Climate Modeling

Climate Sensitivity

Climate Sensitivity

(for modelers) is the globally averaged temperature change in response to changes in radiative forcing due to a doubling of pre-industrial CO_2 levels (in °C units)

CO_2 has increased from its pre-industrial level of 280 parts per million (ppm) to around 408 ppm today. Without actions to reduce emissions concentrations are likely to reach 560 ppm – double pre-industrial levels – around the year 2060.

There are three main measures of **climate sensitivity**

- **Equilibrium Climate Sensitivity (ECS)**

The Earth's climate takes time to adjust to changes in CO_2 concentration. For example, the extra heat trapped by a doubling of CO_2 will take decades to disperse down through the deep ocean.

ECS is the amount of warming that will occur once all these processes have reached equilibrium. Unlike the simpler models, they provide a timetable for the changes that explicitly takes into account the role of the ocean in buffering both the chemical and the thermal response to the burning of fossil fuels. ("**Effective**" when not in equilibrium)

There are three main measures of **climate sensitivity**

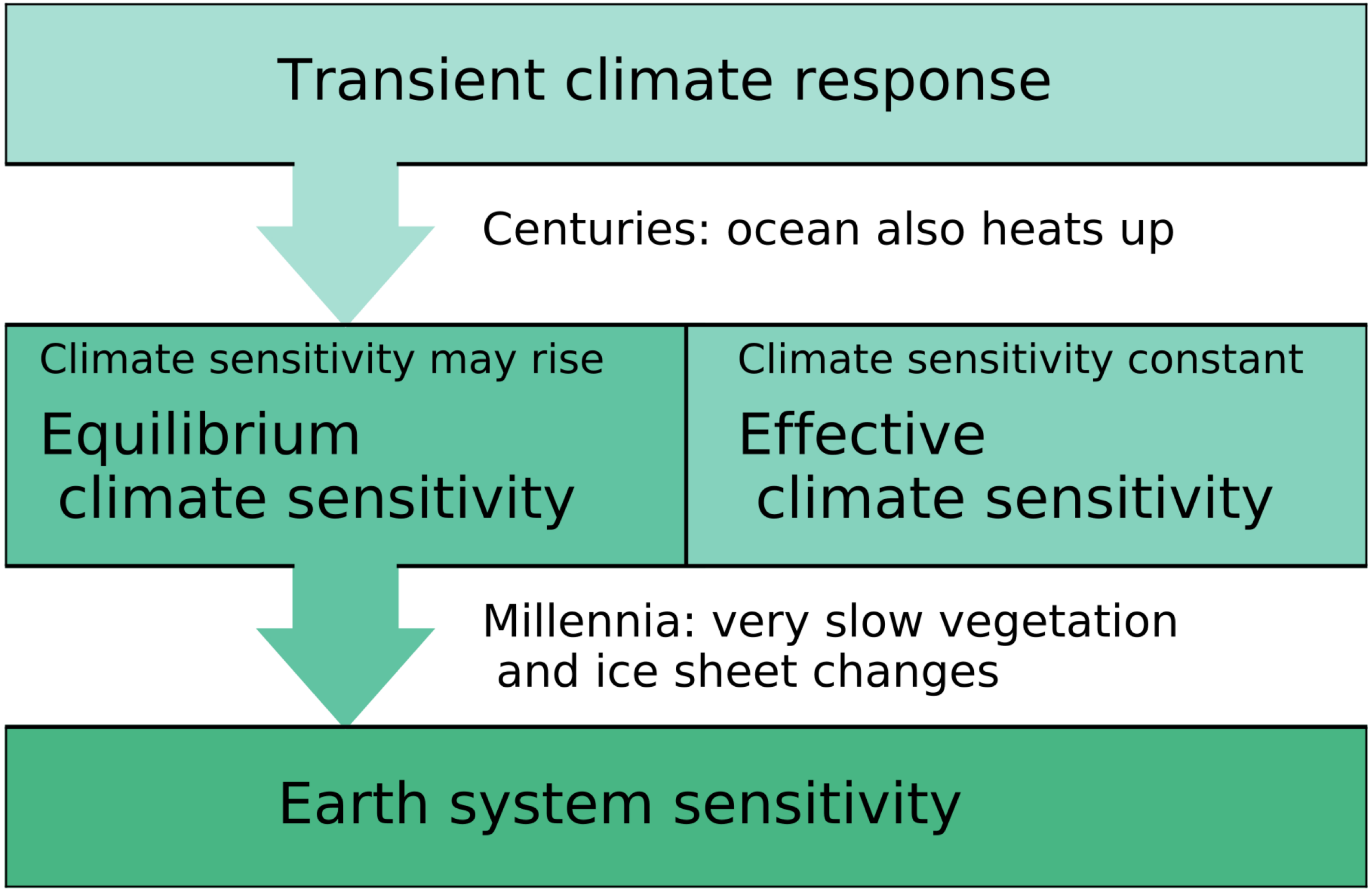
- **Transient Climate Response (TCR)**

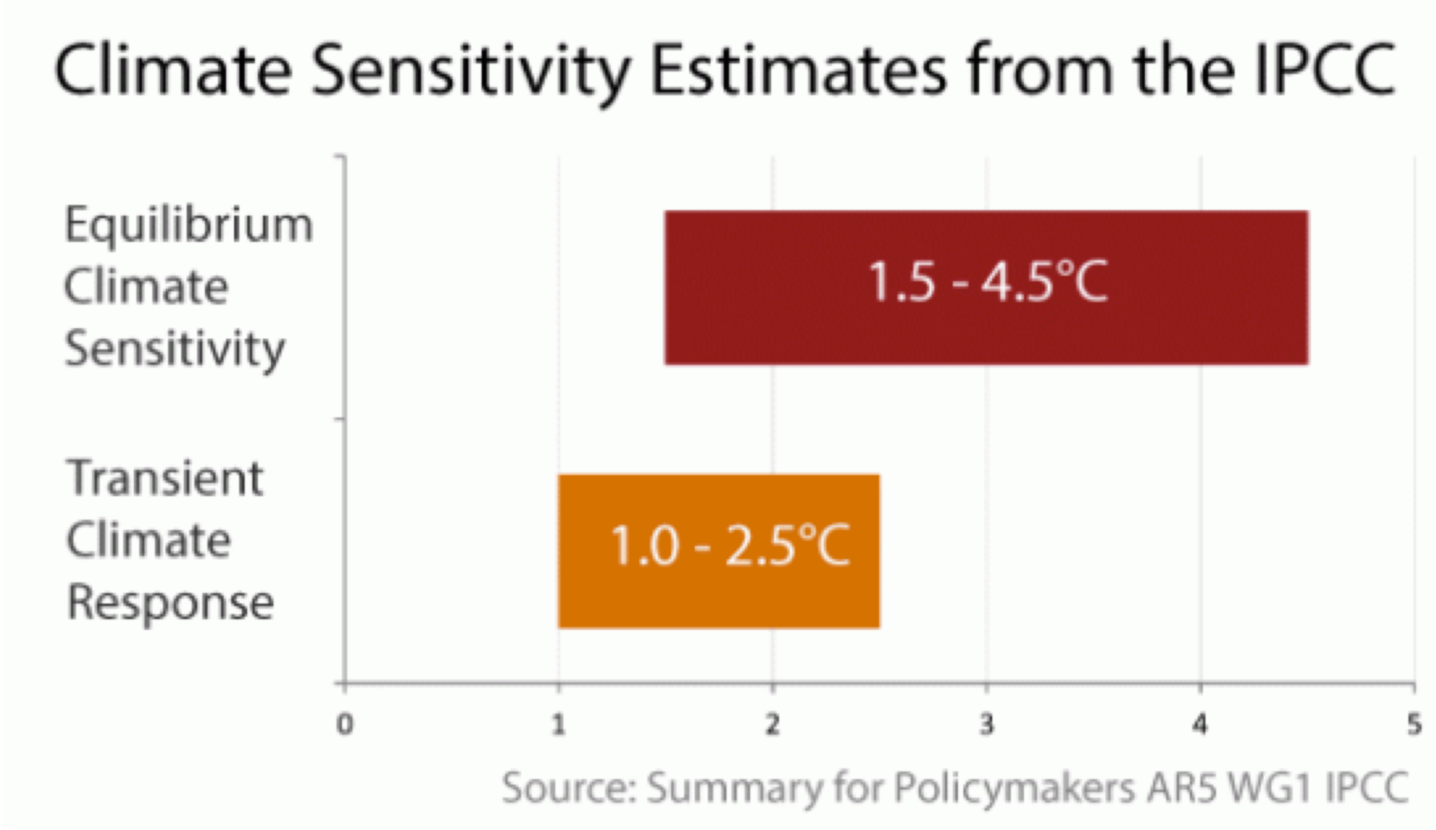
This is the amount of warming that might occur at the time when CO_2 doubles, having increased gradually by 1% each year, calculated over a 20y-period centered at the doubling time.

