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PERSPECTIVES

PALEOCLIMATE

Can the Miocene climate inform the future?

Another climate reconstruction shows a correlation between temperature and CO_2

Herbert *et al*. report on a new method for reconstructing atmospheric CO_2 concentrations over the past 20 million years. Their findings support a long-term covariance of atmospheric greenhouse gases and the global mean temperature.

By **Anna S. von der Heydt**

Atmospheric CO_2 concentrations are rapidly rising. To reliably predict the future, researchers have looked at past climates with comparable CO_2 concentrations, dating back millions of years. Although these past climates are not perfect analogs of the future, they still provide information about how the climate system functions under increased CO_2 concentrations. Because there are no direct observations of past climate states, climate variables need to be inferred from geological data, generally referred to as proxies. On page 116 of this issue, Herbert *et al.* (*1*) present a reconstruction of the evolution of atmospheric CO_2 concentration over the past 20 million years. Their data provide a consistent explanation for the long-term evolution of global temperature and ice sheets on Earth and give a glimpse into its climate future.

The global average surface temperature is expected to rise between 1.4° and 4.4°C by the end of this century relative to the preindustrial temperature, with substantial impacts expected on every aspect of natural ecosystems and human societies (*2*). The anticipated warming depends on how Earth responds to radiative perturbations driven by greenhouse gases in the atmosphere, of which CO_2 plays the most prominent role. Quantitative comparisons of future projected climates between different geological epochs have revealed the Pliocene climate [~3 million years ago (Ma)] as the most similar to the projected climate under the RCP4.5 scenario, which is a likely greenhouse gas trajectory according to the Intergovernmental Panel on Climate Change (IPCC). (RCP stands for representative concentration pathway, with the number representing the level of radiative forcing in the atmosphere by 2100, measured as watts per square meter.) Under the less optimistic RCP8.5 scenario, the world may then stabilize in an Eocene-like climate circa 50 Ma (*3*). However, during the Eocene, polar ice sheets were absent, and geographical boundary conditions were substantially different from those today, which makes direct comparison with future projected climates more difficult.

A more recent warm climate episode in the past is the Miocene, from roughly 23 to 5.3 Ma. One puzzling element of Miocene climate is that its global temperature seemed to be higher than what one would expect given its atmospheric CO_2 concentration (*4*). Proxies suggest global sea surface temperature during the Miocene Climatic Optimum [(MCO), about 15 Ma] to be 11.5°C warmer than that of the preindustrial period, although estimates of atmospheric CO_2 suggest relatively low levels of 450 to 550 parts per million (ppm) (*5*).

Thus far, climate models have failed to reconcile such warm MCO temperatures without assuming atmospheric CO_2 concentrations in excess of 850 ppm (*5*). Herbert *et al.* present newly reconstructed CO_2 concentrations of 500 to 1100 ppm during much of the early Miocene, including the MCO, suggesting that the CO_2 amounts in climate models were not unrealistically high. Most notably, their reconstruction considers the rate at which oceanic crust is produced to be directly related to tectonic degassing rates of CO_2. In previous studies, tectonic degassing rates were mostly assumed to be constant over time, but Herbert *et al.* suggest that tectonic degassing was substantially higher up until the MCO, after which degassing rates declined along with global cooling. The authors arrive at an even warmer estimate of MCO global mean surface temperatures by using organic proxies from higher-latitude sites only. They carefully chose the proxies because during warm climates, organic proxies can become saturated in tropical and mid-latitude sites and can therefore lead to unreliable results.

Hebert *et al.*'s reconstructed atmospheric CO_2 evolution over the past 20 million years tracks with estimated global mean surface temperatures. Therefore, the Miocene climate appears less like an exception to the rule (*4*). With their model for the Miocene providing a temperature and global ice volume evolution that follows the atmospheric CO_2 concentration, different episodes in the Miocene may provide climate states with similarity to future projected climate states. The authors used a carbon budget model to explore how decreasing the tectonic degassing source of CO_2 could lead to declining CO_2 concentrations. Over long time scales, the degassing CO_2 source is balanced by a temperature-dependent sink resulting from the weathering of silicate rocks, extracting CO_2 from the atmosphere (*6*). Because temperature depends on atmospheric CO_2, two parameters enter the carbon budget model—Earth system sensitivity (ESS) and weatherability. ESS relates global temperature and atmospheric CO_2 on long time scales. It differs from a parameter that is more widely used for the future called equilibrium climate sensitivity (ECS). ESS includes slower processes, such as tectonically driven land-ocean distribution, vegetation cover, and land-ice distribution (*7*, *8*), whereas ECS quantifies only the faster responses to CO_2 doubling. By varying the ESS and weatherability within plausible ranges, Herbert *et al.* arrived at their CO_2 evolution, which includes uncertainty estimates that mostly stem from uncertainty in ESS.

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Despite extensive research, both ECS and ESS are subject to considerable uncertainty (*9*). Improving the understanding of climate sensitivity and its evolution on long time scales—e.g., throughout the past 65 million years—is therefore an important challenge for the field of paleoclimate studies (*10*, *11*). The evolution of atmospheric CO$_2$ and temperature throughout the past 20 million years suggests that the Miocene climate is less exceptional than previously thought. Global temperature, land and sea ice volume, and atmospheric CO$_2$ seem to covary on long time scales in ways that are not too different before and after the Miocene. Declining CO$_2$ concentrations over the Cenozoic period reached a first threshold at the end of the Eocene (34 Ma), crossing a tipping point that resulted in a large ice cap on Antarctica. Although this CO$_2$ threshold remains subject to considerable (model-based) uncertainty, the previously reconstructed low Miocene CO$_2$ amounts were at odds with the observation that the East Antarctic Ice Sheet largely disappeared during the MCO.

