

Notes on “Six Degrees: Our Future on a Hotter Planet” (M. Lynas)

Introduction

Mark Lynas was inspired to write *Six Degrees* by the flooding of New Orleans, which is a harbinger of things to come – a “portal into the future”. Not only did it happen decades in advance, but also striking was how quickly the veneer of civilization peeled away as the benighted city descended into such terrible conditions of hunger, thirst and lawlessness in the world's most advanced nation. Gangs of armed young men dominated the place as frailest bystanders haplessly looked on, as the place increasingly resembled a Third World refugee camp. The response was marked by monumental incompetence and to this day around 500,000 remain “climate refugees”. Wrote a degree-by-degree book on global warming based on the IPCC's predictions of a 1.4C-5.8C rise this century based on hundreds of scientific studies; to appreciate the scale, note that global temperatures were around 6C during the depths of the last Ice Age, when massive ice sheets descended into central Europe and southern England was a freezing polar desert blasted by dust-laden winds and suffering winter temperatures of up to -40C. The Channel and North Sea were dry land and agriculture was impossible, with dessication affecting even the tropics. Timescales uncertain; there could be a 2C rise by 2100, or as early as 2030 (or even earlier! If feedbacks are really bad); as is appropriate for a book on the 21st century, it deals with “transient” climate change rather than steady state equilibria. Also speculates on social impacts, e.g. Chinese-Russia war for Siberia, nuclear war between India and Pakistan over the diminishing headwaters of the Himalayan rivers – on this note, see Trausti Valsson's *How the World will Change – with Global Warming*. “Climate change is the canvas on which the history of the 21st century will be painted”.

1. Degrees

- **America's slumbering desert.** Between 1100-1300AD, California had been hit by a mega-drought, resulting in collapse of cultures such as the Chaco – “several locations show evidence of violent conflict – including skulls with cut marks from scalping, skeletons with arrow heads inside the body cavity and teeth marks from cannibalism”. During Holocene Maximum 6,000 years ago, there was greening of the Sahara and precipitation increased in US south-west. But it seared the Great Plains (from Texas / Oklahoma to Saskatchewan / Manitoba) as winter shortened by two months, more heat waves and rain came in battering storms. Though today the Great Plains are one of the world's agricultural grainbaskets, the topsoil is thin and sand dunes lie underneath – though currently “stabilized”, can march again. Dust Bowl arose in 1930's after 25% reduction in rainfall; if 40%+ reduction over decades, will turn to desert – though irrigation can buy time, aquifers are anyway being rapidly depleted by industrialized agriculture. *The future: dessication of California and the Great Plains; wetter south; immigration to wetter Midwest / Great Lakes region.*
- **Already the day after tomorrow?** Gulf Stream is part of Atlantic Meridional Overturning Circulation system, in which warm subtropical waters are cooled by Arctic air and sink as salty brine. Higher rainfall, glacier runoff, greater runoff from Siberian rivers and melting of the ice caps will freshen the water and could stop the great ocean conveyor – as portrayed in *The Day After Tomorrow*. But most forecasts don't find a collapse until AGW is well advanced, which just modulates the warming. However...a 30% drop in intensity registered in 2004; models show a sustained 50% reduction could lower temperatures (2-3C) and result in a drier Europe. On average,

UK blanketed in snow for more than three months, sees temps as low as -16C and ice floes in Thames – a return to the Little Ice Ages in the worst winters. *The future: imminent collapse followed by cold 2010's punctuated by increased dependency on Russian gas, followed by moderate 2020's and hot 2030's in Europe? Or will Europe just remain moderate throughout near future – Atlantic conveyor collapse being dynamically counterbalanced by general GW? -F*

- **Africa's shining mountain.** Melting glaciers around the world, e.g. in Africa, Kilimanjaro and the 'Mountains of the Moon' (Uganda / Congo borders). Destroys ¹⁶O / ¹⁸O record (former is lighter, evaporates easier, so in warmer climates more will fall as rain and end up on mountain glaciers). But main issue (in Africa) is not that the glaciers will vanish (only account for c.5% of downstream river water), but the lower tree cover that traps moisture will burn, thus threatening fish stocks and hydroelectric production. *The future: Kilimanjaro de-iced by 2020.*
- **Ghost rivers of the Sahara.** Nowadays Sahel is marginal scrubland (famines in 1970's/80's corresponding to European darkening), and Sahara is inhospitable desert with only occasional oases of civilization. Yet once Sahara was verdant with elephants, giraffes, gazelles, rhinoceroses, buffalo in rock art... Tributaries of the Nile in north Sudan and Egypt's Western desert; huge shallow lakes in south Algeria with birds, fish and crocodiles. Around 10,000-5,000 years ago the desert edge retreated 500km north, at times almost disappeared. Lake Mega-Chad (borders of Chad, Nigeria and Cameroon), second largest after Caspian; maintained by much higher rainfall – Sahara greened during warm interglacials (heated up N. Africa enough to generate monsoon, like in India). Monsoons occur since land heats up quicker in summer than surrounding ocean → hot continental air rises, sucking in cooler, moist air from ocean → torrential summer downpours and forms agricultural patterns. Theory that Sahara will green as the African monsoon strengthens, BUT... 1) past not perfect analogy as it was based on differences in hemispherical solar heat distribution, but now all world is warming, 2) even then Sahara got just 100mm of rain, not enough to support anything but savannah style vegetation. One model says north Africa gets wetter, south Africa desiccates... other study predicts heavier rain in Sahel and West African coast. BUT other study predicts short interlude of rainfall, followed by ever fiercer drought, which chimes with global study projecting percentage of world surface in grip of extreme drought going from 3% today to 30% in 2100 (i.e. basically uninhabitable) – based on change greater than 1C. Land surface heats → dries up → vegetation lost → topsoil washed away in heavy rainfall. *The future: more rainfall in Sahel and West Africa, and partial greening of Sahara...but as world continues getting warmer, Sahel fully desiccates.*
- **The parched Amazon.** Amazon is fragile and getting drier, making it susceptible to wildfire. In 2005, tributaries of Amazon dried up exposing sand of riverbanks, winds whipping sandstorms, baked mud instead of river, and massive forest fires. Kills trees, they fall, fuel for next round of fires during drought – and when it burns, released massive amounts of CO₂ further turbocharging GW. “The Amazon...is already nearing a critical threshold of temperature tolerance”...when crossed as global warming accelerates, entire Amazon ecosystem will collapse with devastating global consequences. *The future: Amazon will be on the brink. +F*
- **The Arctic meltdown begins.** New meltwater lakes appearing in Arctic regions, while some existing lakes are draining away; infrastructure damage as buildings, roads, railroads and pipelines buckle. Ice-albedo feedback: a) earlier snowmelt means more summer heat goes into air and ground instead of melting snow, b) dark-colored shrubs and forests impinge encroach on once-white tundra and c) melting Arctic ice (reflects 80%) exposes dark ocean water (reflecting 5%), which absorbs more heat, raises temperatures and makes it more difficult for next year's ice to re-form. “Polar front” will move north, drying S. England; Scotland will remain wet. Because of albedo amplification,

every 1C of global warming results in 2C of Arctic warming – already tipping over into state described by palaeoclimatic studies in which Arctic is as warm as current Mediterranean, ice-free year round and air temperatures usually stayed above freezing even during the dark winter. **The future:** *Propelled into oblivion by the ice-albedo feedback, by 2015? the Arctic will be ice-free in summer, and in one or two more decades year round. Massive infrastructure damage in far north due to melting permafrost and feedback due to less snow. +F*

- **Danger in the Alps.** Mountain permafrost melting → more rockfalls.
- **Queensland's frogs boil.** Great Barrier Reef and corals around the world bleached when ocean temps exceed 30C; by 2020's (with less than 1C rise), mass bleaching will be regular affair → seaweed takes over; these insults are in addition to current human attacks in form of overfishing and waste runoff. Polar bears pushed off the top of the world; creatures like pikas shoved off the planet (need cold altitude). Golden toads. **Future:** *many animals will become extinct and coral reefs will bleach and die.*
- **Hurricane warning in the South Atlantic.** As surface ocean temperatures warm (you need 26.5C+ temperature for hurricanes to form) and circulation patterns break down, there will be more and more storms in unexpected places. Storm intensity index doubles over past 30 years – fewer storms, but now they're stronger and last longer. **Future:** *more devastating hurricanes in more chaotic global distribution.*
- **Sinking atolls.** Tuvalu, Kiribati, Marshall Islands, Tokelau, Maldives are doomed worlds, fated to submerge amidst the rising waves in coming decades.

