The Precarious Present;
Is Global Warming Inhibiting an Incipient Ice Age?

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Abstract

The amplifying climate fluctuations of the past 3Myr indicate that an Ice Age is imminent, except that the current rise in atmospheric CO_2 levels is inducing global warming. Forecasts of future developments by means of climate models, a reductionist approach, have significant uncertainties. Empirical predictions are also inadequate because an explanation for Ice Ages is lacking, a consequence of the questionable assumptions that polar glaciers respond primarily to local sunlight, and that the ocean obligingly provides them with fresh water which the atmosphere passively transports from low to high latitudes. These objections draw attention to the global structure of Milankovitch forcing whose main components pose the following questions. (a) How does precession, which merely redistributes sunlight over the course of a year without changing the annual average induce a 20Kyr signal? (b) How do 40Kyr obliquity oscillations, which merely redistribute sunlight spatially without changing the global average, induce 40Kyr oscillations in globally averaged temperature? (c) Could the alternating warming and cooling trends of the saw-tooth signal of the past .8Kyr, and the preceding cooling trend from 3 to 1Myr, be a natural (as opposed to forced) climate mode with feedbacks sustaining trends which thresholds reverse? (The signal would be irregular, except that Milankovitch forcing is the pacemaker of its thresholds.) This reassessment of studies of past and present climates leads to tentative explanations for Ice Ages, offers a strategy for improving climate models, and predicts that rising CO_2 levels will restore the "permanent" El Niño of 3Myr ago.

Significance

Early studies of the Ice Ages regard polar glaciers as isolated phenomena waxing and waning in response to local summer sunlight variations. The more plentiful data available today indicate that glaciers are members of a large cast of interacting global phenomena whose fluctuations have three prominent spectral peaks. The interpretation of the data as the constantly changing superposition of this trio of cyclic signals calls for a new taxonomy of Ice Ages, contributes to the resolution of disputes about the climate at certain times in the past and today – why the ITCZ is north of the equator; whether El Niño can be "permanent" -- and identifies tests for improving climate models that predict the consequences of rising atmospheric CO_2 levels.

1. Introduction

The dramatic amplification of climate fluctuations over the past 3Myr (million years) in fig.1a,b has brought planet Earth to a precarious moment in its eventful history (1). That graph gives the impression that the next Ice Age is imminent, except that the sharp rise in atmospheric CO_2 levels over the past century (fig.1c), an inadvertent byproduct of our recent technological advances, is causing global warming (2). How will the global climate change over the next several decades? An empirical answer builds on Milankovitch's seminal proposal that glaciers wax and wane in response to variations in northern summer sunlight, often taken to be sunlight at 65^0N on 21 June (3). The discovery that the periods of oscillations in Earth's orbital parameters (and hence sunlight) coincide with the periods of the three prominent cyclic signals in records such as fig.1 at first seemed to confirm Milankovitch's hypothesis because those periods of 20, 40 and 100Kyr approximately, correspond to changes in Earth's orbital parameters, precession and obliquity of the axis of rotation, and the eccentricity ε of the orbit. Changes in ε have such a small effect on Earth's incoming energy that they are unlikely to account for the third and most energetic of the three cyclic signals, the one with the shape of a saw-tooth: the brief warming trends that alternate with longer cooling trends in fig.1b. Hayes, Imbrie and Shackleton (4) therefore proposed that Milankovitch forcing amounts to a pacemaker for the timing of the recurrent saw-tooth which involves variations in CO_2 levels. The available data can, in principle, be used to infer future climate changes in response to the current rise in CO_2 levels. However, uncertainties are large because "*...we still lack a unified mechanistic understanding that links changes in Earth's orbit to the Ice Ages*" (5) and there is *"no apparent template for the shape, amplitude, duration, or spatial pattern of an interglacial"*(6). Accurate predictions of future climate changes using empirical methods are not available yet. An alternative approach is reductionist; it appeals to the laws that govern Earth's climate expressed as mathematical equations which are solved by considering a hierarchy of models.

The most complex (comprehensive) models, which take interactions between the atmosphere, ocean and land surface into account, have flaws. A study of the past 10Kyr reveals the "Holocene conundrum": an incipient Ice Age around 6Kyr ago is evident in data, but is absent from models (7). Simulations of Earth's current climate reproduce several aspects realistically, but the models have generated disagreements about the possibility that El Niño, currently a transient visitor, could become a "permanent" resident (8,9), and about the factors that influence movements of the ITCZ (Intertropical Convergence Zone) of heavy rainfall over the warmest surface waters. Does the northerly position of the ITCZ in the Pacific – see fig.2 – stem from the influence of continental geometry on atmospheric winds and oceanic currents (10), or is it a consequence of Earth's global energy budget (11,12,13)? As regards global warming because of rising atmospheric CO_2 levels, there is "*deep dissatisfaction with the ability of our models to inform society about the pace of warming, how this warming plays out regionally, and what it implies for the likelihood of surprises"*(14). The history of weather forecasting provides guidance on how to proceed when both empirical and reductionist methods fail.

