Beyond the Tipping Point

Positive Feedback & the Acceleration of Climate Change

Presented by

David Wasdell

Director of the Meridian Programme

Towards the Anthropocene Extinction Event

www.meridian.org.uk

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Abstract

This presentation introduces a conceptual, top-down, systems-dynamics approach to modelling the whole earth system as a single global entity. It stands in sharp contrast to the bottom-up, integrational approach adopted in familiar climate modelling.

Analysis of the feedback dynamics in climate change alerts us to the existence of a "tipping point" in the whole earth system. Topological presentation offers a landscape with two complex equilibrium zones. One is the current stability of the Holocene epoch, its dynamics grounded in the conditions of the Pleistocene, with oscillations between cold glacial and warmer inter-glacial periods controlled by variation in distribution of received solar energy between the northern and southern hemispheres. The other zone, entered via a slope of runaway climate change, is the higher-temperature solution of the Anthropocene***** Extinction Event.

The natural watershed between the basins has already been passed, and acceleration towards the second solution is underway. Contemporary civilisation faces the choice between continuing the current path towards catastrophe, or introducing powerful negative feedback processes able to halt the runaway climate change and return the planet to a viable and sustainable equilibrium.

Contents

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***** The term ***Anthropocene*** is used by some scientists to describe the most recent period in the Earth's history, starting in the 18th century when the activities of the human race first began to have a significant global impact on the Earth's climate and ecosystems. The term was coined in 2000 by the Nobel Prize winning scientist Paul Crutzen, who regards the influence of mankind on the Earth in recent centuries as so significant as to constitute a new geological era.

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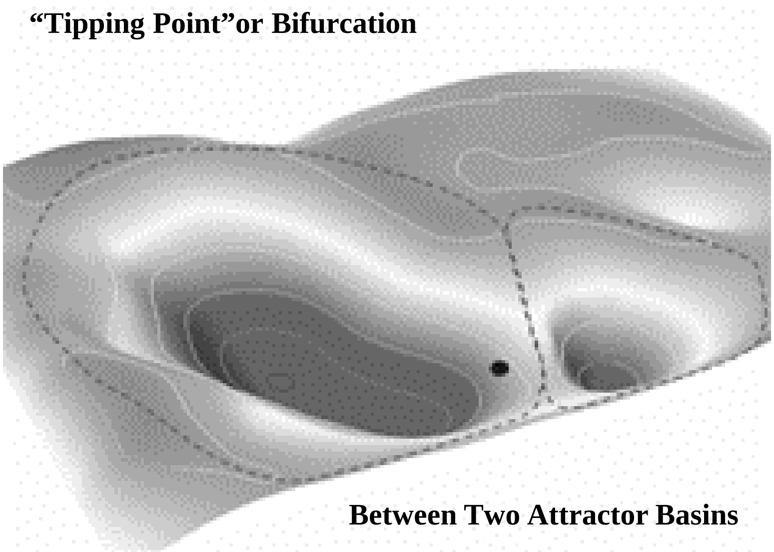
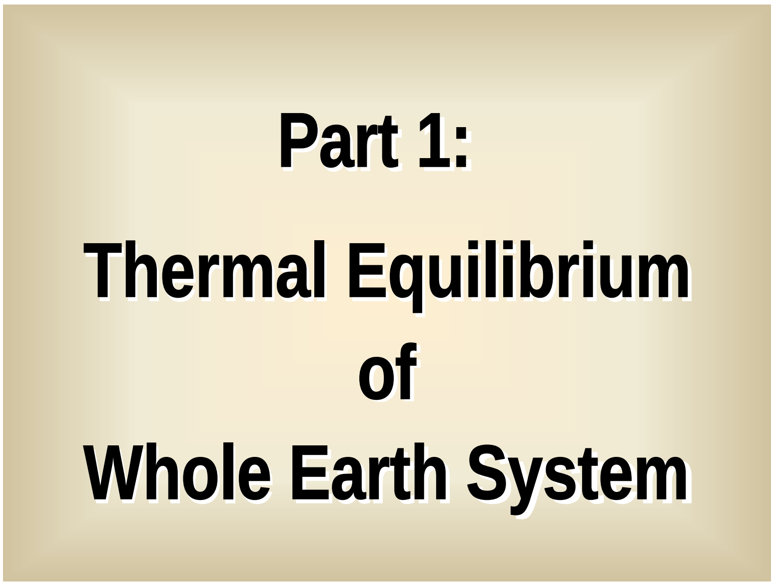
Beyond the Tipping Point

Facing the Anthropocene Extinction Event

We meet at a time at which the planet earth is facing the impingement of a species whose population explosion, exponential resource use, accelerating technological development, unrestrained pollution and dysfunctional behaviour have combined to overstep the conditions of sustainability. It is the argument of this presentation that we have already passed a watershed in the earth-system as a whole, and acceleration towards the second solution is underway. Contemporary civilisation faces the choice between continuing the current path towards catastrophe, or introducing powerful negative feedback processes able to halt the runaway climate change and return the planet to a viable and sustainable equilibrium.

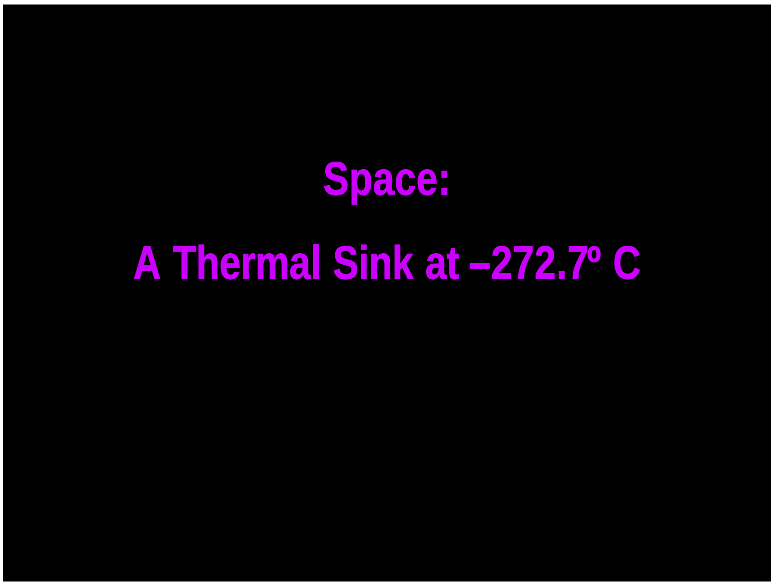


By way of introduction let us explore what is meant by a tipping point or bifurcation. Brian Walker, the Australian founder of the Resilience Alliance, offers this landscape. The ridge-top line marks the bifurcation between attractor basins of complex adaptive systems. In equilibrium topology it represents the tipping-point between alternative zones of stable equilibrium. As negative feedback yields to positive feedback, system behaviour moves up to the watershed, leaving its familiar stability before plunging into the containment of an alternative state.



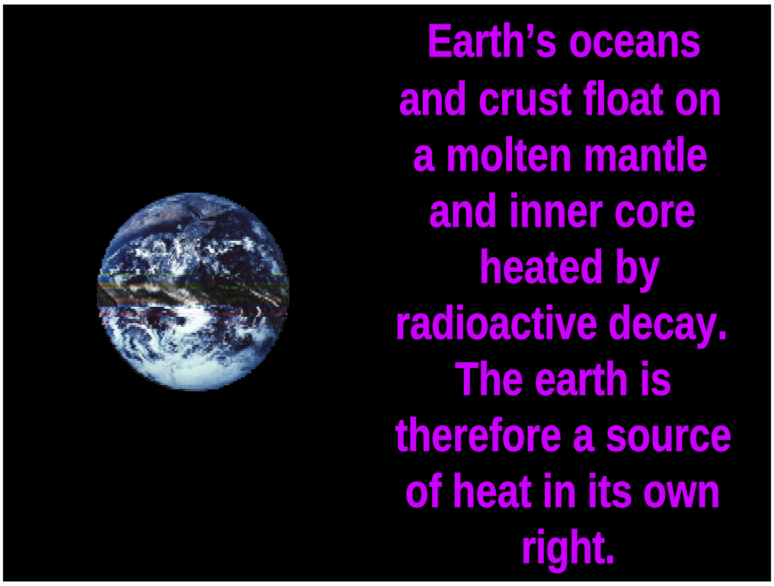
Part 1:
Thermal Equilibrium of Whole Earth System

The first part of the presentation sets the spatial context of the whole earth system in the thermal environment of the solar system of which it is a part.

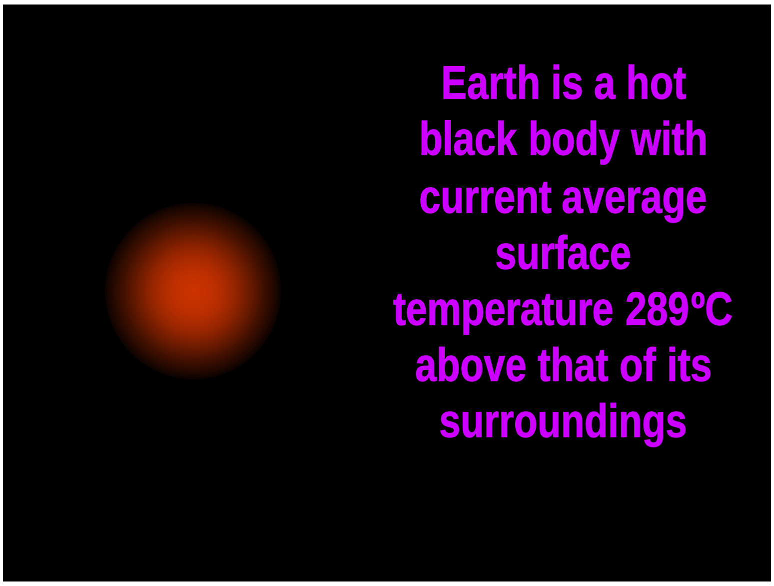


Within the cold thermal context of outer space,

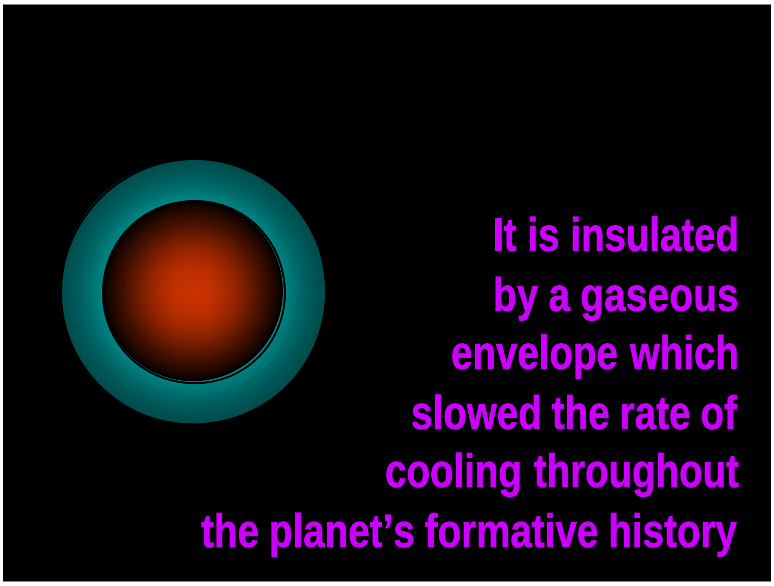
the Planet Earth hangs in all its complex beauty. It is a second generation artefact of cosmic evolution. Almost all its constituent matter has already passed through the furnace of stellar death before aggregating in this sphere of spatial debris.



Gradually, the radioactive decay slows down and the heat generated by the core decreases. The rate of change is significant in geological time but within the time-scale of human civilisation it can be ignored, and the geo-thermal output can be treated as constant.



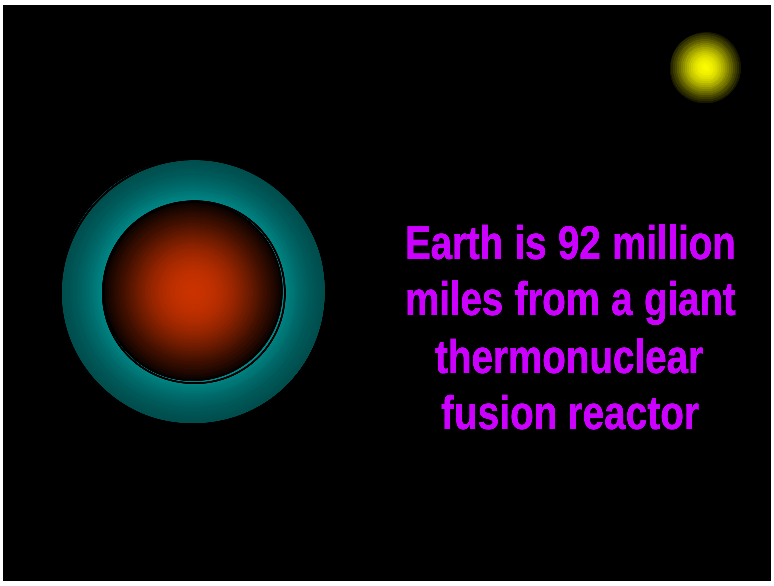
Viewed from the perspective of thermo-dynamics we have a hot body in a cold environment, steadily radiating its heat energy and cooling over time. Two further factors influence the cooling curve, namely atmospheric insulation and solar radiation.



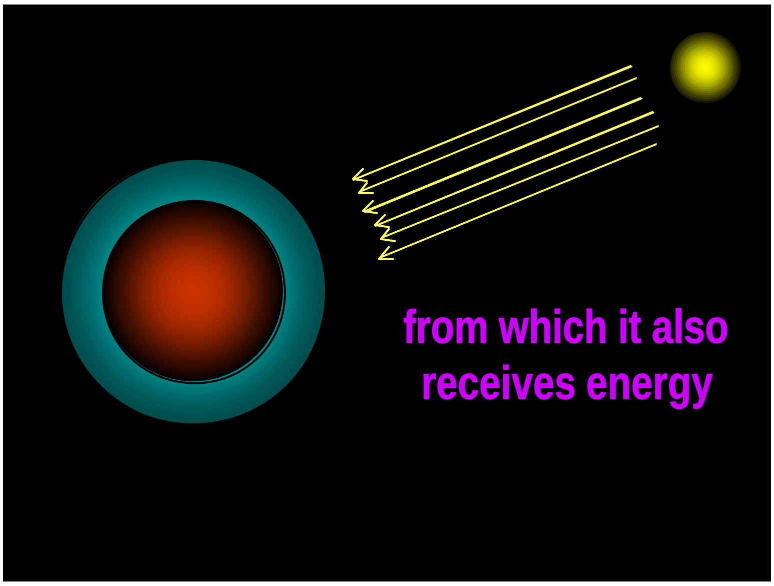
Radiative heat loss is subject to moderation by conduction, convection, scattering, absorption and wavelength transformation. Ocean currents and atmospheric wind systems contribute to the complex patterns of energy distribution. In the neg-entropic envelope of the earth surface, bio-geo-chemical processes of molecular complexification also internalise and store heat energy which would otherwise be lost to the spatial sink.

The presence of an insulating atmosphere slows energy-loss and maintains higher surface temperature. Conversely, radiation detected by a deep-space monitor reveals significant cooling in the attenuated layers of the upper atmosphere, together with a lessening of energy radiated from the warmer layers below.

But the earth is not alone in space!

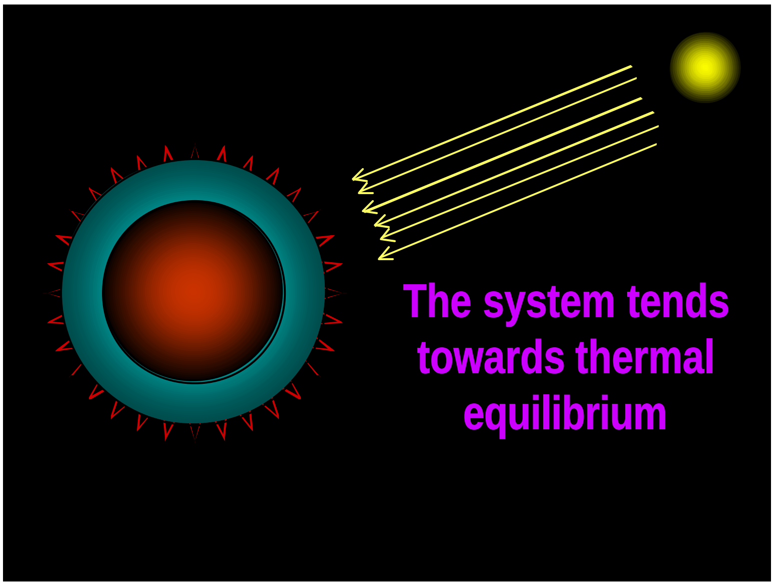


If geo-thermal energy were the only heat source, the earth would have cooled long ago to an icy state totally inimical to any emergent life.

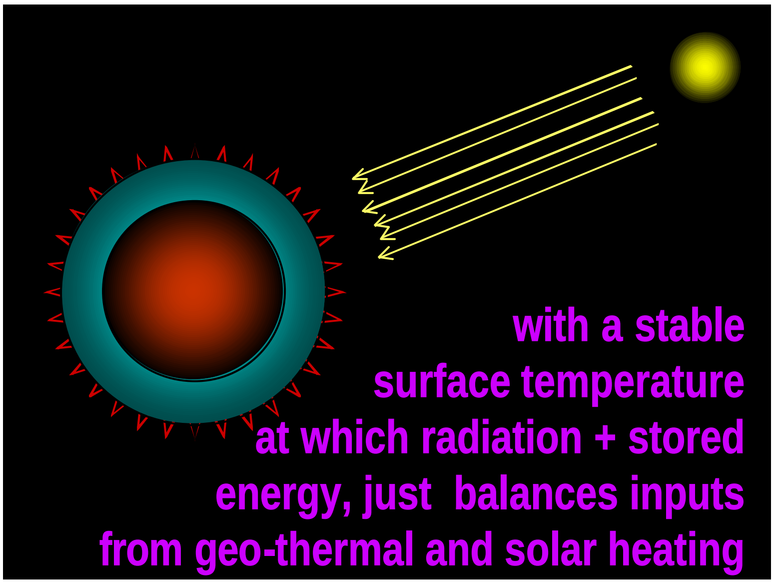


By far the most powerful source of energy driving the earth system is incoming solar radiation. At any given time only half of the earth surface is exposed to sunlight leading to the familiar experience of day-time heating and night-time cooling. The distribution of energy varies from a maximum when the angle of incidence is 90º, to a minimum when incoming light is tangential to the earth surface. Equatorial heat contrasts with relative polar frigidity. Axis tilt sets up the pattern of seasonal variation as the solar maximum migrates from tropic to tropic.

