1997/98 El Niño observed by ERS

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The recent El Niño Southern Oscillation (ENSO) of 1997/1998 is one of the strongest of the century. This event is characterised by abnormally high sea level and sea surface temperatures along the west coast of South America, near the Equator.

With the Radar Altimeter (RA) and the Along-Track Scanning Radiometer (ATSR) on-board the second European Remote Sensing satellite (ERS-2), this event was monitored in great detail. Animations clearly show the development of the latest El Niño. Particularly, the sudden Kelvin wave at its onset is clearly recognised. It can also be seen that this El Niño actually hit the South American coast twice, once in July 1997 and then again in October; both are of great magnitude and initiated unusually early in the year.

Introduction

The 1997/1998 El Niño event was probably one of the most important ever observed. The whole planet has recorded abnormal events that might be related to El Niño effects. Some of them are the direct consequence of El Niño: droughts in Indonesia and northern Brazil, floods in Peru, fires in Indonesia [*Buongiorno et al.* 1997], destruction of a large part of the Brazilian Amazonian forest (equalling the size of The Netherlands), all provoking serious environmental damage. The economic impact has been major, ranging from perturbation in fishing and farming, to great natural disasters causing severe casualties.

El Niño is characterised by a sea-surface temperature increase and an abnormal sea-surface rise in height in the tropical area of the eastern Pacific.

ERS, thanks to its particular payload configuration, was able to provide useful information for monitoring the El Niño event. Indeed, the Radar Altimeter (RA) provides very high accuracy of the sea-surface height while the Along-Track Scanning Radiometer (ATSR) gives very precise measurements of the sea-surface temperature. The repetitive cycle of ERS allows a frequent global coverage of the Earth. ERS-2 was able to observe the premise of El Niño and to monitor the phenomena throughout the event. A description of the data used and the processing performed is detailed below.

Description of El Niño

The whole oceanographic and atmospheric system of ocean currents and winds are constantly redistributing the sun energy absorbed by the water and the atmosphere. In the equatorial zone of the Pacific, trade winds blow fairly constantly from east to west. These winds transport water and cause the sea level to slope upwards from east to west. In the west, water piles up and in the east, upwelling of water from deep cold layers occurs at the surface. The trade winds are maintained by the high-pressure region above South America, where cool and dry air converges, and by the Indonesian low-pressure region, where warm moist air rises, producing cumulo-nimbus clouds and heavy rainfall.

During the Northern Hemisphere winter (Southern Hemisphere summer), the pressure above South America drops and the pressure above Indonesia rises. As a result, trade winds become weaker and upwelling diminishes, such that less cold, fresh and nutritious water rises to the surface in the eastern part. The sea level becomes slightly higher and the ocean temperature increases. Due to this temperature increase, fish patterns alter. Fish start to migrate to cooler zones and fishing yields become significantly smaller. This annual appearance of warmer ocean surface water along the South American coast around Christmas is what Peruvian fishermen used to call *El Niño* (Christmas Child). This period of two to three months was used to repair boats, nets, etc.

However, sometimes this situation gets triggered into an extreme state. Trade winds are extremely weak and may even turn westerly in the western Pacific under the influence of the changing pressure distribution. The potential energy of water (which was piled up by these winds) in the west is released, exciting an eastward propagating Kelvin wave (equatorially trapped) and causing a drop in sea level on the western side of the ocean. At the eastern boundary, the equatorial Kelvin waves split into northward and southward travelling coastal Kelvin waves as well as being partially reflected as Rossby waves. This enhances the sea level and temperature increase on the eastern side of the Pacific, creating an even lower pressure region and thus decreasing the trade winds even further.

This phenomenon, nowadays called El Niño, can persist for a period of several months taking up to an entire year to return to 'normal' conditions.

The set of climatic anomalies referred to as ENSO is the most energetic and best-defined pattern of inter-annual variability. El Niño is the oceanographic component of the climatic fluctuation. The most obvious sign of an El Niño event is the appearance of a massive pool of unusually warm water off the coast of Peru and Ecuador, which builds up within a period of a few months. The warm water pool can be compared to an iceberg: most of it is submerged, but a part of it protrudes above the sea surface as the wedge floats in the surrounding ocean.

