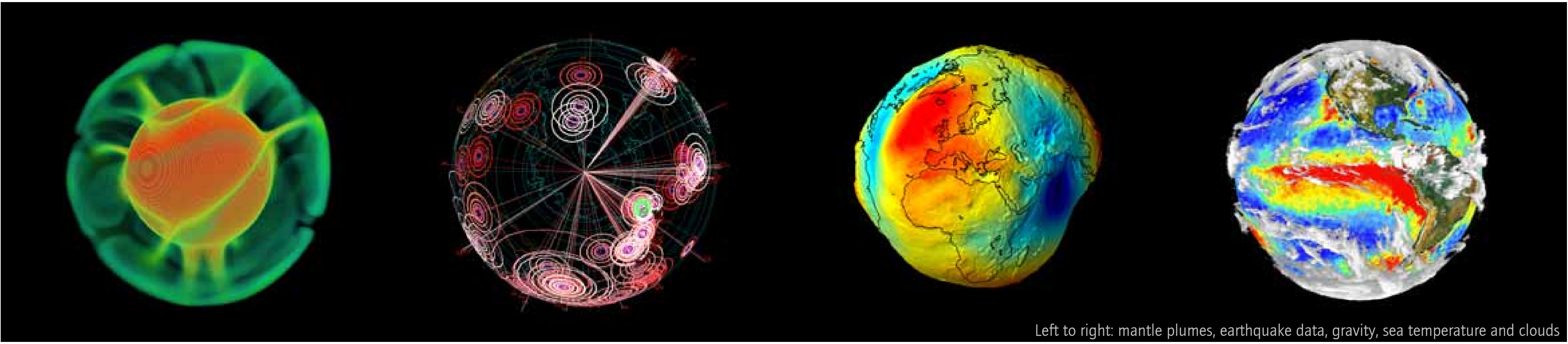
SCIENCEphotoLIBRARY

Virtual Earth

These images show an Earth we could never see in reality. Some show the planet emptied of water, others the invisible strands that make up the magnetosphere. Some show the Earth's past; others its future. Some are so abstract they could be modern art. Others are so realistic they could be mistaken for images of Earth taken from space. Their subject matter ranges from climate patterns to the movement of giant slabs of the planet's mantle. Yet all these images have one thing in common: all of them are made from real Earth data, manipulated by supercomputers and powerful graphics machines into simulations of the processes that shape our planet.



Left to right: mantle plumes, earthquake data, gravity, sea temperature and clouds

Though the people who make them use the same software and graphics machines as Hollywood animators, they are scientific simulations, accurate and informative. Welcome to Virtual Earth, the planet inside a computer.

Too Much Data

The past twenty years have seen a remarkable revolution in the Earth sciences. An unprecedented amount of information has been gathered about the Earth's natural processes, from tectonic forces inside the planet to the magnetosphere.

In fact, there's so much Earth systems data it overwhelms scientists. The US NOAA's recent CLASS project already houses 8.3 million archived files totalling 98 terabytes of global weather observations dating back to the 1890s. And, by 2010, CLASS will be collecting an estimated 5.1 petabytes (1 petabyte = 1,000 terabytes) of data from satellites and other sensors every year.

And the European Space Agency, ESA, estimates that its Earth observation satellites send so many images from space to Earth every day that much of the data is stored in archives spread around Europe and never used.

Yet this data is invaluable in a world of climate change. The problem is, how to turn this tsunami of information into knowledge and insight. The answer is scientific visualisation, because it displays a mass of information in a way the human mind can quickly comprehend. Today's science relies heavily on supercomputers to sift through data and extract the relevant information from it, then powerful graphics workstations are used to generate images and movies:

"Visualisation transforms abstract data into readily-comprehensible images," says E. Wes Bethel, Staff Scientist and visualisation specialist at the Lawrence Berkeley National Laboratory.

"Many environmental systems move too slowly or are too complex to be comprehensible without the aid of visualisation tools," adds Chris Henze, technical lead for the visualisation group at NASA's Advanced Supercomputing Division (NAS) at the Ames Research Center. "Scientific visualisation of simulation data allows one to zoom around at will and run backwards and forwards in time."

One of the first examples of 3-D data visualisation in the Earth sciences is called 'Synthetic Earth'. This is the Earth from space, but with a difference. It's not the real

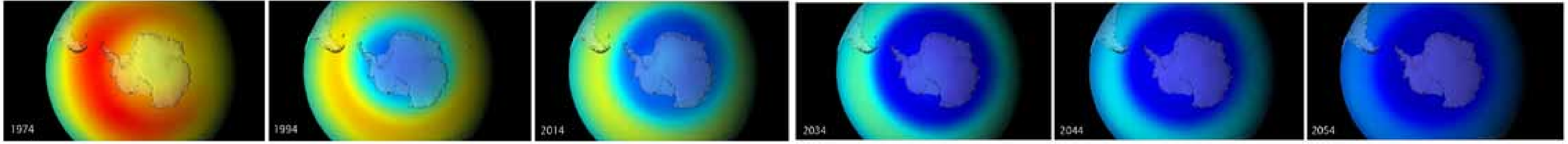
Earth, but neither is it an artist's impression. In fact, it's a simulated Earth - the kind of image we're more used to seeing in special-effects films.

