Southwest Africa

Overview

Southwest Africa covers approximately 3500 km of coast between Angola (7°S, 12°E) to South Africa (35°S, 25°E) at the southern tip of the continent (Figure 1). A significant continental shelf exists below 18°S and the region is influenced by the Benguela Current and one of the strongest known wind-driven coastal upwelling system [LME 2004].

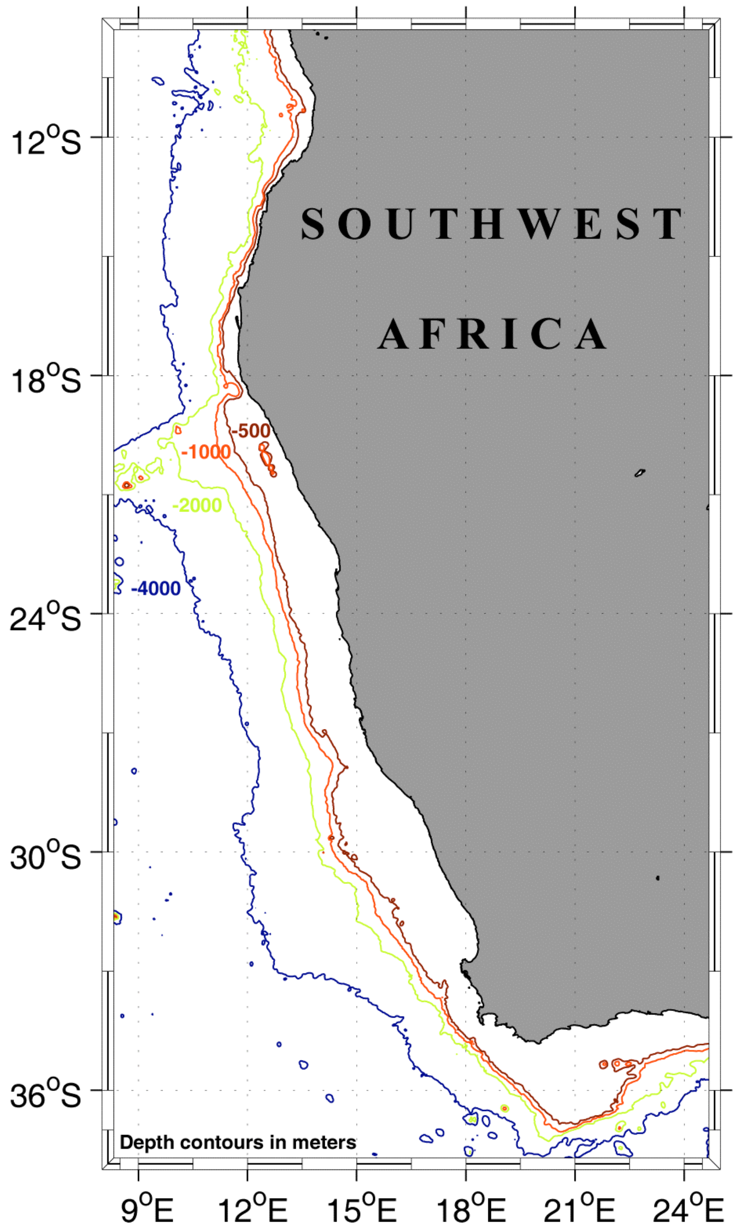


Figure 1. Bathymetry of Southwest Africa [Smith and Sandwell, 1997]

Observations

Apel et al. [1975] first reported the existence of solitons along western coast of South Africa based on ERTS (Earth Resource Technology Satellite) imagery collected in November 1972. Internal waves occur most frequently along the southwest African coast during the austral summer (December to February). Just as in the Northern Hemisphere summer, heating of the upper layers in coastal waters enhances the stratification required for internal wave occurrences. Table 1 shows the months of the year when internal waves have been observed.

Table 1 - Months when internal waves have been observed along Southwest Africa
(Numbers indicate unique dates in that month when waves have been noted)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
3	2	3	6	1						1	4

Table 2 presents a summary of internal wave characteristics from the southwest African Shelf. The values have been reported in the literature and derived from remote sensing data sources.