TCR more closely matches the way the CO_2 concentration has changed in the past. It differs from ECS because the distribution of heat between the atmosphere and oceans will not yet have reached equilibrium.

- **Earth system sensitivity (ESS)**

This includes very long-term Earth system feedbacks, such as changes in ice sheets or changes in the distribution of vegetative cover.

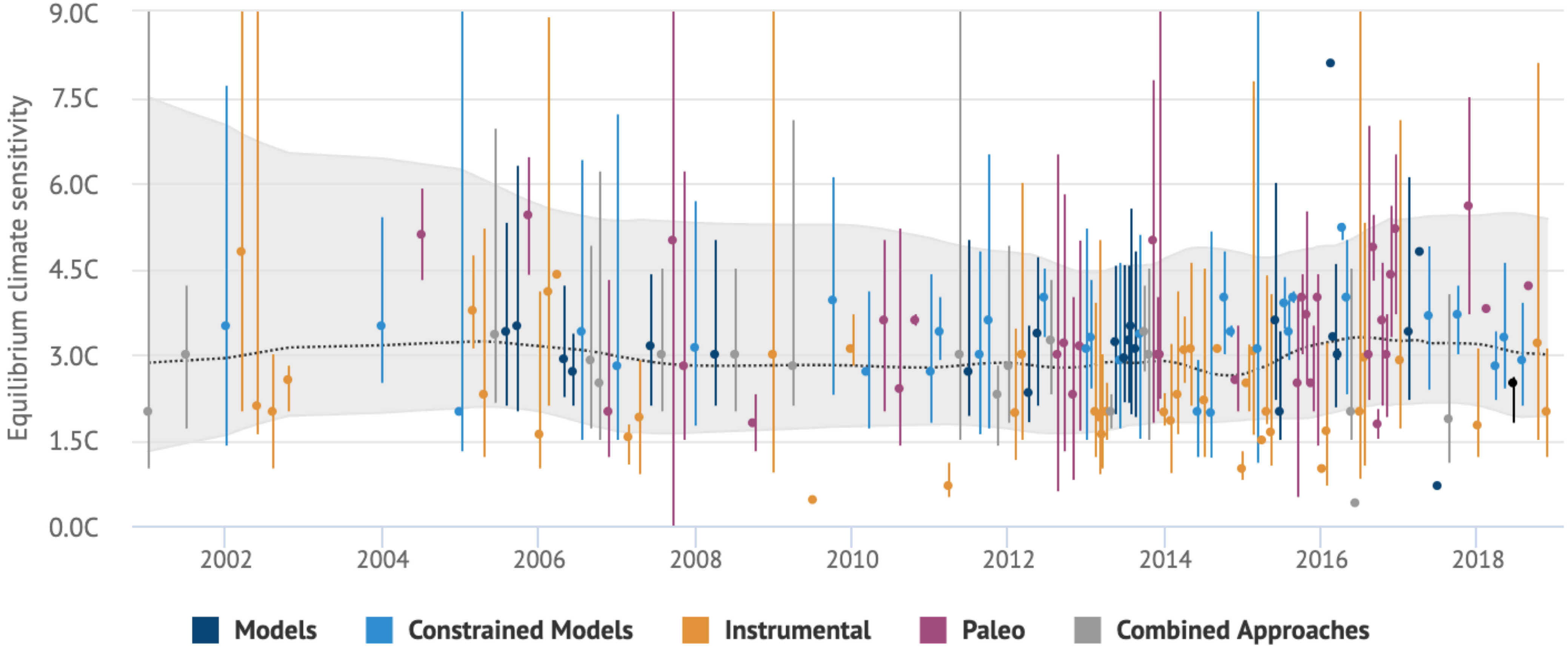

Transient climate response
Centuries: ocean also heats up
Climate sensitivity may rise
Equilibrium climate sensitivity
Climate sensitivity constant
Effective climate sensitivity
Millennia: very slow vegetation and ice sheet changes
Earth system sensitivity