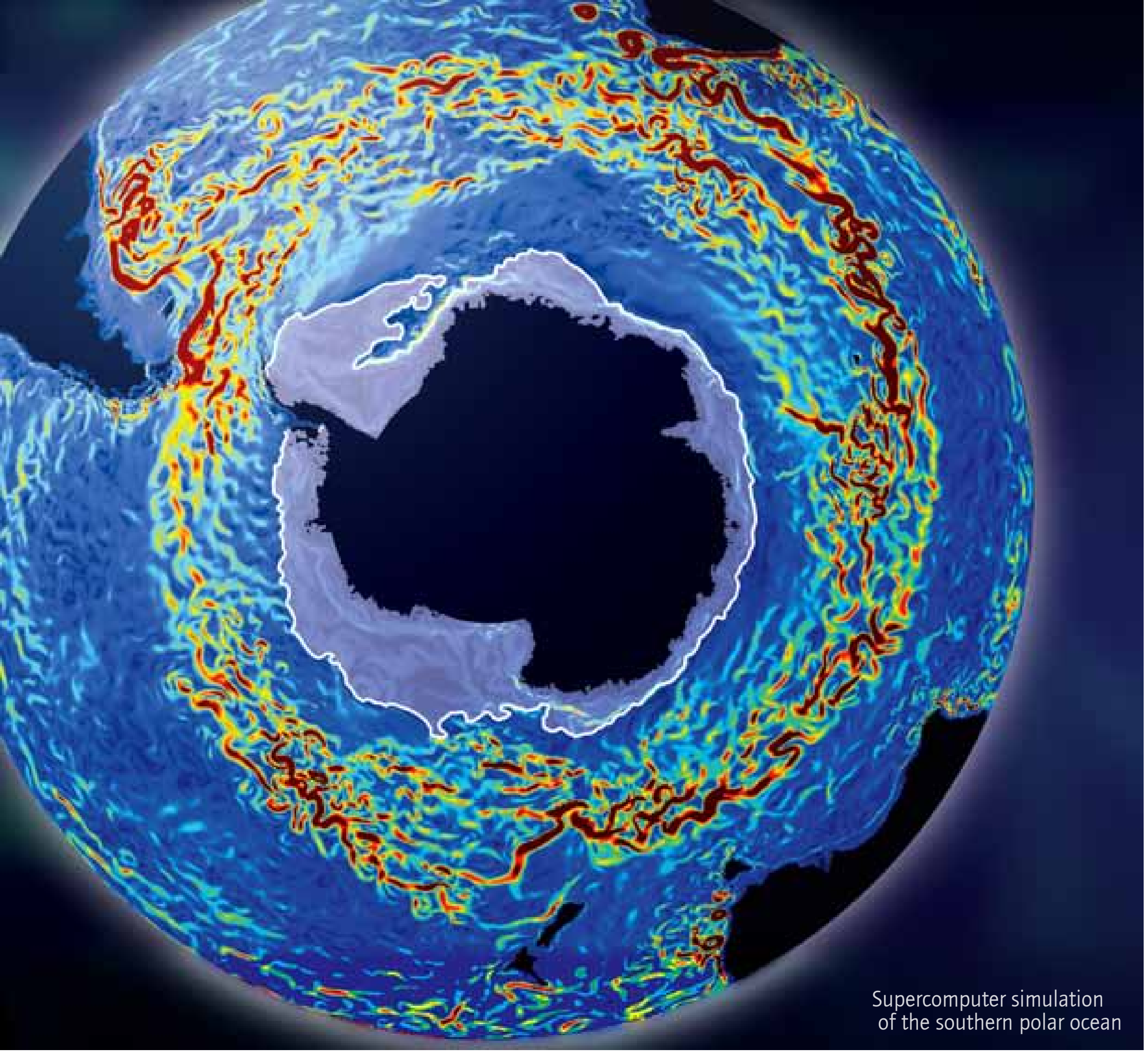
Designed by Professor R. B. Husar of Washington University in the late 1990s, Synthetic Earth was produced for NASA's Earth observation programme, in which satellites measure and map oceans, land and atmosphere. Husar created an electronic collage of Earth's clouds, oceans and land from real data supplied by several satellites and sensors, stitched together by computer.

Husar says his image symbolises the key scientific challenge of Earth observations: "How do the Earth's land, water, air and life interact to produce the environment in which we live?"

The decade since Synthetic Earth has seen the rise of a new breed of technician: the visualiser. Scientific visualisers

Below: ozone hole prediction from 1974 to 2054





Supercomputer simulation of the southern polar ocean

work with scientists to turn years worth of data from instruments all over the world into an image or sequence that can be viewed in a matter of minutes, says Chris Henze. Most large research organisations like NASA, NOAA and the ESA have their own visualisation studios, and they often use the same rendering and animation software as their Hollywood counterparts like Pixar. But instead of creating toys that act and speak like humans, they are translating sensor data into 3-D stills and animations of hurricanes or complex geological formations.

Deep Earth Imaging

Shuo Wang of the University of Minnesota has customised a powerful software package designed for visualising biomedical data. Instead of looking inside the human body, he's looking deep inside the Earth.

Called AMIRA, the application can handle very large datasets and runs on the latest graphics cards. By inputting temperature and other variables into AMIRA, Wang has created high-resolution 3-D spherical models of mantle convection, showing how hot magma plumes rise towards the surface, then fan out before sinking as cooler rock:

"Numerical simulations of 3-D spherical mantle convection are playing an important role in understanding the dynamics of plate tectonics and the evolution of the Earth's mantle," he says.

