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# A Brief Overview of Global Climate Variability And Its Relation to Dominant Modes of Variability

Paleoclimate records indicate an amazing degree of climate stability over a period of 4.6 billion years, this, despite significant changes in solar luminosity and insolation; despite continental rearrangements and re-positioning; despite the dawn of life and its subsequent profound changes; despite bolide impacts, volcanic outpourings, and methane-clathrate dissolution; despite $CO_2$ levels ranging from less than 200 parts per million to a few thousand parts per million; despite ice sheets and absence thereof; despite changes in ocean circulation and more. Global-mean temperature has remained within an approximate ten-degree Celsius range throughout this time. This observation commands consideration of what might convey this remarkable stability.

While enormous assaults on Earth's system have occurred, feedbacks within the system work to regain stability. The more severe the system upheaval, the more time is required for re-establishing stability, but it does re-establish. Often, profound changes in the biosphere result; these changes often play a role in re-establishing climate stability, likely through their effect on both atmospheric greenhouse-gas concentrations and albedo. Extinctions punctuate the record – five of particular note. Some appear tied to warming; some to glaciations. The perturbation leading to these extreme conditions may be prompted by internal or external forcings. Abruptness of change may be the common denominator; although reaching a threshold of instability is more likely, as most extinctions take place over hundreds of thousands to millions of years. They are rarely rapid events.

The Permian-Triassic-boundary extinction stands as an example. This most devastating of all extinctions was perhaps tied to climate change. Several factors played key roles. Numerous mountain-building events led to the formation of a pole-to-pole super-continent, Pangea. Marine regressions, resulting from the landmass building earlier in the Permian, left exposed large expanses of shelf area, eliminating significant shallow-marine habitat. Oxidation of the buried organic matter lowered atmospheric oxygen levels and generated atmospheric $CO_2$. Voluminous outpourings of lava in Siberia spewed out additional and massive quantities of $CO_2$, increasing radiative forcing further. Atmospheric temperatures increased; oceans warmed. Arid conditions, born of the enormous landmass, reduced weathering rates. Weathering of silicate rock draws $CO_2$ out of the atmosphere. $CO_2$ is also drawn down from the atmosphere by dissolving in the surface ocean. Drawdown into the oceanic sink is further enhanced if surface water is subducted to depth. Warming ocean temperatures, consequent of growing atmospheric $CO_2$ content, reduced the efficacy of both mechanisms; gas solubility lowers with increasing water temperature and deep-water formation is inhibited with warming ocean temperatures. Thermal instability, caused by a warming ocean, likely led to the dissolution of submerged methane-clathrate deposits. From this, more greenhouse warming resulted. Sea level rose, flooding terrestrial habitats. A cascade of chemical events – anoxic oceans, stratospheric ozone destruction, and emissions of reducing bacteria that allowed methane to persist in the atmosphere for a time well beyond its typical residency – conspired together to eliminate 95% of the marine species and approximately 75% of terrestrial species[1]. This was not a rapid change. It had been building for eight millions years before it tipped into a catastrophic condition. But over time the planet rebounded, with some unaffected species surviving and with many open niches for new species. Biologic diversification and tectonic rearrangement ultimately brought this extremely out-of-kilter system back to relative equilibrium. This is an extreme example.

While an example like the Permian extinction captures a disproportionate amount of our attention and overshadows the more subdued history of Earth, it is significant to note that the norm for Earth is stability. Earth has been warm and stable throughout most of its history; approximately 90% of it has been ice-free with sea-levels higher than today's. Punctuating long stretches of warm temperatures and high greenhouse-gas levels were brief episodes of cold, likely related to tectonic and biotic changes.

Time on the order of billions of years is incomprehensible. Focus is easier on the more "recent" history.  Looking to a minor fraction of Earth history, beginning about 59 million years ago (1.28% of Earth's history), Earth began to cool significantly. Prior to this time, fragmentation of Pangea and long, slow continental movements had led to the opening of a circum-equatorial current, contributing to warm, balmy conditions that dominated throughout much of the preceding 100 million years-plus. Soon to follow were other dramatic changes in plate tectonic construction, most importantly, the gradual collision of India with the Asian continent, giving birth to immense topographic highs. This topography not only modified weather systems due to altitude and breadth, but led to significant CO2-drawdown due to chemical reactions resulting from intensified weathering. The present-day Rockies were also under construction. For a time, temperatures and CO2 decreased together, following a roughly correlated pattern.

The Paleocene/Eocene boundary of 55 million years ago, thought to be host to another methane-clathrate dissolution event, of smaller scale than that of the Permian, sharply reversed the cooling trend, albeit geologically briefly.

Ocean circulation changes, likely prompted by continued landmass rearrangement - in particular the isolation of Antarctica approximately 30 mya – likely augmented the CO2 drawdown that had been initially accelerated by enhanced weathering. A circumpolar current around the Antarctic landmass developed. This Antarctic Circumpolar Current (ACC) amplified upwelling in the region, allowing for thermal isolation of the continent, enhanced precipitation, and energized global meridional overturning circulation. Sparse and intermittent ice cover at the South Pole began to alter the formerly ice-free globe. Low latitude tectonic shifts closed off a portion of the circum-equatorial current, adding to the circulation changes. The proto-thermohaline circulation, with deep-water formation in the North Atlantic, got its start about this time. Temperatures continued to cool.