Importance of Earth-observation data

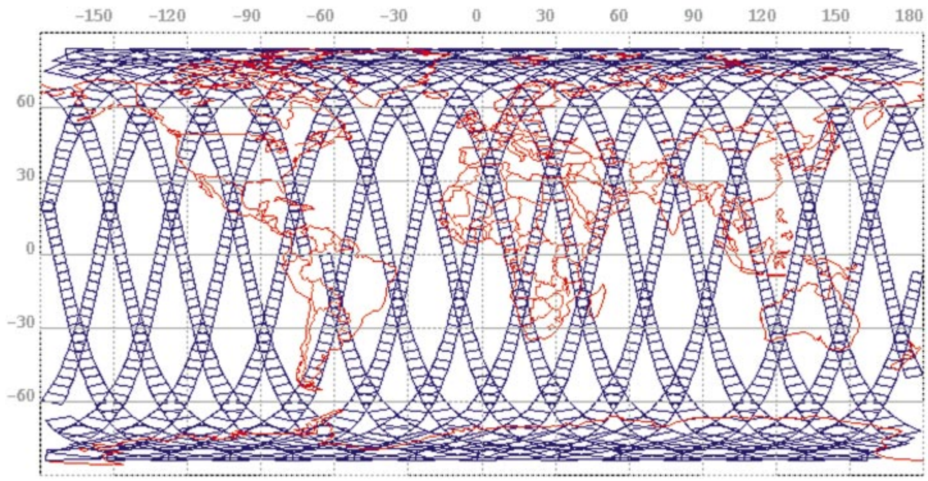
The most severe El Niño episode in recent history occurred during 1982-83. The event came as a total surprise and caused enormous devastation: $ 2.4 billion due to flooding, 280 million due to hurricanes and 5.4 billion due to fires and droughts, totalling over 8 billion (NOAA, El Niño theme page).

Following the 1982-83 disasters, scientists and governments set up extensive observation projects. The observations of the atmosphere and the ocean permit the monitoring of such an event, and the data can be assimilated into climatological models. The models are based on physical laws, but the input of measurements can avoid models from deviating too much from the actual state of the ocean.

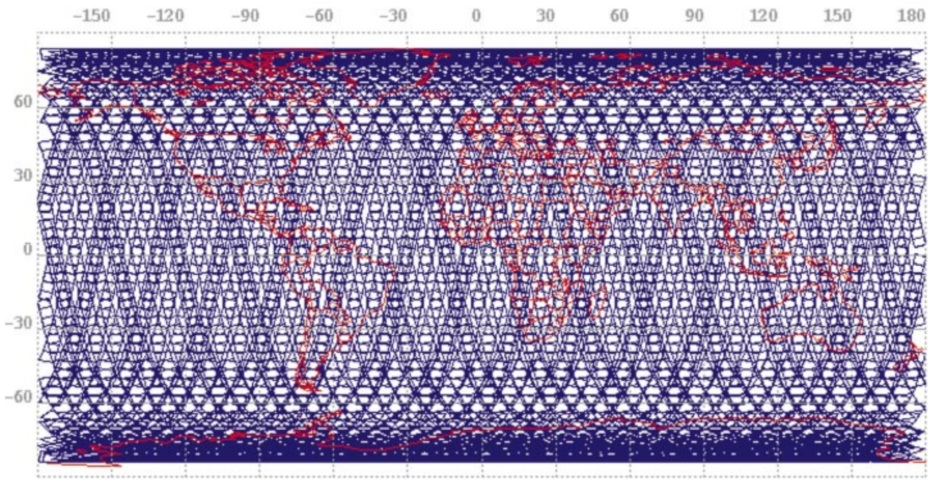
El Niño does not appear regularly, but some researchers claim that the frequency might be increasing due to the CO_2 gasses in the atmosphere. This year's El Niño was different for two reasons:

- scientists forecasted it as one of the worst;
- for the first time, the event was predicted six months in advance.

Although some damage has been limited to certain areas thanks to the early-warning predictions (some governments stocked up on cereals or rice, others advised farmers on their plantations and crops, efficient evacuation methods were put into place, and roads and bridges were reinforced, etc.), this year's El Niño left scars.



①**a** *ATSR spatial averaged sea-surface temperature coverage for 1 day.*



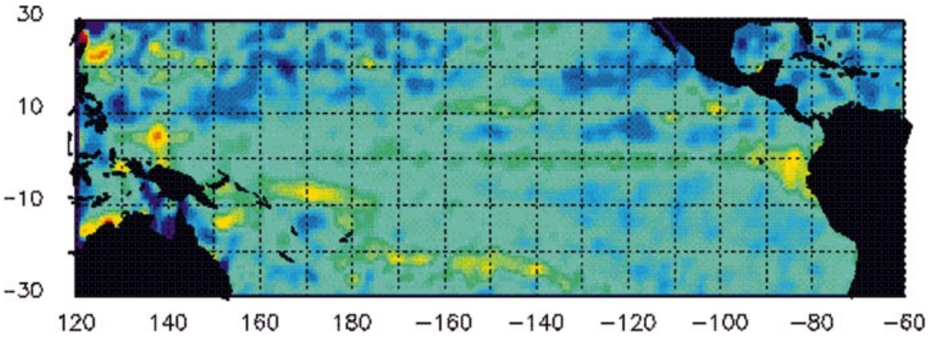
①**b** *ATSR spatial averaged sea-surface temperature coverage for 4 consecutive days.*

In order to monitor an El Niño event, four parameters are very important: wind, ocean temperature, sea-level height and atmospheric pressure at sea level. The Radar Altimeter (RA) onboard ERS-1 and ERS-2 provides sea-surface height (SSH) and the ATSR provides sea-surface temperature (SST).

