1 : Sustainable Electrical Energy - Gaia

This module considers the sustainable aspects of Electrical Energy

Clearly this means we should be aware of associated factors such as the climate change, our impact on the climate, etc.

Systems Engineering, and its forerunning departments, has a long history re this topic

- For instance, various colleagues, including Dr George Whitfield, researched photovoltaic solar systems
- In addition, for many years James Lovelock, of Gaia fame, was a Visiting Professor in Cybernetics

The Gaia hypothesis states that life and the planet have mutual effects on each other, in feedback loops, perhaps for control

Therefore the module includes some lectures on Gaia, although, ironically, Lovelock is critical of sustainability …

Gaia Topics

In my lectures, we will look at Gaia

- On Temperature Control of the planet
- Including DaisyWorld
  - – model showing how life and planet interact
- On the control of composition of gases in the atmosphere
- How it affects temperature, for instance
- How the gases have evolved
- On the control of salt in the sea
- On more recent work / discussion on Gaia

Note, key point, there are numerous complicated 'systems' with many interacting changing components. These feedbacks can provide control: life on the planet often plays a part.

Some References

Books by James Lovelock

- *Gaia -The practical science of planetary medicine*: 1991
- *Gaia – A new look at life on Earth*, OUP 1979
- *The Ages of Gaia*, Norton & Co 1988
- *Revenge of Gaia*, Penguin 2007
- *The Vanishing Face of Gaia 2009*

Some papers, eg

- Andrew J Watson and James E Lovelock
- *Biological homeostasis of the global environment: the parable of Daisyworld*, Tellus (1983) 35B pp284-9

Notes available through Blackboard at:

- *http://www.personal.reading.ac.uk/~shsmchlr/teach.htm*

Let's mention some examples of control

Temperature Control

Since life began on Earth, 3 billion years ago, the output from the sun has increased by 25%.

- Acts as external disturbance.

But life of some form has continued to exist throughout

- Suggests there is some form of control

Basic mechanism, works on long time scales, plants have evolved which are better at photosynthesis,

- So less CO_2 in atmosphere
- As CO_2 is a greenhouse gas, this means less heating
- Counters increased output from sun.

Note, mechanism works slowly, cant react to quick changes

- hence have been 'short' ice ages

Oxygen in Air

When life started, no oxygen in atmosphere

Eventually a little appeared, and amounts increased

This was necessary for more complicated life (like us) to exist

- Need at least 15% of atmosphere to be O_2
- At one time nearly 30%
- But for much of the last million years, O_2 controlled at ~20%

But oxygen continually being created and destroyed

What is controlling it?

Answer, probably, fire.

- If 1% extra, chances of fires beginning doubled – problem
- Life, it is believed, helps : different plants/trees grow depending on fire, and hence O_2, acting to raise / decrease O_2

Salt in Sea

Important that sea has some salt, but too much kills life

Salt is continually created into sea

- eg volcanoes on sea bed

What is taking salt out of sea?

- Answer, around coast lagoons form where sea trapped and water evaporates, leaving salt, extracted from sea

But if sea comes in or rain, salt reabsorbed

- Life helps, in some lagoons, bacteria coat the salt crystals – so they cant be reabsorbed into the sea

Hence they ensure that the salt is removed, salt content controlled

All such examples involved feedback …

Feedback - a Reminder

Gaia can be described as saying Earth is a self regulating, cybernetic organism

What makes Cybernetics standout – feedback : +ve and -ve

+ve : Positive - change a system

-ve : Negative - control a system

Weiner concentrated on -ve f/b - for control. Maruyama in 1963 called for study of "the second cybernetics" +ve feedback.

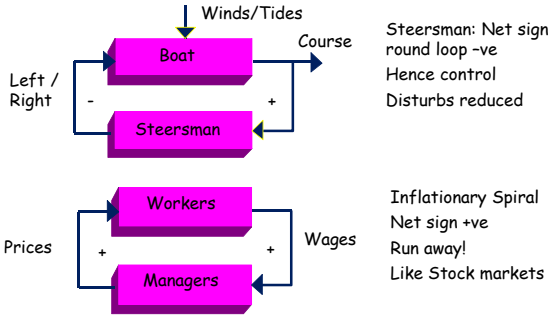
Note, +ve on its own - run away - no use: but can provide rapid change towards desired state, then use -ve.

Many scientists aware of +ve fb loops driving such changes.

Hence, so called tipping points, suggested by some.

Daisyworld is a system with positive and negative feedback.

Feedback Diagrams



Some Positive Feedbacks

Evolution of a star

Particles attracted together → increased gravitational attraction → more particles. Nuclear forces for -ve fb

Formation of waves in water due to wind

Unevenness in water, air blowing over wave forced up and then down over wave; air pressure now greater at peak & less in trough where wave is forced up, increasing wave

Evolution

An organism developed which is better than others has more chance of surviving → more better organisms

Obsession

Mice observed when first given a drink, are incited to drink more: later -ve feedback comes in. Not only mice!

Further Positive Feedbacks

Epidemics

Sudden appearance and later disappearance due to +ve fb.

Illness weakens immune system: more susceptible to disease

Spread of desert

poor soil, plants grow less, soil blown away, poorer soil

Snowball Earth

When start to cool, ice caps grow, planet reflects more heat away, planet cooler – say more on next slide.

Reverse at ice age end: 7° rise in only 20 years

Systems with positive feedback often have negative feedback to stabilise – often at different state.

We will investigate one, but first look at snowball earth and albedo

Snowball Earth and Albedo

When sun shines on planet, its albedo affects what happens

If area is white, the heat is reflected away – cooling that area

If area is dark, heat is absorbed – warming that area

Hence, if planet cools for some reason, ice caps grow

There heat is reflected away, gets colder, ice caps grow further

Albedo = how light / dark planet is on scale 1 white .. 0 black

This concept is used in Lovelock's Daisyworld – a system with positive and negative feedback ..

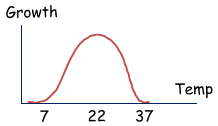
Daisyworld - Interacting Species

Lovelock's Imaginary world to demonstrate Gaia principle

Life & Earth work together to mutual advantage

Grey Planet - black/white daisy seeds in soil

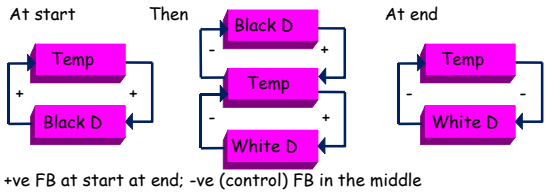
Daisies grow best at 22°C No grow if < 7°C or > 37°C



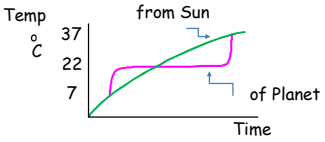
Daisyworld's Sun is heating up - just like Earth's

What happens to Daisyworld's temperature?

