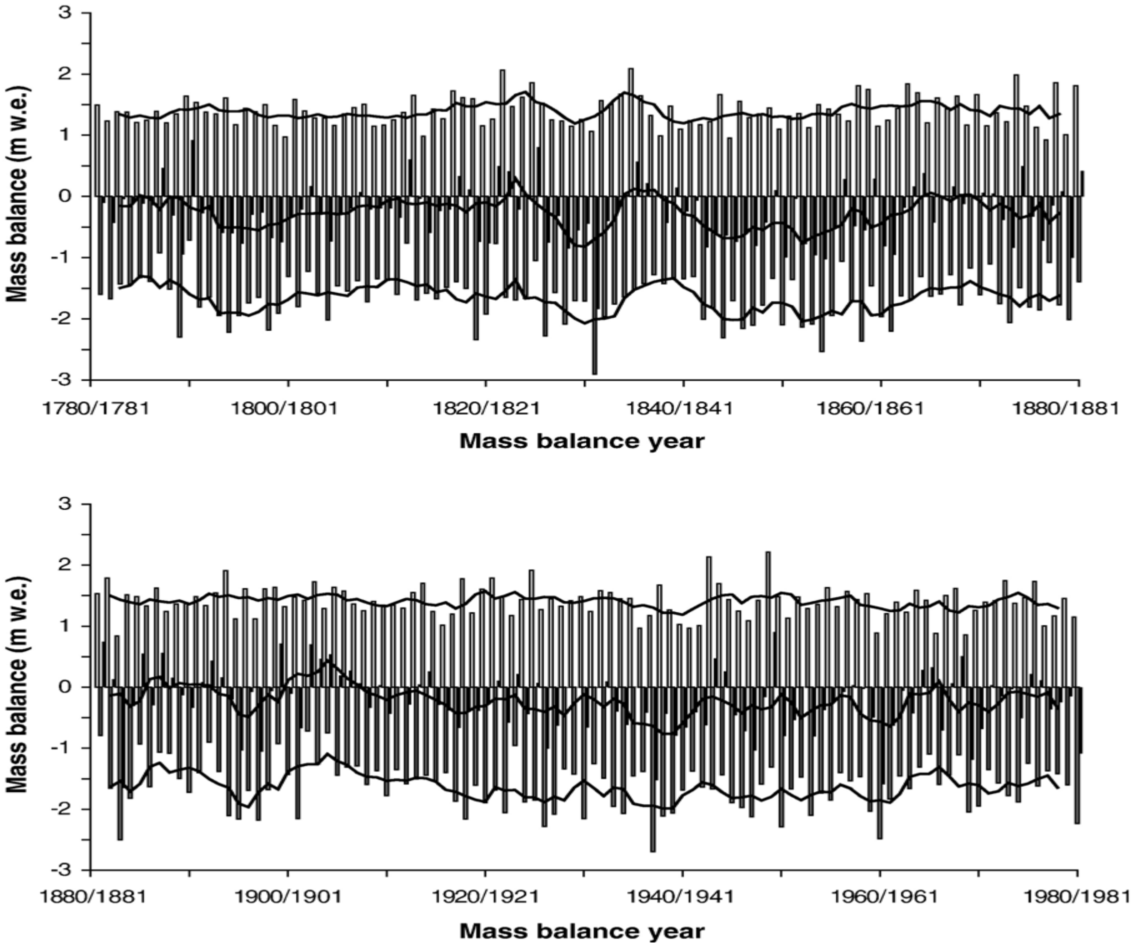

Width scanning

Procedure of isotope ratio analysis of tree ring samples

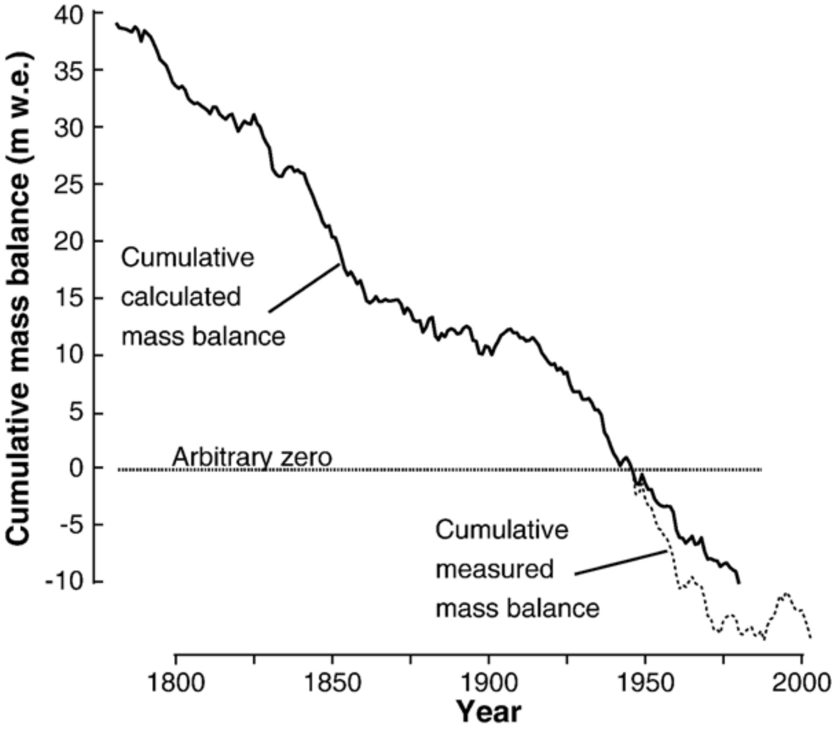


- **Examples of tree ring reconstruction for cryospheric changes**

1） glacier mass balance



White bars: winter balance (b_W); grey bars: summer balance (b_S); black bars: net balance (b_N); black lines: 5-yr running mean.