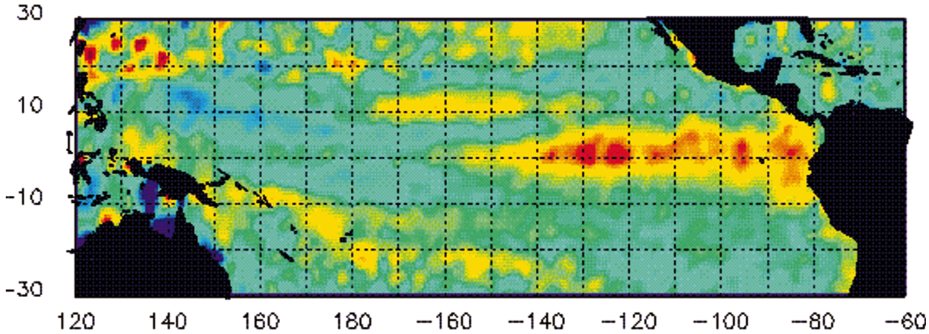
RA instrument characteristics

The ERS-2 RA is a Ku-band (13.8 GHz) nadir-pointing active microwave sensor designed to measure the time-return echoes from ocean, ice and land surfaces [*ESA Bulletin 65,* 1991]. These measurements are repeated 1000 times per second and are averaged for noise-reduction purposes to provide one measurement every 7 km along the track.

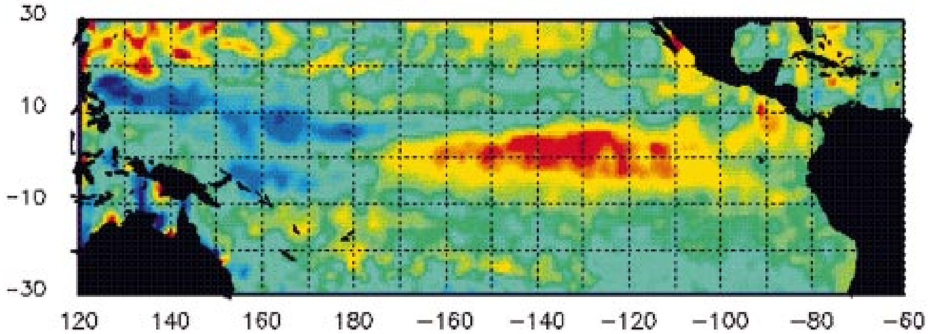
Satellite altimeters consist of a transmitter that sends out short chirped pulses, a receiver to record the pulses after they are reflected by the surface below (e.g. the ocean surface) and an ultra-stable and accurate clock to measure the time interval between emission and reception. The height of the sea surface can be determined by differentiating the orbital altitude of the satellite and the



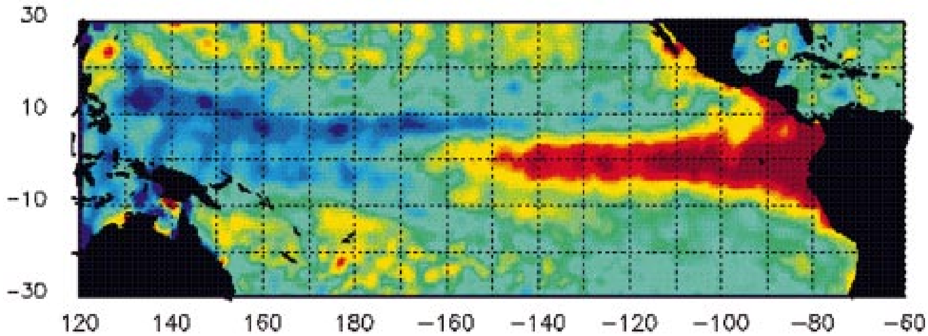
2**a** *Onset of El Niño in the beginning of May 1997, start of the elevated sea level of about 7 cm along the equator and 17 cm near the west coast of South America.*