2. Degrees

- **China's thirsty cities.** North Chinese monsoon – in summer, moist air from oceans → heavy rainfall; in winter, polar northern winds bring dust and freezing temperatures. “Because of how long it took the oceans to absorb heat...the dry winter monsoon responded much more rapidly than the summer one to the changing conditions. The result was a period of drought and continental-wide dust storms, before the summer monsoon pushed far enough inland to bring significant rainfall to the loess plateau” - is this causal mechanism behind the drought and higher temps that have struck north China in recent years, lowering grain yields? Problems with Beijing and Tianjin water supply, economic growth and depleting aquifers; floods in the south. Now there is huge megaproject in construction to bring excess water from the Yangtze to the parched north. **The future:** *China will face inundation in the south and encroaching deserts in the north, amplified by diminishing aquifers and burgeoning industrial demand – will try to resolve this with megaprojects.*
- Half of all released CO₂ now absorbed by the oceans, where it turns into carbonic acid. PH of the oceans from normal 8.2 → 8.1 today → 7.7 in 2100? (Also other pollutants – see Great Pacific Garbage Patch). Great parts of ocean will become too acidic to support calcareous life, e.g. the pteropods in Southern Ocean will have their shells dissolved; also even fish, squid, etc. are not used to this. Tropical corals weaken due to dissolution of their calcium carbonate skeletons; bleaching makes a double wammy. Good for potential shipwrecks, bad for coastal communities previously buffered by corals. Ocean acidification is positive feedback to GW by slowing down the rate of future CO₂ absorption – e.g. planktonic algae called coccolithophores remove CO₂ and when they die their limestone shells float to sea-floor; this cycle now interrupted as they die. Key thing is rapidity of current change which precludes marine organism adjustment. **The future:** *Ocean acidification leading to breakdown of oceanic carbon uptake cycle, accelerating GW; mass oceanic*

extinctions, including death of coral reefs. +F

- **The mercury rises in Europe.** In Europe in 2003, temps reached extended 35C+ (heatwave definition), resulting in 30,000 excess deaths mostly due to heat stress. Resulted in crop losses, forest fires, low rivers → grounded barge traffic, little water for irrigation and hydroelectric production, toxic algal blooms in denuded rivers and lakes, melting glaciers and permafrost on mountains – yet temps just 2.3C above norm. If 2C rise, then typical summer will be like this - “temperatures may soar to highs commonly experienced today only in North Africa, as rivers and lakes dry up and vegetation withers across the entire continent”. Decline in plant growth due to twin stresses of searing temps and drought - “instead of absorbing CO₂ from the air, the stressed plants began to emit it” - nearly happened already in 1998-2002 mid-latitude drought. **The future:** *Europe will move to N. African climate, resulting in crop losses, water shortages (for irrigation, hydroelectricity), grounded barge traffic and melting mountains. Plant decay will turn its vegetation from CO₂ sink to source.* +F
- **Mediterranean sunburn.** Med Europe → hotter and drier as subtropical arid belt moves there; tropical nights (20C+) increase by 1 month and 3-5 weeks of heat waves (35C+) in inland Spain, south France, Italy, Greece and Turkey. Air-conditioning demand during drought and low reservoirs may lead to blackouts. As Saharan heatwaves sweep across the Med, recent emigration from north to south Europe will reverse. **The future:** *a much hotter and drier Med will lead to water shortages, summer blackouts and emigration.*
- **The coral and the icecap.** Sea levels during Eemian interglacial 125,000 years ago were some 5-6 meters higher, when global temps were 1-2C higher. Greenland had shrunk significantly in the south and west. Though IPCC predicted eventual Greenland meltdown, projected it happening over a millennial timescale – not to worry. BUT, “at the end of the last Ice Age...global sea levels shot up by a metre every twenty years for a period of four centuries, drowning tropical coral reefs in Hawaii and submerging low-lying coasts” - Meltwater Pulse 1a some 14,000 years ago at dawn of the Holocene. Greenland melting threshold is 2.7C; as Arctic warms faster, global temp rise will have to be just 1C. Yet models show melting will be slow and partly offset by increased snowfall → thicker ice in the center. But, “current models treat the ice sheet like it's just an ice cube sitting up there melting...” - Howat. As melting proceeds on the surface, “whole rivers plunge down through icy sink-holes called moulins onto the bedrock beneath the ice sheet. This meltwater then acts as a lubricant underneath the ice, speeding up the glaciers as they proceed towards the sea”. So rate will be much faster / risk of catastrophic collapse? Glaciers are thinning, retreating and accelerating AT EXPONENTIAL RATES...ice shelves disintegrating into iceberg armadas. Rate of Greenland ice loss increased by 250% between 2002-2004 and 2004-2006. **The future:** *Gathering meltwater bores moulins and forms underground rivers, lubricating the ice sheet base; meanwhile, glaciers begin to retreat, thin and accelerate at exponential rates – possibly much of Greenland will be gone by the end of the century, raising global sea levels by up to 7m..* +F
- **Last stand of the polar bear.** GW will open up the Arctic shipping routes and spark a new petroleum gold rush (a quarter of the world's undiscovered oil and gas reserves lie under the Arctic Ocean?). Now massive investments – Norwegians building LNG terminal at Hammerfest; Gazprom developing fields, also setting off new polar Great Game as nations assert mineral rights to their sections of the seabed. Forecast – huge areas of ice-free water open up north of Canada, Alaska and Siberia as early as 2025. During Eemian, “sea ice retreated towards the pole and boreal forests invaded tundra, advancing in some places all the way to the edge of the Arctic Ocean itself”; freezing rainfall replaces snow. Polar bears, ringed seals, walrus facing extinction. At 2C rise, “tundra almost completely disappears” while “forests march north”, even reaching Greenland; cold

moss and lichen tundra nearly extinct, clinging on just on the highest mountains and remotest islands in polar regions. Key here is the “Arctic amplifier”, as 2C rise → 3.2-6.6C in Arctic by 2050, meaning speed of the transition could be as high as 1.5C per decade! Arctic people facing cultural extinction. **The future:** *As the Arctic rapidly becomes ice-free, global shipping routes open up and huge new hydrocarbons reserves open to exploitation, ushering in a geopolitical Great Game in the High North. Boreal forests steadily advance into the tundra, freezing rain replaces snowfall and Arctic species face extinction. +F*

- **Indian summer.** India in the midst of breakneck industrialization with burgeoning energy demand for next 2-3 decades. Declines in wheat and rice yields, particularly in Haryana, Punjab and west Uttar Pradesh; West Bengal will gain slightly, but overall 8% fall. (PS. Output already declining as in China). Refugee influxes due to crises in neighboring countries. Bangladesh suffers from stronger monsoon – already today 30-70% of its flat land area repeatedly flooded. In Nepal, melting Himalayan glaciers produce lakes behind unstable walls of moraine rubble left by retreating ice, forming more and more glacial lakes – when they break they result in catastrophic mudflows. (Worst effect of melting glaciers is no more run-off to power the massive rivers delivering fresh water to hundreds of millions of inhabitants of the Indian subcontinent, ushering in water shortages and famine – see later). **The future:** *Agricultural decline in India and refugee influxes into it as Bangladesh is gradually overwhelmed by stronger monsoon (and rising sea levels).*
- **Peru's melting point.** Lima is in one of the driest desert areas in the world (as is half of Peruvian population); the glaciated Andean mountains are its water towers. They will melt with 2C rise (by around 2050). Past civs here, the Moche (200-800) and Chimu (1100-1470) built networks of irrigation canals and aqueducts to bring scarce water in from the mountains; the “periodic crises which engulfed the Chimu and Moche peoples were directly linked to droughts” as highland rainfall failed for years in a row. With every 1C of warming, glaciers go up by 150m (also, mountain temps go up quicker than average global); currently, glaciers seen only at 5000m or higher – so Lima's glaciers doomed to dry up, reverting it to rainfall dependence. Solutions? Bottled water, piped through mountains or made from desalination plants, which are all expensive options. Agriculture crisis. Lima and desert folks forced to move back up to the mountain villages, where water supplies are more plentiful and crops can be grown – subsistence stress and major refugee upheavals. **The future:** *The glaciers supplying Peru's desert areas, including Lima, with water will dry up, leaving it dependent on highland rainfall (prone to drought). Though temporary solutions – bottled water, piped mountain water or desalination plants can be tried – in the end these settlements could be abandoned in favor of mountain villages, ushering in new subsistence stress and upheavals.*
- **Sun and snow in California.** Winter snowpack diminishing in the West, meaning water stress in summer as snow melt replaced by rain. Colorado River already sucked dry by the time it reaches the Gulf of California (supplies drinking water to much of southern California and Arizona). San Joaquin River, diverted to feed California's Central Valley, also failing. “With major cities like Los Angeles and Sacramento all dependent on a network of canals and pipelines for their water, the hydrology of California is more like a giant plumbing system than a set of natural river valleys”. Snowpack declines of 1/3-3/4; Los Angeles heat waves will 4x in frequency; crippling droughts will occur 50% as often. Sierra Nevada snowpack declining and earlier melt produces earlier spring run-offs + growing population, water demand → increasing water crisis. Snowpack declines of 20-70% in Rockies and Cascades farther north. More wildfires due to droughts – according to study, “Current demands on water resources in many parts of the West will not be met under plausible future climate conditions, much less the demands of a larger population and larger economy”. During Dust Bowl (1C), California was a refuge; in 2C, these western havens will see critical water

shortages of their own, calling into question the region's capacity to support big cities and agricultural areas. ***The future:** as California has an intricate hydraulic system, smaller snowpacks (more falls as rain) means less water and earlier run-off in flooding, thus creating an imminent water crisis – not helped by its burgeoning population and economy and increased incidence of severe drought.*