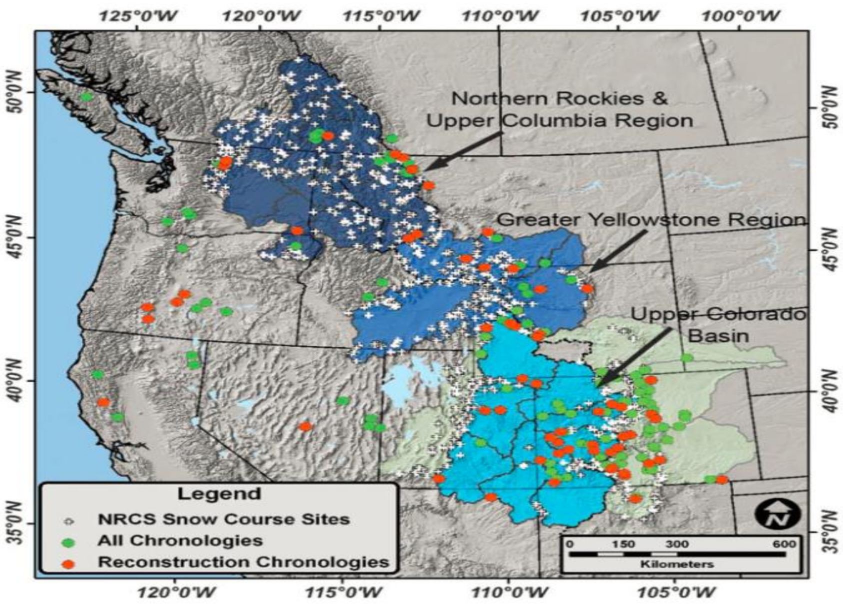


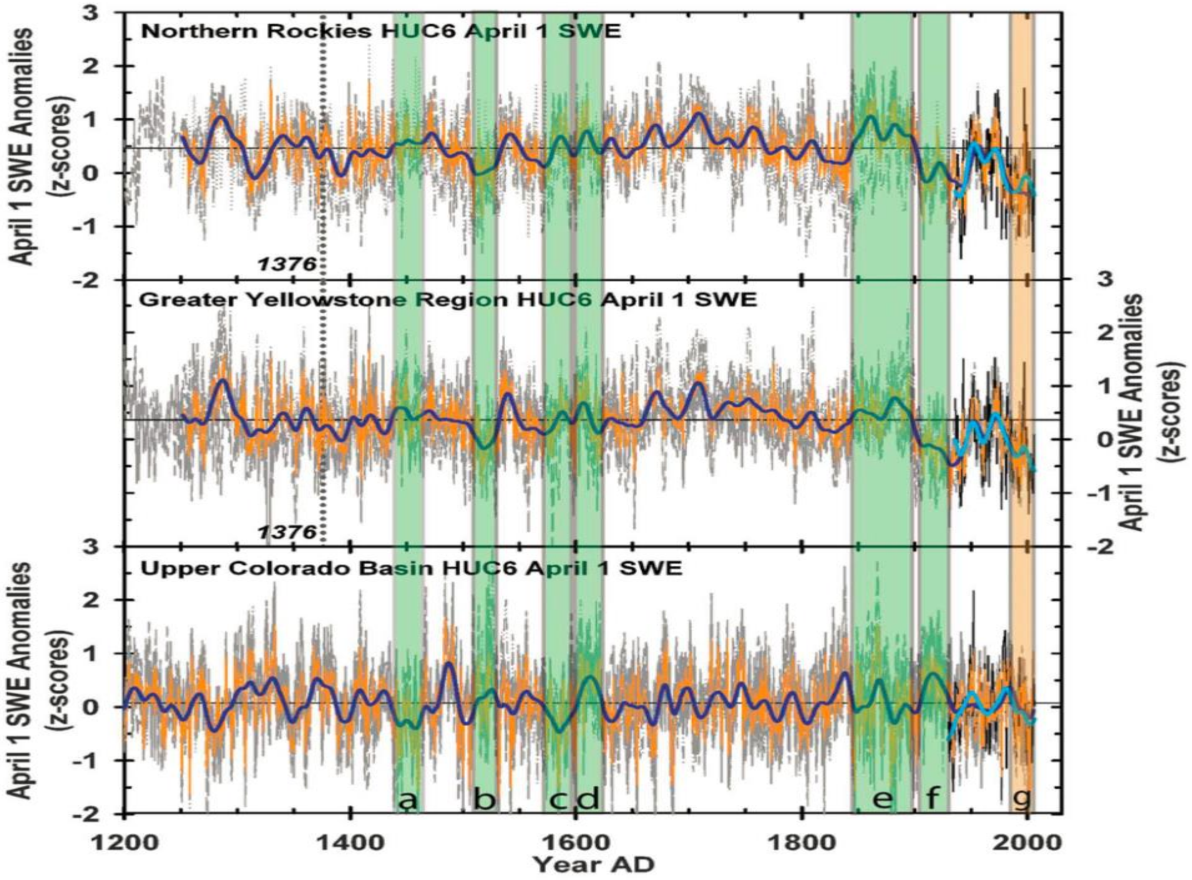
Cumulative mass balance of Storglaciären glacier through tree ring density. Annual mass balance (left), cumulative (right)

(Linderholm et al., 2007)

- **Examples of tree ring reconstruction for cryospheric changes**

2） snow cover

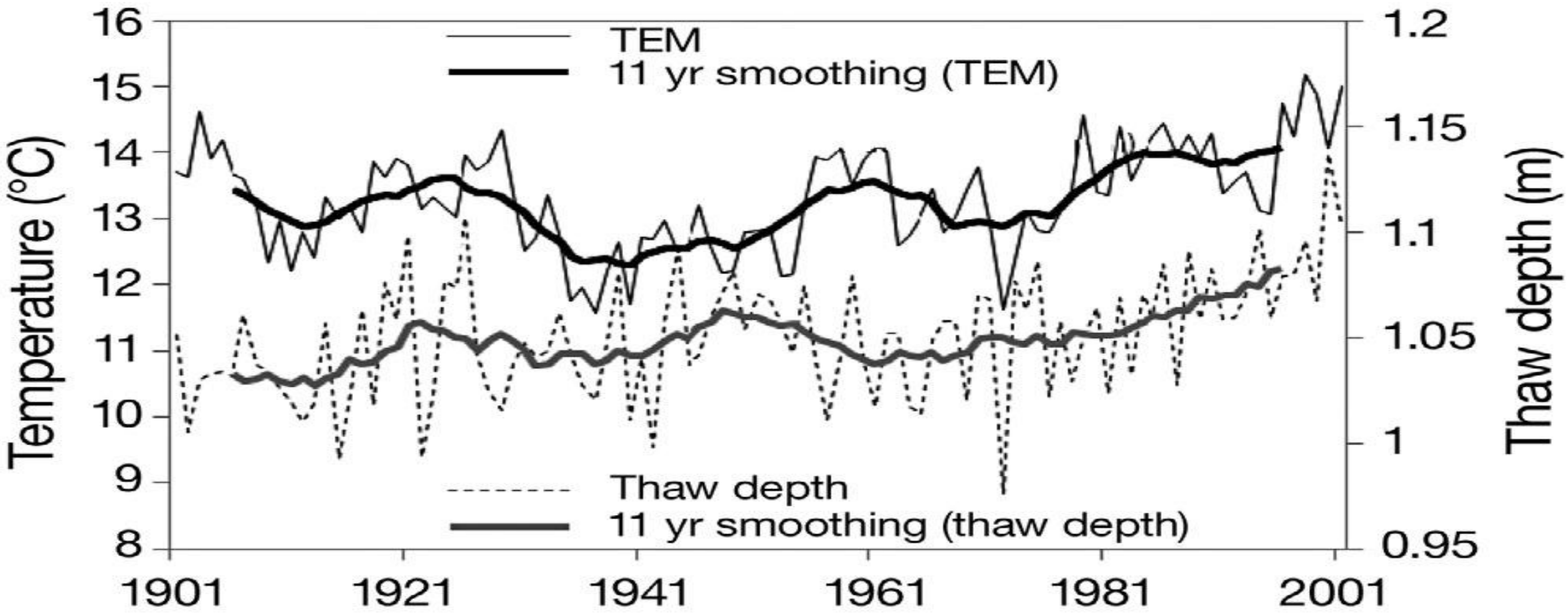




Snow water equivanient (SWE) over Gunnison basin in West USA, reconstructed through tree ring, indicating obvious SWE decrease since 20th century (Pederson et al., 2011)。

- **Examples of tree ring reconstruction for cryospheric changes**

3） Active layer depth of permafrost

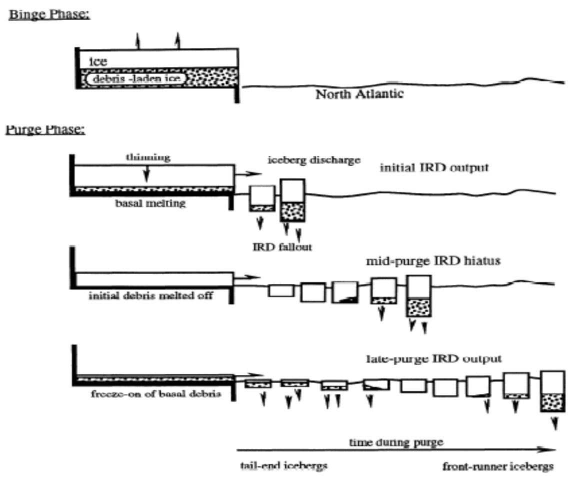


Tree growth over northeast China is sensitive to frozen ground temperature, a case study (above) show that tree ring width can be an indicator of active layer depth of permafrost (Zhang et al., 2011)