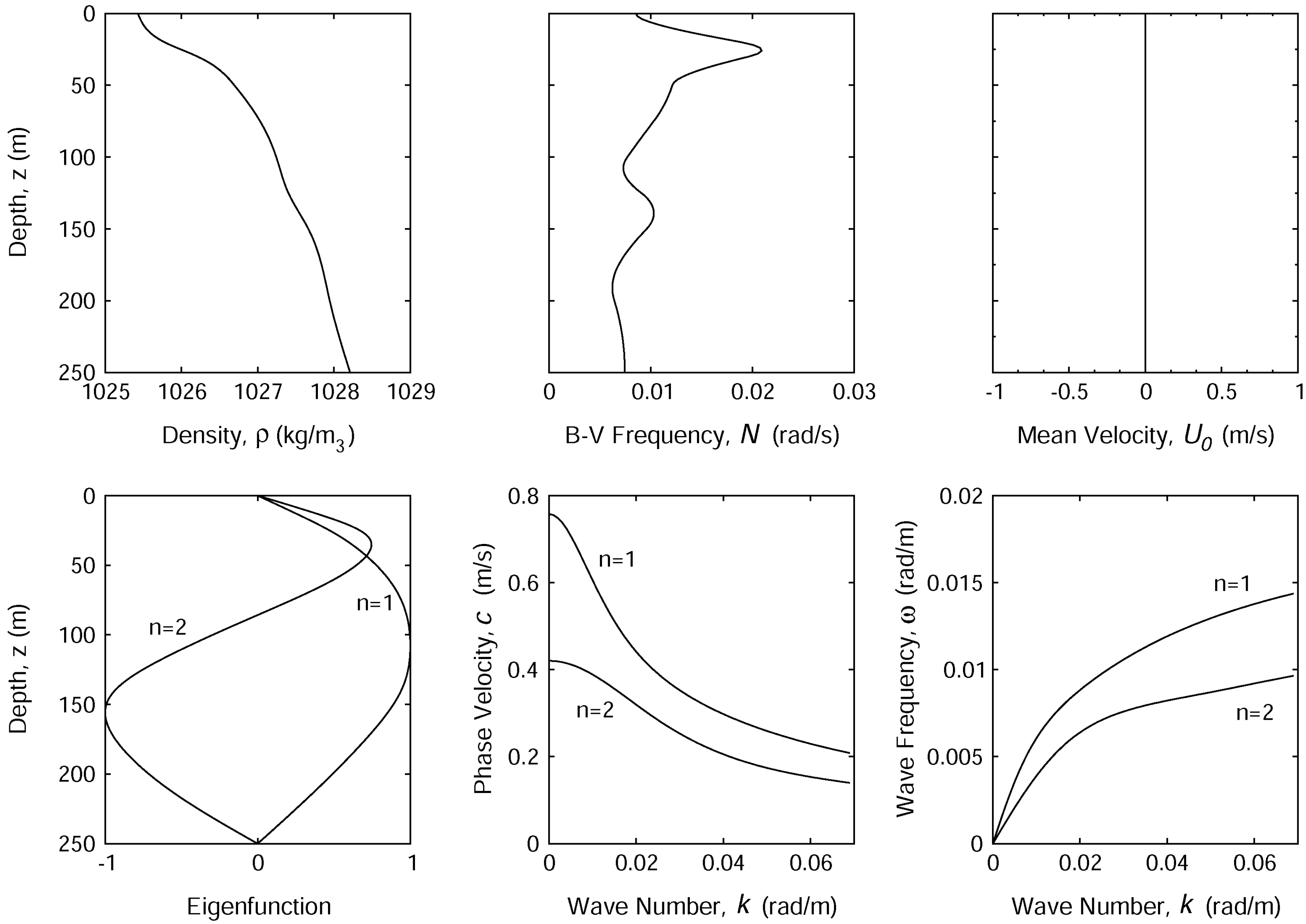
Table 2. Characteristic scales for Southwest Africa continental shelf solitons

Characteristic	Scale
Amplitude Factor	-6 to –20 (m)
Long Wave Speed	0.5 to 1.0 (m s^{-1})
Maximum Wavelength	1.5 to 2.6 (km)
Wave Period	12 to 55 (min)
Surface Width	200 (m)
Packet Length	5 to 15 (km)
Along Crest Length	75 to 100 (km)
Packet Separation	15 to 40 (km)

A typical density profile for the southwest African shelf derived from temperature and salinity data taken from the NODC World Ocean Atlas 1998 is shown in Figure 2. The normalized Mode 1 and Mode 2 eigenfunctions have been evaluated for $\lambda = \frac{2\pi}{k_0} = 1852m$, with H = 250 m. For long waves (k $\rightarrow$ 0) the maximum first mode wave speed (c_0) is computed to be 0.76 m/s without the effect of current shear. This agrees well with values derived from the SIR-C imagery (Figure 8.) Figures 2e and 2f give the phase velocity and dispersion relations for the data. Figure 2 also lists the environmental coefficients and KDV parameters evaluated at wavenumber k_0

Figures 3 and 4 are ERS SAR images over the coast of Angola. Figure 3 shows internal wave signatures that are similar to those observed elsewhere along the coast along with what are most likely upwelling signatures closer to the coast. Figure 4 shows that some internal wave activity is possible even in the region where the extent of the continental shelf is smallest.

Astronauts on board the Space Shuttle photographed internal waves off the coast of Namibia in March and December 1990. Figure 5 (STS035-074-019) was acquired 3 December 1990 and is one of a sequence of four images (STS035-074-016, 17, 18, and 19). The figure shows 4 internal wave packets propagating shoreward; each created during the last four semi-diurnal tidal cycles. The packets have separations of between 17 and 21 km with an implied



KDV Parameters
Mode 1

Wave Speed (k = 0) c_0 (m/s) 0.76
Nonlinear coefficient $1/\alpha$ (m) -99.08
Dispersion Factor $\gamma^{1/2}$ (m) 54.14
Amplitude (KDV theory) η_0 (m) -5.0
Non-Linear Phase Velocity V (m/s) for (s^2=1) 0.81

Figure 2. a) Density Profile derived from NODC World Ocean Atlas 98 Seasonal (Jan - Mar) temperature and salinity data at 30.5^0S, 16.5^0E. b) derived Brunt-Väisälä frequency $N(z)$ c) zero flow current profile d) Normalized vertical eigenfunctions (mode 1 & 2) for $2\pi/k_0$ = 1854m, H = 250 m for density and velocity profiles shown e) phase velocity f) dispersion relation.

propagation speed of around 0.4 - 0.5 m/s with the waves aligned parallel to the bottom topography. The waves in the packet closest to shore are difficult to see near the top of the image because they are being dissipated due to bottom interaction.