While most researchers are interested in the rising mantle plumes, Wang is looking at the so-called 'downdwellings' which, he says, have been neglected even though they're just as important as the hot 'upwellings':

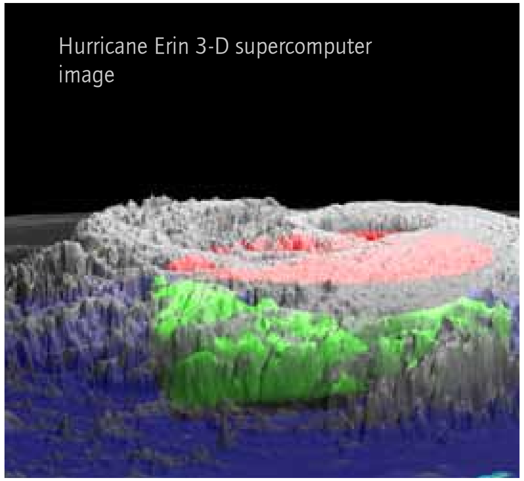
"The goal of our research is to find an efficient way to deal with the tough problem of visualising downdwellings in high-resolution 3-D," he says. "We've observed interesting features, including small, short-lived downdwellings that resemble stalactites."

If Shuo Wang is using software originally designed for biomedical applications to produce 3-D visualisations of the interior of the Earth, other geoscience researchers are adapting medical scanning technologies.

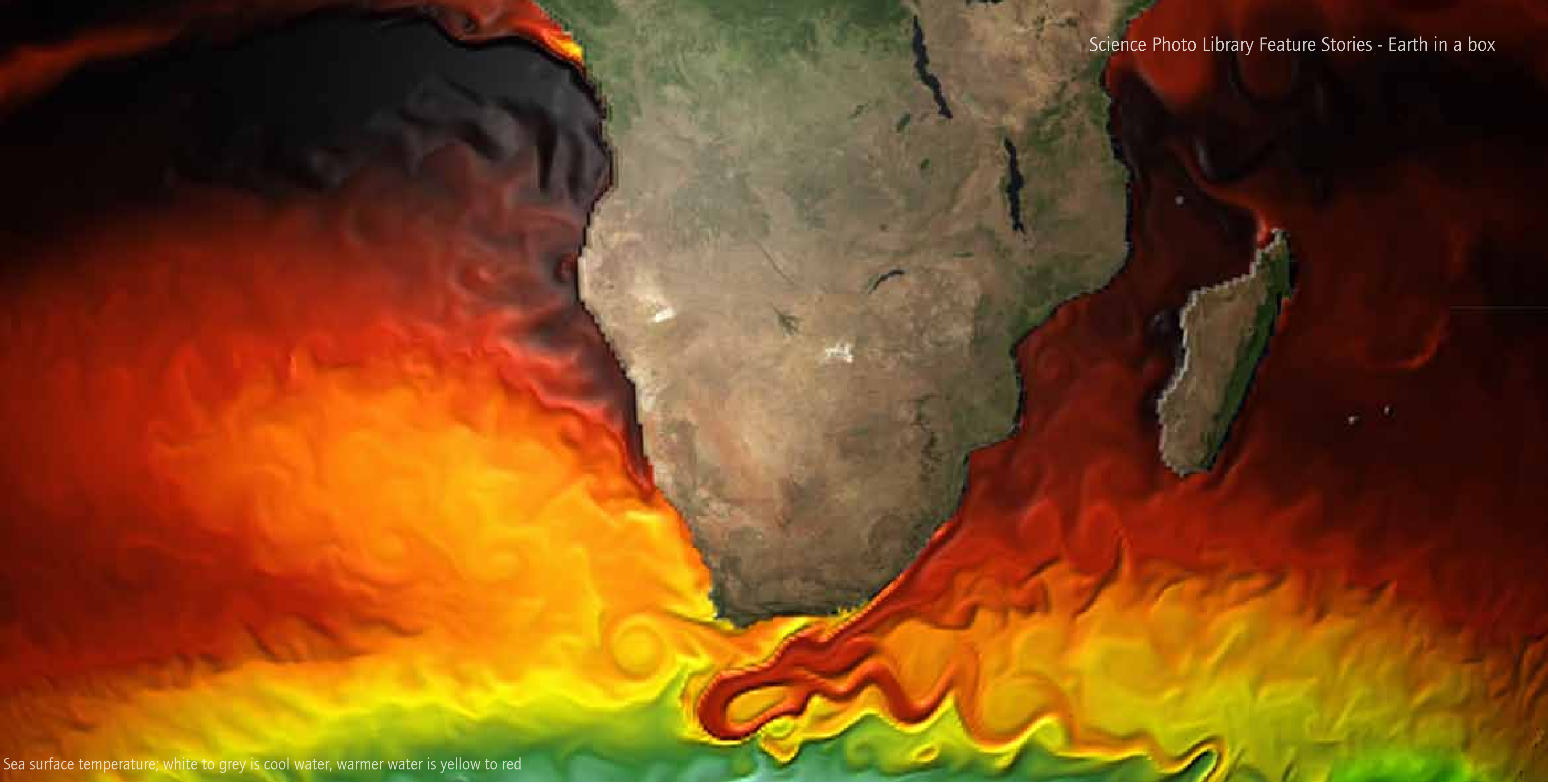
Karin Sigloch of the Department of Geosciences, Princeton University, has used a technique analogous to medical brain imaging to produce a 3-D computer model of a seismically-active slab of the Earth's mantle known as the 'Farallon Plate'. This vast rock lies beneath the western United States, and caused the mountain-building and volcanism that led to the spectacular landscapes of the West.

