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An aerial photograph of a vast, cracked expanse of ice, likely in the Arctic. The ice is a pale, milky blue color, with a network of dark, irregular cracks crisscrossing the surface. The perspective is from a high angle, looking down on the ice. The text of the title is overlaid on the upper portion of the image.

# IS THE MELTING ARCTIC CHANGING MIDLATITUDE WEATHER?

James E. Overland

According to model simulations, a warming Arctic can shift the circulation patterns of the polar jet stream and bring frigid air southward. But has it?



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**T**his past year the average surface temperature of Arctic air was higher than it has ever been—about 2.5 °C above the value measured at the beginning of the 20th century. Global temperatures have also risen over the past century, but the upward trend has not been uniform. Since 1980 the Arctic's temperature rose at a rate more than double that of the Northern Hemisphere average—a relative increase referred to as Arctic amplification. Changes to the Arctic environment, driven by the warming of ocean and atmosphere, are stark and pervasive: Thinning sea ice, retreating glaciers, thawing permafrost, and greening tundra are among the numerous trends that are apparent in today's Arctic.

The region has lost two-thirds of its volume of sea ice during the past three decades. The Arctic snow cover in late spring has similarly suffered a large decline. As the sea ice continues to thin, it exposes an ever-growing area of open water to solar radiation. Because of the large difference in albedo between ice and water, less snow and ice covering the ocean during the Arctic's long summer days means that more sunlight is absorbed. The more the ocean absorbs, the warmer it gets, which in turn melts more ice and snow (see the article by Martin Jeffries, James Overland, and Don Perovich, *PHYSICS TODAY*, October 2013, page 35).

That feedback loop is one reason for Arctic amplification. Another is that while the Arctic warms, its temperature remains lower than that of Earth's subtropics. The Arctic thus loses less radiant heat from the top of the atmosphere than do the lower latitudes.<sup>1</sup> The increase in atmospheric water vapor also traps Arctic heat. Based on more than 20 climate models developed for the Intergovernmental Panel on Climate Change's fifth assessment report in 2013, researchers predict that the winter surface temperature in the Arctic—that is, at latitudes above 60° N—will rise another 4.0 °C, relative to year 2000 values,<sup>2</sup> by 2040. The Northern Hemisphere is projected to increase 1.8 °C, given existing and anticipated levels of anthropogenic carbon dioxide in the atmosphere.

More than record-high temperatures are expected

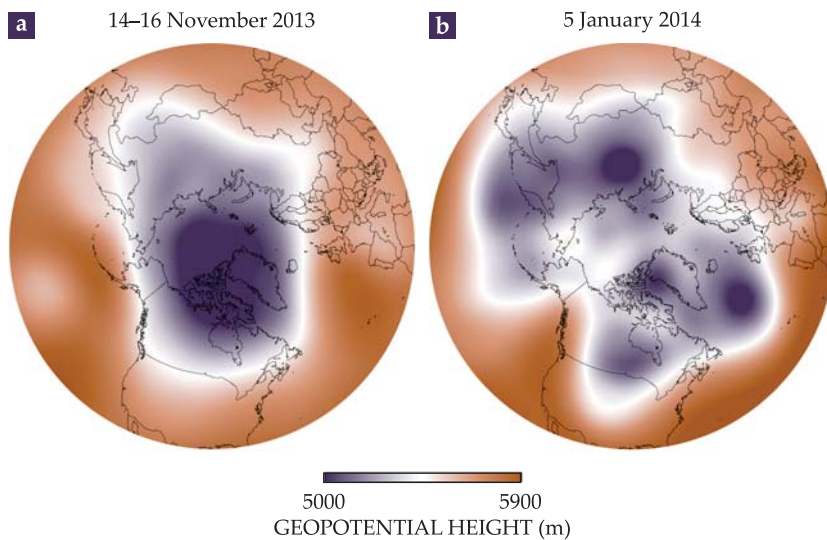
to accompany global warming. Severe weather is also likely: The greater evaporation rate in the warmer air can render crops vulnerable to drought. The increased atmospheric water vapor can also produce heavier rainfall and flooding. And the progressively higher sea level from a warming ocean and melting glaciers can threaten coastal communities.