Up to World War II weather prediction was an holistic exercise in identifying evolving "highs" and "lows," warm fronts and cold fronts, in complex maps drawn on the basis of data collected over huge areas. Entirely different reductionist methods for forecasting weather became available in the early 1950's after the invention of electronic computers capable of solving the equations (laws) that govern atmospheric motion. The limitations of the early computers necessitated a simplification of the equations to gain an understanding of the cause of weather, and of its limited predictability. Subsequently an enormous increase in computer power, and the deployment of huge networks of instruments that monitor atmospheric conditions world-wide contributed to impressive progress in the accuracy of weather forecasts. Today mayors order the evacuation of cities if hurricane forecasts indicate a need to do so; that was not the case a few decades ago. This success depends on the marriage of holistic and reductionist methods, a marriage so successful that computer models, whose development depends on observations, can detect errant observations. That achievement is impressive, but accurate forecasts are limited to a week or two because of the "butterfly effect" which inevitably amplifies tiny errors. Long-term predictions are nonetheless possible by taking advantage of cyclic signals, the climatological seasonal cycle for example. A description of what all Januaries, Februaries etc. have in common permits an empirical prediction, in January, of conditions in June. The prediction is the same for every future June, but in reality each June is wetter or drier, warmer or colder than others. Can climate models do better?

A reductionist approach to this question starts with a simple model for the seasonal cycle: local sunlight variations cause summer to be warm, winter to be cold. The model also explains why seasonal temperature fluctuations are negligible in Honolulu, large in Chicago: the heat capacity of the vast ocean surrounding one city is huge; that of the continent surrounding the other city is small. Despite these successes, the model fails to account for the different seasonal cycles of New York and San Francisco which, at approximately the same latitude, receive the same sunlight. An improved model that includes an atmospheric circulation -- westerly winds blow over the ocean to reach San Francisco, then blow over a wide continent to reach New York -- reduces discrepancies between observations and theory. This is merely a prelude to a model that does even better by including the oceanic circulation that brings cold water to the shores of California because of upwelling, and warm water to the east coast of north America because of the Gulf Stream. The next model in this hierarchy permits the atmosphere and ocean to interact by means of feedbacks, thus generating climate variability neither the atmosphere nor the ocean on its own can produce. Those feedbacks contribute to the striking asymmetries of the tropical climate of today in fig.2.

In the Pacific SST is higher in the west than the east along the equator, and the warmest water in the east is north rather than south of the equator. This SST pattern produces the rainfall pattern in fig.2 because tropical trade-winds winds converge onto regions of high SST, causing moist air to rise into cumulus towers that produce heavy rains. Much of that air subsides over the adjacent stratus-cloud-covered regions of low SST and low rainfall. The atmospheric circulation not only depends on the SST pattern, but also contributes to its creation by driving the oceanic circulation which maintains the thermocline whose undulations determine the SST pattern. (Where the thermocline is deep, SST is high, where shallow, SST is low.) This circular argument -- SST patterns influence and also depend on the atmospheric circulation -- implies that the ocean and atmosphere interact to produce the patterns in fig.2 whose variability includes El Niño, La Niña (15,16), the Indian Ocean Dipole (17), and Pacific Decadal Variability whose description suffers from a paucity of measurements (18). That lack of data handicaps the development of climate models. The models, to cope with complex phenomena such as clouds, their Achilles' heels, have to be "tuned" by means of approximations and simplifications. The current seasonal cycle is inadequate for that purpose, but the range of possible seasonal cycles is wide because of variations in the tilt of Earth's axis, the precession of that axis, and the eccentricity of the orbit. This approach calls for new questions concerning the Ice Ages.

Why do glaciers wax and wane? For more than a century this has been a profitable question to explore, but a focus on polar glaciers that respond mainly to local summer sunlight variations is a drawback. The proposal that Milankovitch forcing serves as a pacemaker for Ice Age cycles (4) implies that those cycles are part of natural climate variability. That variability has a broad spectrum because it depends on interactions between the swift atmosphere, slow ocean and slothful glaciers. These adjectives refer to the adjustment-times of the three different media to changes in their respective forcing functions. The global atmospheric circulation responds swiftly, within a matter of weeks, to changes in the temperature gradient between the poles and the equator, and between land and sea. The ocean takes far longer to adjust to changes in atmospheric conditions -- the winds etc. -- because it depends on slow planetary waves whose speed increases with decreasing latitude. Equatorial oceans therefore adjust relatively quickly and can interact with the atmosphere to produce high frequency phenomena such as the adiabatic interannual oscillations between El Niño and La Niña in fig.3a. The diabatic fluctuations between El Padre and La Madre in fig.3b have far longer timescales because they require that the global oceanic circulation redistribute the warm water above the thermocline. From this perspective a world without Milankovitch forcing has a broad spectrum of climate variability that, at low frequencies, includes recurrent Ice Ages, albeit irregular ones. The few narrow peaks that Milankovitch forcing contributes to the broad spectrum of variability can test the validity of theories and models of the natural variability. (The peaks can serve a function similar to that of tidal peaks in spectra of sea surface height variations: tides can test theories for the adjustment of oceanic currents to changes in the winds by means of equatorially and coastally trapped waves.) These arguments indicate that the original question concerning the response of polar glaciers to local sunlight has too narrow a focus and should be replaced with the following questions:

A. Can the saw-tooth, the most energetic of the three cyclic signals of the past 3Myr, be a natural climate mode that depends on feedbacks to sustain alternating trends which thresholds reverse? Does Milankovitch forcing serve as pace-maker for thresholds?
B. How do 40Kyr obliquity oscillations, which merely redistribute sunlight spatially without changing the global average induce 40Kyr oscillations in globally averaged temperature? Why is the phase of that signal such that tropical SST has a minimum when obliquity favors intense sunlight in low latitudes?
C. How does precession, which merely redistributes sunlight over the course of a year without changing the annual average -- it amounts to forcing at the high frequencies of the seasonal cycle -- nonetheless induce a recurrent signal with a timescale on the order of 20Kyr?

