Sulu Sea

Overview

The Sulu Sea is located in the western Pacific Ocean along the west side of the Philippines (Figure 1). It is a deep-water sea, roughly circular with several exits to the Celebes Sea (to the south), the South China Sea (to the north and west), and the Pacific Ocean (to the east). The Sulu Sea's surface currents come from the south in the summer, while during the winter the currents follow a counterclockwise gyre. [LME 2004]

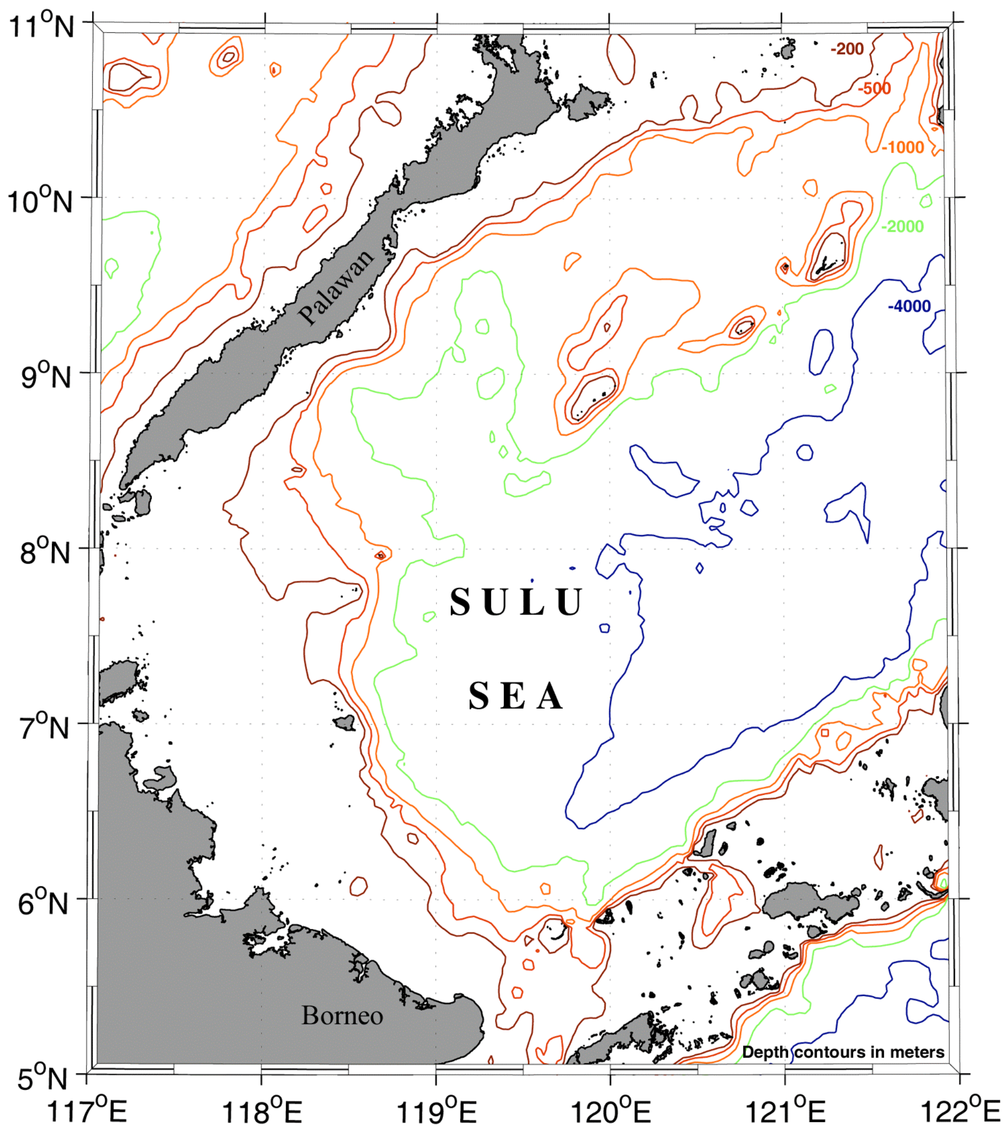


Figure 1. Bathymetry of the Sulu Sea [Smith and Sandwell, 1997].

Observations

There has been considerable scientific study of internal waves in the Sulu Sea both via satellite imagery and in situ observations. Apel et al. [1985] reported that images of internal waves in the Sulu Sea were first captured in U.S. Defense Meteorological Satellite Program (DMSP) visible satellite imagery in the early 1970's. The images showed packets or groups of quasi-periodic internal waves apparently radiating from a small source at the southern boundary of the sea, then spreading cylindrically and propagating north-northwest toward the island of Palawan (Figure 7). The imagery motivated a comprehensive study, called the Sulu Sea Experiment, carried out during April and May 1980. Internal waves in the Sulu Sea occur all year round. Table 1 shows the months of the year when internal waves have been observed.

Table 1 - Months when internal waves have been observed in the Sulu Sea
(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	6	2 (10)	6 (24)	2 (10)	3 (4)	4 (6)	2 (5)	3 (4)	2	7	6

*The numbers in parentheses represent the total occurrence counts including DMSP and MODIS sunglint observations. The sun specular point from these sensors is located over the region from late March through early May and thus biases the distribution.

The Sulu Sea has an average depth of over 4400 meters. It is surrounded by a shallow water regime along the edges of the adjacent landmasses and islands. The water depth in the southern region changes rapidly, from over 4000 m in Sulu Sea to approximately 100 m in the area across the Sulu Archipelago, and then returning to over 4000 m in the Celebes Sea. These bathymetric changes take place over approximately 150-km in horizontal distance. Strong current flow, at times as large as 3.4 m/s in this area, particularly between Pearl Bank and Doc Can Island (to the east) and Pearl Bank and the Talantam Shoal (to the west), are the sources of the Sulu Sea solitons. Internal waves have also been observed among the islands in the Sulu archipelago. The characteristics of Sulu Sea internal waves are presented in Table 2 and Figure 2. The values have been reported in the literature and derived from both in-situ and remote sensing data sources.

Table 2. Characteristic Scales for Sulu Sea Solitons

Characteristic	Scale
Amplitude Factor	-10 to –90 (m)
Long Wave Speed	1.8 to 2.6 (m s^{-1})
Maximum Wavelength	5 to 16 (km)
Wave Period	14 to 110 (min)
SurfaceWidth	1000 (m)
Packet Length	25 to 35 (km)
Along Crest Length	20 to 170 (km)
Packet Separation	70 to 110 (km)

Sulu Sea Experiment 1980: The DMSP imagery of solitons in the Sulu Sea lead to an experiment carried out during April and May 1980, when the NOAA research vessel *Oceanographer* spent 22 days collecting a variety of in-situ measurements around the region on its internal wave activity. The experiment collected, along with other data, in-situ measurements from three moorings each with a phased array of current meters and thermistors located near the wave source (SS1 near 5.8^o N., 119.82^{o}E.), 82 km distant from the source (SS2 - near 6.6^o N., 119.6^{o}E.) and 200 km distant from the source (SS3 - near 7.75^{o}N. 119.0^{o}E.) (Figure 2).