Feedbacks: Blacks heat-Whites cool



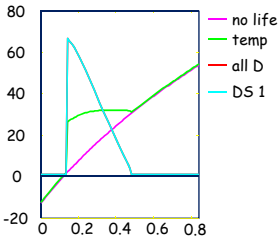
+ve FB at start at end; -ve (control) FB in the middle



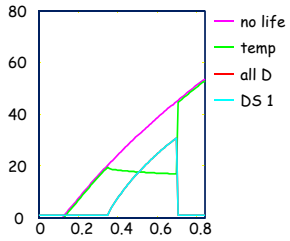
System crashes when too hot
But, for long period, temp constant

Results : Single Species

Just Black Daisies : albedo 0.2

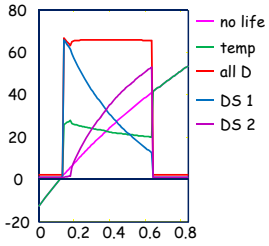


Just white daisies, albedo 0.8

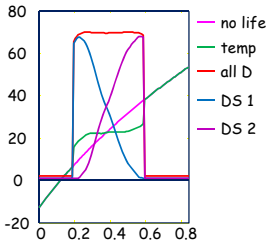


Two daisies

albedo 0.2:0.8

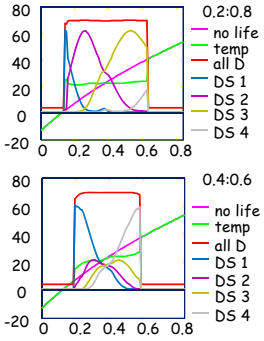


albedo 0.4:0.6

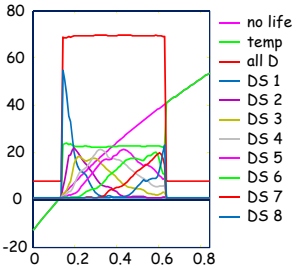


Better control if albedo nearer 0 : 1

Four and Eight daisies



albedo 0.2:0.8

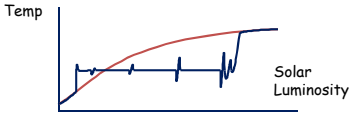


Good argument for biodiversity!

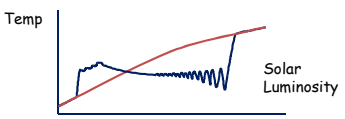
Lovelock Added Perturbations

Foxes and Rabbits added – system still ok.

System stable when perturbed by four plagues that killed 30% of daisies



Also studied periodic plague effect on ability of daisy control



More diversity, better re this plague disturbance

Extensions

The equations so described work for a 'flat' earth

- can extend to sphere by dividing into areas, each receiving different luminosity, and applying method to each area.

Also, to try to address some criticisms of daisyworld, research has been done to add evolution – to see if daisies' albedo can evolve

See the following [Lenton is Lovelock's 'successor']

Lenton, T. M. 1998. Gaia and natural selection. Nature 394: 439-447

T.M.Lenton and J.E.Lovelock 2000 Daisyworld is Darwinian, Constraints on Adaptation are Important for Planetary Self-Regulation. J Theor Biol 206 109-114

Rein Control and Daisyworld

Homeostasis and Rein Control: From Daisyworld to Active Perception, by Inman Harvey, Proc ALife 9 2004

Rein control is where have (at least) two control actions – to move controlled variable up and down (or whatever) - Clynes, M. 1969. Cybernetic implications of rein control in perceptual and conceptual organization. Ann. NY Acad. Sci. 156: 629-670

Harvey's paper presents simpler version of Daisyworld

Shows that any shape 'hat' function works (for daisyworld that is function which defines how daisies grow vs Temp)

In fact principle is so general, it can be applied in many domains … in the paper, for control of a robot.

Next lecture – we look at Earth and Temperature Regulation

2 : Temperature Control

Daisyworld is an imaginary planet, but it does show how life could regulate planetary temperature.

We will consider temperature regulation on Earth:

- Applicability of Daisyworld to Earth
- Greenhouse effect and changing greenhouse gases
- How temperature record is found
- Comment on Climate Change –
  - has temp feedback loop become positive? no control

Ref James E Lovelock

- The practical science of Planetary Medicine, Gaia Press
- But there are other papers … and books

Daisyworld and Earth

Earth life more than two species of daisy, but …

From space: white clouds, polar ice, dark oceans, forests

some reflect heat away, some absorb; life involved? Yes

Daisies not prevalent, but large ecosystems have effect:

Land: in temperate regions coniferous trees like dark daisies

Tropical rainforests, evaporation→clouds : like white daisies

$^2/_3$ Earth is ocean: white clouds over dark ocean significant:

algal ecosystem → Dimethyl sulphide (DMS) → clouds

Overall, therefore, there are effects which can have positive and negative effects on temperature.

Temperature Control Since Life Began

Life began 3.6 billion years ago

Then warm enough; remained so (shown by fossil record)

- Current microrganisms very similar to microfossils
- Abundant evidence of liquid water in rock record
- Earth never frozen or boiled.
- Earth never too hot/cold for life.

But, Sun's output has increased by 25%

- if no regulation either temp < 0^O when life began
- or temperature is now hotter than it is (30^O)

This suggests there must be regulation.

- We will look at various ways suggested to explain this.
- These involve the Greenhouse effect.

How Does a Greenhouse Work?

Even on a cold frosty but sunny day, if you enter a greenhouse with no heater, it is still warm – how?

Almost all heat from sun is in visible part of em spectrum, and this passes easily through glass planes

Inside, the heat is absorbed, by dark plants, soil etc

These warm the air, by radiating heat, at long wavelengths

The radiation is absorbed by glass, not escape greenhouse.

But how apply to Earth, where there are no panes of glass?

We will look at the Greenhouse effect, which in fact was first noted by John Tyndall in 1863

Greenhouse Effect

Solar energy chiefly in visible part of spectrum 0.4..0.7μm

Energy passes thru atmosphere without being absorbed

Some reflected back by clouds, rest warms sea and land

Warm bodies emit radiation (wavelength depends on temp)

So Earth surface emits infrared (4..100μm), some to space

Rest is absorbed in atmosphere

Water vapour absorbs strongly – 4..7μm; CO_2 14..19μm

Some heat reflected from surface absorbed by greenhouse gases and hence not radiated away from Earth, and so warms Earth

Note without greenhouse effect, Earth be 33^O cooler.

Greenhouse Gases

Atmosphere mainly N and O_2 diatomic: can't absorb i.r.

Gases with three or more atoms can absorb infrared, as their larger molecules can naturally vibrate at i.r. freqs

- CO_2 has 3 atoms:
- H_2O (water) and hence water vapour 3 atoms
- NH_3 (ammonia) has 4 atoms
- CH_4 (methane) has five atoms

Note, you need more CO_2 than CH_4 for equivalent heating.

To explain how Earth warm enough when life began – assume Early Earth atmosphere had more GH gases and that the amount of GH gases has changed over time.

For reference we will note these and geological periods.

First Note Geological Time Periods

Hadean - 4.6 to 3.7 billion years ago

- Fiery, Voilent, radiactive -> active vulcanism -> much CO_2.

Archean - 3.7 to 2.5 bya

- Early bacterial life, birth of Gaia
- Atmosphere: N, CO_2 (0.1%) + CH_4 (0.25%), traces O_2

Proterozoic - 2.5 to 0.7 bya

- Switch from reducing to oxidising atmosphere
- Populated by bacteria
- But in mildly oxidising areas, more complex cells developed
  - -> larger life -> more O_2.....