Sigloch has pioneered a technique called 'global seismic tomography' – also known as 'seismic imaging' - which is the science of making 3-D maps of the Earth's deep interior. The technique is similar to Computed Tomography (CT), where the brain, for example, is bombarded with X-rays from all angles. The results are fed into a computer, which constructs a 3-D brain image. Instead of X-rays, seismic imaging relies on an unusual source of data: so-called 'body waves' produced by major earthquakes:

"Only large earthquakes generate waves powerful enough to travel through the entire body of the Earth," says Sigloch.



Hurricane Erin 3-D supercomputer image



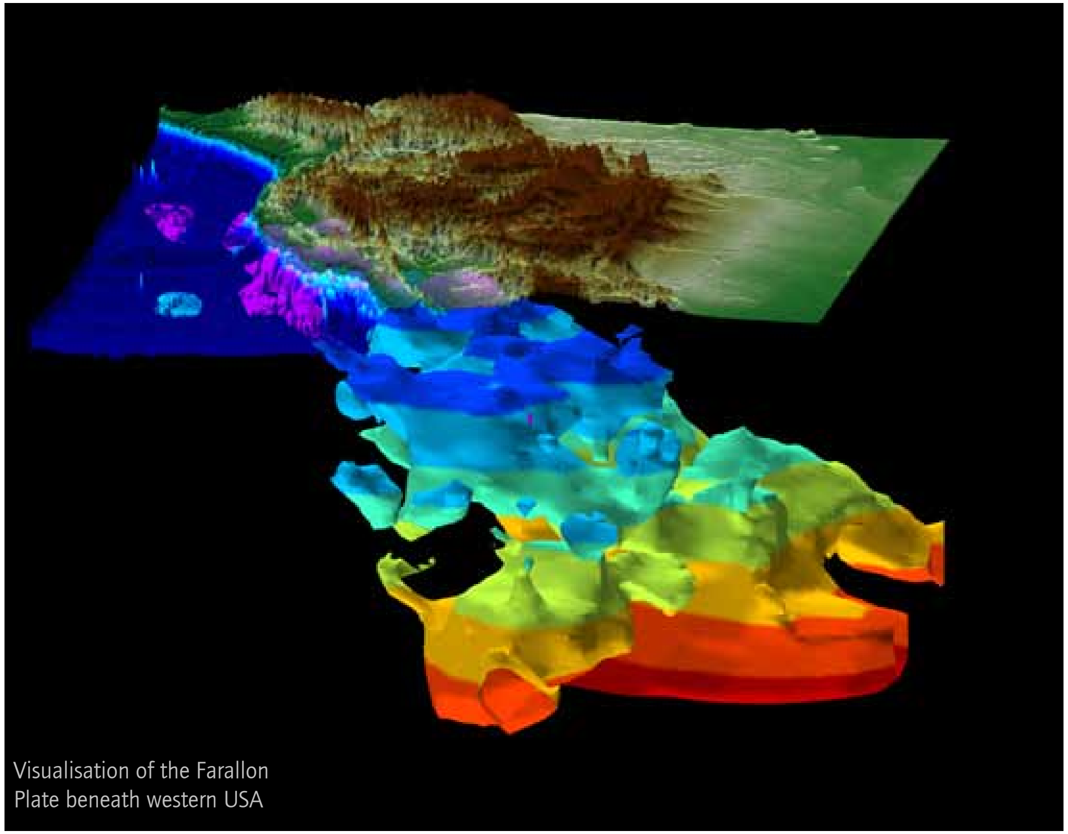
Sea surface temperature; white to grey is cool water, warmer water is yellow to red

Body waves can be used to map the Earth's interior because they travel at different rates depending on the temperature of the material they pass through. Sigloch collected body wave data from over 600 earthquakes recorded by a network of seismic stations across the western US. Since this involved hundreds of thousands of measurements, the process had to be automated before she could generate an accurate 3-D model of the Farallon Plate. But the effort was worth it, says Sigloch, because the model has already shown that the Plate is far more complicated than was previously thought. So she's now building a dataset that will allow her to build 3-D models of the entire globe: "Understanding the Earth's 'convection machine' is of fundamental interest, since it shapes the face of our planet," she says. "And seismic imaging is the most direct approach to the problem."