Before it is assumed that temperature patterns exhibit a consistently intimate correlation with atmospheric greenhouse-gas levels, it is worthy to note that at various times in Earth's history, little correlation appears evident between the two parameters. While many caveats plague accurate proxy determination of atmospheric CO2 levels and trends for times beyond a million years ago, it appears that CO2 levels remained fairly high and fairly constant throughout much of the Eocene (55mya to ~ 34 mya). But during this time temperatures trended downward, culminating in a brief, ephemeral glaciation of Antarctica. CO2 levels began to drop considerably during the Oligocene, from ~ 34 mya to 24 mya, yet temperatures were constant throughout much of the period, ending with a pronounced warming (likely related to the strengthening of the MOC) and then a brief glaciation of Antarctica once again.

In similar fashion, little correlation is apparent between CO2 trends of the Miocene and temperature trends of the same period. CO2 levels were relatively low, comparable to those of the Pleistocene (~ 2 mya), yet temperatures were warmer with far less ice cover than those of the subsequent Pleistocene. This observation underscores the fact that CO2 is but one variable governing Earth's climate. Tectonic arrangement, ocean circulation as dictated by numerous variables, topography, ice cover, and sea level are but a few among a long list of complicating factors. They each affect climate directly, as well as through their effect on CO2.

In the intervening years, snow accumulated slowly and inconsistently on the Antarctic landmass. By about 15 million years ago, ice consistently covered Antarctica and continued to accumulate. The Asian Monsoon developed several million years later, followed closely thereafter with ice accumulation on Greenland. Now both poles were glaciated, no doubt increasing regional climate sensitivity at high latitudes. Vegetation changes occurred, reflecting cooling temperatures. But still, CO2 levels remained fairly constant.

Shifts in the Gibraltar region closed the Mediterranean's delivery of saline water to intermediate subsurface zones of the North Atlantic. Emergence and shifting of landmasses created the Indonesian Maritime Continent between the Indian Ocean and the Pacific. The Panamanian Seaway closed. Not unrelated, flow through the Bering Sea reversed direction, to mainly northward. The MOC strengthened significantly. These changes all occurred before or during the early Pliocene.

Some have suggested that the Pliocene – about 4 mya – hosted a weak, but permanent El Nino [2, 3]. El Nino is a tropical Pacific coupled ocean-atmosphere phenomenon, characterized by warm, zonally uniform temperatures across the tropical Pacifc. Weak easterlies and tectonically governed sources of subsurface water that differ from today likely allowed for this presumed invariant condition. Global mean temperatures were, on average, about 3°C warmer than today – much of that increased warmth found at high latitudes. Sea level was about three to five meters higher than today. But this does not describe the El Nino of today. Today, El Nino is the warm end-member of a system that oscillates on an interannual frequency within a spectrum bounded at the other extreme by a cool end-member, La Nina. That system of the Pliocene, if it has been accurately assessed, was hardly variable. How did the ENSO system become variable, alternating between La Nina and El Nino, as it does today?

Changes continued over the next couple of million years. On this narrowing time-scale, tectonic forces played a less dominant role in climate change. Changing orbital parameters, ocean circulation, and greenhouse-gas content were more influential on this time scale, especially with ice cover enhancing climate sensitivity. Obliquity (axis tilt) was low a couple of million years ago. High-latitude waters cooled. The deep waters of the global ocean, fed by the high-latitude waters, cooled; the thermocline shoaled. The polar-equatorial thermal gradient was increasing, enhancing circulation patterns. Strong easterlies developed. The Walker Circulation intensified shortly thereafter, about 1.75 million years ago, marking the beginning of the Pleistocene – the time of Ice Ages. A cooling planet, with a shallow equatorial thermocline, with an equatorial basin width of a size, such that interference between equatorial planetary-scale ocean waves allowed for the growth and decay of ENSO phases, set the stage for, what some would say, became a Pacific tropical control on global climate [4].

Well resolved ice-core records are available for about the last 700,000 years. From this record, data on temperature and atmospheric gas content can be extracted. This proxy evidence shows that atmospheric CO2 levels and Antarctic temperature during this short time frame have shifted with a great degree of correlation. It has long been thought, yet not confirmed, that temperature changes slightly preceded changes in atmospheric CO2 levels, hinting that throughout the Pleistocene, temperature regulated ocean circulation (through sea-ice dynamics possibly), which in turn influenced the carbon cycle, which acted as a positive feedback. It is further postulated that the poles are anti-phased with one another – warmth over Antarctica in synch with cold temperatures in the Greenland region. This is known as the bi-polar see-saw, and is likely a consequence of fluctuating MOC (meridional overturning circulation) strength, influencing both temperatures and atmospheric greenhouse-gas content. Recently analyzed high resolution cores of East Antarctica confirm an anti-phase correlation on millennial time scales, removing speculation that significant ocean-circulation response was confined to the temporally larger glacial/interglacial scales only[55].

While it is not reasonable to compare modern-day climate to climate of 250 million years ago, or even ten million years ago, as boundary conditions are not comparable, and in many cases, are not well resolved, we can come away with awareness that certain processes or conditions are more often correlated with warmth and others with cold. CO2 is not alone in its influence on climate. Over long periods of time (~ $10^4$ – $10^5$ years and longer), tectonics, weathering rates, changes in the biosphere, changes in ocean circulation, and varying orbital parameters compete with or enhance the role of atmospheric greenhouse gases such as CO2. On short timescales – those relevant to mankind – atmospheric and oceanic dynamics dominate in complicating the role of CO2. Changes in clouds - type, vertical and horizontal distribution, phase, nuclei size, dust contamination, and quantity – alter radiative forcing on scales two to three times that of the doubling of CO2. Changes in albedo due to modifications of sea-ice extent and land cover equally compound the complications. Vertical profiles of water-vapor distribution exert an enormous feedback effect, especially at high levels of the troposphere. These water-vapor profiles are intimately and inversely correlated with deep convection in the tropics, the deep convection being a by-product of warming SSTs. Changes in ocean dynamics, involving the complicated flow regimes of ENSO and the MOC contribute further complications to Earth's heat budget. It is clear, no climate forcing or variable can be fairly considered in isolation.