Phanerozoic - 0.7 bya to now

- Time of plants and animals O_2 at 21%, CO_2 at 0.03%

Ice-cores for Temperature

How can we assess past temperatures?

Ice-cores are taken from Vostok site in Antarctic

Recent data published in Nature by Petit et al

Shows records of Temp, conc of CO_2, CH_4, Trace GHG

Covers up to 420,000 years … 2.2 mile deep core!

High correlation between GHG conc and Temp

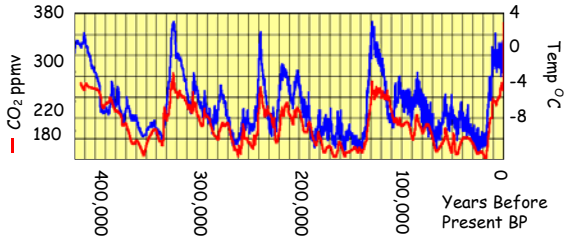
However, cant tell if GHG → Temp, or v.v.

On next slide – see variation of Temp and CO_2

NB can also see graphs including CH_4 and amount of dust

Dust in atmosphere – eg from volcanoes – can affect temperature.

Antarctic Ice Core Data



Note rapid rise in CO_2 recently … no such rise in Temp

– is this cos oceans have been heat sink?

Is evidence that oceans now warming … um

Ice Ages mean Gaia wrong?

Stephen Schneider said to Lovelock

"How can you believe in Gaia when there are ice ages? If there was Gaia it would stop them happening"

Lovelock postulated - Are ice ages (which last 100,000 years) now the normal comfortable state – and the warm interglacials short lived recurrent fevers?

Consistent with the thought that Gaia is now old and hence less able to deal with 'illness'

Makes sense given that temperature control achieved using CO_2 and there is now very little CO_2

Also, up until 2 million years ago, temp more constant

Milankovich Effect

What triggers glaciations / interglacials? Changes in Earths Orbit.

C19th : James Croll developed theory of climate change based on orbit

Generally disbelieved. Milutin Milankovich developed it.

Variations in Earth's orbit : periodic change in energy from sun

- Northern winters say be cooler, southern warmer than av.
- This itself cant explain the temperature change

But if arctic cooler, +ve feedback → ice cap grows, arctic cooler, …

Milankovich effect can trigger temperature changes.

Lovelock says: Gaia stressed (given old age) - small changes in flux from sun enough to destabilise healthy glacial state.

Plant Life and CO_2 – For Control

As Sun heats up, less heating needed on the planet … and hence amount of CO_2 has reduced:

Now 180ppm in glaciations … 280 ppm in interglacials

Close to amount of CO_2 needed by plants to live

Consequently, due to evolutionary pressures, plants have evolved which are better able to cope with less CO_2

Early Earth plants were type C3

About 10 million years ago C4 types evolved

These (inc grasses) have better carbon metabolism

NB in 100 million years, sun's output high enuf that there will be no CO_2 – system will be very different.

What happens when no CO_2 ?

Given that the sun's output is increasing, there will be a time when there will be no CO_2 in the atmosphere.

Lovelock estimates this will be in 100 million years.

Does that mean the end of Gaia?

No – there will be a change in method of regulation

possibly by life affecting clouds over oceans

And possibly a change to a new (warmer) steady state

Temp now 11.5^{O}C in glaciations 14^{O}C in interglacials

25^{O}C in fact a better temperature for plants (not us)

At 25^{O}C, CO_2 would again be in the atmosphere.

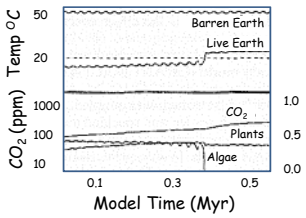
Plants Algae CO_2 and Temp

Lovelock and Kump, Nature 1994; extends Daisyworld
Flat Earth model : temp reg'n coupled with plant / algal ecosystems

Plant growth amplifies CO_2 removal; Algal growth cools by cloud formation

What happens if CO_2 rises?

Graph shows what happens … note to test stability Sun's luminosity fluctuates periodically.
Key result : step change in T



Climate Change

Consider the current debate on CO_2 and temperature

Ice Core evidence suggests they are connected – but there are arguments as to which caused the other

It has been argued that in the past there were negative feedbacks ensuring this was not a problem

Also, that projected CO_2 rise on its own would not have significant effect on temperature

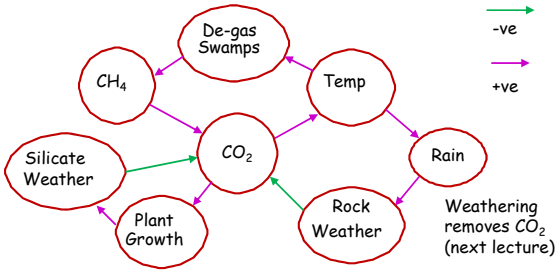
But, now thought: net positive feedback loops

→temperature rise

There are many loops, acting at different speeds

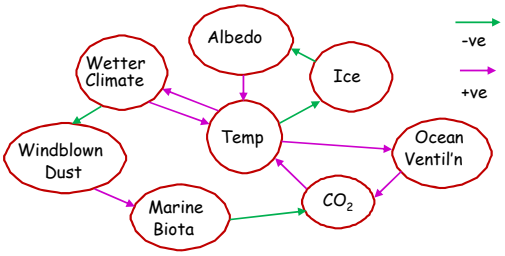
Phanerozoic Feedback

Interpreted from paper by Robet Berner, 'Feedback and Phanerozoic Atmpsophere CO_2 and O_2', GSA, 2002



Current Positive Feedbacks

Adapted from paper by Andrew Watson, 2007



Comment

Does this suggest more positive than negative fb now?

Watson's paper : 'Certainty and Uncertainty in Climate Change Predictions: What Use are Climate Models?'

Environmental and Resource Economics ISSN0924-6460 1573-1502 39, Number 1 / January, 2008

Argues we need better modelling.

One good thing to come from Gaia is that climate scientists usually now include life in models.

However, often the case that if vary parameters within their tolerance levels, get quite varied predictions.

Summary

This lecture has considered temperature control

We have considered that ecosystems, rather than daisies, can explain temperature control methods.

We have seen that Gaia is likely to have ensured sufficiently constant temperature by changing the amount of greenhouse gases in the atmosphere.

We have also seen that this temperature control may in fact be becoming less good .. Gaia is aging.

We will continue this theme next lecture, considering another model, an extension to Daisyworld, showing how gases in the atmosphere changed in Early Earth.

This leads to consideration of the level of, and the control of, oxygen in the atmosphere.

3 : Gas Composition in the Atmosphere

Earth's temperature remained sufficiently constant for life to have existed continually since it began

This lecture will

discuss how the atmosphere has changed

and a (now confirmed) prediction based on Gaia

describe an extension of daisyworld - investigating gas composition in the atmosphere – around Archaen period

We also consider the level of oxygen in the atmosphere

Although, temperature approx constant, there have been large changes in gases, so some say Gaia is wrong

We show this is a misunderstanding of homeostasis.

We start at the start of Gaia ...

What Gas Dominated when Life began?

When life began, greenhouses gases needed so Earth warm enough

But which was the dominant greenhouse gas?

