How *American Mineralogist* and the Mineralogical Society of America influenced a career in mineralogy, petrology, and plate pushing, and thoughts on mineralogy's future role (7382 Revision-1)

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Abstract

My geologic research began at Carleton College. I studied heavy minerals in some midcontinent orthoquartzites, publishing my very <u>first</u> paper in *American Mineralogist* in 1954. As a master's candidate at the University of Minnesota, I investigated igneous differentiation in a diabase-granophyre sill of the Duluth Gabbro Complex. Later, in a Ph. D. program at Johns Hopkins University, I became Joe Boyd's apprentice at the Geophysical Laboratory (GL), and for a time was phase-equilibrium god of the Na-amphiboles. Doctoral research earned me an offer of a UCLA assistant professorship as mineralogist in 1960. There, I continued pursuing amphibole P-T stability relations in lab and field. My glaucophane phase equilibrium research would later be found to have instead crystallized Na-magnesiorichterite. However, amphibole research led me to map field occurrences of HP-LT (high P-low T) blueschists of the Franciscan Complex. Thus, when plate tectonics emerged in the late 1960s, I was deep in the subduction zone. My recent studies focused on the petrology and geochemistry of oceanic crustal rocks, Californian calc-alkaline arcs, and coesite ± microdiamond-bearing crustal margin rocks in various parts of Eurasia. Other works treated global mineral resources and population, mineralogy and human health, and early Earth petrotectonic evolution. I tried to work on important problems, but mainly studied topics that fired my interest.

For the future, I see the existential challenge facing humanity and the biosphere as the imperative to stop our overdrafting of mineral resources. This will require reaching a dynamic equilibrium between the use and replenishment of near-surface resources *(i.e.,* nutrients) essential for life. Earth scientists are planetary stewards, so we must lead the way forward in life-supporting mineral usage, recycling, substitution, and dematerialization. In any event, sustainable development <u>will</u> soon return to the Earth's Critical Zone of life because Mother Nature—the ruling terrestrial economist—abhors long-term overdrafting of resources.

Preface

Part of the 2019 centennial celebration of the Mineralogical Society of America took place at the Geological Society of America annual meeting in Phoenix, AZ. One day's activities featured invited talks by some of our past presidents. Most speakers described exciting new mineralogic studies in progress, whereas mine was a “walk down memory lane.” That review chronicled 66 years of my past scientific studies, and a few lessons learned from them, as well as concerns regarding the future habitability of the Earth. My research efforts involved an integration of mineralogy, petrology, and geochemistry with regional geology and plate tectonics. *American Mineralogist* and Mineralogical Society of America-sponsored *Reviews in Mineralogy* and *Elements* broadened my horizons. Such cutting-edge research compendia inspired me to bridge across several Earth materials disciplines. What success I have had is partly due to them, but also reflects fortunate timing. In hindsight, I marvel at the importance of mantle overturn attending plate formation and destruction in the production and availability of the resources sustaining life.

At Phoenix, I intended to conclude my presentation by emphasizing what I regard as the existential threat facing humans and life in the Critical Zone. But, typically for me, I ran out of time. This more formal report thus attempts to describe my mineralogic journey. It charts a research life and a concern regarding the future of civilization

Formative Years

At Carleton, I studied a heavy-mineral suite of mechanically, chemically resistant, detrital grains characteristic of some multicycle clastic sediments. I was thrilled studying the principles of geology, and was lucky to obtain jobs over seven summers. These included: searching for gravel deposits, *i.e.*, eskers (Minnesota Highway Dept.); working on open-pit and underground mining of soft iron ore on the Mesabi Range (U. S. Steel); mapping the Soudan Formation for magnetic taconite (Jones & Laughlin); prospecting for chalcopyrite in the Duluth Gabbro Complex (Kennecott); logging oil wells in southern Oklahoma (Mobil); and two summers mapping geology in the Bearpaw Mountains, northern Montana (USGS). By this time, I had completed an M.S. degree at the University of Minnesota. I had also published a short note on the St. Peter Sandstone-Glenwood Shale transition (**Fig. 1)**. Unimpressed by my B. S. thesis, Sam Goldich nevertheless helped me to obtain a predoctoral fellowship to Johns Hopkins University. For doctoral research, I studied the P-T stability relations of several Na-amphiboles at the GL.

I regarded myself as a field geologist, but experimental phase equilibrium studies at the GL branded me as a modern mineralogist. This fleeting expertise on amphiboles provided several opportunities for me, and I came to UCLA in January 1960 as assistant professor of mineralogy. I almost didn’t interview because of an Eastern prejudice about Los Angeles. However, visiting UCLA opened an exciting future for me, as I could visualize working in lab and field with first-rate students. I occupied the position vacated by the retirement of Joe Murdoch, who served as president of the Mineralogical Society of America that very year. Thus began an academic career in the fast lane, with colleagues including George Kennedy, Bill Ruby, John Rosenfeld, George Wetherill, Dave Griggs, and George Tunell.

Mineralogy, Petrology, and Blueschists

Immersing myself in teaching mineralogy, experimental phase equilibria, introductory geology, and summer field mapping with geologist-paleontologist Clarence Hall, at UCLA I cobbled together a hydrothermal pressure-vessel laboratory to study the P-T-f_{O_2} stability relationships of Fe-bearing minerals. Also, I began geologic mapping the Franciscan Complex in the Panoche Pass area, a dry-as-a-bone region in the southern Diablo Range, central California Coast Ranges. Publication of several amphibole phase equilibrium papers that I had nearly finished at the GL kept the tenure wolf from the door as I began applying the results of experimentalists and theoretical geochemists to long-term studies of Franciscan field geology. Most of my phase-equilibrium works appeared in other journals, for as an *American Mineralogist* rejectionist acidly noted: “Over a lifetime, only a few specialists would ever read these papers.” Humpf! I published them anyway.

In 1963, I obtained an early sabbatical to the University of Tokyo in order to study with Akiho Miyashiro and Shohei Banno. There I undertook a crystal-chemical investigation of element partitioning among coexisting rock-forming silicates in the HP-LT blueschists of eastern Shikoku. Based on that introduction to the geology of SW Japan, Yotaro Seki, Hitoshi Onuki, Charles Gilbert, and I initiated a more comprehensive US-Japan study of the Sanbagawa Belt, *i.e.*, the Outer Metamorphic Belt of Japan. We then compared it with blueschist-facies metamorphic rocks of the Franciscan Complex. Just at that time, UCLA acquired an early model electron microprobe, so returning to campus, I was able to conduct microanalyses of a wide variety of rock-forming minerals. Assisting Wayne Dollase, we studied the Mössbauer spectra of iron-bearing phases, of course including amphiboles.

$Na_2Mg_3Al_2Si_8O_{22}(OH)_2$

Now I must backtrack a little. My experimental study of the P-T stability relations of glaucophane was, for me, a cautionary tale. I eagerly began this research at the GL because of its relevance to the glaucophane schist problem. Although some authorities viewed blueschists as representatives of a HP-LT metamorphic facies, others noted the common association with serpentinites, and interpreted such metabasaltic rocks instead as formed by metasomatism under low-P greenschist facies conditions. So, running a charge of mixed oxides on the bulk composition Na_2O-3MgO-Al_2O_3-8SiO_2 + excess H_2O, I synthesized amphiboles at the GL. Due to sluggish reactivity, the run products typically crystallized to only ~2-20 % of tiny, hair-like crystals of clinoamphibole; the rest of the charge consisted of the high-T, bulk-chemical condensed assemblage for the glaucophane composition, *i.e.,* En + Fo +

Ab. I made up three different oxide mixes, but invariably obtained only disappointingly small yields of amphibole. Proportions of the high-T, En + Fo + Ab assemblage were sensibly the same, regardless of the amount of fibrous amphibole produced. Moreover, I demonstrated chemical equilibrium by reversing the reaction at several different pressures. The optical properties of the hair-like clinoamphiboles were identical to those of the extrapolated natural end-member. However, unit cell dimensions of the synthetic double-chain silicates were slightly larger than those of natural glaucophane, hinting that cation disorder might have typified the synthetic analogue. Finally, electron microprobe analysis at U. C. San Diego showed that, as far as could be ascertained, the synthesized, very fine-grained amphiboles had the stoichiometric composition of $Na_2Mg_3Al_2Si_8O_{22}(OH)_2$. Judging by these data, I concluded that I had synthesized end-member glaucophane, and that it was stable at high-T and low-P (**Fig. 2**).

Accepting the idea that chemical alteration was responsible for the formation of natural glaucophane under low-P conditions, I began to examine blueschists in the field and lab. I was surprised to discover that the mafic blocks of glaucophane schist scattered about serpentinite bodies were accidental tectonic fragments of metabasalt engulfed in the low-density ultramafic diapirs as (I inferred) the serpentinites buoyantly ascended surfaceward. Most importantly, such mafic blueschists were compositionally normal metabasalts, not metasomatized rocks. And, as other researchers were then reporting, some of the spatially associated Franciscan metagraywackes contained HP-LT neoblastic jadeitic pyroxene + quartz ± metamorphic aragonite. Thus, in spite of low-P phase equilibrium growth of what I thought was synthetic $Na_2Mg_3Al_2Si_8O_{22}(OH)_2$, blueschists clearly represented a distinct HP-LT metamorphic facies. Subdued but wiser, I moved on to other projects. Later workers (Maresch, 1977; Koons, 1982; Carman and Gilbert, 1983; Graham et al., 1989; Tropper et al., 2000; Jenkins and Corona, 2006) eventually showed that my experiments had produced the chemically rather similar Na-magnesiorichterite, a rare low-P clinoamphibole, and that true glaucophane was only stable at high pressures and low temperatures.

My early research on laboratory synthesis of $Na_2Mg_3Al_2Si_8O_{22}(OH)_2$ did inspire me to map and study field occurrences of blueschists in the Franciscan Complex. Judging by the phase assemblages, I concluded that the jadeitic metagraywackes cropping out at Panoche Pass had formed at temperatures of ~200-300 °C and pressures of ~7-8 kbar in what was then thought to have been an oceanic trench (Ernst, 1965). Such physical conditions would have been implausible, if not impossible, for burial depths of 25-30 km on a static Earth, so I knew that I was missing something important. Fortunately, the research received an unexpected boost. In the late 1960s, the reality of descending lithospheric plates capped by basaltic crust was recognized, thereby explaining the anomalous HP-LT, low heat-flow regime beneath oceanic trenches. The advent of plate-tectonic theory found me poking around in the subduction zone! Although experimental synthesis of what I thought was end-member glaucophane was later shown to be slightly off-composition, it did cause me to study a petrologically complex geologic problem just when exciting new interpretations on global tectonics were emerging.

Circumpacific and Alpine Plate Tectonics

Encouraged by plate-pushing based on studies of HP-LT blueschists and related rocks in western California and SW Japan, in 1970 I began several research projects on the crustal metamorphism and inferred mineralogic nature of the deep crust and upper mantle of the western and central Alps (**Figs. 3, 4**). Peter Bearth and Volkmar Trommsdorff were helpful guides to many world-famous Alpine field localities that we examined. Naturally, some Swiss colleagues were not impressed to have an Ausländer parachute in and explain how it all happened geologically, based on spending two years in Basel and Zürich. I understand this lack of unreserved acceptance, but nevertheless enthusiastically forced well-studied classic Alpine occurrences—crustal nappes and mantle peridotites—into the then-new plate-tectonic paradigm. It was a largely appropriate fit, and a heady time to be in the Earth sciences. I failed to fully appreciate many of the geologic and structural intricacies of the Alpine crust and upper mantle, but teamed up with Swiss and Italian colleagues to generate new P-T-X constraints on analyzed mineral parageneses. In the process, I had much fruitful, illuminating collaboration with Europeans friends, especially with petrotectonicians such as Giorgio Dal Piaz and Giovanni Piccardo. We also had an excellent time!

Then in the late 1970s, J. G. Liou, John Suppe, and I started several research studies collaborating with geologists from Taiwan National University and the Geological Survey of Taiwan. Petrotectonic-geochemical projects included investigations of the paired metamorphic belts of eastern Taiwan, the subduction-zone deformational history of Tertiary sedimentary mélanges, and the petrotectonic evolution of the East Taiwan Ophiolite. C. S. Ho and Bor-Ming Jahn were important contributors to these productive research efforts.

A 9-month sabbatical to New Zealand during 1982-1983 was enormously stimulating for me, especially studying geologic field relationships in South Island with Chuck Landis. But, after reconnaissance, I concluded that the accretionary Torlesse composite terrane was sufficiently different from the Franciscan, both depositionally and petrotectonically, that it would be unwise for me to attempt a comparative study. So, by the early 1980s I returned to mapping the geology and studying the tectonics and mineralogy-petrology-geochemistry of several markedly contrasting terranes in California with which I was already familiar.

Pacheco Pass, White-Inyo Range, and Klamath Mountains

I had begun mapping at Pacheco Pass, central Diablo Range ~40 km north of Panoche Pass, during the earlier US-Japan comparative study of the Sanbagawa and Franciscan HP-LT metamorphic belts. I finally finished the geologic map of the Pacheco Pass Quadrangle, including a more quantitative micro-analytical study of the regional HP-LT subduction-zone conditions *i.e.,* ~150-200 °C, 7-8+ kbar (Ernst, 1993). The study area consists of a stack of dominantly right-side-up, eastward-inclined, chiefly metasedimentary Franciscan thrust sheets (**Fig. 5**). As analyzed U-Pb ages of detrital grains of igneous zircon later showed (Ernst et al., 2009), the times of graywacke deposition of course decrease upward within each stratal packet; in contrast, structurally lower, westerly Franciscan sheets exhibit progressively younger depositional ages than those of the overlying allochthons. This architecture attests to the sequential underflow, offloading, and imbrication of the clastic units. In aggregate, the thrust sheets comprise an Upper Cretaceous accretionary prism. In fact, the Franciscan collage of allochthons present throughout much of northern and central California marks the existence of a long-lived oceanic trench and convergent plate junction along the accretionary margin of western North America during Cretaceous and Paleogene time.