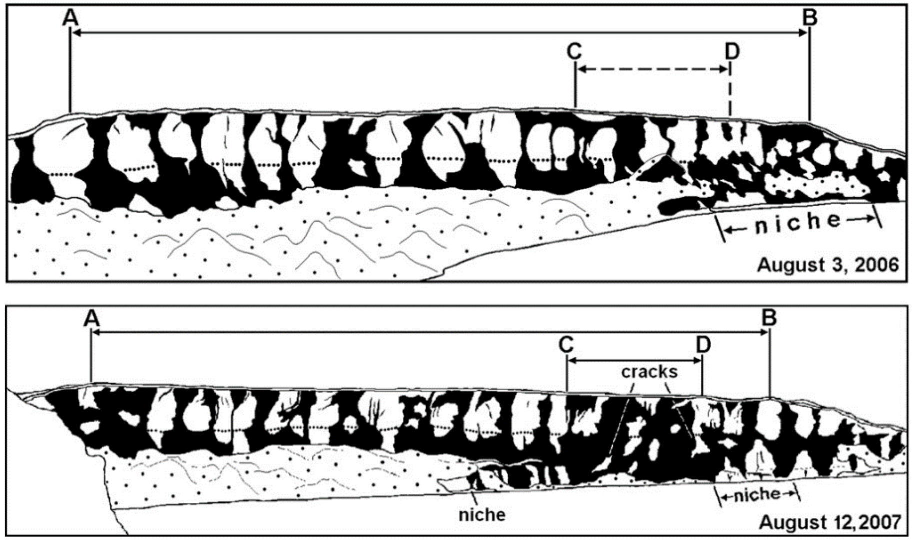
● Other media

glacier varve (冰川纹泥)

Geomorphology (冰川地貌)



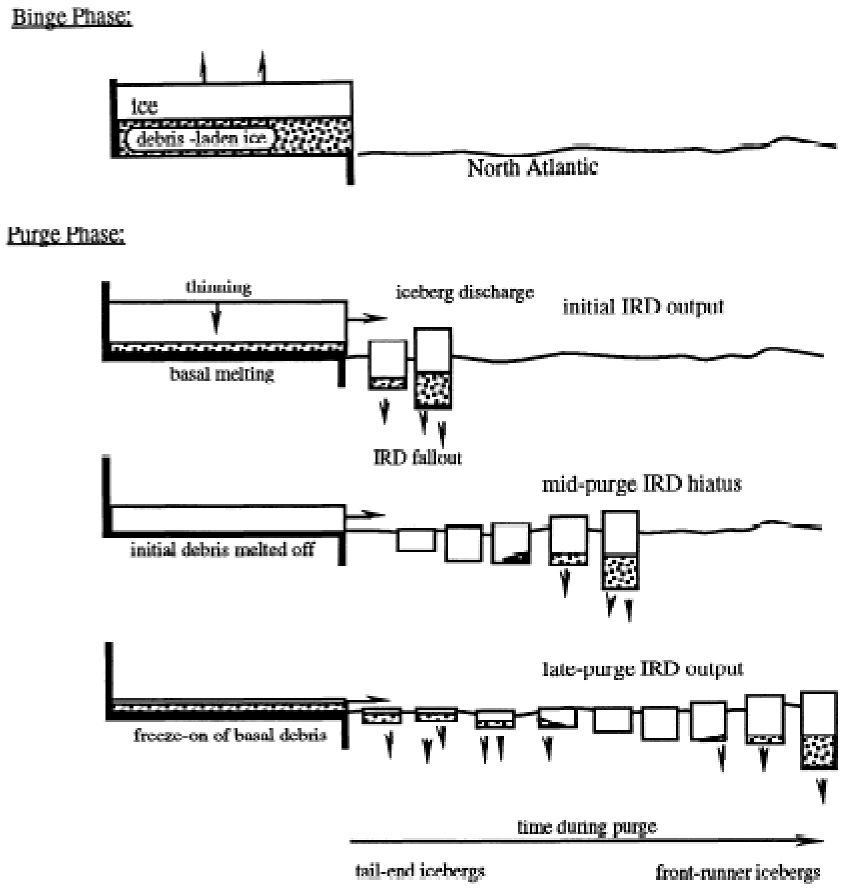
Ice raft (冰筏沉积)



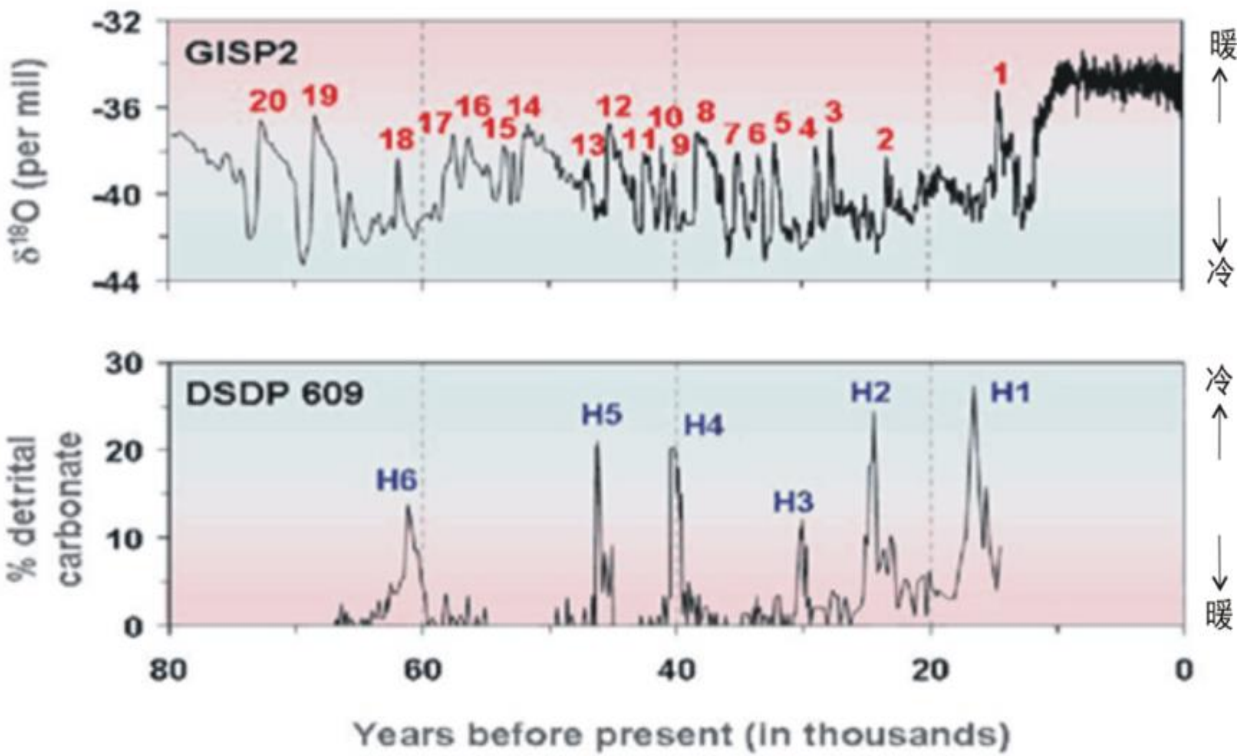
Peatbog(冻土泥炭层)、ice wedge (冰楔)

Biological residue and manure deposits
(生物残体与粪土沉积层)

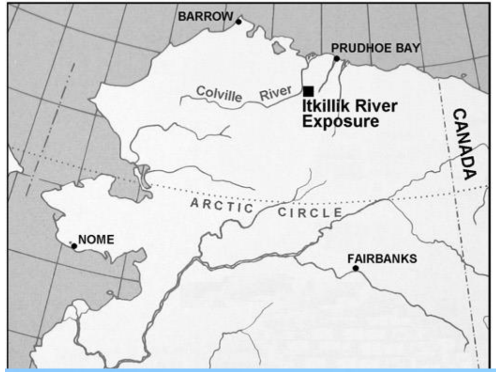
Ice raft



Process of ice-raft release （Alley, R)