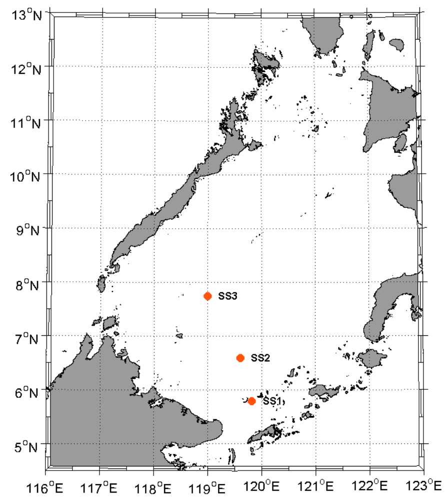
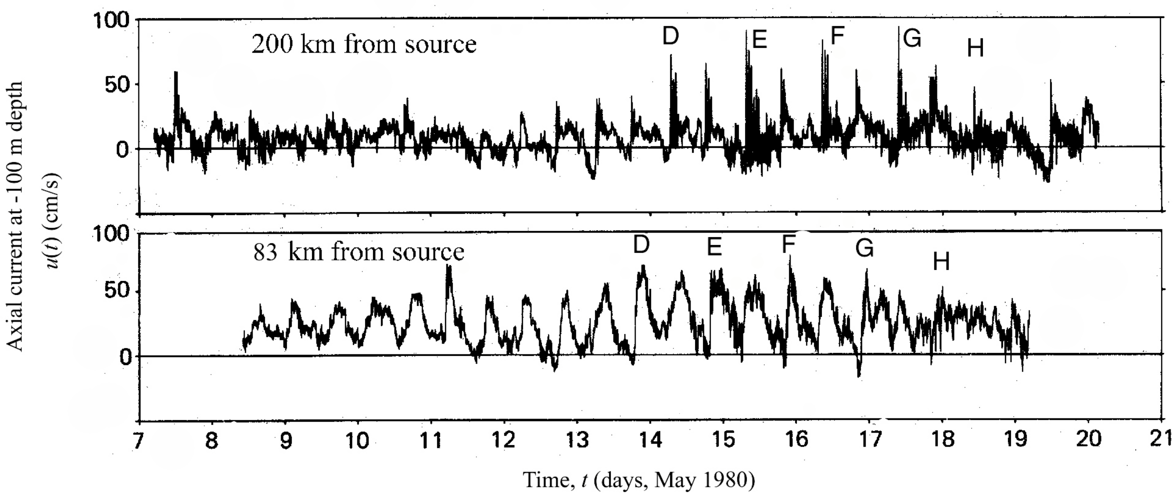


Figure 2. (Left) Map showing the location of the moorings deployed during the 1980 Sulu Sea Experiment

Figure 3. (Below) Current meter observations in the Sulu Sea over 11 days, spanning neap (early times) and spring (later times) tides. Solitons appear at D through H. Asymmetry between adjacent packets is due to semi-diurnal and diurnal differences, while the longer-term modulation is due to the fortnightly tides [After Apel et al., 1985]



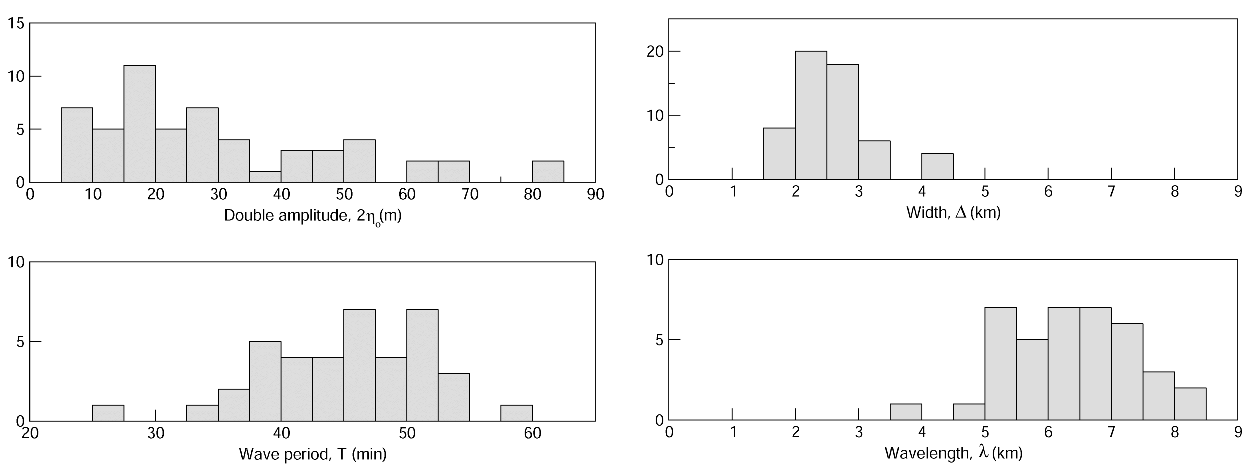


Figure 4. Histograms showing the distribution of amplitude ($2\eta_o$), period (T), full width at half amplitude (Δ) and wavelength (λ) for 56 well developed solitons in 17 internal wave packets observed at mooring SS3. [After Apel et al., 1985]

Figure 3 shows the axial currents for the instruments at a depth of 100 m for moorings SS2 and SS3. The data show that semidiurnal current variations dominate the record. Solitons (labeled D through H) are the sharp spikes superimposed on the semidiurnal peaks. The period between 8 and 12 May was relatively inactive with only a few packets containing two or three small amplitude solitons. In contrast, 12 to 18 May showed intense internal wave activity. All totaled the moorings yielded data on 56 well developed solitons distributed over 17 internal wave packets. Characteristics of the solitons observed at SS3 are presented in Figure 4.

Figure 5 shows a typical density profile for the area derived from temperature and salinity data collected on at the SS2 Mooring near 6.6^o N, 119.6^{o}E. The normalized Mode 1 and Mode 2 eigenfunctions have been evaluated for $\lambda = \frac{2\pi}{k_0} = 2120m$, with H = 3000 m. For long waves ($k \to 0$) the maximum first mode wave speed (c_0) is computed to be 2.09 m/s with the effect of current shear (2.04 m/s without). Figures 5e and 5f give the phase velocity and dispersion relations for the data. The red curve includes the effect of current. Table 3 presents the environmental coefficients and KDV parameters evaluated at wavenumber k_0

Table 3. Environmental coefficients and KDV parameters (λ_0=2120) Sulu Sea solitons (without current)

Long Wave Speed c_0 (m/s)	Nonlinear coefficient $1/\alpha$ (m)	Dispersion Factor $\gamma^{1/2}$ (m)	Amplitude (KDV theory) η_0 (m)	Non-Linear Phase Velocity V (m/s) for (s^2=1)
2.04	-93.8	132.6	-21.8	2.36
(with current)				
2.09	-96.3	138.1	-24.2	2.43

Figures 9, 10 and 12 are ERS SAR data from the Sulu Sea acquired in 1996 and 1997. The intersoliton separations vary between 2 km, shortly after formation (Figure 12) to approximately 14 km as the waves approach Palawan Island (Figure 9). Interpacket separations are approximately 100 km for the three packets visible in Figure 9.