To answers to these questions this paper builds on that of Zachos et al (19) and briefly reviews the available observational and theoretical studies of the climate variability of today, and of the past 3Myr. Section 2 adopts a reductionist approach and considers a world with a diurnal cycle, but with neither seasons nor Milankovitch cycles. The response to precisely-known external forcing, obliquity and precession, discussed in sections 3, provides tests for the validity of the results in section 2. Each of the three prominent cyclic signals in the climate records has distinctive properties. Because their superposition changes continually, the three amount to a template for interpreting records such as fig.1, and provide numerous tests for the improvement of climate models. The holistic approach of section 4, and a new taxonomy for Ice Ages, facilitate identification of these tests. Section 5 concerns the limitations of a strategy based on cyclic signals.

2. Natural Climate Variability

The Earth without Milankovitch forcing -- it rotates around an axis at a fixed tilt once a day, and orbits the Sun in a circle once a year -- has a global atmospheric circulation driven by equator-pole sunlight gradients. It features easterly tropical winds that converge onto the ITCZ where air rising into cumulus towers produce heavy rainfall. Some of the air, after subsiding over the subtropical deserts, continues poleward, transporting heat and moisture, first from low latitudes to westerly Jet Streams in mid-latitudes, then to higher latitudes by means of chaotic weather phenomena attributable to instabilities of those jets. This circulation intensified around 3Myr when the appearance of polar glaciers increased the pole-equator temperature gradient. From 3Myr onwards the albedo feedback of glaciers contributed to the cooling trend in fig.1, and to the growth of glaciers until they were so enormous that geothermal heat from below destabilized them, causing them to break up. This happened around 1Myr ago whereafter Ice Ages were recurrent and acquired the shape of a saw-tooth because snow accumulates slowly, melts more rapidly. Thus can an atmosphere over a stagnant ocean explain some of the features of the fluctuations in fig.1, but the appearance of cold surface water in tropical upwelling zones around 3Myr, and the subsequent rate of prolonged cooling in fig.1 require a more realistic model, one that allows the atmosphere to interact with an ocean in motion.

The salient feature of the oceanic thermal structure, the zone of sharp vertical temperature gradients that separates cold, dense water at depth from warm surface waters, has undulations that are reflected in the SST patterns of fig.2. (Where the thermocline is deep, SST is high, where shallow SST is low.) The oceanic circulation that maintains the thermocline has the two components shown schematically in fig.4. One shallow and wind-driven, the other is deep and thermohaline. Water in the deep ocean is so uniform in temperature and salinity that it must have its origin in a few small surface regions in high latitudes where cold, saline water sinks into the abyss. The deep water has to return to the surface, but where it does so was at first a puzzle. Downward diffusion of heat has to warm up cold water that rises to the surface, but in most of the ocean the measured diffusivity is too small for this purpose, by an order of magnitude (20). It is mainly in the Antarctic Circumpolar Current where the stratification of the ocean is very weak that deep, cold water rises into the surface layers and then flows back to regions of sinking in wind-driven currents. Both the shallow and deep components of the circulation have meridional overturning components, the conveyor belts in fig.4. They are intriguingly different in the three ocean basins. Whereas the Atlantic Ocean has both deep and shallow meridional over-turning components, the Pacific has only the shallow one, and the Indian Ocean has neither. These differences between the three ocean basins are consequences of the dependence of oceanic density D on temperature T and salinity S:

$$D = 1 - \alpha T + \beta S \qquad \text{so that} \qquad \Delta D = -\alpha \Delta T + \beta \Delta S \tag{1}$$

where α and β are positive constants. In fig.4 the cold water that wells up to the surface at the equator increases its temperature as it flows to P and also increases its salinity because of evaporation. The highest salinities today are at the surface in the subtropics (around P) where rainfall is minimal. Further north, increasing rainfall decreases surface salinities and hence density, but falling temperatures counter that tendency. In the Atlantic today rainfall patterns are such that the cold, saline water that arrives at Q is sufficiently dense to sink into the deep ocean. The Pacific is different. Heavy rains over its north cause the density difference $\Delta D = 0$ between P and Q so that there is no sinking of surface water into the deep ocean at Q. The Indian Ocean does not extend sufficiently far north for there to be latitudes P and Q, but intense wind-stirring brings cold water to the surface off northeastern Africa where it gains heat from the Sun before drifting southward in the Agulhas Current. In the Pacific and Indian Oceans the water below the thermocline has its origin in the Antarctic Circumpolar Current, not at the surface in the north somewhere. Today only the Atlantic has cold saline water sinking into the deep ocean in the far north. If fresh water were to flood the northern Atlantic, either because of higher rainfall or because of the melting of glaciers over Greenland, then the Atlantic's deep thermohaline circulation could shut down and that ocean will become similar to the Pacific today where heat transport depends on wind-driven currents.