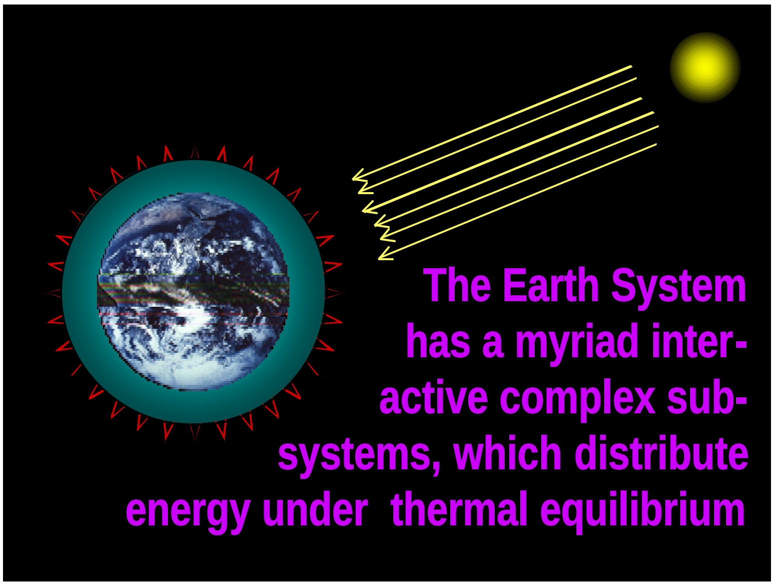
Patterns of oceanic and atmospheric energy distribution drive heat from the equator towards the poles, keeping the tropics cooler and the polar regions warmer than would otherwise be the case.



Over the five thousand million years since its formation, the earth's inner source of heating has slowly decayed, but the temperature of the sun (and hence the energy received from it by the earth) has gradually increased. Throughout its history, the whole earth system consistently tends towards a state of thermal equilibrium



with a stable surface temperature at which radiation plus stored energy just balances inputs from geo-thermal and solar heating. This is the condition of zero radiative forcing. Small changes in hemispherical distribution of received solar energy move the radiative forcing incrementally away from zero. The changes are then reflected in gradual response of the earth system. Surface temperature adjusts until the thermal equilibrium is restored and radiative forcing returns to zero. Please note that this definition of "radiative forcing" takes into account the negentropic nature of the biosphere. Thermal equilibrium is not at the point when received and radiated energy just balances, but when the received system input just balances the total of radia ted and negentropically stored energy.

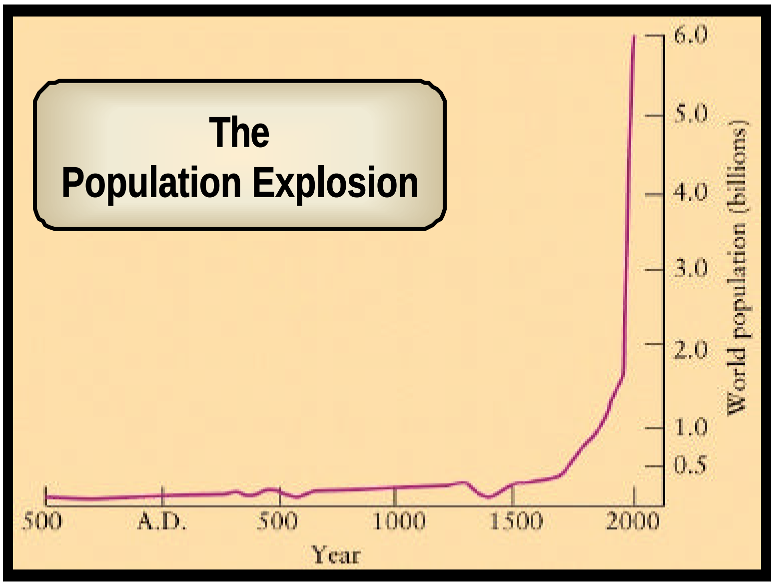


If only things were that simple! Now we have to add a little complexity.

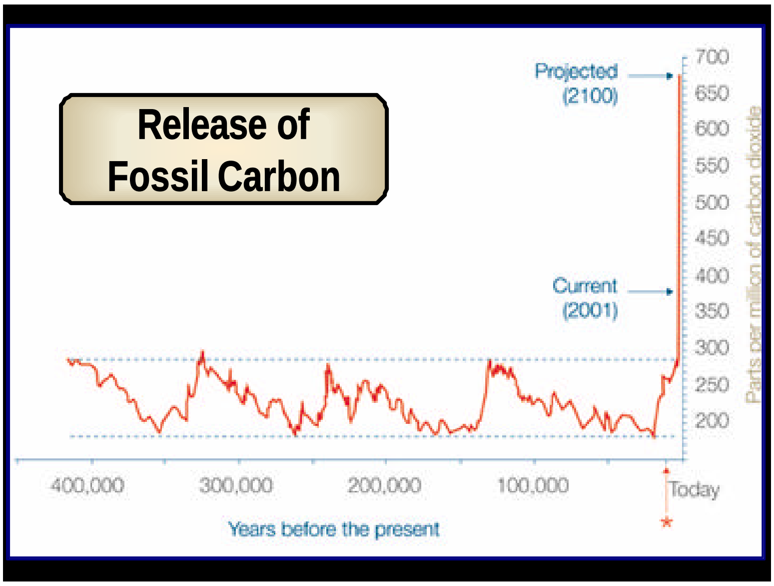
Oceans; Currents; Ice; Land; Mountains; Deserts; Forests; Rivers; Atmosphere; Climate; Weather (winds, clouds, temperature, precipitation); Geological; Chemical; Life-based; (biological, bacterial, algal, fungal, fauna and flora)…. The list is almost endless. Most of these dynamic and co-evolutionary sub-systems are subject to profound complexity with interrelated attractor basins, feedbacks, tipping-points and instabilities which all respond to change in (and may influence) the contextual or environmental thermodynamic parameters of the global macro-system.

(One of the most critical research questions is the extent to which the behaviour of the co-evolutionary population of complex sub-systems of energy re-distribution, has the power to change the dynamics of the containing macro-system, which is not itself an emergent phenomenon developed by co-evolutionary ordering from the set of complex sub-systems.)

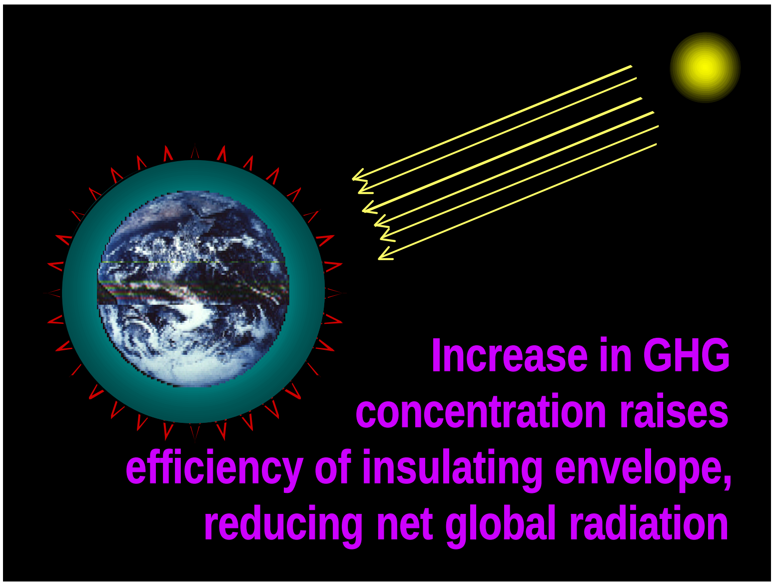
With current tectonic configuration, the blocking of Pacific-Atlantic currents between the Americas, the Elevation of the Himalayas and the High Tibetan plateau, the great energy transfer engines of atmosphere and ocean distributing heat from tropics to polar regions, and the complex dynamics of living systems, this is the earth system as we know it in recent geological history. The average surface temperature mobiled rhythmically between the cold glacial and the warmer inter-glacial periods. The pattern followed the small changes in hemispherical distribution of received solar radiation as slow and incremental shifts in radiative forcing were restored to zero, so maintaining the thermal equilibrium. Until, that is, the industrial revolution, initiated in Britain, took off globally in a really big way.



The biological infestation has been driven into unsustainability by human attack on the constraints of all naturally occurring negative feedback loops that would otherwise limit the species population. It has been resourced by mining carbon-based fossil energy, stripping of current assets, and mortgaging of future income secured against assumed sustained exponential economic growth.

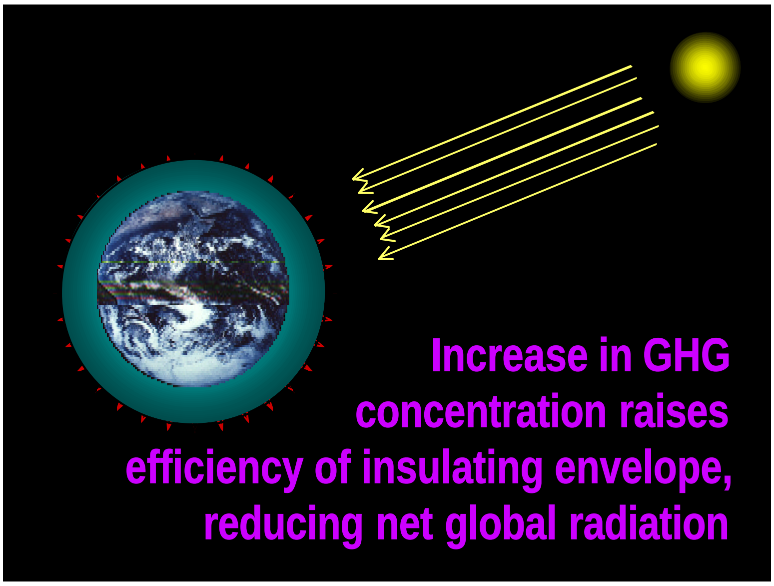


As a by-product humanity has discharged CO_2 into the atmosphere in sufficient quantities to disturb the previously stable thermal equilibrium of the earth system. Significantly the carbon-based fossil-energy stores involved, represent historically sequestered material naturally removed from the atmosphere over millions of years during conditions of global warming. We have simply reversed that process in a very short time-span.

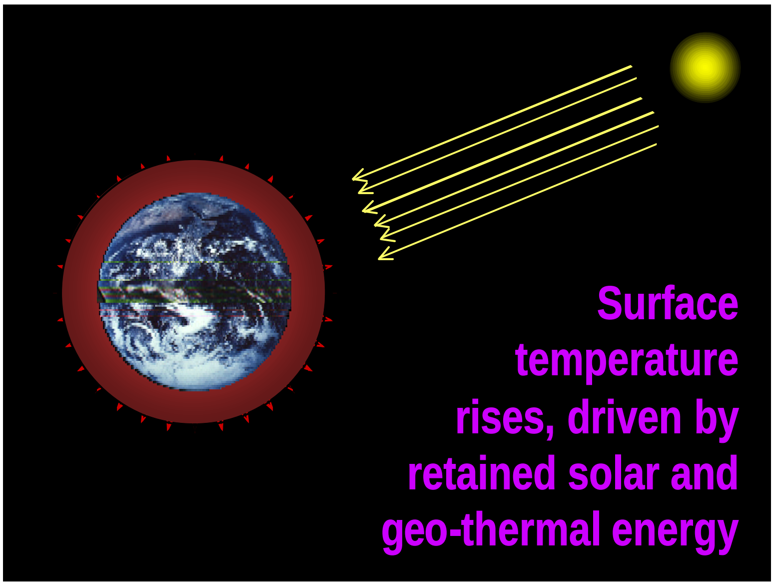


In geological history there have been several major disturbances of the basic thermal equilibrium. In each case sharp changes in atmospheric constitution have been generated by asteroidal impact or massive volcanic activity. There is typically a release of short-lived aerosol particulates, sulphur gasses which wash out as acid rain, and a sharp and longer lasting rise in concentration of atmospheric carbon dioxide. The resultant abnormally enhanced greenhouse effect drives radiative forcing significantly away from equilibrium. Each event precipitated un-damped positive feedback and runaway global warming. Under these conditions, previously stable bio-geo-chemical systems were disturbed and most extant life-forms became extinct. It took several millennia for the atmospheric CO_2 to be naturally sequestered, thermal equilibrium to be restored and radiative forcing to return to zero. It took several million years for the evolutionary biosphere to regenerate.

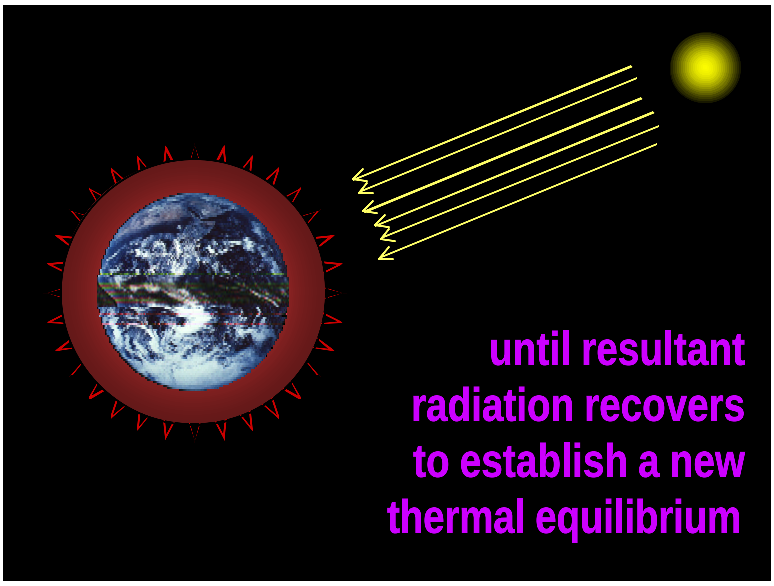
The industrial revolution is in the process of increasing the concentration of atmospheric greenhouse gasses on a similar scale to that which set off the geological extreme events. In addition, the anthropogenic disturbance is progressing some thirty times faster, making natural adaptation that much more difficult.



With the atmosphere comparatively transparent to inbound short-wave solar radiation, increased greenhouse effect traps outgoing long-wave radiation in the infra-red part of the spectrum. Radiative forcing moves significantly away from equilibrium. Energy radiated from the earth system is lower than energy received from the sum of solar and geo-thermal inputs.

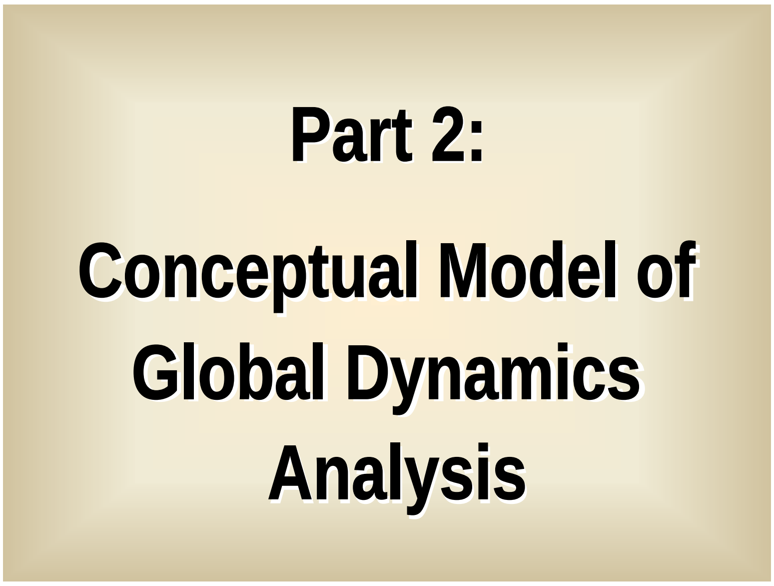


Resultant global heating begins to drive average surface temperatures upwards, with time delays due to thermal inertia and endothermic damping.



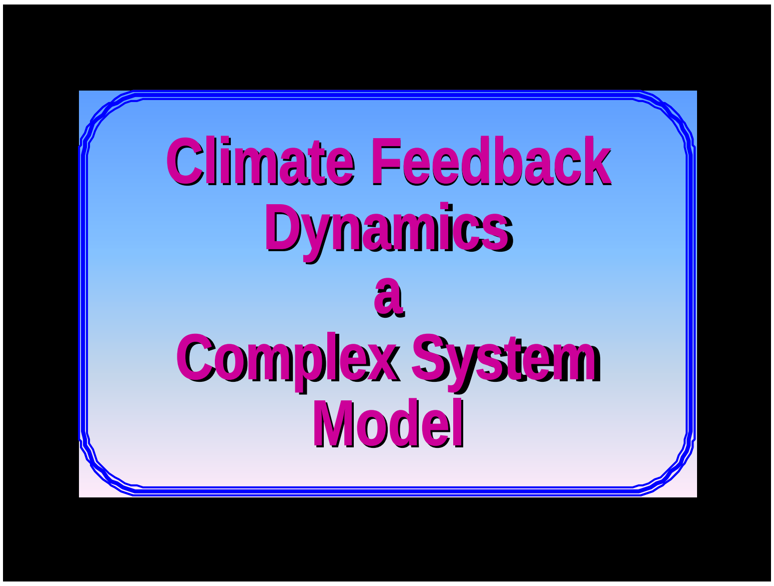
Temperature rises gradually until it generates a new rate of radiation that just balances the received energy (less energy stored in the negentropic processes of bio-geo-chemical complexification), so returning radiative forcing to zero and re-establishing the thermal equilibrium of the system.

