CLIMATE CHANGE

Vanishing breed. Climate change is hammering Adélie penguins on Antarctica's Torgersen Island, Jennifer Blum says.

Winds of Change

Antarctica's fate is not as simple as that of an ice cube melting in the sun, scaled up a trillionfold

PALMER STATION, ANTARCTICA—To Jennifer Blum, the empty nests on Torgersen Island are a harbinger of doom. The rugged outcrop is home to one of the largest colonies of Adélie penguins on the Antarctic Peninsula, a crooked sliver of land flanked by dozens of islands that reaches north toward the tip of South America. But the Adélies here are fading fast. There are fewer than 2000 breeding pairs, a quarter of the number found in the 1970s. Each spring, Blum, an ornithologist with Polar Oceans Research Group, a nonprofit in Sheridan, Montana, and her colleagues monitor colony size and breeding success. "You see a lot of newly abandoned nests every year," she says. "The changes have been staggering."

Blum's group has charted similar declines on nearby islands. She and others blame climate change. On the Antarctic Peninsula, the mean annual temperature is –3°C, more than 2° warmer than it was 50 years ago. Over the past 5 decades, winter temperatures have risen a staggering 6°C, or five times the global average. Roughly nine out of every 10 glaciers on the peninsula are retreating, says Hugh Ducklow, director of the Palmer Long-Term Ecological Research Station here on the western coast of the Antarctic Peninsula. Coastal ice persists only 5 months a year, three months fewer than 30 years ago.

Warming has warped the peninsula's food web. But "global warming is only part of the story," says David Thompson, a climate researcher at Colorado State University in Fort Collins. An unsung force now shaping the frozen continent's future is changing wind patterns. Retreating sea ice and stronger winds have caused seawater to mix more deeply, a process that churns sunlight-dependent phytoplankton into the ocean's depths. As a result, phytoplankton biomass has declined by 12% over the past 30 years. Higher on the food chain, that means fewer krill and fish larvae. These creatures are also getting hammered by the loss of sea ice, which hides them from predators.

More crucially, the complex interplay between air, sea, and ice has emerged as a central theme underlying climate change in Antarctica. Shifting wind patterns and corresponding ocean changes can explain climate responses across the continent. "It's quite a fabulous piece of climate science," says Robert Bindschadler, a glaciologist at NASA Goddard Space Flight Center in Greenbelt, Maryland. "It shows how the atmosphere is connected to the ocean, and how they impact the ice in a beautiful chain of events."

"People used to think Antarctica responds to global warming like a giant ice cube"—with rough uniformity—says Amelia Shevenell, a paleoclimatologist at the University of South Florida, St. Petersburg. "We now know this is not the case."

Ghosts in the machine

Antarctica's climate is strongly affected by westerly winds that buffet the Southern Ocean. High atmospheric pressure over the midlatitudes pushes air toward the poles. As the winds rush south, they turn eastward with Earth's rotation. In the past few decades, air pressure along the Antarctic coast has often been lower than in previous decades, which strengthens the westerlies and drives them farther south, bringing more warm air to the Antarctic Peninsula. "In years when this happens, there is a 70% chance that the peninsula is warmer and has less sea ice," says Sharon Stammerjohn, an oceanographer at the University of Colorado, Boulder.

Human activity is partly to blame. Thompson's group, working with climate scientists Susan Solomon of the U.S. National Oceanic and Atmospheric Administration and Nathan Gillett of the University of Victoria in Canada, has found that changes in westerlies during austral summer are caused