Soliton spacing variations across the wave front can be observed on the left (west) side of the solitons in Figure 10 and, to a lesser extent, in the bottom packet in Figure 9. These spacing variations are due to local bathymetry as discussed in detail in Zeng and Alpers [2004]. Figure 11 shows that the retarded portion of the wave packet was propagating over the area located inside the 500-meter isobath. Figure 9 shows refraction effects around the San Miguel Islands where small solitons appear to be radiating away nearly orthogonal to the main wave [Alpers and Vlasenko, 2002]. Finally, a very faint wave front appears to be propagating southward from Palawan Island; the wavelength suggests some kind of reflection of the incident solitons.

Figure 12 shows that in the region around Pearl Bank at least three possible sources exist for the Sulu Sea solitons, one between Pearl Bank and Doc Can Island the other two between and Pearl Bank and the Talantam Shoal [Zeng and Alpers, 2004].

Sulu Archipelago: Figures 13 and 14 show that in addition to the large solitons that propagate across the Sulu Sea toward Palawan Island, smaller scale internal waves can be found in and around the Sulu Archipelago. Figure 13 is an enlargement from Figure 6 showing a single soliton packet propagating from Pearl Bank SSW toward Tawitawi Island. The lead intersoliton separation is roughly 1.5 km with an along crest length of 35km.

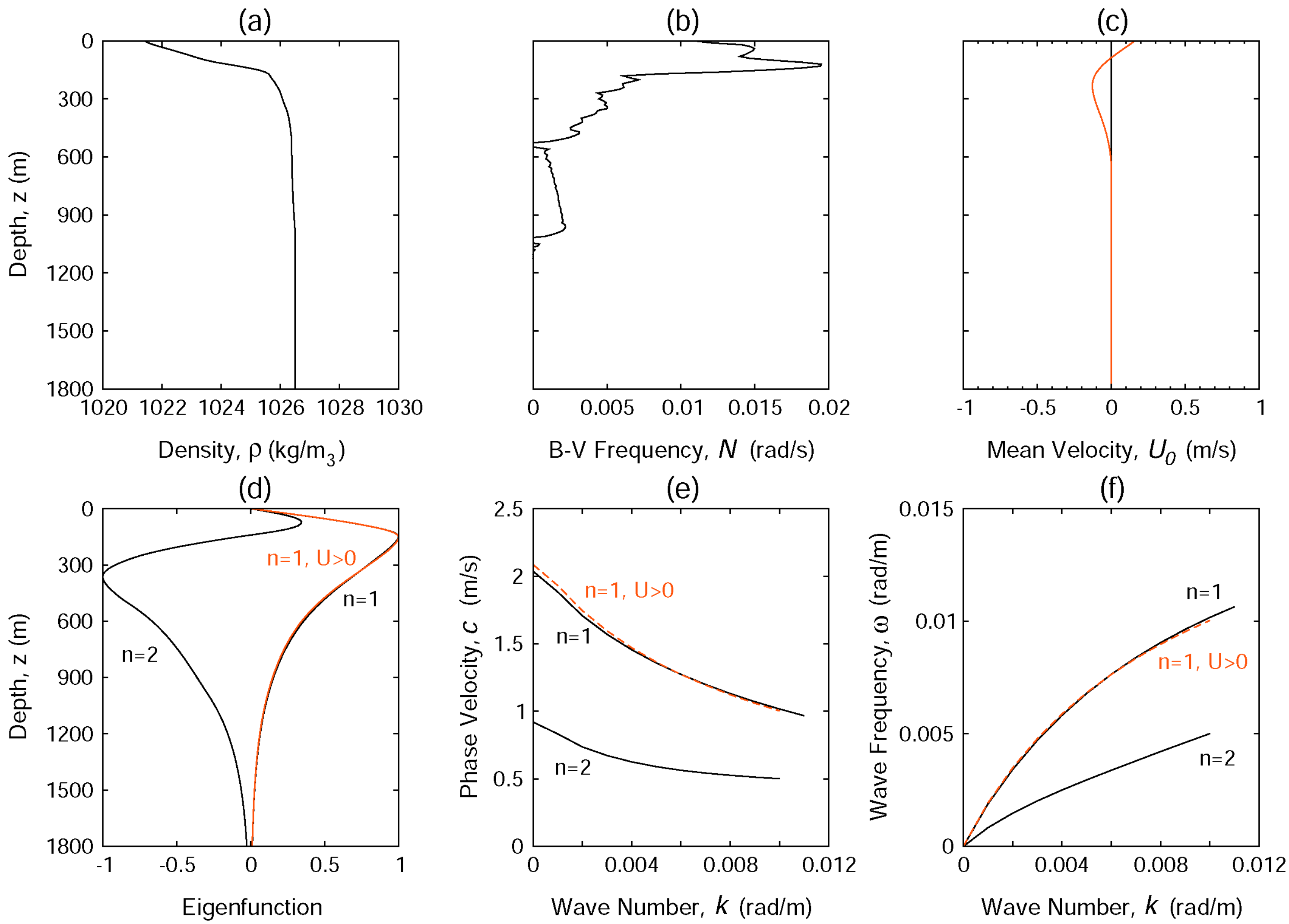


Figure 5. a) Density profile derived from data collected at mooring SS2 (near 6.6°N. latitude, 119.6° E. longitude, depth ≈ 3500 m) during April and May 1980 b) derived Brunt-Väisälä frequency $N(z)$ c) current flow profile d) normalized vertical eigenfunctions (mode 1 & 2) for 2 /πk_0 = 2120 m, H = 3000 m for density and velocity profiles shown e) phase velocity f) dispersion relations. The red curves show the effects of current, U > 0.

Figure 14 shows an Astronaut Photograph of Internal waves in the Sibutu Passage acquired 19 November 1990. The internal waves in the passage are located northeast of Sibutu Island and west of Tawitawai Island. The waves are radiating to the NNE toward Pearl Bank with a lead soliton separation approximately 1.6km.

References

Alpers, W., and V. Vlasenko: 2002, "Study of secondary internal wave generation by the interaction of an internal solitary wave with an underwater bank by using ERS SAR imagery and a numerical model", Proceedings of The Sixth Pan Ocean Remote Sensing Conference (PORSEC 2002), Bali, Indonesia, 3-6 September, Vol. I, 165-169,

Apel, J. R., and J. R. Holbrook, 1983a: Internal solitary waves in the Sulu Sea, Johns Hopkins APL Tech. Digest 4, No.4, 267-275.