However, the human intervention has not been a simple level shift in concentration of CO_2. Greenhouse gas levels are subject to a still accelerating rate of accumulation, pushing the radiative forcing further and further away from equilibrium. Thermal inertia means we are only just beginning to see the effects of global heating in a slight rise in average surface temperature. Meanwhile the myriad sub-systems respond in a matrix of co-evolutionary complexity, with potential tipping points that precipitate varied phenomena of climate change around the world. Then there is the question of feedback dynamics, triggered by the release of anthropogenic CO_2, and affecting not just the behaviour of localised sub-systems, but governing the emergent thermal equilibrium of the global-system as a whole.

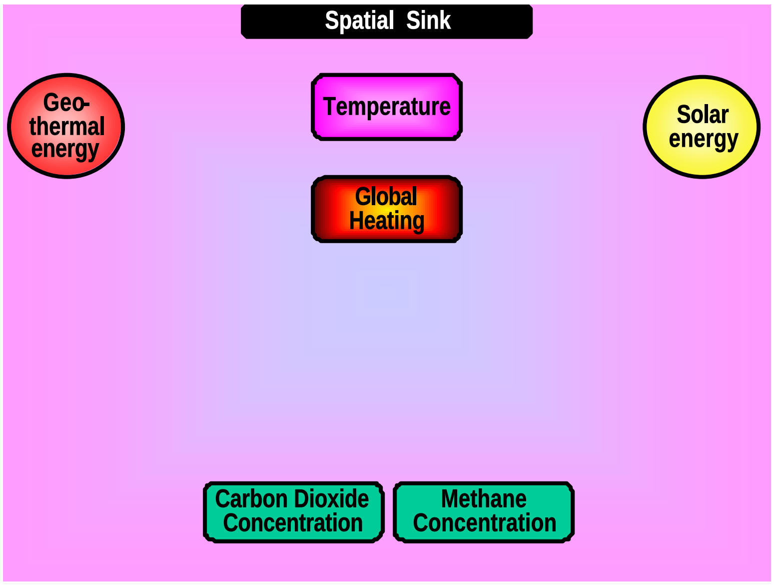


Part 2:
Conceptual Model of Global Dynamics Analysis

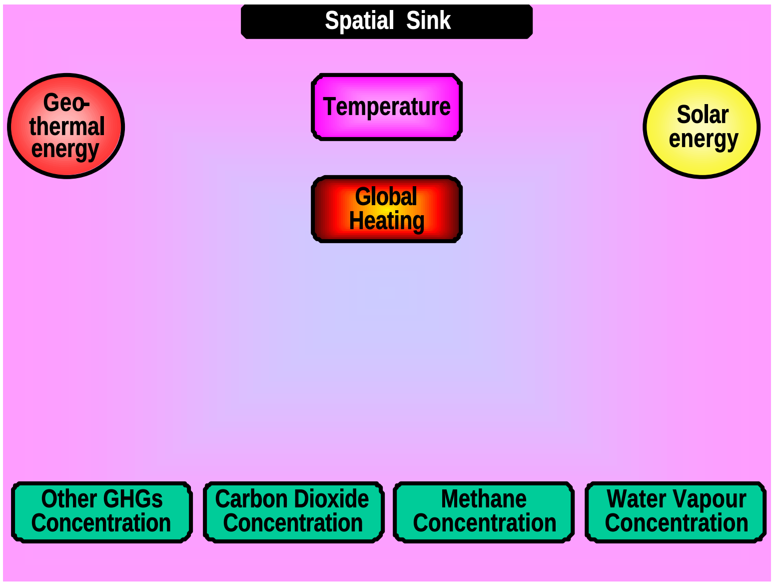
The second part of the presentation sets out the conceptual model of the systems dynamics analysis of the global level of climate change.



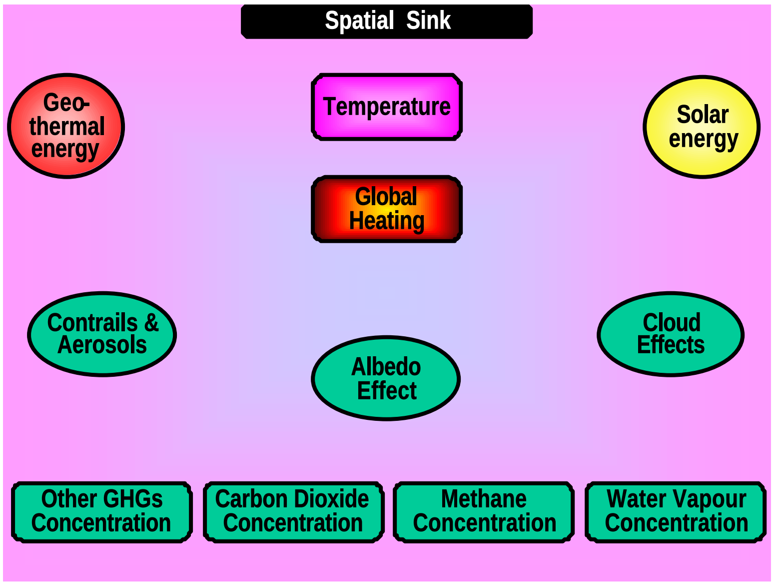
Exploring the dynamics of the global feed-back system is now **the most critical** research agenda, with urgent implications for current strategic decision-making for our whole world-community.



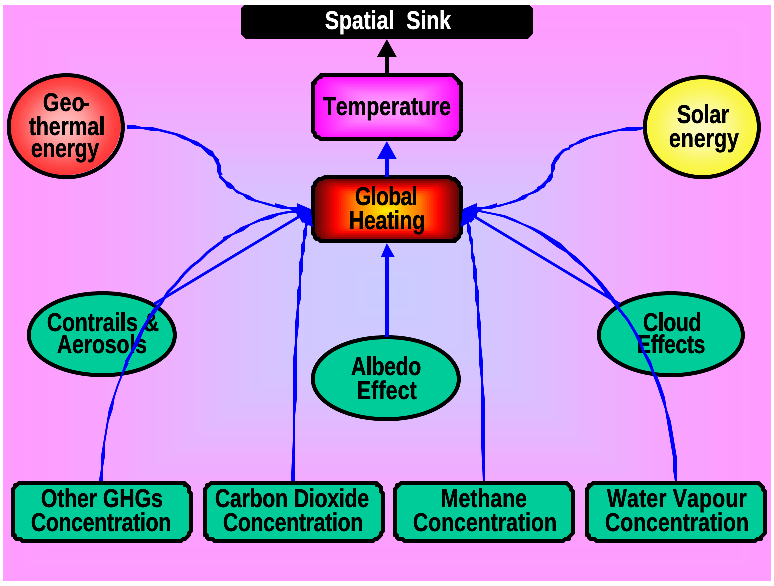
In the given context of the two heat sources and cold spatial energy-sink, we begin by assembling the basic elements that drive climate change. The greenhouse effect of increase in **CO_2** and **Methane** concentration, initiates **global heating** as a result of which **temperature** starts to rise. **Geo-thermal heating** is included for completeness, though its order is small compared to solar energy and so in practice we can ignore it at this level.



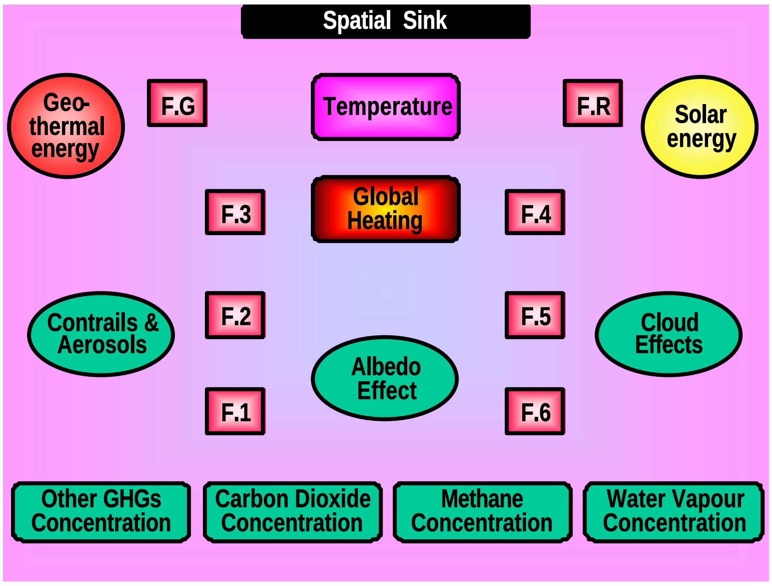
Then we add in **other anthropogenic greenhouse gasses** together with increase in **concentration of water vapour**.



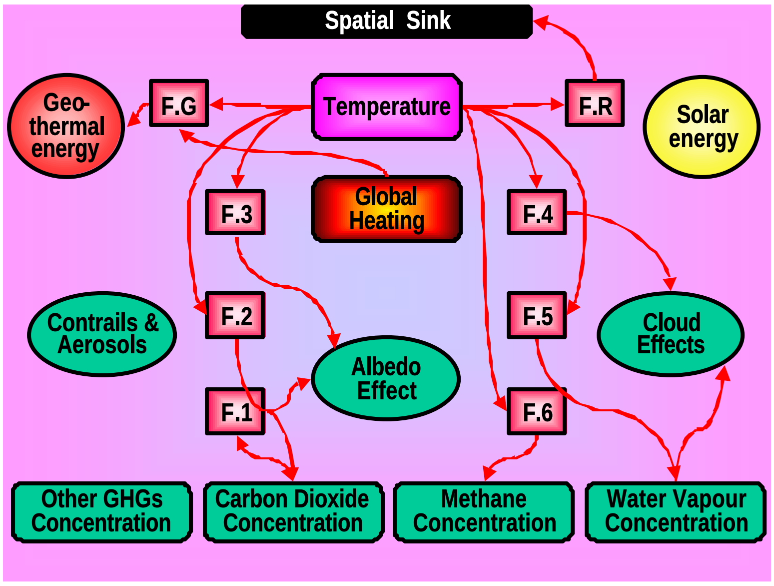
Effects of aircraft **vapour trails**, particulate **aerosols** released in forest fires and industrial process, the **Albedo effects** and finally the complex contribution of **cloud systems** complete the set of drivers of global climate change.



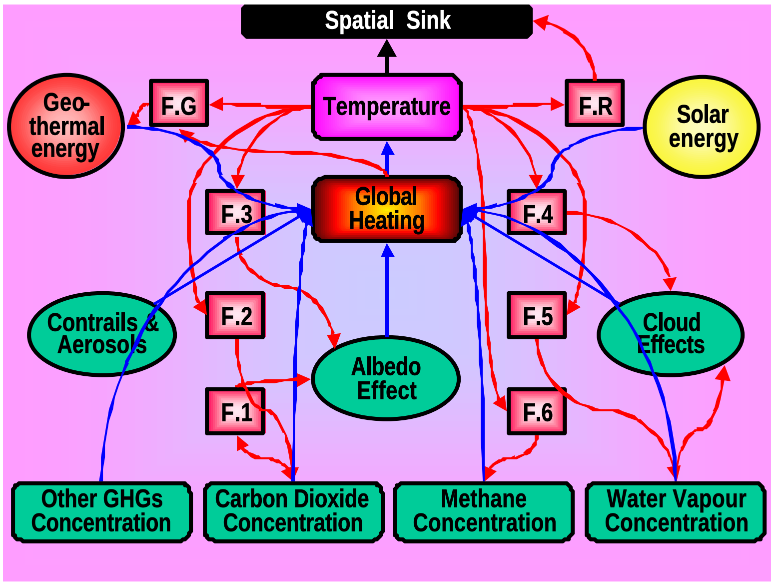
Taken together these elements drive radiative forcing away from equilibrium, so generating global heating which in turn leads to increase in average global temperature, albeit subject to complex sub-system energy-distribution dynamics, endothermic damping, thermal inertia and consequential long time delays. Eventually temperature rises to the point at which radiative loss to the spatial sink establishes a new thermal equilibrium. That is the standard model of climate change. Interacting with that model are the accelerating effects of feedback dynamics to which we now turn.



Six major categories of feedback process can now be identified in addition to radiative feedback between rising temperature and spatial snk, together with geothermal feedback which is of a lower order of significance.

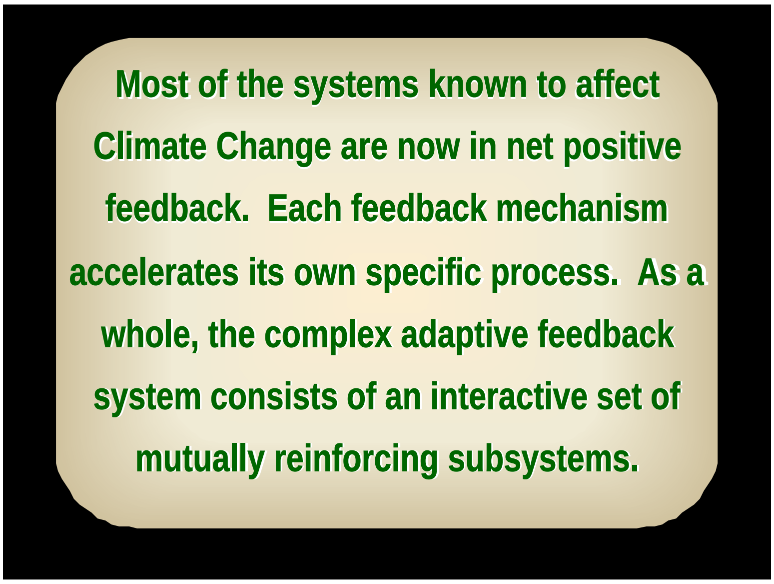


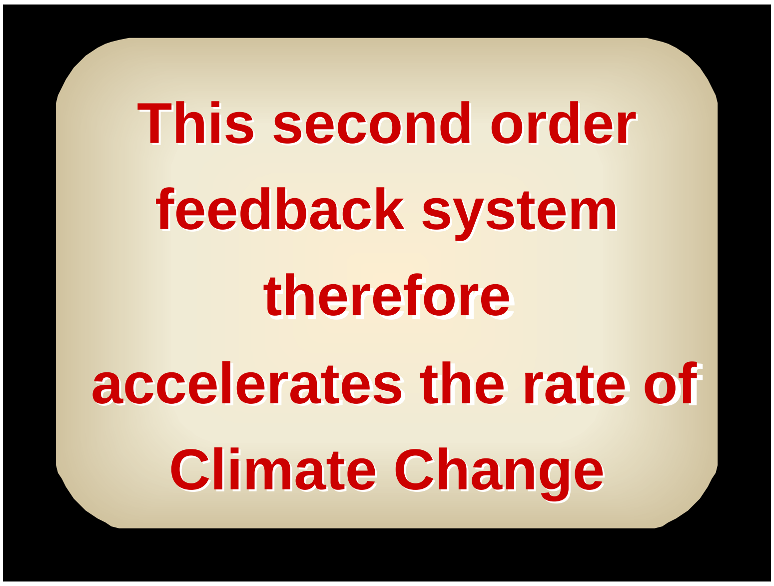
Non-linear relationships link the feedback drivers and their target systems. For example, **F1** is driven by increase in concentration of atmospheric CO_2. It lowers capacity for CO_2 absorption and so increases CO_2 concentration. All other feedback categories are driven by rise in temperature and therefore only come into action once GHG driven global heating begins to take effect.



We can then complete the model by overlaying the complex adaptive feedback system on the standard climate change model. **Appendix 1** lays out the details of the various subsystems, categories of feedback and specific feedback mechanisms. Those who are interested can explore the material further on the Meridian web-site. (In presentation mode we can explore the sections via interactive hyperlinks).

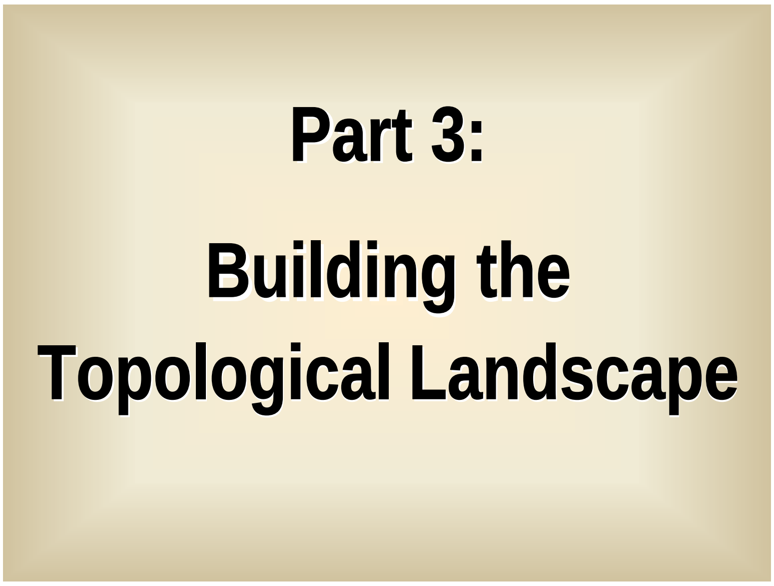
Feedbacks not only affect the specific functions on which they operate. Their output also changes the driver conditions for other feedbacks, which in turn reinforce the driver of the initial mechanism.





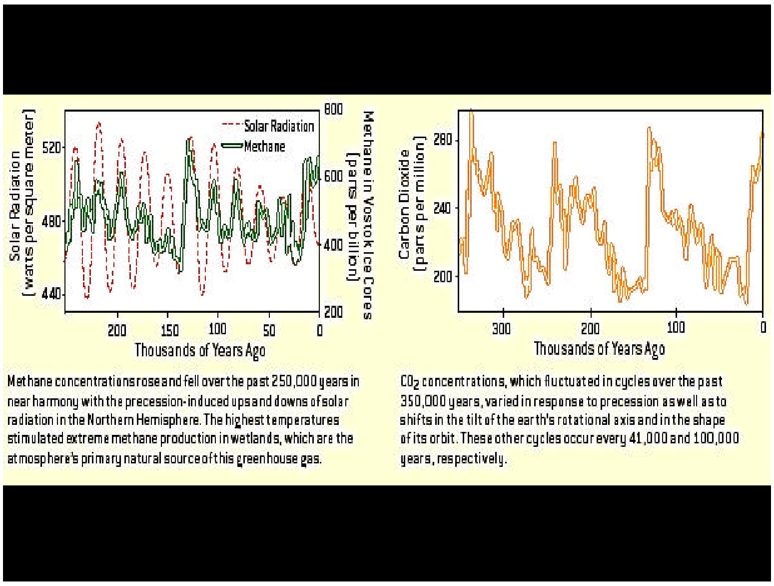
The inclusion of the complex feedback system in our study of the cumulative effects of greenhouse gas emissions leads to a fundamental shift in our understanding of the dynamics of climate change. The development calls in question the inadequate assumptions underlying all current strategic approaches to the control of global warming. It is as significant as the original recognition that human emissions from the combustion of fossil fuels could lead to potentially dangerous levels of climate change. Our world climate responds as a complex adaptive system in which small interventions (GHG emissions) can precipitate large, non-linear effects with long time-delays.