Arctic warming may be responsible for another kind of severe weather: bouts of abnormally cold weather a thousand kilometers south of the Arctic circle. The frigid temperatures ex-

perienced in the eastern US and Europe during the snowy winters of 2009–10, 2010–11, and 2014–15, for instance, have been linked by some scientists to Arctic changes over the past decades. In 2012, climatologists Jennifer Francis and Stephen Vavrus proposed that warming of the Arctic can modify the shape of the jet stream—the fast-flowing air currents that circle the planet—enough to directly influence the weather at midlatitudes.<sup>3</sup>

Scientific opinions differ, however, on whether such episodes of extreme weather are random events or are discernible contributions from the Arctic.<sup>3–5</sup> After all, cold snaps even more severe than those from the past few years hit the US in the early 1960s, in the late 1970s, and earlier in the 20th century, when Arctic sea ice was thicker and more extensive than it is today.

Despite the controversy among atmospheric scientists, national and international agencies actively encourage research on the topic. The World Meteorological Organization (WMO), for example, supports the Polar Prediction Project, and the US's CLIVAR (Climate Variability and Predictability Program) has the stated mission to facilitate observations and analyses of climate change. More is at stake than just public and scientific curiosity. An important question is whether Arctic amplification can become a new tool for extended weather forecasting. According to the literature, resolving the



**FIGURE 1. THE ARCTIC POLAR VORTEX**, the persistent cyclone that flows counterclockwise around the North Pole, is driven by the temperature difference between the cold Arctic and warmer, lower latitudes. The flow, which is primarily west to east, may adopt a relatively circular global pattern (**a**) or a wavy one (**b**). In this circular example, measured in November 2013, the winds circulate around an extended low-pressure region—or, equivalently, a region of low-altitude, gravity-adjusted height of constant pressure, the so-called geopotential height shown here for 500 hPa. Less than two months later, the vortex had morphed into a pattern of multiple high- and low-pressure zones. In that wavy configuration, the jet stream, the southernmost border (white) of the polar vortex, can meander southward into midlatitudes (30°–60°), carrying cold Arctic air with it. (Image courtesy of the National Oceanic and Atmospheric Administration.)

issue depends on a fuller understanding of the fundamental dynamics of atmospheric circulation features. In this article I lay out the current state of the science.

## POLAR VORTEX

In the winter, little solar radiation reaches the Arctic surface, and the region cools by the loss of IR energy to space. The loss is balanced by the transfer of energy from lower latitudes via atmospheric winds and ocean currents. On a rotating Earth, the north-south temperature difference produces cyclonic winds that flow primarily west to east across midlatitudes and the sub-Arctic. The counterclockwise wind pattern in the upper atmosphere surrounding the North Pole is traditionally called the polar vortex. (A twin Antarctic vortex flows clockwise in the Southern Hemisphere; see the article by Anne Douglass, Paul Newman, and Susan Solomon, *PHYSICS TODAY*, July 2014, page 42.)

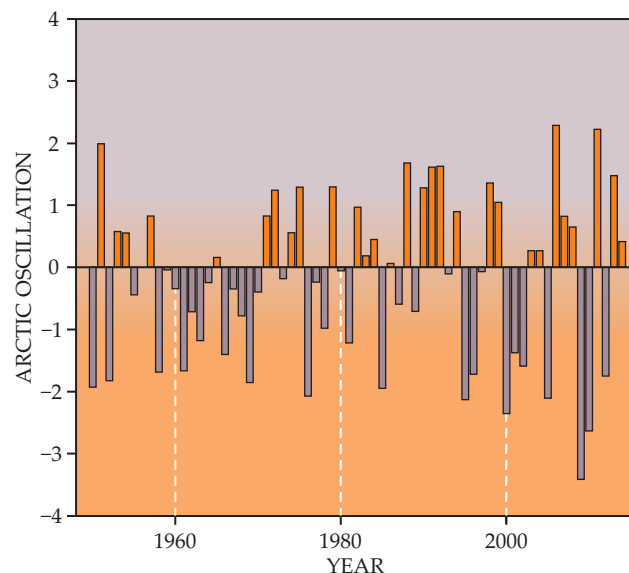
Weather tends to follow the direction of the mid-altitude winds. Figure 1 illustrates two configurations of the polar vortex; the winds follow contours of constant color. One configuration (left) from November 2013 had a relatively circular flow pattern around the North Pole, and the other (right), which emerged less than two months later, had a wavy flow pattern from numerous low-pressure centers. The jet stream (the white region) borders the polar vortex along its southernmost edge.