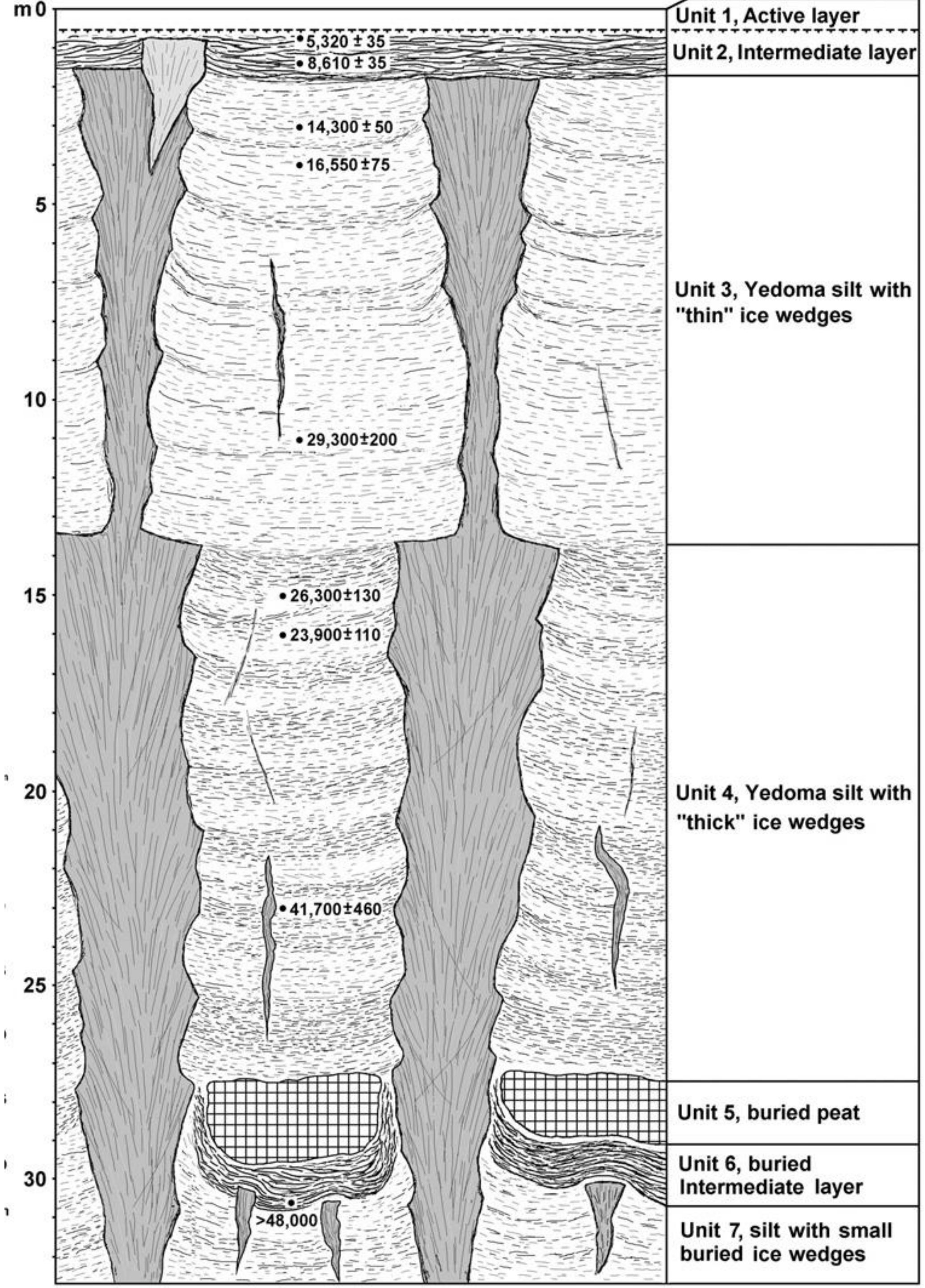


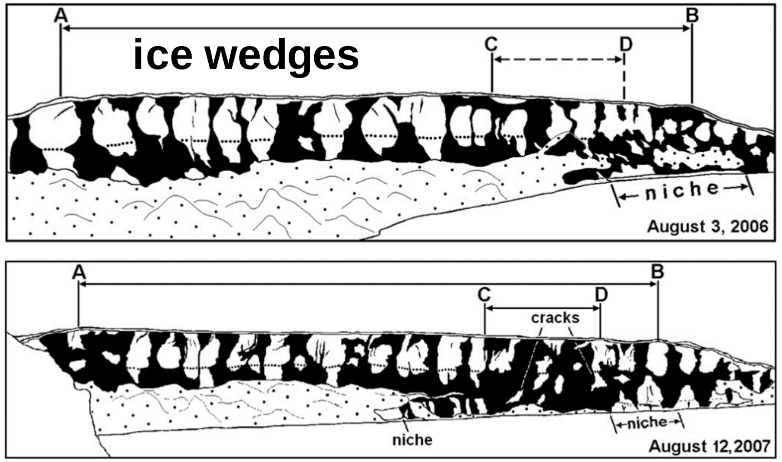
Correspondence of GISP2 temperature changes to ice-raft events in ocean deposition of north Atlantic （Henrich events）

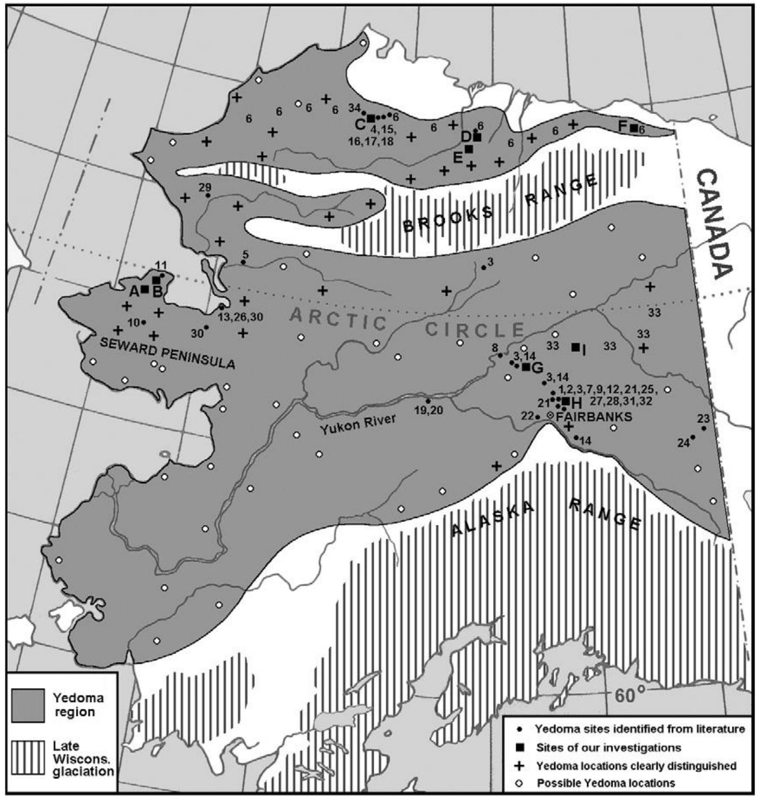


Cryostratigraphy of late Pleistocene syngenetic permafrost (yedoma) in northern Alaska, Itkillik River exposure