Collaborating with Clarence Hall and Clem Nelson, my geologic mapping in the central White-Inyo Range, easternmost California, started in 1978. The region contains a well-ordered Neoproterozoic to Cambro-Ordovician passive margin section of interlayered carbonate and siliciclastic strata (Ernst et al., 1993). These Atlantic margin-type deposits represent stratigraphic equivalents of a well-studied sedimentary section exposed to the SE in the Death Valley area. They chronicle the ~600-700 Ma break-up and dispersal of the Neoproterozoic supercontinent Rodinia. In the White-Inyo Range, lower Paleozoic rifted-margin sedimentary rocks are overlain by basaltic and andesitic volcanic arc rocks of mid- and late Mesozoic age, signaling the transition to a convergent plate junction. Calc-alkaline Jura-Cretaceous granitic plutons, petrologically similar to the voluminous composite batholithic magmas of the Sierra Nevada, coevally invaded the entire White-Inyos. Analyzing phase assemblages for bulk-rock major + trace element + stable isotope geochemistry, I studied the regionally developed contact metamorphism of the old carbonate-siliciclastic and overlying volcanogenic sections. Using similar methods, I also assessed the multistage, heterogeneously injected magmas and inward solidification history of the mafic Barcroft Granodiorite, a large plutonic complex in the center of the range.

Starting in 1979, I took part in topical studies and regional geologic mapping projects in the Marble Mountain Wilderness area of the central Klamath Mountains, northernmost California. At times, the investigation involved collaboration with Mary Donato, Cal and Melanie

Barnes, Bob Coleman, and Brad Hacker. The USGS supported our initial work, and for two seasons we had weekday helicopter transportation. The Klamath Mountains include upper Paleozoic and lower to mid-Mesozoic oceanic cherts, argillites and minor carbonate strata, as well as interstratified ocean-floor volcanogenic units in a series of imbricated, east-dipping accretionary allochthons. These map units mark the western, oceanic edge of the North American continent juxtaposed against paleo-Pacific oceanic crust. The imbricated tectonometamorphic complexes attest to chiefly greenschist- and lower amphibolite-facies P-T conditions. However, traces of blueschist are present locally, suggesting prior existence of HP-LT terranes, now overprinted and exhumed. Geochronologic, stable isotopic, and bulk-rock petrologic-geochemical data support the view that the Klamath accretionary complex is an oceanward NW salient of the Sierra Nevada volcanic-plutonic arc (Ernst, 1999).

Eurasian Deep Continental Lithospheric Underflow

The most exciting development in metamorphic petrology over the past ~35 years has been the astonishing discovery of ultrahigh-pressure (UHP) coesite and microdiamond crystals present as inclusions in contractional-margin sialic crustal rocks (Chopin, 1984; Smith, 1984; Sobolev and Shatsky, 1990). These remarkable mineralogic occurrences, first reported in the western Alps, coastal Norway, and northern Kazakhstan, reflect P-T conditions attending profound subduction of continental lithosphere to depths of ~90-140+ km. Parts of these terranes then returned surfaceward prior to the re-establishment of thermal equilibrium. Ascent of each UHP complex apparently was propelled by sialic slab buoyancy relative to the denser surrounding mantle. As a minor player working with J. G. Liou, Bob Coleman, Nick Sobolev, Vlad Shatsky, Nick Dobretsov, Mary Leech, Ruth Zhang, and others in eastern China, the south Urals, and central Asia, I helped document additional UHP complexes exhumed along various convergent plate junctions. More than 20 UHP terranes are now recognized (Liou et al., 1998, 2009). All such tracts are of Phanerozoic metamorphic age, suggesting a gradually declining heat flow (and lithospheric plate thickening and enlargement) during thermal relaxation of the Earth.

Attending exhumation-decompression, the now-resurrected contractional complexes were intensely overprinted by low-P mineral assemblages. Traces of relict UHP phases were preserved only in strong, refractory, aqueous fluid-tight host minerals (*e.g.,* zircon, pyroxene, garnet) typified by low rates of intra-crystalline diffusion. Isolation of these inclusions from the annealing rock matrix impeded back-reaction of the UHP phases during decompression. Most recognized HP-LT and UHP complexes in the upper crust are imbricate sheets, consisting mainly of low-density quartzofeldspathic lithologies ± serpentinites (*e.g.*, Henry, 1990; Michard et al., 1995; Ernst, 2001; Kaneko et al., 2003). Dense mafic and peridotitic rocks make up less than ~10 % of each exhumed subduction complex. Heat was likely conducted away from the buoyant UHP sheets as they rose along the refrigerating subduction channel. The more massive UHP terranes apparently were subducted at shallower inclinations and rebounded over a longer period of time compared with small, thin, rapidly exhumed sheets (Kylander-Clark et al., 2012). Round-trip prograde-retrograde P-T loops were completed in ~5-20 Myr, and rates of ascent to mid- crustal levels approximated earlier descent velocities (**Fig. 6**). Unless all these conditions were satisfied, such UHP rocks were completely transformed by retrogression to low-P mineral assemblages, obliterating evidence of the earlier profound subduction event. How many convergent-plate junctions that involved very deep underflow are no longer detectable due to complete, thermally driven retrogression on exhumation?

Start of Plate Tectonics

Working on the Precambrian Iron Range of northern Minnesota as an undergraduate, I was stunned by the then-well-known ancient age of the Earth. Based on computations and data provided by astrophysicists, geochemists, and planetologists (*e.g*., Taylor, 1992), we accept that the proto-Earth began forming at ~4.54 Ma by planetesimal sweep-up during condensation of the solar nebula. Accretion apparently included cataclysmic collision with a Mars-size asteroid (Wetherill, 1990). Such impacts rapidly elevated the overall thermal budget and partial fusion of the early Earth. Additional heat was supplied by primordial radioactivity, infall of the Fe-Ni core, mantle oxidation (Armstrong et al., 2019), and devolatilization; chemical-density stratification evidently attended planetary growth. After the thermal maximum peaked at ~4.4 Ga, the near-surface gradually cooled as a Hadean magma ocean solidified. By ~4.3-4.2 Ga, H_2O oceans and a dense CO_2-rich atmosphere apparently enveloped the planet. Near-surface temperatures clearly had fallen far below the low-P solidi of peridotite, basalt, and granite, ~1300, ~1120, and ~950 °C, respectively. At less than half their melting T, the growing rocky scum would have existed as thin surficial platelets bounding the Hadean Earth (Jackson et al., 2008). Any stagnant-lid circulation would have been overwhelmed by thermally induced mantle convection, because efficient heat transfer required vigorous bodily overturn in the early, hot planet. Thus, bottom-up flow, *i.e.,* plume ascent, carried deep-seated heat toward the surface. Bottom-up control diminished gradually as shallow-level cooling, lithospheric plate growth, and top-down, plate descent increased (Ernst, 1991; Ernst et al., 2016).

Evolutionary stages (**Fig. 7**) evidently included: (a) ~4.5-4.4 Ga, the magma ocean solidified, forming ephemeral, ductile platelets; (b) ~4.4-2.7 Ga, small oceanic and sialic crustal plates formed, but ware destroyed by mantle return flow before ~4.0 Ga; sialic crust-capped material then began to accumulate gradually as largely subsea lithospheric collages; (c) ~2.7-1.0 Ga, progressive, contractional suturing of old shields and younger, marginal orogenic belts led to large cratonal plates typified by continental freeboard (*i.e.,* epeiric seas), multicycle sedimentary differentiation, and episodic glaciation during transpolar plate drift. Stagnant-lid mantle overturn likely occurred episodically beneath supercontinental plates; (d) ~1.0 Ga-present, giant, stately moving thick plates now cap laminar-flowing mantle cells. Primitive plate tectonics—*i.e.,* mantle plume-induced sea-floor spreading, transform faulting, and lithospheric platelet subduction—apparently characterized Earth history by Hadean time.

Mineral Resources and Human Health

At least since 3.5 Ga (Schopf, 1982), the terrestrial biosphere has maintained a dynamic equilibrium with readily available Earth materials, *i.e.,* nutrients, derived from the near-surface crust, hydrosphere, and atmosphere. This relationship was (and still is) chiefly powered by solar energy. Pliocene Australopithecine evolution and the appearance of *Homo sapiens* nearly 300,000 yrs ago did little to alter this situation while our species survived as hunter-gatherers. However ~10,000 yrs ago, the onset of rudimentary farming began to allow diversification of human labor, the rise of civilizations, and utilization of Earth resources at rates greater than, eventually far exceeding those of natural replenishment (Ruddiman, 2005; Stephens et al., 2019). Although large, Earth resources other than sunlight are present in finite abundances. Current anthropogenic overdrafting of such commodities reduces future availability, and likely the ultimate planetary carrying capacity for civilization. Demographers forecast the World population at ~9-10 billion by 2050. Intensive use of Earth materials has certainly enhanced the quality of life for people in the Developed Nations. Nevertheless, natural background processes such as erosion and volcanic eruptions, and human activities involving agriculture, construction, industrial development, transportation, non-renewable energy extraction-consumption of mineral resources have led to serious public health hazards. Among natural and human-induced risks are bio-accessible airborne dusts and gas species, soluble pollutants in agricultural, industrial, and residential waters, and toxic chemicals in foods and manufactured products. At moderate levels of ingestion, many Earth materials are necessary for life; however, underdoses and overdoses adversely impact human well-being and longevity.

With rise of the worldwide digital info-network, economic globalization, and accelerating industrial thrust of Developing Nations, the attainment of natural resource sustainability has emerged as a strategic imperative (Matson et al., 2016). Exponentially increasing consumption of Earth materials and ubiquitous environmental degradation will require substantially improved, universal public health care. Actions must involve integrating global cooperation among social scientists, politicians,, geoscientists, epidemiologists, and a wide range of medical researchers.

Preserving the Biosphere for Humanity

Environmental scientists know that human viability depends critically on a richly diverse, functioning biosphere. The web of life provides food production, biochemical and medical commodities, clean water, and a host of other ecological services and products. However, this seamlessly interconnected biological system began to be degraded by human activities during the transition from a hunter-gatherer economy to a settled, agriculture-based civilization. Stresses on living systems have vastly accelerated with exponential growth of the human population, intensified by industrialization and the application of modern medicine. These factors are causing an ongoing catastrophic loss of many plant and animal species. The IPCC Fifth Assessment Report of 2014, and the U. S Governmental Fourth National Climate Assessment of 2018 quantitatively document the precipitous declines in diversity and viability of the near-surface realm of the Earth, home of the biosphere. Mainly reflecting global warming, specific areas of deleterious human-induced climate change in the United States include: the global increase in T with rising atmospheric CO_2 and other greenhouse gas species; warming of America except for a few southern states; increasing episodes of mega-precipitation; progressive loss of snowpack in the western conterminous United States; ongoing decrease in Arctic sea ice and in the aggregate global mass of glaciers; gradually increasing severity of U. S. drought conditions coupled with an increasing magnitude and frequency of wildfires; progressive sea-level rise and increasing ocean heat content; elevated acidity of the circum-Hawai'i Pacific Ocean (**Fig. 8**). Related but not included in this list are other, equally serious anthropogenic impacts such as ubiquitous deforestation, groundwater overdrafting, loss of wetlands, atmospheric and surface-water pollution, degradation of soils, and an accelerated habitat fragmentation-destruction—all resulting in the accelerated loss of biodiversity. The World's sixth mass extinction is well underway, and humans are mainly responsible for it, as documented by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, 2019. What to do?

Energy—the Essential Link to Sustainability

You wouldn't know it by the activities of our political and socio-economic systems, but many of the World's people and institutions are quite aware of the broad range of threats posed by ongoing climate change. Fortunately, scientists and engineers already possess a wide-ranging set of technological capabilities with which to ameliorate some of the most adverse effects of human-caused climate change. What is now required to address it is an international, coordinated effort. Currently lacking is the political will to deal with this interdisciplinary problem. Actions must include the phased transition to a carbon-free, solar- and/or hydrogen-fusion-powered energy system; moreover, clean energy must be of virtually infinite availability and renewability. With universally accessible, cheap energy, much would be possible. Climate modification could include CO_2 capture and sequestration, a broad range of conservation measures, substitution, dematerialization, recycling, and implementation of a set of thoroughly tested geotechnical solutions. We must address this multi-dimensional spectrum of problems, including a transition to greater social equity. It is a difficult but doable project, and mainly requires the will to act.

Unfortunately, a yet more severe challenge looms, reflecting widespread environmental degradation attending unfettered economic development combined with population growth. In my opinion, the existential threat facing us is the urgent need to achieve a state of resource sustainability, and to decouple this usage from the present commodity-based economy (*e.g.,* Jackson and Victor, 2019). This condition (**Fig. 9**) will require reaching a dynamic equilibrium between near-surface planetary resource utilization and sunlight*:* it is physically impossible for consumption of materials to long exceed recharge rates. Moreover, a sustainable, equilibrium state must be achieved, not just for a generation, but for ~100,000 yrs! In my view, it is unclear whether or not we can attain such a condition, given at least three factors: (a) The Second Law of Thermodynamics will not ever be repealed; resource recycling involves entropy increase and mass dispersal. (b) Humans obey behavior hard-wired in *Homo sapiens* over the millennia as survivor hunter-gatherers (Harari, 2014). Encountering other humans, the options of sub-tribal groups were simple, fight or flight. Not among the options were concepts of negotiation and cooperation. And (c), our current economic system is largely material-based.

Perhaps a transition to universally available, cheap, renewable energy will allow effective collaboration and the achievement of sustainable development. In concert with resource conservation, we must quantify the unquantifiable*, i.e.,* assign monetary values to concepts such as human interactions, the natural environment (*e.g*., costs of environmental degradation, and values of provided ecological services), human health and well-being, arts and culture, leisure activities, sports, mental and physical security, etc. In the process, dematerialization combined with such an economic reorientation might preserve civilization and a viable web of life

High Time to Act?

The Earth accreted attending condensation of the solar nebula at ~4.54 Ga, an almost incomprehensibly distant past. Life existed on-and-near the surface at least since ~3.5 Ga, and has evolved spectacularly over geologic time. So what’s the hurry? With the appearance of *Homo sapiens* in sub-Saharan Africa less than ~300,000 yrs ago, and a human generation of ~20 years, ~15,000 generations of anatomically modern humans have trod the Earth, earning a living through opportunistic food gathering. Prior to the advent of farming no more recent than ~10,000 yrs ago, it appears that that our planet has witnessed a total of ~500 generations of proto-civilization, ~29 since invention of the printing press and the Renaissance, ~11 since the Industrial Revolution, and ~3 since the wake-up publication of Rachel Carson's *Silent Spring*. Humans are responsible for the rapidly accelerating extent and magnitude of global change. Yet, we still behave like hunter-gatherers. The 2019 report by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services suggests that we may have a few generations to reach a global equilibrium with the Earth's resource base in order to ward off the collapse of civilization (*e.g*, Diamond, 2006). Of course, regional resource exhaustion has happened before. The Minoans, Mayans, Easter Islanders. and the populations of Haiti and Madagascar exemplify the unsustainable exploitation of terrestrial resources. The age of global sustainable economic development clearly is upon humanity. Whether we heed the accumulated evidence or not, Mother Nature, environmental economist in charge, does not tolerate the overdrafting of nutrients, and eventually punishes organisms indulging in such practices………that would be us!