Apel, J.R., J.R. Holbrook, J. Tsai, and A.K. Liu, 1985: The Sulu Sea internal soliton experiment. J. Phys. Oceanogr., 15 (12), 1625-1651.

Large Marine Ecosystems of the World: LME #37: Sulu-Celebes Seas, January 2004 http://na.nefsc.noaa.gov/lme/text/lme37.htm

Lui, A.K, J.R. Holbrook, and J.R. Apel, 1985: Nonlinear Internal Wave Evolution in the Sulu Sea. J. Phys. Oceanogr., 15 (12), 1613-1624.

Smith, W. H. F., and D. T. Sandwell, Global seafloor topography from satellite altimetry and ship depth soundings, Science, v. 277, p. 1957-1962, 26 Sept., 1997. http://topex.ucsd.edu/marine_topo/mar_topo.html

Zeng,K., and W. Alpers, 2004, “Generation of internal solitary waves in the Sulu Sea and their refraction by bottom topography studied by ERS SAR imagery and a numerical model”, International Journal of Remote Sensing, Vol.25 (7-8), 1277-1281

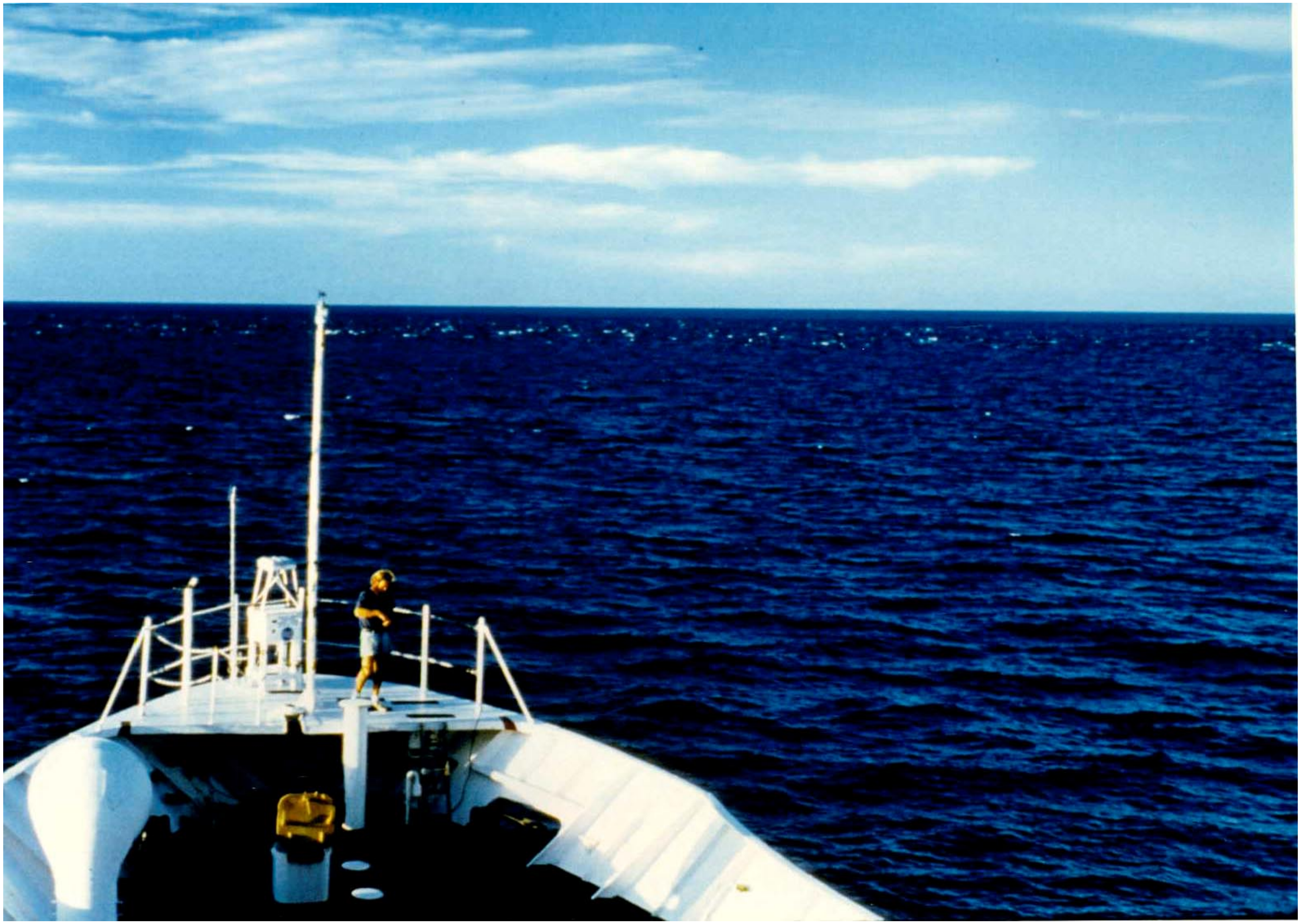


Figure 6: Photograph of the surface of the Sulu Sea surface taken as a soliton approaches the NOAA research vessel Oceanographer. The breaking surface waves had approximately 1-meter amplitude and were audible as they passed the ship. [After *Apel and* Holbrook 1983]