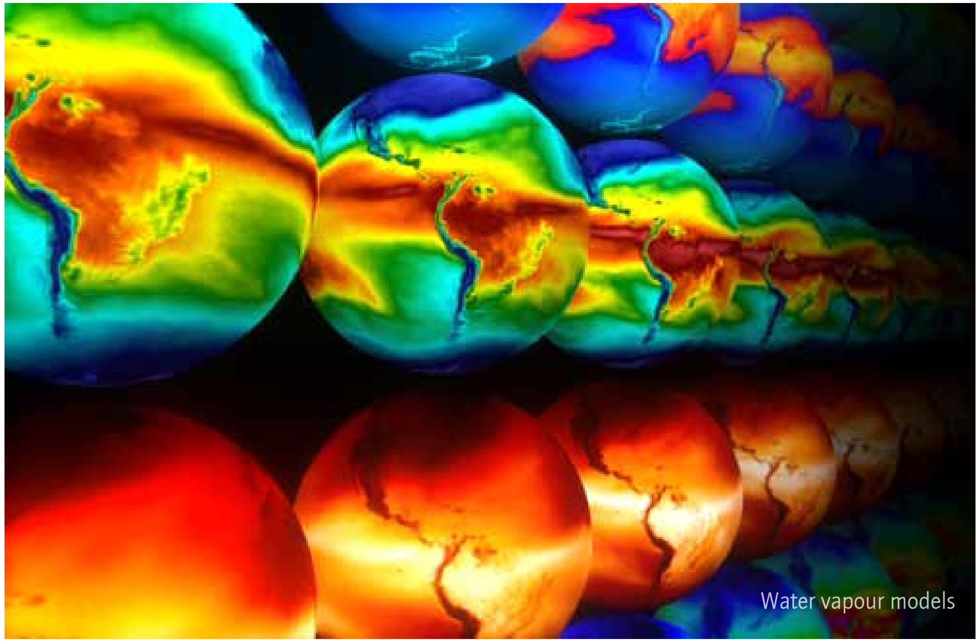
Monster Models

The real monsters of Earth visualisation are the global models. These are mathematical representations of the key processes that shape Earth's climate: the atmosphere, land surfaces, oceans and ice cover. They are amongst the largest software programmes ever written, and even with today's supercomputers, they take months to run. Global models divide Earth into a grid of thousands of cells, analogous to the pixels on a computer screen.

Unlike a pixel, however, a cell may be 3-D, with levels that rise from the surface of the Earth to the stratosphere.



Visualisation of the Farallon Plate beneath western USA



Water vapour models

This produces thousands, if not millions, of individual ‘grid boxes’. Each box has a set of data points – for an atmospheric model, for example, measurements of air temperature, pressure, wind speed and humidity. These are fed into equations derived from the laws of physics, and run through a supercomputer for a specified period of model time, which could be a day, a year, or a decade. Some of them can be run backwards into the past, or forwards into the future:

“Climate models are the best way of capturing our understanding of the physical climate system,” says Thomas Delworth, research scientist at NOAA’s Geophysical Fluid Dynamics Laboratory (GFDL), who works on simulations of sea surface temperatures using GFDL’s CM2.4 climate model.

“In other fields, like chemistry and biology, you can do repeated experiments in the laboratory, but, of course, we only have one planet Earth. We’re essentially putting planet Earth into a computer, and we can run many experiments on these virtual Earths. That allows us to better understand both how the climate system works, and how it might change in the future.”

Twenty years ago, an average climate model grid would be about 500 km on a side. They worked, but were regarded as crude, like an old-fashioned black and white television. Today’s’ models are more like HDTV.

NCAR’s Community Climate Model CAM3 has four times the resolution of most climate models – similar to the weather prediction models on TV. At this resolution, CAM3 becomes so detailed both in space and time it can generate objects as small and fast-moving as typhoons.

Ocean world

The importance of the oceans to planet Earth – the only water world we know of – is enormous. They are, in effect, the thermostats that keep global temperatures within the boundaries necessary for life. Yet, until the past few decades, very little was known about ocean circulation:

“We don’t really know what our oceans are doing,” says Matthew Mazloff, a researcher at the Scripps Institution of Oceanography. “Unlike the atmosphere, which has been systematically studied for hundreds of years, the oceans have only been studied for a few years.”

That changed during the 1980s, when concerns about climate change led to the largest systematic study of the world’s oceans ever undertaken. The result was a flood of data - so much, in fact, that researchers were overwhelmed by it. The only way of making sense of so much data from so many diverse sensors was to put it into computer models and visualise it.

One of the largest of all ocean models

is called ECCO (Estimating the Circulation and Climate of the Ocean): a working high-resolution ocean model that can show the entire ocean at any given time, whether it's in the past or the future. Eventually, ECCO will simulate all of the world's oceans in a computer. The model's resolution is so high that it can actually show individual currents and eddies in the ocean. Yet ECCO only became feasible in the last two years, when computing power caught up with the model's size and complexity:

"The ocean estimation and prediction problem is possibly the most computationally intensive problem in science," says Mazloff.

Mazloff has his own ocean model, called SOSE, or Southern Ocean State Estimate. The Southern Ocean is a huge expanse of water, 13 times the size of the United States, which encircles Antarctica. Because it stores and moves huge amounts of water around the planet, it plays a critical role in regulating Earth's climate. Yet, due to its remoteness, very little is known about it.

SOSE is essentially a high-resolution section of ECCO, like a blown-up part of a photograph. Where ECCO has a resolution – the size of its grids - of about 100 km, SOSE's is just 16km.