Carl Sagan and G.Muller propose early Earth warm cos greenhouse blanket of ammonia, NH_3. But NH_3 destroyed by u.v. (7% of solar radiation is u.v.) – need too much

Hart and Owen suggest 10% of atmosphere was CO_2.

This is fine, but now 300 times less CO_2: how was it decreased?

Amount of CO_2 set by how much injected & how much lost

Volcanoes emit CO_2 early Earth much radiation & vulcanism

Vulcanism ↓, cos Earth less radioactive & less internal heat

Now vulcanism down by factor 3 - not by a factor of 300 …

Rock Weathering Theory

Walker and Kasting proposed: as sun warms, less CO_2 as

more removal by rock weathering and increased rainfall.

CO_2 & calcium silicate react →

calcium carbonate (limestone)

Basalt rock - exudate from volcanoes - rich in CaSi

dissolves when immersed in rainwater saturated with CO_2

Geochemists stated life has no effect on these reactions

what CO_2 is made by consumers is taken back by plants

Model is ok, but not account for 300 fold decline in CO_2.

Life and Rock Weathering

In early 1980s, Lovelock made prediction about organisms in soil enhance rock weathering

"When plants grow, they pump CO_2 from air into soil [10 fold enrichment of CO_2 in air pockets in soil compared with air above soil]. When tree dies, most of it eventually oxidized through action of decomposers and converted to CO_2. Much conversion is in soil next to CaSi rock in presence of water"

1989 Volk & Schwartzman show weathering of basalt rock 1000 times faster with organisms than with sterile rock.

Confirmed Lovelock prediction of early 1980s.

More on Life and CO_2

In oceans, some algae take silicic acid to make skeletons

Others take Calcium bicarbonate to make CaCO skeletons

Ocean algae also pump CO_2 from air, and the skeletons drop to sea bed taking solidified CO_2 to ocean floor.

So amount of CO_2 affected by life on planet

- actively regulated.

Note: compartmentalising science led to Geochemists incorrect view, that CO_2 purely a geochemistry cycle.

Cybernetic view better - include life.

This work led Lovelock to produce a computer model to see how gas composition in atmosphere changed.

Lovelock's Early Climate Model

A more complicated, direct descendant of Daisyworld

Instead of daisies have primitive plants (photosynthesizing bacteria)

taking in CO_2,

turning into Carbonaceous matter of their bodies

giving off O_2.

Also have few consumers in few pockets of O_2.

And have fermenters (methanogens), converting plant's carbonaceous material into CO_2 and CH_4.

Photosynthesizers acted like white daisies

Methanogens like black daisies

Planet climate determined by proportion of gases

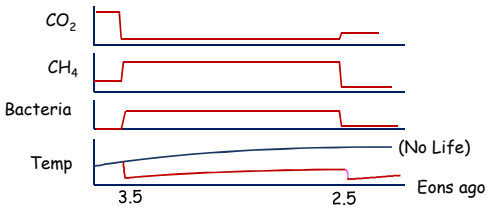
Graphical Results

Init: Sun's output 25% < now; CO_2 = 300 times higher;

Run: CO_2 down (used by photosynthesisers), rapid temp ↓.

Gases reach steady state: CH_4 ~ 0.25%; CO_2 10% → 1%

Fast ↓ of CO_2 consistent with rock weathering record.



Continued

Consistent with theory that CH_4 chemically dominant in Archaen

CH_4 more potent than CO_2. 0.25% provides enough warming

Temp stable thru Archaen period - abrupt decrease at end.

Caused by sudden appearance of O_2 : rapid +ve feedback.

Model is stable, resistant to perturbation (internal and external), suggests plausible levels for climate and gases

Note: initial T drop may have lead to a snowball earth.

If paras outside certain range, atmosphere fails:

Planet too cold for life – dead – explain Mars/Venus?

If run with just biosphere or just weathering:

Biosphere main source for change in concentrations

Weathering, H escape and CH_4 oxidation → fast changes

Oxygen In The Atmosphere

Composition of atmosphere odd - incompatible gas mix - breaks rules of chemical equilibrium - yet constant

Chemically, O_2 is dominant gas

enough O_2 for fires to light

provides chemical potential difference wide enough for birds to fly, us to run, us to keep warm

Over time, amount of O_2 has varied, now risen to 21%.

We will look at the variation of O_2 over time.

Why O_2 rise ? Especially as for some life O_2 poisonous.

Why is O_2 now at 21%?

We will consider Oxygen cycle & feedback mechanisms.

Oxygen - The Polluter?

O_2 start believed to be the first pollution incident:

led to mass extinction.

Now realised:

O_2 poisonous, mutagenic & carcinogenic

→ limit life span

oxidative metabolism:

processing food & water when with O_2

→ radicals destroy cells:

so life developed antioxidants

But high metabolic rate means low life span

But Oxygen is Good

But, O_2 opens up possibilities

consumers recycle organic matter faster than methanogens

O_2 changed environmental chemistry

oxidisation of N → nitrates increased on surface

more nutrients made available

→ increase abundance of life

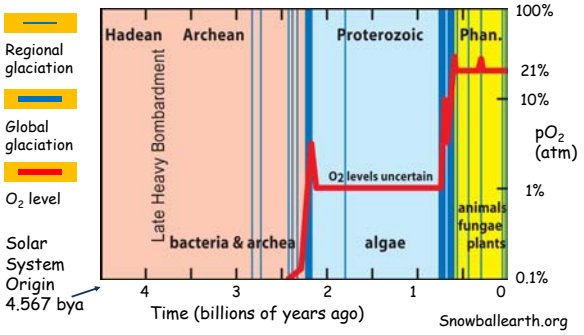
O_2 encourage surface blooms of algae →

deny light & O_2 to life below, which dies,

such dead plants enrich methanogens →

more C ↓ which leads (as we shall see) to O_2 in air

Showing link of O_2 and ice-ages



Oxygen, Methane and Carbon

Most O_2 made by photosynthesis … then used up :respiration

A closed cycle - so how come O_2 in atmosphere?

Was thought: water vapour → H & O, H light so escapes

O left in atmosphere, but this not produce enough O_2

Now thought: small amounts of C from CO_2 buried - freeing O_2

photosynthesis: $CO_2 + H_2O \rightarrow O_2 + CH_2O$ (organic matter)

Animals consume this, CO_2 go to air; 1% CH_2O in soil:

methanogens convert to $CO_2 + CH_4$

CH_4 escapes to air, reacts with $O_2 \rightarrow CO_2 + H_2O$

0.1% organic matter (C) buried in rocks; hence some O_2

Rest of O_2 produced by plants, used by animals, by reaction with rocks & gases in volcanoes & by weathering

Evolution of Oxygen in Archaean

Some life which requires O_2, but only small pockets

Are photosynthesisers, but are many reducing elements

Atmosphere 1% CH_4 dominates atmosphere's chemistry

NB many undersea volcanoes – more reducing than on land as they erupt at lower temps

Later: more land volcanoes – as land masses stabilise

So vulcanism ↓ → less Fe & Su (O_2 removers)

more oxic consumer organisms → photosynthesis → O_2

Throughout a steady burial of C and hence increase of O_2

When 2 O_2 molecules per CH_4, $CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O$

End of Archaen - CH_4 not dominant – ice age 'cos temp ↓

O_2 in Proterozoic & Phanerozoic

Little known, world of microorganisms, unicellular life

Not vigorous enough to ensure O_2 (as can't bury C)

O_2 stayed at about 1%

Until Large plants evolved – start of Phanerozoic

whose carbonaceous matter more easily buried

Berner et al (2003) suggest O_2 rose to 35% then

confirmed by carbon isotopes of fossil plants

consistent with giant insects (insect size rises with O_2)

This excess O_2 → wildcat fires (catastrophic?) : O_2 ↓ ?