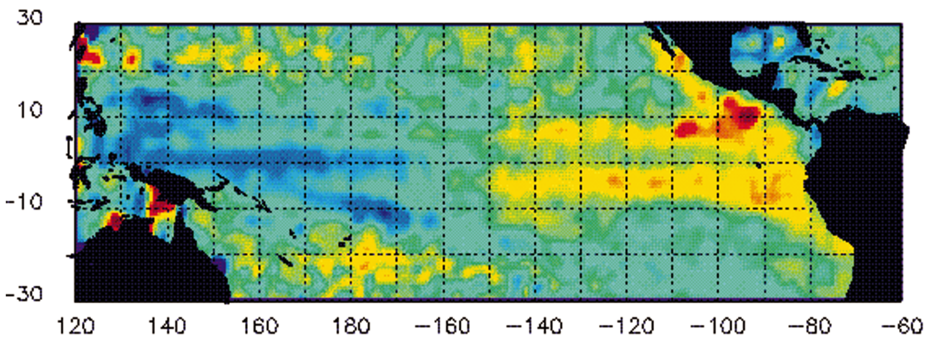
2**b** *Developed El Niño which reaches the South American coast in July 1997 with sea-level elevation maxima of 30 cm along the equator.*



2**c** *Rebounced El Niño in September 1997. There are still considerable anomalies in the central Pacific along the equator (max. 30 cm), but the sea level dropped back to 7 cm off the South American coast.*

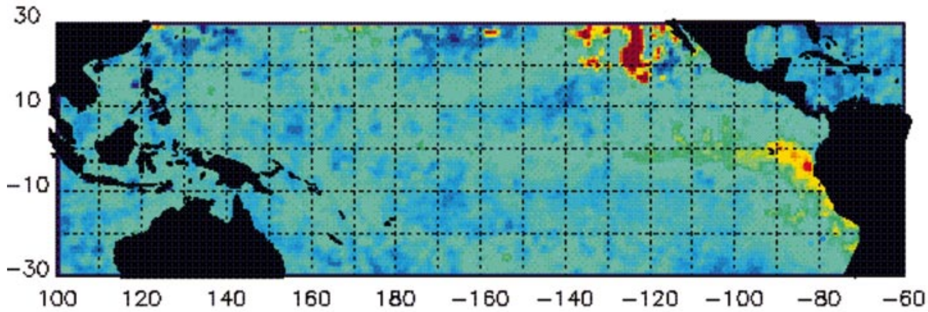


2**d** *The second hit of the severe El Niño episode reaches the South American coast in its most developed state on 7 Dec. 1997, with anomalies higher than 35 cm. Meanwhile the sea level at the Australian side has decreased.*

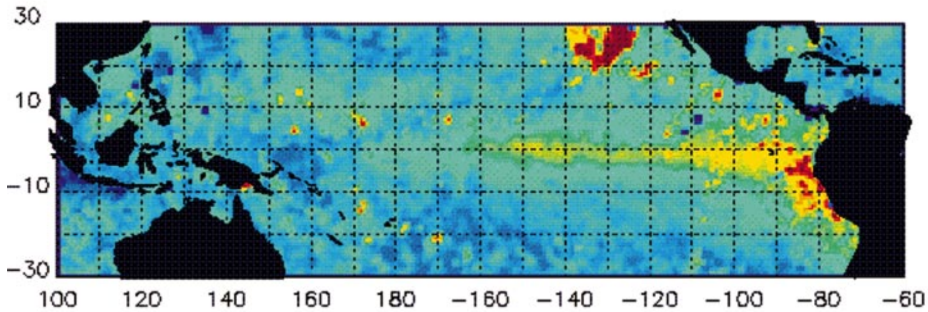


2**e** *Fading of the intense and high anomalies at the South American coast, the signal is partially reflected as coastal Kelvin waves propagate northward and southward along the coast.*

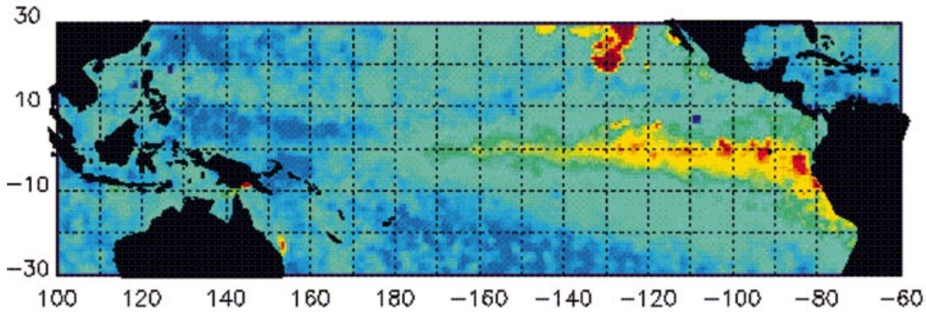
③**a** *Start of the warming-up of the sea surface in the eastern Pacific around the equator, measured by ATSR during the last week of May 1997.*



③**b** *Development of warm surface layer during the first week of July 1997. The mean anomaly reaches about 5 K in the eastern equatorial Pacific.*



③**c** *The warm sea-surface signal intensifying and persisting eastwardly at the end of August 1997. The anomalies are bigger than 6 K.*



radar range measurement. Furthermore, the slope of the echo leading edge is related to the height distribution of the reflecting facets and thus to the ocean wave height. Finally, the power level of the echoed signal depends on small-scale surface roughness and thus on wind speed.