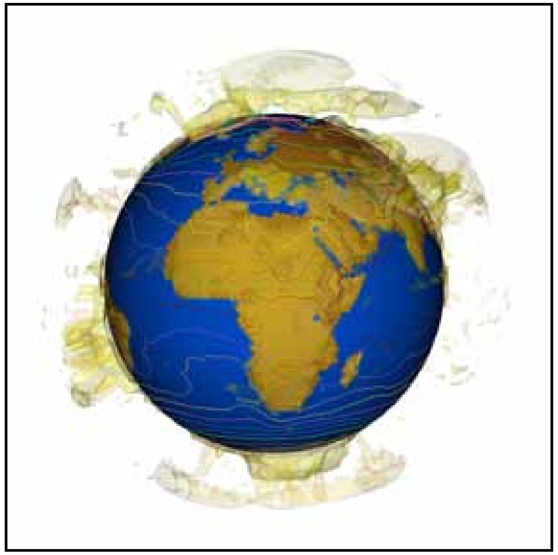
To make SOSE work, Mazloff had to put billions of ocean observations into trillions of equations that follow the laws of physics and fluid dynamics. To do this, he needed the fastest supercomputer he could find.

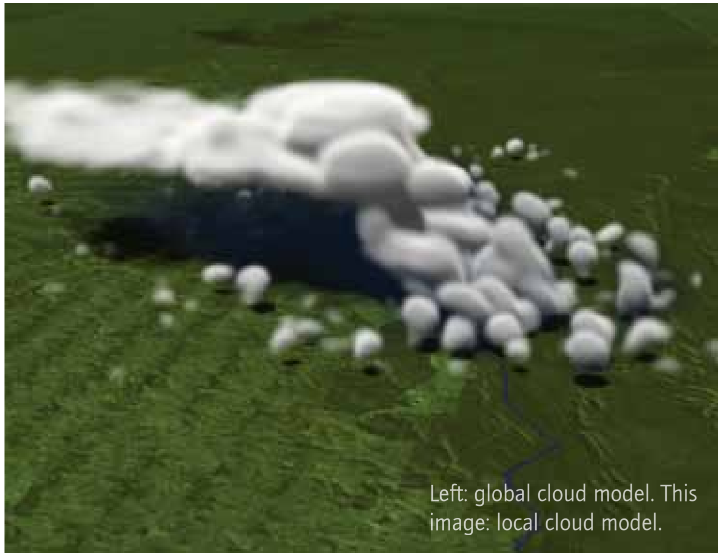
We are now entering the era of 'petascale computing', where speed and storage are measured in numbers so vast they are beyond comprehension. Petascale computers are capable of processing a petaflop of data with storage systems that can hold over a petabyte of data. One petaflop is a quadrillion floating-point operations every second; one petabyte is a quadrillion bytes of data. Such numbers are mind-numbing: basically, petascale computers are the fastest and most expensive on the planet; there are only a handful of them; and their development has partly been driven by the needs of Earth simulations.

To run SOSE, Mazloff needed nearly 5 million computing hours on two petascale computers, one of which, Ranger, is currently the world's 8th fastest. The result is a simulation of how the Southern Ocean is behaving at any given moment:

"A main feature of the Southern Ocean is the Antarctic circumpolar current, which is probably the biggest system of currents on Earth," says Mazloff. "But these currents are small by global scales, so you couldn't resolve them with the

Visualisation of the Net Ecosystem Exchange (NEE), green shows strong photosynthetic activity, red shows more CO2 output through respiration





Left: global cloud model. This image: local cloud model.

Background image: Gulf stream - ocean temperature

global models. If you want to see what the Southern Ocean is doing daily, you need to resolve these fast narrow streams of current with a high-resolution model."

Cloud Modelling

One of the biggest problems in simulating climate is clouds. How, exactly, do they form? What determines the number of clouds in a given area? How does wind affect them? David Randall, an atmospheric scientist at Colorado State University, hopes to answer these questions with a Global Cloud Resolving Model (GCRM) that will use supercomputers to simulate Earth's atmosphere in ten-second 'snapshots'. Randall's GCRM will have unprecedented resolution: a grid size of 4 km rather than the 100 km of most atmospheric models.

Like the ocean models, the sheer numbers involved in Randall's model are staggering. The GCRM will have 100 million cells, each of which is a column of 128 separate layers reaching from the surface of the Earth to the stratosphere. That's 128 billion (S: will you check this? Ta) individual measurements of wind, temperature and humidity put into equations and processed to give a simulated atmosphere every ten seconds:

"No-one has done this before," says Randall. "The GCRM will be able to simulate individual clouds' growth and death."

Needless to say, Randall's model requires a petascale computer to run it. In fact, the simulation runs on the second fastest computer in the world - Jaguar, an 80,000-processor Cray XT at Oak Ridge National Laboratory, Tennessee, which has been clocked at 1.3 petaflops. Yet even Jaguar struggles with the GCRM: it takes 24 hours of continuous processing to generate several petabytes of output data that represent a couple of model days.

Randall's model will be able to simulate large thunderstorms, cumulus and cirrus clouds. The latter are important, says Randall, because "cirrus clouds block Earth's infrared radiation from flowing out to space, and that tends to warm the climate. If we have more cirrus in the future, that will enhance warming. If we have less, it will reduce warming."

At present, computers like Jaguar are too slow to run the GCRM for more than a few weeks. Ideally, Randall would like to simulate an entire year – the basic unit of global climate. But, eventually, petascale computers will become more powerful, and forecasters will be able to run the GCRM far into the future.

Prediction Machines

Simulations and scientific visualisation are probably the best tools scientists have for understanding how the planet's systems work. But their value exceeds scientific discovery. They have practical benefits, too. Simulations of tectonic processes, for example, may help in understanding how earthquakes are created. Probably the greatest benefits will come from the climate models' ability to forecast possible futures for the planet.