NB Andrew Watson PhD thesis on burning

On Marine Life and O_2 Control

Redox Stabilization of the Atmosphere and Oceans by Phosphorus-Limited Marine Productivity

Van Cappellen and Ingall, Science 1996

Burial of limiting nutrient phosphorus is less efficient when bottom waters are low in oxygen.

Phosphorus burial in the oceans provides a powerful forcing mechanism for balancing production and consumption of atmospheric oxygen over geologic time.

The oxygen-phosphorus coupling further guards against runaway ocean anoxia.

Crucial in producing more complex life in Phanerozoic ?

O_2 Feedbacks in Phanerozoic

Ref: Robert Berner: Feedback and Phanerozoic Atmospheric CO_2 and O_2: GSA Annual Meeting, 2002

"controversial simple feedbacks due to control by O_2 of weathering and burial of organic matter and pyrite"

-ve fb on nutrient controlled organic matter burial

-ve fb on organic matter burial due to greater global fires and incr photorespiration due to higher O_2

+ve fb organic matter burial due to microbially resistant charcoal and increased erosion due to greater fires due to higher O_2

On Fire for Control

Fire frequency sensitive to O_2 rise from 21% Was thought:

More O_2 → fire ↑ → trees ↓ → C burial ↓ → less O_2

But, normally 0.1% of C buried, but all of charcoal buried

so more O_2 means more C burial so more O_2!

Some trees (conifers, eucalyptus) drop branches in forest

these burn readily – all material burned little C for burial

some conifer seeds depend on fire to be released

Other trees, hardwood trees like Oak, burn easily

when oak burns, charcoal is generated, more C burial

Thus if oaks dominate, more C burial, more O_2, more fire, less oak, release conifer seeds, more conifer, less C burial, less O_2.

Rein control

Marine Life and Control of O_2

In recent years, O_2 pretty constant

Fire helps, but also…

Suppose atmospheric O_2 rose substantially

Marine zooplankton would eat and respire organic matter produced by algae in the ocean at an increased rate

So less organic matter buried, so O_2 decreased

If O_2 down, less feeding & respiration by zooplankton

So more organic matter produced by algae would end up in sediments and oxygen would rise again.

Clearly negative feedback

Comprehensive Model

Lenton and Watson : "Redfield revisited 2. What regulates the oxygen content in the atmosphere?"

Global BioGeochemical Cycles Vol 14 pp249-268, 2000

Have dynamic feedback model of P, N, C and O_2

Covers C burial for generating O_2:

P burial in oceans incr ocean nutrients – a –ve fb re ↓ O_2

Fire freq sensitive to ↑ O_2, transfers P to sea, P burial ↓

O_2 ↑ suppress biological amplification of rock weathering and hence input of P – most effective O_2 regulation

Also have land plant mediated –ve fb on P weathering

With these, model shows O_2 19-21% over last 40Myr.

Criticism of Gaia

But these models shows amounts of O_2, CO_2, CH_4 have changed

"Gaia claimed to keep consistency, to be homeostatic, yet 3 most important atmospheric gases have varied"

Erroneous - shows failure to understand homeostasis - it is not a fixed state of constancy, but a dynamic state of constancy.

Consider (appropriate analogy for Cybernetics) ship's auto-pilot

autopilot will follow a course , despite winds and tide

but if storms arise, or rocks ahead, should change course

rapidly change to new course then homeostasis resumes

Homeorhesis

This is sudden change from a stable state

Termed coined by C.H.Waddington - a genetist

consider controlled growth of fertilised egg until adult.

mass, form and functions change,

but pH, ionic strength, etc, constant

Gaian history characterised by constancy and homeorhesis

Negative feedback gives constancy

Positive feedback gives change

BUT CONDITIONS FOR LIFE HAVE BEEN MAINTAINED

Next– week we consider Ozone Layer and the Oceans.

4 : Ozone Layer and the Oceans

We have seen changes in the levels of gases in the atmosphere
We note the feedback mechanisms in place controlling levels
These include the effect of marine life on, for instance, O_2 levels
In this lecture,
- We first look at the other molecule with O atoms : ozone O_3
- Then we consider the ocean in more detail
- Specifically we look at its effect on climate

Let's start with ozone

Ozone

Initially Earth had no ozone layer (cos little O_2).
- u.v. got to primordial soup → chemical reactions → life ?

Now have ozone layer, but must not be too thick or too thin
- some u.v. must get through, to generate vitamin D
- less protection from u.v. → skin cancer, cataracts

Ozone constantly produced and destroyed - a dynamic process, but layer must be right. Suggests some control.
- If too thin, u.v. gets thru to atmosphere just below, where O_2, but, u.v. + O_2 → O_3 to thicken it

Thus we have a feedback loop
- But now ozone layer is depleted - by CFC's –
- a disturbance so large that feedback system at limits?

On Ozone Destruction

The thinning is different at the poles
- Antarctic 50%, Arctic 6%

On Destruction
- if X is a catalyst, like NO or Cl:

$X + O_3 \rightarrow XO + O_2$ $\quad$ $XO + O \rightarrow X + O_2$

Most Cl compounds react in troposphere, not reach stratosphere
- But, CFCs stable, long lived,
- They can reach stratosphere, split into Cl atoms

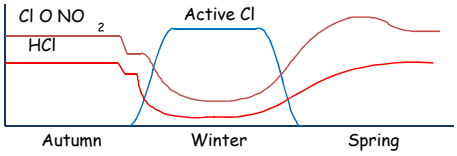
Many Cl atoms locked in chemical reservoirs, so why the O_3 'hole'?

More On Ozone Destruction

Polar vortex traps v. cold air over antarctic
Polar stratospheric clouds (PSCs) form in low temp (-78°) ~July
PSCs react with Cl reservoirs (HCl & $ClONO_2$) to release Cl
PSCs mop up nitrates & N from stratosphere,
- free Cl & little N

Sunlight returns (Sept) Cl react with ozone → hole
As temp incr, PSCs evaporate, vortex breaks up, ozone incr
But gradual drop in ozone concentration over southern hemisphere
Arctic: less problem as
- temp higher, PSCs less, polar vortex less

Change Through Year



Cycle natural - but
over many years CFCs have lengthened peak of active Cl

But …

But reduction in O_3 has meant:
- change in flux of radiation in lower atmosphere
- affects production of cloud condensing nucleation (CCN)
- increased cloud cover →
  - increase planet albedo → temp drops →
  - more PSC → less ozone → increased cloud → cooler

Is ozone layer thinning to counter the greenhouse effect?

Gaia and Oceans

Without water there will be no life: without life no water

So study of oceans important: we consider life & oceans

Oceans important as they affect climate regulation

Also part of the sulphur cycle - life enhances this cycle

Salinity of ocean appears never too high to allow life

This suggests there is some regulation

By biological and possibly tectonic processes

We will thus look at the oceans and their roles in Gaia

We will also look at life in the oceans

We will also consider salinity regulation – and role of life

We will also consider the sulphur cycle

Oceans and Climate

Oceans : 96% of Earth's water; experience 86% of its evaporation; receive 78% of rain – clearly significant.