ATSR instrument characteristics
The Along-Track Scanning Radiometer developed by a consortium of laboratories led by the Rutherford Appleton Laboratory has been flying onboard the ERS satellites since 1991 [*ESA* 1992]. ATSR-2 has three visible and near-infrared channels centred at 0.55, 0.65, 0.86 mm and 4 infrared channels centred at 1.6, 3.7, 10.8 and 12 mm [*Stricker et al.* 1995].

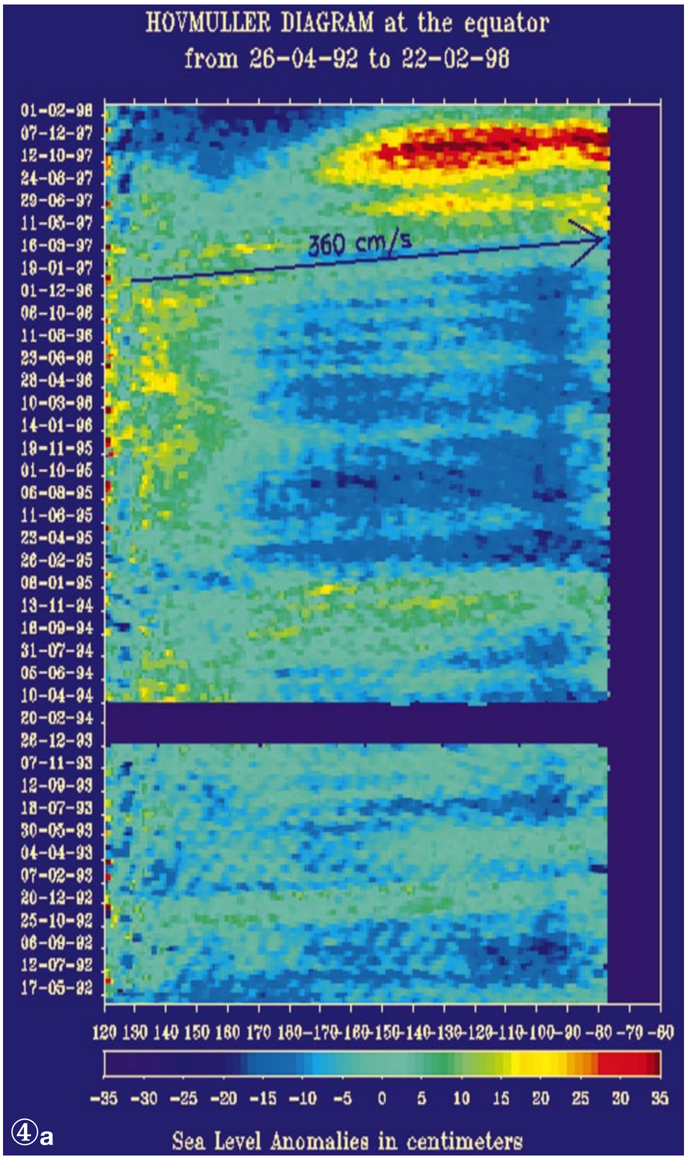
The ATSR is an instrument using conical scan system producing a double view of the same surface (55° forward and nadir) with a 512-km swath allowing a full repetitive coverage in 4 days with a resolution of 1 km (Fig. 1).

The instrument is equipped with a very precise onboard calibration system, which provides an excellent accuracy of the measurements. Its high-radiometric sensitivity (signal-to-noise better than 0.05 in all MIR and IR channels for temperatures > 270 K) [*Mason* 1991] together with 12-bit digitalisation enable the detection of fine sea structures and sea temperature variation.