- **Feeding the eight billion.** US will be OK – purchasing power (world grain markets?), winter wheat better in MidWest/Great Lakes (Indiana, Illinois, Ohio, Michigan, Wisconsin); more maize in North Dakota and Minnesota; more potatoes throughout the north; 50% fall in soybean/sorghum in south-east. More popular vegs and fruit, strawberries, courgettes, etc, in UK; wheat and maize expand into western Russia and south Scandinavia, all helped by fertilising effect of higher CO₂ too. New opportunities in Canada, though adjustment difficult. Salmon declines in Canada, North Sea cod virtually wiped out. BUT in S. and C. America the staple maize will decline in all countries except Chile and Ecuador (especially subsistence farmers w/out new technology); majority of Africa will tip over into crop failure and hunger, the worst hit being Burkino Faso, Swaziland, Gabon, Zimbabwe, Mali and Botswana. Congo has more rains, but lesser dry season to allow its farmers to burn off land for next year's crops – so uncertain. Lesotho and Ethiopia will benefit as yields increase in their mountainous areas. “With assiduous planning and adaptation, the world need not tip into serious food deficit. However, if the temperature rises past two degrees, preventing mass starvation will be increasingly difficult...” Especially in drier subtropics, life will become precarious and the most destitute nations will slip into structural famine and crisis. ***The future:** In warming world, the US holds steady with production moving from Great Plains and the West to the north and Mid-West. Europe is a mixed picture with similar northward shift; great potential in Canada and Russia, but will be difficult to develop. The countries that contributed least to GW are worst off – though mountainous and equatorial regions hold, maize yields decline throughout the drier subtropics, incipating structural famine in the most destitute nations.*
- **Silent summer.** Though humans survive, GW inflicts grave toll on nature and biodiversity – in addition to already ongoing sixth mass extinction of life on Earth due to human activity (background rate of extinction 100-1000x above natural). Spring comes earlier, on average species are moving their ranges 6km towards the poles and 6m up mountains. Birds silent. Butterflies can only disperse by 2km a year; ground beetles at 200m. Forests less than 1km. GW looks set to move at 30km a year – which they find unmanageable and will become extinct as they're overrun by a rapidly changing climate. (PS. Note bees). Grasslands can't move if soil farther north is different minerally. Over a third of species threatened with extinction, ushering in an “Age of Loneliness” on a devastated planet. Silent Summer - “a never-ending heatwave, devoid of birdsong, insect hum, and all the weird and wonderful noises that subconsciously keep us company”. Biodiversity is of great utilitarian as well as aesthetic concern – fish and fuel wood; soils broken down by bacteria; crops wouldn't set seed unless pollinated by bees; many life-extending medicines developed from natural substances made by plants and animals; carbon sequestration in the oceans into limestone and chalk. In principle can be replaced by technology (e.g. hydroponics – synthetic rooting material and cocktail of chemicals), but the system is very complicated, not understood and could be unrealistic to artificially replicate. ***The future:** ongoing sixth great extinction turbocharged by GW, which unleashes climate change that many species are too slow or too specialized to escape. More than a third of current species die off, ushering in a hot, silent summer – an increasingly artificial and fragile world tries to compensate for nature's prior services (through hydroponics, species transfers, systems studies, bioengineering, fish farms, etc).*

3. Degrees

- **What every Botswanan wants.** Rain obsession in hot, dry dusty land (Kalahari desert, most land is uncultivable). Cattle, diamonds, tourism. While tropics and mid-latitudes drown in floods, subtropics bake to death – rain clouds over Indian ocean form and pour back rain into the ocean, leaving southern Africa with just the dry fall-out. In models, south Africa dries up (pushing people already at edge of subsistence into structural famine); north Africa gets more rain. Kalahari, the epicenter, goes from largely scrub and savannah, to true hyper-arid desert with raging sandstorms, diminishing vegetation (like US Great Plains, much of Kalahari region are “stabilized” sand dunes). This region extends into Zambia, Angola, Namibia, western Zimbabwe, northern South Africa. Now held together by vegetation and low wind speeds; later, increased evaporation due to heat and doubled wind speeds erode away the topsoil, starting in Southern Dunefield but eventually encompassing all. Botswana covered by dunes in entirety by 2070; villages, capital cities, etc. ***The future:** Though tropics and mid-latitudes will drown in floods, the subtropics bake the death – including much of sub-Saharan Africa, where increased evaporation and higher winds erode away the landscape to reveal the sand dunes of the greater Kalahari desert – making human habitation impossible.*
- **Perils of the Pliocene.** Models pretty reliable (back-casting), but many factors unknown (e.g. extent of “global dimming” - another approach is paleoclimate. 1C = early Holocene 6-9kyrs ago; 2C = Eemian 125k yrs ago; 3C = Pliocene (3mn yrs ago). Tropics (east African forests) and polar region all forested. Stunted shrubs growing prostrate in Transantarctic Mountains (cold winds); northern Greenland had conifers; 15C warmer in Ellesmere Island in winter. Both poles and tropics warmed up. Plant stomata indicate CO₂ levels of 360-400ppm – equal to today's levels. Of course due to thermal inertia reaching new equilibrium at 3C will take a few centuries; but much quicker if humans continue dumping mass amounts of CO₂ into the atmosphere. ***The future:** conifer forests and shrubs sprout up in Greenland and melted Antarctica, and extensive tropical forests in East Africa.*
- **The Christ Child returns.** A permanent El Nino Southern Oscillation (ENSO) prevailed during Pliocene. Floods in Peru's Atacama desert; droughts in Indonesia and Australia, Amazonia to Papua New Guinea, India, southern Africa; milder north-east US winters and dampened Caribbean hurricane season; California floods and drier European winters; Amazon doomed to dessication. ***The future:** permanent super-El Nino in which Peru, California get more storms and floods; Amazon dessicates; drought in southern Africa, northern Africa, India, Indonesia, Australia; milder US winters and calmer Atlantic hurricanes; drier European winters.*
- **The death of the Amazon.** The near-total collapse of Amazon rainforest could generate self-sustaining “carbon cycle feedback” - perhaps almost happened in 2005, when fresh water had to be flown into remote villages, fires erupted and whole stretches of rivers turned into meandering mud. 3C rise, the soil shifts from carbon sink to carbon source (as do the warmer seas), thus further pumping up 250ppm of CO₂ between 2050 (3C) and 2100, thus creating 1.5C of further warming to finish at 4C-5.5C rise by 2100. Already evidence of big increase in soil CO₂ emissions. Amazon, home to half of global biodiversity, 10% of net primary productivity; Amazon River contains 20% of all water discharged into world's ocean (fed by Andean snowmelt, torrential downpours). Already under siege for cattle ranches, soya plantations, roads and illegal logging. After 2C rise, there is tidal wave of destruction starting from north-east, rainfall declines to almost zero and temperatures reach Saharan highs of an average 38C. No vegetation except bits of grassland and savannah at the edges. Amazon not used to fires: trees continue dying after burning, regeneration is slow (allowing

sunlight to penetrate forest canopy and further dry out the forest floor) and rainfall suppressed by months-long resulting clouds of smoke. Final conflagration: months-long blanket of choking smog across the whole region; Sun blotted out by leaden pall hanging overhead, grey drizzle of light ash; gigantic walls of flame marching across the remaining forest. "In the deepest parts of the basin, where once the only sound was the howling of monkeys and the rustling of leaves, a moaning wind has risen. Dust gathers in the lee of burned-out tree stumps. Nearer to the ground, a gentle hissing sound is heard. Sand dunes are rising. The desert has come". ***The future:** Increasing incidence of drought in Amazon basin culminates in massive, months-long conflagration which covers the region in choking smog and blocks out the Sun. The world's hydrological engine and greatest repository of biodiversity turns into a sweltering desert of sand dunes and muddied gorges. +F*