When the polar vortex is strong, driven by a large north-south pressure gradient, so are the westerly winds. But as the vortex weakens, wind directions can shift and meander north and south. A wavier jet stream thus has the potential to bring cold air to midlatitudes and warm air northward.

Because of the complexity of the atmospheric physics behind circulation patterns, though, it's unclear exactly how a warming Arctic may give rise to a wavy jet stream. Although changes in north-south temperature differences can influence the jet stream, winds flowing strictly west to east are unstable on a rotating planet; instabilities cause north-south meanders in the wind pattern and eventually generate high- and low-pressure centers and severe weather, such as locally strong, cold winds and snow. When and where such instabili-

ties form is unpredictable beyond a week or so in advance; meteorologists refer to atmospheric winds as chaotic, random, or internally variable. Indeed, the position of the jet stream over the Atlantic Ocean can naturally vary in latitude by up to 10° yearly.

In addition to that internal variability, forced variability in the wind pattern complicates the picture. Sea-surface temperature anomalies in the tropics, midlatitudes, and ice-free parts of the Arctic all influence atmospheric temperatures. Low-



**FIGURE 2. ARCTIC OSCILLATION (AO) INDEX VALUES** are mapped for 65 years of consecutive Decembers. The AO index gives a rough indication whether Northern Hemispheric wind patterns primarily circulate west to east (positive AO) or are wavy (negative AO), veering north and south. The index magnitude indicates the strength of the pattern. Note the increase in magnitude of both signs of the AO during the past decade. (Data adapted from [http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily\\_ao\\_index/ao.shtml](http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml).)



altitude, warm air increases the height of mid-altitude constant-pressure surfaces—the so-called geopotential, or gravity-adjusted, heights—and changes in the slope of those pressure surfaces influence the local winds. The greater the slope, the greater the wind speed. So long as the anomalies persist, they can be considered an external forcing on the atmosphere. And because the atmosphere can support waves, the external forcing need not remain local but can affect distant regions, an interaction known as teleconnection.

The energy associated with just the internal variability of midlatitude weather systems is larger than that associated with the external-forcing contribution from a warming Arctic. One must distinguish the effects of Arctic forcing on midlatitude atmospheric circulation not only from those of random events, but also from those driven by tropical and subtropical temperature anomalies. Detecting the Arctic influence is challenging because of its small signal-to-noise ratio. Compounding those difficulties is the relatively short period of time—roughly 15 years—over which major Arctic amplification has occurred.