Westerly winds in mid-latitudes, and easterly winds in the tropics exert on the ocean a torque that drives gyres which include intense jets such as the Kuroshio Current and Gulf Stream. Fig.5 shows the Pacific gyres and their meridional over-turning cells as the trajectories of a few water parcels over a period of 30 years (21). The parcels start at the surface in extra-tropical subductions zones where convergent Ekman drift facilitates downward motion (subduction) along surfaces of constant density to depths of about 200m. Some parcels flow northward in the intense Kuroshio, some equatorward. They take a few decades to complete a circuit. Mixing processes are minimal during the subsurface part of the journey except when the parcels return to the surface in intense currents, such as the Equatorial Undercurrent, whose strong vertical shear is associated with mixing that increases the temperature of the water as it rises. The ocean gains heat in such tropical upwelling zones and, by means of the conveyor belts, transports that heat to regions of loss in the extra-tropics, mainly where cold continental air blows over warm currents such as the Kuroshio. See fig.2c. In a state of equilibrium the heat gained in the tropical upwelling zones balances the loss in the extra-tropics. Should the loss decrease (because of a warmer atmosphere for example) then warm water accumulates in the tropics so that the thermocline deepens until loss and gain are again in balance (22). This influence of extra-tropical conditions on the depth of the tropical thermocline, and on SST patterns brings feedbacks into play.

The tall cumulus towers over regions of high SST, and the low stratus decks that cover cold, tropical upwelling zones, involve different feedbacks. One is associated with the release of latent heat when water vapor condenses into raindrops in cumulus clouds, intensifying the low-level winds that converge onto the regions of high SST. An entirely different feedback involves the highly reflective stratus clouds over the tropical areas of low SST, subsiding air and low rainfall in fig.2. The descending air creates a temperature inversion that favors these clouds which shield the ocean from sunlight, thus lowering SST, and strengthening the temperature inversion. The joint albedo feedbacks of polar glaciers, and tropical stratus clouds sustain the cooling trend from 3 to 1Myr, and lead to thresholds

The growth of glaciers inevitably caused them to become so huge that geothermal heat destabilized them. Enormous glaciers imply high oceanic salinity. What happens when fresh water from melting glaciers floods the saline ocean? Could the absence of a surface density gradient all the way from the equator to Q in fig.4 shut-down, not only the deep conveyor belt, but the shallow one too? The answer in fig. 6 shows the consequences of increasing the flux of fresh water onto the ocean surface in an idealized model of wind-driven surface currents (23). In that model, freshening of the surface water leads to a threshold for the oceanic circulation, between points A to B. At B the poleward transport of heat has collapsed so that the heat gained accumulates in low latitudes and deepens the thermocline. This deepening is diabatic, in contrast to the deepening during El Niño. The density difference $\Delta\rho$ across the thermocline determines its depth which depends on the deep thermohaline circulation on centennial timescales, and on the shallow wind-driven currents on decadal timescales. (The wind-driven currents penetrate to the ocean floor and there is no thermocline when $\Delta\rho = 0$.) Changes in oceanic salinity on millennial timescales, associated with the saw-tooth signal of glaciers that wax and wane, affect both the wind-driven and deep thermohaline circulations, and hence the depth of the thermocline (23).

Ocean-atmosphere interactions create the east-west asymmetry of the tropical Pacific in fig.2, and also its north-south asymmetry in the east where the ITCZ is north of the equator. In a world without Milankovitch forcing, the ITCZ, when displaced from the equator into one hemisphere, remains there because the cross-equatorial winds that converge onto the ITCZ induce upwelling and low SST on the other side of the equator (24,25,26). In a world symmetrical about the equator, the ITCZ can be in either hemisphere, but it is currently north of the equator in the Pacific, possibly because of geometry: the inclination, to meridians, of the western coast of the Americas. That inclination causes the northeast and southeast trade winds that converge onto the ITCZ to favor coastal upwelling and cold surface water south rather than north of the equator -- see fig.2 – provided the thermocline is sufficiently shallow for the winds to bring cold water to the surface. These arguments have generated debates that, in part, stem from poor nomenclature: the term ITCZ for the collection of all tropical convective zones with heavy rainfall. In reality the seasonal movements of the ITCZ over the Americas – it follows the Sun in migrating back and forth across the equator – are divorced from ITCZ movements over the adjacent Pacific when a shallow thermocline brings ocean-atmosphere interactions into play. Additional factors that influence ITCZ movements include the energy budget of planet, and the relative roles of the oceanic and atmospheric circulations in balancing that budget (11,12,13).