Most changes in climate throughout Earth's history have been slow by human standards; yet there are exceptions. There were extraordinarily abrupt changes during the last glacial period. These abrupt changes, occurring between about 15 and 90 thousand years ago, resulted in regional temperature increases in the Greenland area of 10°C within a matter of a decade or so. Cooling followed at a gradual rate, returning to pre-warming conditions within a few centuries. These millennial-scale interstadial/stadial (warm/cold) events within a glacial episode - Dansgaard-Oeschger events - occurred in succession, each cold event a little colder than the preceding one, reaching a maximum cooling known as a Heinrich event. During the periods of gradual cooling, it appears that downwelling slowed in the North Atlantic and increased off Antarctica. During the Heinrich events, downwelling in the North Atlantic ceased.

It is not a trivial matter to note that such wild temperature swings are not a signature of interglacials. While millennial-scale fluctuations in temperature, winds, and other parameters can be found in the Holocene (current interglacial) record, they are of minor scale – insignificant in comparison to the Dansgaard-Oeschger events. No answer to the conundrum of vastly differing amplitudes of climate response between glacials and interglacials is forthcoming. Could ocean flow patterns associated with ENSO phases play a role in the stability of an interglacial? A key difference between glacials and interglacials is sea level. During glacials, sea level is too low for flow through the Bering Strait. Could this cessation of fresh-water contribution to the Arctic be a clue?

As orbital variations increased solar insolation across the globe, perhaps initiating a rejuvenation of a glacially sluggish MOC and allowing evasion of CO2 from the deep ocean to the atmosphere, augmenting the changes initiated by orbital rearrangements, glacial conditions began to lose their grip on the planet. Deglaciation ushered in relatively rapid temperature increases; yet shortly thereafter, once again fell victim to cooling influences – perhaps MOC-governed. This early Holocene event was the cold period of the Younger Dryas. After a shaky beginning, the current interglacial took hold. A maximum of solar insolation due to a greater axis tilt contributed to warming temperatures. CO2 levels rose from about 180 ppm to 280 ppm. Throughout the first few thousand years of the Holocene, tilt remained high and precessional insolation began to increase, as well. Temperatures as warm as $20^{th}$ century temperatures dominated for thousands of years, between 11 and 5 kya (different regions experienced warmth at different times within this range.). The Arctic was on average 1.5°C warmer than the $20^{th}$ century. Within this time, global mean temperatures were occasionally up to 2°C warmer than those of the $20^{th}$ century. A regional cold event punctuated this mostly warm period about 8 kya. Other than that, warmth was dominant.

Geologically speaking, the entire Holocene has been relatively stable; yet despite the relative stability, these past 10,000 years have not hosted a gradual and linear temperature trend. The record of the current interglacial, while devoid of wild temperature swings that are signatures of glacial periods, shows that the stability, as we define it by societal standards, witnessed during the brevity of a human lifetime, is an illusion. For example, after peak warmth in the early-mid Holocene, a gradual cooling ensued. But, and significantly but, the temperature trend looks more like a roller-coaster track than a slide. Thousand-year-plus warm periods interrupted the cooling trend. These warm episodes were centered at about 4.2 and 1.5 kya. Increasing warmth during the latter warm period likely paved the way for the success of Roman times 200 BC to 200 AD and the Viking colonies on Greenland. These pronounced relative warm periods and the frigid crush of the Little Ice Age from the 13$^{th}$ century to the mid-19$^{th}$ century all appear extreme when examined adjacent to our clement climates of the last 150 years. Variability within the modern-era's century-plus time frame has been particularly damped. Slight deviations of warmth in the 1930s, particularly in the Arctic region (more rapid warming and equal in magnitude to that of today), interrupted by cooling of the 60s and 70s, interrupted again by warming beginning at the end of the 1970s to the end of the late 1990s, followed by a stagnation of temperature increase, are examples of variability that pale in comparison to previous temperature excursions within our warm interglacial - a time of overall relative stability with respect to the glacial periods.

Excursions of the earlier Holocene can be tied to variability of solar output. While orbital parameters are currently coinciding to yield increasingly lower insolation values, solar output variability, separate from orbital configuration, can change on scales from decades to millennia. Can the current Modern Solar Maximum explain a portion of today's warmth? Can the repeated intervals of warming over centuries within an interglacial slowly diminish ice extent; pushing Earth to a threshold condition dictated by rising sea levels and lowered albedo? After all, the last interglacial had sea levels several meters higher than today's. What part of the equation in today's warming is natural? Of course, anthropogenic land-use and trace-gas emissions have added a new wrinkle to the climate regime. How can they be viewed in the context of Earth's climate history? All are good questions to ponder, not capable of being answered here.

Narrowing our view to just our modern-day situation, we stand witness to rapidly changing boundary conditions. Emissions of anthropogenic greenhouse gases have raised CO2 levels by about 35% from the typical interglacial levels within the last 150 years. How does this affect Earth's climate? How might this rapid change affect Earth's feedback systems? If indeed they play a regulatory role, can they respond fast enough to maintain global stability?