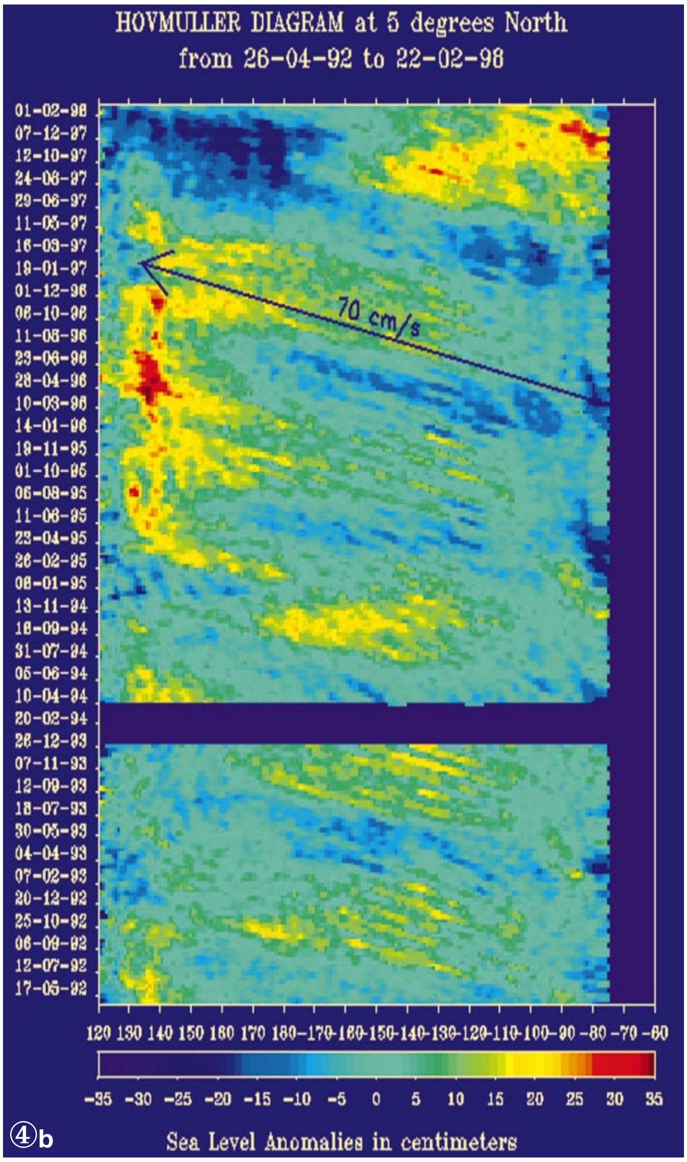
Both of these instrument types, but greatly improved, will continue to fly on Envisat-1 to be launched end 1999 [*ESA Bulletin 76,* 1993]. This will ensure the continuity of the measurements.

RA data flow, products and processing
For the monitoring of the sea-level height, the ERS-1 and ERS-2 Radar Altimeter OPR (Ocean Product) [*ESA* 1993] data are used and enhanced with precise orbits form the Delft University of Technology (from April 1992 until November 1997). The sequence has been kept up-to-date (until end March 1998) with ERS-2 OPR data taken before its final stage. This has allowed the monitoring of the El Niño event with a delay of only a few weeks. This time lag is necessary in order to:

– obtain the data transmitted through the Prince Albert ground receiving station, which covers the zone around the equator near Peru and Ecuador;
– calculate the wet tropospheric correction, which has a magnitude similar to the El Niño signal.



Time/longitude diagram of sea level anomalies along the equator observed by ERS-1 and ERS-2 radar altimeters, spanning from April 1992 until March 1998. Kelvin waves associated with El Niño events can be seen propagating eastwardly at a velocity of about 3.6 m/s.



Time/longitude diagram of sea-level anomalies along the 5°N as observed by ERS-1 and ERS-2 radar altimeters. Rossby waves migrate towards the west at regular intervals and with a velocity of about 70 cm/s.

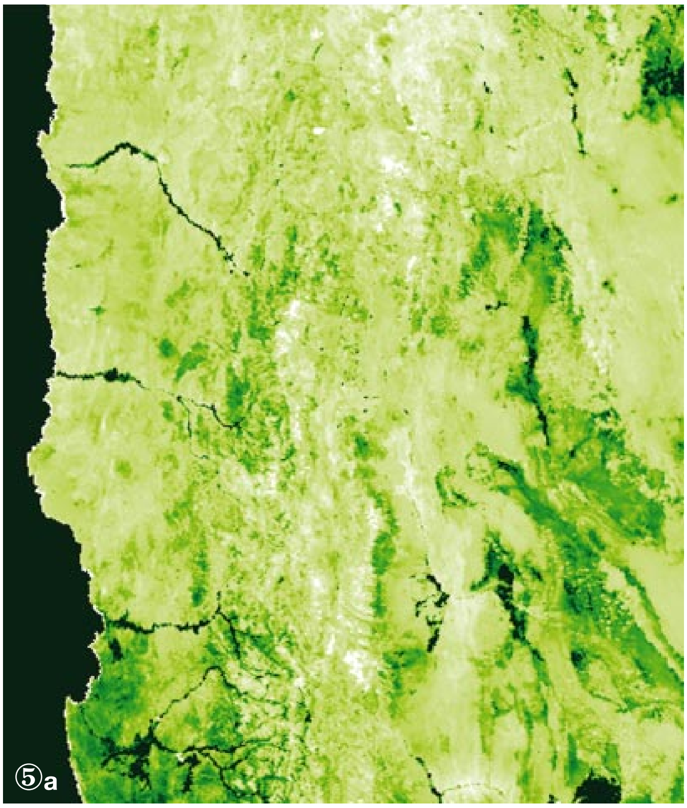
The correction is obtained from measurements of the water-vapour content by the Microwave Radiometer (MWR) onboard ERS-2. This correction is absolutely necessary for the observation of El Niño because warm waters stimulate cloud production and water evaporation.