Paul Newman, an atmospheric physicist at GSFC, used a model that simulated all the ingredients for ozone depletion to forecast a future in which the Montreal Protocol of 1989 was never implemented. Instead of phasing out ozone-destroying compounds like CFCs, their production continued - to devastating effect. The model results show that, by 2054, sixty percent of atmospheric ozone has been destroyed, not just over the poles, but everywhere.

Ultraviolet radiation falling on mid-latitude cities like London, Paris, Berlin and Rome is so intense it causes sunburn in less than ten minutes. Skin cancer rates in Europe rocket. And it's not just humans who suffer. Plants and animals are also affected by DNA mutations caused by solar UV.

Newman's model results were turned into a visualisation called 'World Avoided' by NASA Goddard's Scientific Visualization Studio. It's a stark series of images that show the globe gradually turning blue and violet – the colours of near-zero ozone. The series is easy to follow – the eye naturally processes colour and time information. But if it weren't for the visualisers, Newman's model would have been a simple graph or chart with nothing of the impact of World Avoided.

Newman points out that through global political willpower, the Montreal Protocol was signed and ozone depletion is levelling out. He sees this as an encouraging example of international co-operation that could also be applied to CO2 levels and climate change:

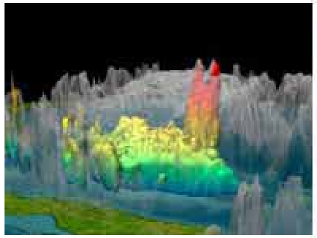
"We simulated a world avoided," says Newman, "and it's a world we should be glad we avoided."

Over the next decade, the climate models now being tested on petascale computers will become more refined, faster and reliable. They will be able to run into the future, answering many 'what if?' scenarios. With climate change a reality, the beautiful but scary visuals that come out of the models may help create more Montreal Protocols. The virtual Earths may help save the real Earth.

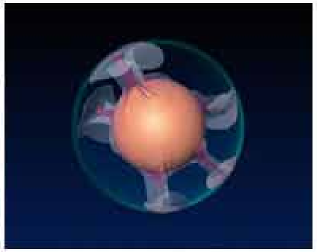
ENDS 2950 WDS © SCIENCE PHOTO LIBRARY 2009
WRITTEN BY JON TRUX

FULL PICTURE SET

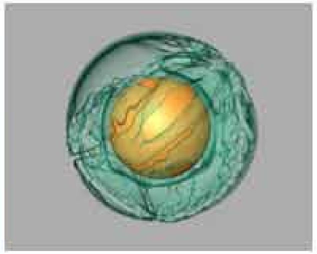
For captions and credits, please refer to the captions.txt file



