# How oceans and atmospheres move heat around on Earth and other planetary bodies

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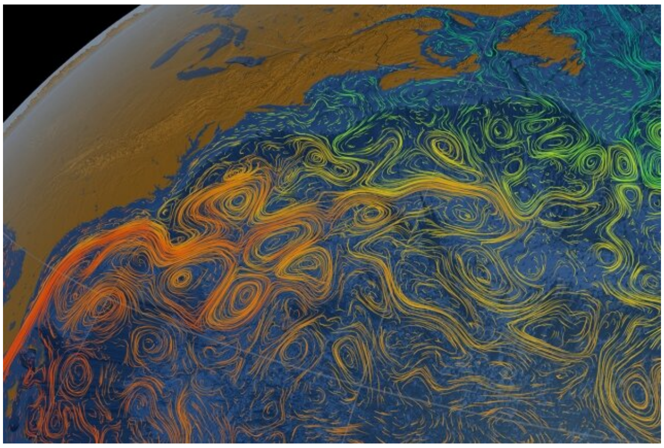

This visualization shows the Gulf Stream's sea surface currents and and temperatures. Credit: MIT/JPL project entitled Estimating the Circulation and Climate of the Ocean, Phase II (ECCO2)

Imagine a massive mug of cold, dense cream with hot coffee poured on top. Now place it on a rotating table. Over time, the fluids will slowly mix into each other, and heat from the coffee will eventually reach the bottom of the mug. But as most of us impatient coffee drinkers know, stirring the layers together is a more efficient way to distribute the heat and enjoy a beverage that's not scalding hot or ice cold. The key is the swirls, or vortices, that formed in the turbulent liquid.

"If you just waited to see whether molecular diffusion did it, it would take forever and you'll never get your coffee and milk together," says Raffaele Ferrari, Cecil and Ida Green Professor of Oceanography in MIT's Department of Earth, Atmospheric and Planetary Sciences (EAPS).

This analogy helps explain a new theory on the intricacies the climate system on Earth—and other rotating planets with atmospheres and/or oceans—outlined in a recent PNAS paper by Ferrari and Basile Gallet, an EAPS visiting researcher from Service de Physique de l'Etat Condensé, CEA Saclay, France.

It may seem intuitive that Earth's sun-baked equator is hot while the relatively sun-deprived poles are cold, with a gradient of temperatures in between. However, the actual span of that temperature gradient is relatively small compared to what it might otherwise be because of the way the Earth system physically transports heat around the globe to cooler regions, moderating the extremes.

Otherwise, "you would have unbearably hot temperatures at the equator and [the temperate latitudes] would be frozen," says Ferrari. "So, the fact that the planet is habitable, as we know it, has to do with heat transport from the equator to the poles."

Yet, despite the importance of global heat flux for maintaining the contemporary climate of Earth, the mechanisms that drive the process are not completely understood. That's where Ferrari and Gallet's recent work comes in: their research lays out a mathematical description of the physics underpinning the role that marine and atmospheric vortices play in redistributing that heat in the global system.

Ferrari and Gallet's work builds on that of another MIT professor, the late meteorologist Norman Phillips, who, in 1956, proposed a set of equations, the "Phillips model," to describe global heat transport. Phillips' model represents the atmopshere and ocean as two layers of different density on top of each other. While these equations capture the development of turbulence and predict the distribution of temperature on Earth with relative accuracy, they are still very complex and need to be solved with computers. The new theory from Ferrari and Gallet provides analytical solutions to the equations and quantitatively predicts local heat flux, energy powering the eddies, and large-scale flow characteristics. And their theoretical framework is scalable, meaning it works for eddies, which are smaller and denser in the ocean, as well as cyclones in the atmosphere that are larger.

## Setting the process in motion

The physics behind vortices in your coffee cup differ from those in nature. Fluid media like the atmosphere and ocean are characterized by variations in temperature and density. On a rotating planet, these variations accelerate strong currents, while friction—on the bottom of the ocean and atmosphere—slows them down. This tug of war results in instabilities of the flow of large-scale currents and produces irregular turbulent flows that we experience as ever-changing weather in the atmosphere.

Vortices—closed circular flows of air or water—are born of this instability. In the atmosphere, they're called cyclones and anticyclones (the weather patterns); in the ocean they're called eddies. In both cases, they are transient, ordered formations, emerging somewhat erratically and dissipating over time. As they spin out of the underlying turbulence, they, too, are hindered by friction, causing their eventual dissipation, which completes the transfer of heat from the equator (the top of the hot coffee) to the poles (the bottom of the cream).

## Zooming out to the bigger picture

While the Earth system is much more complex than two layers, analyzing heat transport in Phillips' simplified model helps scientists resolve the fundamental physics at play. Ferrari and Gallet found that the heat transport due to vortices, though directionally chaotic, ends up moving heat to the poles faster than a more smooth-flowing system would. According to Ferrari, "vortices do the dog work of moving heat, not disorganized motion (turbulence)."

It would be impossible to mathematically account for every single eddy feature that forms and disappears, so the researchers developed simplified calculations to determine the overall effects of vortex behavior, based on latitude (temperature gradient) and friction parameters. Additionally, they considered each vortex as a single particle in a gas fluid. When they incorporated their calculations into the existing models, the resulting simulations predicted Earth's actual temperature regimes fairly accurately, and revealed that both the formation and function of vortices in the climate system are much more sensitive to frictional drag than anticipated.

Ferrari emphasizes that all modeling endeavors require simplifications and aren't perfect representations of natural systems—as in this instance, with the atmosphere and oceans represented as simple two-layer systems, and the sphericity of the Earth is not accounted for. Even with these drawbacks, Gallet and Ferrari's theory has gotten the attention of other oceanographers.

"Since 1956, meteorologists and oceanographers have tried, and failed, to understand this Phillips model," says Bill Young, professor of physical oceanography at Scripps Institution of Oceanography, "The paper by Gallet and Ferrari is the first successful deductive prediction of how the heat flux in the Phillips model varies with temperature gradient."

Ferrari says that answering fundamental questions of how heat transport functions will allow scientists to more generally understand the Earth's climate system. For instance, in Earth's deep past, there were times when our planet was much warmer, when crocodiles swam in the arctic and palm trees stretched up into Canada, and also times when it was much colder and the mid-latitudes were covered in ice. "Clearly heat transfer can change across different climates, so you'd like to be able to predict it," he says. "It's been a theoretical question on the minds of people for a long time."

As the average global temperature has increased more than 1 degree Celsius in the past 100 years, and is on pace to far exceed that in the next century, the need to understand—and predict—Earth's climate system has become crucial as communities, governments, and industry adapt to the current changing environment.

"I find it extremely rewarding to apply the fundamentals of turbulent flows to such a timely issue," says Gallet, "In the long run, this physics-based approach will be key to reducing the uncertainty in climate modeling."

Following in the footsteps of meteorology giants like Norman Phillips, Jule Charney, and Peter Stone, who developed seminal climate theories at MIT, this work too adheres to an admonition from Albert Einstein: "Out of clutter, find simplicity."

**More information:** Basile Gallet et al. The vortex gas scaling regime of baroclinic turbulence, *Proceedings of the National Academy of Sciences* (2020). DOI: 10.1073/pnas.1916272117

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