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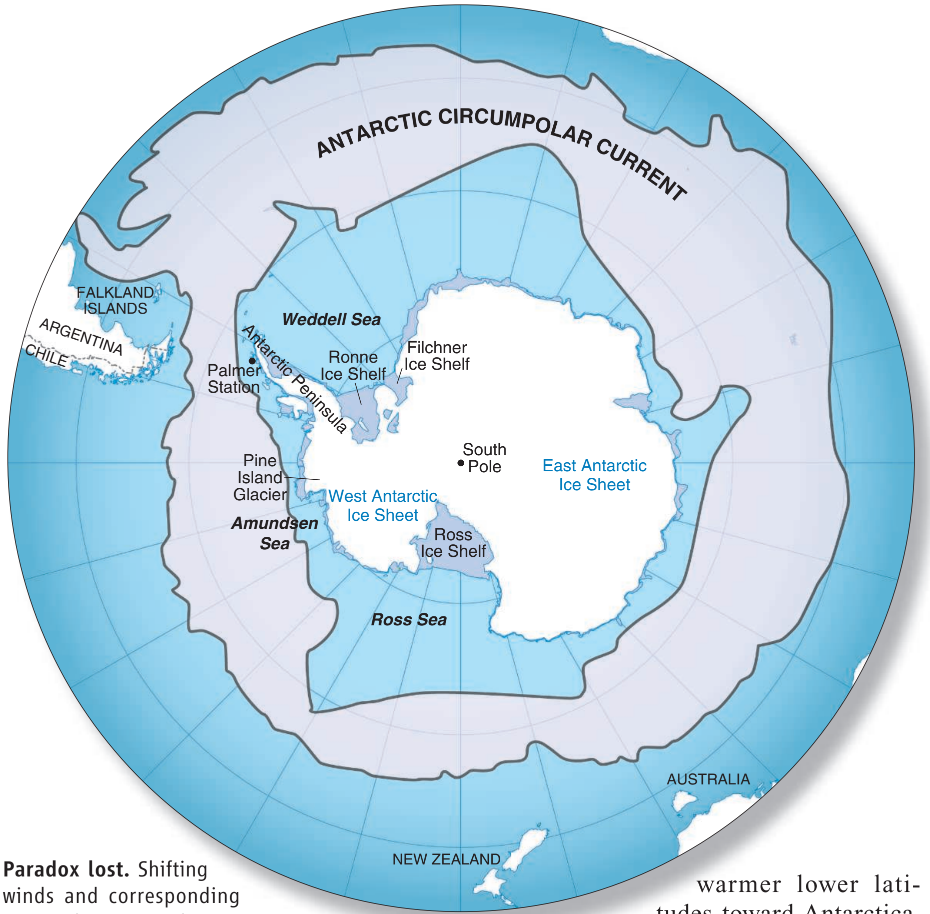
by the ozone hole over Antarctica, a thinning of the ozone layer in the stratosphere due to decades of consumer use of halogenated chemicals. Ozone absorbs solar radiation; the cooling strengthens surface westerlies and nudges them toward the South Pole. Climate models show that rising concentrations of greenhouse gases amplify that effect on the westerlies. At the same time, lower coastal air pressures suck cold winds from the pole, spreading a deep chill across the Antarctic interior. This helps explain the apparent paradox of the peninsula warming even as average temperatures in most other parts of the continent—except the Amundsen Sea in western Antarctica—have budged little.

Ocean temperatures are another ghost in the machine that could explain what's happening in the Amundsen region, which has experienced accelerating ice loss in recent decades. Sea surface temperatures in the central tropical Pacific, near the International Date Line, have been rising since the early 20th century. The warmer water heats the overlying air, which rises, expands, and meanders south, getting a push from the subtropical jet stream off eastern Australia. About 50° south of the equator, a high-pressure center steers the air mass in the same direction as the westerlies.

"You can think of the westerlies like a tightly wound guitar string," says David Battisti, a climate scientist at the University of Washington, Seattle. "Pinging on that guitar string by changing tropical convection, you send out waves." His team's modeling shows that as westerlies intensify, loops of warm air detach and pile up over the Amundsen Sea. Cyclones steer this warm air into the continent's interior. That could explain the correlation between warming in the central tropical Pacific and rising winter temperatures in western Antarctica, Battisti says.

The El Niño–Southern Oscillation (ENSO) is plucking a different section of the guitar string. ENSO is a climate pattern that lurches between two states: El Niño, when tropical eastern Pacific surface waters are unusually warm, and La Niña, when they are exceptionally cool. By analyzing all ENSO events in the past 30 years, Stammerjohn and colleagues found that El Niño is closely linked to warming and light sea ice in the Amundsen Sea, but cooling and heavy sea ice in the Antarctic Peninsula. Modeling shows that El Niño tends to induce a persistent high pressure center west of the peninsula. This draws cold winds from the continental interior to the peninsula and pushes warm winds from the ocean over the Amundsen Sea.