Mineralogists' Leadership Role

Sixty-six years ago, my research efforts began mineralogically, and gradually widened to include various aspects of petrotectonics and planetary habitability. I became concerned about biospheric viability and health of the Critical Zone very late in my career. Thus, I have only played a teacher's role in the amelioration of adverse environmental effects wrought thus far by humans. However, all of the World's people now need to help reach a sustainable state of resource consumption through their activities. Geoscientists are especially knowledgeable in this regard, being uniquely capable stewards of the only planet that our descendants will ever populate. Earth scientists must direct far more attention in the future to life-supporting mineral and energy resource usage, commodity recycling, substitution, and dematerialization than in the past. Our research must illuminate how civilization can flourish in equilibrium with a finite resource base. With or without humans, the planet eventually <u>will</u> return to the long-term dynamic equilibrium between evolving life and near-surface resource utilization. For humans to achieve sustainable development, we must act incisively as environmental leaders to preserve our civilization and the supporting biosphere, a very tall order indeed. Will we at least try?

Now, an Octogenarian's Free Advice

I treasure my association with the Mineralogical Society of America, so here's a few lessons I have learned during 66 years of the relationship: (1) I almost didn't come to UCLA because of an ill-founded prejudice. So, don't dismiss possible career opportunities before examining them. (2) If you trust your research, make sure you publish it, or someone else will. Don't take no for an answer. (3) We all work hard on research projects, and regard our results as the <u>truth</u>. But everyone has limited vision and judgment; so do not fret if an investigation turns out to be imperfect. Learn from it and move on. (4) Most importantly, although everyone must be involved, mineralogists must accept that Earth scientists are among the primary caretakers of the blue planet. A healthy web of life depends what we do or fail to do, so let us treat the Earth with care, knowledge, respect, and like medical practitioners, do no harm. We must act to preserve both the resource base and the web of life………If not us, then who?

Acknowledgments

My teaching and research efforts have been guided by far too many mineralogists and institutions for me to provide a proper list of acknowledgments—but you know who you are! However, two universities, UCLA and Stanford, supported my scholarly efforts for 30 years each**.** I owe these very special academic institutions, and their student-colleague-teachers (many people have been simultaneously all three) a profound debt of gratitude. Without their support, I would have learned little. Allen Glazner, Frank Spear, and Mickey Gunter provided helpful feedback on a draft manuscript in their attempts to improve this review of my scientific journey. Lastly, Brad Hacker, Peter Heaney, and Mark Cloos reviewed this work for *American Mineralogist*; Cal Barnes served as editor. To these and all other colleagues, I express my sincere thanks for the help!

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Figure Legends

Fig. 1. Petrographic study of heavy-mineral suites from outcrop and drill-core samples, defining the reworked sedimentary transition from the St. Peter Sandstone to the overlying, conformable Glenwood Shale near Carleton College, Northfield, MN (Ernst, 1954).

Fig. 2. Experimentally determined stability relations (Ernst, 1961) on the bulk composition Na_2O-3MgO-Al_2O_3-8SiO_2 + excess H_2O for what I thought was end-member glaucophane. Later researchers (Maresch, 1977; Koons, 1982; Carman and Gilbert, 1983; Graham et al., 1989; Tropper et al., 2000; Jenkins and Corona, 2006) showed that my work actually synthesized Na-magnesiorichterite—close but no cigar!

Fig. 3. Simplified metamorphic zonations on subducted lithospheric plates in **(a)** SW Japan (Hashimoto et al., 1970), **(b)** the California Coast Ranges (Bailey et al., 1970) and **(c)** the Alps (Ernst, 1971). Arrows indicate increasing HP/LT metamorphic grade and recovered depth of crustal material carried down by oceanic plate underflow.

Fig. 4. Generalized thermal structure of a descending oceanic crust-capped plate based on observed heat flow data and metamorphic P-T ometry (Ernst, 1976). Rough down-bowings of the ~200, ~500, and ~800°C Isotherms are sketched.

Fig. 5. (**a**) Regional geology and (**b**) interpretive cross-section of the Pacheco Pass 7.5 minute quadrangle, central Diablo Range, California Coast Ranges (Ernst, 1993).

Fig. 6**.** P-T paths of subduction, followed by buoyancy-propelled exhumation to mid-crustal levels for continental crustal collision (thick-dashed purple curve) as exemplified by UHP imbricate thrust sheets exposed in the Kaghan Valley, western Himalayan syntaxis (*e.g.*, Kaneko et al., 2003); and oceanic plate underflow (thin-dashed blue curve) as shown for the central California Coast Range sector of the Franciscan HP/LT belt (*e.g.*, Ernst, 1993). The P-T petrogenetic grid is after Liou et al. (1998).

Fig. 7. Schematic, transitional stages in evolution of the Earth's crust-mantle system, modified after Ernst et al. (2016). Mantle convection is illustrated, but cell sizes and shapes are not constrained. Oceanic crust is shown in dark green, continental crust in pink. The increasing thickness of lithospheric plates over time is exaggerated for clarity. Early Earth advective heat transport chiefly by at episodic (or more likely continuous) bottom-up mantle convection and plume ascent are indicated in red-orange. Cooling, enlarging oceanic plates and chemically-mineralogically buoyant cratonal plates gradually began

to dominate mantle overturn through top-down, dense oceanic crust-capped slab descent. Temporally limited mantle convection probably occurred beneath chemically buoyant, stagnant lids following supercontinental accretion; thermal build-up in the sublithospheric mantle then resulted in continental rifting and dispersal.

Fig. 8. Graphic summary of a few of the many aspects of environmental degradation, focusing on the conterminous United States (U. S Governmental Fourth National Climate Assessment of 2018, Volume II). Long-term observations document the accelerating decrease in health and viability of the Critical Zone, *i.e.,* the terrestrial near-surface realm occupied by the biosphere.

Fig. 9. Three types of population growth curves: **(a)** unconstrained growth, supported by an unlimited supply of resources; **(b)** finite growth limited by resources provided at a near-constant recharge rate; **(c)** temporary growth, then biological collapse through exhaustion of finite, non-renewable resources.

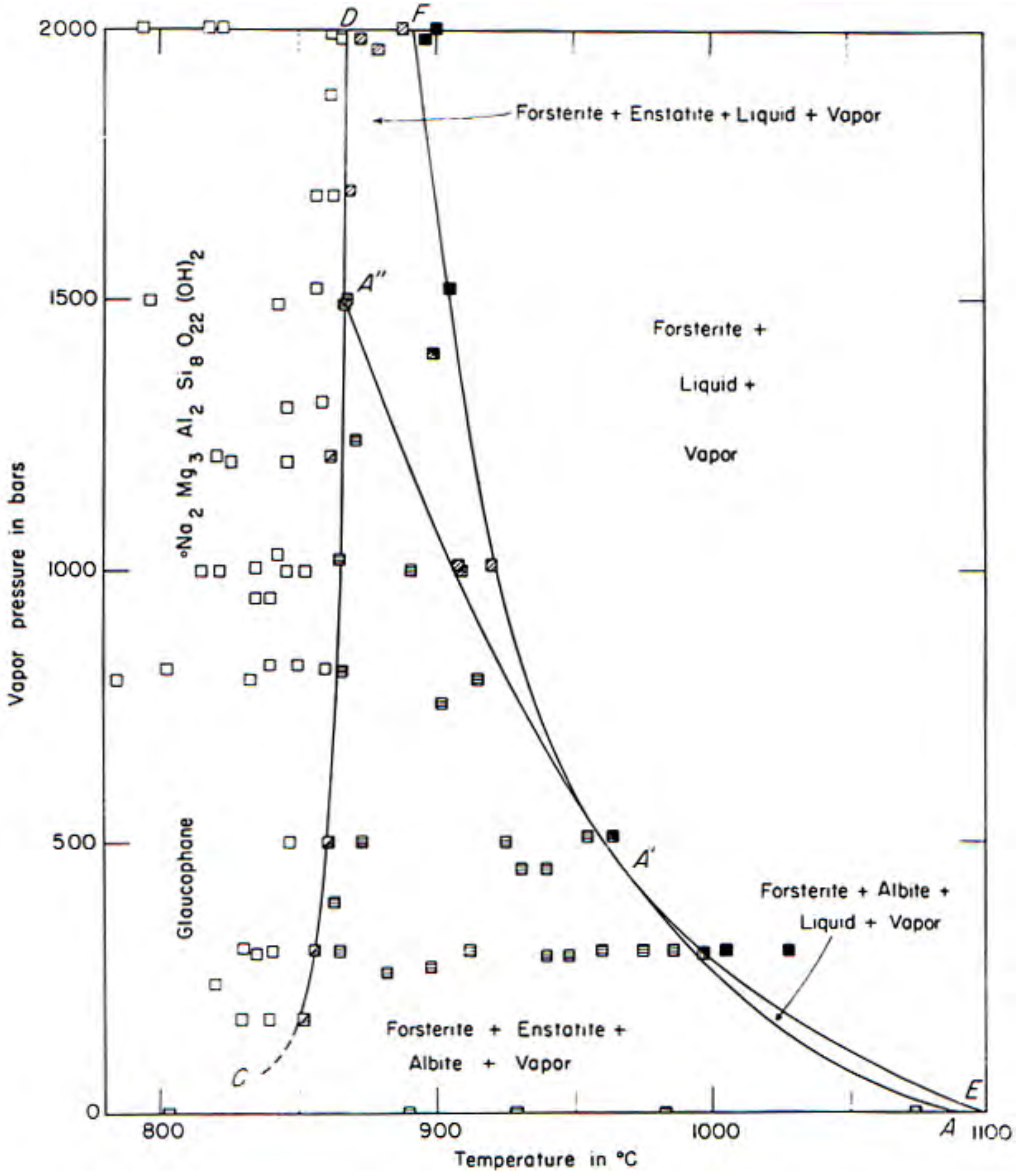
1

THE ST. PETER SANDSTONE-GLENWOOD SHALE CONTACT

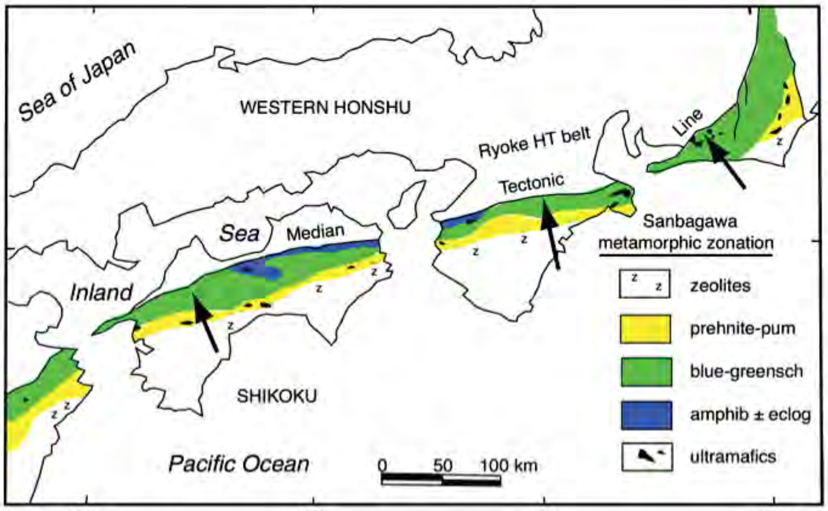
BY

W. G. ERNST

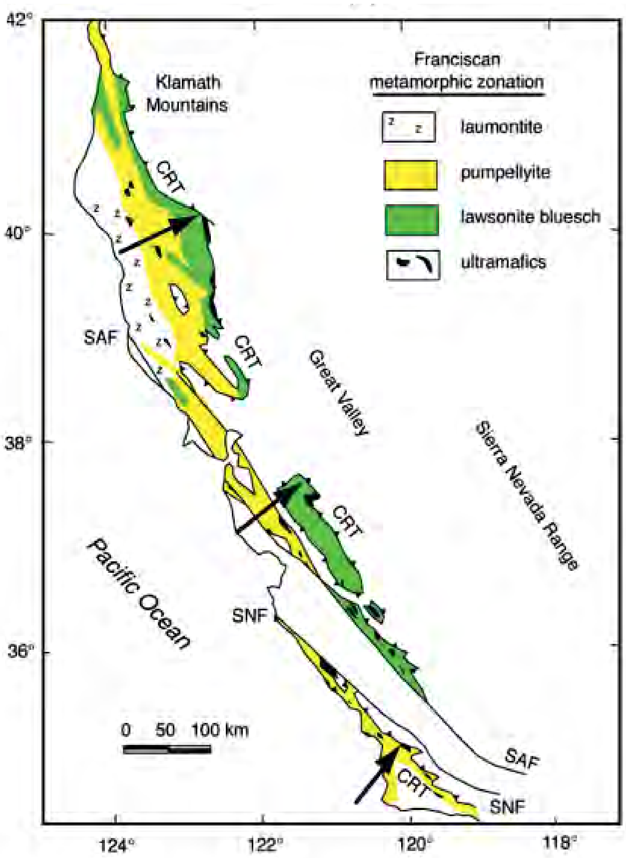
Reprinted from *American Mineralogist,* **39**: 1025-1031 (1954)


D
F
2000
1500
1000
500
0
800
900
1000
A
1100
E
Forsterite + Enstatite + Liquid + Vapor
A''
Forsterite + Liquid + Vapor
$^{\circ}Na_2Mg_3Al_2Si_8O_{22}(OH)_2$
Vapor pressure in bars
Glaucophane
A'
Forsterite + Albite + Liquid + Vapor
Forsterite + Enstatite + Albite + Vapor
C
Temperature in °C