- **Australia's Ash Wednesday.** Australia will become even hotter and drier, windier summers; massively increasing fire risk. Agricultural collapse everywhere except Tasmania and northern areas watered by more powerful monsoon. Murray-Darling to lose half its flow; Perth is yet more vulnerable. Fire, heat and drought; agricultural decline; salt water creeps up stricken river systems, poisoning groundwater supplies. When it burns: pyro-cumulonimbus (fire-driven thunderclouds), black hail, tornados, smoke penetrates stratosphere and weaves a trail around Earth. ***The future:** much of interior and southern Australia increasingly inhospitable due to trinity of fire, heat and drought – leading to agricultural decline and huge conflagrations.*
- **Houston, we have a (hurricane) problem.** Warm seas unleash 180 mile an hour Hurricane Odessa against Houston. Howling winds, evacuation chaos, tamed river Buffalo Bayou becomes wild – underground car parks and malls flooded, storm drains spout floodwater and manhole covers blown off, abandoned cars and detritus float down rapidly rising river. Galveston underwater and buffeted by waves tens of meters high; "squalls of water and spray hown up the concrete canyons, which far above, glass windows explode with the force of the blast"; "only concrete and steel survives" – the "era of the super-hurricane has begun". With more energy in hotter seas to power tropical cyclones, and strongest storms will be more deadly than anything experienced today. ***The future:** From Houston to Shanghai, many coastal cities will experience far more powerful hurricanes.*
- **Dawn over a new Arctic.** Reduction in / elimination of Arctic sea ice will exacerbate the drying of western North America – rain shunted off to Canada and Alaska, bringing drought the American West – California, and inland from Nevada to Wyoming. Greenland experiences phenomenal water loss to emerging glacial rivers, as ice edge retreats and new land opens up; huge new blue lakes form, trapped between gravelly moraine and retreating ice cap. Blue lakes form across the whole ice sheet; as elevation of ice cap falls, so do temperatures, further accelerating melting. Icelandic ice caps disappear even sooner. Opens up agricultural potential, as Scandinavian growing seasons match that of southern England / northern Germany; but most of Arctic is rocky and acidic, with thin soils. ***The future:** Rainfall shifts north to Canada and Alaska, resulting in further drought in the West. Greenland in rapid meltdown, with massive glacial rivers and lakes. Though growing seasons in the High North increase, being thin, rocky and acidic their soils are unlikely to compensate for lost breadbaskets. +F*
- **Mysteries of the Maya.** Descendants of Maya civilization uninterested in its monuments... Classic Maya long gone by the time the Spanish came, with just a few primitive subsistence farmers eking out stunted maize and beans from the poor soils. Drought; irrigation depended on reservoirs with 18 months of spare capacity...series of droughts weakened faith in the ruler and led to revolt and dissolution. Overpopulation, destruction of forest cover, erosion again prevalent in south Mexico and Central America...with warming, these subtropics will get arid and experience droughts. "It is hard to see how the tens of millions who currently live in Central America could survive for long in

such marginal lands"...agricultural collapse, no food aid, emigration leaving behind ghost towns.

***The future:** Central America will experience severe droughts and agricultural collapse, forcing mass emigration that will again leave behind ghost towns and monuments to a lost culture.*

- **Mumbai's monsoon.** Without annual monsoon watering, fertile, overpopulated plains of India and Bangladesh would be arid and lifeless – if it fails, millions will starve (if it 's too strong, there's flooding). Since monsoons depend on land-ocean heat differentials, monsoon is unlikely to fail in warmer world. Monsoon is weaker when colder (e.g. during Ice Ages); modern pollutants like aerosols (sulphur dioxides and particulates released by fires) form "Asian Brown Cloud", however, might reverse this. However, consensus is that monsoon will increase, leading to: 1) increase in average rainfall results in more extreme floodings, 2) more variability – so more years of drought, and more years of extreme flooding and 3) already wet areas become wetter (Indian west coast, Bay of Bengal, Bangladesh, north-east India) and already dry areas become drier (northern India, southern Pakistan). ***The future:** although may get weaker due to Asian Brown Cloud, monsoon will probably get strong, leading to more variability (increased catastrophic flooding AND droughts) and exacerbation of current humidity differentials (wetter in Indian west coast and north-east, Bay of Bengal, Bangladesh; drier in north India, south Pakistan).*
- **Where the Indus once ran.** Heavily glaciated Himalayas water all main Indian rivers – Indus, Ganges and Brahmaputra, as well as Mekong, Yangtze and Yellow. Karakoram range waters Pakistan, with more glaciers feeding it than Ganges and Brahmaputra put together; but valley floor has shimmering heat haze, arid – so Indus is particularly dependent on mountain water. Global warming greater at big heights and glaciers already melting fast. At first, Indus will get swollen with extra melt as glacier retreat accelerates; but afterwards, river's flow will slow to a trickle, with the great, braided plain of the Indus River becoming empty for months at a time. Flows peak in 2030 by up to 90%; fall by half by 2080 (and running dry further upstream); downstream reduction from 20% to 40%. With little rain on Punjabi plains or lawless mountains of Balochistan, Pakistani agriculture almost entirely reliant on water from Indus flowing into irrigation canals criss-crossing the Punjab... faces destruction of breadbasket. Also, in China 23% of population lives in regions where glacial melt is main dry-season water source; 70% of dry-season flow of Ganges, and half of India's other rivers, comes from melting glaciers. Blackouts in hydroelectricity dependent India during summer; two of Indus tributaries (Chenab and Sutlej) rise in India, so conflict over how much can be stored behind dams in upstream reservoirs. In Pakistan, crisis in food production -> crisis in economy (dependence on rice and sugar exports from irrigated Punjab). In Sindh, totally reliant on Indus for inflows into canal system, farmers will face conflict with Punjab; who in turn are outcompeted by big cities like Lahore, Hyderabad and Karachi. As the Indus runs dry, people flee to overcrowded cities; no global food stocks to feed them; tensions with India as refugees stream out; failed state, rule of the gun and nuclearized anarchy as "the river that sustained their civilization for centuries runs dry, and the breadbaskets which it supported are overcome by the spreading desert", as shimmering white of old glaciers gives way to bare rubble and sun-baked soil. ***The future:** Since Indus Valley is essentially desert, the river is reliant on Himalayan ice-water melt; will first swell, but will later dry up for months at a time during the dry season. This will devastate the canal-watered Punjabi breadbasket and usher in a subsistence crisis in Pakistan, resulting in nuclearized anarchy and perhaps a last-ditch war with India.*
- **The last drops of the Colorado.** Colorado no longer a natural river, but (like Sacramento and San Joaquin rivers) a giant plumbing system with all its water allotted. A series of droughts in the early 2000's nearly pushed the system over the edge...between a quarter and half the time during the second half of the twenty-first century, the system would essentially fail. Storing river water is

essential to balance out seasonal changes in flows. Snow will have turned to rain in lower-elevation basins...average date of spring snowmelt from the higher mountains will be coming a month or more earlier in the year, so precious water will need to be released from the dams to safeguard against flooding, wasting much of it as runoff. Long summer drought will become even longer. All of the Pacific coast of the US is critically dependent on snowmelt (e.g. Seattle, Washington's Yakima valley, even Alberta which depends on irrigation water from the Rockies). Forests under pest attacks (California's oak woodlands) and increased wildfires. **The future:** *Due to greater winter rainfall and quicker snowmelt, incidence of drought will increase on American west coast – devastating California, Washington and Alberta agriculture.*

- **Sinking the Big Apple.** In NY area, most rail, tunnel and airport entrances lie at elevations of only 3 metres or less...NY vulnerable to storm surges since right-angle bend between New Jersey and Long Island funnels water right into the city's harbor; close call in December 1992, when nor'easter pushed massive storm surge onshore – shorted out whole NYC subway system (stranding people on trains and in stations), submerged FDR Drive / other Manhattan roadways and Battery Park tunnel; flood levels of 0.5m higher would have led to mass loss of life. Stronger hurricanes, perhaps stronger nor'easters, lead to many NY "perfect storms"...entire areas like Lower Manhattan become economically unviable due to frequency of submersion. Plans to construct flood barriers to protect against storm surges at; between Staten Island and New Jersey @ Arthur Kill, the Narrows at mouth of NY Harbor, and across Upper East River at the North Shore of Queens...to protect three most vulnerable parts of NY @ Lower Manhattan, Coney Island and Rockaway Beach. **The future:** *Due to stronger storm surges due to more powerful hurricanes and nor'easters will increase NYC's vulnerability to catastrophic flooding, and will make parts of it economically unviable – in response, the city may construct billion-dollar flood barriers to shield itself.*
- **Storms gather in Europe.** Thames barrier will need to be raised with increasing frequency as storms become more powerful; though cities can be protected, lots of towns, villages and huge swathes of farmland in the Thames estuary will have to be abandoned as people retreat inland from the raging seas. More extreme cyclones will track across western Europe...intense cyclones become more frequent worldwide...more gales sweep across the North Sea, resulting in stronger storm surges on coasts of Germany, Denmark, Holland – which is particularly vulnerable and will have to accept significant contraction in land area. Planetwide intensification of the hydrological cycle...northern Europe experiences 20% more rainfall by 2070's, concentrated in heavy events (winter flooding). Droughts and floods both increase, devastating agriculture and population centers...Alps face same problems as the western US in north Italy, Bavaria, Spain, Rhine, etc. Med rim will be transforming into desert...Sahara will be on the march north. **The future:** *Stronger storms in North Sea put London and Netherlands at increasing risk due to storm surges. Droughts and floods both increase; Alpine glacier melting causes same effects on the Rhine as aforementioned Colorado, while parts of the Mediterranean rim will be desertifying.*
- **Africa's fever.** East Africa to get more humid, even as sand dunes pile up in Botswana and the south...Somalia, Kenya, Tanzania, Mozambique see more extreme rainfall, flooding and resulting malaria, which migrates uphill due to warming (Zimbabwe hit particularly hard). Malaria future also depends on economic growth and healthcare; some studies show that counter-intuitively, hundreds of millions more people are at risk of contracting malaria in a scenario with LOW greenhouse emissions! (because econ growth / health will be less). Africa sees unanimous increase in malaria, however; along with AIDS, will continue to extract toll on the working age population. **The future:** *increased rainfall in East Africa results in more flooding and malaria infestation, further compounding Africa's development crisis.*