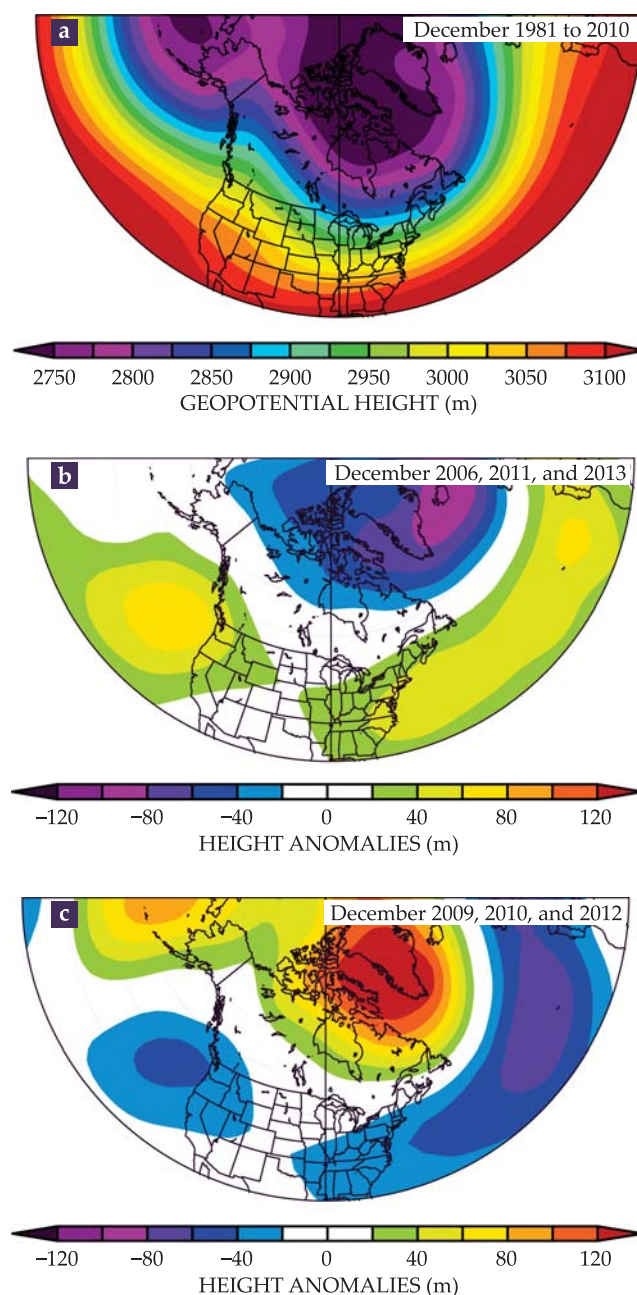
## THE POSSIBLE AND THE ACTUAL

Scientists are wrestling not only with how large and consistent an impact on climate to expect from Arctic warming but with whether it is even recognizable. This past year climatologists Elizabeth Barnes and James Screen broke the linkage issue down to three questions: Can Arctic warming influence the midlatitude jet stream? Has it significantly done so? Or will it do so in the future?<sup>26</sup> Extensive simulations strongly suggest that near-surface Arctic warming and loss of sea ice can modify the midlatitude circulation. In most of those simulations, unsurprisingly, the responses were small compared with internal variability. And as Barnes and Screen point out, the mere plausibility of causal connection implies neither that Arctic warming has exerted a discernable influence in the past nor that it will do so in the future; other factors that control midlatitude weather may be too obscuring.

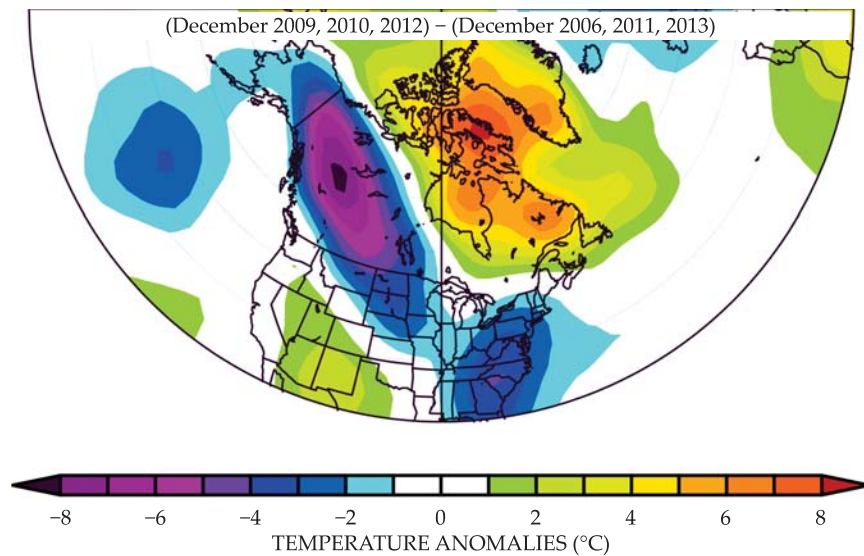
Model results from several studies by Screen and others this past year<sup>7–9</sup> show little support for future seasonal average midlatitude cooling trends or increases in the number of extreme weather events over the Northern Hemisphere. Other results suggest that if the Arctic does affect severe weather to the south, its influence is regional in extent and episodic, even within seasons.<sup>10</sup>

Fortunately, one can look for patterns in the variability itself using what's known as the Arctic oscillation (AO) index to discern correlations with episodes of severe weather. The AO index is a measure of the dominant pattern of sea-level pressure variations north of about 55° N latitude. A positive AO corresponds to a strong zonal, or west–east, direction to the wind flow, exemplified by figure 1a, whereas a negative AO corresponds to a more north–south flow, characteristic of the wavy jet-stream pattern, exemplified in figure 1b, thought to produce the abnormally cold midlatitude winters.