In March 1990 four images (STS036-082-075, 76, 77 and 78) were sequentially taken during mission STS-036 of space shuttle Atlantis passing over the western coast of Africa. Like Figure 5 these photographs show several internal wave packets off the Namibia coast. Figure 6 shows two groups of internal waves propagating in two different directions. Zheng et al. [1997] analyzed this imagery and noted that all of the internal waves were in water depth less than 500 m with intersoliton separations between 1.08 and 2.27 kilometers and crest lengths between 50 km to 100 km. Both wave groups were propagating shoreward with one group propagating toward the northeast, the other toward the southeast. As waves from the two groups meet they under go complex soliton - soliton interaction. Examination of the bathymetry in the area shows a sharp variation in the distance of the 500-m isobath near 18.5^{o}S, 11.5^{o}E. This "edge" is most likely the source of the southeast propagating solitons. Since they are not aligned parallel to the underlying shelf topography, these southeast packets will begin to refract towards the shore due to bottom interaction.

Figure 7 is an ERS SAR image acquired of Namibia. Like Figure 4, dark area believed to be upwelling is present along the coast. The internal wave pattern is more complex indicating a number of internal wave sources along the shelf.

Figure 8 is a SIR-C (Shuttle Imaging Radar - C) image off the Atlantic coast of South Africa acquired on 11 April 1994. This image is taken in the same geographic area as the ERTS presented in Apel et al. [1975]. Three distinct leading crests are visible strongly oriented along the isobaths, with crest lengths in excess of 60 km. Figure 8 also shows the ERTS image overlaid with the SIR-C image and a local bathymetry map. The waves appear to form just inside the 200-m isobath, with a possible very weak signature visible just outside the 200 isobath. Interpacket separation is approximately 35 km, which implies a propagation speed of around 0.75 m/s on the shelf. The distinction between packets disappears as they approach shore since the phase velocities of the waves are reduced by both the shoaling and (usually) by the decreasing pycnocline depth. The result is that the leading waves in one packet over take the tailing waves in the previous packet and the interpacket boundary disappears.

Figure 9 is also a SIR-C image taken on 11 April 1994 but off the southern coast of South Africa. A negative print of the image is presented to enhance the wave signatures. The figure shows the internal waves propagating along, rather than towards the visible coast. The most pronounced wave signatures are those at the middle left of the image. The direction of propagation (approximately east) indicates that the waves were probably generated at the western edge of the Agulhas bank. The left most soliton has an along crest length greater than 60 km. The second set of internal waves signatures can be seen across the lower half of the image (bottom right to left across on the image) implying an approximately westward propagation. The signatures are faint but more then a dozen waves are visible with wavelengths on the order of 3.5 km stretched out over more than 40 km. The weak signature and long uniform wavelengths are characteristic of solitons after several days of propagation. This life span means that the waves were generated a few hundred kilometers to the east. The most likely source is the continental shelf break near the southeast corner of Africa. The generation region may be associated with the Agulhas current which runs near the continental shelf break in that area [Apel, 1999; Grundlingh 1982].