- **Paradise lost.** In Amazonian Venezuela, tabletop mountains (tepui) with fabulous biodiversity will lose it. In tropics, bleaching / acidic ocean will kill remaining reef systems, lots of extinctions everywhere, etc. Not all go at once – some are just doomed ("living dead").
- **Growing food in the greenhouse.** John Sheehy: "In rice, wheat and maize, grain yields are likely to decline by 10% for every 1C rise over 30C; over 40C, yields are reduced to zero" (plants have thermal threshold tolerance...grains particularly vulnerable during flowering and setting seed). Food production in tropics, where temps are already close to or at 30C, yields will begin their long downward slide, therefore there is a "generalized shift of crop production away from the tropics and towards the more temperate higher latitude regions". North Africa and south Africa lose rainfall; agriculture in Africa's semi-tropical arid areas is rainfed, so highly vulnerable...projected crippling declines in wheat, corn and rice production. After 2.5C rise, even breadbaskets in temperate mid-latitudes suffer due to soaring summer temperatures and drought. In US, southern areas close to sub-tropics suffer most; droughts interspersed with heavier rainstorms; new pests and diseases necessitate heavier pesticide use. Even in Canada increases in cereal crop production is limited by water availability; but where water is plentiful, Canadian corn, soybeans, potatoes, winter wheat benefit; range over which staple crops are planted shifts hundreds of kilometers to the north. Yet even with gains closer to the poles, global food situation becomes increasingly precarious: IPCC says "net global food deficit beginning to drive up market prices once the 2.5C threshold is passed". Structural famine in subtropics; gargantuan population transfers; "never before has the human population had to leave an entire latitudinal belt across the whole width of the globe". Climate refugees increase tensions in recipient northern nations: US may close Mexican border; European fascists come to power promising to keep out Africans. "Undaunted, many of these new climate refugees make the journey on foot, carrying what they can, with children and old people trailing behind. Many of them die by the wayside. Uprooted, stateless, and without hope, these will be the first generation of a new type of people: climate nomads, constantly moving in search of food, their varied cultures forgotten, ancestral ties to ancient lands cut forever" – will not remain passive, since they know that the world they inherited is not one they created, "The resentment felt by Muslims towards Westerners will be tame by comparison. As social collapse accelerates, new political philosophies may emerge, philosophies which seek to lay blame where it truly belongs – on the rich countries which lit the fire that has now begun to consume the world". ***The future:** Since grain yields decline at temperatures higher than 30C, agriculture in the arid sub-tropics become increasingly untenable (southern and northern Africa, central America, south India / Indonesia). In North America, agriculture moves north to the Mid-West and east Canada (west and south-west become dry). Net global food deficit after 2.5C rise – even mid-latitudes suffer due to extreme floods and droughts, structural famine grips the subtropics and creates hundreds of millions of climate refugees – resulting in rich-nation isolation or fascism, and eco-extremist movements amongst the uprooted, cultureless nomad masses.*

4. Degrees

- **Death on the Nile.** Threatened by encroaching waves, "modern Alexandria's two harbors form the busiest seaport in the country and support 40% of Egypt's industry"; benefits from summer tourism. Is most important Egyptian city after Cairo. Already below sea level, even a small sea level rise will submerge much of the city. Bangladesh will lose much of its land area, displacing tens of millions from the fertile Meghna delta. Boston, Mumbai, Shanghai, NYC, London, Venice – many of the world's premier commercial and financial centers, are similarly threatened. Will become like

modern New Orleans, fortified islands under assault from rising seas, with discrete risk of catastrophic breakdown. If failure, "who will pay to rebuild a city twice? ...in the long term, the only solution will be for millions of coastal dwellers to retreat inland, as civilization's map is continually redrawn with constantly changing geographic boundaries". Inland cities face constant stream of refugees from the coast, particularly when large storms hit...as economic shocks due to direct losses, social instability, declining public confidence and insurance payouts cascade through the financial system, the funds to support displaced people and build new living areas will become increasingly scarce"...refugee cities may themselves become endangered and submerged in the decades and centuries to come". Island nations hard hit, since higher lands are usually denuded and marginal...the most fertile lands often lie just above sea levels, so food and water supplies are hit as salt water penetration poisons aquifers and kills crops; eventual rises of 25m inevitable after 2C warming (paleoclimate), possibly within centuries – so inland drought and coastal inundation, Scylla and Charybdis, will stretch human capacity for adaptation to the limit. ***The future: many of the world's fertile low-lying farmland and urban commercial centers vulnerable to rapid sea level rise. Entire countries like Bangladesh and Holland at risk; cities will become besieged fortresses under constant risk of catastrophic breakdown. As land is submerged, resulting economic shocks break the credit and insurance systems and leave fewer resources to support displaced people, as the world is wracked by the Scylla of inland drought and the Charybdis of coastal inundation.***

- **The heart of Antarctica.** Much of the base of the West Antarctic is grounded below sea level – and that makes it vulnerable to collapse. Glaciers retreating and speeding up; losing 90-150 cubic km of ice per year already. As warmer oceans erode west Antarctica's edges, the stability of the whole ice sheet is called into question. Since much of the center of the great ice mass is even deeper below sea level than its edges, penetrating seawater could lift much of the ice cap off its seabed foundations – adding 5m to global sea levels within a few decades. West Antarctic is shielded by massive, Texas-sized Ross and Ronne ice shelves – thought to be safe for now. Yet along Antarctic Peninsula, three ice shelves have disintegrated: Wordie, Larsen A and Larsen B, resulting in much faster glacier flows upstream – 4C rise is more than enough to break up the Ross and Ronne ice shelves. If East Antarctica melts, will raise sea levels by a further 50m – yet it's shielded by Transantarctic mountain range (super safe!). Yet E. Antarctic sheet is anchored below sea level...those submarine beds extend to the very center of the ice sheet, so collapse via back door. Destabilization of both Antarctic ice sheet could yield sea level rises of meter or so every twenty years – well outside humanity's adaptive capacity. At 4C earlier, there was no ice at either pole. ***The future: If Ross and Ronne ice shelves disintegrate, then West Antarctic ice cap will get uncorked and will collapse within decades, raising global sea levels by 5m; is later followed by East Antarctic ice cap, leaving the poles ice-free and raising total sea levels by a further 50m. +F***
- **Capitalism with Chinese characteristics.** China's late industrialization has come at a heavy cost - ¾ lakes are polluted by agricultural or industrial runoff; Yellow River is depleted and toxic; almost all coastal waters polluted by sewage, farm pesticides, oil spills – causing an average 90 poisonous red tides a year; massive topsoil loss; acid rain and unclean air in major cities. Globally, no more room for expansion due to oil and food limits – if China reaches US consumption levels, the human ecological footprint will virtually double. At 3C+ rise, China's agricultural production crashes; yields of staples like rice, wheat and maize will decline by nearly 40%, more if water for irrigation runs out. Can use its industrial / trade balance clout to close the gap on world food markets; but by this points agriculture will be crashing in most places – western US, Great Plains, Pacific coast of S. America, southern Africa, western Indian subcontinent, Australia except the far north and Tasmania; India becoming simply too hot -> faster evaporation in hot climes makes soil drier in

places like Rajasthan, Punjab and neighboring Pakistan. World drought hotspots: SW North America, Central America, Med, S. Africa, Australia; during winter, its SE Asia; during summer, its Amazon, Siberia and West Africa. Positives include: opening up of sub-polar lands in Canada and Russia (though doesn't imply higher rainfall or decent soils); new drought-resistant crops bio-engineered; fertilization effect of increased CO₂ levels – precarious situation, "with major global breadbaskets dusty and abandoned, rising demand will be chasing rapidly diminishing supply". Historical precedents numerous (death by drought). Ozymandias – Look on my works, ye Mighty, and despair! ... Nothing beside remains. Round the decay; Of that colossal wreck, boundless and bare; The lone and level sands stretch far away". **The future:** *China's continuing industrialization putting unprecedented and unbearable strains on world energy resources and ecological services. Its agricultural production will crash at 3C+ rise by perhaps 40%. As mentioned, many of the world's mid-latitudinal breadbaskets in fast decline; arid subtropics are desertifying; sub-polar agriculture and new drought-resistant crop strains will not reverse the situation. Incipient socio-political collapse across the sub-tropical belt.*