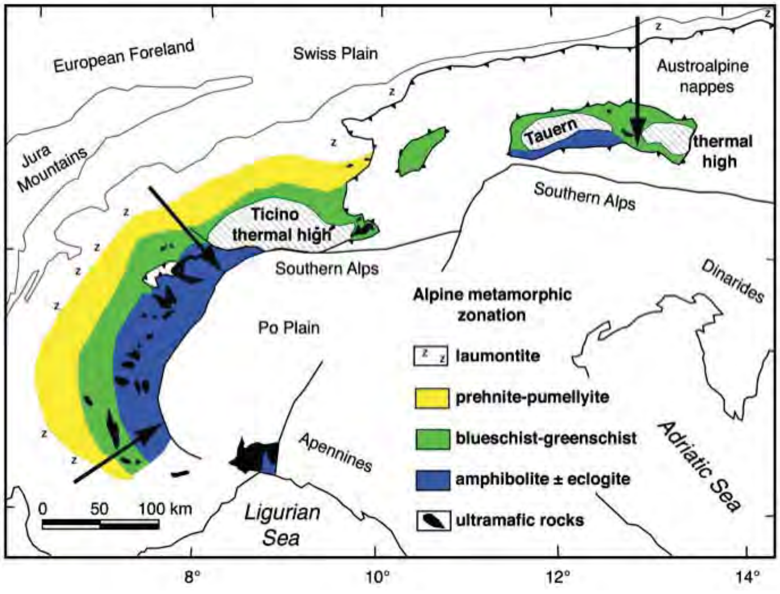
(a)

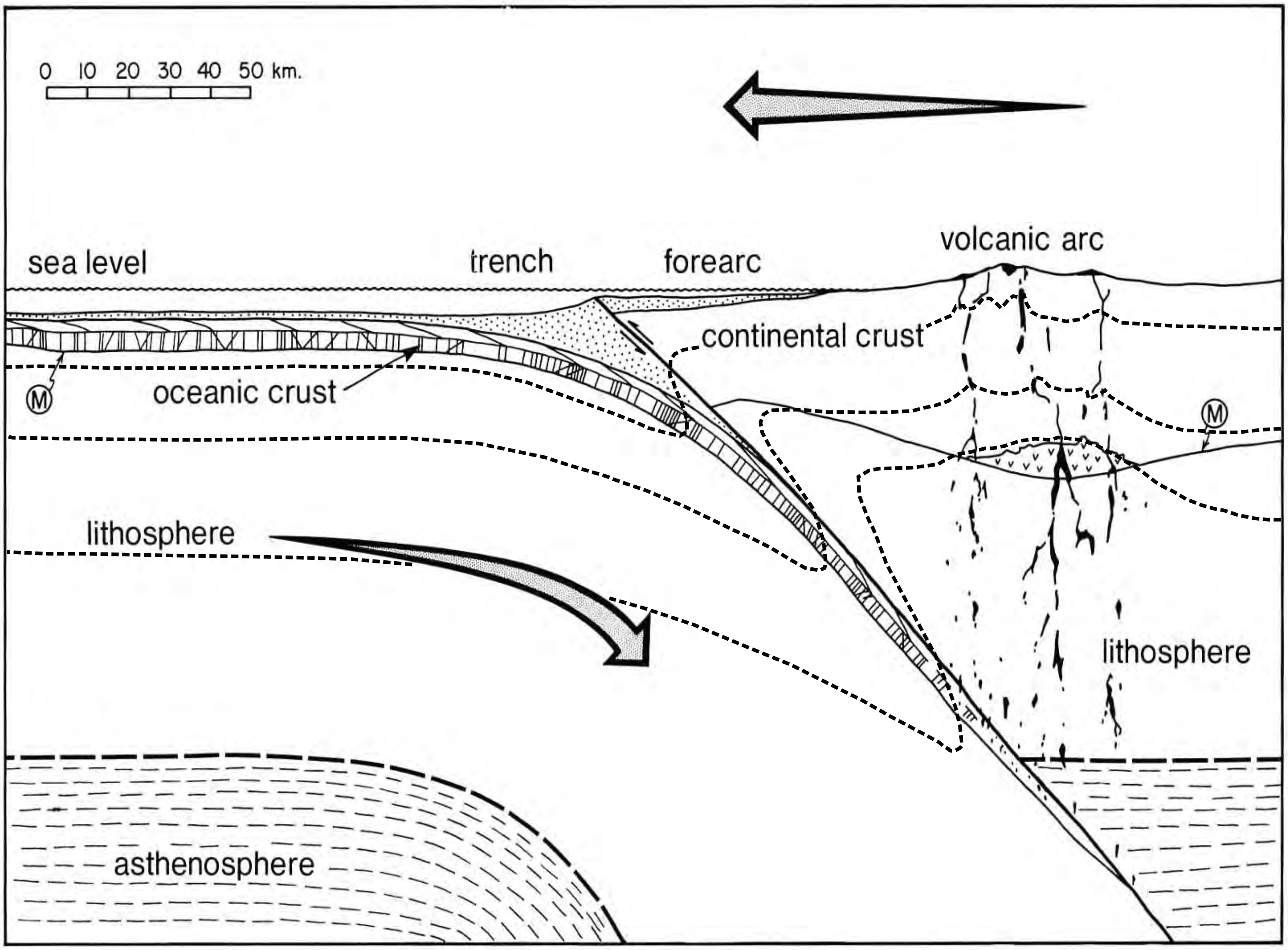

Sea of Japan
WESTERN HONSHU
Ryoke HT belt
Line
Tectonic
Median
Sea
Inland
SHIKOKU
Pacific Ocean
Sanbagawa metamorphic zonation
zeolites
prehnite-pum
blue-greensch
amphib ± eclog
ultramafics
0 50 100 km
34°
132°
134°
136°
138°

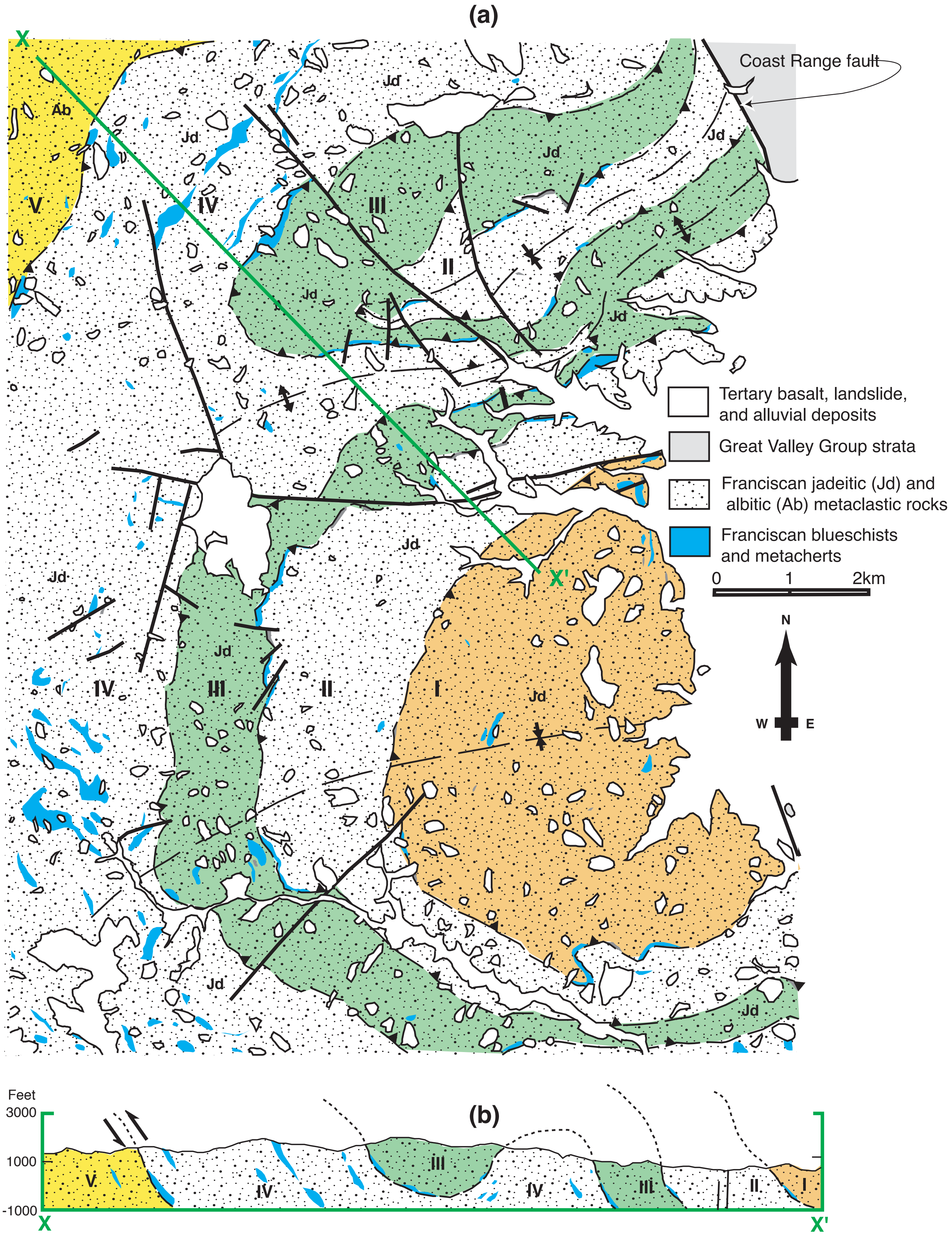
(b)

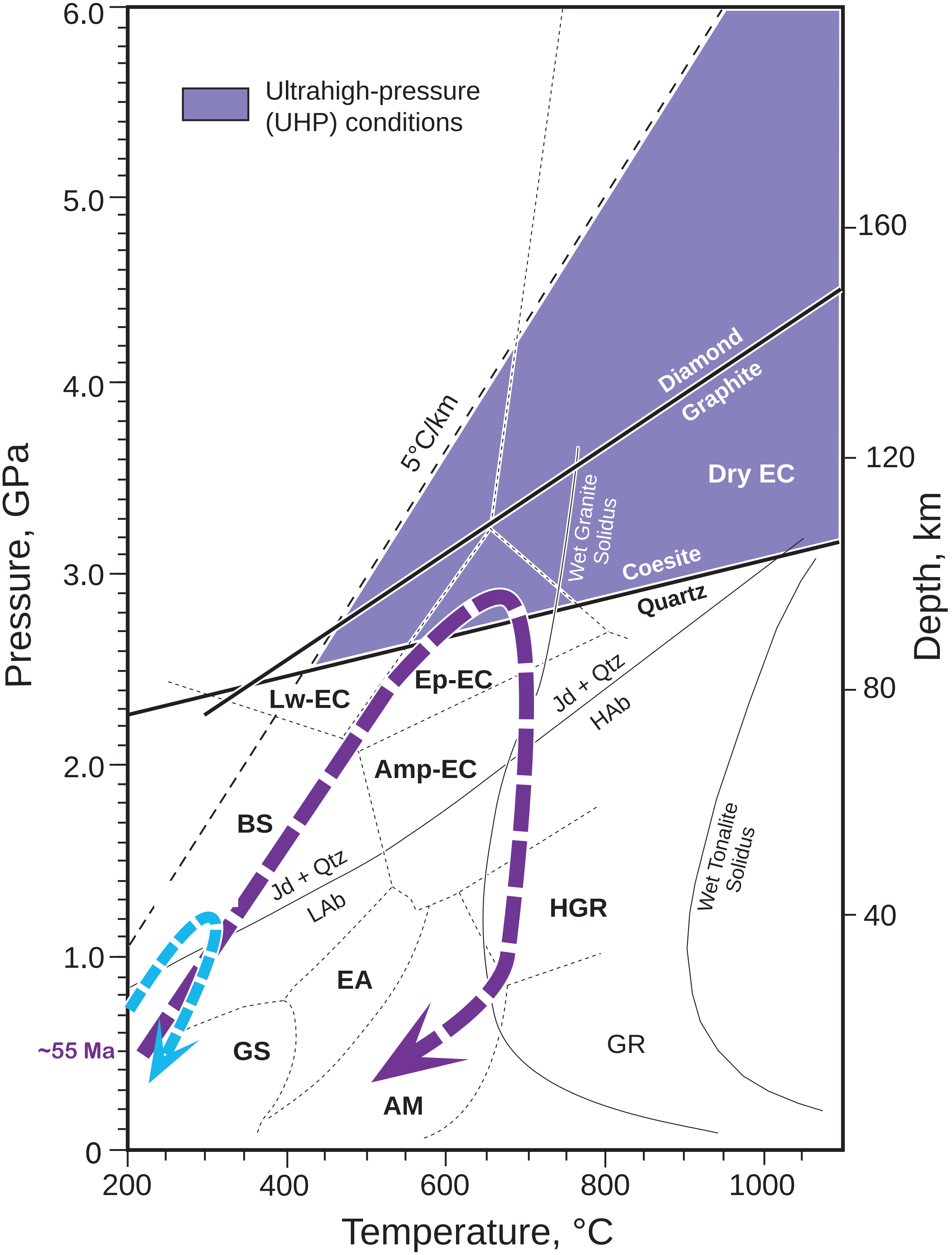

Klamath Mountains
Franciscan metamorphic zonation
laumontite
pumpellyite
lawsonite bluesch
ultramafics
CRT
SAF
Great Valley
Sierra Nevada Range
Pacific Ocean
SNF
0 50 100 km
42°
40°
38°
36°
124°
122°
120°
118°