One curiosity that stands out in the paleoclimate record is a remarkable stability in the tropics. While some data are subject to revision, the conclusion remains steady, that tropical temperatures varied little over Earth's history while the high latitudes have hosted a broad range of temperatures. Our modern climate behavior does not contradict this finding.

It appears that the ENSO system in the tropical Pacific allows for the maintenance of time-mean thermal stratification through a two-step process of heat accumulation followed by heat export. *Sun '04 and Sun & Zhang '06* [5-6] characterize this collective system as a heat pump that works to regulate stability in the tropical Pacific. Temperature contrast between the western warm pool in the tropical Pacific and equatorial thermocline water in the Pacific is correlated to the frequency and intensity of ENSO phases. Thermocline waters are fed by water subducted at mid-to-high latitudes. With the cooperation of robust easterly winds, this cool thermocline water is upwelled in the eastern Pacific, enabling the tropical system to absorb vast quantities of atmospheric heat into upper ocean storage. This heat is collected, subducted, and later transported by oceanic and atmospheric means to higher latitudes where it can be more efficiently lost to space, thus cooling the planet.

Noting that ENSO regulates tropical climate, it is clearly conceivable that it also contributes to the stability of global climate. Through negative feedback processes involving inventory of moisture content in the upper atmosphere, cloud changes, oceanic transport changes, and atmospheric teleconnections, the tropics work to minimize temperature variations in the low latitudes and thereby contribute to global climate stability[7-11]. ENSO phases further contribute to climate stability through teleconnected influences that ultimately regulate the thermohaline circulation via direct and indirect means.

The tropics do not work alone. While they host ENSO, a dominant mode of global-climate variability, there is one other key player influencing global climate variability – the annular modes. Annular modes *((AM), the Northern Annular Mode and Southern Annular Mode (NAM, SAM), also known as the Arctic Oscillation and Antarctic Oscillation (AO, AAO))* are pronounced seasonal tropospheric expressions of the stratospheric polar vortex. The westerly wind strength defining the phase of the annular modes is affected by numerous forcings – solar variability[12-14], volcanic activity, aerosols, greenhouse-gas content[15], sea-ice extent, regional SSTs[16], and convection in the tropics[17]. Guided by the effect these variables have on the polar-equatorial gradient of geopotential height in the stratosphere, strong westerly winds, extending from the stratosphere to the surface during the hemisphere's winter months, encircle a central low-pressure region. Frigid polar temperatures are confined within this wind-bounded region. Equatorward, the westerly winds coax warmer air and ocean water poleward, bathing the mid-latitudes in temperatures warmer than their latitude would host without this response. A strong polar vortex, associated with a positive annular mode phase, allows for mild winters in the mid-latitudes and few polar outbreaks (Arctic blasts). The polar regions remain frigid. Due to the isolation of its air mass and its inventory of ozone-destroying chemicals, stratospheric ozone levels plummet during a positive annular mode. A negative phase of annular mode, associated with a weakened vortex, hosts the opposite set of conditions.

An annular mode begins to develop in the hemisphere's late fall or early winter. At this time the stratospheric polar vortex begins to couple with tropospheric westerly winds. This is when the vortex is most susceptible to external perturbations. Planetary-scale Rossby waves coursing east to west within the troposphere can be re-directed vertically upon impact with anything impeding its flow – topography or sharp air-mass fronts. If a vertically propagating wave hits the polar night jet encircling the vortex at stratospheric levels and is able to penetrate the wall of winds, it can elevate temperatures up to 50°C within the vortex upon the wave's descent. These sudden warmings are called stratospheric sudden warmings (SSWs). This causes the westerlies of the vortex to slow or reverse. The vortex decays. If this vortex damage occurs early enough in the cooling season, conditions may allow for the vortex to re-build its strength throughout the remaining months of winter. If the structural damage happens late in the season, chances are unlikely that it will re-build strength. On the other hand, if the vortex is strong when a planetary wave assaults its periphery, the impinging wave will actually impart momentum to the vortex before the wave is deflected equatorward, thereby imparting extra strength to the vortex. One can see that the vortex's strength and its reaction to planetary wave impact is largely a matter of timing.

Fluctuations in mean global climate from interannual to decadal and possibly millennial timescales largely can be attributed to these two modes of variability – ENSO and the annular modes[18]. These two dominant modes of variability and subordinate partners that represent distinct regional patterns of winds, ocean currents, sea-level pressure, precipitation distributions, and temperature fluctuations emerge from a background of global climate noise. Some of these subordinate partners include the QBO, MJO, PDO, ACW, IOD, PNA, NAO, and TAV. All appear to be quasi-cyclic with that quasi-cyclic periodicity, itself, changing on quasi-cyclic time frames. Variability on scales of days to multiple decades can be identified from this collection of oscillatory behavior. All patterns are seemingly interconnected, directly or indirectly, on a variety of time scales, working to counteract slight perturbations to the global system, regulating global climate within a narrow range of variability. Much of the variability appears to be internal; yet the systems are not immune to external perturbations – solar variability, fluctuating on timescales of decades to millennia, likely plays a far bigger role than is currently appreciated. A mechanism by which small changes in solar output are translated into palpable effects remains elusive; although variability of the ultra-violet portion of its spectrum and its effects on the stratosphere offers a promising possibility.

It was noted above that convection in the tropics is one forcing that can affect the integrity of the polar vortex. Convection in the tropics is able to affect annular mode behavior through one of the ancillary patterns of variability, the Quasi-biennial Oscillation (QBO). This pattern governs high-altitude atmospheric communication between the high and low latitudes.