M. Kanevskiy [a,*], Y. Shur [a], D. Fortier [a,b], M.T. Jorgenson [a,c], E. Stephani [a]

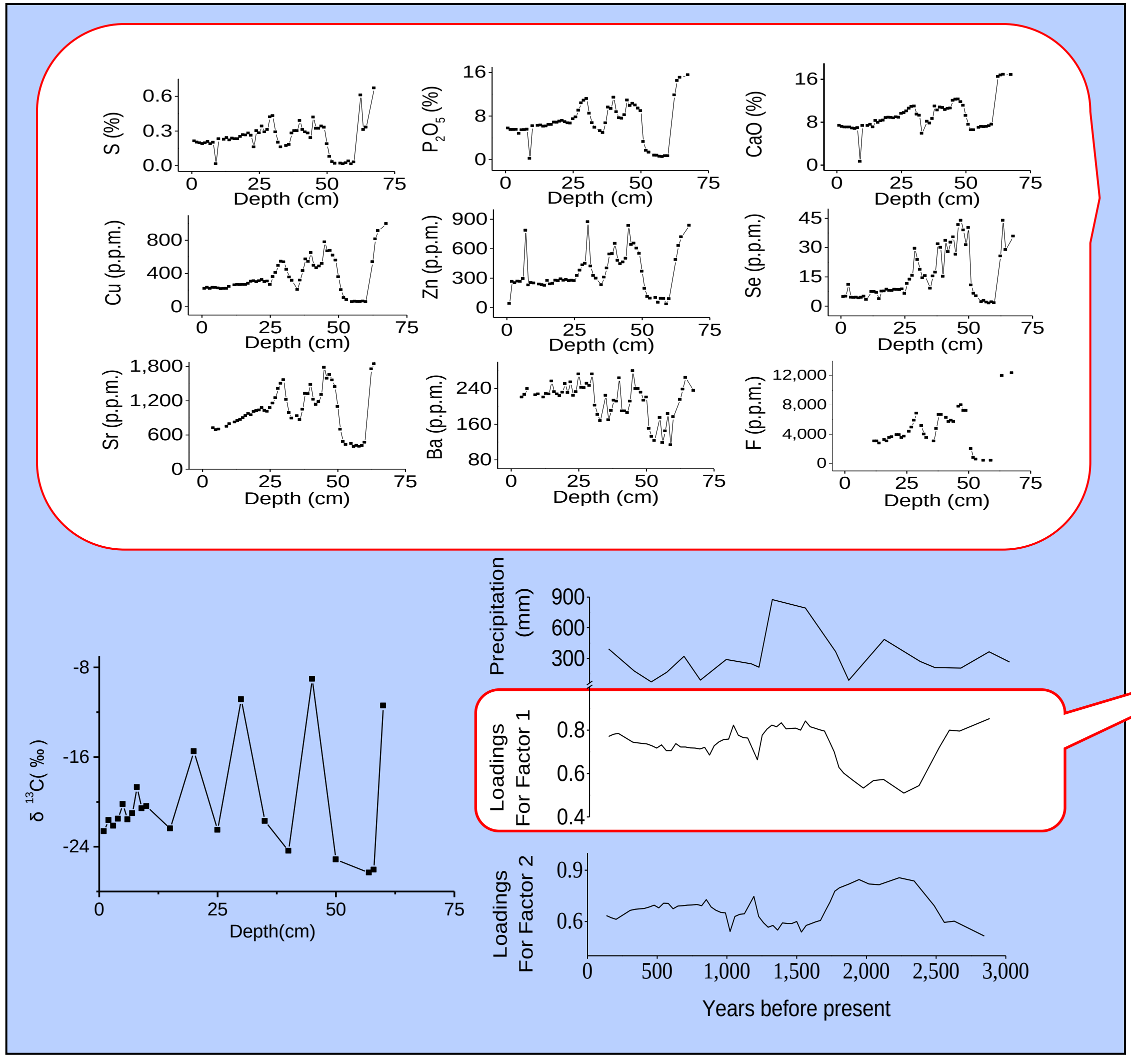




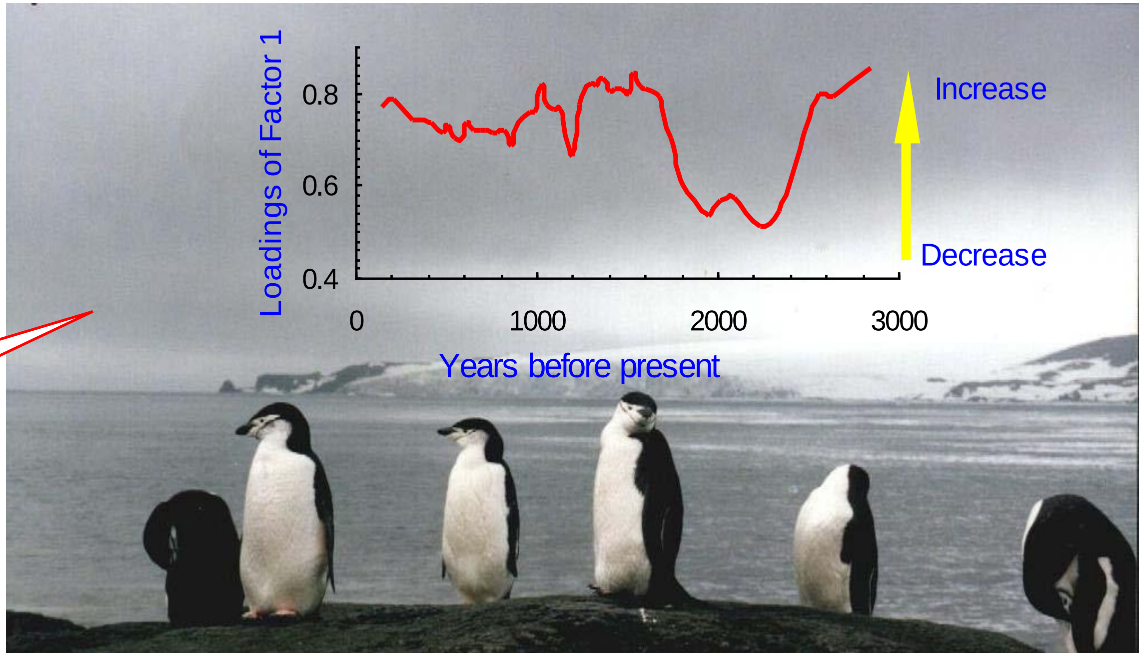


(V. Romanovsky, 私人交流)

- **manure deposits (multiple indicative elements) in a lake core of Antarctic Peninsular show penguin population changes in the last 3000 yrs**



During 1800 to 2300aBP, roughly the minimum temperature of the New Ice Age, the number of penguins decreased sharply. Between 1400 and 1800aBP, when the climate was relatively cool, there were more penguins.