- **The sands of Europe.** "Civilizational collapse, like the blast wave of a neutron bomb, will sweep across the globe", "overtaking a planet whose natural defense mechanisms have already been severely damaged by human activity" (most fertile soil stripped of trees and grasses, and appropriated for farmland; oceans sucked dry by gigantic factory ships; 40% of world photosynthetic productivity appropriated by humans) – thus endangering free ecological services (cloudforming plankton; Amazonian hydrological engine; sea life sequesters CO₂ into chalk and limestone, etc). Double wammy – turning up the heat AND disabling the Earth's thermoregulation systems by cutting forests and polluting oceans. Dramatic changes now – Greenland in full meltdown; collapsing West Antarctica; shut-down of Atlantic circulation (will only slightly moderate more extreme warming in UK); world's "weather will go increasingly haywire, with wilder storms mobilizing undreamt-of ferocity as they strike ever larger areas"...long days of summer, with soaring temps reducing "forests to tinder and cities to boiling morgues". New deserts spreading in southern Europe...much less summer rainfall, far longer heatwaves across the Med: Spain, Portugal, southern France, Italy, Greece, Turkey; ripple effects in Ukraine and southern Russia). Wildfires across the Alps; water supplies plummet as last Alpine glaciers melt away. During summer, London and Switzerland could see temps of 45-48C (as in Marrakech today); England's SE now water-stressed. In eastern Europe, snow will become an oddity; summers much drier without snowmelt, leading to soaring temperatures across continental interiors – Caspian will drop by 10m. Extreme heatwaves across south Eurasia / Russia. Hydroelectric power dwindles in Europe; demand for AC; more and more blackouts, grid collapse? Desalination plants in the Med. Conflict and chaos may return to Europe, as Med residents flock north to the Baltic, Scandinavia and Britain. **The future:** *Earth hit by a double wammy, since humans turned up the heat at the same time they disabled the global thermoregulation system by cutting forests and polluting the oceans. Across southern Europe, perennial summer drought and heatwaves of unimaginable ferocity reduce forests to tinder and cities to boiling morgues...ripple effects in south Russia and Ukraine. London and Alpine regions acquire a North African climate; in eastern Europe, snowmelt becomes an oddity – making their summers much drier. Blackouts, flight to the north and incipient socio-political collapse.*
- **Into thin air.** Atlas Mountains – above tree line, a few stunted shrubs; clumps of grass on barren lower slopes, with only a moonscape of rock and scree above. Browns, greys and reds...faintest smears of snow on the highest summits...in corries and high valleys below, curved ridges of moraine rubble mark former extent of long-forgotten glaciers...lower valleys cut by chasms where flash

floods tore debris from the mountainside, leaving huge boulders isolated amidst wide fans of alluvium...now all chasms dry except occasional muddy pool from recent rainstorm...shimmering heat haze and bare rock. Describes the future de-glaciated Alps. As they melt, risks of: avalanches of wet snow; flash floods; blackouts due to hydropower dependence (effects on Rhine, Danube). Europe's water tower runs dry. *The future: Alpine glaciers melt, in the process unleashing avalanches of suffocating wet snow, flash floods, and eliminating Europe's water tower and unshoring in blackouts in hydropower-dependent areas...at the end, drought turns the Alps from verdant green to baked-earth browns, just like the Atlas Mountains.*

- **Blight gets a battering.** Lifeboat UK...drought in SE, north and west will still get reliable watering thanks to Atlantic weather systems...which become far stronger. More storm surge flooding due to westerly gales, though numbers of storms will decline. SE England afflicted by severe flooding due to rain bursts; don't mitigate drought since much of it runs off quickly or evaporates instead of recharging groundwater supplies. Homes untenable in regularly inundated flood plains...particularly severe in Lancashire/Humber corridor, Thames Valley, eastern Devon, towns around Severn estuary. Universal coastal erosion (stormier weather, sea level rise). Snowfall disappears entirely. *The future: in Lifeboat UK, more severe but fewer storms in the NW and Scotland; more severe floods in low river plains and droughts in SE; coastal erosion everywhere.*
- **A buried message in Texas.** In arid south-central Texas (savannah, near tributary of Guadalupe River meandering towards Gulf of Mexico, a few cattle). Was eroded by rain: "in response to pounding thunderstorms – interspersed with increased droughts – the soils which had built up over previous millennia simply began to wash away"; "with greater summer aridity and more frequent, intense rainfall" – could again trigger the kind of events which destroyed fertility across a massive area of Texas many thousands of years ago. The entire world experiences more convective rainfall – small, violent cloudbursts like thunderstorms, as opposed to the gentler rain associated with the passage of frontal depressions – with longer dry periods in between. In central and northern Europe, heavy precipitation increases (particularly over wintertime Scandinavia), accompanied by drought and desertification in the Mediterranean. Winter cyclones more intense and destructive, but less frequent. Tropical hurricane numbers remain steady, but increase in intensity. In Korea, rainfall rises by a quarter – but land temperature increases of 6C also drive up evaporation, resulting in a drier land surface than before. Temp rise predominates now – "heavaves of undreamt-of ferocity will scorch the Earth's surface"; Europe -> Middle East; Sahara crosses Strait of Gibraltar. "Even where cultivable soils remain, heavy cloudbursts accelerate erosion, converting once fertile plains into gullied badlands, just like the Texas plains. With world food supplies crashing, humanity's grip on its future will become ever more tentative". *The future: In warmer world, rainfall becomes more convective – characterized by small, violent cloudbursts like thunderstorms. Happens in central and northern Europe, SE England and Korea. Even where cultivable soils remain, not succumbing to desert, these heavy cloudbursts accelerate erosion and convert once fertile plains into gullied badlands capable of supporting only marginal grazing. +F*
- **Siberian roulette.** Sea ice long disappeared in Arctic – summer North Pole sees nothing but open ocean; even during dark polar winter, much of the ice fails to re-form. Southern boundary of permafrost shifts hundreds of km north – large areas of Siberia, Alaska, Canada and southern Greenland fall into melt zone. Unstable zones shift and collapse roads and infrastructure – badly affects Siberia and Far East (Yakutsk, Norilsk, Vorkuta find themselves built on quicksand; Trans-Siberian Railway suffers extensive subsidence; Arctic Ocean moves into Siberia. Extinctions. Lakes drain and rivers alter course, as 30% more fresh water drains into Arctic Ocean from extra rainfall and thawing ground; as snow and ice retreat, trees grow in the mossy tundra...new bogs appear in

ground once frozen as solid as concrete. Thawing Arctic soils reveal one of the most dangerous feedbacks – around 500bn tonnes of carbon are estimated locked up in permanently frozen Arctic soils. Where lakes / marshes drain and soil dries out, enters as CO₂ as soil bacteria rots it out; anaerobic bacteria moves into still wet areas for oxidising decomposition, producing vast quantities of methane – a much more potent gas than CO₂. In some areas carbon dissolves into water directly, and is released as CO₂ from lakes, rivers and the Arctic Ocean. IS ALREADY HAPPENING. Watercourses draining defrosted peatland had far higher carbon counts than rivers running over still frozen permafrost areas; same with methane emissions from defrosted mire. ***The future:** Extensive infrastructure damage in areas of melting permafrost and ice-free North Pole, Arctic rivers increase their flows and new trees and bogs appear in the tundra. This opens up a massive methane sources, and is released straight or as CO₂ from the new bogs and carbonized lakes and rivers. +F*

5. Degrees

- **A new world.** Is coming into being @5C. Ice sheets disappear; rainforests burn away; seas inundate coastal cities and penetrate far inland into continental interiors, where temps are 10C+ higher than now – humans herded into shrinking zones of habitability. Evaporation and precipitation both increase; in the tropics, the convergence zone of the trade winds builds up tremendous downpours, which together with more intense S. Asian monsoon raise downstream flows of Ganges and Brahmaputra by 50%. Siberian, Canadian and Alaskan rivers increase their flows dramatically; resurgent E. Asian monsoon strengthens Yangtze and Yellow River (20-30%). Syukuro Manabe: expanding deserts include North American desert, Sahara, Kalahari, Patagonia, Australia and Gobi into NE China; new desert area in NE Brazil (collapsed Amazon) and drying across the southern half of the US; "two globe-girdling belts of perennial drought clearly unfold", with northern belt encompassing central Americas, southern half of Europe, western Sahel and Ethiopia, southern India, Indochina, Korea, Japan, western Pacific; southern belt encompassing southern Chile and Argentina, eastern Africa, Madagascar, most of Australia and Pacific islands. Higher evaporation reduces available soil moisture in semi-arid regions, cutting rainfall further and turning them into full-scale deserts. Considered together with exhausted fossil aquifers and disappearance of snow and glacial melt from mountain chains, widening zones of the planet experience huge drops in carrying capacity (e.g. Cairo, Lima can only be sustained in middle of deserts through river or underground supplies). Yemen relies for almost all its fresh water on a fossil aquifer which is rapidly depleting; Saudi Arabia becoming more desperate at finding water. India, China and the US see rapidly dropping water tables. Since far north opens up (Siberia, Canada) – all major rivers there see big increases in flows (higher rainfall) and experience largest temp increases, dramatically lengthening growing seasons – BUT model also projects "summertime drying in continental interiors, dessicating soils which might otherwise be available to growth crops"; major engineering works like dams to hold winter rains become essential. May be simply too hot to grow arable groups in continental climates – Siberia already sees extreme heatwaves and forest fires in summer, and "even northern Canada and the former Soviet Union exhibited agricultural production declines in the 5C world". Possible solution – concentrate populations and farming colonies on Arctic coasts of Russia and Canada (moderating maritime influence will keep summers cool); but they may not take them in, resulting in wars like China invading Russia and usage of nukes. Also, "recently glaciated soils tend to be thin, rocky and poor, with little in the way of nutrients or organic matter" (AK: perhaps just enough for subsistence?). Agricultural expansions, wildfires, new pests, etc, will destroy subarctic boreal forests of Canada, Russia, Scandinavia and Alaska. ***The future:** A new*

world comes into being – ice free Arctic, burnt out rainforests, summer heatwaves, rapid inundation of coastal areas and climate increasingly bifurcated into storms and drought. Two globe-girdling belts of perennial drought appear; higher evaporation desertifies already semi-arid regions. In tandem with disappearing snow and glacier melt and depleting fossil aquifers, and dessication of continental interiors, populations may have to be moved to the (poor and acidic soils of the) far north en masse – stoking conflict and war.