Born of vertically propagating planetary-scale waves from tropical convection, the QBO is characterized as an equatorially centered, oscillating set of descending stratospheric winds. Alternating easterly and westerly winds descend from about 60 km to about 20 km with a period of about 22 to 28 months. These winds set up pathways between the high and low latitudes that either facilitate or hinder travel of mid-latitude vertically propagating Rossby waves. When the QBO winds are easterly, due to the narrow waveguide structure set up by these winds, quasi-stationary waves (QSWs) are prevented from easy travel toward the equator. Instead, the waves find easier passage poleward, where they interfere with the vortex. Thus, planetary waves are far more likely to weaken the polar vortex during the year when the QBO wind is flowing to the west (easterly). Conversely, when the winds are westerly, passage to the tropics is easy for the QSWs. The QBO wind structure accounts for this. Thus, the vortex is typically strong during the QBO-west phase. Conversely, annular mode strength influences tropical convection.

One means by which annular mode strength influences tropical convection is through tropospheric communication. Empirical evidence shows a strong correlation between a strong NAM and westerly wind bursts, often associated with the onset of an El Nino.

Convection in the tropics is further correlated to the annular modes through the QBO because of the behavior of the planetary waves. During a QBO-west, when the vortex remains strong and planetary waves are diverted equatorward, convection in the tropics is suppressed. The equatorward traveling waves thermodynamically lower the tropical tropopause and affect vertical wind shear in such a way that convection is diminished. Because planetary waves are focused poleward during QBO-east, tropical convection is more likely to be enhanced while the vortex is weakened.

In turn, a warm ENSO event weakens the NAM, especially during a QBO-east. During the maximum anomaly of an El Nino, the NAM typically weakens one to two percent yet rebounds in strength by two to three percent a few seasons later[19].

ENSO is not the only recurring convective pattern within the tropical Pacific. Separate from, yet related to ENSO, is the Madden-Julian Oscillation (MJO). The MJO is a net-eastward traveling organized collection of multi-scale convective systems that circumnavigates the globe every 30 to 90 days, with a maximum amplitude revealed in the Indian and West Pacific Oceans. It is often associated with the onset of an ENSO warm event, being most vigorous prior to the peak of an El Nino event. The activity moves eastward with the ENSO SST anomaly[20]. MJO activity is anomalously low after the El Nino event and during non-El Nino events. [21] MJO may trigger an ENSO with associated westerly wind bursts, or it may establish conditions favorable for ENSO evolution through the reduction of zonal SST asymmetry. A few mechanisms have been proposed: 1) The MJO can cool the WEP. 2) An easterly zonal current, forced eastward by westerly winds of the MJO, can advect the eastern edge of the western pool. 3) Oceanic Kelvin waves, forced by the MJO, can propagate to the east, depressing the thermocline along its path. All would work to reduce zonal temperature contrasts, setting the stage for a warm event. MJO may well coincide with primed conditions in the tropical Pacific to help initiate an El Nino. Obstructing the clarity of the connection is the difference in periodicity of the two phenomena[20].

The MJO can also affect the annular modes. The MJO sends quasi-stationary waves – a train of alternating geopotential high and low heights – poleward and eastward that can directly affect the vortex of the annular modes (AM). If the AM is strong, it can resist perturbation from these waves. Recall, waves that impinge upon a strong vortex will be re-directed equatorward, imparting more momentum (strength) to the vortex in the process. This correlation can often be observed in the stronger SAM. The SAM is stronger than the NAM due to hemispheric differences in landmass configuration and topography; the minimal extent of land in the SH reduces dynamical interactions of planetary wave activity. Without this dynamical wave activity, the vortex escapes impacts that could lead to its weakening. *Matthews & Meredith '04* [22] found that during the austral winter, approximately seven days following anomalous MJO convection in the Indian Ocean, anomalous westerlies develop around almost the entire circle at 60°S. This pattern projects strongly onto the already robust SAM, enhancing the westerlies, and thus the acceleration of the eastward ocean current, the ACC. The strength of the SAM westerlies peaks about seven days following the peak of an MJO event and the ACC enhancement follows three days after that.

There seem always to be exceptions to the rule. In late September of 2002, such an exception occurred. A sudden-stratospheric warming (SSW) led to the sudden breakdown of the Southern Hemisphere polar vortex. No such event had been recorded in the SAM since observations began in the 1950s. It appears to have been tied in with the PSA. The PSA (Pacific-South America pattern) is associated with thermodynamics within the Pacific Ocean. There is a Northern Hemisphere counterpart, the Pacific North American pattern (PNA). These patterns are highly tortuous paths in the atmosphere, carved by intense high and low pressure systems. The strength of the PNA/PSA patterns fluctuates decadally and correlates positively with the strength and frequency of El Ninos. The PSA pattern played a prominent role in a precedent-setting event in 2002. Late in that year, in mid-September, anomalous deep convection in the South Pacific Convergence Zone (SPCZ) in the tropical South Pacific spawned a Rossby wavetrain of quasi-stationary Rossby waves (QSW), from which a blocking-flow configuration developed. The wavetrain traveled eastward over 21,000 km over a nine-day period. Upward-propagating waves emanated from the ridge that had propagated into the South Atlantic. This wave activity led to the unprecedented breakdown of the vortex. While this was the strongest event of the year, leading to the breaking apart of the vortex, three minor events of similar source and nature preceded this final event, thereby weakening the polar night jet (PNJ – east-to-west wind belt that encircles the polar vortex) substantially. In addition to the amplified PSA pattern that led to this event, unusually strong easterlies occurred in the equatorial upper stratosphere. Recall that when the QBO is in its easterly phase, not only is tropical convection enhanced, but waves vertically propagated from the enhanced convection cannot travel easily back to the tropics; instead, they are often re-directed poleward, where they interact with the vortex. Thus, tropical convection and the amplifying effects of the east phase of the QBO led to a breakdown of the SAM, the collapse of the Antarctic ozone hole, anomalously warmer temperatures over the pole (most of Antarctica), and anomalously cooler temperatures over the western peninsula. Westerlies were less intense both in the stratosphere and the troposphere. When this occurs in the Northern Hemisphere, temperatures in the mid-latitudes are cooler. Tropospheric anomalies persisted for approximately 90 days[23].

