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The Rapidly Changing Arctic and Its Impact on Global Climate

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Abstract Arctic sea ice has significant seasonal variability. Prior to the 2000s, it retreated about 15% in summer and fully recovered in winter. However, by the year 2007, Arctic sea ice extent experienced a catastrophic decline to about $4.28\times10^6\,\mathrm{km}^2$, which was 50% lower than conditions in the 1950s to the 1970s (Serreze *et al*., 2008). That was a record low over the course of the modern satellite record, since 1979 (note that the year 2012 became the new record low). This astonishing event drew wide-ranging attention in 2007–2009 during the 4th International Polar Year. The dramatic decline of sea ice attracts many scientists' interest and has become the focus of intense research since then. Currently, sea ice retreat is not only appearing around the marginal ice zone, but also in the pack ice inside the central Arctic (Zhao *et al*., 2018). In fact, premonitory signs had already been seen through other evidence. Before the disintegration of the Soviet Union, US naval submarines had been conducting an extensive survey under the sea ice and taking measurements of sea ice thickness. Their measurements revealed a gradual decrease of ice thickness to 1.8 m during winter by the end of the 20th century, in contrast to the climatological mean of 3.1 m (Rothrock *et al*., 1999). However, this alarming result did not draw much attention since the Arctic was still severely cold at that time.

Key words Arctic Ocean; climate change; sea ice retreat; freshwater accumulation; Arctic amplification; global impacts

1 The Rapidly Changing Arctic Environment

The key to the dramatic decline of the sea ice is the enormous source of extra thermal energy that melts the ice. The first hypothesis posited that the heat came from the mid-latitudes, but observations showed that there was no significant increasing trend in heat input into the Arctic (Yang *et al*., 2010). In addition, there was no unusual solar activity. The remaining possibility was that the Arctic gained the extra heat by itself through some internal processes.

Clouds reflect sunlight back to space contributing to cooling of the earth's surface while water vapor acts like a blanket to keep the earth's surface warm. Are they the culprits for the extra heat? There was no evidence that clouds shrunk or water vapor content increased (Kay and Gettelman, 2009). The well-known hypothesis is the ice-albedo feedback mechanism, wherein ice has a higher albedo, reflecting much sunlight back into space, while the ocean has a lower albedo and absorbs more solar energy. The absorbed and stored solar energy could melt thesea ice further and trigger a positive feedback loop (Winton, 2013). The positive feedback effect is used to explain the source of the extra heat. Despite this, many scientists are still not convinced. They have argued that there wasnot a dramatic shrinking of sea ice in earlier decades while this positive feedback was also present.

More details have been revealed in later studies. The sea ice interior structure is porosities in contrast with pure water ice. Studies have revealed that the sizes of sea ice bubbles are larger, making the ice 'softer' to break (Hunke *et al*., 2011). Furthermore, Arctic sea ice has been thinning, rendering it more vulnerable to compression under wind forcing, forming ice ridges. More ice ridges in summer favor wider coverage of melt pond formation, which, in turn, accelerate melting and breaking of sea ice. This triggers a positive feedback effect. The percentage of multiyear sea ice (sea ice that can survive for more than 1 year) is declining as the Arctic is getting warmer. To this day, multiyear sea ice is disappearing almost everywhere in the Arctic Ocean except for the northernmost regions of the Canadian Arctic Archipelago. This makes it more difficult for scientists to find an area with thick enough floating sea ice to set up an ice camp for research.

Climatologists are keen on sea ice loss because it alters the heat budget at the sea surface. More heat is released into the atmosphere with the warming air temperature over the Arctic. This warming is 2.5 times the global average value, which is commonly noted as 'The Arctic Am-

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plification' (Kumar *et al.*, 2010). Our studies showed that during summer, the ocean warms the atmosphere markedly over ice-free regions while it releases a negligible amount of heat to the atmosphere over ice-covered regions. The Arctic amplification is most evident in spring, fall, and winter, when the sea ice is in its frozen state, but the air-ocean heat flux is not significant. This makes the ice-albedo feedback hypothesis suspicious.

What about storms? Extratropical storms are frequently swept across the Arctic. Other storms are formed in the Arctic (Fig.1). The ocean provides more heat to the formation of storms and increases storm intensities as the sea ice declines. A rapid decline in sea ice is usually associated with the presence of storms (Simmonds and Keay, 2009). For example, the new record low for sea ice extent overall was in 2012 (Schultz, 2013) while the minimum sea ice extent for the central Arctic region was in 2016 (Yamagami *et al.*, 2017). Thinner sea ice is more vulnerable to break up by storms. This highlights the importance of synoptic processes on Arctic sea ice.