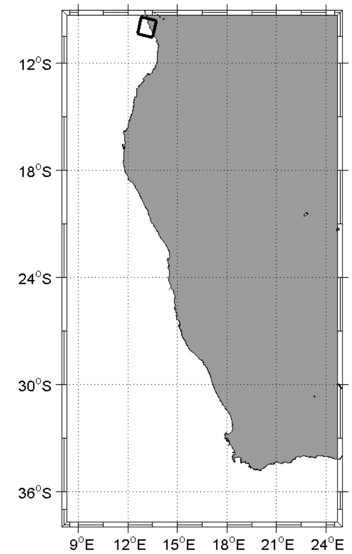
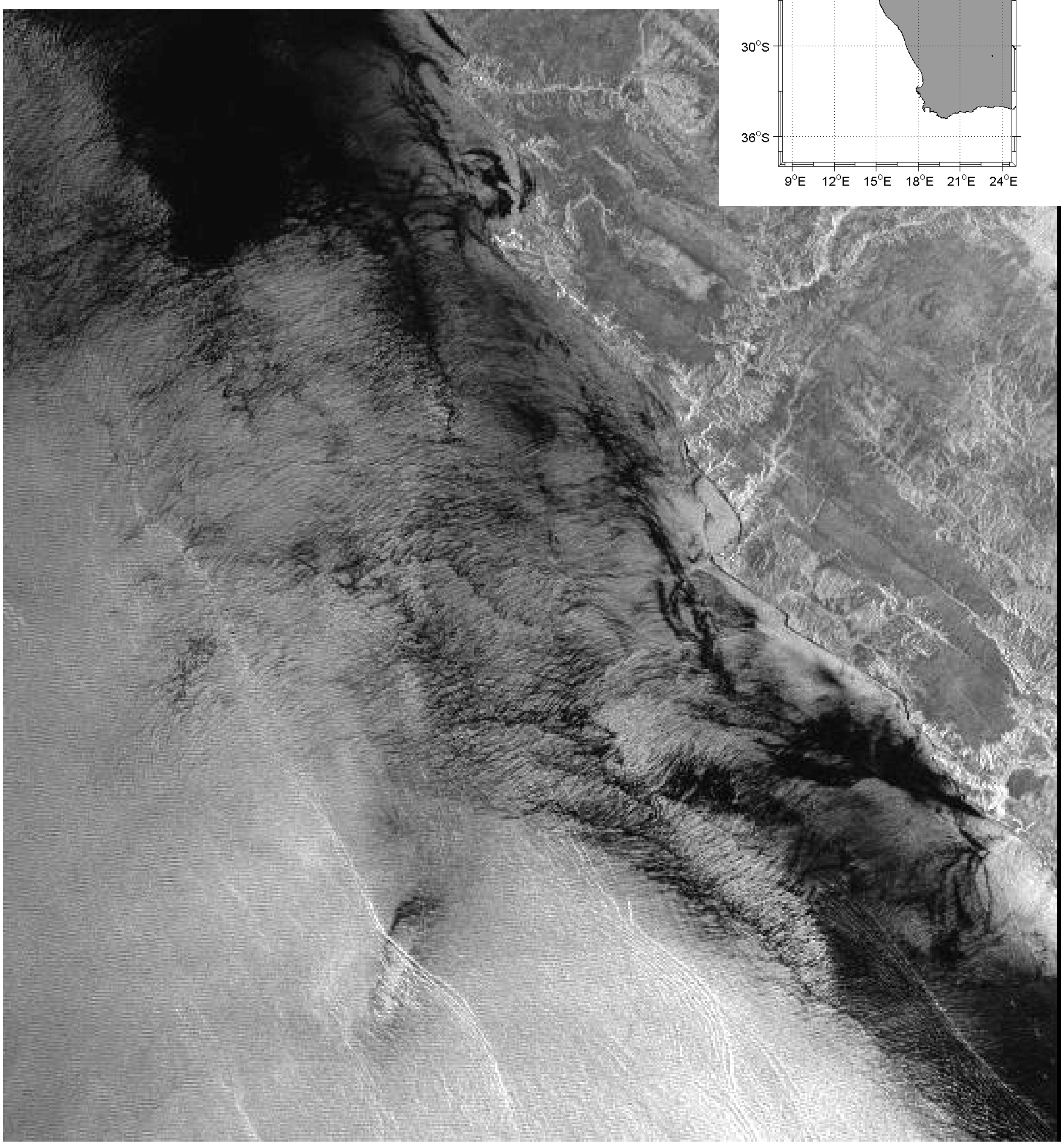
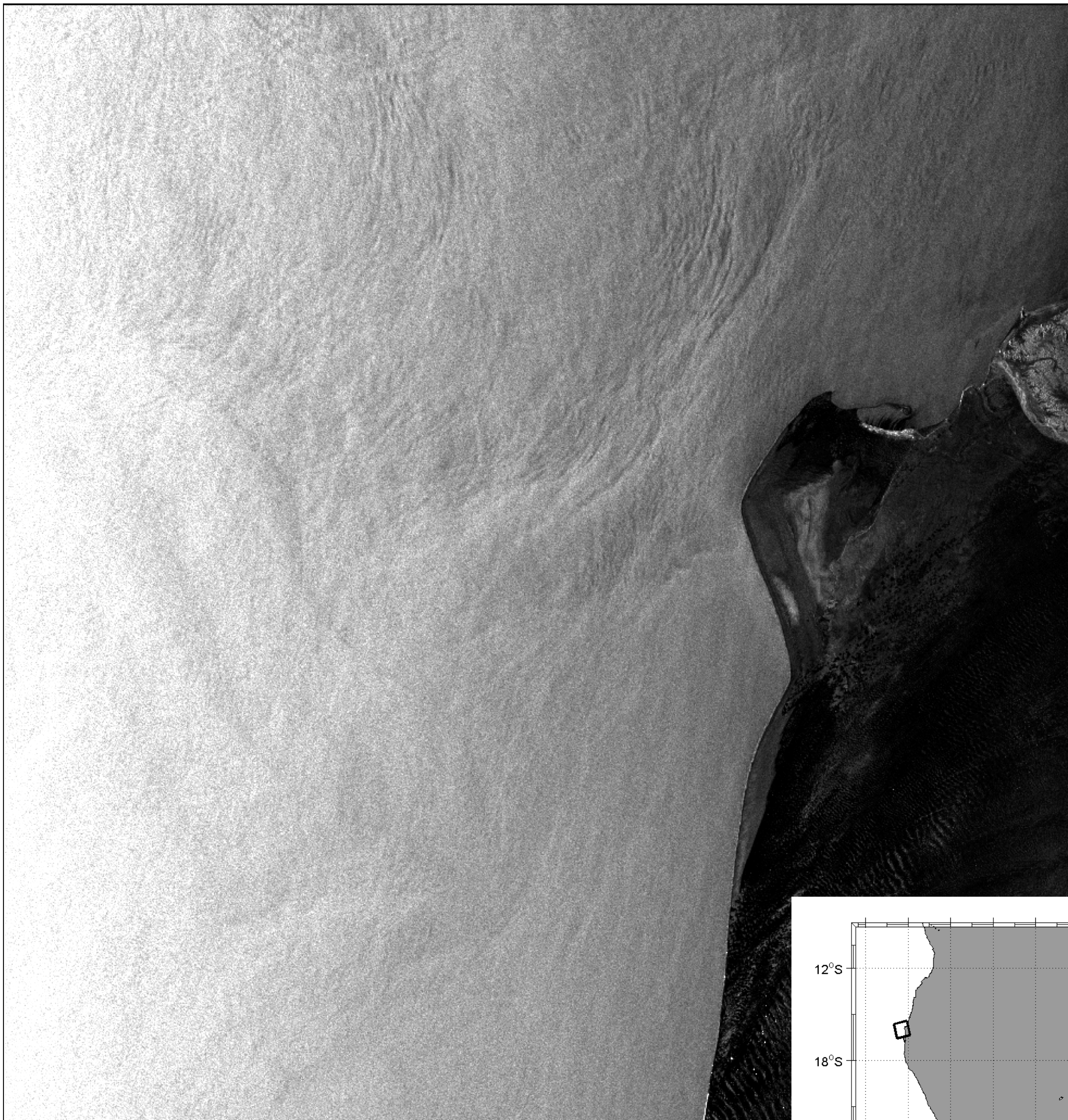