Earth's albedo ~31%, that of open ocean 10-20%

Ocean absorbs over 80% of incoming radiation

But means white clouds over oceans significant – we will show life plays a role here

Ice caps over ocean have albedo 30-70% - but at poles where less solar radiation

Ocean largest carbon store of CO_2 – so far it has absorbed ~33% of excess CO_2 due to man : future?

Clearly the oceans have potential to affect climate.

Salt and Climate

Freezing point of sea water is –1.91 ^{O}C: salt reduces temp.

Helps prevent oceans forming ice caps

Ice is less saline than water and less dense, so it floats

If ice sunk, water at surface would freeze.

Water below icebergs, high pressure, too warm to freeze

Global warming:

melt ice cap → dilute sea, less salt in ice than H_2O

→ more sea → more rock weathering → more salt (-ve fb)

That seems ok, but in fact it is more complicated – so we will look at what is in the ocean, and how water circulates and how global warming can affect this …

Life in the Ocean

Appears to be little, but in fact is much life in ocean

Under microscope see blooms of photosynthetic algae

major producers near surface

Grazed by zoo plankton : food for larger marine organisms

In their shells, micro flora segregate Ca and Si

These rain to sea bed, form sediments, affecting plates?

Strange animals near hot vents on sea bed

vents affect ocean composition source/sink of nutrients

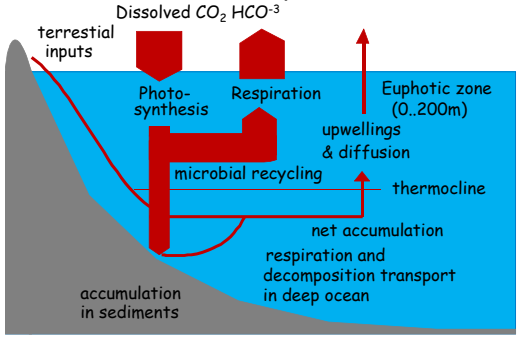
CO_2 also in ocean – part of the CO_2 regulation cycle

Trace gases released by algae (eg Dimethyl sulphide, DMS)

These may effect in cloud formation & climate control

Next slide shows some movements that occur

Ocean Ecosystem



Currents – Gaian circulatory system

Generated by temperature and salinity 'Thermohaline'

Fresh water light – floats on surface; salty water sinks

Salinity ↑ or Temp ↓ → Density ↑ sea levels ↓ (and vv)

Differences in height related to ocean circulatory system

Warm surface water near equator travels to poles, replacing sinking cold water – eg gulf stream

Cold currents then travel towards equator

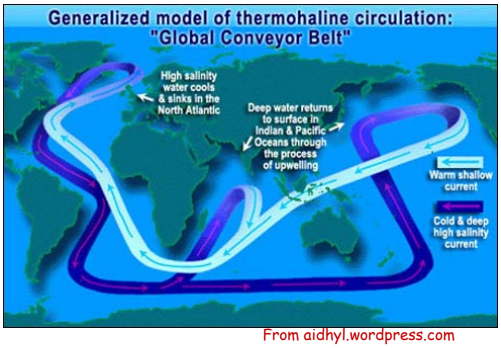
They rise to surface bringing nutrients (Ph & N)

If ice caps melt, sea less saline … alter these currents

Global Conveyor Belt (next slide) for storage/moving heat

Top 3m of oceans stores more heat than all of atmosphere

Thermohaline Circulation



From aidhyl.wordpress.com

Circulation and Climate Change

Positive feedbacks reinforce thermohaline circulation

In N Atlantic it enhances salinity & density

thereby maintaining the circulation

Convective vertical mixing removes freshwater near surface preventing surface layer of freshwater which could stop convection

Models of these show a saddle point for amount of fresh water circulation can sustain

Suggested that climate change could trigger a major change

A smaller change may move gulf stream to S of Iceland

Could lead to another major change on Climate.

Also - Study of Central America

Past rapid climate changes disturbed circulation system

Changes move climatic equator separating N S trade winds

In Caribbean, surface waters evaporate, incr salinity – helps reinforce Gulf Stream starting in W Atlantic

Water vapour blown to Pacific, where rains, decr salinity.

This process however can amplify Climate Change

In last ice-age, E Pacific colder, trade winds went South, but could not cross Andes, so Pacific salinity not decr

Instead, rain in Amazon basin, so decr salinity in Atlantic

This reduces Gulf Stream, thereby reinforcing cool period

So Climate Changing affecting Gulf Stream a concern

On Temperature / CO_2 / Oceans

See http://www.skepticalscience.com/skakun-co2-temp-lag.html

Address Climate Sceptics who say CO_2 rise follows temp rise

Suggest Earth Orbit Cycles trigger initial warming

→ melts arctic ice

→ fresh water in oceans

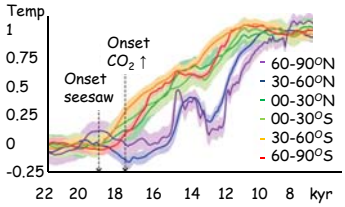
→ disrupt currents

→ S hemisphere warms

→ releases CO_2

→ N hemisphere warms

(Normalised Temp)



CO_2 lags temp initially, then is driving force

Life Controlling Salinity of Oceans

Keeping Earth moist & suitable for life needs good control

If 25% of water dried away, ocean life not possible,

Oceans be 6% salt – too saline for cell membranes

Ocean salinity affected by chlorine – the chloride ion

Constant input of Cl into sea – from rivers and vulcanism

I/p rate sufficient (over 800 million years) for salinity > 5%

Too high for life, but has been life, so must be control.

Not absorbed (Cl ions unreactive) or consumption by biota

In fact, Chloride ions leave oceans trapped in sediments

And by exchange with other ions in rocks on ocean bed

Important sink is in evaporite deposits – life helps

Salt Burial: Lagoons, near continents

Sea water trapped, evaporates (by Sun), Salt deposits form; eventually lagoon full of salt

Salt becomes resistant to re-solution, covered by soil and sediments, so salt is buried.

Q: Is rate of production & removal balanced by life?

Greg Hinkle and Lynn Margulis studied evaporite beds

Found bacterial mats in layers : Green and red microbes on surface; Anaerobic bacteria + fibrous microbes remains below; under which are deposited salt mats

Surface bacteria coat salt crystals with water repellent varnish, so resistant to re-solution in rain water

So bacteria encouraging drying of lagoon & so salt burial

Sulphur, the Sea and Climate

The sulphur story

Sulphur lost from land

as sulphate ions in rivers which run into sea;

Sulphur gained by

Weathering of sulphur bearing rocks;

Sulphur extracted from ground by plants;

burnt fossil fuels putting sulphur in air

But this does not balance that which is lost.

How is Su returned to the land so that land organisms are not starved of this essential element?

Dimethyl Sulphide, DMS

Conventional wisdom:

Hydrogen Sulphide emitted from sea

But this oxidises easily and gives off a stink … unlikely

Challenger suggested marine organisms emitted DMS

Lovelock, 1971 holiday, made crude gas chromatograph

found all algae emitted some DNS

a red-hairy algae particularly excelled!