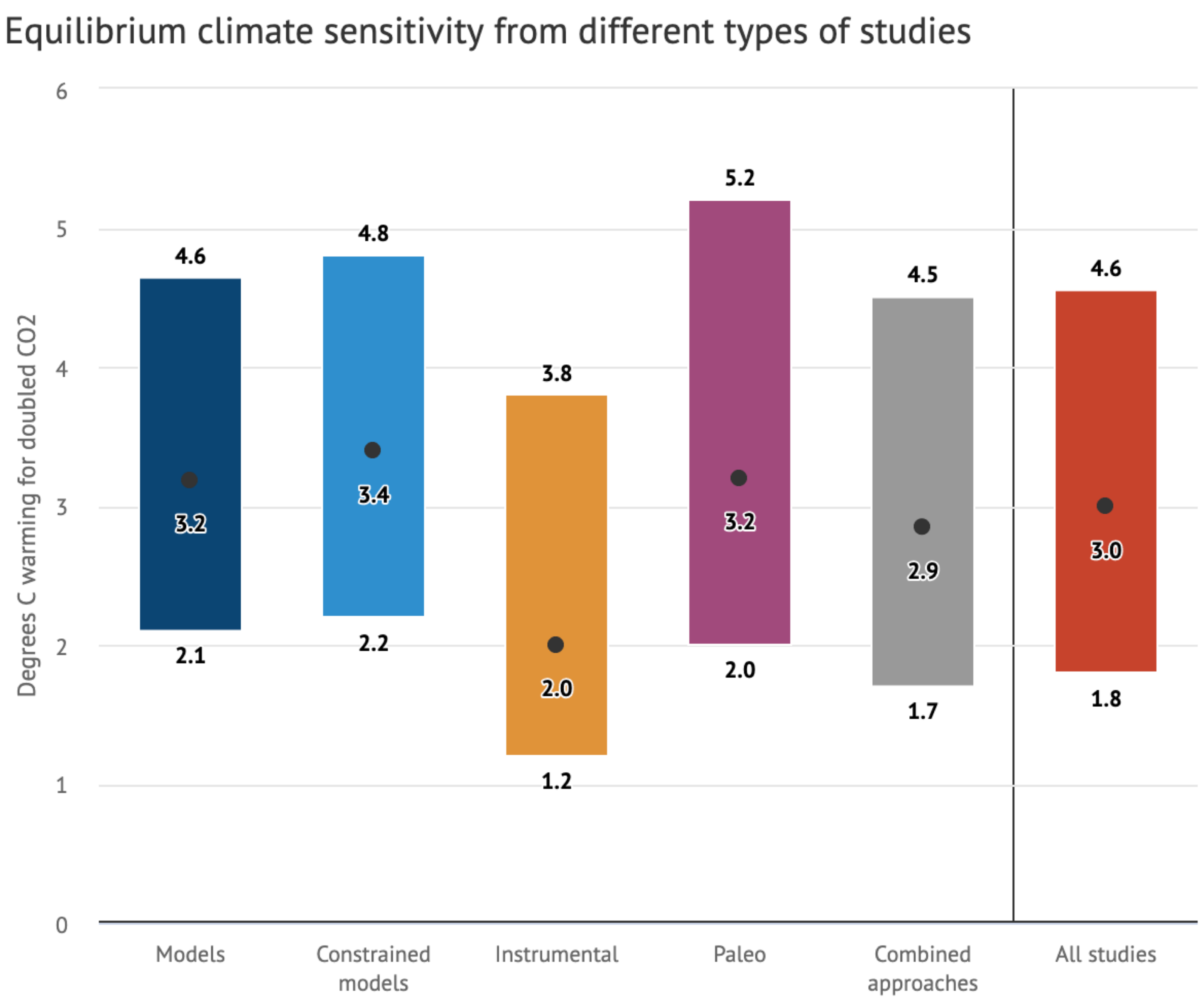


Climate Sensitivity Estimates from the IPCC
Equilibrium Climate Sensitivity
1.5 - 4.5°C
Transient Climate Response
1.0 - 2.5°C
0
1
2
3
4
5
Source: Summary for Policymakers AR5 WG1 IPCC

- Climate sensitivity is typically estimated in 2 (4) different ways:
- From data, by (**1**) using observations taken during the industrial age or (**2**) by using temperature and other data from the Earth's past
- By modelling the climate system in computers, either with (**3**) simple EBMs or (**4**) more complex coupled atmosphere-ocean global climate models
- For coupled atmosphere-ocean global climate models the climate sensitivity is an emergent property; rather than being a model parameter it is a result of a combination of model physics and parameters. By contrast, simpler energy-balance models may have climate sensitivity as an explicit parameter.

Timeline of published equilibrium climate sensitivity studies





Equilibrium climate sensitivity from different types of studies
Degrees C warming for doubled CO2
6
5
4
3
2
1
0
4.6
3.2
2.1
4.8
3.4
2.2
3.8
2.0
1.2
5.2
3.2
2.0
4.5
2.9
1.7
4.6
3.0
1.8
Models
Constrained models
Instrumental
Paleo
Combined approaches
All studies

Climate “Tipping Points”

- In climate studies the idea of a ‘tipping point’ is widely understood and employed to explain the observation that, under some circumstances, ’little things can make a big difference’. Thus, common usage is that a small change can have large, long-term consequences for a system, sometimes. In 2007 the IPCC introduced a famous, diagram to illustrate the thresholds beyond which climate cannot be pushed without consequences
- For the concept of tipping points to be useful in climate modelling, it is important to be clear about what qualifies as a tipping point, and about the aspects of the climate system (or its subsystems) that can undergo changes resulting from ‘tipping’ over a threshold