It can be seen with this limited discussion of interactions that signals sent between these two dominant modes, ENSO and the annular modes, directly and through intermediary patterns, convey a network of opposing feedbacks that may contribute to stability of the global climate system, absent extreme cases of external perturbation.

Additional complications to this picture arise when one considers changing background conditions. Background conditions in the Pacific coincide with variability of the ENSO system. *Federov & Philander '00* [24] suggest that one can see a distinct interdecadal variability of ENSO behavior, oscillating between periods of strong variability and periods of weak variability. They attribute such changes to changes in background state, citing depth of thermocline and time-averaged easterly wind stress as the two critical parameters. Increasing thermocline depth and/or decreasing easterly wind stress have stabilizing effects, leading to reduced variability.

These background changes can be associated with an El Nino-like oscillatory pattern of climate variability centered over the Pacific Ocean and North America known as the Pacific Decadal Oscillation (PDO). This phenomenon is poorly understood. It is expressed as an interdecadal oscillation in basin-wide SST distribution[25], operating on two scales – 15 to 25 years and 50 to 70 years[26]. While the PDO refers to variability in the North Pacific, there is a South Pacific counterpart. Some claim that the PDO's variability is a result of ENSO, or of random forcings, or shifts in subtropical gyre strength. These remain speculations. Its cause remains unknown[26].

A PDO warm phase features a strong Aleutian Low. Its strong counterclockwise winds usher warm SSTs from the tropics, up along the western coast of North America. In the central and northern portions of the basin, SSTs are anomalously cool. A PDO cool phase shows a weakened Aleutian Low, a cooler tropical and western coastal regions, and warmer-than-normal central and northwestern basin SSTs. Anomalies extend through the depth of the troposphere and are well expressed as persistence in the Pacific North American (PNA) pattern – a deep Aleutian Low over the Pacific basin and a strong high pressure over western North America El Nino events are often expressed through an enhanced PNA pattern, an observation that emphasizes the often-similar characteristics of the two phenomena[27].

Empirical studies indicate that ENSO influence on North American climate is strongly dependent upon the phase of PDO. There is reason to believe that frequency and intensity of ENSO phases correlate to PDO phase. An above average number of La Ninas tend to occur during a cool phase of the PDO and an above average number of El Ninos during a warm phase of PDO. An El Nino superimposed on a warm PDO phase will amplify the effects of the El Nino expression. Thus, the phase of PDO appears to modulate the strength and frequency of events[28]. This observation may contradict the speculation that the PDO results from decadal variability of ENSO.

Decadal variations are particularly relevant to the observation that ENSO also finds a connection to Antarctica. Signals are sent in both directions. In one situation, atmospheric patterns affect sea-ice extent (SIE) off Antarctica directly by steering storm activity. Storm activity during an El Nino is shifted to the Atlantic sector, leading to an increase of sea-ice extent in the Weddell Sea sector. This leads to enhanced deep-water formation in the Atlantic sector of the Southern Ocean, which promotes competition with the North Atlantic Deep Water (NADW) formation, possibly leading to slowing of the MOC, cooling the northern high latitudes and warming the southern high latitudes[29-30].

Atmospheric patterns also teleconnect to the Antarctic region via an oceanic connection. The pathways are complex, but an equatorially encircling wave pattern related to ENSO (the global ENSO Wave (GEW)) imparts its signals to the oscillatory ACW (Antarctic Circumpolar Wave)[31], which communicates the ENSO signal to the high southern latitudes and loops back to reinforce the ENSO signal[31-32]. The nature of the GEW-ACW pathway varies on a decadal scale.

ENSO finds itself correlated to activity in both the Atlantic and Indian Ocean basins. Variability inherent within each basin is modified by the phase of ENSO. Changes include those in the atmosphere and the ocean. In turn, changes within the Indian Ocean can zonally modify an El Nino event[33-36]. Temperatures in the Tropical Northern Atlantic (one component of TAV (tropical Atlantic variability), correlated to El Nino, are inversely correlated to phase of the NAO/AO[37], which can communicate changes via planetary waves back to the tropical Pacific, facilitated by the QBO.

ENSO can also affect the meridional overturning circulation (MOC), whose strength, in turn, dictates the amount of heat distributed to the high latitudes of the Northern and Southern Hemispheres. If the MOC is strong, temperatures in the North Atlantic warm; if the MOC is weak, heat typically builds in the high latitudes of the Southern Hemisphere. ENSO has an effect on the MOC through atmospheric channels as well as oceanic ones.