The most sombre outcome of the new research is that we face not just the need to adapt to a shift of a few degrees and its consequences, but that we may well be in the early stages of setting in motion a major extinction event like those in geological history which wiped out between 80 and 95% of all life on earth.

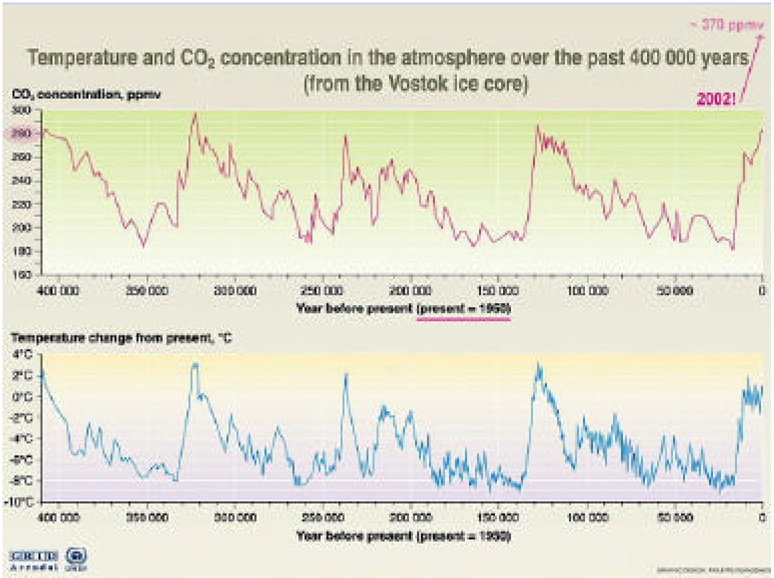


Part 3:
Building the Topological Landscape.

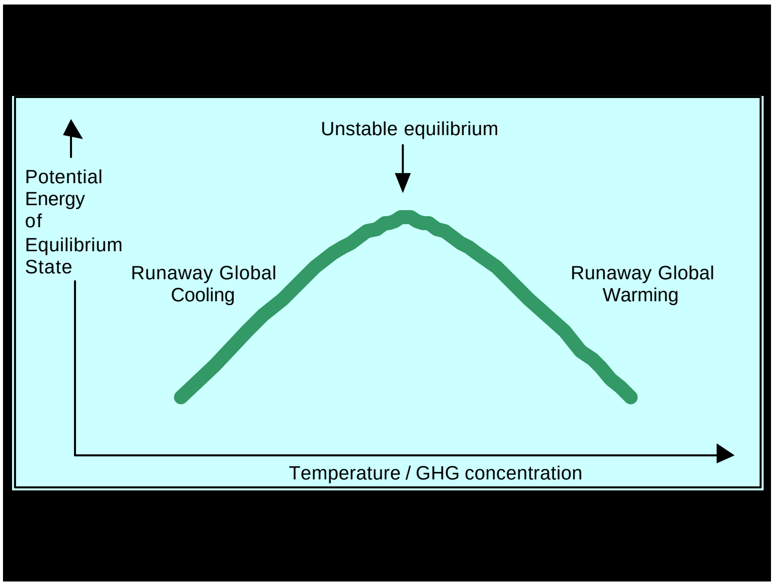
In the third part of the presentation, we move on to explore the behaviour of this complex, feedback-coupled climate system over time, focussing particularly on its dynamics, equilibrium states and tipping points. We will then build a 3D topological landscape on which the watershed and various strategic choices facing us can be clearly mapped.



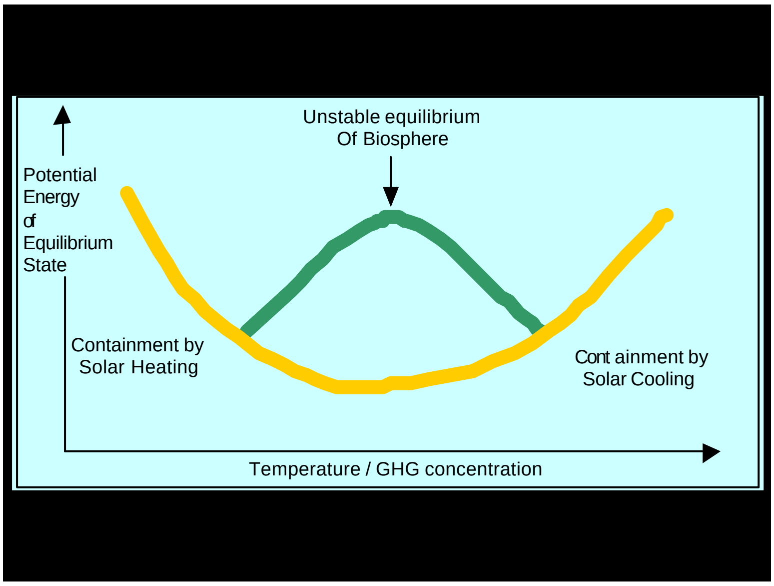
In recent years, cores drilled in the Antarctic and Greenland ice sheets have provided evidence about the earth's past climate, including changes in the concentrations of the greenhouse gasses. A three-kilometer-long ice core retrieved from Vostock Station in Antarctica during the 1990s … confirmed that concentrations of CO_2 and methane rose and fell in a regular pattern during virtually all of the past 400,000 years….. These increases and decreases in greenhouse gasses occurred at the same intervals as variation in the intensity of solar radiation received in the northern hemisphere due to precession of the earth orbit, and tilt and wobble of its axis of rotation. The imbalance in hemisphere behaviour is generated by the change in temperature-driven response of land-based biological systems, since the northern hemisphere has a far greater land mass than the ocean-dominated southern hemisphere.



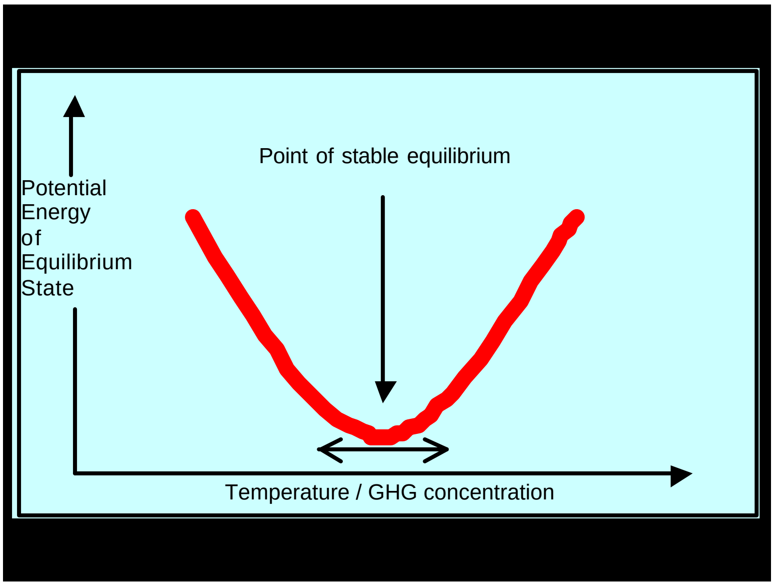
However, the changes in global heating or cooling were significantly greater than the small variations in energy received from the sun in the northern hemisphere. Small changes in insolation triggered weak positive feedback in the earth system, whether of heating or cooling.



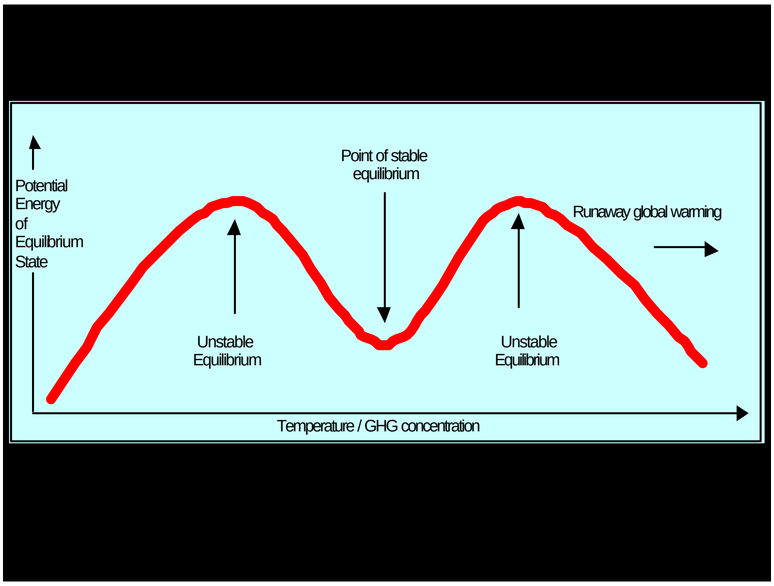
This amplified the effect of the change in solar heating. Cyclical changes in global temperature are the combined result of shifts in received solar energy in the northern hemisphere, and their amplification by the changing greenhouse effect. The GHG production and resulting changes in concentration of atmospheric GHGs, therefore constitute an inherently unstable equilibrium. From its tipping point, **increase** in northern hemisphere heating sets off runaway global warming. Conversely, from the same point, **decrease** in northern hemisphere heating sets of runaway global cooling.



This unstable equilibrium is contained by the changes in northern hemisphere heating. As energy received from the sun starts to decrease after reaching its maximum, it provides a more powerful negative feedback that halts and reverses the weaker positive feedback of the biosphere. Runaway global warming is stopped and reversed. Similarly, at the other end of the cycle, as energy received from the sun starts to increase after reaching its minimum, it again provides a more powerful negative feedback that halts and reverses the weaker positive feedback of the biosphere. Runaway global cooling is stopped and reversed.

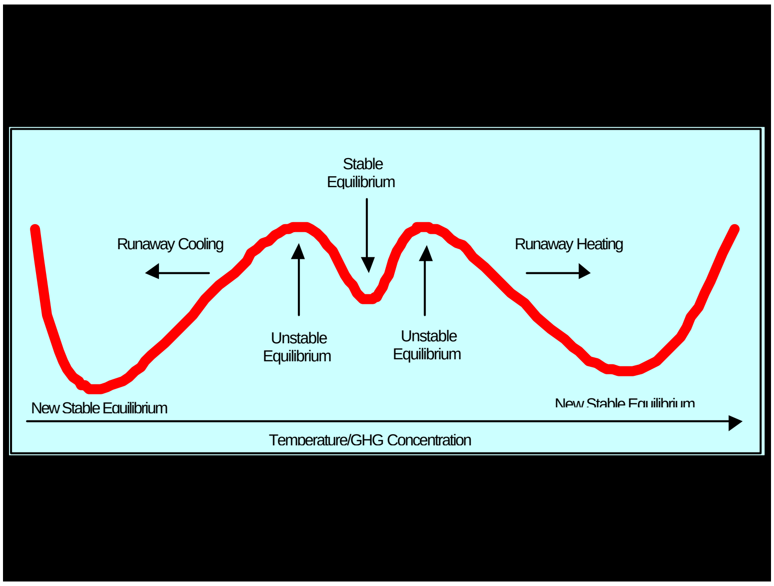


The combined effect of these two interacting features results is the stable equilibrium of the illustration. This analysis alerts us to one very significant proviso. Should any intervention occur to the system dynamics that neutralises the damping effect of changes in solar energy received in the northern hemisphere, then the underlying unstable equilibrium of the biosphere would be exposed without containment. Runaway climate change would proceed without further control. It is precisely such an intervention that has been initiated by the industrial revolution.



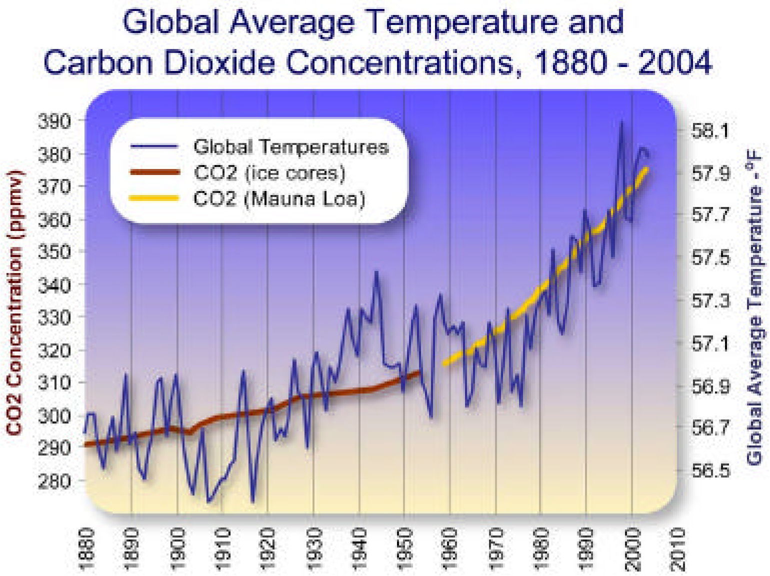
The impact of extreme events, however, illustrates limits to the stable equilibrium. To the left, cooling feedback loops overwhelmed the homeostasis, precipitating the "snowball earth" effect. Slow degrade in the feedback process effected by out-gassing of CO_2 from volcanic activity, led to an eventual recovery of the base equilibrium. To the right, massive release of CO_2 as a result of major volcanic activity in the Siberian region, also overwhelmed the stability and set off positive feedback loops, precipitating runaway global warming and eliminating most life forms at the end of the Permian period.

The central stability (controlled by the damping effect of the negative feedback loops), when disturbed beyond a given range, is subject to increasingly powerful positive feedback processes which push it towards the peak of the unstable equilibrium. Here the negative and positive feedbacks just balance each other. As the positive feedback loops begin to dominate, they move the system beyond the unstable point into accelerating change.

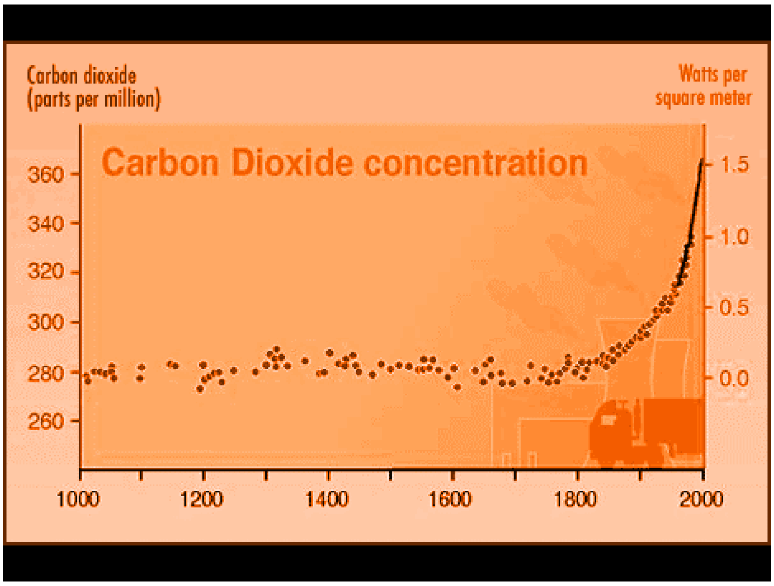


On Planet Earth, these extreme responses are themselves subject to boundaries, creating a wider form of equilibrium, the maintenance of which has enabled the evolution and maintenance of life on this planet (in contrast to conditions on Mars and Venus whose equilibrium basins would be to the far left and right of the diagram). Eventually a new equilibrium is achieved at some distance from the base position. In these extreme conditions the environment is hostile to most life-forms. The biosphere takes many millions of years to recover once the system has returned to the central equilibrium. Five major extinction events have occurred in Geological history. Humanity has just triggered the sixth.

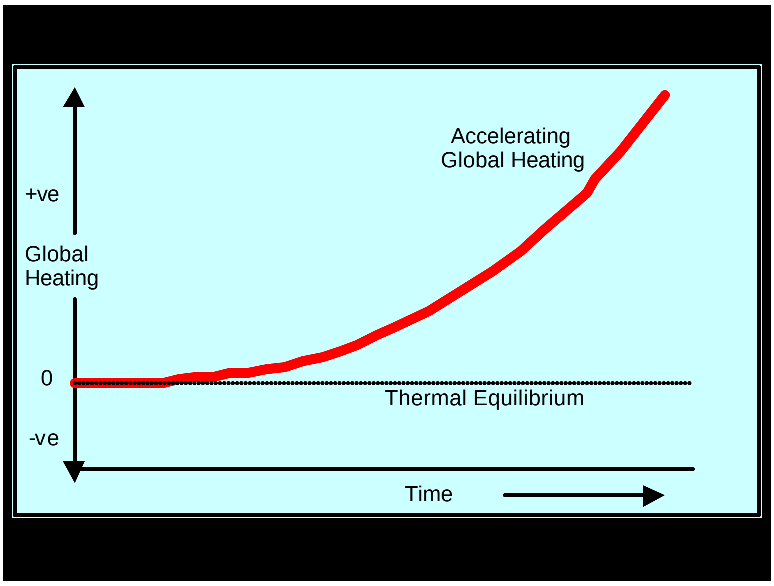
Human emission of GHGs began to accumulate in the atmosphere with the onset of agriculture and deforestation some 8,000 years ago. By the start of the industrial revolution the resultant global warming of some 0.8ºC had almost exactly compensated for the small amount of expected cooling. Since the start of the industrial revolution and the accelerating oxidation of deposits of fossil bio-mass, the rate of accumulation of atmospheric GHGs has speeded up dramatically. The time-scale, although appearing slow in relationship to the individual human life-span, is some 100 times faster than the paleo-geological perturbations of the basic equilibrium. Furthermore, both time-frame and scale of the change have more in common with the extreme events which led to the historical overwhelming of the stable equilibrium.



