Low-latitude forcing:
A new insight into paleo-climate changes

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Received: May 23, 2021; Accepted: July 14, 2021; Published Online: July 16, 2021; https://doi.org/10.1016/j.xinn.2021.100145
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Citation: Wang P. (2021). Low-latitude forcing: A new insight into paleo-climate changes. The Innovation 2(3), 100145.

The origin of glacial cycles is central to paleo-climate research. A major breakthrough of Earth science in the 20th century was the discovery of orbital forcing of the glacial cycles, known as the Milankovitch theory. The periodicity of the glacial cycles over the last million years was successfully explained by the variations of June solar insolation at 65°N. In responding to the changes in the Arctic polar ice sheet driven by insolation, the production of the North Atlantic deep water drives the global climate changes through the "great conveyor belt" of the global ocean. Despite the unsolved problems embedded in the theory, it has become accepted wisdom in paleo-climatology.

In the past 30 years, however, Chinese scholars have made a series of important advances in the field of orbit-scale climate change research, with numerous discoveries in East Asia and the South China Sea challenging the conventional concepts. In contrast to the classical orbital forcing theory based on high-latitude processes, a new concept has been put forward that highlights the role of low-latitude processes, involving new visions in hydrological and carbon cycles in the global climate system.

Role of low-latitude processes in global hydrological cycles

The climate system is pervaded by hydrological cycles, i.e., transitions of three water phases: ice, water, and vapor. The liquid-solid transition prevails in high-latitude areas while vapor-water transition constitutes the low-latitude hydrological processes. About a half century ago, deep-sea records provided convincing evidence for the 100-kyr (1,000 years) cycles of glaciation, supporting the dominant role of high-latitude processes. In recent years, however, a prominent 20-kyr cyclicity of precession forcing (Figure 1A), rather than 100-kyr glacial cycles, has been found in cave speleothem records1 as well as in the South China Sea, indicating the predominance of low-latitude hydrological processes in monsoon regions.

In the results, two kinds of orbital forcing on Late Quaternary climate changes can be distinguished: the 100-kyr-dominated cycles of ice-sheet changes related to high-latitude processes, and the 20-kyr-dominated cycles of global monsoon changes caused by low-latitude processes. The dual feature of orbital forcing implies that climate changes of Earth are not dictated by the ice sheet alone. In essence, the development of bipolar ice sheets is characteristic of only a minor part of the prolonged history of Earth, and climate changes in an ice-free world can be driven mainly by the low-latitude processes.

Long-eccentricity carbon cycle in global ocean

Another major finding in paleo-climatology is the pervasive occurrence of the 405-kyr long-eccentricity cycles (Figure 1A) in oceanic carbon cycling over the last 200 myr (million years) and beyond. As a basic rhythm of changes in the carbon reservoir, long eccentricity is likened to the "heartbeat" of the Earth system. The 405-kyr cyclicity has been fairly stable over the last 5 myr in the South China Sea and in the oceans, but was disturbed in the last 1.6 myr, with the cyclicity extended to ~500 kyr.

The 405-kyr long-eccentricity cycles in the oceanic carbon reservoir, like the 20-kyr precession in the hydrological cycle, is related to low-latitude processes in the climate system. The best example is the Late Cretaceous carbonate sequences from the Mediterranean to the South Atlantic, where the pervasive precession and eccentricity cycles were discovered 20 years ago. In contrast to much faster water cycling in the Earth surface system, the residence time of carbon in the ocean may reach 130–140 kyr, which exceeds the duration of a single glacial cycle.

Meanwhile, the long-eccentricity cycle of low-latitude origin could be disturbed by ice-sheet development in the high latitudes. Thus, the 405-kyr...
cycles in the oceanic carbon reservoir have been obscured since 1.6 myr by formation of the abyssal carbon reservoir in the Southern Ocean in response to ice-sheet development. A similar event occurred at 13.9 myr when the 405-kyr cycles were restrained during the rapid growth of the ice sheet at the South Pole.

**Microbial carbon pump and dissolved organic carbon**

The above discussions raised two related questions: what is the mechanism that drives the long cycle changes of the carbon reservoir and what mechanism is responsible for its disturbance or obscuration? In answer to the first question, the low-latitude hydrological cycling driven by the global monsoon caused the varying supply of nutrient elements from land to ocean, which in turn changed the balance between the biological pump and the microbial carbon pump (MCP).

Recent progress in microbial oceanography has revealed a remarkable role of the MCP in the oceanic carbon cycle. Marine dissolved organic carbon (DOC), produced by microbial processes, is the largest reservoir of reduced carbon in sea water and mostly persists over long periods (>10^3 kyr) in the ocean as "refractory DOC." In the results, two types of newly generated organic carbon can be distinguished in the ocean: rapid versus slow cycles related to the biological pump versus the MCP, with production of particulate organic carbon (POC) and DOC, respectively (Figure 1B).

All this led to a newly proposed "DOC hypothesis" to explain the long-term carbon cycles in the ocean: the nutrient supply enhanced by the global monsoon rainfall controls the periodic changes in POC/DOC deposition in the ocean, whereas since 1.6 myr the formation of the deep ocean carbon reservoir and the reorganization of ocean circulation have become so powerful as to obscure the long-eccentricity signal in the carbon cycling.

**Low-latitude forcing of climate changes**

All of the above discussions highlight the role of low-latitude processes in global climate changes and challenge the classical wisdom that global climate changes always originate from the high latitudes and that the observed variations in the low latitudes are nothing but a passive response to those in the high latitudes. The concept of low-latitude forcing of climate changes is understandable, as Earth’s climate system is driven primarily by solar insolation and incoming sunlight is largely concentrated in the low-latitude regions. Moreover, the prevailing role of low-latitude forcing of climate changes is also based on the fact that the ice-free "hot-house" regime exceeds two-thirds of the geological history by length, whereas the development of bipolar ice sheets is limited merely to the most recent 2–3 myr.

In sum, the concept of low-latitude forcing of climate change has made a good start as a new research direction. Unlike the ice sheet in the high latitudes, however, the water vapor in the low-latitude hydrological cycling is hardly visible or preserved in the geological records. To date no paleo-vapor proxy has been identified, and the physics of clouds remains an enigma even for modern meteorology. Nonetheless, the difficult issues are usually those where scientific breakthroughs are made. With our collaborative efforts, this new concept may lead to major contributions to global climate research.

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**DECLARATION OF INTERESTS**

The author declares no competing interests.