First looking at ENSO's effect on the MOC through atmospheric processes, *Latif et al. '99*[38] use model studies to show that atmospheric feedbacks responding to an increased frequency of El Nino events stabilize the thermohaline-circulation component (THC) through increasing salinity in the North Atlantic. The increased salinity is due to enhanced freshwater export from the Atlantic. A shift in the Walker circulation leads to anomalous subsidence over the tropical Atlantic, increasing evaporation and reducing Amazon runoff to the Atlantic. The salt anomaly that develops in the tropical region is exported poleward and mixes within the subtropical gyre. The entire North Atlantic surface salinity increases. This anomaly is carried to the region of deep-water formation where it overrides the impact of freshwater delivery due ice melt to warming in the high latitudes.

*Schmittner et al. '00* [39] base their study on a similar premise – El Nino phases result in positive salinity anomalies in the North Atlantic due to enhanced freshwater export from the Atlantic. The opposite scenario happens during a La Nina. They conclude that if the number of El Nino years is balanced by a similar number of La Nina years, the effects on the THC will balance. But, they reason, if a phase of ENSO persisted, the impact on the THC could be profound. La Nina conditions lasting longer than 70 years would lead to a collapse of the THC in their model studies. Prolonged periods of El Nino enhance the THC.

Do teleconnections, east to west, via ocean flow, as orchestrated by ENSO phases, also play a role in modifying Earth's climate? ENSO phases regulate ocean flow through the Indonesian Throughflow [40-41] and the Bering Strait [42]. In turn, this leads to salinity changes in the North Atlantic. During an El Nino, the warm pool is shifted eastward; the

Aleutian Low strengthens and shifts southeastward. As a consequence of the former, ocean flow through the ITF decreases. Reduced flow through the ITF promotes a positive phase of the Indian Ocean Dipole (IOD) [34-36,43]. Easterlies over the Indian Ocean strengthen. This leads to the suppression of the formation of high-salinity eddies off the southern tip of Africa via the Agulhas Current, leading to a reduction in the delivery of salinity to the Atlantic [44-48]. In addition, subtropical gyre strength in the North Atlantic weakens; slowing transport of water northward. Consequent of increased flow through the Bering Strait, fresher water from the Pacific is delivered to the Arctic region through the high-latitude route[46, 49-50]. Both ocean-flow consequences of a persistent El Nino pattern could conceivably lead to a freshening of the North Atlantic, albeit on the order of decades, leading possibly to a cooling of the North Atlantic. El Nino's relationship to a cooling North Atlantic via this mechanism, operating on the order of decades, stands in opposition to the conclusion of El Nino's more immediate enhancing effect on the North Atlantic THC through salinity increase. Whether the timing of these flow regimes coincide to create the North Atlantic freshening as envisioned by the author, is only a guess – little more than an idea on a napkin. But, considering these flow regimes have been evaluated individually, it seems their collective interaction and possible influence on THC flow is worthy of future study.

And finally, *Delworth and Dixon '00* [51] find that an enhanced positive phase of the AO leads to an augmentation of the THC through enhanced winds, and thus enhanced heat extraction leading to cooling and increased density. This effect persists for a decade or so, ultimately losing out to the enhanced melt water resulting from the amplified warmth in the region. If one assumes the negative phase of AO leads to the opposite result of reduced heat extraction from the ocean, and thus no augmentation of the THC, and if one considers the relationship of El Nino with a negative-phase AO, then one might speculate that this feedback works in opposition to the influence suggested by *Latif '99* and *Schmittner '00*.

Thus, on decadal timescales, with atmospherically teleconnected signals from El Nino leading to increased THC and El Nino-associated negative AO phase impacts leading to the opposite, does this imply a negating of competing feedback effects, and thus to a stabilization of the THC, at least on these timescales? And where might the ocean-gateway hypothesis fit in, if it holds any merit at all? If a persistent El Nino were to ultimately lead to a freshening of the North Atlantic over decadal timescales due to the "gateways" hypothesis, could this tip the balance in favor of a slowing of the THC? Or might an increase of sea-ice extent in the Atlantic sector of the Southern Ocean during El Nino-like regimes enhance downwelling in the Weddell Sea and lead to a further reduced MOC? Does the net balance of feedbacks reveal a relationship of a long term El Nino to a slowing THC, a cool North Atlantic, and a warm Antarctica? Or instead, do the opposing feedbacks counteract one another? And on a shorter time frame, does the interplay of ENSO-related feedbacks on the THC explain the decadal variability of strength of the THC?

## THOUGHTS IN CONCLUSION:

This paper has attempted to bring together the numerous oscillatory patterns and their interconnectedness with one another, ultimately connecting the two dominant modes of climate variability – ENSO and the annular modes. With oceanic and atmospheric signals criss-crossing the globe latitudinally, longitudinally, and vertically, feedbacks operate on a variety of timescales. The Holocene, the interglacial that began with fits and starts about 10,000 years ago, has been quite stable, relative to the preceding glacial. It is tempting to assign this stability to these temporally diverse teleconnected feedbacks operative in our present-day world.

If one considers the MOC to play a secondary, yet critical role in maintaining or disrupting this climate stability, and if one recognizes the multiple controls on the MOC strength, many of those dictated by ENSO dynamics, what is to be concluded about Holocene stability? Are the tropics "control central", with ENSO phases responding to changes in heat flux and responding with signals that initiate global chain reactions that work remotely to balance the system within a narrow, oscillatory range?