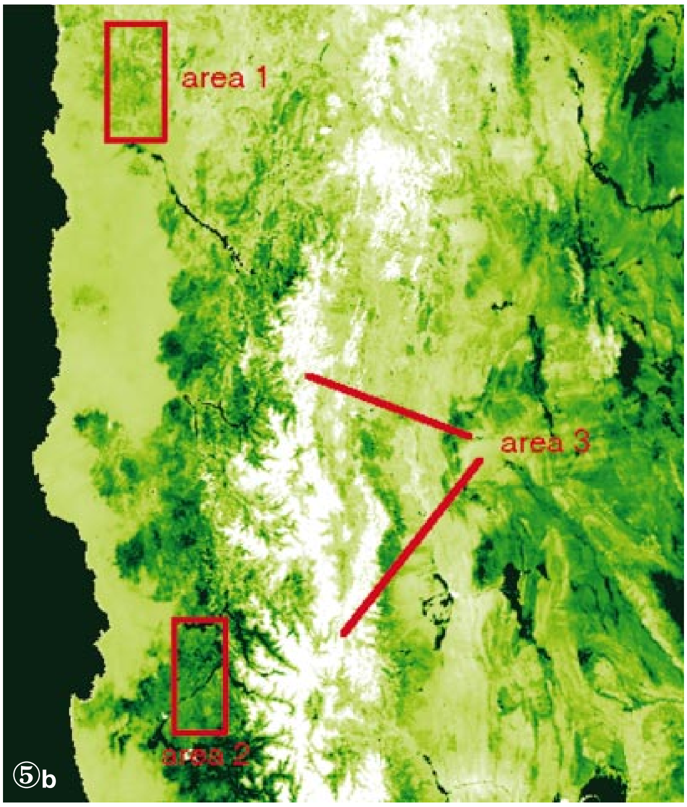
These OPR data have been corrected for bias jumps, oscillator drift, dry tropospheric, wet tropospheric and ionospheric path delays, solid earth and pole tides, ocean tides and loading, sea-state bias, inverse barometer. Ohio State University MSS95 was taken as a reference mean sea-surface height. The orbit correction from the OPR was not applied as such, but data refinement was achieved by performing a minimisation of the sea level differences at crossovers of ascending and descending tracks with a maximum interval of 17.5 days.

The relative sea heights were mapped to regular grids with a resolution of 1° x 1°. The grids are calculated every 7 days, but the data span for each solution is 16 days (being a sub-cycle of ERS-2's repeat cycle) centred around the epoch. The grid mapping uses a Gaussian function with a spatial scale of 1.2° to weight the along-track measurements to the grid points.

ATSR data flow, products and processing

The sea-surface temperature was monitored using the SADIST-2 products averaged sea-surface temperature





ATSR image over Chile (South of Atacama desert), Soil Adjusted Vegetation Index. The sea has been masked. The data was acquired on 9 Jan. 1997, before the start of El Niño. The area in the north of the image is very dry (low SAVI value). The snow coverage in the mountain area is not very extended.

Same area as 4a. Data acquired on 25 Dec. 1997 during the El Niño event. The vegetation as measured by the SAVI has increased 25% in area 1 and 50% in area 2. The snow coverage (area 3) is heavier.

(ASST) [*Bailey et al.* 1995]. Rutherford Appleton Laboratory (RAL) produced the ASST, which contain spatially-averaged sea-surface temperatures at 10-arcmin and half-degree resolution, using nadir-only and dual-view retrieval algorithms. In order to respond to Climate User Community requirements (TOGA/WRCP), ATSR has been designed to measure sea-surface temperature with an accuracy better than 0.3 K, which is a significant improvement when compared to the previous infrared sensor [see *Zavody et al.* 1995 for more details].

A composite was made using 10-day periods. During overlaps, priority was given to the highest temperature in order to reduce the remaining atmospheric effect.

Because the time range in which the ERS products has been available is relatively short (since July 1991), no accurate long-term mean has yet been established. Instead, differences of the ASST were created with respect to ASST data concurrently acquired in 1995. This implies that no annual cycle is present in sea-surface temperature anomalies, as shown in the images. 1995 was considered to be a relatively normal year, without any important irregularities.