Figure 3. ERS-1 (C-band, VV) SAR image off the coast of Angola acquired on 12 January 1996 at 0920 UTC (orbit 23499, frame 3807). The image shows internal wave signatures indicating propagation shoreward. The dark areas adjacent to the coast are very likely upwelling signatures. Imaged area is 100 km x 100 km. ©ESA 1996. [Image courtesy of The Tropical and Subtropical Ocean Viewed by ERS SAR http://www.ifm.uni-hamburg.de/ers-sar/]





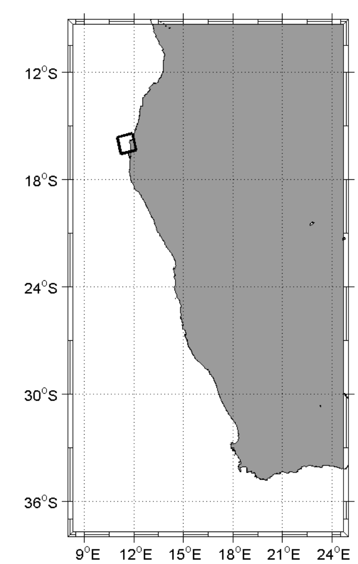


Figure 4. ERS-2 (C-band, VV) SAR image off the coast of Angola acquired on 27 April 1997 at 2204 UTC (orbit 10475, frame 6867). The image shows weak internal wave signatures of continental shelf solitons. Imaged area is 100 km x 100 km. ©ESA 1997. [Image courtesy Werner Alpers University of Hamburg, Hamburg Germany]

