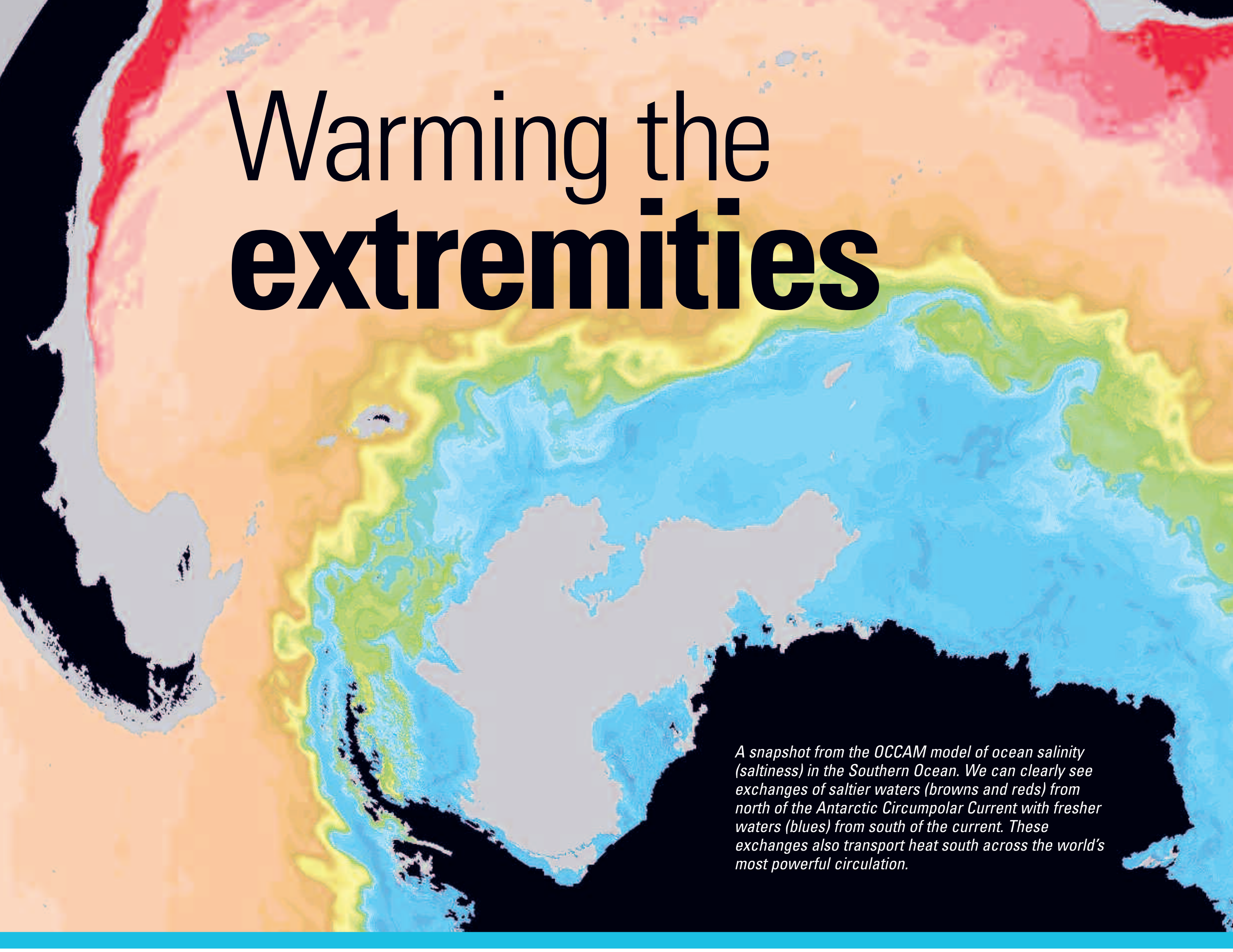
Warming the extremities



A snapshot from the OCCAM model of ocean salinity (saltiness) in the Southern Ocean. We can clearly see exchanges of saltier waters (browns and reds) from north of the Antarctic Circumpolar Current with fresher waters (blues) from south of the current. These exchanges also transport heat south across the world's most powerful circulation.