The Arctic Ocean is a semi-enclosed ocean dominated by the Beaufort Gyre (anticyclonic circulation) and the Transpolar Drift (Figs.1 and 2), in contrast to the other semi-enclosed ocean in the northern hemisphere, which is dominated by cyclonic circulation. In earlier times, the Arctic Ocean was dominated by thick sea ice, which restricted the air-ocean heat flux, resulting in the formation of the Beaufort High. The Beaufort High drives the anticyclonic Beaufort Gyre. There is concern that the anticyclonic circulation could transform to a cyclonic circulation as the sea ice declines. In this case, both the climate and sea ice would change dramatically. However, this should not happen for at least another decade because of the large amount of freshwater in the Beaufort Gyre.

Fig.1 The ocean circulation system of the Arctic Ocean (adapted from Proshutinsky and Krishfield, 2019).

The Arctic is getting warmer, which is melting the glacier and increasing river runoff into the Arctic Ocean. These water sources contribute to the freshwater budget in the Beaufort Gyre. River runoff increased by about 27% during 2000–2010 compared with the period prior to 1989 (Haine *et al.*, 2015). These river runoffs accumulate in the Beaufort Gyre instead of flowing *via* the Transpolar Drift Stream and exiting the Arctic Ocean. Currently, the Beaufort Gyre contains about 23300 km^3 of fresh water, which is 5–6 years flux of river runoff and at least double that of the 20th century (Haine *et al.*, 2015; Proshutinsky and Krishfield, 2019).

The accumulation of fresh water changes the buoyancy flux and ocean pressure gradient, which, in turn, accelerates the ocean current. Although the increment in the ocean current is relatively small (about 3–5 $\mathrm{cm\,s}^{-1}$), it is significant for the large-scale ocean circulation (Zhong *et al.*, 2018). The large amount of fresh water in the Beaufort Gyre contains tremendous oceanic potential energy that will take decades to dissipate. As a result, the Beaufort Gyre should remain for a very long time.

Although there has been no fundamental change in the Arctic Ocean circulation system, there has been a minor change in the origin of the Transpolar Drift. The previous documented source region of Transpolar Drift is north of the New Siberian Islands, while a newly identified source region is in the Chukchi Borderland (Steele *et al.*, 2004; Morison *et al.*, 2012). This complicates the circulation system. The flow direction of the continental slope current off the East Siberian Sea changes. The slope current usually flowed westward, benefiting the freshwater flow out of the Arctic Ocean *via* the Transpolar Drift. In contrast, the slope current has recently flowed eastward, causing freshwater to accumulate into the Beaufort Gyre (Zhao *et al.*, 2015).

More and more studies have shown that the Arctic Ocean and atmosphere have been changing as well as the Arctic sea ice. The Arctic is no longer notable only as a severely cold and harsh environment. The International Arctic Science committee has proposed the concept of the

'New Arctic' (Evengård *et al.*, 2015); however, what we know now is just the tip of the iceberg. More secrets remain to be revealed.

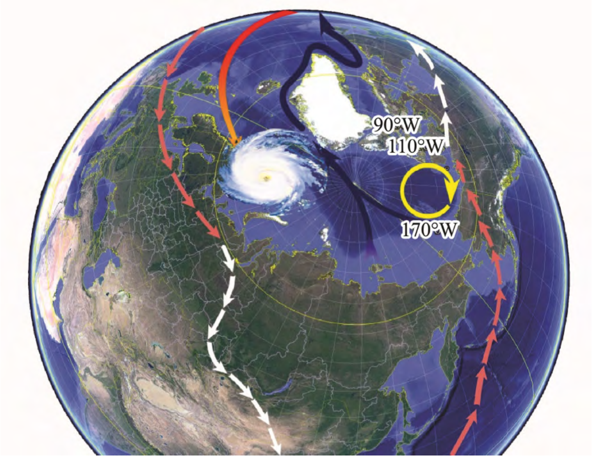

Fig.2 Schematic diagram for Arctic variation and its impacts on the mid-latitudes. White arrows represent the pathway of cold air from the Arctic, while blue lines represent the Transpolar Drift and cold current.

2 The Far-Reaching Effect of the Changing Arctic

The global air temperature is gradually increasing as a result of an increase in atmospheric greenhouse gases. Over the last 30 years, scientists have made great efforts to study this phenomenon. Human activities are responsible for the increase in greenhouse gases, which is a difficult to resolve at present. However, some have claimed that global warming showed a hiatus in the last decade (Katsman and van Oldenborgh, 2011) except for the Arctic region, where there has been continuous significant warming (Screen *et al.*, 2012). The Arctic warming has an alarming effect on global climate. However, the details of this effect are still not clear. Three potential dynamical pathways linking Arctic amplification to mid-latitude weather include: changes in storm tracks, changes in the jet stream, and changing planetary waves and their associated energy propagation (Cohen *et al.*, 2014). North America, Europe, and Asia are the three most sensitive regions to the far-reaching effects of the changing Arctic.