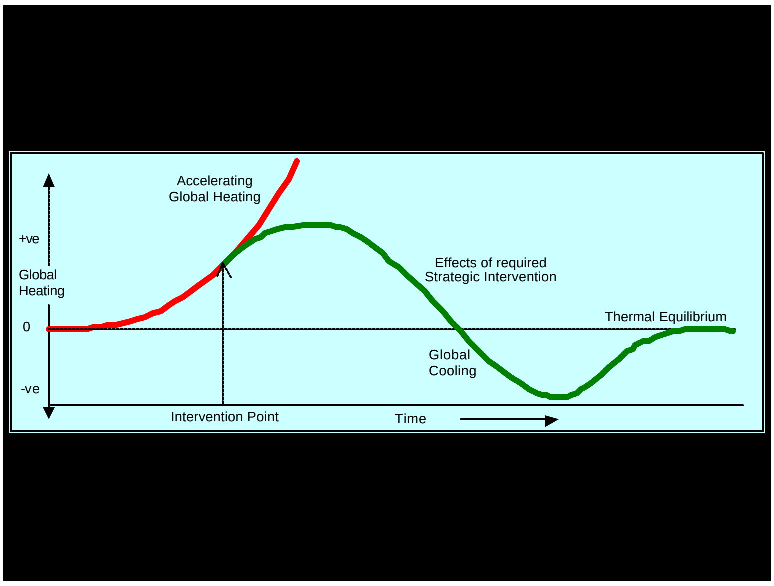
As emissions soared, so the cumulative concentration of atmospheric CO_2 began to rise from its pre-industrial base of 282 parts per million, increasing through the current figure of some 381 ppm, and accelerating past its projected value of some 550 ppm by 2050 unless significant action is taken meanwhile. Global warming has slowly followed suit, albeit with significant time delay since the atmosphere and oceans can take decades to adjust to reach new temperatures. It is also masked by industrial aerosols, and damped by endothermic processes. Temperature increase seen today probably represents the Global Warming due to CO_2 levels of the 1960's.



The effect of time-delay in thermal response results in the accumulation of greenhouse gasses driving radiative forcing away from equilibrium. In 2006, atmospheric concentration of CO_2 stands at 381 ppm. When the effects of CO_2 equivalent emissions are added to this figure, the GHG concentration now stands at over 420 ppm. To this should be added the radiative forcing due to reduced Albedo effect, the increase in methane released from store and the effects of increased levels of atmospheric water vapour. As a first order approximation, radiative forcing is therefore currently running in excess of 3 watts per square metre, and accelerating sharply



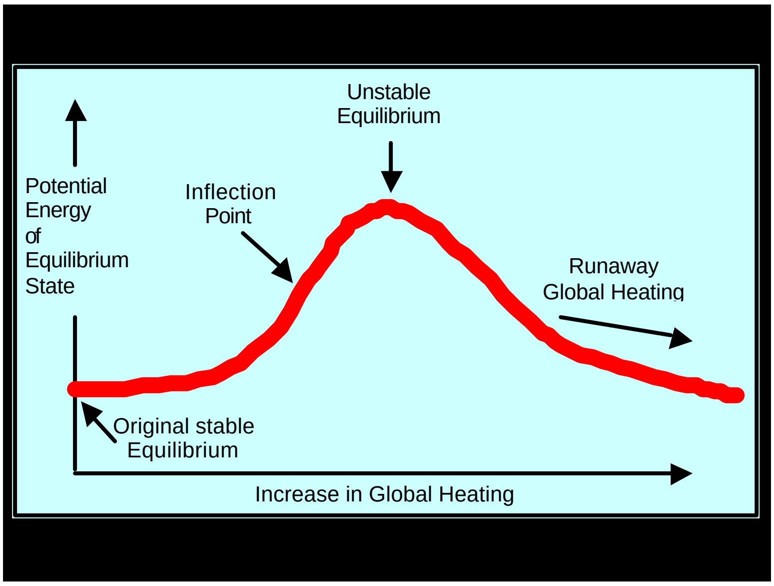
In geological time (apart from the extreme events) thermal equilibrium of the whole-earth system was sustained. Radiative forcing stayed close to zero. Most climate models operate in conditions of near equilibrium. However, the pace and scale of anthropogenic intervention is accelerating radiative forcing away from equilibrium. It is under these conditions that the **effects of positive feed-back loops in the process must now be taken into account, and dynamic climate models generated that operate in far-from-equilibrium conditions**.



Let us now explore the kind of intervention strategy required to re-stabilise the equilibrium.

Sustainability of human life on earth requires the re-stabilising of geo-solar thermal equilibrium at a temperature close enough to the maximum of the warm inter-glacial periods. As an intervention, that entails the slowing, halting and reversing of the increase in global heating, followed by a sustained period of global cooling with negative radiative forcing. Eventually the radiative forcing would need to stabilise at zero with the temperature held constant at the new and acceptable thermal equilibrium. **The effective achievement of such a strategic intervention would only be possible if and while the capacity to reduce GHG concentration outweighed the combined (and time-delayed) power of the set of positive feedback mechanisms. If those criteria were not met, we would face uncontrollable, runaway climate change for the foreseeable future with potentially catastrophic consequences.**

If we are to understand the context of such an intervention and the risks of failure, we need to examine more closely the conditions of the underlying equilibrium topology:



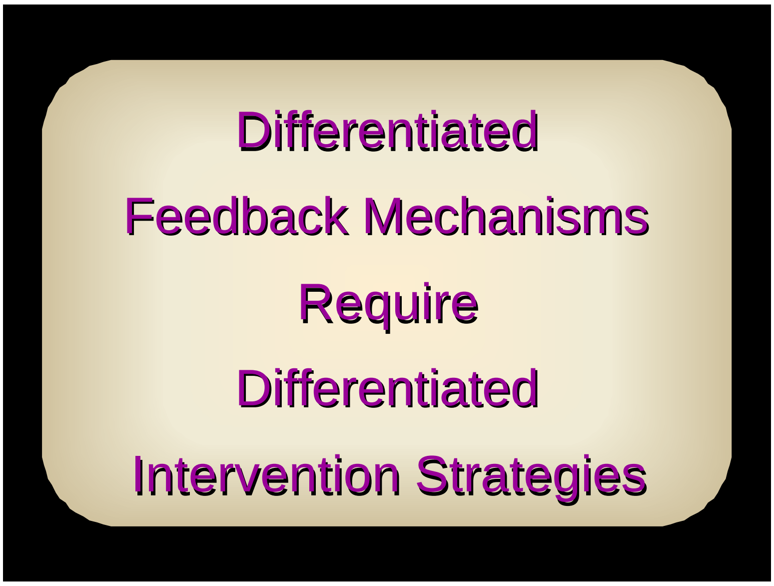
Near the origin the equilibrium is stable. Disturbance is returned to the origin by a constraining set of change-damping negative feedback processes. (In effect the weak positive feedback dynamics of the bio-geo-chemical system were contained by the negative feedback damping dynamics of change in solar radiation received in the northern hemisphere). Driven by accumulation of anthropogenic greenhouse gasses, the energy input from global heating rises, positive feedback loops engage and start to weaken the damping effect and the curve passes its inflection point. As the positive feedbacks gain in relative power they eventually balance the negative feedbacks and the topology flattens out into the rounded summit of an unstable equilibrium or "tipping point". Once that watershed is passed the dynamics are dominated by the positive feedback loops and global heating accelerates away from the original conditions of the stable equilibrium state.

The naturally occurring negative feedback mechanism, that held global temperature and GHG concentration in a stable equilibrium down the ages, has now been overwhelmed by the rate and scale of human industrialisation. So Dennis Meadows writes: "What we really need is to find some major new negative feedback relations". They are not out there to be found. **If we are to have any hope of returning climate change to a stable equilibrium with**

survivable temperatures, we will have to design and implement the negative feedback processes ourselves.

The most effective mechanism that is still open to us is the reduction of GHG emissions on such a scale and in such a time-frame that it will actually slow, halt and reverse the increase in GHG concentration.

However, the intervention would also need to out-perform the temperature-dependent positive feedback system that will be triggered during the long period of rising temperature. It will also have to compensate for the effects of the long, slow, clathrate release as the slow mixing of warm surface water reaches down to the clathrate deposits on the shallow ocean floors. The required outcome is the eventual return of the level of global heating and its equivalent global temperature, to a survivable and stable equilibrium.



The first set of CO_2-dependent feedback loops, which increase CO_2 concentration and drive global heating, can be neutralised by stabilising CO_2 concentration itself. That requires a reduction in CO_2 emissions to a rate which can be totally absorbed by the environment, a level which is itself degrading over time.

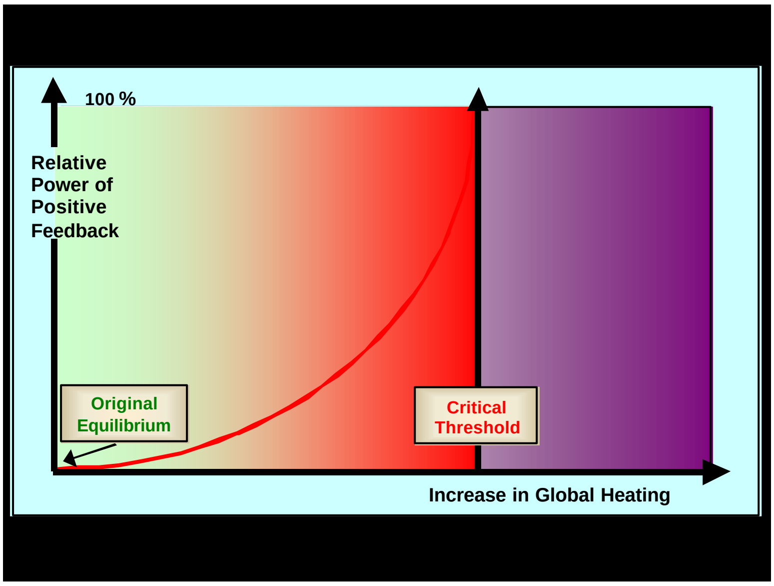
The second set of hybrid loops are driven by rising temperature but result in increased CO_2 concentration. Since there is a significant time-delay in the stabilising of global temperature for any given CO_2 concentration, these loops would continue to be active after the point at which the first set had been neutralised. Rising temperature would therefore continue to lead to increased CO_2 concentration. That in turn would reactivate the first set of feedback loops which are themselves dependent on CO_2 concentration. During the period before temperature increase had been halted, neutralisation of this process would therefore require further reduction in emissions to levels significantly below the environmental absorption capacity.

The third set of feedback loops are temperature driven and independent of the CO_2-emission cycle. These continue to drive temperature upwards for as long as temperature is actually increasing. They also set off mechanisms of global heating which are themselves subject to long time-delays in reaching their full effect. The albedo effect, the increase in water-vapour concentration and the release of methane from thawing permafrost are three of the most powerful positive feedback loops driving the acceleration of global heating. The hotter it gets the more powerfully active this set of feedbacks becomes, setting in motion an uncontrollable chain-reaction with a long built-in time-delay. **Containment of this set of positive feedback loops and their transformation into a negative feedback process will require a dramatic reduction in GHG emissions at the earliest possible date** in order to ensure the lowest possible peak of the temperature trajectory. It is not clear whether that window of opportunity is still open.

New research indicates that if the thermohaline conveyor collapses, there would be a sharp rise in ocean floor temperature in the far north Atlantic. The change would be of the order of 5º C. and would be sufficient to trigger a major release of methane clathrates. That would contribute to a rapid increase in positive feedback in the climate system.

The slow cascade of methane clathrates poses a particular difficulty since it may take several centuries for the mixing of warmer ocean-surface water to begin to reach and release the frozen deposits. Resultant increased concentration of atmospheric methane increases the greenhouse effect, temperature continues to rise with long inertial time delay, so continuing the warming of ocean surface water and sustaining the slow clathrate cascade. Atmospheric methane also degrades chemically to produce an increasing source of atmospheric CO_2 which enhances the feedback. The process constitutes a long term instability. It is a threat to any sustainable containment of climate change that we are able to mobilise.

It is therefore imperative to explore the limits of our power to intervene in the complex feedback system. The reduction in emission of human-generated GHGs is the only current intervention by which we can make a difference in the system dynamics (though possible massive increase in Albedo effect by seeding cloud formation over tropical ocean areas, or creating reflective clouds high in the atmosphere, are also being investigated).



On the vertical axis we now map the relative power of the positive (change accelerating) feedback processes as a percentage of the power of the negative (damping) intervention of reduction in GHG emission.

At the origin, when GHG concentration was still virtually undisturbed and environmental absorption of emissions could still handle all we produced, power to contain system disturbance by reduction in emissions was 100%, and the positive feedback dynamics were inactive. As emissions started to exceed environmental re-absorption capacity, the GHG concentration started to rise. That set in train eventual (time-delayed) response of the temperature disturbance. By the time global warming became detectable, positive, change-reinforcing, feedback loops had already started to play their part. As global heating continues to rise, the power to make a difference in the feedback balance by reducing emissions, starts to decline. Eventually the positive feedback process takes control and all further effect of emissions reduction is nullified.

The critical feedback threshold at which this takes place represents the closing of the window of opportunity during which human initiatives to generate negative (system-damping) interventions are still able to halt global warming and return it to a stable, life-sustaining, equilibrium.

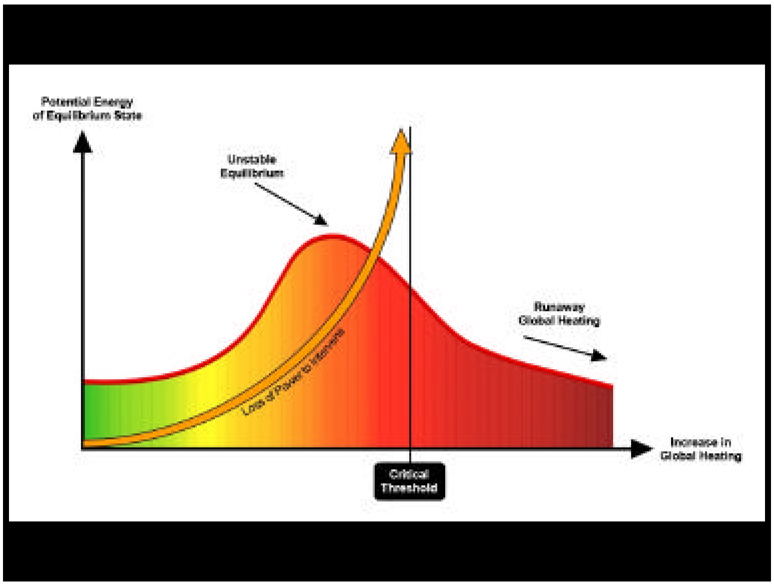
The more powerful the positive feedback loops become, the more massive and costly is the intervention needed to return the system to equilibrium. As the energy exchange approaches the critical threshold, the power ratio between positive feedback and controlling intervention (and the total cost of making an effective intervention) reaches a vertical asymptote. In other words it approaches infinity.

Beyond that critical threshold in global heating there is no further intervention capable of damping the system. The runaway chain-reaction of uncontrollable climate change will have been initiated, leading inevitably to the sixth or "Anthropocene" extinction event.

Current strategies assume no limit to the time-scale within which it is still possible to intervene effectively. They also deny any degrade in the ability of emissions-reduction to control the rate of global heating however high it becomes. In so doing they gravely underestimate the power of positive feedback. **These are false assumptions that are placing the future of our civilisation in extreme danger.**

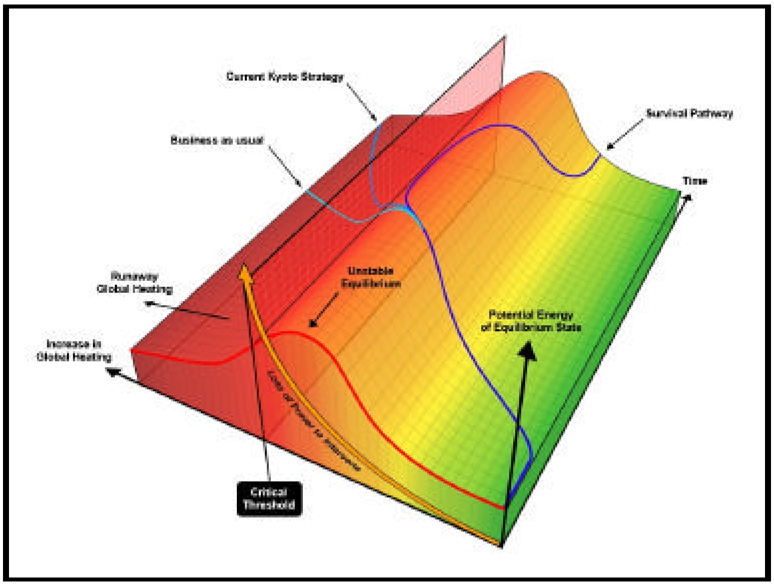
Current economic cost analysis of mitigation of climate change discounts future cost against cumulative inflation (de-valuation of future wealth), justified by assumptions of unconstrained patterns of future growth. Critical threshold analysis inverts this economic scenario. Mitigation cost is now at its lowest level. It escalates as the critical threshold is approached. It would absorb an increasing proportion of global GDP to the point where it becomes economically impossible to make a significant difference, however much money is diverted to the task.

We are now ready to combine the critical threshold graph in a single diagram with the previous equilibrium topology surface.



Pre-industrial accumulation of human-generated GHGs just cancelled out the natural damping negative feedback system, leaving the earth in balance in a condition of unstable equilibrium. Exponential increase in GHG concentration driven by the industrial revolution then tipped the system over the top of the hill and into the present state of accelerating climate change. The effects of human-generated emissions are being amplified by an increasingly powerful set of positive feedback mechanisms, the behaviour of which is driven both by increase in GHG concentration and also by the time-dependent effects of temperature change. The further we move away from the position of unstable equilibrium, the more powerful the positive-feedback system becomes, and the faster is the resultant rate of climate change.