Paradox lost. Shifting winds and corresponding ocean changes explain a seeming contradiction: the Antarctic Peninsula and Amundsen Sea growing warmer even as the continent's interior keeps its cool.

Nearing the tipping point?

It's not just the air that's growing warmer. The westerlies over the Southern Ocean produce the strongest ocean current on the planet, the Antarctic Circumpolar Current. As much as 4 kilometers deep and 1000 kilometers wide, the current moves 140 million tons of water per second. "Any changes in this powerful current will have a profound impact," says Michael Meredith, an oceanographer at the British Antarctic Survey in Cambridge, U.K.

As the westerlies are propelled farther south by the ozone hole and atmospheric warming, they tug the Antarctic Circumpolar Current south, pushing ocean heat from warmer lower latitudes toward Antarctica.

"The stronger winds also stir up more eddies," Meredith says. "These swirls of ocean currents, tens of kilometers in diameter, are effective engines to pump warm water towards Antarctica." The Southern Ocean is already feeling the heat. Since the 1950s, the Antarctic Circumpolar Current's sweet spot—its warmest water at 700 to 1000 meters below the surface—has increased by about 0.2°C, twice as much as the global average warming at that ocean depth. Through research cruises and year-round monitoring at Palmer Station, Stammerjohn and colleagues have charted a steady rise in ocean heat content since the 1990s in waters along the peninsula's continental shelf. They estimate that 80% of the added warmth is from a greater volume of deep, warm water welling up onto the shelf.

This kind of upwelling is unique to the Southern Ocean. As the westerlies drag the currents around Antarctica, surface water flows north with Earth's rotation, and is replaced by warm deep water from below. "At the peninsula, the circumpolar current skirts right along the coast, and stronger winds could easily lift up more deep water onto the shelf," says Ducklow, an ecologist at the Marine Biological Laboratory in Woods Hole, Massachusetts. On

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the continent, meanwhile, climate models forecast that cyclones caused by central Pacific warming could also flush more warm deep water onto the continental shelf in the Amundsen Sea. There, a robotic submarine has probed beneath Pine Island Glacier, which is sliding into the ocean at a rate of 4 kilometers a year. The sub's missions are shedding light on how deep water may erode ice sheet stability (see sidebar).

The climate changes down south could have far-reaching ramifications. The preeminent concern is sea levels: how high they will rise as ice sheets succumb to a global warm-up. A less intuitive consequence is how changing conditions in waters off Antarctica will affect the global ocean's cooling and gas exchange. Climate change could influence the amount of cold salty water that sinks to the ocean bottom. Antarctic Bottom Water, as it's called, pools at only a few spots around the continent, where seawater is cooled by overlying air and rendered saltier as ice forms. More than 60% is concentrated in one location: the Weddell Sea, east of the Antarctic Peninsula, where projected changes in ocean currents could accelerate ice sheet disintegration, making the surface water fresher and lighter.

In recent decades, a combination of warmer air, lighter sea ice, and more ice shelf melting has made waters fresher and lighter in parts of the Antarctic coast, says Gregory Johnson, an oceanographer at the University of Washington, Seattle. From ship-based surveys in the Southern Ocean, Johnson and colleagues found that the volume of Antarctic bottom water has decreased by 10% per decade over the past 30 years. Bottom water circulates globally and mixes with warmer waters above, much like refrigerants cooling a fridge. Less bottom water, Johnson says, "could affect heat exchange and climate regulation on a global scale." Loosening that bridle on ocean temperatures could have catastrophic consequences for the global climate and for sea life, experts say.

