Criteria for Dangerous Warming. The United Nations Framework Convention on Climate Change (www.unfccc.int) has the objective "to achieve stabilization of GHG concentrations" at a level preventing "dangerous anthropogenic interference" (DAI) with climate, but climate change constituting DAI is undefined. We suggest that global temperature is a useful metric to assess proximity to DAI, because, with knowledge of the Earth's history, global temperature can be related to principal dangers that the Earth faces.

We propose that two foci in defining DAI should be sea level and extinction of species, because of their potential tragic consequences and practical irreversibility on human time scales. In considering these topics, we find it useful to contrast two distinct scenarios abbreviated as "business-as-usual" (BAU) and the "alternative scenario" (AS).

BAU has growth of climate forcings as in intermediate or strong Intergovernmental Panel on Climate Change scenarios, such as A1B or A2 (10). CO_2 emissions in BAU scenarios continue to grow at $\approx$2% per year in the first half of this century, and non-CO_2 positive forcings such as CH_4, N_2O, O_3, and black carbon (BC) aerosols also continue to grow (10). BAU, with nominal climate sensitivity (3 ± 1°C for doubled CO_2), yields global warming (above year 2000 level) of at least 2–3°C by 2100 (10, 17).

AS has declining CO_2 emissions and an absolute decrease of non-CO_2 climate forcings, chosen such that, with nominal climate sensitivity, global warming (above year 2000) remains <1°C. For example, one specific combination of forcings has CO_2 peaking at 475 ppm in 2100 and a decrease of CH_4, O_3, and BC sufficient to balance positive forcing from increase of N_2O and decrease of sulfate aerosols. If CH_4, O_3, and BC do not decrease, the CO_2 cap in AS must be lower.

Sea level implications of BAU and AS scenarios can be considered in two parts: equilibrium (long-term) sea level change and ice sheet response time. Global warming <1°C in AS keeps temperatures near the peak of the warmest interglacial periods of the past million years. Sea level may have been a few meters higher than today in some of those periods (10). In contrast, sea level was 25–35 m higher the last time that the Earth was 2–3°C warmer than today, i.e., during the Middle Pliocene about three million years ago (32).

Ice sheet response time can be investigated from paleoclimate evidence, but inferences are limited by imprecise dating of climate and sea level changes and by the slow pace of weak paleoclimate forcings compared with stronger rapidly increasing human-made forcings. Sea level rise lagged tropical temperature by a few thousand years in some cases (28), but in others, such as Meltwater Pulse 1A $\approx$14,000 years ago (33), sea level rise and tropical temperature increase were nearly synchronous. Intergovernmental Panel on Climate Change (10) assumes negligible contribution to 2100 sea level change from loss of Greenland and Antarctic ice, but that conclusion is implausible (17, 34). BAU warming of 2–3°C would bathe most of Greenland and West Antarctic in melt-water during lengthened melt seasons. Multiple positive feedbacks, including reduced surface albedo, loss of buttressing ice shelves, dynamical response of ice streams to increased melt-water, and lowered ice surface altitude would assure a large fraction of the equilibrium ice sheet response within a few centuries, at most (34).

Sea level rise could be substantial even in the AS, $\approx$1 m per century, and cause problems for humanity due to high population in coastal areas (10). However, AS problems would be dwarfed by the disastrous BAU, which could yield sea level rise of several meters per century with eventual rise of tens of meters, enough to transform global coastlines.

Extinction of animal and plant species presents a picture analogous to that for sea level. Extinctions are already occurring as a result of various stresses, mostly human-made, including climate change (35). Plant and animal distributions are a reflection of the regional climates to which they are adapted. Thus, plants and animals attempt to migrate in response to climate change, but their paths may be blocked by human-constructed obstacles or natural barriers such as coastlines.

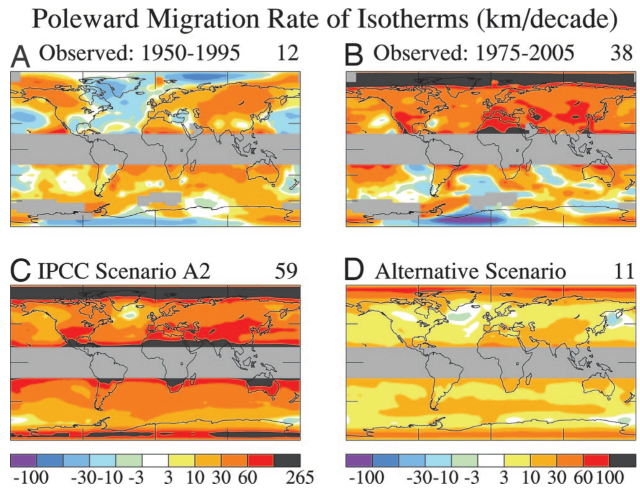

Fig. 6. Poleward migration rate of isotherms in surface observations (*A* and *B*) and in climate model simulations (17) for 2000–2100 for Intergovernmental Panel on Climate Change scenario A2 (10) and an alternative scenario of forcings that keeps global warming after 2000 less than 1°C (17) (*C* and *D*). Numbers in upper right are global means excluding the tropical band.

A study of 1,700 biological species (36) found poleward migration of 6 km per decade and vertical migration in alpine regions of 6 m per decade in the second half of the 20th century, within a factor of two of the average poleward migration rate of surface isotherms (Fig. 6*A*) during 1950–1995. More rapid warming in 1975–2005 yields an average isotherm migration rate of 40 km per decade in the Northern Hemisphere (Fig. 6*B*), exceeding known paleoclimate rates of change. Some species are less mobile than others, and ecosystems involve interactions among species, so such rates of climate change, along with habitat loss and fragmentation, new invasive species, and other stresses are expected to have severe impact on species survival (37).

The total distance of isotherm migration, as well as migration rate, affects species survival. Extinction is likely if the migration distance exceeds the size of the natural habitat or remaining habitat fragment. Fig. 6 shows that the 21st century migration distance for a BAU scenario ($\approx$600 km) greatly exceeds the average migration distance for the AS ($\approx$100 km).

It has been estimated (38) that a BAU global warming of 3°C over the 21st century could eliminate a majority ($\approx$60%) of species on the planet. That projection is not inconsistent with mid-century BAU effects in another study (37) or scenario sensitivity of stress effects (35). Moreover, in the Earth's history several mass extinctions of 50–90% of species have accompanied global temperature changes of $\approx$5°C (39).

We infer that even AS climate change, which would slow warming to <0.1°C per decade over the century, would contribute to species loss that is already occurring due to a variety of stresses. However, species loss under BAU has the potential to be truly disastrous, conceivably with a majority of today's plants and animals headed toward extermination.

Discussion

The pattern of global warming (Fig. 1*B*) has assumed expected characteristics, with high latitude amplification and larger warming over land than over ocean, as GHGs have become the dominant climate forcing in recent decades. This pattern results mainly from the ice–snow albedo feedback and the response times of ocean and land.