The scientific community has established the broad concepts of climate change in the public and political conscience. As our attention shifts towards reducing uncertainties, we need to better understand previously glossed-over details of the Earth system. All NERC disciplines have a part to play in this process, both collaboratively and within their own specialties. Here at the National Oceanography Centre, Southampton, we are looking at how we can use computer models to examine details of the ocean's role in the overall system.

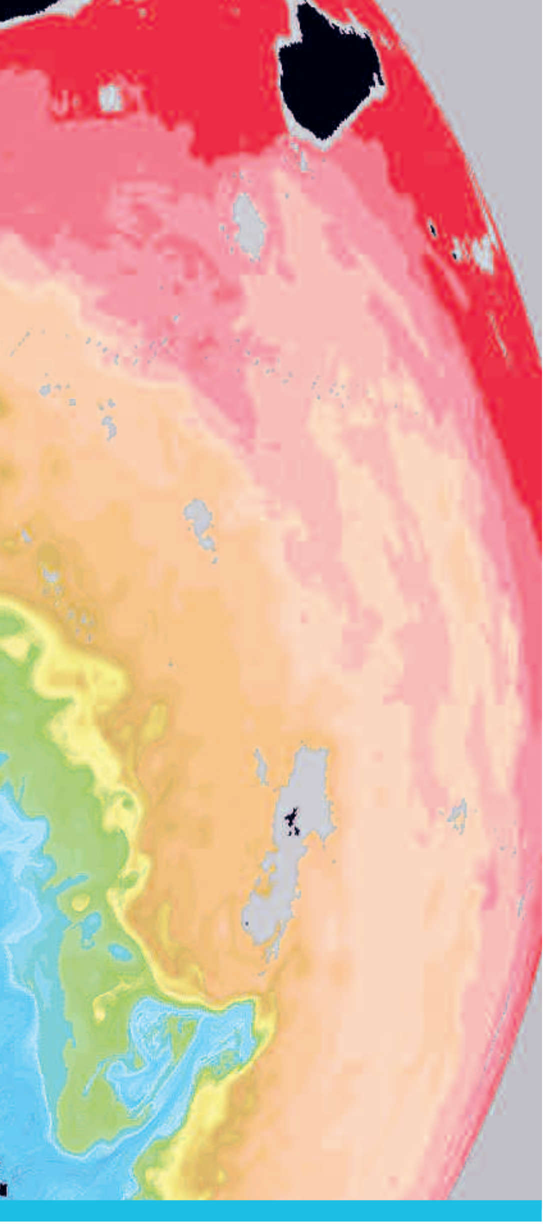
Proportionally, more heat from the sun reaches the planet at the equator than at the poles, but it is lost to space uniformly around the globe. Excess heat must move away from the equator towards the poles otherwise the equatorial regions would just get hotter and hotter. This process maintains the Earth in (hopefully) near thermal equilibrium.

The atmosphere and ocean transport roughly equal amounts of heat away from the equator by complex physical, chemical and biogeochemical processes. For example, solar heating drives large-scale atmospheric circulation patterns.

In the oceans the well-known western boundary currents move the majority of heat towards the poles. These flow north in the northern hemisphere, for example, the Gulf Stream off the coast of Florida and the Kuroshio Current off the coast of Japan, and south in the southern hemisphere. These currents, which are caused by the rotation of the planet, can only exist where there is land, a western boundary, to lean against, the eastern seaboard of the United States in our Gulf Stream example. In the Southern Ocean, between the southern tip of South America and the northern tip of the Antarctic Peninsula, no boundary exists at all from the sea surface down to a depth of two kilometres. The flow in the Southern Ocean is dominated by the Antarctic Circumpolar Current (ACC), the greatest of all ocean currents, which completely encircles Antarctica. Alternative processes must provide the poleward transport of heat in this region. If we want to reduce uncertainty in climate change predictions, we need to understand how the Earth warms its southern extremity.