These results concerning climate variability in the absence of Milankovitch forcing assist the interpretation of paleo-climate records. During the Cenozoic the decrease in atmospheric CO_2 levels associate with the drifting of continents induced global cooling that was greater in high than low latitudes. The surface temperature in polar region determines the temperature of the water in the deep ocean everywhere, including the tropics. However, if tropical surface water, under the influence of the local atmosphere, cools less than the water at depth, then the density difference $\Delta\rho$ across the tropical thermocline increases. This decreases the depth of penetration of wind-driven currents and the thermocline rises. Over the past 50Myr, as the temperature of the water in the deep ocean decreased by 12^0C (27), the increase in $\Delta\rho$ elevated the thermocline until, around 3Myr ago, it was so shallow that cold surface waters appeared in tropical upwelling zones, around the time glaciers appeared on northern continents. Polar glaciers and cold, cloud-covered tropical upwelling zones are partners and, from 3Myr onwards, accelerate the elevation of the thermocline, expanding the upwelling zones as the glaciers grow in size. The rising thermocline lowers SST in the eastern but not the western equatorial Pacific. See fig.7 (28). As SST in the eastern equatorial Pacific decreases, so does SST in mid-latitudes (29), consistent with the argument that the shallow wind-driven oceanic circulation in fig.6 contributes to a balanced heat budget for the ocean. The trends from 3Myr onwards lead to thresholds during the MPT (Mid-Pleistocene Transition) from 1.2 to .7Myr: huge glaciers become unstable; high oceanic salinities permit a flux of fresh water to disrupt the heat transport of wind-driven currents; low temperatures in the deep ocean approach the freezing point of saline water and terminate the prolonged cooling trend around .9Myr. At such low temperatures the density of sea water depends mainly on salinity and the equation of state (1) is inaccurate (30). A further factor, the rise in atmospheric dust-levels from 3Myr onwards, facilitates iron-fertilization of the oceans especially around Antarctica, and hence affects atmospheric CO_2 levels (31). The results from highly idealized models described thus far provide the following qualitative explanation for the saw-tooth signal composed of trends: the growth and decay of polar glaciers are associated with (i) the intensification and weakening of the atmospheric circulation which contributes to (ii) an increase and decrease in the oceanic loss of heat which induce (iii) the rise and fall of the tropical thermocline and hence (iv) the expansion and contraction of cloud-covered tropical upwelling zones thus reinforcing (v) the waxing and waning of polar glaciers which depend on random atmospheric disturbances and therefore are irregular. The cold phase of the saw-tooth is an abbreviated version of the prolonged cooling trend from 3 to 1Myr, and has the ocean losing heat to the atmosphere so that the thermocline rises. During the warm phase the thermocline deepens, but this is not necessarily the opposite of the cold phase because the wind-driven circulation (fig.6) collapses when enough fresh water overflows the saline ocean (23).

3. Obliquity and Precession Signals

Forcing at a period of 40Kyr is sufficiently long for glaciers to wax and wane, and for the ocean to approach a balance between the heat lost and gained across its surface. The oceans are slow to respond, the torpid glaciers even slower, so that 40Kyr oscillations in global ice volume should lag behind those in equatorial Pacific SST. In the observations SST does indeed lead by several thousand years (32). Further tests for the theoretical results are the interactions between the jagged saw-tooth and the smooth obliquity oscillations. The two signals have much in common because their timescales are sufficiently long for both signals to be subject to the constraint of a balanced oceanic heat budget on which the climate mode in fig.3b depends. The albedo feedbacks that sustain the prolonged cooling trend from 3Myr onwards, amplify the superimposed 40Kyr oscillations. The 40Kyr oscillations have such a large amplitude by the time of the Mid-Pleistocene Transition (MPT), that they interact with the saw-tooth signal that emerges during the MPT. They become the pacemakers of the thresholds that reverse the saw-tooth trends. Over the past 2Myr, a remarkable 33 of the 36 most recent major Ice Ages terminated when Earth's obliquity was increasing (33). Histograms show that the saw-tooth recurs every 80 or 120Kyr (34). This is possible because several different thresholds can terminate a trend (as mentioned in section 2.) The 100Kyr peak in spectral analyses of climate records can therefore be a consequence of data that resolve 40Kyr signals poorly. Another possibility is that the 100Kyr signal stems from variations in the eccentricity of Earth's orbit which modulates precession.

Precession signals require a nonlinear seasonal cycle. In the case of monsoonal rains over tropical landmasses, the nonlinearity comes from heavy rains in summer when sunlight is intense, and light rains or none in winter when sunlight is weak. The annual average of rainfall then depends on summer (not annually averaged) sunlight. Perihelion in summer intensifies sunlight, and rainfall too, but the weak sunlight when perihelion is in winter some 10Kyr later has little effect on the low rainfall in that season. Hence rainfall records have a 20Kyr cycle (with a 100Kyr eccentricity modulation) that is correlated with variations in local summer sunlight. An example is the record from the San Bao caves in southeastern China (31^0N,110^0E) in fig.8 (35). According to this explanation, the precession signal in records of monsoonal rains should be out of phase in the two hemispheres. (Summer in one hemisphere coincides with winter in the other.) Such anti-symmetry relative to the equator is evident in some records (36), but exceptions include the rainfall record in Chinese loess from 34^0N,107^0E which resembles records of global ice volume and is poorly correlated with rainfall records from the nearby San Bao caves in fig. (37). Does this imply that rainfall over southeastern China depends on the response of polar glaciers to the precession component of local sunlight variations, often taken to be sunlight on 21 June at 65^0N? Slothful glaciers are less likely to respond to local forcing at the high frequencies of the seasonal cycle than to "integrated summer insolation" which filters out precession (38). Despite this argument the global ice volume records have precession signals, albeit sporadic ones. A solution to this puzzle can be found in the eastern equatorial Pacific where the currently nonlinear seasonal cycle of SST implies a local precession signal that is evident in paleo-climate records, albeit one that is present on some occasions, absent on others. The same sporadic signals appear in records of global ice volume. Apparently precession signals from the eastern equatorial Pacific influence the global climate, including polar glaciers. Why are those signals sporadic? Fig.9 has clues.