For the Europe climate, the German scientist Rahmstorf (1994) proposed that Arctic warming could make it colder. The northward flow of Atlantic water warms Europe. As the Atlantic water flows north, it becomes colder after releasing its heat to the atmosphere, and its density increases, resulting in deep convection in the Greenland Sea. This transformed colder and denser Atlantic water sinks and finally flows out of the Nordic Sea via the subsurface layer, which drives the northward flow of Atlantic water at the surface. This vertical circulation is well-known as the oceanic conveyor belt. As the Arctic warms, it makes the sea surface warmer and the melting glacier water reduces the sea surface salinity. Both of these two effects reduce the sea surface density, which weakens the vertical convection. Studies have shown that the vertical convective depth is reduced from 3000 m to less than 1000 m over the Greenland Sea as the Arctic warms (Ronski and Budéus, 2005). If vertical convection stops, the oceanic conveyor belt would stagnate (Rah- mstorf, 1997). In this case, both the air temperature and sea surface temperature would drop in the Nordic Sea. Europe would be as cold as the same latitudinal zone in Canada, and the northern hemisphere would cool enough to possibly relieve or compensate global warming.

Arctic warming could also make North America colder. There have been more episodes of severe winter cold plunging into the east coast of America as the Arctic has warmed. American climatologists Francis and Vavrus (2012, 2015) proposed that this is the result of a more meandering westerly wind (a high-speed wind along the polar front) around the earth at the temperate latitudes. These meanders are also known as Rossby Waves. As the Arctic gets warmer, the meanders migrate over the populous land masses of the mid-latitudes. This leads to the southward flow of cold air, which causes episodic extreme cold winters across eastern America. Ironically, such extreme winter cold has caused some American politicians to believe that global warming is a hoax.

Recent studies indicate that Arctic sea ice decline has led to more frequent Eurasian blocking events (*e.g.*, Mori *et al.*, 2014; Luo *et al.*, 2016). There exists a positive feedback between the sea ice variation and the Ural blocking (Chen *et al.*, 2018). The presence of the Ural blocking, or an upper-air anticyclone over northern Eurasia, induces a cold mid-latitude Asia and a warmer Arctic by means of meridional air exchange (Wu *et al.*, 2013). In contrast, a cold Arctic is linked with heat waves in the mid-latitudes (Wu and Francis, 2019).

A north-south gradient of background tropospheric potential vorticity (PV) derived by the air temperature difference between the Arctic and the mid-latitudes has been found to establish a link between recent winter Arctic sea ice decline and mid-latitude extreme cold (Luo *et al.*, 2019). Atmospheric blocking is found to be more persistent in weakened PV gradient regions over Eurasia, Greenland, and northwestern North America due to weakened energy dispersion and intensified non- linearity. The stronger and more southward extending cold surges are connected to sea ice decrease over the northern Barents-Kara seas, which is guided by the longer lasting upper level European blocking that corresponds to a weak tropospheric polar vortex and weaker meridional PV gradient. The dynamical mechanism behind cold air intrusions into Asia is similar to that of North America, but due to the obstruction of the zonal-oriented high mountains across China, extreme cold events are not as frequent as they are in America.

3 New Insight into Global Climate Change

As we can see from the previous sections, the Arctic amplification makes the mid-latitude regions colder instead of warmer. This is a robust result in terms of synoptic and climate scales. We hypothesize that Arctic warming was a key regulating factor in the hiatus in global warming over the last decade.

The enhancement of westerly wind meanders allowed more cold air to plunge into the mid-latitude regions, providing a cold source for relief from global warming. At the same time, more warm air from the south would surge into the Arctic as compensation (Overland and Wang, 2016). For example, in January 2016, the air temperature across eastern America dropped to −40℃, while it rose to 2℃ in the Arctic (Cullather *et al*., 2016). This seems to suggest that the global warming hiatus and the Arctic amplification might have been dominated by the same process.

There is a key question regarding the global warming hiatus, *i.e.*, where did the extra heat absorbed by increased CO_2 in the atmosphere go? Many researchers believe that the heat has been stored into the ocean. For example, Chen and Tung (2014, 2018) proposed that the extra heat goes into the intermediate layer of the North Atlantic Ocean. Although the details of this mechanism are not clear, it is supposed to correspond with the vertical convection of the Nordic Sea. Is it possible that the global warming hiatus was a result of weak vertical convection? This remains to be further investigated.

Arctic warming is an important, complex aspect of the global climate. Whether it is a blessing or a curse remains to be seen. The more one attempts to understand it, the more unknowns are revealed. The rapidly changing Arctic calls for a comprehensive international collaboration.

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