Sun et al., *Nature*, 2000

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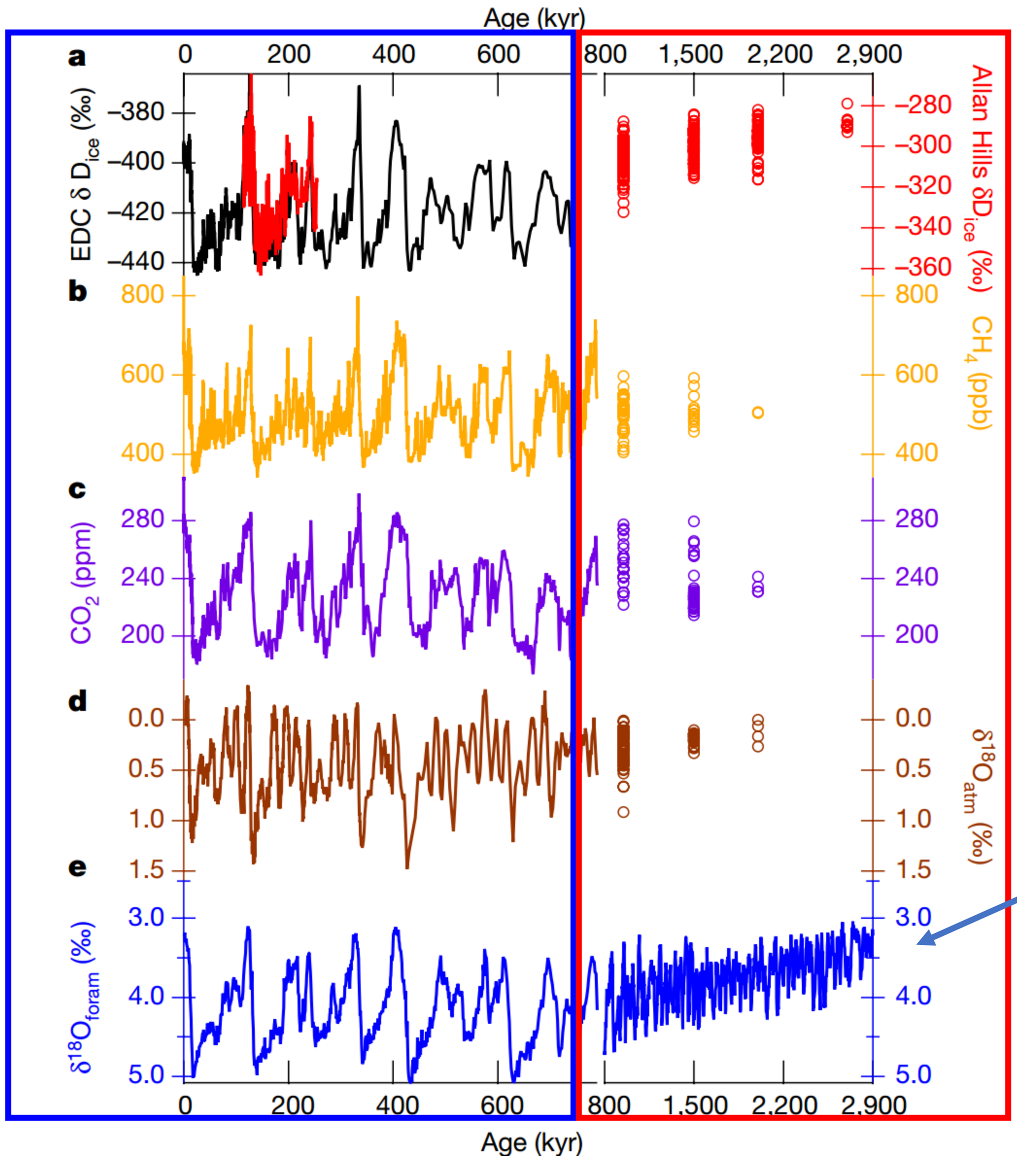
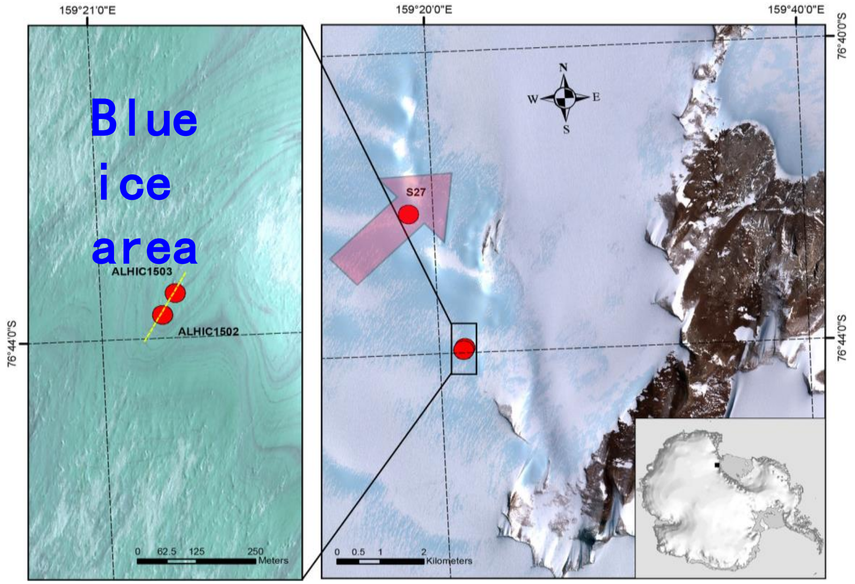
6. **Gaps and prospective: e.g., MPT, TP, warming levels**

1. MPT(Mid-Pleistocene Transition): need longer records exceed 1Ma BP



young ← **0.8 Ma** → old



discontinuous records back to 2Ma, Allan Hills Antarctic

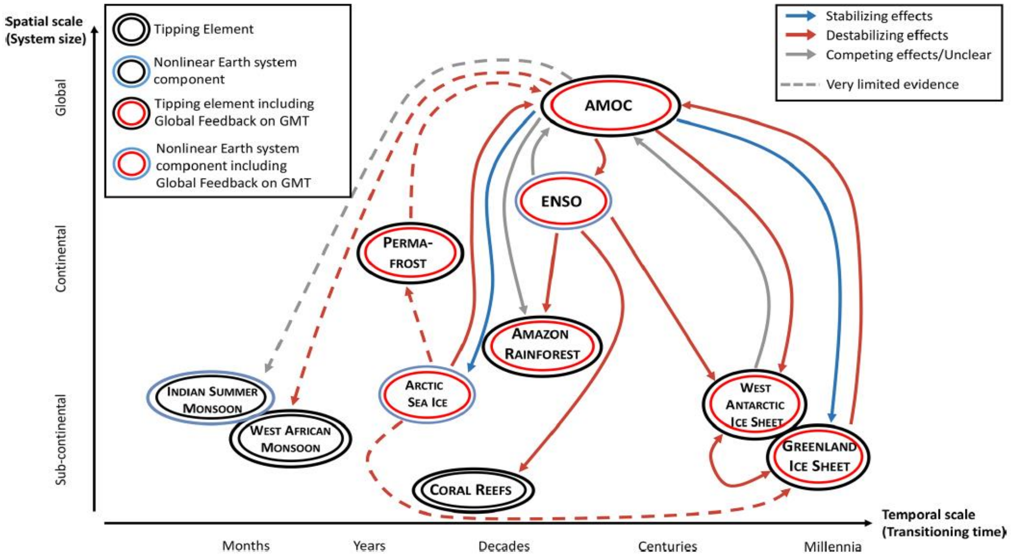
Yan, Y et al., 2019

MPT in deep ocean records:

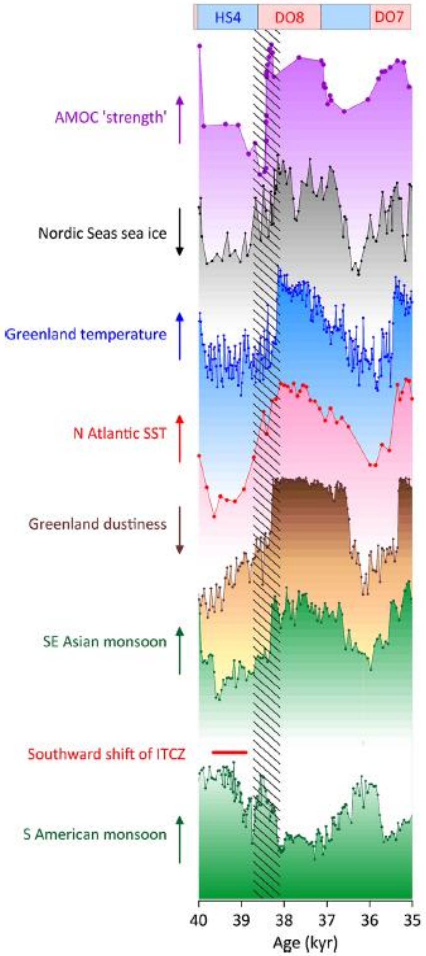
1. 100 thousand cycle Milankovitch theory of last 1Ma
2. 40 thousand cycle during 2.8~1.2Ma