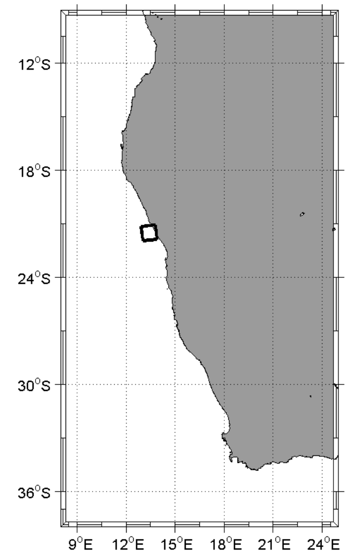
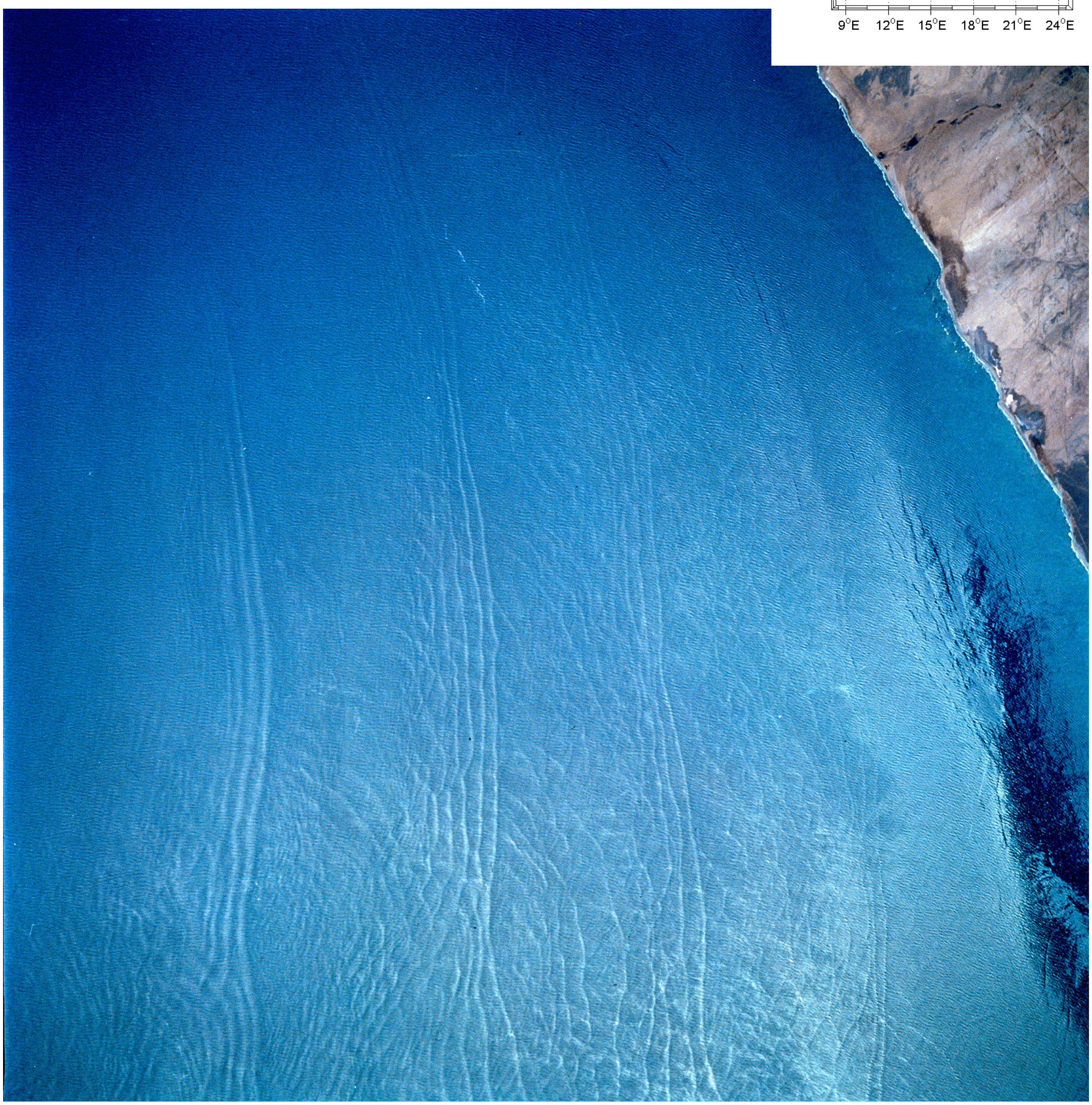


Figure 5. Astronaut photograph (STS035-074-19) off the coast of Namibia acquired on 3 December 1990 at 0923 UTC. The image shows the signature of four packets of continental solitons. The packets were generated at successive intervals of the semidiurnal tidal cycle over the 48 hours. Imaged area is approximately 80 km x 80 km. [Image Courtesy of Earth Sciences and Image Analysis Laboratory, NASA Johnson Space Center (http://eol.jsc.nasa.gov)]



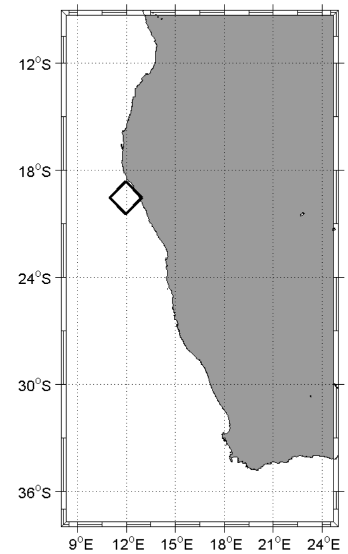
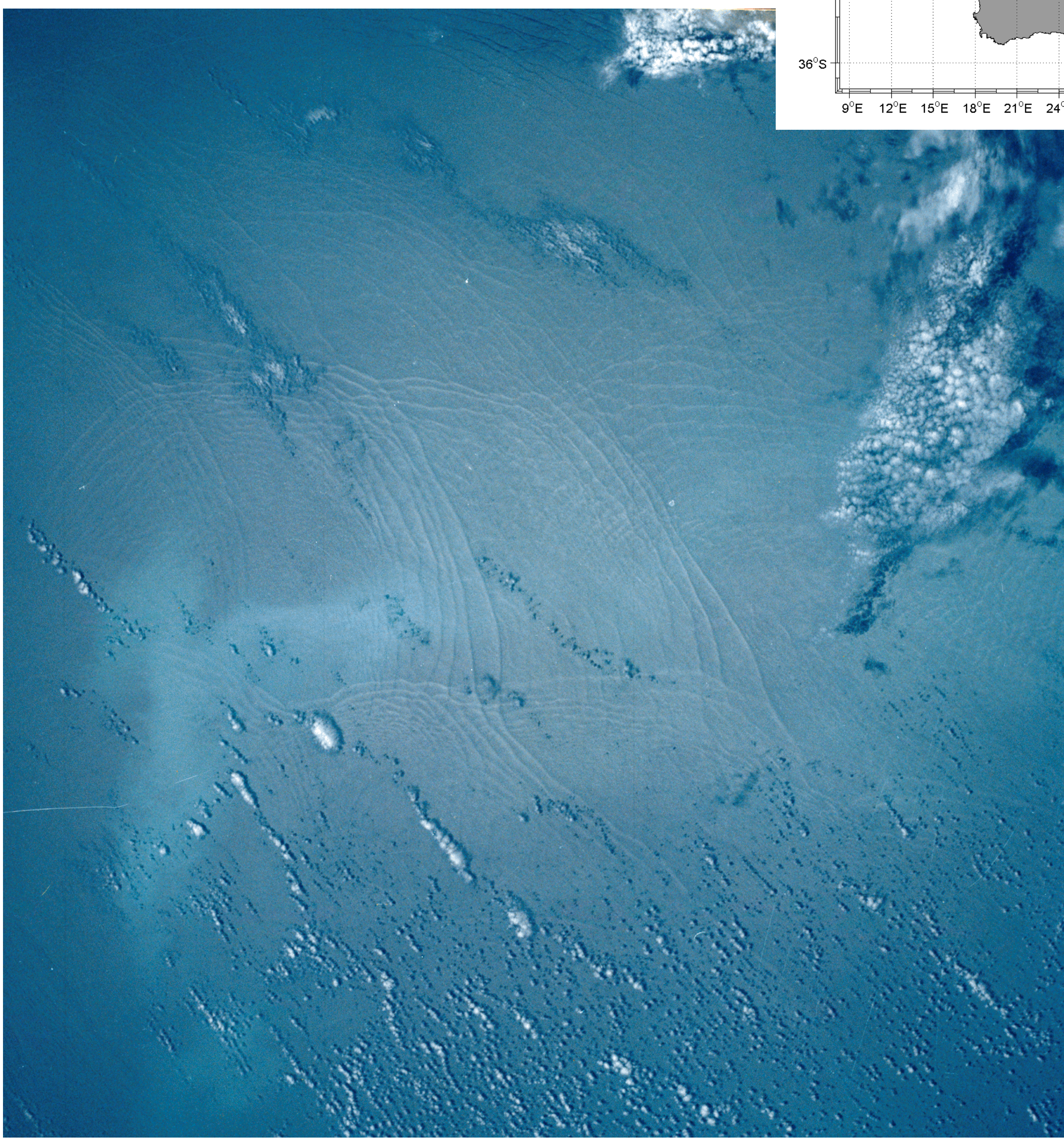