Much of this paper's speculation rides on variability internal to the Earth system. Largely ignored to this point, is Earth's major source of energy - incoming solar radiation. This paper does not pretend to offer educated insight into the influence of solar variability on climate, yet it is worth mention that its variability on decadal to orbital scales likely plays a role in behavior of both ENSO and the annular modes. Its significance is something I cannot defend or debate. But it is worth consideration, nevertheless. Increased solar variability on decadal scales, for example, during the boreal winter, weakens the Aleutian Low and shifts it northwestward [52-53]. Flow through the Bering Strait is reduced. In the tropical Pacific, the increased solar intensifies the ITCZ and SPCZ, increasing precipitation there, strengthening the SE trades, displacing the ITCZ further north, amplifying upwelling in the EEP – a La Nina-like regime.[54] The warm pool is shifted more westward, amplifying flow through the ITF. A negative phase of the IOD is induced. More saline eddies are spawned off the Agulhas Current as a result [44-45]. Increased salinity is delivered to the Atlantic. Windstress curl over the North Atlantic increases with increased solar. The Atlantic ITCZ migrates north. The subtropical gyre is strengthened. Perhaps all work together to amplify transport of heat and anomalously high salinity poleward.

In addition, increased solar variability on a decadal scale likely amplifies the Arctic Oscillation. In model studies[12] in which multiple levels of the stratosphere are allowed to participate with amplified amounts of ultra-violet radiation from the high phase of a solar cycle, stratospheric dynamics respond in such a way to strengthen the vortex. A positive AO amplifies THC flow initially, according to Delworth's hypothesis mentioned above, intensifying, for a few decades, the formation of deep water.

Could this collection of processes, nudged along by amplified solar output, work together, balancing negative and positive feedbacks to changes in the tropical Pacific and annular modes to regulate the THC flow? Would the balance be a slight net increase in the THC with increased solar output? Would this lead to slight warming in the northern high latitudes? Would reduced solar have the opposing effect?

Could this collection of processes be nudged along by other factors – episodes of intense volcanic activity, accumulation of greenhouse gases, an oscillatory behavior between a strong polar-equatorial temperature gradient and a weak one, not related to external processes? Do the positive and negative feedbacks closely balance, at least during interglacials, which have historically been extraordinarily stable, at least once the initial stages are passed?

A caveat must be mentioned here, one that may be a clue to the difference in behavior between glacials and interglacials. During a glacial and the early stages of an interglacial, when climate is highly unstable and variable, sea level is too low for flow to exist through the Bering Strait. Thus, this freshening agent for the Arctic Basin and into high latitudes of the North Atlantic would not be operative during a glacial. If flow through the BS during an El Nino could augment freshening of the North Atlantic and it was absent during a glacial, could this have led to a system prone to excessive build-up of salinity? Could this have contributed to a less damped MOC, the unchecked acceleration leading to the abrupt warmings of the Dansgaard-Oeschger events, leading subsequently, through a chain of events, to the opposite, to extreme cool events? It's an idea, obviously one with many flaws, but an intriguing possibility, noting that frequency and strength of El Nino/La Nina phases, according to *Sun et al*[5], might be a response to polar-equatorial gradients, thus forcing us to look at the entire global network as an oscillating system, with equatorial conditions forcing high-latitude conditions, which in turn, force equatorial conditions.

**GLOSSARY:**

| | |
|---|---|
| AAO | Antarctic Oscillation |
| AABW | Antarctic Bottom Water |
| AAIW | Antarctic Intermediate Water |
| AO | Arctic Oscillation |
| ACC | Antarctic Circumpolar Current |
| ACW | Antarctic Circumpolar Wave |
| CEA | Central Equatorial Atlantic |
| CEP | Central Equatorial Pacific |
| EEP | Eastern Equatorial Pacific |
| ENSO | El Nino Southern Oscillation |
| EUC | Equatorial Undercurrent |
| GE | Gyre Exchange |
| GEW | Global ENSO Wave |
| IOD | Indian Ocean Dipole |
| IOZM | Indian Ocean Zonal Mode |
| IPO | Interdecadal Pacific Oscillation |
| ITCZ | Intertropical Convergence Zone |
| ITF | Indonesian Throughflow |
| MJO | Madden-Julian Oscillation |
| MOC | Meridional Overturning Circulation |
| NADW | North Atlantic Deepwater |
| NAM | Northern Annular Mode |
| NAO | North Atlantic Oscillation |
| NE | Northeasterly or northeasterlies |
| NEC | North Equatorial Current |
| NECC | North Equatorial Countercurrent |
| NH | Northern Hemisphere |
| NPO | North Pacific Oscillation |
| OLR | Outgoing Longwave Radiation |
| PDO | Pacific Decadal Oscillation |
| PNA | Pacific North American (pattern) |
| PNJ | Polar Night Jet |
| PSA | Pacific South American (pattern) |
| QBO | Quasi-biennial Oscillation |
| QSW | Quasi-stationary waves (Rossby wavetrain) |
| SAIM | South Asian Monsoon |
| SAM | Southern Annular Mode |
| SE | Southeasterly or southeasterlies |
| SEC | South Equatorial Current |
| SH | Southern Hemisphere |
| SLP | Sea-level pressure |
| SO | Southern Oscillation |
| SOI | Southern Oscillation Index |
| SPCZ | South Pacific Convergence Zone |
| SSH | Sea-surface height |
| SSS | Sea-surface salinity |
| SST(s) | Sea-surface temperature(s) |
| SSW | Sudden stratospheric warmings |
| TAV | Tropical Atlantic Variability |
| TIW | Tropical Instability Waves |
| THC | Thermohaline Circulation |
| TNA | Tropical North Atlantic |
| WEA | Western Equatorial Atlantic |
| WEP | Western Equatorial Pacific |
| WHWP | Western Hemisphere Warm Pool |
| WWB | Westerly Wind Bursts |
| WWP | Western Warm Pool |

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