It is no surprise that, historically, fully configured climate models have failed to explain these processes. The difficulty arises because the oceans are turbulent and full of motions with a wide range of time and space scales. While surface currents change minute by minute, a molecule of water can take thousands of years to complete one trip around the global thermohaline circulation – the giant current, driven by heat and salinity, that distributes heat from the equator around the globe. Scales range from the molecular to thousands of kilometres. How can we model such a complex system?

Scientists model turbulent flows using mathematical equations. We derive these equations by expressing the turbulent properties of the water in terms of average



The world's strongest current, the Antarctic Circumpolar Current, whips around the Southern Ocean. The laws of physics state that heat must cross it in order to reach Antarctica. But how? The devil is in the detail, say **Andrew Coward** and **Mei-Man Lee**.

values plus what turns out to be a very significant fluctuating component. In mathematical expressions where there is just one lone fluctuating component we can ignore it because, over time, all the fluctuating components average out to zero. However, some of the more complicated parts of the equations involve expressions where we multiply together the fluctuating components. These don't disappear during the averaging procedure. In fact they become such an important part of the system we can't ignore them, so we approximate (parameterise) them using experimental or observational evidence.

How does this help our calculations? Poleward transport of heat across this current is most likely carried out by fluctuating components. In the Southern Ocean the circumpolar current makes some north-south deviations but the west to east flow dominates. The important bit is the correlation between the north-south velocity fluctuations and the temperature fluctuations. We call this correlation the eddy heat transport. If we go back to chemistry experiments in school this movement resembles Brownian motion, where molecules randomly move, collide and rebound off each other. But imagine it on a vast scale with patches of ocean a few hundred kilometres across moving and colliding. The problem for oceanographers is that in practice climate models split the world down into a series of grid boxes well over a hundred kilometres across and between 20 and 500 metres deep. This captures most large-scale ocean processes but doesn't even partially resolve the eddy heat transport, a feat that requires at least a 10km spatial resolution. At the same time collecting observations to test our approximations is physically very difficult and prohibitively expensive too.

To see what this rather mathematical description means in practice, take a look at our model. It shows ocean salinity (saltiness) on a layer of constant density in the Southern Ocean (the depth of this layer varies from around 200m below the surface near Antarctica to around 1000m at the northern extent). We can see an exchange of saltier waters from north of the circumpolar current (browns and reds) with fresher waters from south of the current (blues) by a series of small meanders and pinched-off water parcels. An animation of such images would reveal a great deal of activity. Small features are constantly forming and dissipating within the eddy-rich environment of the large current. Those same features that transport salt and freshwater are, of course, also transporting heat across the circumpolar current.

Since the late 1980s, NERC has funded high-resolution ocean models. The current model, OCCAM (Ocean Circulation and Advanced Climate Modelling), has a spatial resolution of approximately 10km and 66 vertical levels. We routinely put this global ocean model through its paces using 512 computer processors at a time, whilst applying atmospheric conditions to the surface of the ocean, which vary every six hours. The post-processing of the vast amounts of model calculations is almost a Grand Challenge problem itself but for the first time we can see how and where the poleward transport of heat occurs in the Southern Ocean.

By careful analysis we can work out not only where and how but also precisely how much heat crosses the circumpolar current. By calculating how much heat flows through each of the 2.5 million grid cells that our model splits the Southern Ocean into, we have shown that at some latitudes the eddy transport is the major component of the total heat transport. Furthermore, this heat flow in quite considerable; individual grid cells can have as much as 100 GigaWatts of heat passing through them. To put that into context, the wintertime peak demand for electricity in the UK is of the order of 50GW. Climate models will need to approximate this transport better, a goal which remains elusive, or we need to build models that can resolve the processes. Based on such evidence we can expect the next generation of climate models to have much higher resolutions and to place ever greater demands on NERC's high performance computing. ❖

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