Figure 6. Astronaut photograph (STS036-082-76) acquired on 1 March 1990 at 1254 UTC. The image shows internal wave propagating in two different directions toward shore. As the solitons meet they wave fronts interact to produce a complex pattern. Imaged area is approximately 80 km x 84 km. [Image courtesy of Earth Sciences and Image Analysis Laboratory, NASA Johnson Space Center (http://eol.jsc.nasa.gov).]



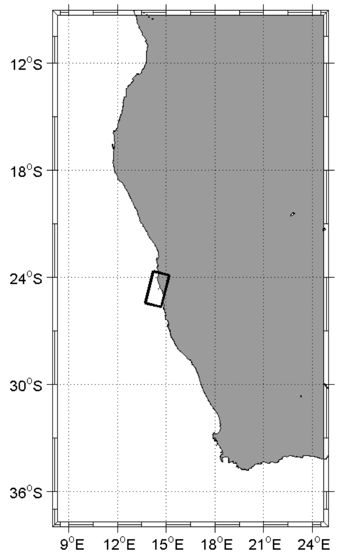
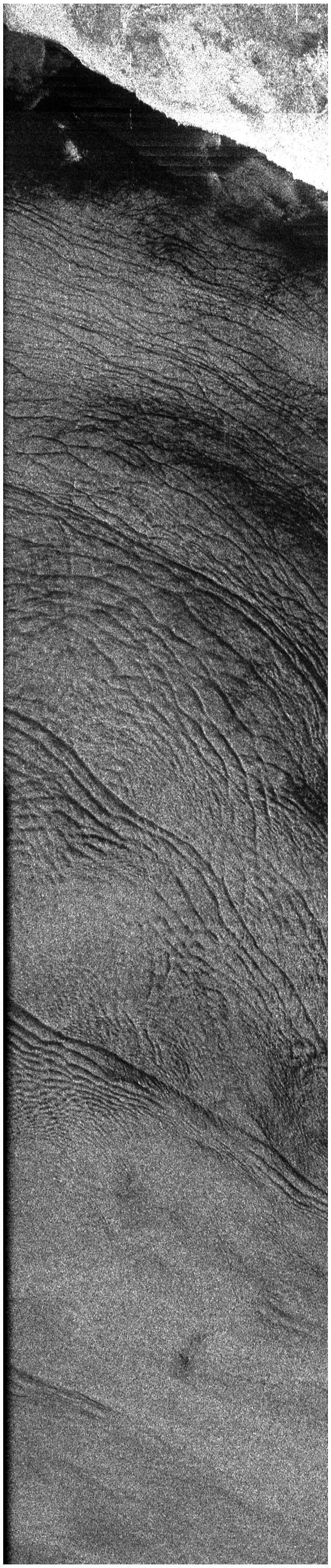


Figure 7. ERS- 2 (C-band, VV) SAR image off the coast of Namibia acquired on 10 December 1995 at 0904 UTC (orbit 3425, frames 4095 and 4113). The image shows a variety of internal wave signatures indicating a number of source locations. The dark areas adjacent to the coast are regions of low surface roughness believed to be caused by upwelling. Imaged area is 100 km x 200 km. ©ESA 1995. [Image courtesy of The Tropical and Subtropical Ocean Viewed by ERS SAR http://www.ifm.uni-hamburg.de/ers-sar/]