Today, at the equator, near the Galapagos Islands, SST and rainfall have maxima once a year, around March, even though the Sun crosses twice a year. This is the case in fig.9a but in fig.9b from the central Pacific the seasonal cycle is far more linear than in fig.9a. The reason for this difference is the downward slope of the thermocline depth from east to west because of easterly winds. Calculations with an idealized coupled ocean-atmosphere model indicate that ocean-atmosphere interactions are inhibited when the thermocline is either too deep (so that the equatorial upwelling of cold water is weak), and also when the thermocline is too shallow so that upwelling is overwhelming (39). Hence sporadic precession signals, which depend on a nonlinear seasonal cycle, could be a consequence of changes in the thermocline depth, changes associated with obliquity and saw-tooth signals. This means that the origin of the precession signal with a period of 100Kyr in records of the waxing and waning of polar glaciers could be SST variations in the eastern equatorial Pacific -- they affect the global climate – rather than the precession component of sunlight variations at 65^0N on 21 June. Both precession and obliquity can be pacemakers for the saw-tooth whose period of recurrence can be 80 or 120Kyr (32), and occasionally is 100Kyr.

These considerations answer some puzzles in the records, but several remain. At present sunlight at the equator has maxima twice a year, but what happens when it has a maximum once a year at either the vernal or autumnal equinoxes? This question has been explored with a climate model in which the depth H of the thermocline is that of today, but the effects of changes in H are yet to be examined (40). Although comprehensive climate models have been used to simulate past seasonal cycles at maxima and minima of obliquity (41,42), and in the early Holocene 10Kyr ago (43), the results have not yet been used to improve the models, in part because information about the climate at each of those times is scant. A way to overcome that problem is discussed next.

4. An Holistic Approach

The present climate is one of the brief interglacials that separate prolonged Ice Ages. The Eemian, some 120Kyr ago, is another. Why are the current interglacial more prolonged than the Eemian when sea-level and temperatures were higher than today? Each interglacial is distinct, but they nonetheless have common features. (The same is true of glacial maxima.) A taxonomy for Ice Ages facilitates identification of how they are similar, and how they differ. The one in fig.10a based on MIS, Marine Isotopic Stages uses odd numbers and gray columns to designate periods of deglaciation, even numbers and white columns for periods of glaciation. This is useful for the period 3 to 1Myr when 40Kyr cycles were prominent but once the saw-tooth becomes dominant, the thresholds of its trends are the obvious boundaries between periods of glaciation (in white) and deglaciation (in yellow) in fig.10B. The prelude to a threshold for the deglaciation phase of a saw-tooth starts during its glaciation phase when obliquity is at a minimum. Next the intensification of polar sunlight as obliquity increases, plus geothermal heating from below, gradually overcome the feedbacks that sustain glaciation. After some 10Kyr there is an abrupt transition, from a white to a yellow column in fig.9B, to the deglaciation phase of the saw-tooth. Now the thermocline deepens, atmospheric CO_2 levels rise, and a flux of fresh water onto the ocean surface causes the collapse of the shallow wind-driven oceanic circulation provided oceanic salinity is high enough. The deglaciation continues for about 10Kyr by which time obliquity is at a maximum, and warm interglacial conditions prevail. The subsequent decrease in obliquity elevates the thermocline, reduces SST in tropical upwelling zones, and initiates the onset of a new glaciation phase of the saw-tooth. This cycle of glaciation and deglaciation repeats several times, with variations that depend on factors such as the size of the glaciers when they reach a threshold, and the salinity of the ocean at that time. When glaciers disintegrate, flooding of the saline ocean with fresh water disrupts the wind-driven oceanic circulation and reduces the SST gradient along the equator, to degrees that vary from one deglaciation to the next. In fig.10C the SST gradient along the equator disappears during deglaciation W3 and W7 but not W1. The weakening of SST gradients between Japan and California during W1 (44) indicates that W1 had a spatial structure more complex than W3. The music, a theme with variations, would be entertaining even if Earth's orbit were a circle, but the orbit is an ellipse. This brings precession into play, and enriches the music.