The wall marking the critical threshold rises through the down-slope, beyond the peak of the unstable equilibrium. The window of opportunity within which human intervention (by reduction in GHG emissions, increased cloud albedo, etc.) is able to contain the process of global heating and return the system to equilibrium, lies to the left of the critical threshold. It is not yet clear how close to that threshold we are in reality, or whether in fact it has already been passed. Loss of power to intervene in the system becomes absolute as the wall is approached. **The closer we come to the critical threshold, the more massive and costly the required intervention becomes.**



Let us now introduce the dimension of time from left to right along the front horizontal axis. The lines of the previous diagram are now stretched out as surfaces within the volume of the resultant three dimensional space.

The tipping point, or watershed, is now represented by the ridge stretching from left to right. Near to the front face is the green valley area of historically stable equilibrium. The surface rises from the valley through the inflection line, where the positive feedback loops begin to influence the system. It then climbs on up to the unstable equilibrium at the summit of the ridge where the positive and negative feedback processes just cancel each other out. Over the hill the positive feedback loops are dominant and drive runaway global heating and the resultant climate change.

The vertical wall of the critical threshold reaches up through the downward slope on the far side of the ridge. It contains the area within which human intervention is still able to return the system to a stable equilibrium. As the wall is approached the power of this intervention decreases rapidly, and the reduction in emissions required to stabilise the system becomes massive and increasingly costly.

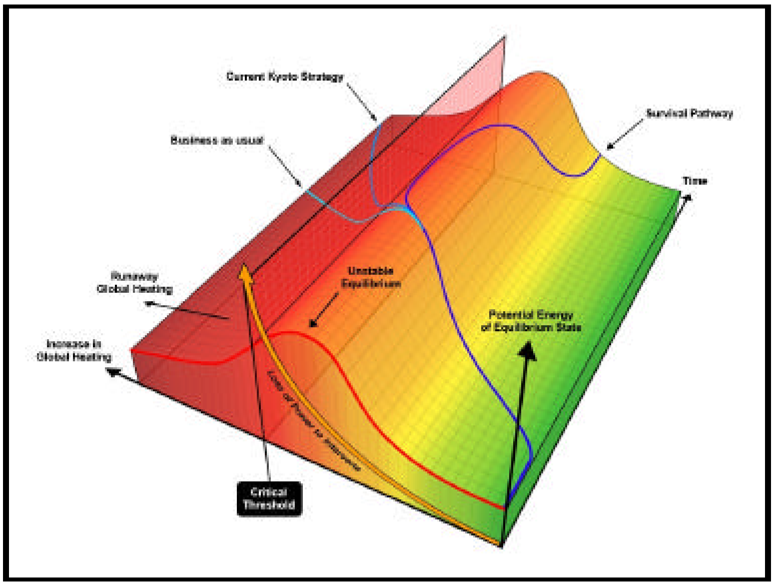
Inactivity is not neutral. Every passing year reduces even further the window of opportunity within which it is still possible to avoid the chain-reaction of uncontrollable runaway climate change. It also drives up the cost of achieving any desired outcome.

We are now in the early stages of runaway Climate Change.

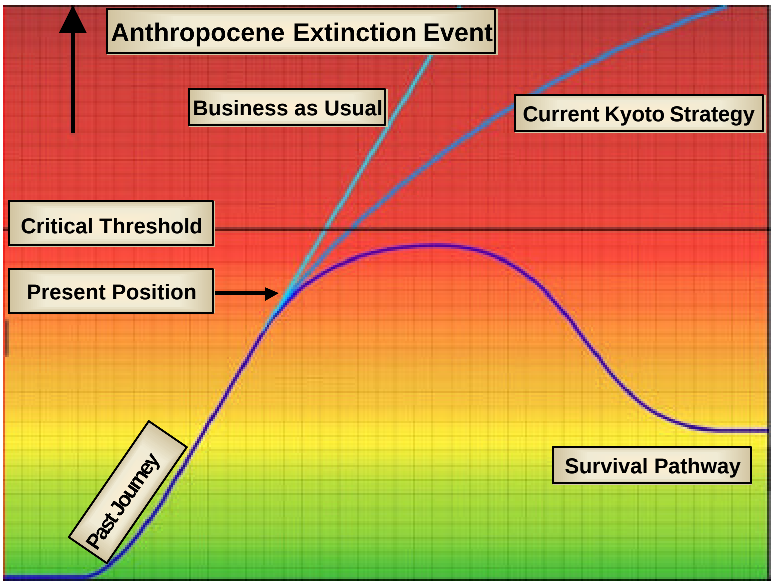
There does not appear to be any naturally occurring negative feedback process in place to contain its effects.

Strategically we have to generate a negative feedback intervention of sufficient power to overcome the now active positive feedback process.

Then maintain its effectiveness during the period while temperature-driven feedback continues to be active.



So today we are facing a watershed in the whole earth system that places the issue of sustainability in a new and critical context. Without effective action we **will** trigger the Anthropocene Extinction Event. If we look down on the landscape, we see that



Four ways meet at the present crossroads. The unalterable past of our historic journey opens into three choices:

The **"business-as-usual" path** stretches downwards on the steepening slope, passes through the wall of the critical threshold and descends ever-further into the vale of positive feedback, the landscape of runaway climate change.

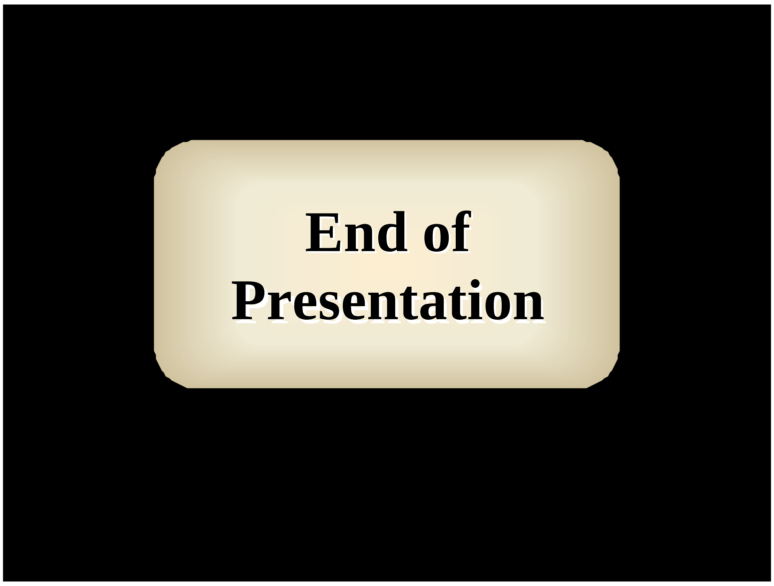
The Current Kyoto strategy, aimed at slow reduction of the rate of increase in GHG emission and, eventually, decrease in the volume of emissions themselves, even if successful, does not reduce GHG concentration. It merely reduces the rate at which GHG concentration rises. Global heating continues to increase, though at a somewhat reduced rate. Positive feedback processes (particularly the temperature sensitive ones) are not de-activated but slightly damped. The projected path through the equilibrium landscape deviates slightly to the right. The descent is slowed, but continues inexorably down the slope, away from the ridge and on past the critical threshold into the domain of runaway climate change.

The Survival Pathway is the only intervention that can halt the descent, turn it along a contour-line and then make it climb slowly back up and over the ridge. It requires a strategy of sustained reduction in GHG concentration, stabilising and reducing the rate of global heating and initiating a period of global cooling. That scenario would have to be held in place whatever positive feedback loops were activated in the long period before the rise in global temperature was halted, reversed and brought into a constant stable equilibrium. It would then have to sustained until the potential instability of the methane clathrate cascade had been effectively contained. The sharper and faster the intervention is effected, the more hope we have of averting an otherwise inevitable climate catastrophe of our own making, the Anthropocene Extinction Event.

We cannot afford any further delay in effective action. Any procrastination increasingly risks global bankruptcy in financing the needed intervention, and massive human suffering in carrying it through to completion. It also threatens our ability to regain control before the system is overwhelmed by the positive feedback loops and drifts inexorably into runaway global warming. To allow the powerful vested interests of the social, economic and political systems to continue to hijack the world and hold it

to ransom for the sake of short term profit, political power, and national protectionism, would be an act of collective suicide.

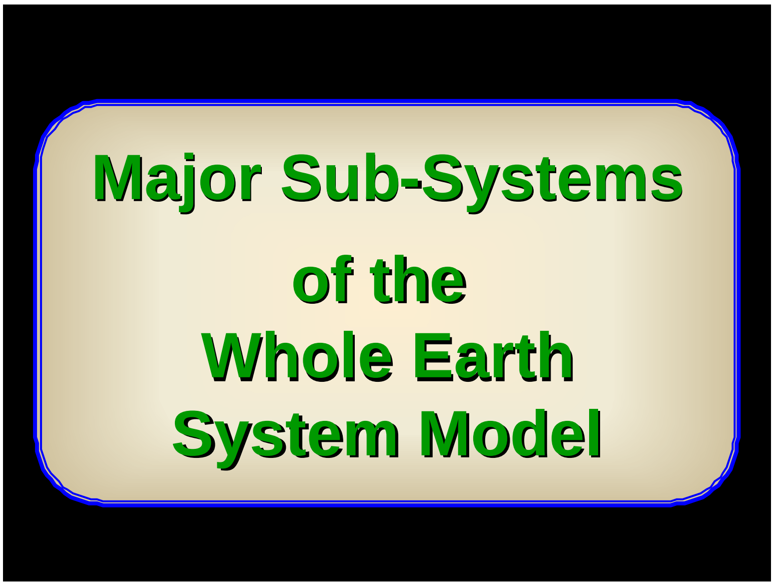
We have a job to do. It is far more difficult and more urgent than we had previously thought. The effects of failure would be catastrophic on a scale that few of us had dreamed of, even in our worst nightmares, just a few short months ago.



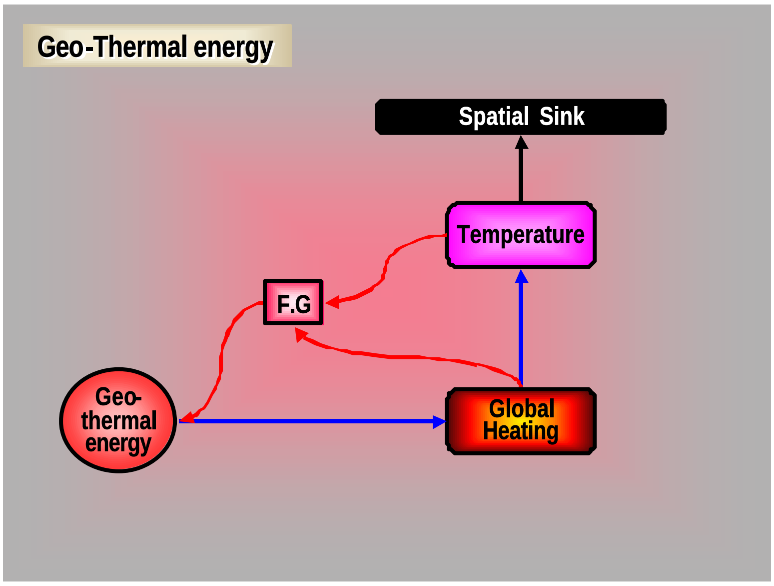
Appendix 1:

Sub-systems of the Whole Earth System Model

Exploration of the details of the conceptual model, begins with an examination of the major cycles or sub-systems. It is followed (Appendix 2) by a listing of the eight feedback categories, distinguished by originating driver and influenced target system. Then (in Appendix 3) there is a detailed description of the specific feedback mechanisms involved in each cycle and category.



For the sake of completeness we will start this first Appendix with the dynamics of geo-thermal energy exchange, even though the order of heat-flows involved is likely to be negligible in comparison to the power of the solar-driven processes. The other cycles (Radiative, Carbon; Albedo; Water-vapour; Methane, and Human Activity) are then treated in order.

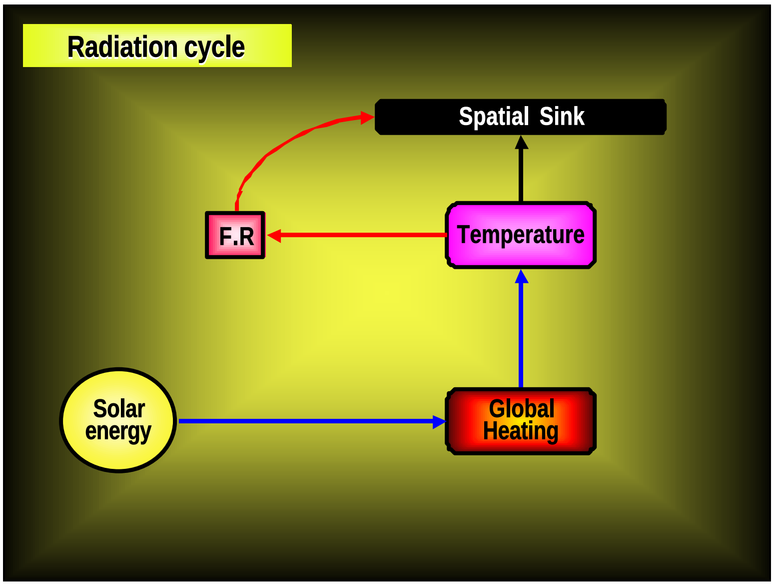


Heat energy generated by radio-active decay of heavy elements in the earth core, surfaces via conduction, convection and radiation through the mantle to the solid crust. Within the rock layer conduction continues the heat transference with a temperature-profile of the order of some 17ºC per kilometre of depth. Eventually heat reaches the crust surface to be carried onwards via conduction, convection and radiation, through the media of oceans and atmosphere. As a direct driver it imparts energy to the atmosphere, contributing to surface temperature.

The rate of change in the system is geologically slow and can be ignored within the time-scale of immediate human civilisation. The energy flows are also small in comparison to those driven by received solar radiation, but are included here for the sake of completeness in the earth system model.

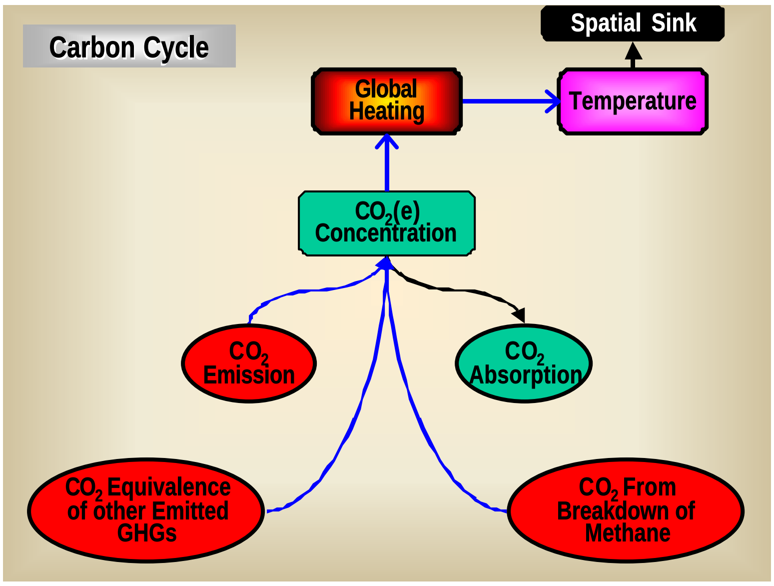
While radiative forcing is close to zero and the earth system is in stable thermal equilibrium, geo-thermal energy provides a virtually constant background warmth. Radiation in the form of long wave-length infra-red is partially contained by the greenhouse effect of atmospheric gasses. Loss of geo-thermal energy from the earth surface balances energy output from radio-active decay and the sub-system maintains its own condition of thermal equilibrium.

Feedback in this cycle is caused by inhibition of surface radiation and convection of geo-thermal energy due to rise in surface temperature of land masses and also by increased greenhouse effect.



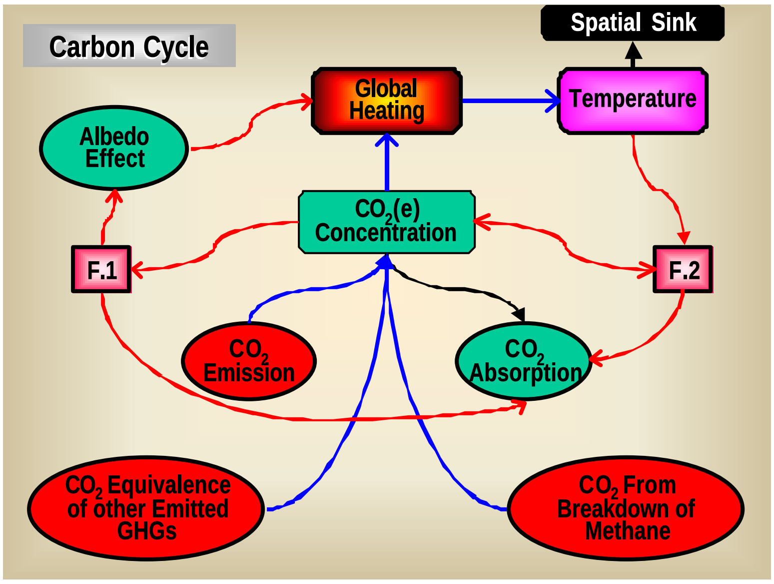
Solar radiation is the dominant source of global heating. The resultant average global temperature is moderated by the bio-geo-chemical systems and by the land-ocean-atmosphere dynamics. Heat is ultimately lost to the spatial sink by infra-red radiation, though a small amount of solar energy is continuously sequestered via neg-entropic molecular complexification.

Feedback in the radiation cycle is driven by increased average global temperature precipitating eventual increase in energy discharge via infra-red radiation to the spatial sink. The mechanism acts as a negative feedback process which restores thermal equilibrium to the whole earth system.