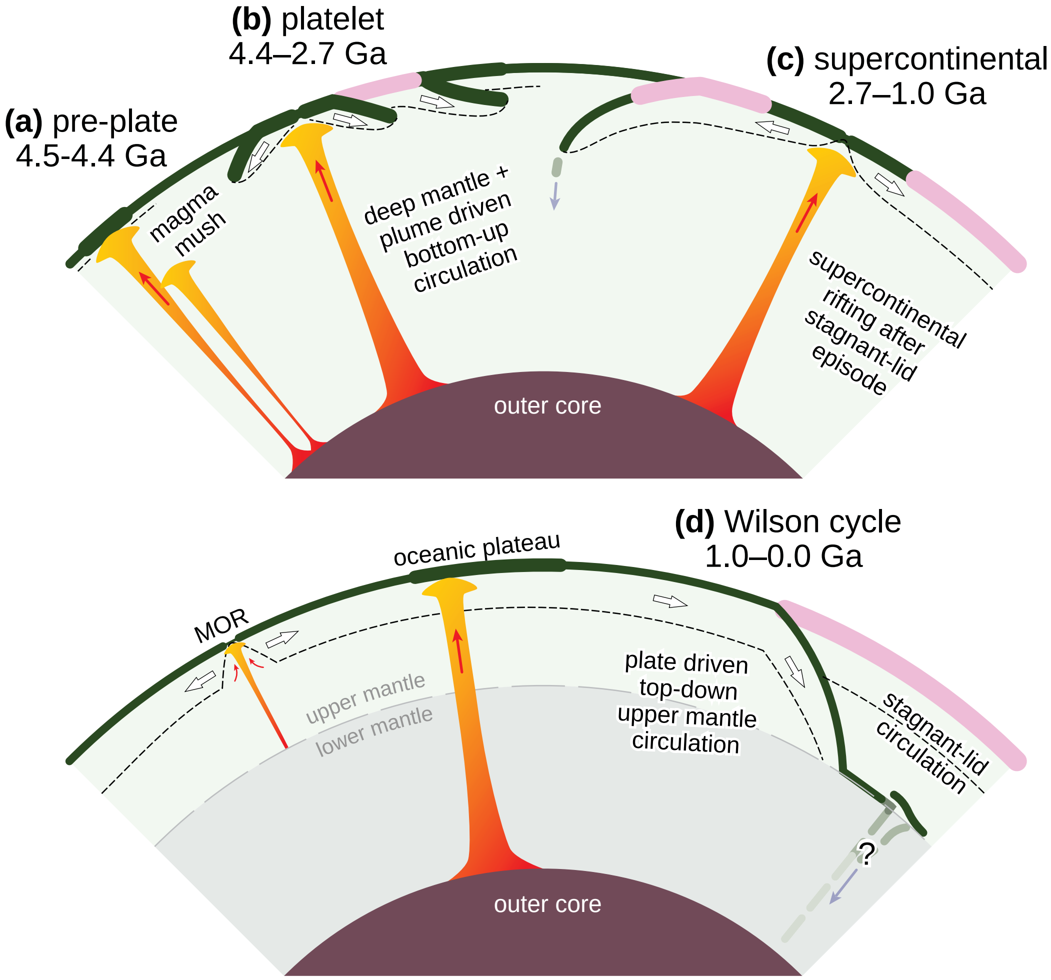
(c)


European Foreland
Swiss Plain
Austroalpine nappes
Jura Mountains
Tauern
thermal high
Ticino thermal high
Southern Alps
Southern Alps
Dinarides
Po Plain
Alpine metamorphic zonation
laumontite
prehnite-pumellyite
blueschist-greenschist
amphibolite ± eclogite
ultramafic rocks
Apennines
Adriatic Sea
Ligurian Sea
0 50 100 km
46°
44°
8°
10°
12°
14°


0 10 20 30 40 50 km.
sea level
trench
forearc
volcanic arc
continental crust
oceanic crust
Ⓜ
Ⓜ
lithosphere
lithosphere
asthenosphere

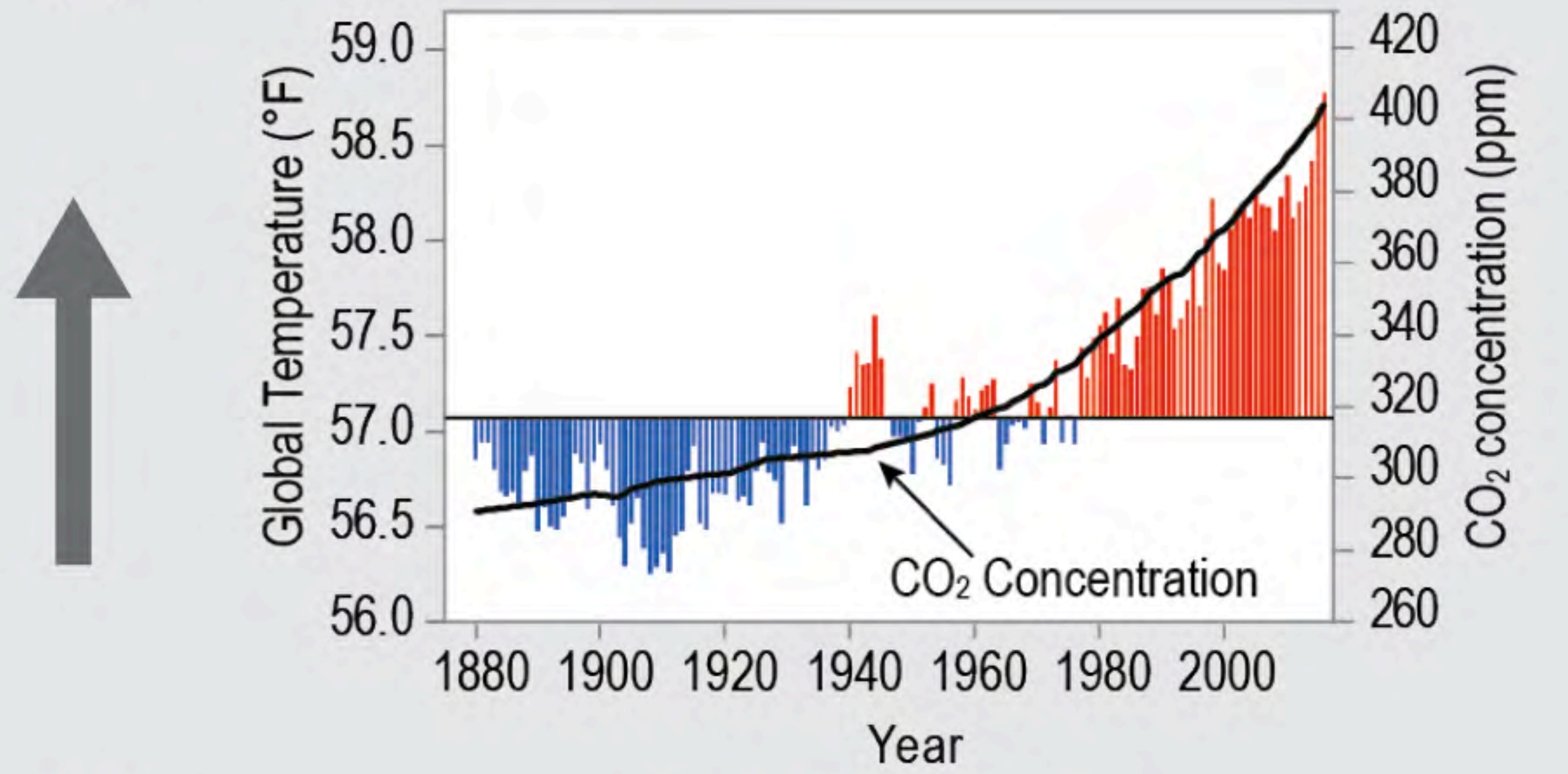

(a)
X
X'
Coast Range fault
Ab
Jd
V
IV
III
II
I
Tertary basalt, landslide, and alluvial deposits
Great Valley Group strata
Franciscan jadeitic (Jd) and albitic (Ab) metaclastic rocks
Franciscan blueschists and metacherts
0
1
2km
N
W
E
(b)
Feet
3000
1000
-1000


Ultrahigh-pressure (UHP) conditions
Pressure, GPa
Depth, km
Temperature, °C
6.0
5.0
4.0
3.0
2.0
1.0
0
200
400
600
800
1000
160
120
80
40
5°C/km
Diamond
Graphite
Dry EC
Wet Granite Solidus
Coesite
Quartz
Lw-EC
Ep-EC
Amp-EC
Jd + Qtz
HAb
BS
Jd + Qtz
LAb
HGR
Wet Tonalite Solidus
EA
GS
AM
GR
~55 Ma

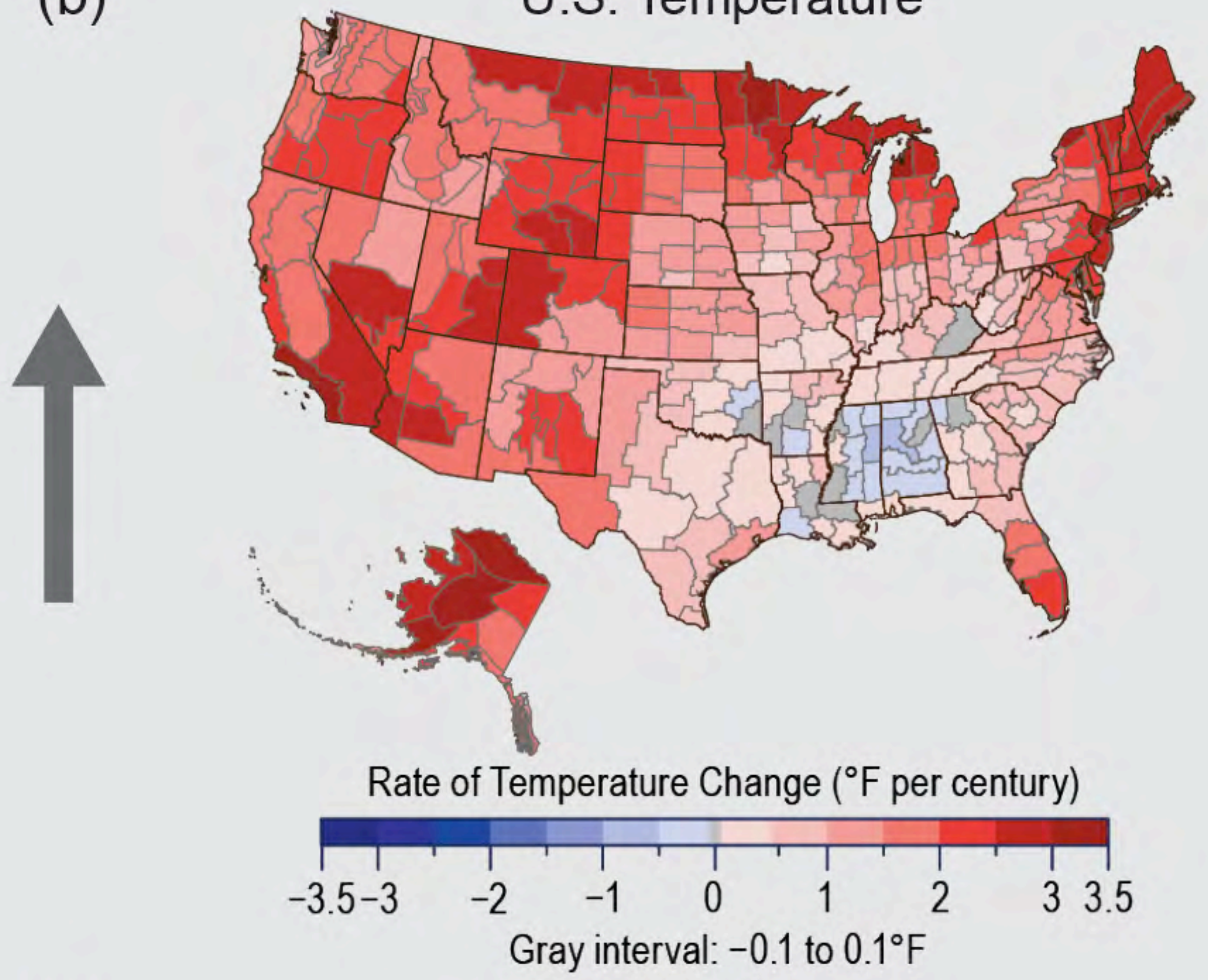

(b) platelet
4.4–2.7 Ga
(a) pre-plate
4.5-4.4 Ga
(c) supercontinental
2.7–1.0 Ga
magma
mush
deep mantle +
plume driven
bottom-up
circulation
supercontinental
rifting after
stagnant-lid
episode
outer core
(d) Wilson cycle
1.0–0.0 Ga
oceanic plateau
MOR
upper mantle
lower mantle
plate driven
top-down
upper mantle
circulation
stagnant-lid
circulation
?
outer core

WEATHER AND CLIMATE

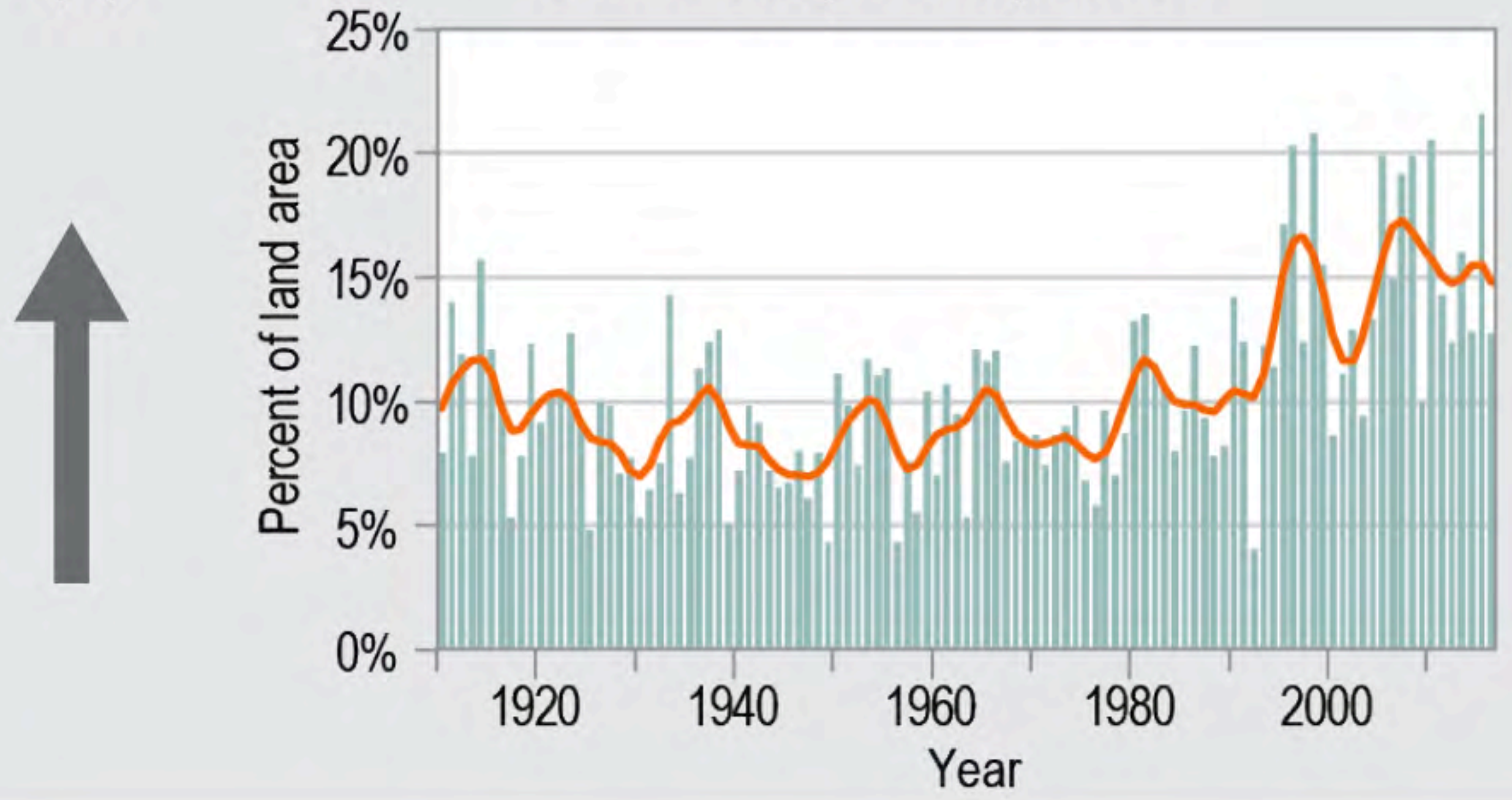
(a) Global Temperature and Carbon Dioxide