Of the 36 most recent major Ice Ages, 33 terminated when obliquity was increasing. Obliquity is an effective pace-maker of the thresholds of saw-tooth trends because those two cyclic signals both have timescales sufficiently long to be subject to the same constraint: a balance between the oceanic gain of heat in low latitudes, and loss of heat in the extra-tropics. The green column in fig.8B is one of the rare exceptions when obliquity did not serve as a pace-maker. Such isolated events depend on factors that modulate the response to precession: a large eccentricity ε for Earth's orbit, and a thermocline depth H neither too large nor too small in the eastern tropical Pacific. In fig.10B the phase of the green event is earlier in SST than in global ice volume, consistent with the hypothesis that the eastern Pacific SST variations can strongly influence the global climate. Precession rarely induces a warm event such as P in fig.10B, and far more often supplements obliquity as pace-maker of thresholds. Precession has a shorter timescale, 20Kyr, than obliquity and can cause an interglacial to be brief when eccentricity ε is large. That was the case during the Eemian at the end of W3 some 130Kyr ago. Since that time, a decrease in eccentricity has contributed to the current Holocene inter-glacial -- it started 10Kyr ago -- being of longer duration, and having lower sea level and temperature than the Eemian. The taxonomy in fig.10B identifies tests for the "tuning" and improvement of comprehensive climate models.

5. Discussion

Climate variability over the past .8Myr amounts to a theme-and-variations musical composition. The theme, the saw-tooth signal, recurs every 80 or 120Kyr, and interacts with obliquity and precession signals to produce several different variations. The one now in progress started some 20Kyr ago at the time of the Last Glacial Maximum, completed a deglaciation phase that lasted 10Kyr, and is now in the warm, interglacial phase which, in this variation, is more prolonged than the previous one, the Eemian, some 120Kyr ago, because of a decrease in the eccentricity ε of Earth's orbit. Since the beginning of this interglacial, the early Holocene when the Sahara had lakes because perihelion coincided with the northern summer solstice in June, perihelion has drifted from June to early January where it is today. The present climate therefore corresponds to the cold phase of the precession signal and features a desert in the Sahara. Eccentricity ε is small so that termination of the current interglacial and the onset of the next Ice Age now depends on obliquity which, since its maximum 10Kyr ago, has been decreasing. This is elevating the thermocline, and contributes to the cooling that, in some data sets started around 6Kyr ago (7). As obliquity continues to decrease over the next 10Kyr the thermocline will continue to rise, the cold phase of the saw-tooth will come into play, and the next Ice Age will be underway, except that atmospheric CO_2 levels are rising because of human activities.

If the global warming associated with the current rise in CO_2 levels reduces the oceanic loss of heat in the extra-tropics then, over the course of several decades, the tropical thermocline will deepen until there is a renewed balance between the oceanic loss and gain of heat. The result could be a "permanent" El Niño, similar to the one that prevailed up to approximately 3Myr ago. The required increase in the depth of the equatorial thermocline is modest. It can be estimated on the basis of El Niño and La Niña oscillations today. Their effect on SST, by means of thermocline fluctuations, is large in the eastern but small in the western equatorial Pacific because the time-averaged depth H of the thermocline is practically zero in the east, but on the order of 100m in the west. This means that a modest diabatic increase in H -- see fig.3 -- can induce a "permanent" El Niño. Some models succeed in simulating such a climate (45), but some fail, probably because of their poor treatment of clouds. "Tuning" can remedy that flaw.

The strategy of using cyclic signals to test and improve models has advantages – it can explain how both obliquity and precession contribute to spectral peaks at 100Kyr in records of global ice volume; see section 3 -- but also has drawbacks which the climatological seasonal cycle exemplifies. That cycle is a powerful tool for anticipating climate changes years and decades hence because it reduces uncertainties in the description of a particular seasonal cycle, by filtering out of the explicit presence of atmospheric storms. The problem is that the storms transport heat poleward. and thus affect the climatology. Hence studies of the climatology require investigations of storms, hurricanes etc. in particular years to explore the inter-dependence of climate and weather. The low frequency counterparts of weather are the Heinrich, Dansgaard-Oeschger, Younger and Older Dryas events not directly related to Milankovitch forcing. In the same way that an exceptionally intense hurricane can be the distinctive feature of a particular summer, so the Younger Dryas can be the distinctive feature of the deglaciation that started at the Last Glacial Maximum 20Kyr ago. However, that deglaciation is unique for another reason: the superposition of the three prominent cyclic signals changes continually. To what degree do the properties of the those three signals depend on events such as Younger Dryas? Simulations of the past 10Kyr (7), 20Kyr (46), and 130Myr (47) can in principle provide answers.

The different circulations of the Pacific, Atlantic and Indian Oceans are interdependent because they exchange water, salt, energy etc. At present the Pacific absorbs considerable heat in the tropics, loses some of it in higher latitudes, and also exports warm water to the Indian and Atlantic Oceans. How will the rising CO_2 levels affect that state of affairs? Answers are available from models that have been “tuned “ to reproduce the climate of today, but is that “tuning” appropriate for a world with a very different climate, one with a “permanent” El Niño for example? A model should be capable of simulating the climate of today, and various other climates too (48,49,50). Additional tests for the models include the striking differences between the seasonal cycles of the Atlantic and Pacific because of the different dimensions of those two basins. In any ocean a change in the slope of the thermocline along the equator depends on waves that propagate along the equator. The Pacific is so wide that a change is possible interannually, but not seasonally. In the far narrower Atlantic the seasonal cycle near the equator resembles interannual El Niño in the Pacific. This implies a more energetic precession signal in the Atlantic than the Pacific, and could be a factor in heavy rainfall over the Sahara at certain phases of the precession signal. How will obliquity oscillations in the Atlantic affect its precession signal? How will this affect oceanic salinity which is of crucial importance to the deep thermohaline circulation that links the three ocean basins to the Southern Ocean where the exchange of CO_2 between the ocean and atmosphere is particularly large. Studies of that exchange require the integration of physics and biology. An example of such integration in climate studies is the finding that the evolution of baleen whale gigantism coincided with the appearance of nutrient-rich surface waters in low latitudes around 3Myr ago (51). A marriage of reductionist and holistic approaches can answer the puzzles that climate fluctuations of the past 3Myr pose, and can improve the accuracy of forecasts.