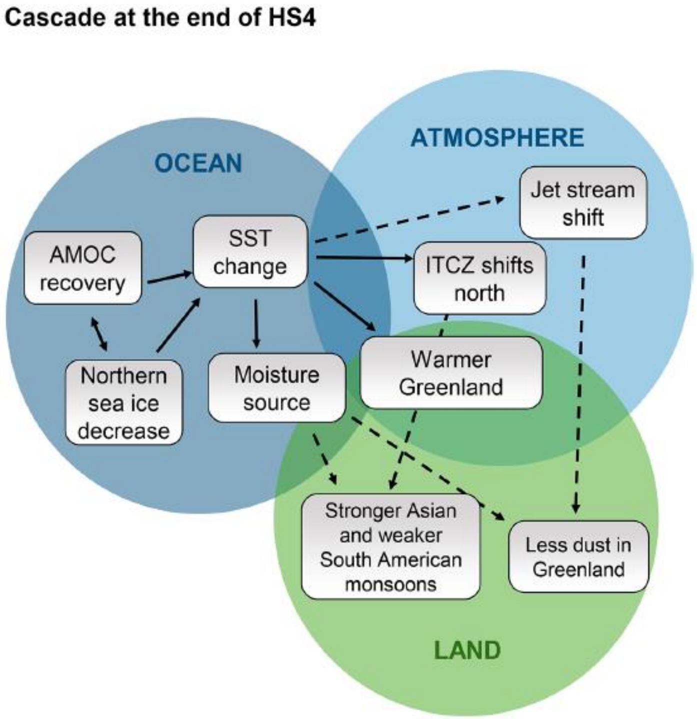
Ice core → evidence for CO_2 concentration

2. Tipping point of Earth system: paleo-records are key reference for future



N. Wunderling et al.: Climate tipping point interactions and cascades: a review

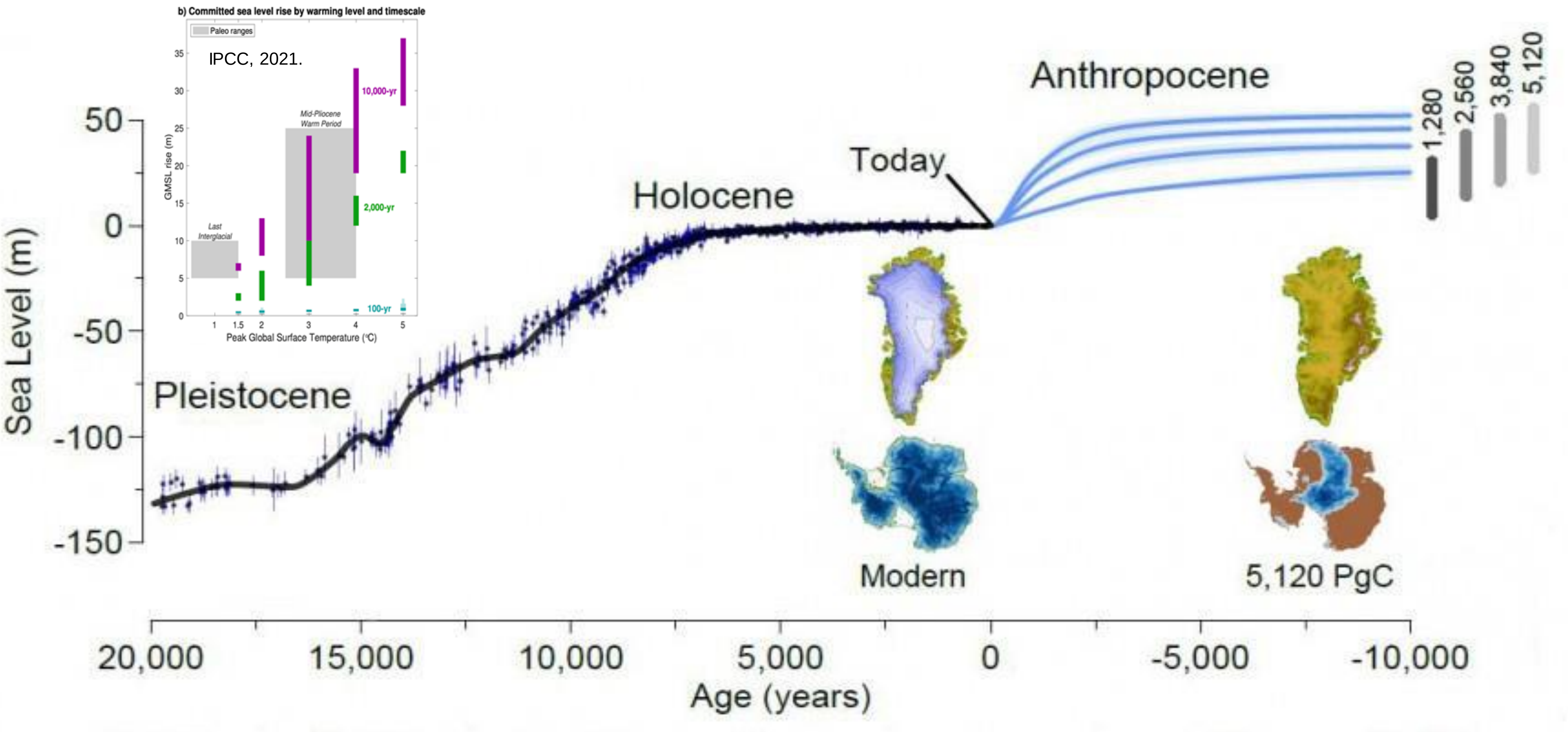




Climate proxy indices spanning the transition from HS4 into D/O event 8.

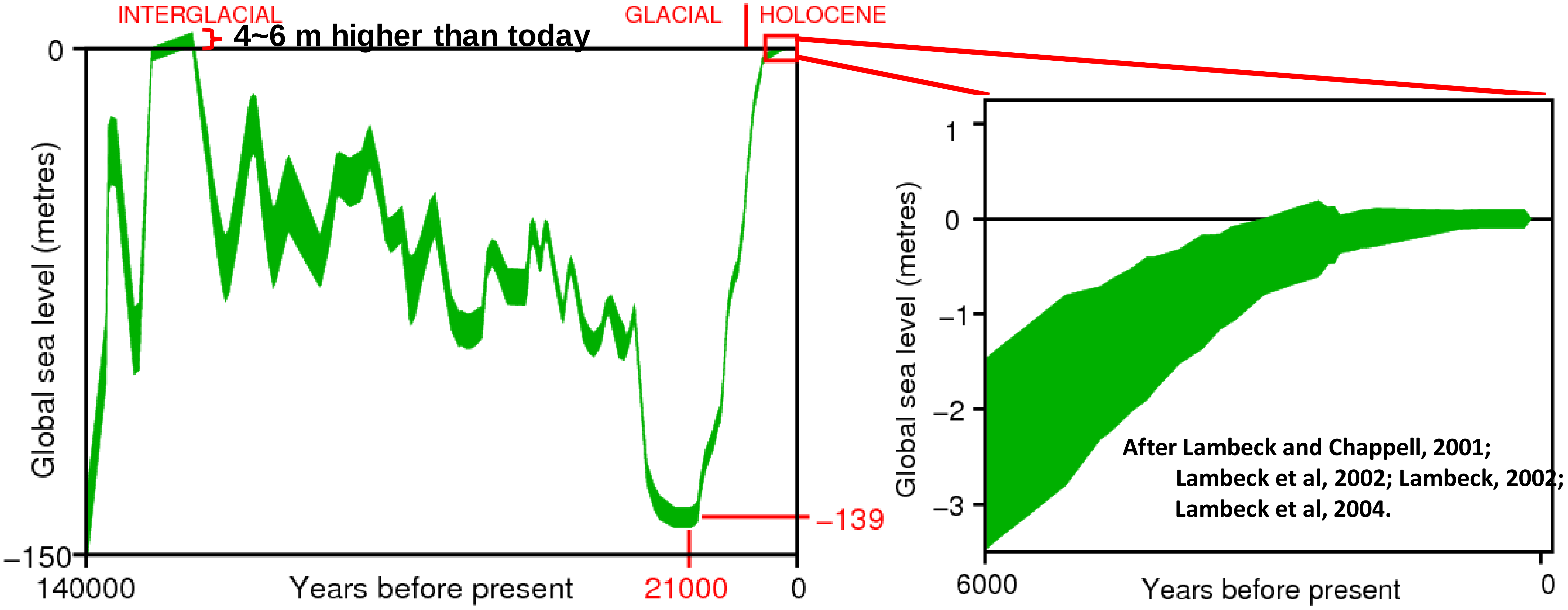
From top to bottom: AMOC strength (Henry et al., 2016), Norwegian Sea ice cover (Sadatzki et al., 2020), Greenland temperature (North Greenland Ice Core Project members (NGRIP), 2004), North Atlantic SST (Martrat et al., 2007), dust accumulation in Greenland (Ruth et al., 2007), Asian monsoon intensity (Cheng et al., 2016), and South American monsoon intensity (Kanner et al., 2012). The horizontal red bar indicates the period when the ITCZ assumed a more southerly position (Wang et al., 2004). The hatched region spans the transition from HS4 to D/O8 and represents an estimate of the relative age uncertainty among the records shown (i.e., it is generally not possible to tell which changes occurred earlier or later within the overall sequence). Vertical arrows indicate the direction of increase for each parameter.