(b) U.S. Temperature

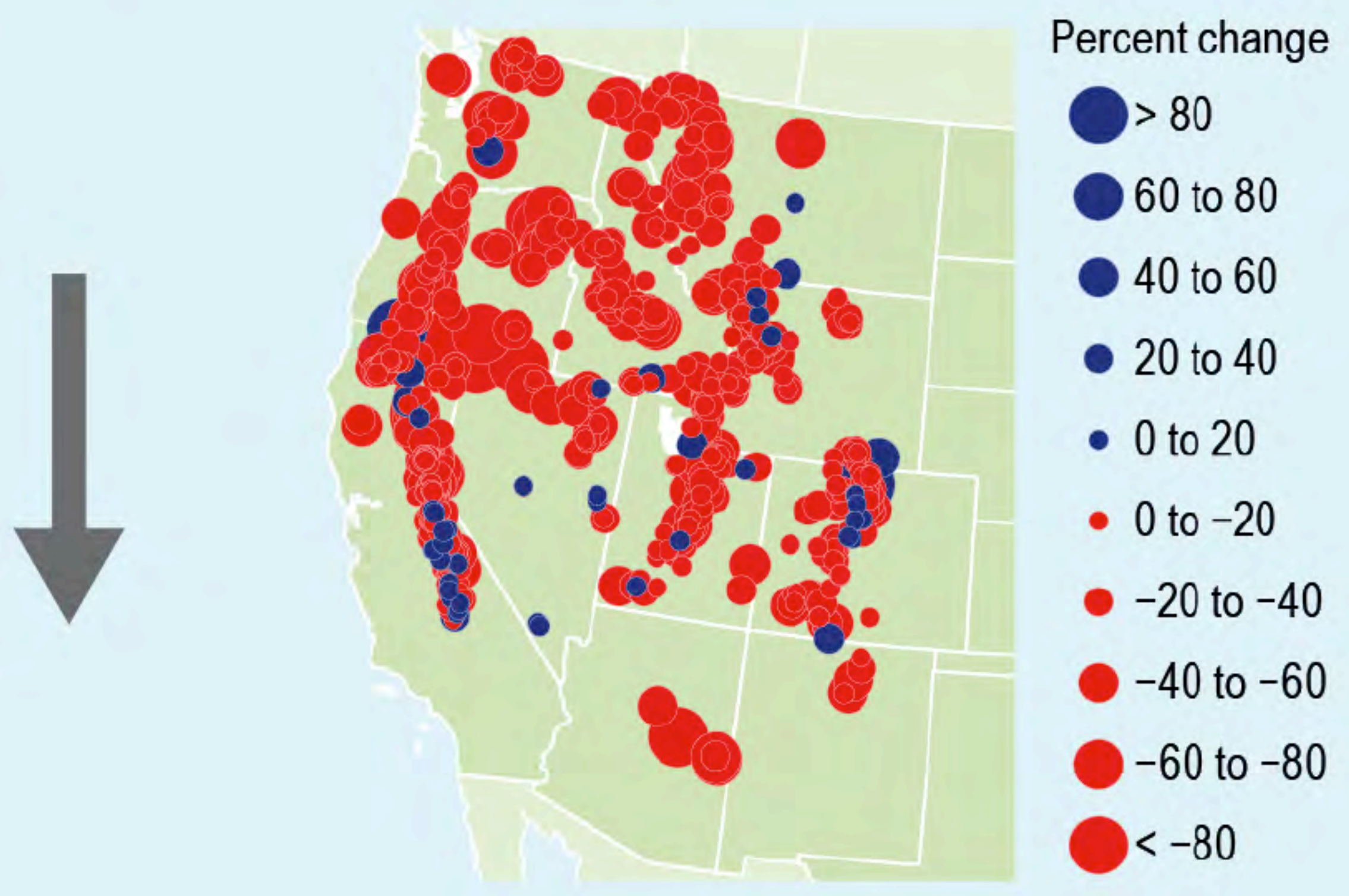


(c) U.S. Heavy Precipitation

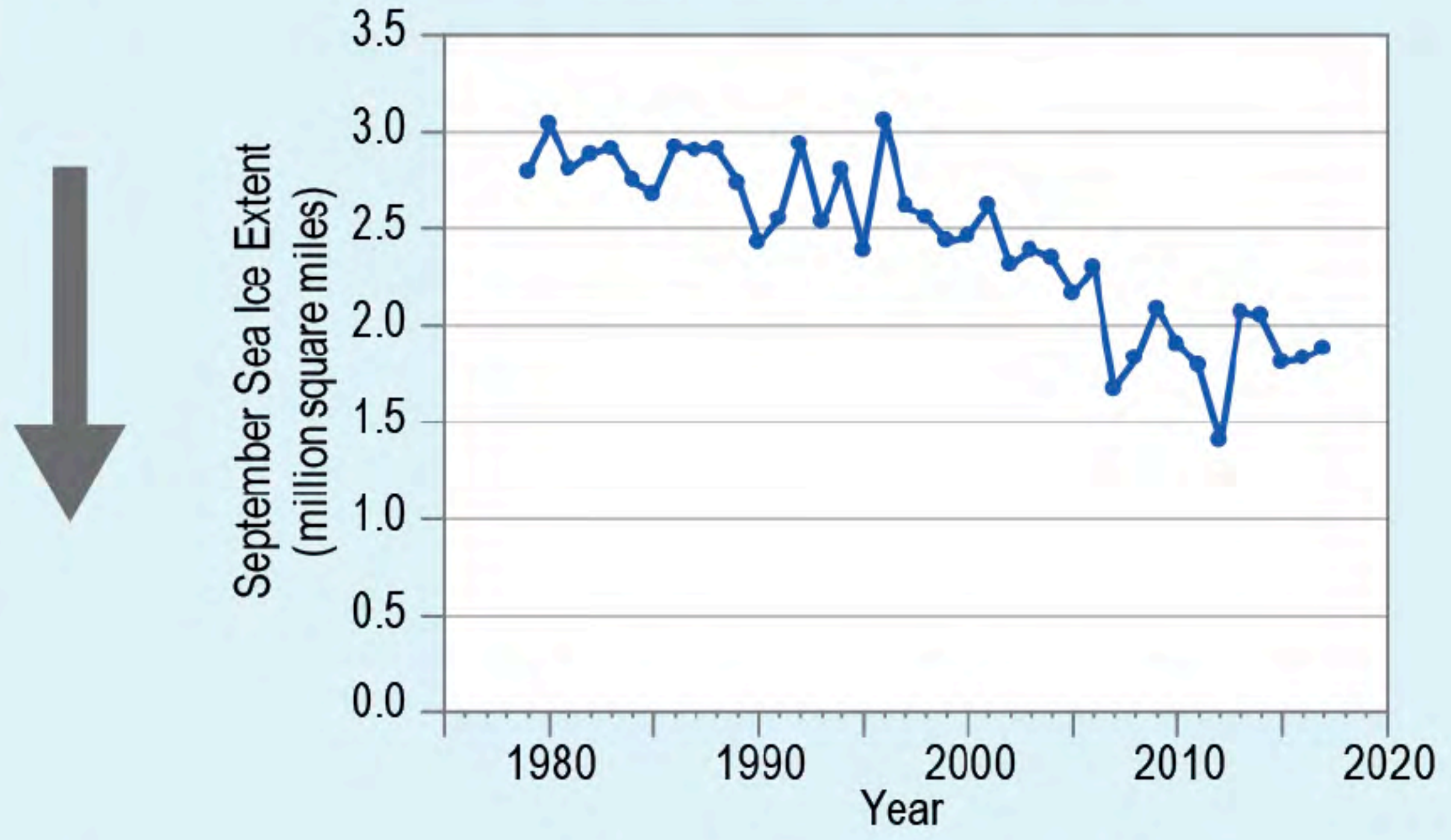


SNOW AND ICE

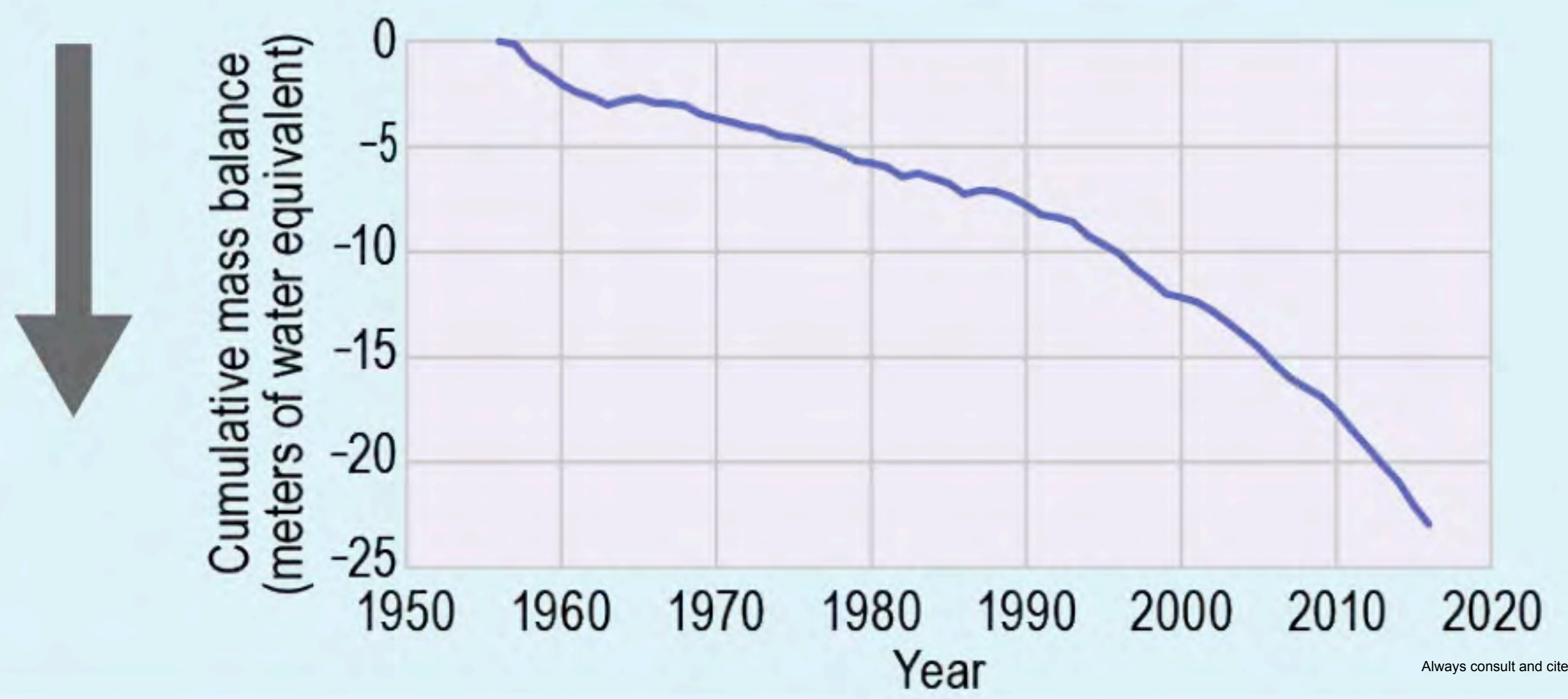
(d) Western U.S. Snowpack



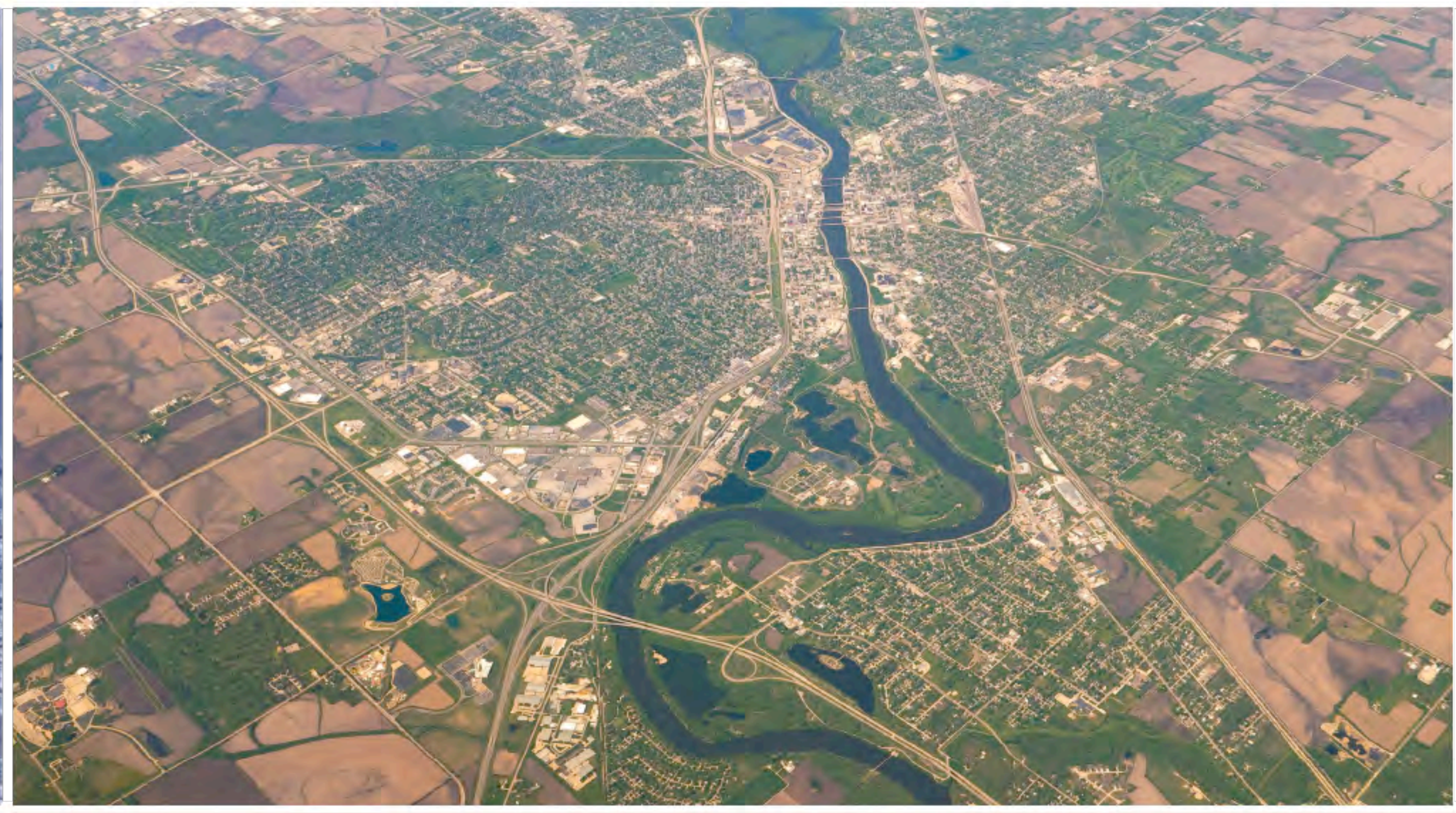
(e) Arctic Sea Ice Extent



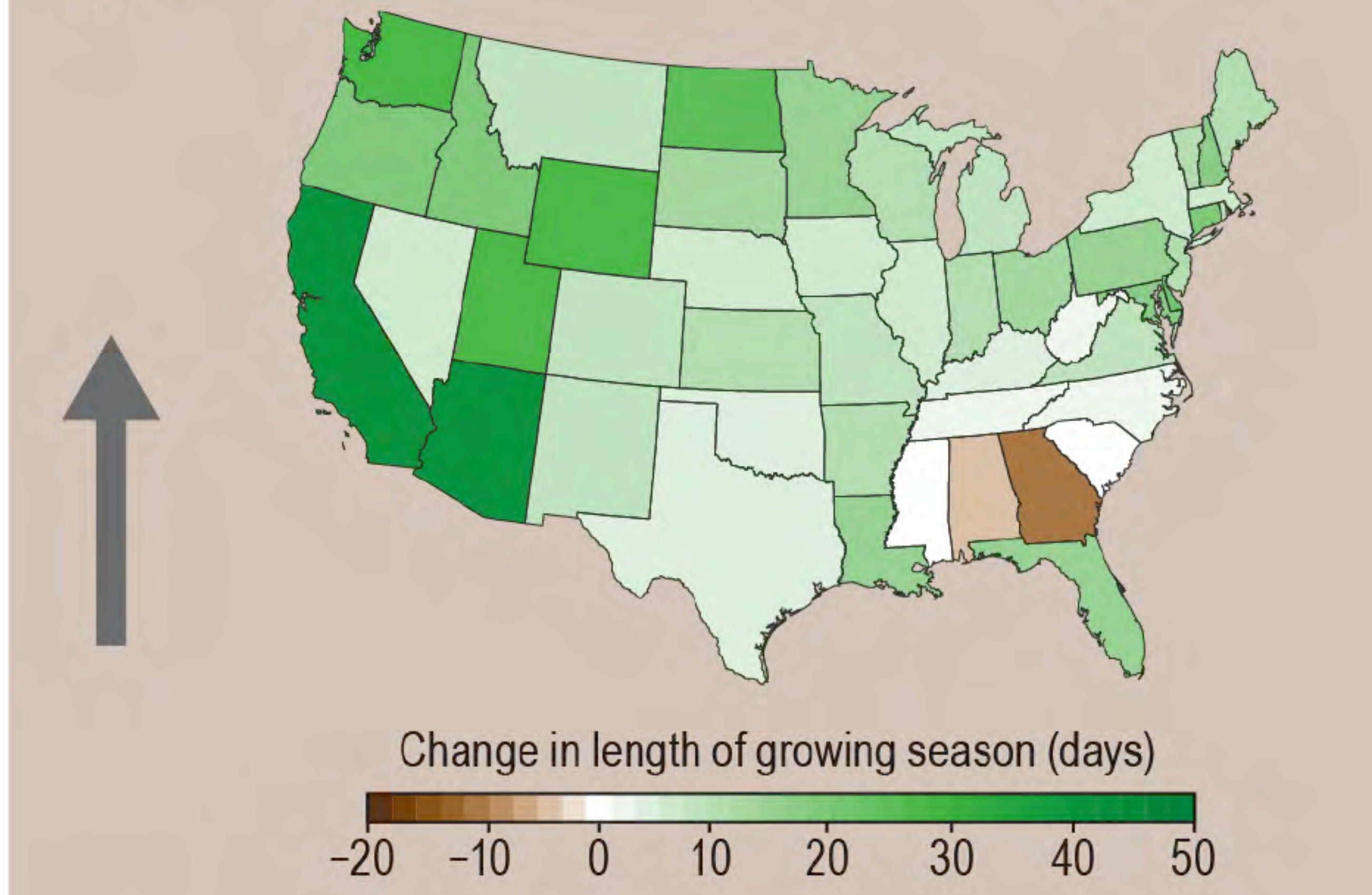