In the meantime, there are fears that the Southern Ocean may be losing capacity to store carbon in its depths, which may spur global warming. It accounts for about 40% of the total global ocean uptake of atmospheric carbon dioxide. Stronger upwelling stirs up deep carbon-laden waters. "This can increase carbonate levels in the surface and lead to more outgassing and less uptake," says Corinne Le Quéré, a biogeochemist at the University of East Anglia in Norwich, U.K. Her team has found that the Southern Ocean has absorbed less carbon in the past 30 years despite rising industrial emissions.

All climate signals point to a grim outlook for the frozen continent. Models predict that the westerlies will grow stronger and drift southward; the central tropical Pacific will continue to warm; areas that are not warming now, such as the Weddell Sea and the Ross Sea, will become hot spots in less than a century if greenhouse emissions are not curbed; and ENSO cycles will grow more intense and flip more frequently. "The implications for Antarctica will be dire," Shevenell says. Consequences could include widespread ice sheet disintegration, ecosystem deterioration, and disruption of global ocean circulation.

The Antarctic Peninsula is already at the vanguard of climate change—and may be approaching the point of no return. "It might be a good place to develop a capability to predict when the Earth system is close to the tipping point," Ducklow says. "It's like the canary in a coal mine for what's coming for the rest of the planet."

–JANE QIU

Jane Qiu is a writer in Beijing. Her trip to the Palmer Station was supported by the Marine Biological Laboratory's Logan Science Journalism Fellowship.

Slip Sliding Away

Pine Island Glacier is part of the weak underbelly of the West Antarctic Ice Sheet. It and other glaciers that flow into the Amundsen Sea are at the foot of the fastest melting ice shelves on the continent. Pine Island Glacier is sliding into the ocean at a rate of 4 kilometers a year and contributes a whopping 4% to the recent global sea level rise of 3 millimeters a year.

To find out what's going on, in 2009 a team led by oceanographer Stanley Jacobs of Columbia University's Lamont-Doherty Earth Observatory in Palisades, New York, and glaciologist Adrian Jenkins of the British Antarctic Survey sent a submarine beneath the Pine Island Glacier Ice Shelf: the floating tongue of ice where land-bound glaciers meet the ocean. Compared with data gathered 15 years ago, their findings were alarming. They detected 50% more meltwater gushing from the cavity and a widening gap between the ice and an underwater ridge crest, probably due to sustained melting.

As a result, the current flowing into the ice cavity was 77% stronger in 2009 than it was in 1994. "What goes into the cavity is the warm deep water," Jacobs says. "You can trace it all the way to the edge of the continental shelf hundreds of kilometers in the north." The deep water is 3.5°C warmer than the freezing point at 1 kilometer below the ocean surface, where it encounters the ice. "It's very effective at melting ice from the shelf base at that depth," Jacobs says. As the shelf thins, the ice loses its grip on the sea floor and ice moves more rapidly into the sea.

Bombs away. A crack in Pine Island Glacier, imaged in late 2011, presages the calving of a 900-square-kilometer iceberg.

This increased basal melting has turned out to be a common mechanism of ice loss in coastal Antarctica. In a recent survey, glaciologist Hamish Pritchard of the British Antarctic Survey and his colleagues found that basal melting accounts for thinning at 20 out of 54 ice shelves. "The fastest thinning takes place on the coast of western Antarctica," Pritchard says. "It's invariably at places where deep warm water can access ice shelves through submarine trenches across the continental shelf."

Other regions also may not be safe from melting for long, says Hartmut Hellmer, an oceanographer at the Alfred Wegener Institute for Polar and Marine Research in Bremerhaven, Germany. His group's climate models found that water in the cavity underneath the Filchner-Ronne Ice Shelf in the Weddell Sea would be 2°C warmer by the end of the 21st century under a conservative estimate of carbon emissions and economic growth. Warmer cavity water would increase basal melting 20-fold, resulting in 1.6 trillion tons of ice loss a year. That would freshen waters at the ocean surface and allow deep warm water of the circumpolar current, which now largely stays away from the continental slope, to penetrate into the trough underneath Filchner-Ronne, an ice shelf the size of Spain that's fed by ice streams from both the West and East Antarctic ice sheets. That could conjure a nightmare scenario: "There would be serious implications for the stability of both ice sheets," Hellmer says.

–J.Q.

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