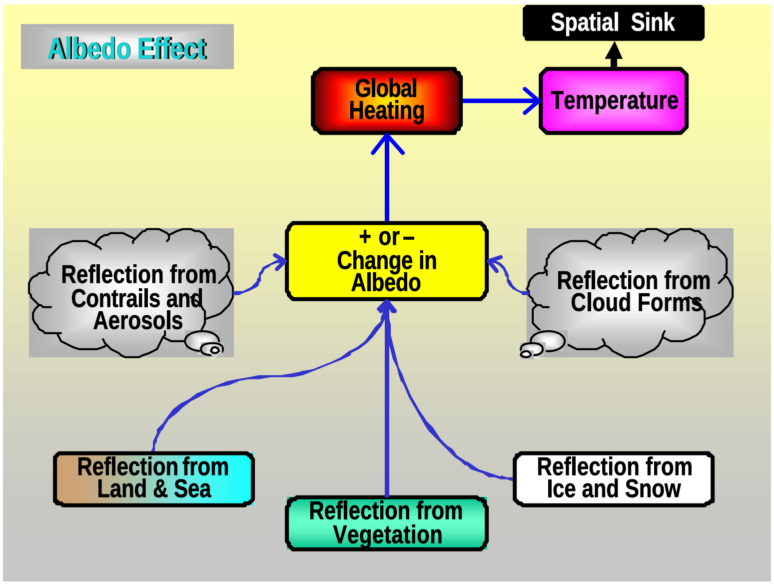
Current atmospheric concentration of CO_2 stands at 381 ppm. When the effects of other anthropogenic GHG emissions are calculated in terms of CO_2 equivalence, the figure increases to approximately 425 ppm. It is rising at 2.0 ppm per year, and the rate of increase is itself rising. The store of atmospheric CO_2 (e) is fed by emissions of CO_2 and CO_2 equivalent gasses from all sources including the out-gassing of volcanic activity. CO_2 also joins the store from the atmospheric breakdown of methane which is the subject of a separate cycle (see **4.e** below). The store is diminished by the sink of CO_2 absorption by all means, so that increase in CO_2 concentration is the net sum of all sources less all sinks.

The rising level of concentration of atmospheric CO_2 increases the greenhouse effect, drives radiative forcing away from zero, increases global heating and results in slow increase in global temperature.



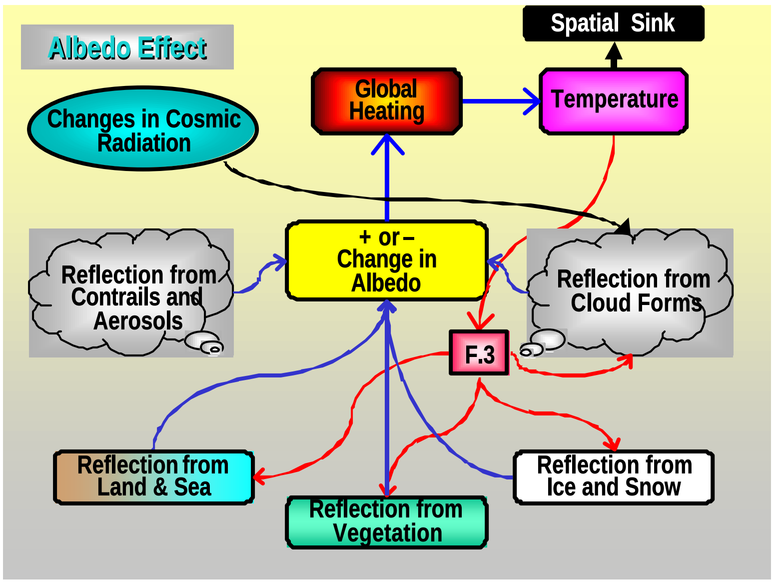
Two feedback categories are associated with the carbon cycle. **F.1** is driven by increasing concentration of atmospheric CO_2. One CO_2-driven feedback with effect on tropical cloud albedo is included in this category as a matter of convenience.

F.2 on the other is hand is driven by rising temperature (or by a combination of increase in both temperature and concentration of atmospheric CO_2). It also acts on the absorption sinks, degrading their capacity to sequester CO_2 from the atmosphere.



Change in the total amount of solar energy reflected back out into space from the earth as a whole determines the Albedo effect. If reflected solar energy decreases, more heat is retained and temperature increases. Conversely if more solar energy is reflected, less heat reaches the earth surface and average temperature decreases.

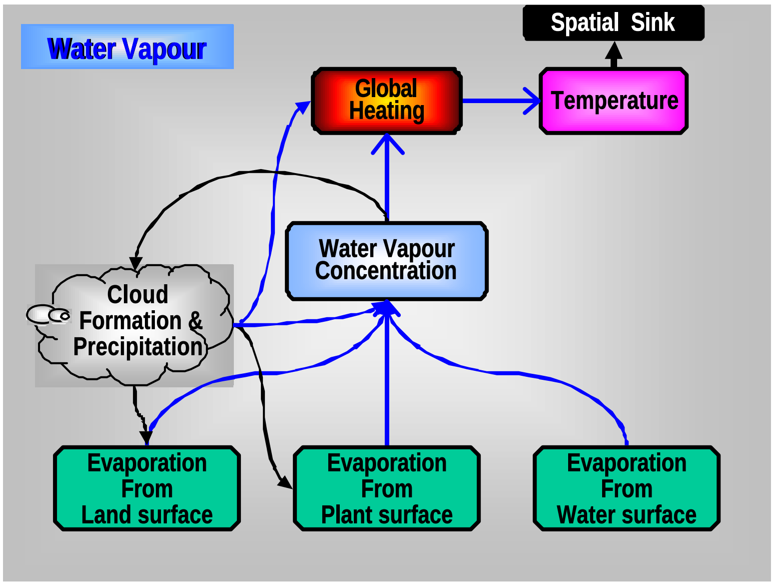
The global summation hides an almost infinite complexity of local variation and change in Albedo, driving sub-system or niche changes on a variety of scales.



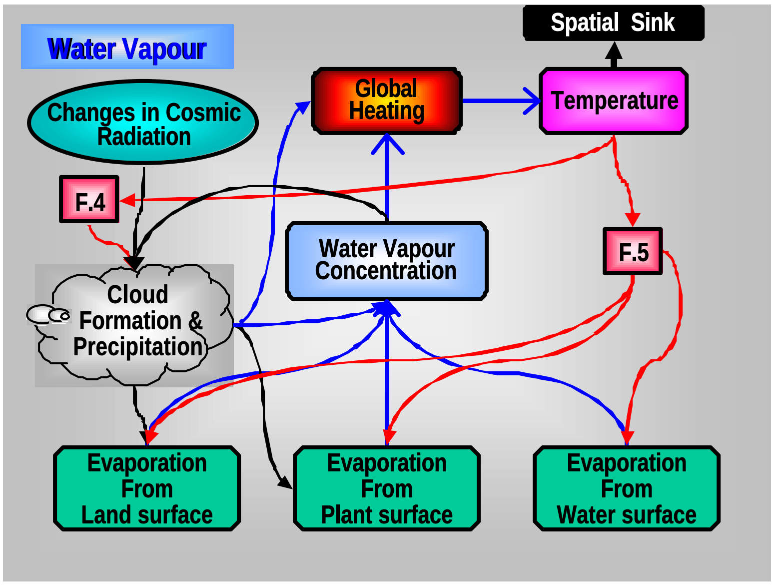
Cosmic radiation is understood to influence cloud formation in the upper atmosphere, (and therefore the Albedo effect of high clouds). The 22 year cycle in cosmic radiation activity can be expected to add a periodic ripple to cloud Albedo. However, if significant change occurs at sensitive points in the non-linear complexity, it could precipitate larger or longer lasting effects.

Sunlight is reflected from the vapour-trails of high-flying aircraft leading to surface cooling in areas subject to high density aircraft activity. Airborne particulates (aerosols) also scatter and reflect light, masking the greenhouse effect, whether the aerosols arise from forest fires, volcanic eruption, or industrial activity and the burning of fossil fuels.

Feedback category **F.3** is driven by rising temperature. It operates across a variety of functions to change Albedo and reinforce global heating.



Water vapour is the most dominant greenhouse gas. It maintains earth's surface temperature within a life-supporting range. Human industrial activity and the combustion of fossil fuels have no appreciable direct effect on the concentration of atmospheric water vapour. Deforestation and change in land use alter the rate of evaporation from vegetation and land surface and so influence air humidity. However, the vast extent of the ocean/atmosphere interface is the main controlling factor. The water cycle of evaporation, condensation, cloud formation and precipitation maintains the stability of complex climate conditions for a given average global surface temperature.



Anthropogenic rise in global heating, driven by emission of CO_2 and its atmospheric accumulation, has begun to increase the temperature of the ocean surface layer and of the lower atmosphere above it. This initiates a set of temperature driven feedback mechanisms with profound effects on climate change. Evaporation is an endothermic process, so increased evaporation takes up energy from global heating and stores it in the atmospheric water vapour. Temperature change at the ocean/air interface is therefore less than would otherwise be expected. The latent heat is released higher in the atmosphere as the water vapour condenses during cloud formation. The resultant heat energy raises the temperature of cloud systems, and increases the energy of storm events.

Hotter air can store higher concentrations of water vapour before reaching dew-point, but once that new level has stabilised, the continued raised levels of evaporation drive increased density of cloud-cover and resultant increase in precipitation. Feedbacks in the water cycle are divided into two categories.

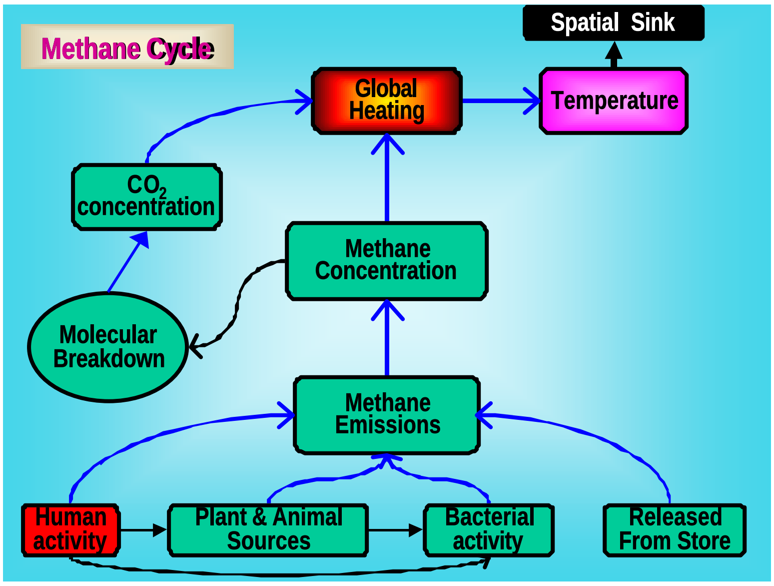
One of the possible interventions designed to halt anthropogenic climate change is a **shift from fossil fuels to hydrogen** as a mobile source of energy. Production of hydrogen would also have to be conducted in such a way as to ensure that no greenhouse gasses were emitted in the process. Some commentators have queried whether emitting water vapour (the by-product of burning hydrogen) as a replacement for CO_2 would be any gain, since water vapour is such a powerful greenhouse gas in its own right.

Several responses are in order:

- Firstly water vapour can be condensed at source, while the sequestration of CO_2 is much more difficult.

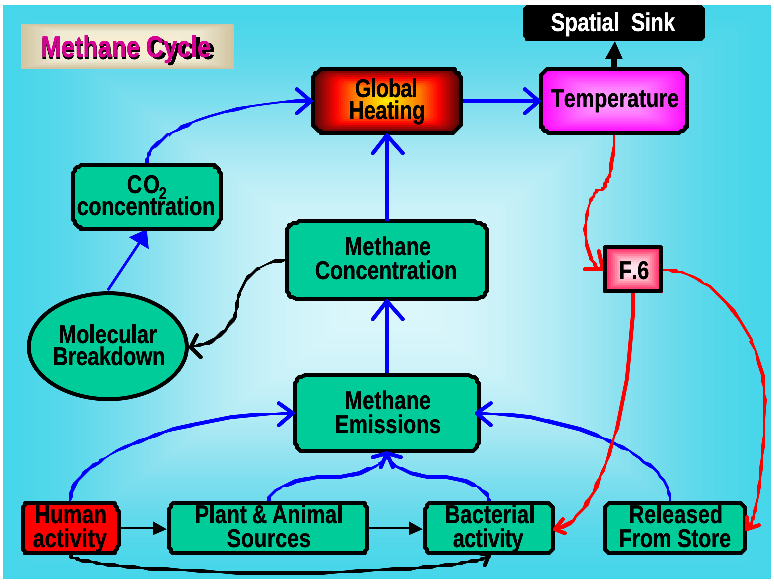
- Secondly, water vapour can have a very short atmospheric life before condensing and returning to the earth surface as precipitation. CO_2, on the other hand, has an atmospheric life measured in centuries or even millennia.

Finally, while anthropogenic emission of CO_2 makes a significant difference to the atmospheric concentration of the gas, there is such a vast stock of water vapour already in the atmosphere, that the additional amount generated by a hydrogen economy would be completely insignificant.



Although itself a carbon compound, the methane cycle is treated separately from the carbon-dioxide dominated carbon cycle for the sake of this analysis. The atmospheric life of a methane molecule is much shorter than that of a molecule of carbon-dioxide. Methane breaks down into CO_2 and water vapour. The higher the concentration of atmospheric methane, the greater the rate at which atmospheric CO_2 is added into the carbon cycle. Molecular breakdown is the main sink of atmospheric methane, itself a greenhouse gas some twenty-four times more powerful than carbon-dioxide.

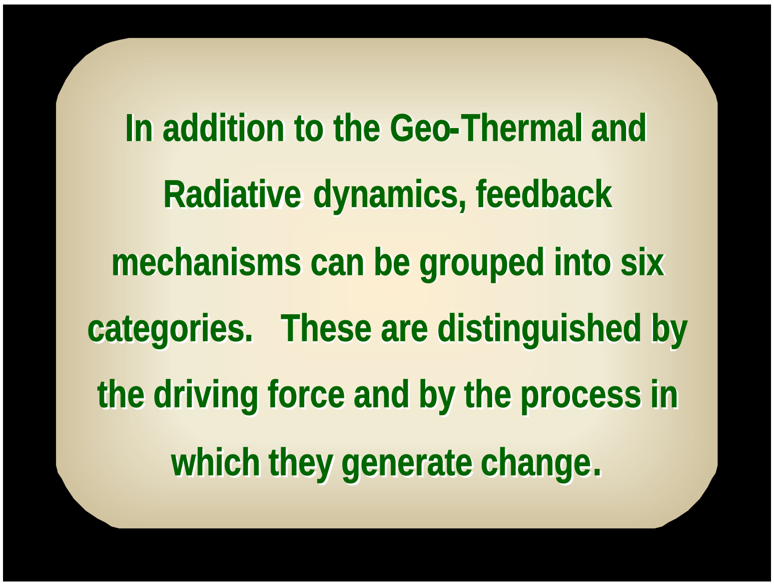
The multiple sources of methane emission are set out at the base of the diagram.



The final feedback category, **F.6**, is driven by rising temperature and therefore responds with a time-delay, as a secondary process to the primary increase in global heating caused by anthropogenic emission of other greenhouse gasses.

Appendix 2:

Feedback Categories of the Whole Earth System Model



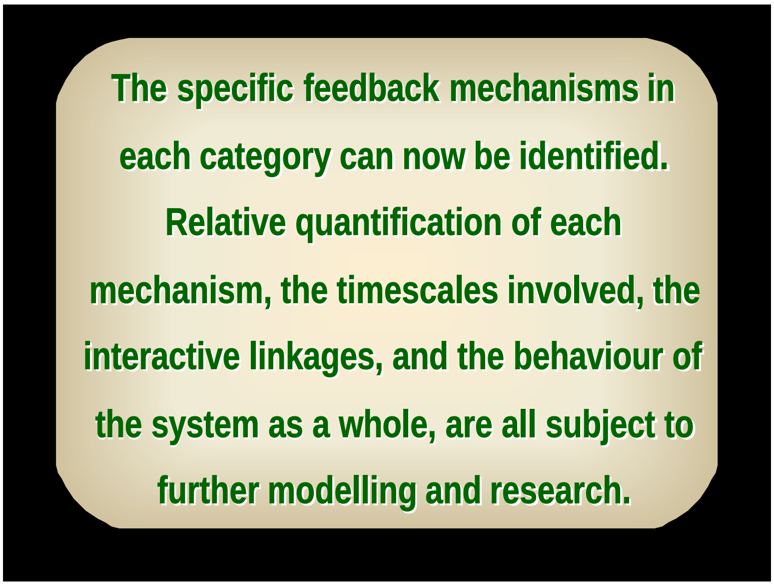
Feedback Category Key

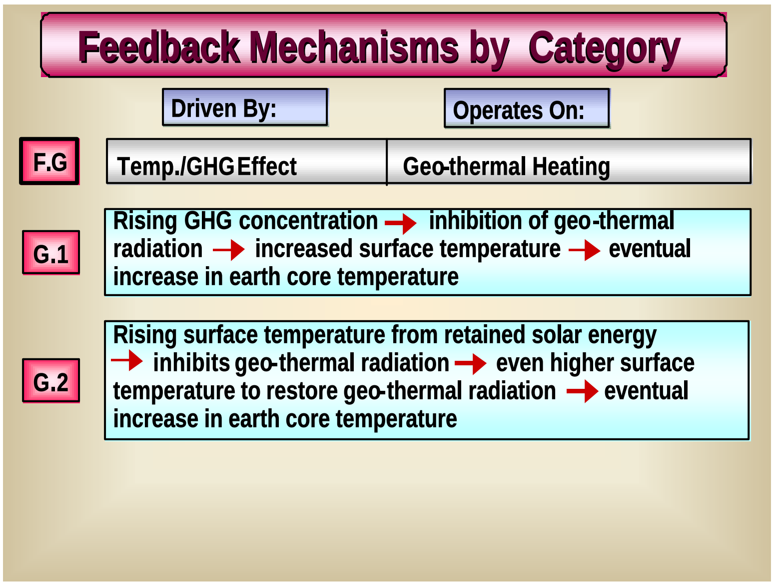
	Driven By:	Operates On:
F.G	Temp./GHG Effect	Geo-thermal Heating
F.R	Temperature	Radiative Forcing
F.1	CO_2 Concentration	CO_2 Absorption Rate
F.2	Temp./CO_2 Concentration.	CO_2 Concentration/Absorption
F.3	Temperature	Albedo Effect
F.4	Temperature	Cloud Formation
F.5	Temperature	Evaporation
F.6	Temperature	Methane Emissions