- **Blast from the past.** During Eocene 55mn years ago, temps were above zero ever during polar darkness and alligators / other warm-loving animals swam in the Arctic waterways. Deep-sea extinction – sudden warming of ancient Antarctic waters had deprived bottom-dwellers of oxygen...deep ocean had turned anoxic, poisonous to oxygen breathing life. Methane hydrates (icelike combination of methane and water), only stable when very cold or under very high pressure. If destabilized (submarine slides, deep sea warming, etc), can explosively turn from ice to gas – releasing methane, 20x more potent than CO₂, into the atmosphere. "Summer heatwaves scorched the vegetation out of continental Spain, eaving a desert terrain which was heavily eroded by winter rainstorms"; "the oceans turned suddently acidic as vast amounts of CO₂ dissolves in the water"; exacerbation of seasonal extremes in North America, with monsoonal storms lashing the slopes of the Rockies / Utah (and supporting tropical vegetation there). Rainforests of dawn redwood in the high Arctic (which created water vapor and insulated themselves during long polar darkness). Mediterranean algae thrived in the Arctic, which is by now always unfrozen. Off New Jersey, ocean temps are at 33C; sediment pours off the land in tremendous flash floods. At CO₂ levels of 1000ppm, temps were 5-10C higher, acidic oceans, rapidly changing ecosystems, ice-free poles and extremes of wet and dry – the Palaeocene-Eocene Thermal Maximum (PETM). Rate of greenhouse gas addition is now about 30x faster than then; "we are halfway to the kind of searing global heatwave that was then experienced by life on Earth", based on isotope ratios in rocks. Classical feedback mechanism – destabilized methane hydrates / clathrates due to warming deep oceans further increase warming. Though, since it takes centuries for surface temps to propagate to ocean depths, there is yet hope hydrates won' destabilize and collapse all at once, thus postponing apocalyptic runaway warming to Venus. Arctic Ocean is "relatively shallow and likely to see the most extreme warming, so the methane hydrate response there could be much faster". ***The future:*** *The oceans turn acidic, ecosystems collapse, poles are ice-free and extremes of wet and dry prevail. Methane hydrates kept bottled up as ice under low temps and high temp; should they be destabilized by EQ's, submarine slides or warming deep-ocean temps, they will explosively turn into gas and accelerate GW – due to its shallow depth and extra rapid warming, Arctic Ocean may be the locus. +F*
- **Tsunami warning.** Possibility: "large-scale methane hydrate releases destabilise the sloping ocean bottom and spark similar massive avalanches". They will unleash tsunamis, of course. ***The future:*** *possibly EQ's or methane hydrate releases destabilise sediment downslope of continental shelves in shallower seas, resulting in submarine slides, tsunamis and further methane releases.*
- **The prospect for humanity.** Though there were fascinating species and lush forests up to the Arctic, during PETM, big extinction still happened over a 10,000 year period; now its happening over a single century. Another deception – impression that PETM was well-watered, with emergent heavy monssons watering now semi-arid places: "the first plant migrants to arrive in Wyoming were small-leaved and drought-tolerant, suggesting that the PETM began dry as well as hot" ...supports modeling evidence showing growing deserts and water shortages, for the monsoons of the later PETM will take thousands of years to evolve...during the transition, higher temps lead to more evaporation, leaving already arid areas even drier. "A resurgent Chinese monsoon is unlikely to give

any imminent relief to the drought-stricken north of the country, and why Pakistan's failing glacial rivers will not be replenished any time soon by a stronger Indian monsoon" ...collapse of Amazonian ecosystem and extreme aridity in northern half of South America. Refuges – tropics too hot to support most food crops; subtropics out of productin due to perennial droughts – the "belt of habitability" contracts towards the poles (applied to seas too, due to destruction of coral reefs and warming of the oceans). A new era of enforced localism for humanity...sensitive and volatile capital markets will surely have collapsed...unpleasant political philosophies. Wars for Lebensraum – high north, rainy highland regions in Africa, Siberia). Northern Europe, British Isles and Scandinavia valuable (though drier due to Gulf Stream collapse)...in south, westerliers continue delivering plentiful rain to Patagonia and Tierra del Fuego in Chile...ice-free Arctic Peninsula and colonization. Tasmania, New Zealand's South Island remain within temperate rainfall belt and could house Australians, Indonesians – though their land area is too small. "Sea level rise will already have turned many coastal cities into wave-battered ghost towns, their abandoned buildings crumbling into beach sand with each passing storm"...inundations of low-lying plains like Nile, Yangtze and Meghna deltas and fertile flatlands further hit agriculture. "Methane hydrate deposits...it would look a if the sea was boiling, perhaps with the faint yellow flames dancing above the churning surface as some of the methane burns off". Tsunamis – submarine slide, shudder in the water, huge speed, retreat of water from the shore, white line on the horizon, wall of water, deadly debris flow of mud and flotsam and jetsam. "Life would be precaurious anywhere that is not securely located tens of metres above the restless seas". ***The future:** Though monsoons will eventually emerge, in the beginning arid areas will become much drier – Pakistan and northern China remain doomed. Enforced localism as belts of habitability retreat towards the poles and highlands, as the tropics become too hot and the subtropics too dry. Northern Europe, British Isles, southern tip of S. America, and defrosted Antarctica are new refuges. Coastal cities long abandoned, and the great river valleys and fertile flatlands are gradually submerged. Life near the seas is precaurious due to heavy storms and tsunamis.*

- **Survival.** With crops, water supplies failing and carrying capacity of the land much diminished, the world descends into anarchic violence. New holocausts. Wars fought with guns, grenades and nuclear weapons. Mass return to hunter-gathering unfeasible due to lack of appropriate culture and the fact the land couldn't sustain anywhere near 6bn foragers (further disaster for biodiversity due to large-scale survivalism). In densely populated regions like Europe or China, it is not an option. Global Malthusian crisis and die-off (Lovelock – "the cull"), lowering world population by the billions. ***The future:** Global Malthusian crisis and large-scale dieoff, as crops fail, rivers run dry and industrial civilization fights its last wars with guns, grenades and nuclear weapons.*

6. Degrees – doom!

- **The Cretaceous world.** 10-15C hotter, flooded, extreme greenhouse, chalk, ferns, cycads and conifers, lush subpolar forests, Russian Far East enjoyed year-round Mediterranean sunshine despite 2-month period of polar darkness, champsosaurs swam in warm, shallow marshes of the Canadian Arctic, tropical breadfruit trees on western coast of Greenland. "Some rock formations show aggregated deposits called 'tempestites', formed by the rubble from intense storms. These ferocious hurricanes – much stronger than today's, thanks to the hotter oceans – even left their mark on the ocean floor, building up big hummocks" – biggest during hottest phase. More intense hydrological cycle drove much heavier rains...in flooded, tropical interior of North America, it was 4000mm a year. Tropical Atlantic = 42C!; in subpolar S. Atlantic, it was 32C, hotter than most of the deep

tropics today. Equator = broad humid belt with heaviest rains, most ferocious storms – but few coral reefs and almost no rainforests. Broader arid area = drought-resistant plants and animals encompassed rest of the tropics and subtropics, including all of Africa, S. America and southern US and Europe. Higher mid-latitudes = warm, humid, subject to frequent intense burning and drought. Polar = humid, temperate supported lush forests in Siberia and Antarctic Peninsula. No ice caps; 20C oceans at North Pole; evergreen forests at the South Pole. 3x-6x today's CO2 levels, though Sun was weaker then. Gaia – slow sequestration of carbon by marine calcium carbonate platforms in the subtropics; vegetation (big domes of peat built up beneath forests and within swamps, gradually compressed into coal – found at large in Alaska North Slope, northeast Russia, western Canada, interior US, Germany, northern China, Australia, New Zealand, Antarctica?). Though the Cretaceous was somewhat pleasant, if hot and sticky, it occurred over millions of years; the current pace of change threatens mass extinctions of ecosystems which have no hope of adapting in time.