Realised algal emissions of DMS part of Gaia

But work largely ignored til Andreae in 1980s who showed organisms do emit enuf DMS to return Su to land

Climate Feedback Loop

Andrae's work also showed marine organisms emitted much DMS partic. over 'desert' areas of oceans far from land

Led meteorologists Charlson and Warren to propose :

rapid oxidisation of DMS in air over the ocean could form sulphuric acid droplets - make nuclei for cloud formation

Feedback Cycle to control DMS is

Algae → DMS → non sea salt sulphate

Cloud condensation nuclei (CCN) → incr cloud cover

lower surface temp & more wind

→ reduce DMS output

As ocean is 2/3 of land, affecting clouds is significant

How do Algae Benefit from DMS?

Algae don't altruistically return sulphur to land, nor produce clouds to cool planet, so why do they do it?

Answer:

dimethylsulphonio propionate DMSP is a betaine

helpful for organisms in salty environment as not toxic,

unlike NaCl

DMSP: could well be cellular response to salt stress suffered by marine algae

Also DMS → cloud → rain/winds;

bring nutrients from air to algae;

also stir up sea, bring nutrients from below

So Sulphur cycle

Marine algae die or are eaten

→ sulphur betaine

→ DMS into air

On shore breezes bring DMS to land (non sea salt)

→ deposited to ground

→ enhance growth of plants,

→ increase rock weathering

→ nutrients to sea

Increased flow of nutrients beneficial to land & sea ecosystems

Life part of feedback loop - beneficial to life.

Summary

These four lectures have considered some of the feedback mechanisms affecting Earth

Generally these involve life

These feedback loops help in the control of temperature, salinity, oxygen, ozone, etc

However, the systems are complicated, and interact

Some of the feedbacks are (perhaps only now) positive

That could mean that they may lead to tipping points where systems rapidly change to different states

In the rest of the module, Ben will consider Sustainability issues which may help …

Near the end, I will give one more lecture, reflecting on Gaia...

5 : More on Gaia

Gaia began with Lovelock and Margulis musing in the 1960s

Lovelock has commented that in fact Gaia started in 1789 when James Hutton wrote *I consider the Earth to be a super-organism and that its proper study should be by physiology."*

Thus in the 1970s and 1980s there were very few people researching in Gaia

Now there are many more (though Lovelock has retired)

There are still many who disagree, and there is some useful debate about the Gaia Hypothesis.

This lecture points out some of this ... You are encouraged to read further.

1992: JEL Lecture to UN Uni, Tokyo

'But even so, today's Geochemists and biologists still believe that their science explains it all. For example, the eminent geochemist H.D. Holland, in his book The Chemical Evolution of the Atmosphere and Oceans, said: '

"The regulation of the Earth's chemistry and climate can fully be described by geochemistry and geophysics alone. To geochemists there is only one source of carbon dioxide, volcanoes and only one sink for the gas, the weathering of calcium silicate rocks."

But however powerful their computer models, they can't properly account for the current low level of CO_2 in our atmosphere, nor the fact that oxygen remains constant at 21%. Also their models are often unstable.

Changing Gaia Hypothesis

The first statement of the hypothesis was:

"Life regulates the climate and the chemical composition of the atmosphere at an optimum for itself."

That was wrong. Lovelock says he should have said

"The whole system of life and its material environment is self-regulating at a state comfortable for the organisms."

Why – first definition led to criticism of conscious control

From the start, Gaia has been a top-down systems view of the Earth, the hard science view of a physical chemist with an interest in control theory.

'I do not know whether Gaia theory is right or wrong. To me it is just a useful way of looking at the Earth.'

Some Recent Comments

2002 in 'Climate Change' there were papers by Tim Lenton (Lovelock's successor), James Kirchner and Tyler Volk

Kirchner: Gaia hypothesis: fact theory and wishful thinking

Lenton : Testing Gaia, the effect of life on earth's habitability and regulation [Volk's paper not on www]

2003 in the same journal there were some follow up papers

Kirchner: The Gaia Hypothesis: conjectures and refutations

Lenton & Wilkinson : Developing the Gaia Theory

Kirchner has been making useful critical comments for some time, for instance his 1998 spectrum on the Gaia hypothesis – weak to strong (c.f. weak/strong AI)

Kirchner's Gaia Hypotheses Spectrum

Hypotheses	Specification	Status
Influential	Biota has substantial influence over certain aspects of the world	Supported
Co-evolutionary	Biota influences abiotic environment, latter influences evolution of biota	Debated
Homeostatic	Interplay between biota and env. Is characterised by stabilising -ve fb loops	Debated
Teleological*	Atmosphere kept in homeostasis not just by biosphere but in some sense for it	Daisy-world
Optimising	Biota manipulates its environments to create favourable conditions for itself	Sceptical

* self driven to move towards goals [teleology: study evidence for design]

Kirchner : 'traditional resistance to Gaia as cant be falsified'

Kirchner's 2002 Paper

THE GAIA HYPOTHESIS: FACT, THEORY, AND WISHFUL THINKING – Part of Abstract

Organisms can greatly affect their environments, and the feedback coupling between organisms and their environments can shape the evolution of both. Beyond these generally accepted facts, the Gaia hypothesis advances three central propositions:

biologically mediated feedbacks contribute to environmental homeostasis,

they make the environment more suitable for life

such feedbacks should arise by Darwinian natural selection.

These three propositions do not fare well under close scrutiny.

In the paper

Since he 'started debate' in 1989, seen encouraging trends
- now accepted organisms do affect their environment
- most extreme versions of Gaia Hypothesis abandoned
- Proponents have worked on Gaia and natural selection

Gaian proponents helped educate wider audience

Too ambitious "Gaia means life/planet stabilise environ."
- more accurate to say biota naturally selected for environment ..

Douglas Adams description of Gaia – "imagine a puddle, waking up and exploring surroundings – this depression here its really comfortable … as wide and deep as I am .. the same shape as me … it must have been made for me!"

Critical of Daisyworld : feels important to include natural selection

Developing The Gaia Theory

Lenton and Wilkinson's 2003 response to Kirchner and Volk

'As noted by Kirchner, there is a need for more dialog'

They write with the intention of helping to clear a pathway 'towards a future for Gaia theory' (Volk's phrase)

Aim to clarify outstanding differences, resolve them …

Mostly they address specific criticisms of Kirchner

How has life survived for so long?
- Pure luck? No feedback mechanisms
- Lucky Gaia : have feedback, but lucky that regulatory
- Probable : Expect planets with much life to have reg fb

Reg fb -> speed return to or incr range of steady state

Kirchener responds 2003

2003 The Gaia hypothesis : conjectures and refutation

Although a critic, K largely agrees with main themes. Way forward:

Move away from Daisyworld – perhaps stop using name Gaia

Get more scientific evidence

Answer key questions, such as:

- What controls the magnitude and duration of glacial /interglacial periods, and why have they changed?
- Why has the anthropogenic increase in atmospheric CO_2 only resulted in a $1^{O}C$ temperature rise, given ice core data?
- What controls the patterns of extinction and diversification in the fossil record, and how are they linked to changes in climate?