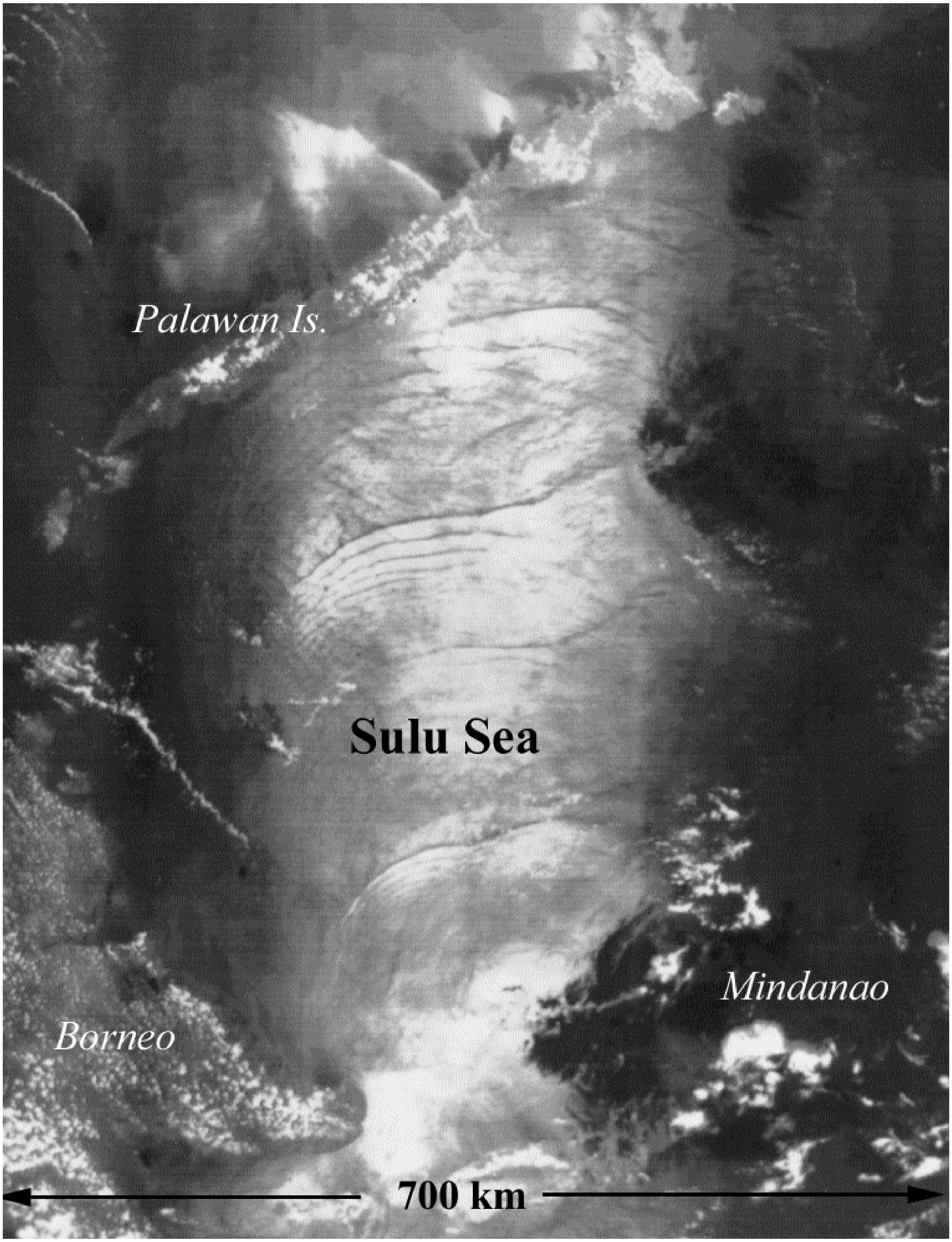


Figure 7. DMSP 1-km resolution visible light image of Sulu Sea acquired on April 1973 at 0419 UTC. Solar reflection shows roughness modulations from five groups of large internal solitons propagating across the Sulu Sea. Figure courtesy of U.S. Air Force.

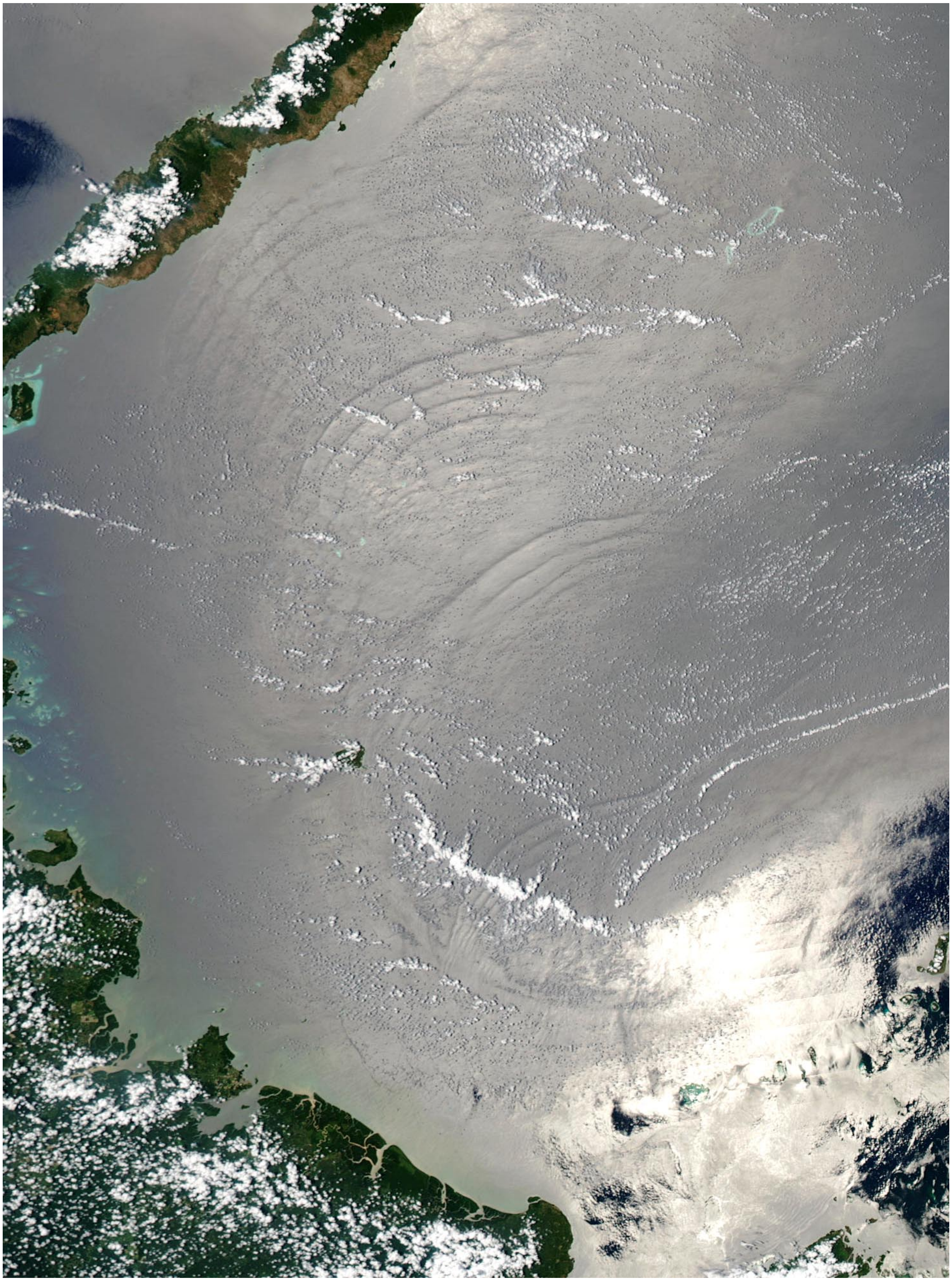


Figure 8. MODIS (Bands 1,3,4) 250-m resolution visible image of the Sulu Sea acquired on 8 April 2003 at 0520 UTC. Four packets of large solitons are visible in the sunglint region. Imaged area is 370 km x 500 km.