In order to fill the missing data due to persistent cloud coverage, an interpolation in time and space has been applied.

El Niño observation

This year El Niño was also observed at ESRIN using ERS RA and ATSR data, and data visualisation tools. From May 1997, a slight rise in the sea level along the equator and at the South American coast was noticed, probably a Kelvin wave propagating from west to east, transporting warm water and an increase in the sea level. By July 1997, the wave reached the South American coast and seemed to partially rebounce in August and September 1997. In October 1997, the wave reached the South American coast for the second time, but with more strength than in July. It heavily and rapidly intensified until December 1997, from which time the signal partially rebounced, but also split into northern and southern coastal Kelvin waves (Fig. 2). The warm water (higher sea level) was visible all along Ecuador, Peru and part of Chile towards the south, and along Colombia, Costa Rica, Nicaragua, Honduras, Guatemala, San Salvador and Mexico towards the north (Fig. 3).

The propagation of waves can best be seen in time/longitude diagrams (Fig. 4). These plots show the sea-level anomalies for particular latitude bands as a function of longitude (horizontal axis) and time (vertical axis). Along the equator (Fig. 4a), the Kelvin waves associated with El Niño can be seen at irregular intervals and strengths, but all with a typical velocity of almost 360 cm/s. Note that the 1997-98 El Niño actually consisted of two Kelvin waves and that the sea-level anomaly was about three times stronger than during the 1993 and 1994 events.

Just north of the Equator (at 5°N, Fig. 4b) Rossby waves can be seen propagating westward. Again, these phenomena progressed in very sharp trains across the Pacific. This took about a year during which their signal remained evident. Their propagation velocity was about 70 cm/s and decreased towards higher latitudes.

Teleconnections
El Niño affects the climate drastically around the equatorial Pacific but can also impact all parts of the world. The effects of El Niño beyond the equatorial Pacific are called ‘teleconnections’. Although the mechanisms for certain teleconnections are not yet fully understood, some effects have been recorded each time, or have at least a high statistical occurrence probability when an El Niño events occurs. The predictions of the consequences of El Niño have the highest probability for zones closest to the tropical Pacific, such as the droughts in northern Australia, Indonesia and northern Brazil associated with big fire events [*Buongiorno et al.* 1997] and torrential rains floods along the coast of Ecuador and Peru.

Using ATSR-2 products it was possible to show the vegetation increase in a desert area (northern Chile) and snow coverage after or during the El Niño event. This was caused by the unusual precipitation over the area (Fig. 5).

Conclusion
ERS missions have proved to be able to provide useful information for monitoring an El Niño event. Thanks to the RA and the ATSR instruments, it has been possible to observe the first signs of El Niño and to follow its evolution. In order to further exploit the great potential of these data for ENSO dynamic research, they were made available to ocean modellers for model assimilation.

The ground data-processing of Envisat-1, ESA’s next-generation Earth observation mission now under development, will permit observations of the tropical Pacific with high-quality fast-delivery RA and ATSR data released in less than three hours. This is an asset since the early detection of the onset of an ENSO event allows governments and individuals to react timely and take appropriate measures to minimise the possible drastic impact, for instance: stocking-up on foodstuffs to compensate penurious fishing and farming, preparing for drought- or flood-related diseases, advising the best course of action for livestock, intensifying fire prevention and fire-fighting capacities.

Acknowledgements
We would like to thank the Rutherford Appleton Laboratory for the ATSR data processing.

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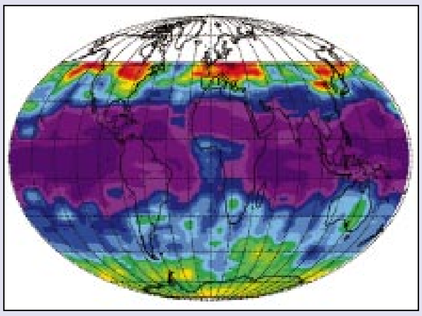

In anticipation of the launch of Envisat in the year 2000, with its group of three atmospheric chemistry instruments, it has been decided that the time is opportune to encourage interactions between the various groups of scientists working on these instruments and those already exploiting data from the GOME (Global Ozone Monitoring Experiment) instrument currently flying on ERS-2.

With this general objective in mind, the European Space Agency (ESA) is therefore organising a meeting at ESTEC, namely *ESAMS ’99*, which will have two specific objectives:

– to describe the three ‘chemistry’ instruments which will be flown on Envisat and to present for review the algorithms being developed for them;

– to provide a working forum for scientists to exchange information on activities linked to GOME and the chemistry instruments on Envisat.

Further information on arrangements for this workshop and the various instruments will be found on the ESTEC Conference Web site: *http://www.estec.esa.nl/CONFANNOUN/.*