***The future:** Mediterranean climate at the poles, tropical at high latitudes; extremely powerful storms driven by hot oceans. Arctic was humid and temperate, supporting lush forests; higher mid-latitudes were warm and humid, but subject to intense droughts and burning; below that there was a dry belt; the tropics saw the heaviest rainfall and severest storms, but little biodiversity. Though life can flourish after many, many years of stabilization, the current rate of change means our ecosystems have no hopes of adapting in time.*

- **Oily oceans.** Oxygen levels declines in the oceans during warming spikes, turning them anoxic. The seas became stagnant ponds, with only a thin layer of life in the uppermost oxygenated sections. Theory: catastrophic methane hydrate releases warmed the climate so much the oceans stopped turning over – the lighter warm layer stayed as a lid on the colder layers below, shutting off oxygen and leading to massive dieoffs. Why tropical oceans look as clear and pristine – so low in nutrients, that almost nothing can survive in them, making them marine deserts; in contrast to well-mixed colder oceans nearer the poles, which support plankton blooms – seas murky, green and support fisheries. During "ocean anoxic events", all the world's oceans turned into deserts. Another theory – global algal bloom due to sheer amount of top-soil washoff.
- **The end-Permian wipeout.** Took place at a time of rapid 6C warming. Almost entire plant cover of the globe was removed in catastrophic bout of soil erosion, meaning something had scythed through forests, swamps and savannahs – leaving no anchoring for the precious soil once the monsoons arrived. Fungal spike and proliferation of toadstools which sprouted quickly on the dying trees and shrubs. Dramatic wet to arid transition; newly meandering river from Garden of Eden to Death Valley. Deserts reached 45 degrees north (central Europe, north USA); invaded as far north as 60 degrees (near Arctic Circle); forests retreated. Extremely hot deserts; high evaporation from coastal seas leaves it salty and dense, dragging warm water to ocean depths (in contrast to today, where it is cold water at the poles which sinks – will later become too hot to do so); killed bottom-dwelling organisms as seas turned stagnant and anoxic. Warm water expanded, raising sea levels by 20m during Permian crisis, flooding continental shelves and creating shallow, hot seas. Hotter oceans spawned "hypercanes" of staggering ferocity (today storms limited by colder water at depth and higher latitudes) – these storms had enough energy to circumnavigate the whole globe, perhaps repeatedly. Increased water vapor at high latitudes, further feeding warming; triggered devastating flash floods when it hit a coast. AND eruption of Siberian traps -> poisonous gases and CO2, torrential monsoons of sulphuric acid stripping land of remaining vegetation. Oxygen levels dropped from 21% to 15% as most vegetation died; with warm water reaching ocean depths, methane hydrates began stirring. Much of the initial methane release will have dissolved in the water column, accumulating over time; as stream of bubbles rose higher, each successive layer of

water gradually reached saturation point – once the explosive was primed, all it needed was a detonator. Small disturbance on seafloor -> drives methane-gas-saturated parcel of water upwards -> bubbles begin appearing, as dissolved gas fizzes out with the reducing hydrostatic pressure -> make parcel of water still more buoyant, accelerating its rise thru water column -> as water surges up, drags surrounding water up with it, spreading the process -> as sea surface, water is shot hundreds of meters into air as released gas blasts into atmosphere; resulting shockwaves propagate in all directions, triggering follow up eruptions (happened in 1986, Lake Nyos in Cameroon – asphyxiating CO₂ gas cloud). Methane cloud "loaded with water droplets, it spreads out over the land surface like a toxic blanket" ...is flammable and can ignite from a spark in concentrations of 5% +, sending fireballs across the sky (like fuel-air explosives)... "with a supersonic blast, it is the pressure from the shockwave itself which ignites the mixture, pushing out an explosive front at speeds of 2km / sec and vaporising everything in its path". This kill mechanism could destroy terrestrial life almost completely; a major oceanic methane eruption could "liberate energy equivalent to 10⁸ megatonnes of TNT – 10,000x greater than world's stockpile of nuclear weapons". Short-term nuclear winter, followed by renewed global warming. Furthermore, as vegetation and animal carcasses roted in the stagnant oceans, "large quantities of hydrogen sulphide were building up in the depths". Poisonous at minute concentrations, smelling of rotten eggs; would kill all oxygen-breathing life forms in the oceans; would attack and destroy the ozone layer – letting in UV radiation. 95% of species on land and seas wiped out – only sparse vegetation survived and it took 50m years to restore biodiversity. ***The future:** global ocean convection shut down, resulting in "ocean anoxic event" killed oxygen-breathing marine life. Warm seas expanded and inundated land, powering hypercanes of incredible ferocity that circled the globe repeatedly. Catastrophic methane hydrate releases resulted in extraordinarily powerful metastasizing fireballs that released more energy than contained in the world's nuclear stockpiles by orders of magnitude, resulting in nuclear winter followed by renewed warming. Hydrogen sulphide built up in the anoxic ocean depths, killing all oxygen-breathing marine life and decimating terrestrial life when released into the atmosphere – where it also broke down the ozone layer, letting in UV radiation. Earth transitioned into Death Valley / Mad Max surrounded by Waterworld all the way to the Arctic Circle. +F*

- **Back to the future.** End-Permian repeat more unlikely – better circulation of oceans due to better ocean circulation, there is more oxygen in atmosphere, humans more inventive and adaptable; BUT Anthropocene Mass Extinction already under way (so Earth now less resilient – what remains of nature is under siege in island reserves between agricultural and urban deserts); as temps rise and real deserts shift to mid-latitudes, these islands will be submerged by changing climate. Rate of change is vastly faster – end-Permian took at least 10,000 years, our warming could happen within a century. Ultimate nightmare scenario – "oceanic methane eruptions near large population centers, rapidly wiping out billions of people"; ocean stratification and hydrogen sulphide poisoning – "partly enclosed basins like the Mediterranean or the Gulf of Mexico will be the first to go" (or already anoxic Black Sea, which has a cold, oxygenated lid) – human smell picks up hydrogen sulphide in trillions per million range (afterwards olfactory nerve becomes paralysed), which will be silent killer first in coastal areas, then continental interiors – survivors will be exposed to UV. Hell on Earth. Humans more adaptable and clever (stockpiling, artificial atmospheres, omnivores, etc – AK: but what about the energy sources for this?). ***The future:** exploding methane fireballs, hydrogen sulphide poisoning and UV will ravage an already fragile ecosystem, even threatening human extinction. AK – good thing is that it will take 100's of years for deep ocean to warm up. +F*

Choosing our Future

Necessary to reduce greenhouse emissions within a few years to avert bad destinies. Kyoto Protocol ineffective and humanity gets further away from the IPCC's stabilization scenarios with every passing year. Even if emissions stop now, rise of 0.5-1C inevitable; many things are already living dead, like the Alpine glaciers and Great Plains breadbasket and probably Arctic – palaeoclimate paints even worse picture, locking us into the Pliocene with its 3C rise and 25m sea level rise – Lynas thinks there's now a less than 50% chance of averting runaway global warming. Two big uncertainties: 1) future emissions (will be increasingly constrained by resource depletion) and 2) "climate sensitivity" – though most models give a rise of 3C for doubling of pre-industrial CO₂ levels, a few go as high as 11C (one of the big unknowns is "global dimming", which may have given impression that the climate is half as sensitive as it really is) – sulphur aerosols cut global warming by 1940-60? But aerosols scrubbed out of atmosphere in days by rainfall, but CO₂ remains for centuries. If aerosol shield removed, temps can follow upper range of IPCC predictions (which themselves can be raised from 5.8C (AK: in 4th report, already raised to 6.4C), to 7.7C. Make that Eight Degrees!

Need to stabilize @ <2C, because then numerous catastrophic feedbacks kick in – Amazon burning (+250ppm of CO₂ and +1.5C) -> accelerated release of CO₂ and methane from Siberian permafrost -> ocean methane hydrate release -> mass extinction apocalypse. ASSUMING LOW CLIMATE SENSITIVITY, 25% chance of overshoot @ 400ppm; more than 80% chance @ 550ppm (likely end result). To achieve former, CO₂ emissions need to peak by 2015 and decline rapidly, falling 90% by 2050. Yet emissions now rising faster than ever.

How? Contraction and convergence plan globally. But cutting is difficult, Lynas admits – would have been done already if cheap and feasible; industrial civilization depends on cheap fossil fuels, which are even turned into food through NG-made nitrogen fertilisers and oil-powered tractors and combine harvesters. Says will not indulge in platitudinous, wishful statements about necessity of renewables. Notes shifting from coal to biomass will result in deforestation, as in late 19th century.

Stresses need for values change – now curtailed by social pressure to live high-energy lifestyle, blame games, denial, manufactured "needs", tragedy of the commons, faith in future technological fix, etc. West based on denial of resource limitations – the farce of GDP. Peak oil discussion. Necessity of knocking in "wedges" (seven will reduce 2055 emissions to those of today – i.e. Still not enough) – increase world vehicle fleet fuel efficiency from 30mpg to 60mpg; halve distance traveled by each car; efficient buildings; efficient electricity generation; quadrupling of gas-fueled power stations if they displace coal; new 700 1GW nuclear power stations; "carbon capture and storage" techs applied to 800 similar sized coal plants. [AK: consider the sheer scale of this – unrealistic. Vehicle fleet expanding fast in emerging markets] For renewables, you need: 2mn 1MW wind turbines (50x increase from today!!); solar PV needs 700x increase from today; 4mn 1MW turbines one wedge to displace fuel-cars in favor of hydrogen. [AK: out of all of these, massive nuclear power sounds like the most realistic option; gas close to peak; biofuels, CC, "hydrogen economy" are mostly scams.

Where I disagree with Lynas – wind power emphasis [low energy intensity, low EROEI; nuclear is the only hope]. Proposes "carbon rationing" as a parallel virtual currency – monumentally stupid idea, since its extremely regressive and will breed extreme resentment towards the rich, and will preclude formation of new values: you need green socialism to effect real change.