Within the paleoclimate community, the mounting Miocene proxy data continue to drive the need for a coordinated effort to compare different Miocene models (*12*). The Miocene climate could also provide information and understanding of nonlinear or tipping point behavior of specific climate subsystems—such as polar ice caps, the global ocean circulation, or tropical rainforests—relevant for future climate change (*13*). A better understanding of the Miocene climate will provide important insights for understanding the future climate of Earth. ■

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ACKNOWLEDGMENTS

A.S.v.d.H. acknowledges support by the program of the Netherlands Earth System Science Centre (NESSC), financially supported by the Ministry of Education, Culture and Science (OCW) and the TiPES project (TiPES contribution no. 161), which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 820970.

10.1126/science.abq6542

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NEUROSCIENCE

Sleeping off stress

Social defeat activates midbrain cells, promoting sleep and reducing anxiety in mice

By **Marian Joëls**[1,2] *and* **E. Ronald de Kloet**[3]

When a mouse is placed in the cage of an aggressive conspecific (the "resident"), usually the intruder is quickly defeated. This experience of social defeat causes stress to the intruder. When social defeat takes place during the inactive phase of the day, most of the defeated animals subsequently fall asleep. On page 63 of this issue, Yu *et al.* (*1*) show that a small group of cells in the ventral tegmental area (VTA), projecting to the lateral hypothalamus, is activated by social defeat. This pathway is key to restorative sleep after social defeat, preventing a lasting state of anxiety.

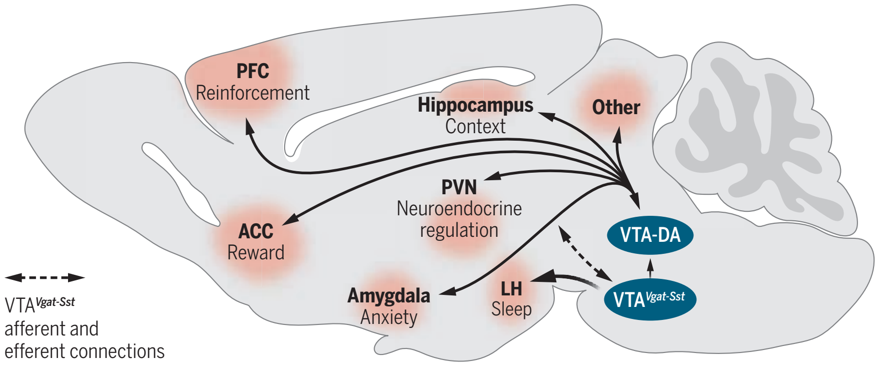
These VTA cells are γ-aminobutyric acid (GABA) neurons, and not the classical dopamine neurons that regulate reward processing and reinforcement learning (*2*), social competence (*3*), motivation, and stress coping (*4*). Yu *et al.* find that after social defeat in mice, input from brain areas such as the paraventricular nucleus of the hypothalamus, the lateral preoptic area, and periaqueductal gray activates 15 to 20% of all VTA GABAergic cells that express the vesicular GABA transporter (VTA^{Vgat}). These are particularly somatostatin-expressing cells (VTA$^{Vgat\text{-}Sst}$) and not parvalbumin-expressing cells. The VTA$^{Vgat\text{-}Sst}$ cells show increased activity up to several hours after social defeat and project to the lateral hypothalamus. Activation of this pathway is both necessary and sufficient to promote rapid eye movement (REM) and non-REM sleep onset, as well as sleep duration, after social defeat. The authors found that sleep after social defeat normalizes raised plasma corticosterone concentrations and keeps anxiety at bay. Conversely, sleep deprivation (or any interference with VTA$^{Vgat\text{-}Sst}$ cell-mediated activation of the lateral hypothalamus) sustains stress-induced elevation of corticosterone concentrations and anxiety-like behavior.

Exactly how sleep is induced after social defeat remains unresolved, as is the nature of the cells to which the VTA$^{Vgat\text{-}Sst}$ cells project. It might seem straightforward that these VTA interneurons project onto GABAergic cells in the lateral hypothalamus, which are known to locally inhibit orexin-producing cells (*5*). Orexin is a neuropeptide that, among other things, is important for arousal and wakefulness. By inhibiting orexin-producing cells, faster sleep onset, longer sleep duration, and reduction of anxiety would be predicted. However, attempts by Yu *et al.* to demonstrate a role of orexin blockade on, for example, anxiety were inconclusive.

The relationship between social defeat–induced sleep, restoration of plasma corticosterone concentrations, and prevention of

Social defeat activates interconnected brain systems

Somatostatin (Sst)-expressing γ-aminobutyric acid (GABA) neurons in the mouse ventral tegmental area (VTA$^{Vgat\text{-}Sst}$) that project to the lateral hypothalamus (LH) are necessary and sufficient to promote sleep and attenuate anxiety after social defeat. Social defeat also activates other pathways, connecting the VTA mesocorticolimbic dopaminergic (DA) system to, e.g., the amygdala, nucleus accumbens (ACC), prefrontal cortex (PFC), paraventricular nucleus (PVN), and hippocampus. These systems are often interconnected, processing various elements intrinsic to a social defeat experience.



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Science, 377 (6601), • DOI: 10.1126/science.abq6542

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