(f) Global Glacier Mass Balance



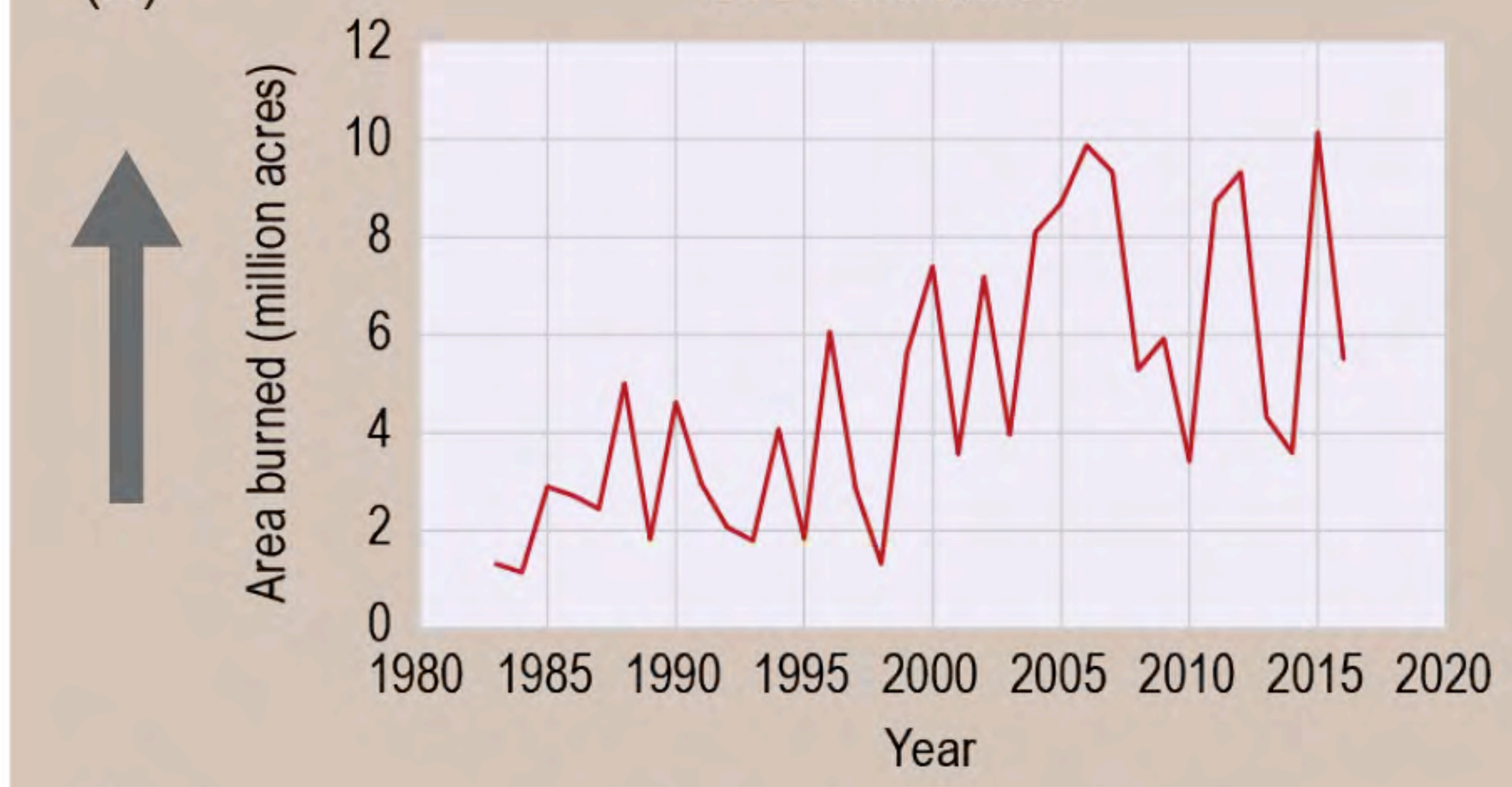
LAND AND WATER



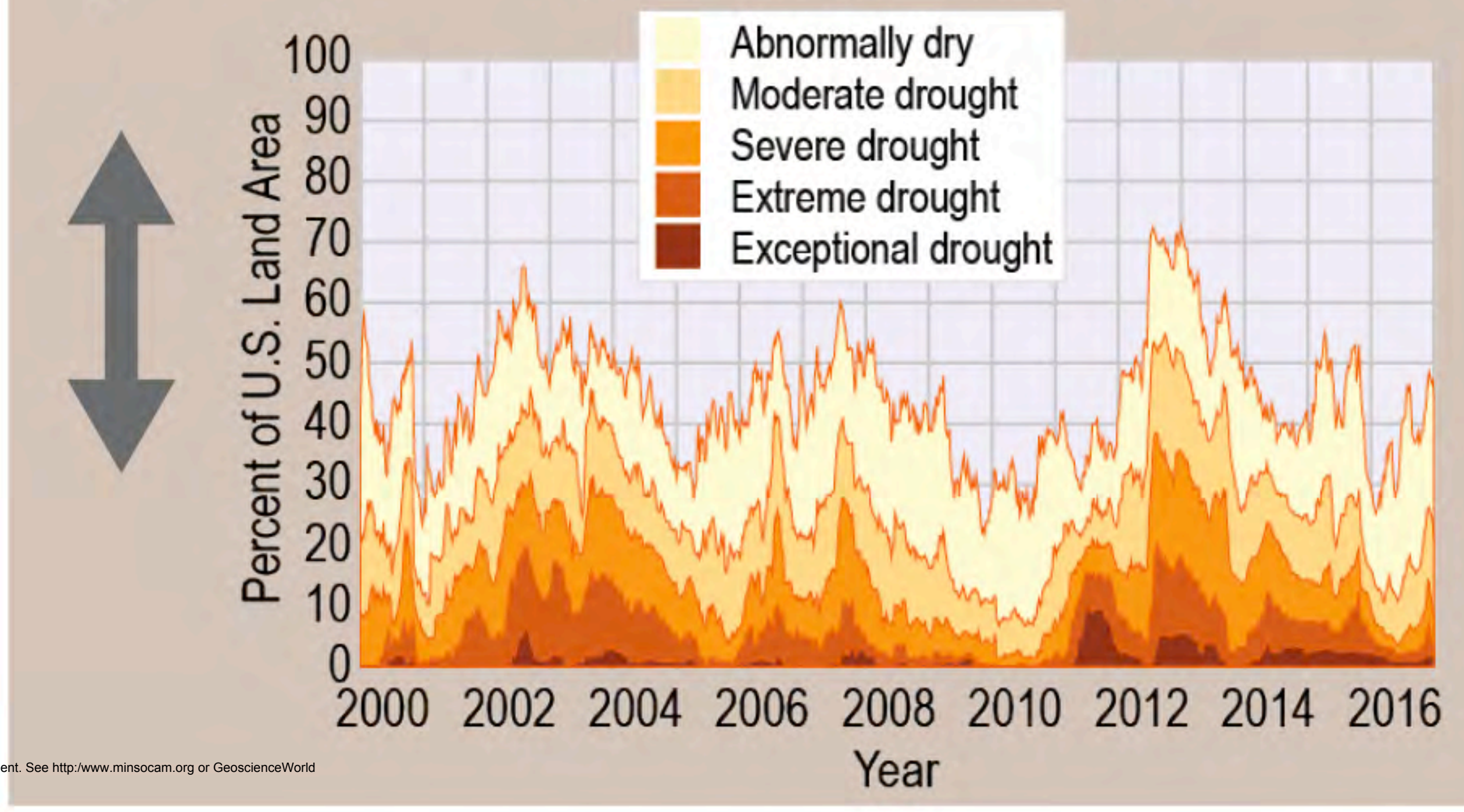
(g) U.S. Growing Season Length



(h) U.S. Wildfires

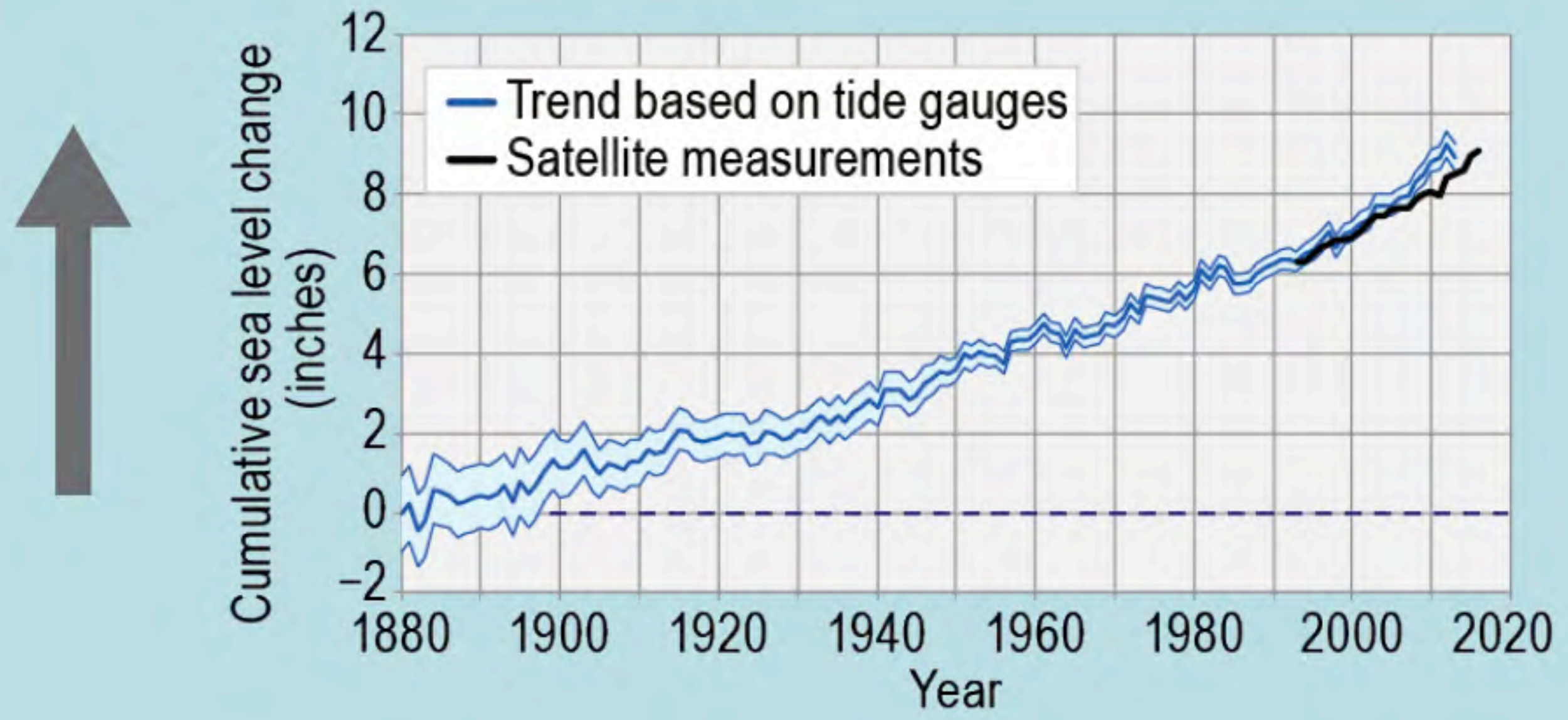


(i) U.S. Drought Conditions

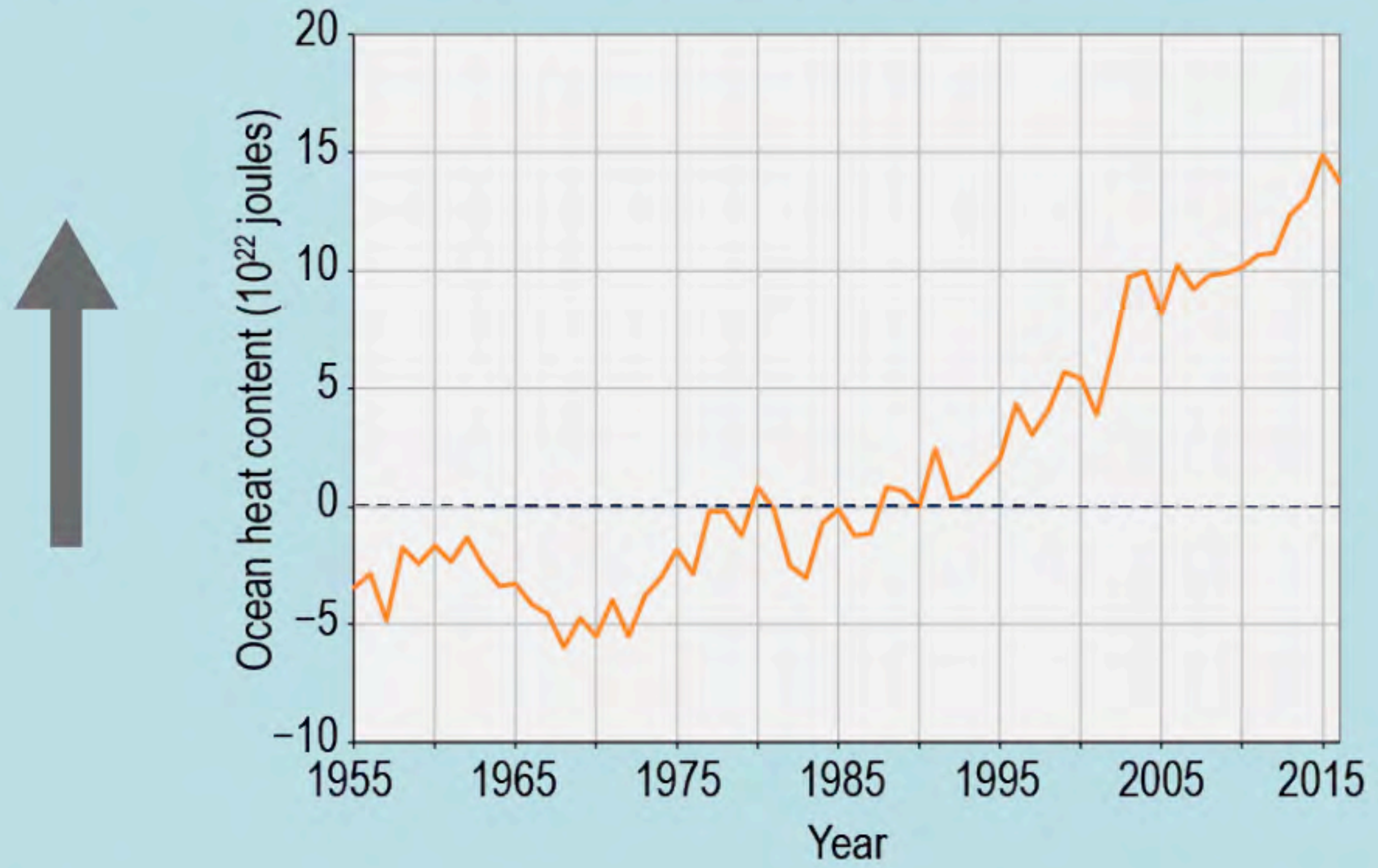