3. Future warming levels (therefore emission)： determine global ice volume and sea level



Clark et al. 2016.

Warming level of Eemian period (MIS-5e) and its clue for our future

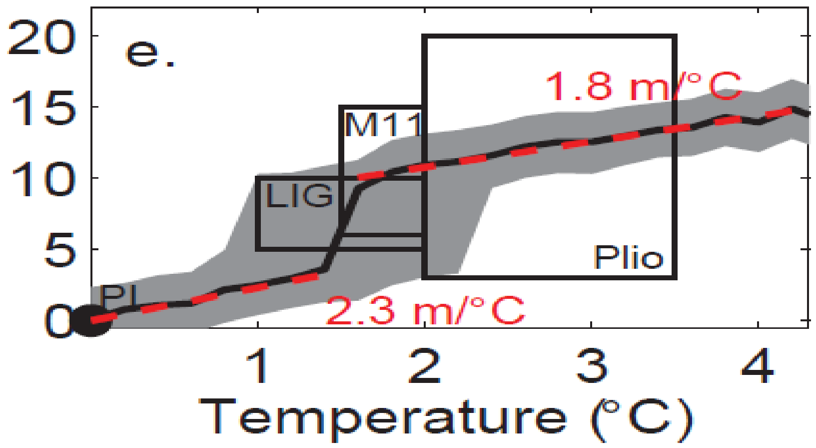


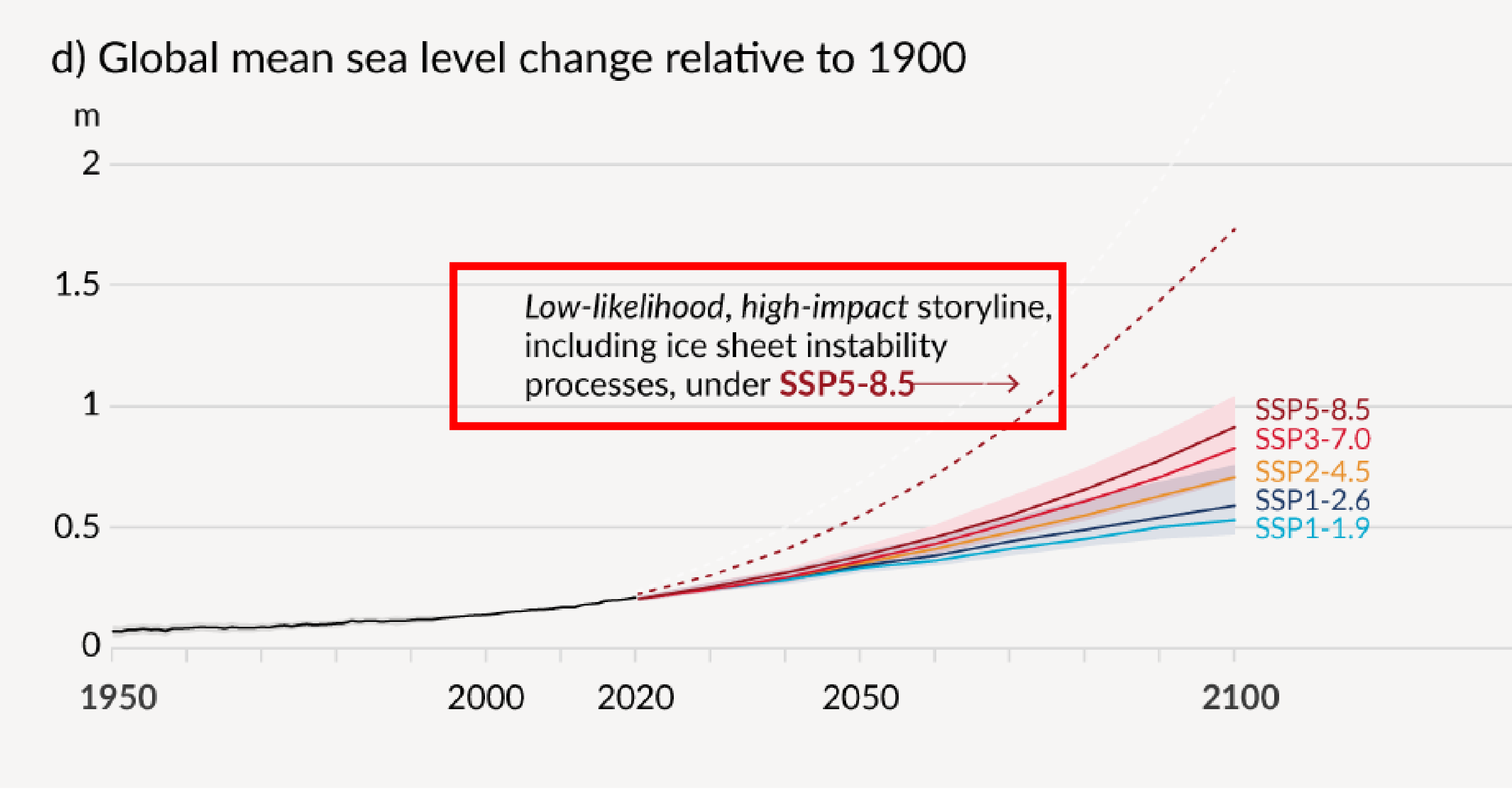
NEEM ice core indicate：

It was 4-6m higher of GMSL than today, Greenland melted almost completely

Sea level rise speed largely depend on warming level and response time

IPCC AR5, 2013





IPCC AR6, 2023

Summary

- Cryospheric archives provides multiple proxies to climatic and environmental changes in history
- Dating is critical before explaining
- The present is the key to the past (James Hutton, 1785) : present processes study is crucial (Zhang Yülan's talk soon)
- Gaps remain: further information are needed to meet nowadays' challenges in science frontier, such as MPT, tipping point, warming level, etc.

THANKS FOR YOUR ATTENTION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回应
应用
设置
离开会议
暴雨预警
已启动
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10:29
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Xiao Cunde (效存德)
中科院西北研究院

Storyline（叙事线）：

A way of making sense of a situation or a series of events through the construction of a set of explanatory elements. Usually, it is built on logical or causal reasoning. In climate research, the term storyline is used both in connection to scenarios as related to a future trajectory of the climate and human systems or to a weather or climate event. In this context, storylines can be used to describe plural, conditional possible futures or explanations of a current situation, in contrast to single, definitive futures or explanations.

Physical climate storyline

A self-consistent and plausible unfolding of a physical trajectory of the climate system, or a weather or climate event, on time scales from hours to multiple decades (Shepherd et al., 2018). Through this, storylines explore, illustrate and communicate uncertainties in the climate system response to forcing and in internal variability.

Scenario storyline

A narrative description of a scenario (or family of scenarios), highlighting the main scenario characteristics, relationships between key driving forces and the dynamics of their evolution.

IPCC AR6 Glossary