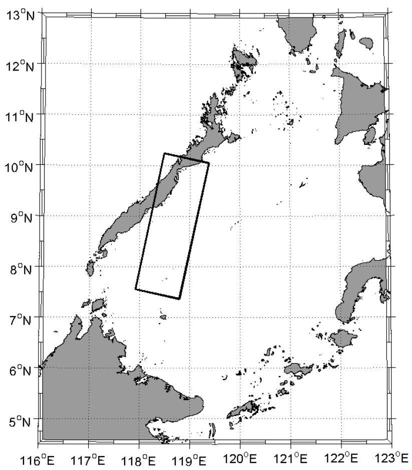
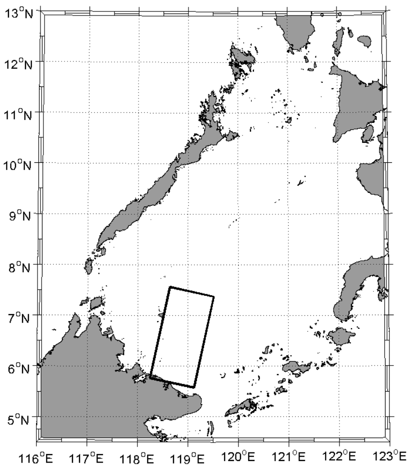


Figure 9. ERS-2 (C-band, VV) SAR image of the Sulu Sea acquired on 7 April 1996 at 0230 UTC (orbit 24726, frames 3411, 3429, 3447, 3465). The image shows three internal wave packets generated on successive semidiurnal tidal cycles. Interpacket separations are approximately 100 km and 90 km. Secondary internal waves are seen generated from a coral reef (dark area near center) and the shelf break. Imaged area is 100 km x 400 km. ©ESA 1998. [Image courtesy of The Tropical and Subtropical Ocean Viewed by ERS SAR http://www.ifm.uni-hamburg.de/ers-sar/]



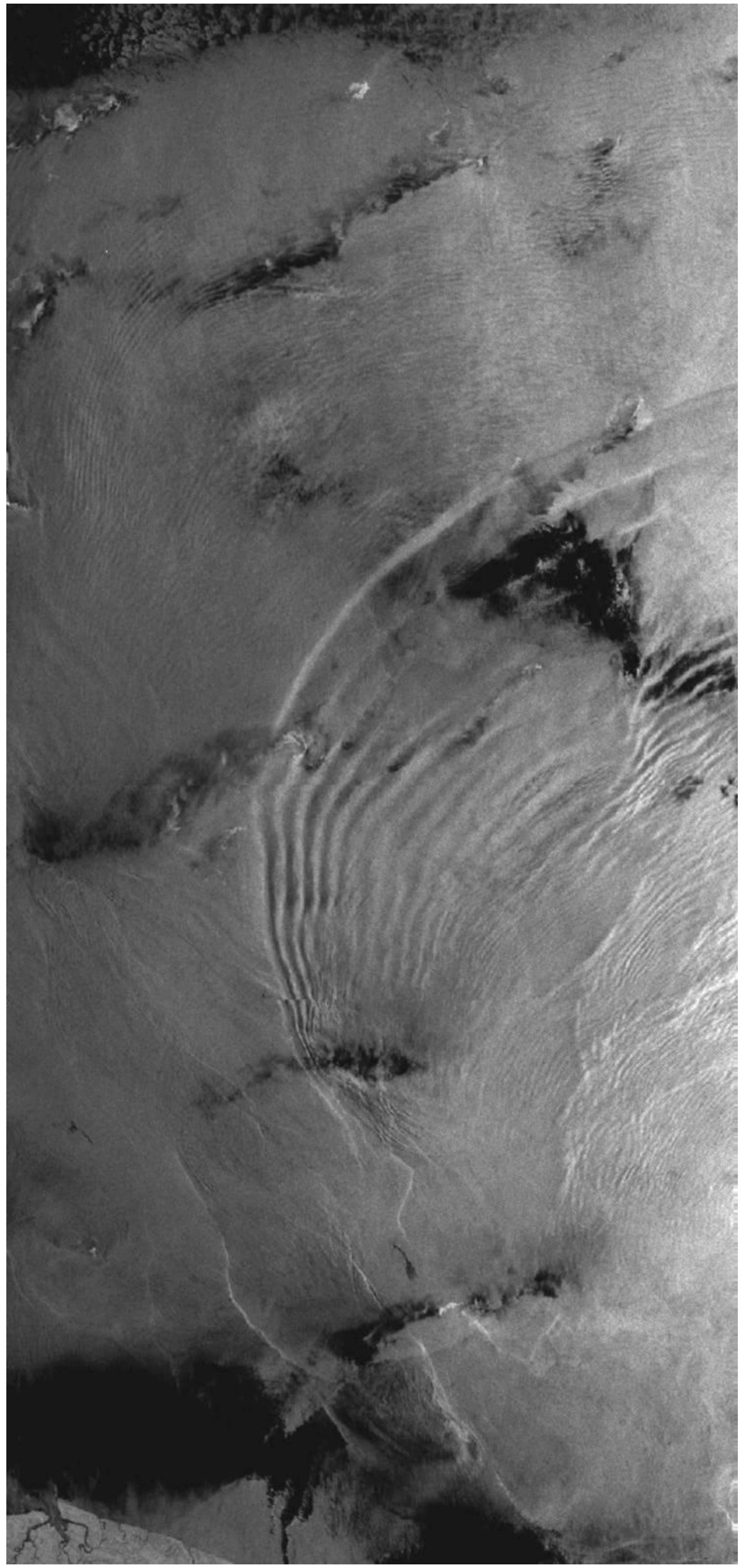


Figure 10. ERS-2 (C-band, VV) SAR image of the Sulu Sea acquired on 3 July 1996 at 0227 (orbit 6284, frames 3483, 3465). The image shows a mature internal wave packet whose distance between the first and the second soliton varies from 6.5 km to less than 1 km due to bathymetric variations. The retarded portion of the wave packet has been traveling over areas located inside the 500-meter isobath, the remainder outside the 1000m isobath. Imaged area is 100 km x 200 km. ©ESA 1998. [Image courtesy of The Tropical and Subtropical Ocean Viewed by ERS SAR http://www.ifm.uni-hamburg.de/ers-sar/]