Figure 2 shows the evolution in the AO index in Decembers for the past 65 years. Interestingly, the AO index reveals greater variability in wind patterns over the past decade: Both positive and negative AO values have increased in magnitude relative to earlier years in the time series.<sup>11</sup> Although the increased variability may be caused by internal atmospheric dynamics and



**FIGURE 3. GEOPOTENTIAL HEIGHT ANOMALIES.** (a) Thirty years of December height data for 700-hPa pressure levels are averaged and mapped over the Western Hemisphere. The progressively lower heights to the north drive the winds primarily from west to east on a rotating Earth. (b) Anomalies in the heights are averaged for three Decembers (2006, 2011, and 2013) with positive Arctic oscillations, which reinforce the strong westerly winds, and (c) three Decembers (2009, 2010, and 2012) with negative oscillations, which counteract the westerly winds and favor a wavy jet stream. (Adapted from ref. 11.)



**FIGURE 4. AIR-TEMPERATURE ANOMALIES** from a 30-year mean near the surface. Mapped here over the Western Hemisphere are the averaged anomalies for three recent Decembers (2009, 2010, and 2012) when the Arctic oscillation index was negative, relative to three Decembers (2006, 2011, and 2013) when the index was positive. The relatively warm (red and orange) air over Baffin and Hudson Bays west of Greenland helps reinforce the wavy wind pattern favored by the negative Arctic oscillation by locally decreasing the density of the air. The warm air thus increases the constant-pressure heights in the atmosphere over Greenland (see figure 3c), which weakens the north–south temperature gradient that powers the jet stream. Resulting northerly winds over western Canada bring relatively cold air into central Canada and the US. (Adapted from ref. 11.)

has occurred over a period too short to yield definitive proof for or against linkages, it does yield information about current Arctic atmospheric conditions not emphasized in the studies mentioned above, which point to decreased atmospheric variability in a future Arctic. During the past five winters (2009–10 through 2013–14), the months of December and January have exhibited twice the expected number of negative AO events.<sup>11</sup> An increase in AO variability could be an early sign of destabilization in the Arctic jet stream. But is the increased wind variability related to recent thermodynamic changes in the Arctic?

## ASIA AND NORTH AMERICA

Evidence behind a connection comes from case studies in north-central Asia and the eastern US.<sup>10,12</sup> In the first case, analyses of field observations over the past decade and of simulations suggest a direct linkage between the regional loss of sea ice in the Barents and Kara Seas north of Eurasia during the autumn months and cold, stormy conditions experienced in eastern Asia. The winters were colder during years with negative phases of the AO than during years with positive AO phases.

The chain of causality is complex. The atmospheric forcing starts with a loss of sea ice and relatively warm ocean temperatures. As the atmosphere cools below freezing in early winter, the thin sea ice readily transmits the ocean’s heat and moisture

to the atmosphere. Locally warmer Arctic air reduces the north–south temperature gradients, which in turn reduce the strength of the westerly winds. Thanks to the slower wind, atmospheric pressures can build over Siberia, and cold air can collect on the east side of the Siberian high-pressure region. Smaller-scale storms can then sweep that cold air further eastward to China, the Koreas, and Japan. In 2014 Masato Mori and colleagues used a wind circulation model to show that the probability of severe winters in those countries has more than doubled because of the reduction in Barents–Kara sea ice.<sup>13</sup> The association with cold weather in eastern Asia is to date the most consistently supported of the possible regional Arctic–midlatitude linkages.

The Arctic’s influence on North America is more speculative. It’s thought that instead of initiating midlatitude weather, the Arctic reinforces existing patterns—specifically a wavier jet stream. Internal instabilities in the atmosphere influence the wind pattern over the North Pacific Ocean and largely determine whether the downstream wind pattern over North America is primarily zonal or wavy. Nonetheless, consider recent years with large December AO index values of both signs since 2006. Figure 3a shows, for reference, a 30-year average of the December altitudes for a 700-hPa pressure level. The figure’s subsequent two panels, 3b and 3c, map the height deviations from that mean pattern for three Decembers (2006, 2011, and 2013) with large positive AO values and three Decembers (2009, 2010, and 2012) with large negative AO values, respectively.<sup>11</sup>

In figure 3b, the negative height anomalies (blue) are centered near Greenland, a pattern that strengthens the north–south height gradient in positive AO years and thus strengthens the westerly winds over central and eastern North America. By contrast, in the negative AO years averaged in figure 3c, positive height anomalies (red and orange) are centered on Greenland. They counteract the influence of the low-height center in the region’s fundamental climatology (figure 3a) and divert the winds from a more zonal pattern into a more north–south one, carrying cold air south and warm air north.