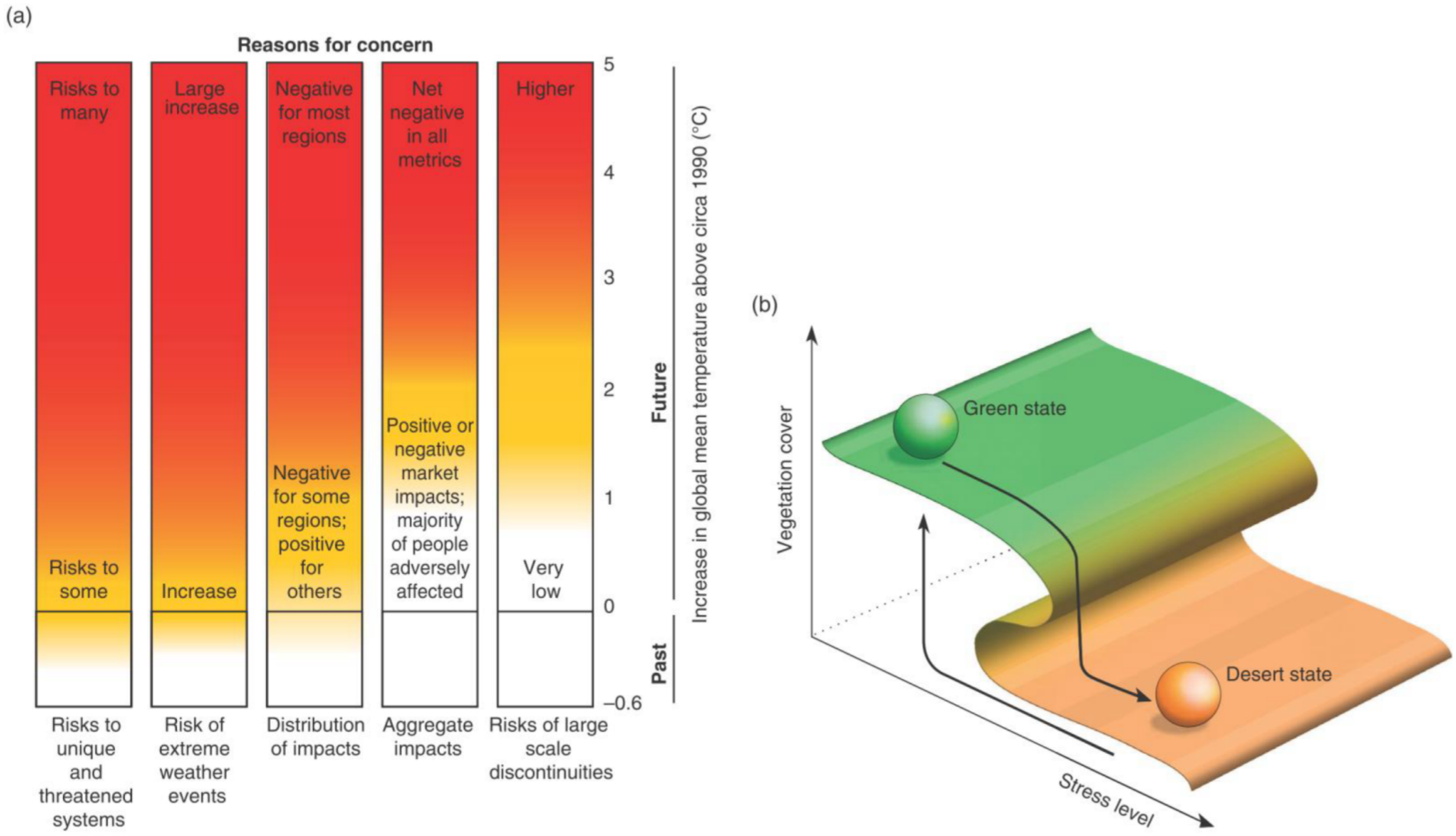


Figure 2.16 Different ways of picturing climate change risk, especially the transition from a hospitable to a less hospitable regime. (a) The so-called 'burning embers' – reasons for concern about human-induced warming from ca. 2007. Source: Smith et al. (2009). Reproduced with permission of the IPCC. (b) Bistable behaviour of an observed climate state showing the shift from a 'hospitable' (*green*) state to a 'desert' (*brown*) state. Source: Sole (2007). Reproduced with permission of Nature Publishing Group.

Climate "Tipping Points"

- It was not until the late 2000s that more formal definitions began to be used in climate, and climate model, analysis
- **'tipping elements'** = largescale subsystems (or components) of the Climate system that might be switched (under particular circumstances) into a qualitatively different state by small perturbations.
- **'tipping point' =** a point in a system's behavior where a small perturbation forces the system to a new state (or puts it on a path to such a state) from where return to the original state cannot be achieved by a small reverse perturbation. For a system to possess a tipping point, <u>there must be strong positive feedback </u>in its internal dynamics

Climate “Tipping Points”

There are different tipping points in climate systems theory:

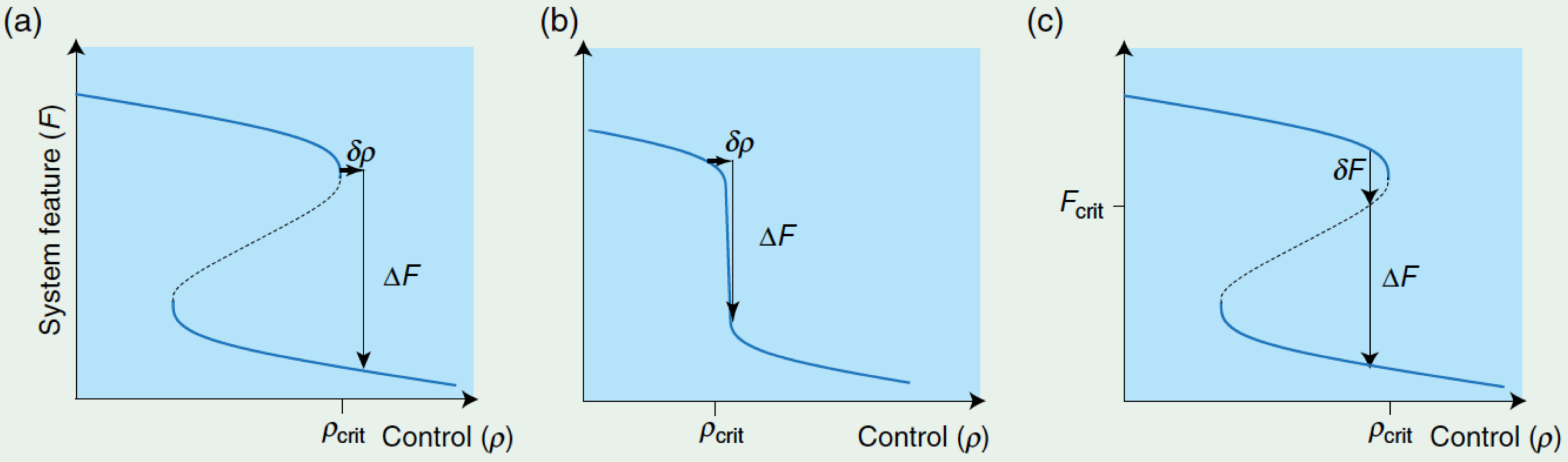
- Time-independent (equilibrium) solutions of a system state such that a single state moves into another single state and, once the threshold is passed, no return is possible
- Time-independent (equilibrium) bifurcation solution of a system state such that, once passed, one of two alternative states is entered and, again, no return is possible
- Noise-induced transition in which no external change has occurred but only an internal ‘noise’ disturbance, which has pushed the system into a different state.

Defining climate tipping points

There are ways to formalise the notion of tipping points. For a system to qualify as a tipping element, it must be possible to identify a single control parameter (ρ), for which there exists a critical control value (ρ_{crit}), from which a small perturbation ($\delta\rho > 0$) leads to a qualitative change in a crucial feature (F) of the system (ΔF) after some observation time ($t > 0$). In this definition, the critical threshold (ρ_{crit}) is the tipping point, beyond which a qualitative change occurs – this change may occur immediately after the cause or much later.

One type of 'tipping point' is synonymous with a 'bifurcation point' in the equilibrium solutions of a system, as schematically illustrated in (a). This tipping point is characterised by irreversibility. However, other classes of non-linear transition can meet the definition above. For example, (b) shows the (time-independent) equilibrium solutions of a system, but here they are continuous (there is no bifurcation) and therefore the transition is reversible.

The third class of climate tipping point is noise-induced transitions (c). In such cases, internal variability (a small change in a feature, δF) causes a system to leave its current state (or attractor) and transition to a different state (or attractor).



Climate “Tipping Points”

- Recent climate analysis has established that there can also be ‘rate-dependent tipping’. In this situation, the system undergoes a large and rapid change, but only when the rate at which it is forced exceeds a critical value.

- We can se tipping points in simple numerical EBMs with (ice-albedo) feedback!

Models estimate equilibrium climate sensitivity

Equilibrium climate sensitivity can be estimated from models without requiring the lengthy simulations to reach equilibrium. In one example of this process, the models were perturbed by a $4 \times CO_2$ forcing and the response of the models to this was monitored.[21] The models gradually move to a new equilibrium temperature over time to reduce (eventually to zero) the energy imbalance.

If the net radiation imbalance is plotted as a function of temperature change, then the climate sensitivity is deduced from the slope of the line and the equilibrium temperature change from the intersection of the line with the x-axis.

This shows the equilibrium climate sensitivity (ECS – arrowed and divided by 2 because this experiment was for $4 \times CO_2$).