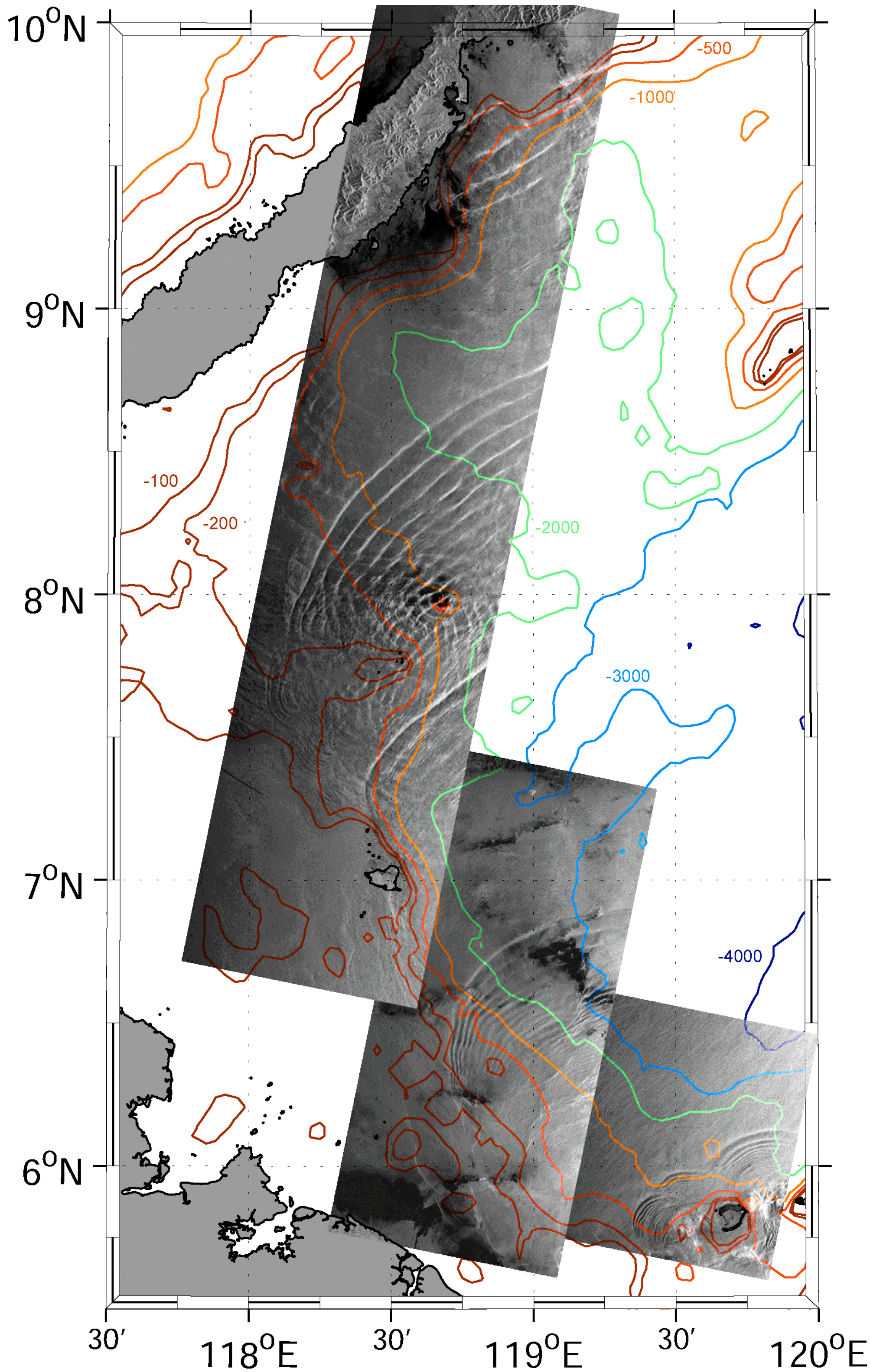


Figure 11. A composite image of ERS-1/2 data from 30 January 1998, 3 July 1996 and 7 April 1996 [see Figures 9, 10 and 12.] shown with the local bathymetry. [Smith and Sandwell, 1997] ERS images ©ESA 1996, 1998. [Images courtesy of The Tropical and Subtropical Ocean Viewed by ERS SAR http://www.ifm.uni-hamburg.de/ers-sar/]

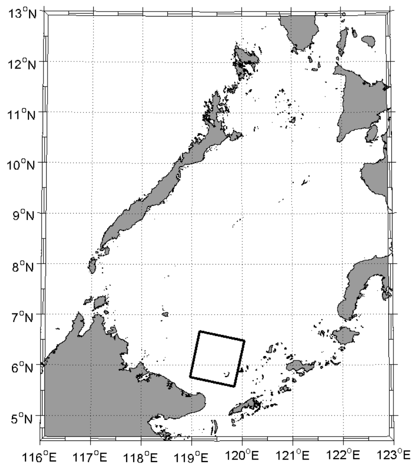
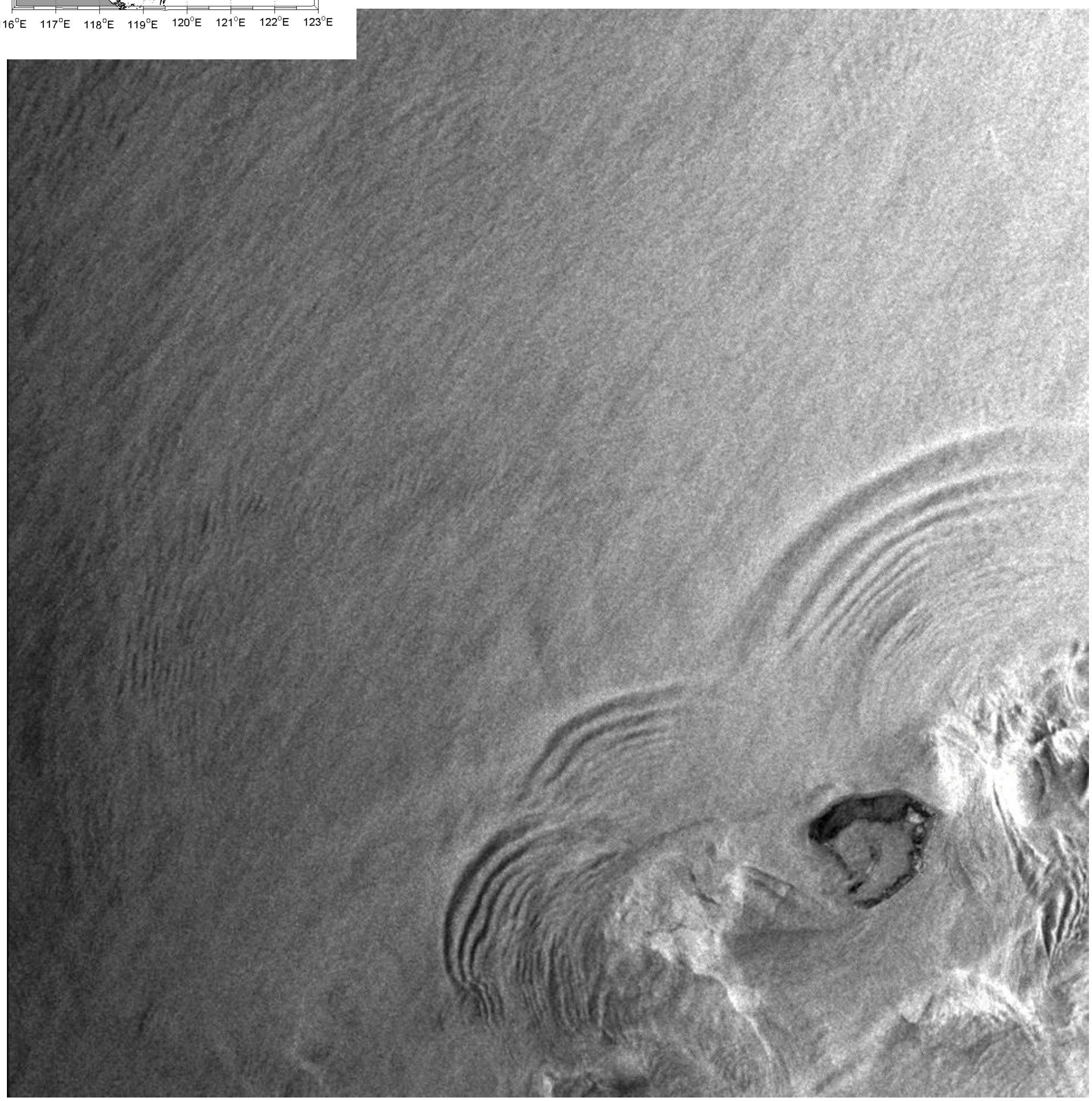