Scientists Debate Gaia, 2004

Lovelock and Margulis wrote Forwards

Then 31 papers from various scientists, notably

Lenton - Clarifying Gaia: Regulation with or without Natural Selection

Schneider- Gaia : Towards a Thermodynamics of Life

Wilkinson - Homeostatic Gaia: An Ecologists Perspective

Watson - Gaia and Observer Self-selection

Downing - Gaian in the Machine : The Artificial Life Approach

Quite clear, people talk of Gaia Theory – and look at specific details

Lenton

Attempts to resolve current debates on Gaia Theory

Gaia is a planetary scale open thermodynamic system with abundant life supported by flux of free energy from nearby star.

Environment profoundly altered by life; remarkably stable – due to feedbacks often involving life, transformed by evolution

Argues environmental effects are by-products of natural selection

Where environmental changes alter benefit of an evolve trait, feedback on selection occurs.

Concludes better to understand Earth Systems Science by thinking in terms of non-linear, circular logic of feedback systems

Time to stop debating Gaia, rather to understand Gaia…

Schneider

"Nature abhors a Gradient" description of thermodynamics

Views life as thermodynamic dissipative entity some way from equilibrium, sustained by ability to degrade energy gradients

Gaia : tapping gradient between hot sun and frigid outer space

Life result of energy processes, never violating 2nd Law of T-D

Concepts connect life and non life at fundamental level

Concludes that the development and evolution of Gaia is a thermodynamic and genetic process

Wilkinson

Is long term persistence of biosphere due to luck or do feedback loops increase likelihood of such persistence

Critics argue these feedback loops could not evolve as require high level selection not at the gene/individual level

W points out that 'mutualisms' are common in ecology and Gaian feedbacks are likely to be mutualistic by-products

But, how could regulation develop without selection?

Answer, look at population models

Concludes biosphere regulation is theoretically possible

Hence criticisms of Gaia by biologists are not valid

This should be an important area for further research

Watson

Asks: is long term regulation [by life] an inevitable property of biospheres, or has Earth been lucky?

Suggests, if biospheres intrinsically regulate, increases chance that intelligent beings can be produced

Although quite good control, been major changes, regulatory mechanism not good enough to ensure intelligent observers exist- supports lucky Gaia idea

Also, believes that formation of simple life may be common, but evolution to complex life unlikely – as many critical steps needed: eg origin of photosynthesis

Downing

Artificial Life – about emergent phenomena

Gaia Theory perfect specimen for Alife dissection

Natural Selection at individual level reconciled with emergence of large scale Gaian patterns : recycling and homeostasis

Alife provides tools for testing Gaian claims

Claims Alife has 'bio-logic' which explains various life systems

Gaia needs 'Gaia-logic' to help unify different Gaia concepts

Concludes the A-Life perspective is crucial in assessing thoroughly whether Gaia is a general, possibly prevalent, phenomenen

The Revenge of Gaia, 2007

Deliberately not another book on Global Warming

Speaks as 'planetary physician' whose patient (Earth) has a fever

Our most important concern : declining health of patient

Important that consider Earth to be alive (unlike Mars / Venus)

Sustainable Development : balancing (if possible)

social well being; economic prosperity; environment protection

Believes its too late

lung cancer victim not cured by stopping smoking!

We know that Earth has some regulation

been too slow to realise that regulation is failing

Severity of Earth's illness : inevitable we pass tipping points

Positive Feedback

Believes Gaia is in vicious cycle of positive feedback, amplifying

Extra heat from green house gases

Or from melting ice caps

Changing structure of oceans

Destruction of tropical forests

Even if we stopped polluting, using more land/sea for fuel/food

it would take 1000 years to recover

On Energy

So, believes environmentalists naïve re 'sustainable development' and 'renewable energy'

Believes Nuclear energy should be promoted (better if fusion) as part of an energy 'portfolio'

Cease using fossil fuel asap, no more natural habitat destruction

Already we are farming too much (for food) : Biofuels not sensible.

Burning Coal / Oil - generate too much CO_2

Halve emissions if burn Natural gas (Methane),

but some escapes and Methane stronger greenhouse gas

Hydro-electricity good – but need rivers

Wind – believes advocates over sell

Solar – ok, but cells still expensive (getting cheaper)

Vanishing Face of Gaia

2009 – book – sub title "A Final Warning"

Consistent with increasingly apocalyptic predictions

Gaia is in trouble – infected – by us - polyanthroponomia, humans are so plentiful they do more harm than good

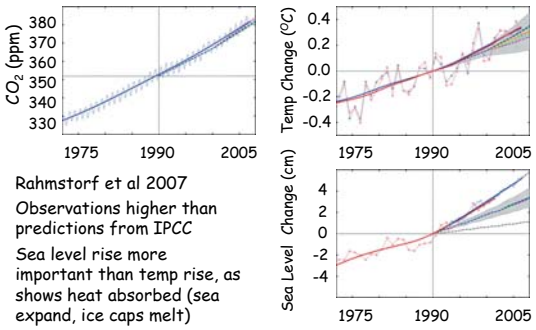
We have pushed the feedback systems too far – negative feedback systems have become positive …

Current attempts to be green – recycling, renewable energy, reduced carbon foot prints – too late

We are heading for global catastrophe – only pockets of humanity will be left.

Graphs on next slide part of evidence matters worsening

IPCC Predictions and Data



Rahmstorf et al 2007

Observations higher than predictions from IPCC

Sea level rise more important than temp rise, as shows heat absorbed (sea expand, ice caps melt)

Geoengineering to address issues?

Physical means – eg manipulating planetary albedo

sulphuric acid droplets in stratosphere : reflect solar radiation

Biological means – to reduce CO_2 from atmosphere

plant trees (even artificial trees)

fertilise ocean algal systems

Active Gaian geoengineering – change climate feedback to negative

enhance Carbon burial – as part of carbon cycle

99.9% of C taken by photo synthesisers, returned by consumers to air as CO_2 or Methane

Instead, convert agricultural waste to 'char', bury in soil.

Now 10-30% of C returned as CO_2 or Methane

Finally - Lovelock Summary Article

Gaia: The living Earth

Nature **426**, 769-770 (2003) | doi:10.1038/426769a

Claims major achievement of Gaia - change of style of Earth Systems Models to include responsive Biota

these modules influence climate change conferences

Notes Earth getting old – less able to resist disease – planetary impact may be catastrophic

Gaian theory reconciles evolutionary biology & geology – extending not contradicting Darwinian theory

Its greatest value – metaphor – reminds us that we are part of Earth system – should work with it

Gives following table of predictions/confirmation

Gaia Predictions and Confirmation

Mars lifeless atmospheric evidence, 1967	Viking 1977
Elements transferred ocean to land	DMS 1973
Climate Regulation – life enhanced rock weathering, 1981	Microorganisms found
CR by cloud albedo affected by algae, 1987	Under test
Archaen Atmosphere dominated CH_4, 1988	Accepted
O_2 at 21% ± 5% for 200 m years, 1989	Under test
Boreal forests reg. climate like DW, 1988	In Cl models
Biodiversity needed in regulation, 1992	Ok in models
Interglacial result of 'system failure', 1996	Controversial

Summary

Thus the Gaia Hypothesis

has come a long way

has evolved

has been influential in thinking

has generated ideas for research

But there is more to be done

It is nice to think that 'cybernetic' approach to understanding of environment has been so useful.