The complete set of feedback categories with their drivers and operational functions, is laid out like this:

Appendix 3:

Feedback Mechanisms of the Whole Earth System Model

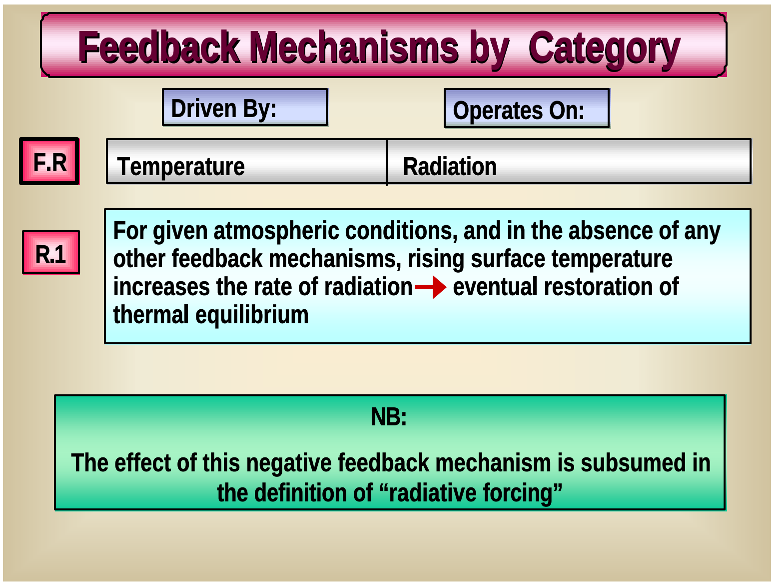




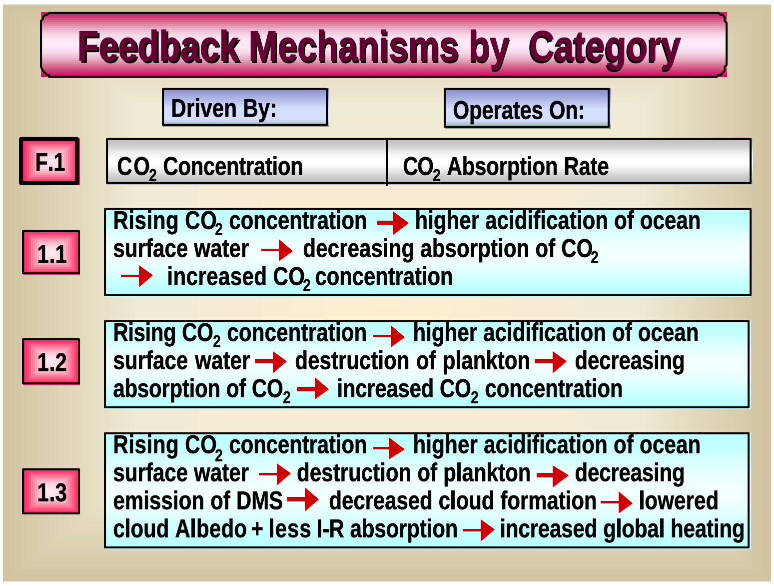
As rising concentrations of greenhouse gasses drive radiative forcing away from zero, they also trap an increased proportion of radiant geo-thermal energy which adds to the process of global heating and incrementally increases surface temperature (see Feedback **G.1**). Higher surface temperature inhibits discharge of geo-thermal energy and over geological time leads to slight increase in the temperature of the earth core as the sub-system regains thermal equilibrium.

The second feedback mechanism in this category (see Feedback **G.2**) is driven by retained solar energy leading to increase in surface temperature. Again, over geological time, slightly raised temperature of earth core is needed to drive sufficient geo-thermal energy outwards across the warmer surface, so compounding global warming.

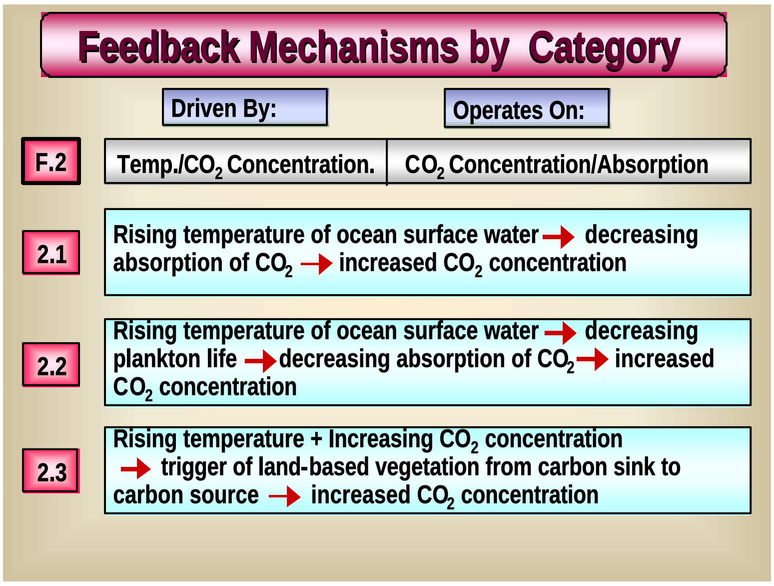
Initial estimates indicate that the order of magnitude of these factors is small in relation to the other feedback processes involved. Further quantitative assessment is now essential before the contribution of geo-thermal energy to global heating can be determined.



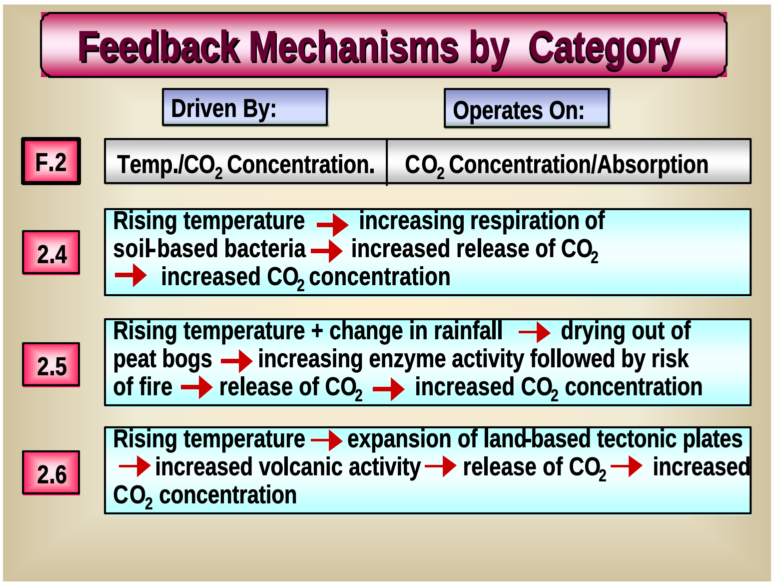
The adjustment of levels of infra-red radiation to the cold spatial sink is the means by which the whole earth system establishes thermal equilibrium with its environment. The feedback mechanism **R.1** eventually damps further rise in global temperature when all other contributing factors have stabilised. Radiative forcing is reduced to zero and continues at close-to-equilibrium values with a new and stable high-temperature solution to the earth system. Long-term decay of methane and sequestration of CO_2 by laying down carbon-based rock systems or otherwise storing carbon-rich compounds, gradually lowers global temperature and restores the Holocene equilibrium



All three feedbacks in category **F.1** are associated with the effects of increased acidification of surface layers of ocean water. This also reduces the population of those algal biota of the plankton layer which excrete di-methyl-sulphide into the atmosphere (see **F.1.3)** This gas oxidises to form an aerosol of minute crystals that act as droplet seeds in the formation of low level tropical clouds. Absence of such seeding decreases cloud cover, reduces reflection of sunlight (the albedo effect), diminishes droplet-based absorption of infra-red radiation, and so enhances global heating.

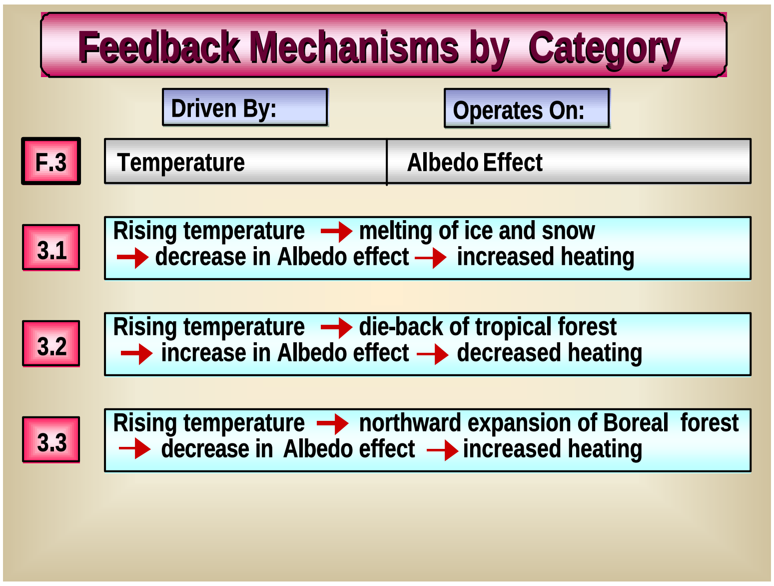


The second category (**F.2**) brings together the mechanisms that are driven by rising temperature and act to reduce sinks or enhance sources of atmospheric CO_2.

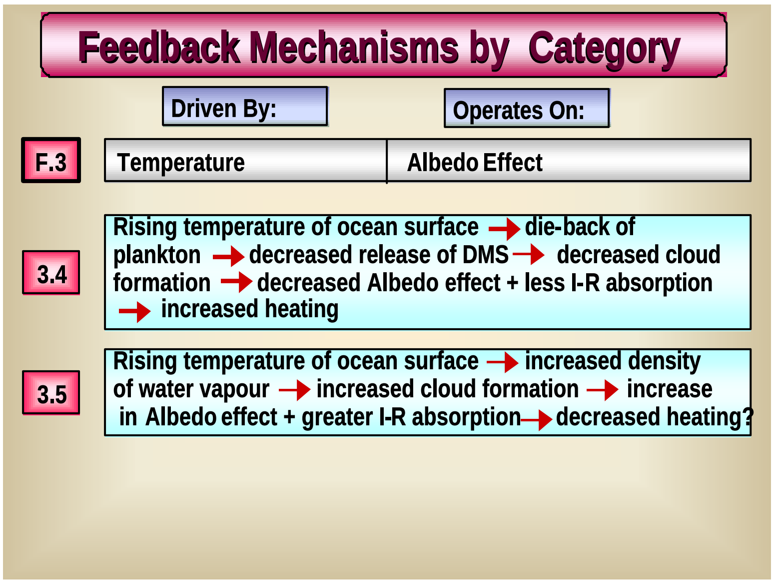


All of these are secondary phenomena in that their driver is the (time-delayed) result of the primary greenhouse effect caused by anthropogenic emission of GHGs. Reduction in emissions or even reduction in concentration of atmospheric CO_2 does not damp these feedbacks. They continue to accelerate climate change throughout the period while temperature continues to rise.

As land temperatures rise, thermal expansion of tectonic plates increases stress at the inter-plate boundaries. Ocean-covered plates do not experience thermal expansion. It is expected that incremental increase in sub-duction will occur leading to rise in both seismic and volcanic activity. The latter would generate increased out-gassing of CO_2 and therefore constitute a positive feedback mechanism, though the order is expected to be small.

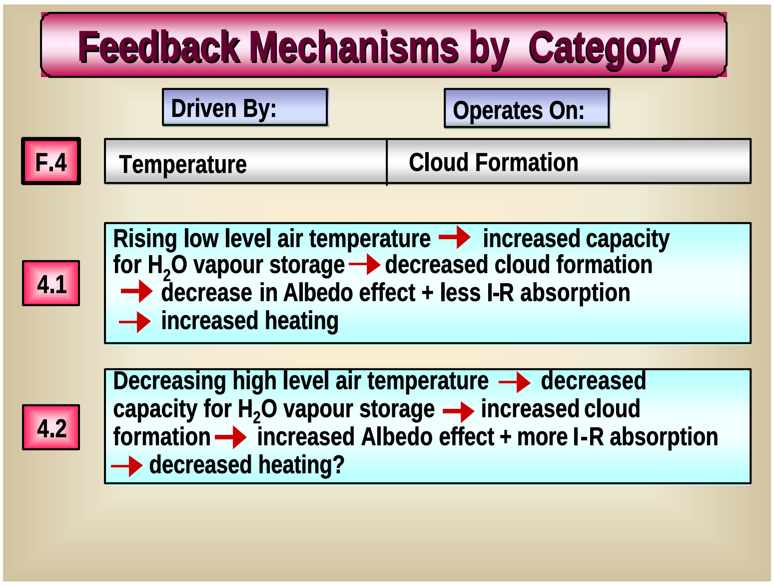


Feedbacks **3.1** and **3.3** are positive loops, accelerating global heating, while **3.2** is a negative feedback which damps the system change.

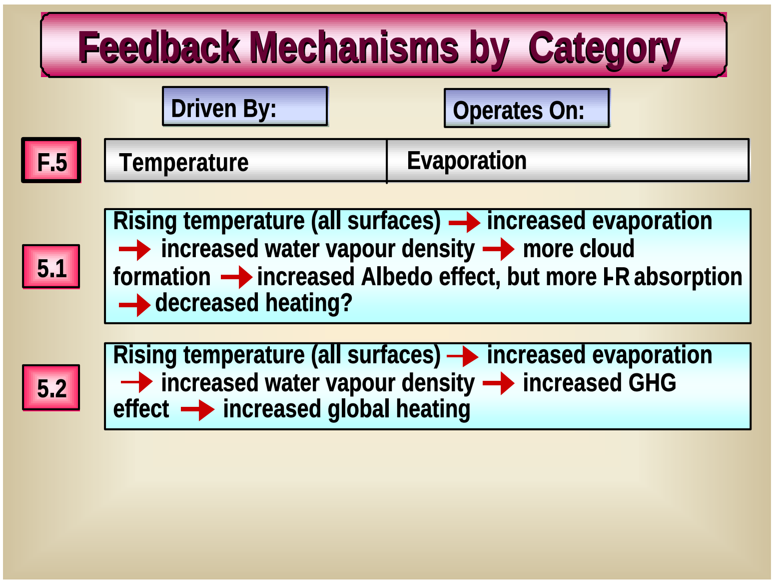


The temperature driven feedback **3.4** is similar in effect to the CO_2 driven feedback **1.3**. The Albedo effect of increased cloud cover resulting from rising surface temperatures at the ocean/atmosphere interface, is compounded with lowered absorption of infra-red radiation to constitute another positive feedback process, enhancing global heating.

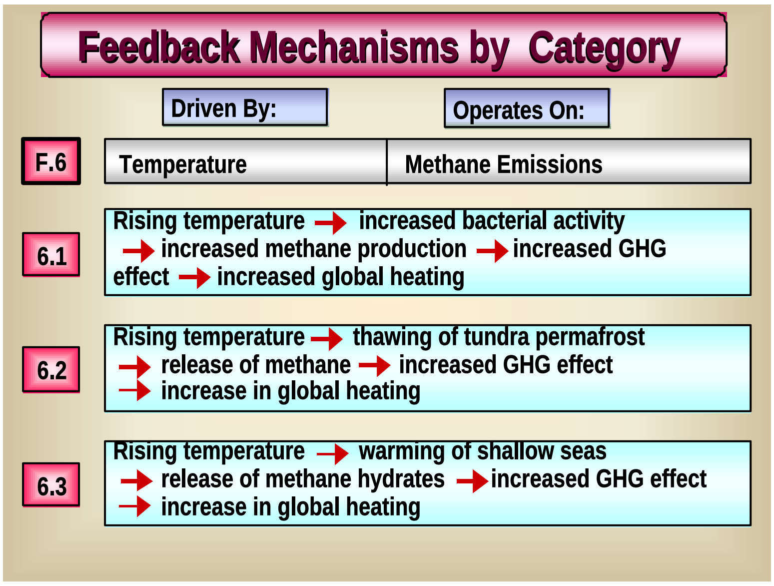
Feedback **3.5** sets off two behaviours which operate in opposite directions. It is difficult to determine the net effect.



Dense cloud cover also acts as an insulating blanket quite apart from the greenhouse effect of (uncondensed) water vapour. Increased cloud density therefore also adds to the retention of heat energy in the lower atmosphere, contributing to global heating and driving yet another feedback process, moderated by the change in Albedo effect.



Some of the water-cycle feedbacks are positive and accelerate global heating, others are negative, damping the behaviour. Modelling of this complex but powerfully influential system is difficult, leading to major uncertainties in contemporary climate science.



The first two feedbacks are already responding to the rising temperature of the earth surface. As a high-latitude phenomenon, tundra permafrost is subject to temperature increases that are several times higher than the global average. As a result we are now seeing the initial thawing of Siberian permafrost across an area the size of France and Germany combined. Methane release is an accelerating outcome of that process.

The third feedback in this category, **F.6.3**, is subject to longer time-delay as warming of sea-bed water depends on slow mixing from the warmer surface layers, even in quite shallow areas. There are vast stores of methane trapped or “frozen” in crystal lattice form in sea-bed deposits. They will eventually start to be released by global warming. It will be a gradual, sequential, cascade process, which, once initiated, will accelerate global heating over a long time-span, quite beyond the reach of any further human intervention.

Paleo-climatologists now affirm that release of methane hydrates was probably the feedback process largely responsible for amplifying global warming during the paleocene-eocene thermal maximum, some fifty-five million years ago. It was triggered by an increase in the concentration of atmospheric carbon-dioxide due to volcanic release of between 0.3 and 3 p-tons of CO_2. We are in the process of releasing a similar order of atmospheric greenhouse gas, with no exemplar events in the history of the current period of alternating glacial and inter-glacial states.

D. Wasdell.
Meridian Programme
August 2006