OCEANS AND COASTS

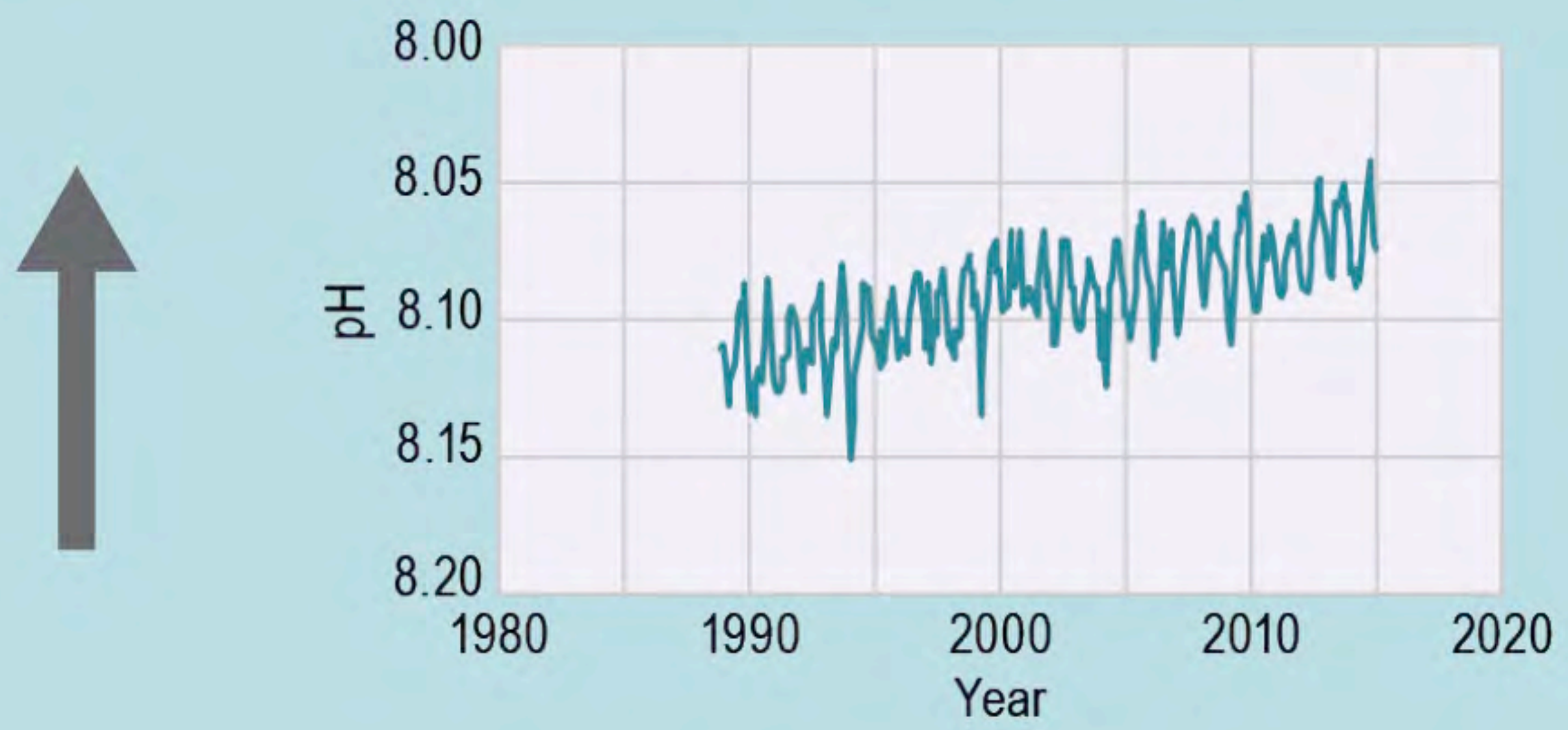
(j) Global Sea Level

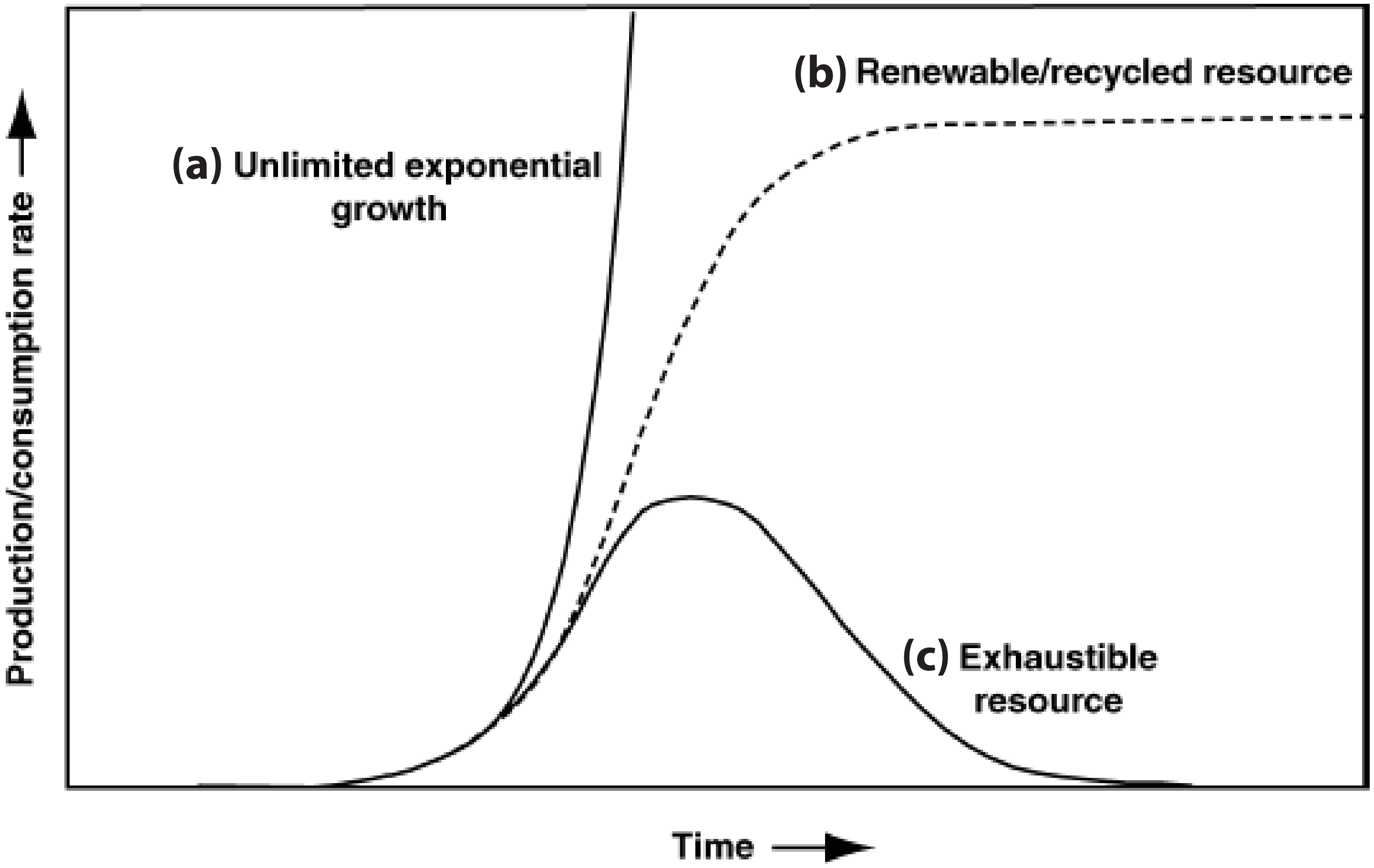


(k) Global Ocean Heat Content



(l) Hawai'i Ocean Acidity




(a) Unlimited exponential growth
(b) Renewable/recycled resource
(c) Exhaustible resource
Production/consumption rate
Time