Figure Captions

Fig.1(a) A measure of global ice volume fluctuations over the past 5Myr provided by the global benthic $\delta^{18}O$ stack, (2). (b) Fluctuations of the past 400Kyr in (a) with red lines indicating the alternating trends of the saw-tooth. (c) The temperature and atmospheric CO_2 fluctuations over the past 400Kyr, measured in Antarctic ice cores (xx). Human activities cause the red spike at the end of the CO_2 record.

Fig. 2 In the tropics (a) sea surface temperature patterns (^{0}C) are highly correlated with (b) rainfall patterns (mm/day). (c) The flux of heat across the ocean surface.

Fig.3 Schematic of equatorial thermocline displacements involving (a) an adiabatic, horizontal redistribution of warm surface waters (left panel) as occurs during the oscillation between El Niño and La Niña; and (b) diabatic changes in thermocline that can induce El Padre (or permanent El Niño) when the thermocline is deep, and La Madre conditions when the thermocline is shallow.

Fig.4 Schematic of the two main components of the meridional ocean circulation. The red region denotes the domain of the wind-driven circulation, which involves upwelling at the equator, poleward Ekman drift, and subduction in the subtropics with a return flow in the upper 200 m. In the Atlantic the thermohaline circulation has both an upper branch with waters subducting in the far north, travelling southward, and upwelling in the Southern Ocean (*light blue*), and a lower branch with waters downwelling in the southern polar region (*dark blue*).

Fig. 5. The tropical wind-driven circulation. The paths of water parcels over a period of 16 years after subduction off the coasts of California and Peru as simulated by means of a realistic oceanic general circulation model forced with the observed climatological winds.

Fig. 6 Changes in the meridional oceanic heat transport (in petawatts) across a fixed latitude of an idealized model ocean as the flux of fresh water onto the ocean surface increases. That flux measures only precipitation, but evaporation minus precipitation is such that the mean salinity of the surface remains constant. The vertical dashed black lines represent the effect of changes in the mean salinity on the "cliff" between La Madre and El Padre conditions. An increase in mean salinity facilitates a transition to El Padre, causing the dashed black line to move to the left. The bottom panels show the thermal structure in the equatorial plane when El Padre prevails at point A (right panel) and when La Madre prevails at B (left panel). For details see (14).

Fig 7 (Top) SST records in the western equatorial Pacific (red line, ODP site 806) and in the eastern equatorial Pacific (blue line, site 847), both based on Mg/Ca, and that for the eastern Pacific based on alkenones (green dots, site 847). Larger circles are for the data based on Mg/Ca but from ODP sites 806 (red) and 847 (blue). Pink shading denotes the early Pliocene.
(Bottom) Alkenone-based SST records for the California margin (black, ODP site 1014), the Peru margin (blue, site 1237), and the West African margin (green) site 1084.

Fig. 8 A composite record from caves in southern China of variations in $\delta^{18}O$ that provide a measure of rainfall in the area (16). The values of $\delta^{18}O$ are offset by 8.5%0. (b) Sea surface temperature record from the eastern equatorial Pacific (15). (c) Benthic oxygen isotope record, a measure of global ice volume (2).The straight red lines represent trends of the saw-tooth. (d) Normalized insolation at 0^0N, on June 21 (red) and obliquity (black). In (a), (b), and (c) normalized insolation at 0^0N on June 21 is plotted for reference. Time series in (b) and (c) have been normalized.

Fig 9: The seasonal cycle in SST (color), rainfall (contours) and wind (arrows) along 95^0W near the Galapagos Islands where the equatorial thermocline is shallow, and along 140^0W in the central Pacific where the thermocline is deep.

Fig.10 A. Global ice volume as measured in terms of the benthic oxygen isotope stack. The taxonomy known as the Marine Isotopic Stages, uses odd numbers and gray shading to indicate periods of glaciation, even numbers and white columns to indicate periods of deglaciation. Superimposed are obliquity(blue) and precession (red) variations.
B The same graph as in A is here divided into periods of glaciation in white, and deglaciation in yellow on the basis of saw-tooth thresholds. The column with green shading indicates one of the sporadic warm episode induced by precession. Superimposed are sunlight variations at the equator attributable to precession.
C: Sea surface temperatures (Mg/Ca derived) at (top) $0^0$19'N $159^0$21'E (5) and (bottom) $2^0$15'N $90^0$57'W (6).

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