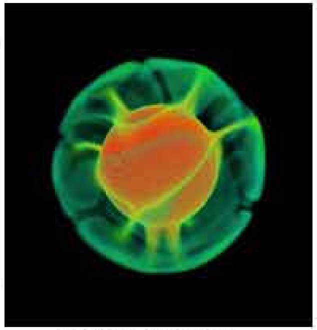
e1550207.jpg



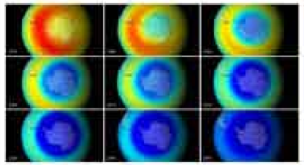
C0029125.jpg



C0029131.jpg



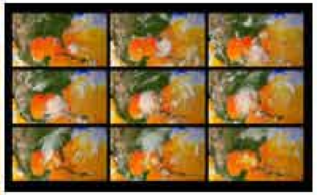
C0029135.jpg



C0029156.jpg

C0029168.jpg

C0029190.jpg

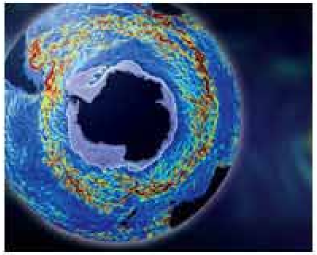


C0029191.jpg

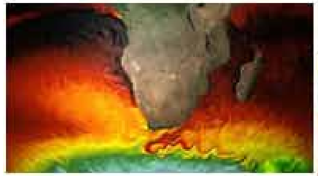
C0029201.jpg

C0029238.jpg

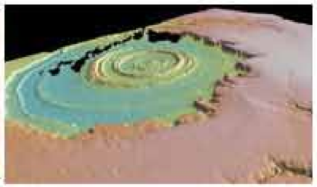
C0029239.jpg



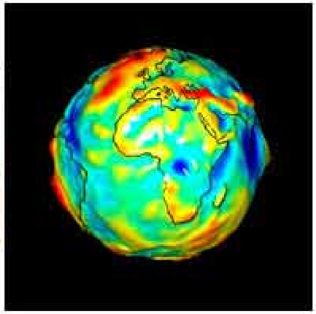
C0029240.jpg



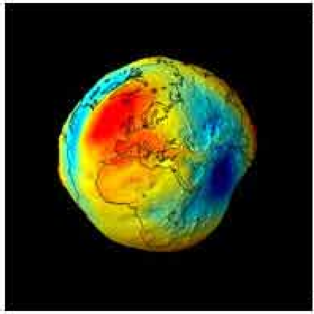
C0029243.jpg



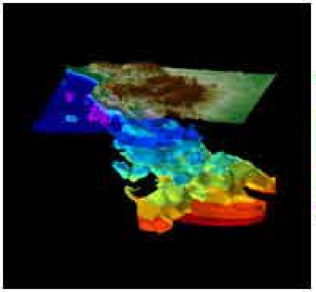
C0029246.jpg



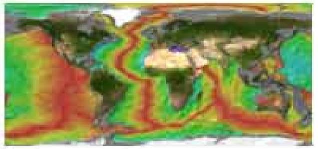
C0029415.jpg



C0029418.jpg

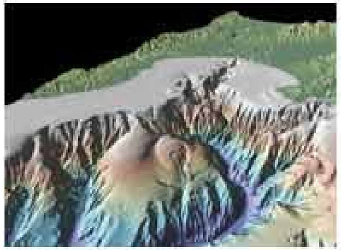


C0029421.jpg



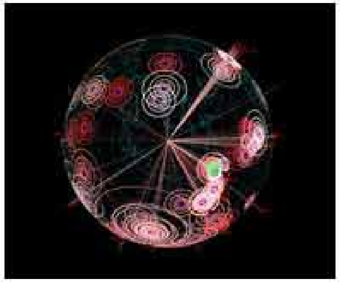
C0029425.jpg

For further information, please contact: seymour@sciencephoto.com

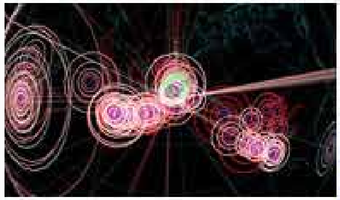


C0029430.jpg

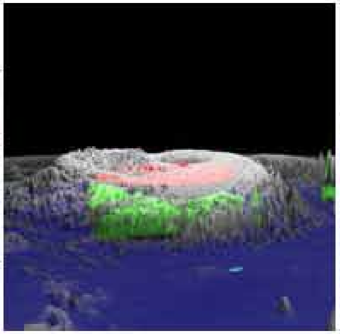
C0029468.jpg



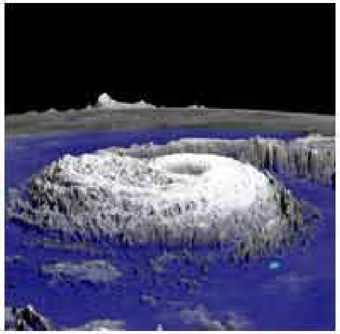
C0029472.jpg



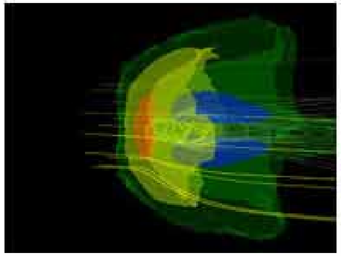
C0029473.jpg



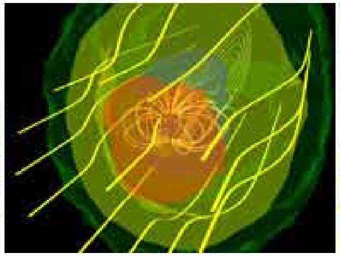
C0029476.jpg



C0029480.jpg

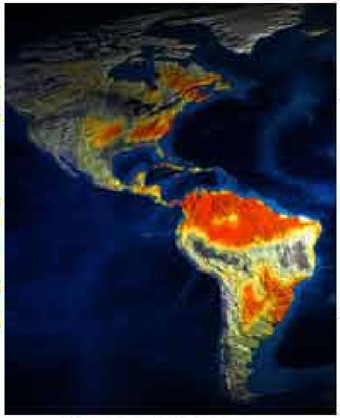


C0029482.jpg



C0029484.jpg

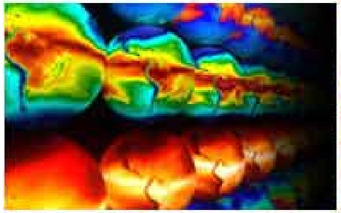
C0029485.jpg



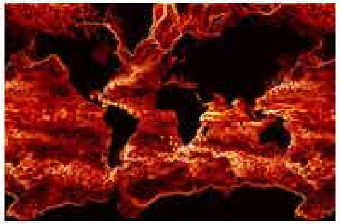
C0029496.jpg

C0029500.jpg

C0029501.jpg

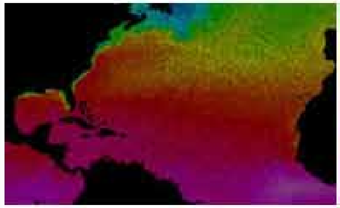


C0029503.jpg

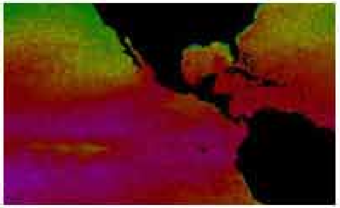


C0032149.jpg

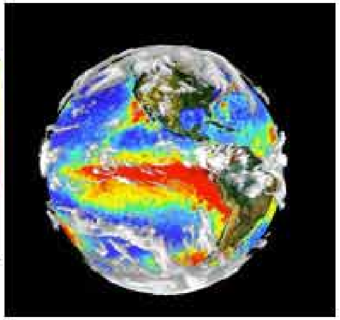
C0032151.jpg



C0032152.jpg



C0032154.jpg



e1100045.jpg