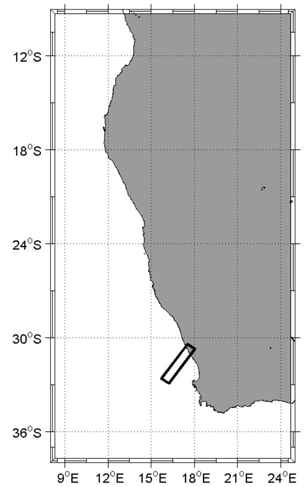
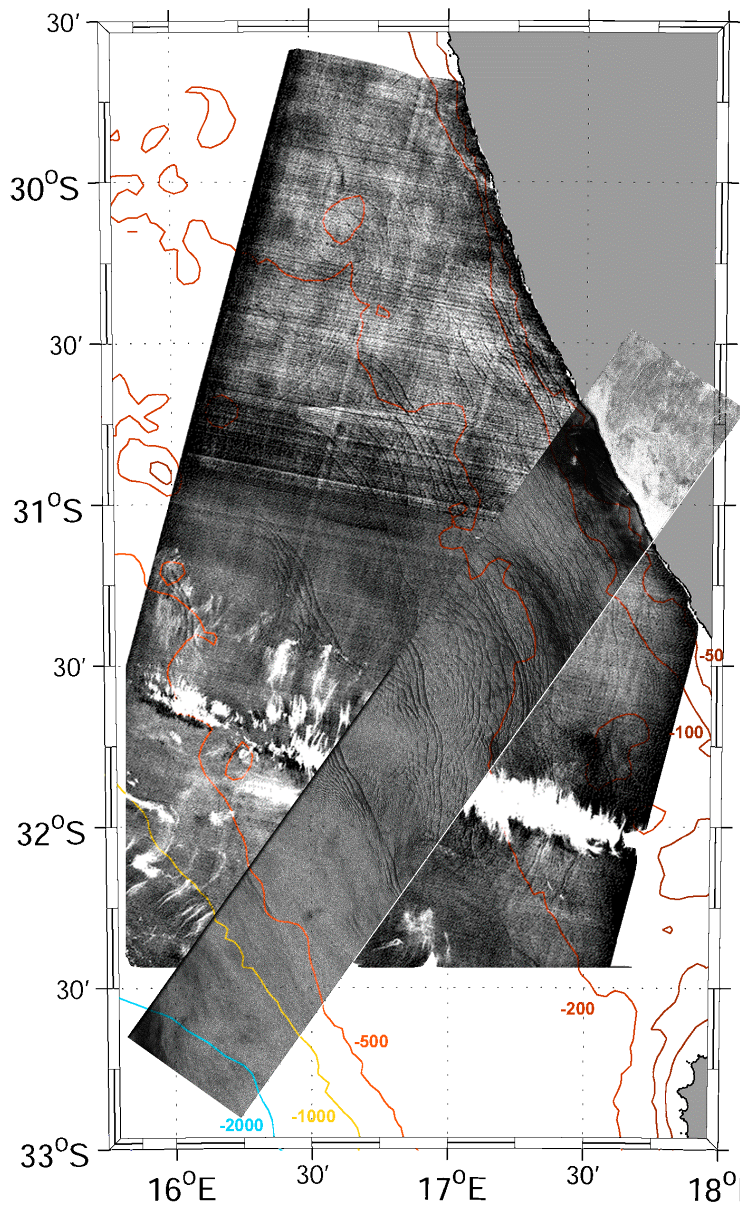


Figure 8. (Left) SIR-C data of internal waves off the Atlantic coast of South Africa acquired 11 April 1994 at 0122 UTC (Data Take 26.7). The imaged area is 60 km x 300 km. (Below) SIR-C data shown with the 1972 ERTS image from Apel et al. [1975] and the local bathymetry [Smith and Sandwell, 1997]. The strong agreement in wave signatures between the two images, taken over 22 years apart, attests to the reproducibility of the generation process.



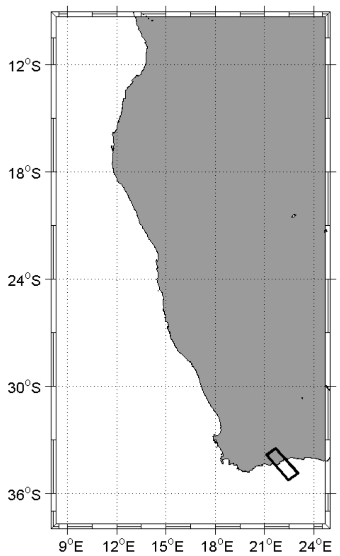


Figure 9. SIR-C data off the southern coast of South Africa acquired on 11 April 1994 at 1543 GMT (DT 36.8). The image shows strong signatures of eastward (left to right) propagating internal waves in addition to fainter signatures of larger spaced westward propagating internal waves (left to right). The imaged area is 60 x 110 km. A negative print of the image is presented to enhance the wave signatures.

References

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