## STATE DEPENDENCE

The warm temperature anomalies over Baffin and Hudson Bays in figure 4 occurred during negative-AO Decembers relative to positive-AO Decembers and are consistent with the greater heights west of Greenland for the negative-AO cases in figure 3c. Those warmer temperatures increase the vertical distance between different constant-pressure surfaces in the atmosphere, which in turn modifies the wind patterns.

Climatologist Kevin Trenberth and colleagues recently argued that forced changes in thermodynamic variables, such as increases in temperature and moisture, from global warming tend to show sustained impacts on the environment, whereas changes in dynamic variables, such as wind circulation, appear to be mostly random and chaotic.<sup>14</sup> The same argument applies to how Arctic warming may be linked to remote weather: Ther-



modynamic processes in the Arctic may reinforce and prolong, but not necessarily cause, an already wavy wind pattern. Thus, given two possible Northern Hemispheric patterns, zonal and wavy, one does not necessarily find, either in simulations or field observations, the same midlatitude response from similar Arctic forcing.<sup>7,15</sup> The difference implies that the connection between Arctic warming and midlatitude regions is state dependent, determined by whichever large-scale atmospheric wind pattern is dominant at any given time.

Two years ago, in an analysis of simulations in which sea-ice concentrations were reduced at a known rate, Screen and his colleagues concluded that if the ice loss was the only change in the system, it would take at least 50 years to distinguish the forced signal from internal variability in the large-scale wind pattern.<sup>16</sup> But even rather well-accepted climate models can have trouble capturing some of the regional atmospheric dynamics associated with linkages. In a recent comparison of results from two models and from two data sets, which assimilate observations into the simulations, the models compared poorly with observations near 60° W longitude,<sup>17</sup> a critical region for potential Arctic links to eastern North America.

As Barnes and Screen point out, the jury is still out on whether Arctic warming has tangible implications for weather at lower latitudes.<sup>6</sup> Researchers continue striving to incorporate Arctic-specific physics into their models. For example, the effects of clouds and sea ice on climate are important but especially difficult to simulate. Better constraining the forecasting models greatly depends on increasing the number of observations of Arctic regions. Despite the current controversy over how the changes in the Arctic are manifest over the more populated parts of our planet, the predicted doubling of Arctic amplification over the next decades provides a strong incentive to understand how Arctic change interacts with a mostly chaotically varying jet stream. Extending weather forecasts from a week to a month or more would provide one way to anticipate and adapt to whatever is in store for us.

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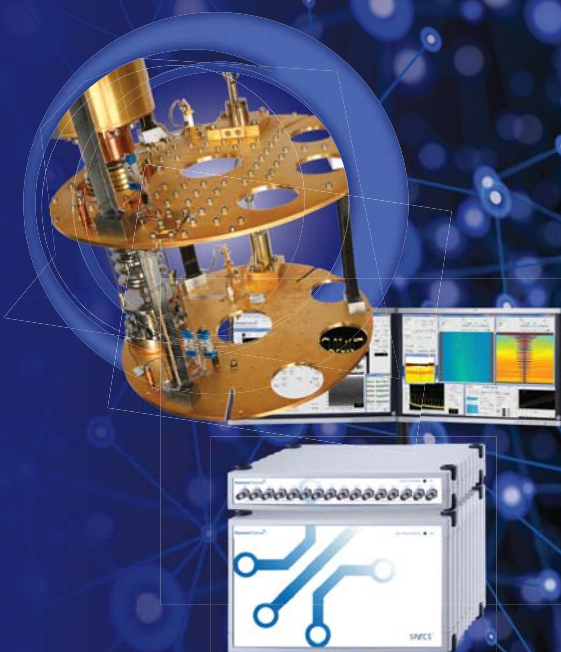
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