Figure 12. ERS-2 (C-band, VV) SAR image of Pearl Bank acquired on 30 January 1998 at 0224 (orbit 14529, frame 3483). The image shows three recently generated internal wave packets from the region around Pearl Bank. The individual packets will combine to form the large individual soliton packets that propagate across the Sulu Sea. Imaged area is 100 km x 100 km. ©ESA 1998. [Image courtesy of The Tropical and Subtropical Ocean Viewed by ERS SAR http://www.ifm.uni-hamburg.de/ers-sar/]



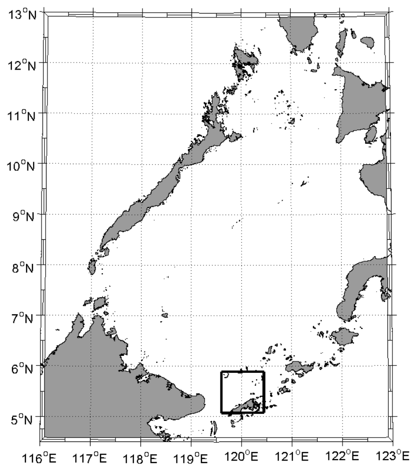
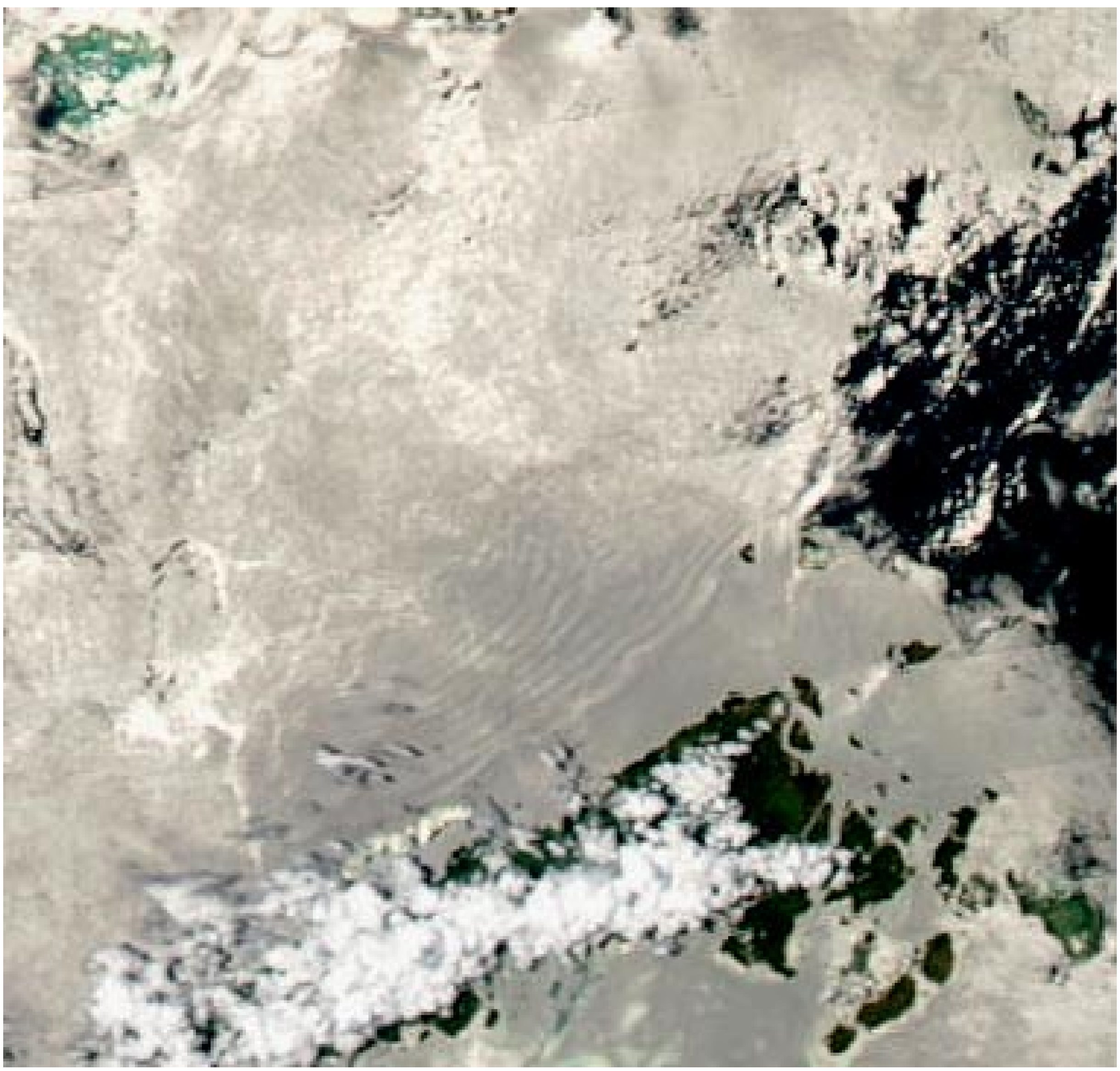


Figure 13. MODIS (Bands 1,3,4) 250-m resolution visible image of the Sulu Sea acquired on 8 April 2003 at 0520 UTC. [see Figure 8 for the larger scene]. The image shows a single internal wave packet propagating south-southeast near Tawitawi Island. Pearl Bank is visible in the upper left. Imaged area is 95 km x 90 km.



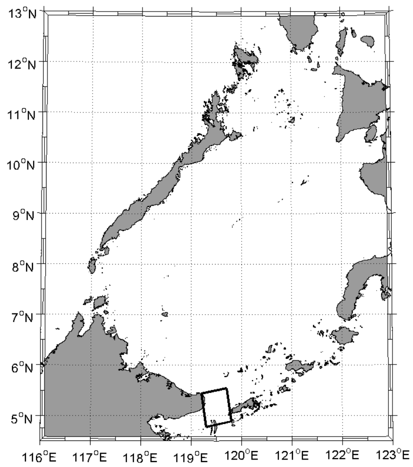
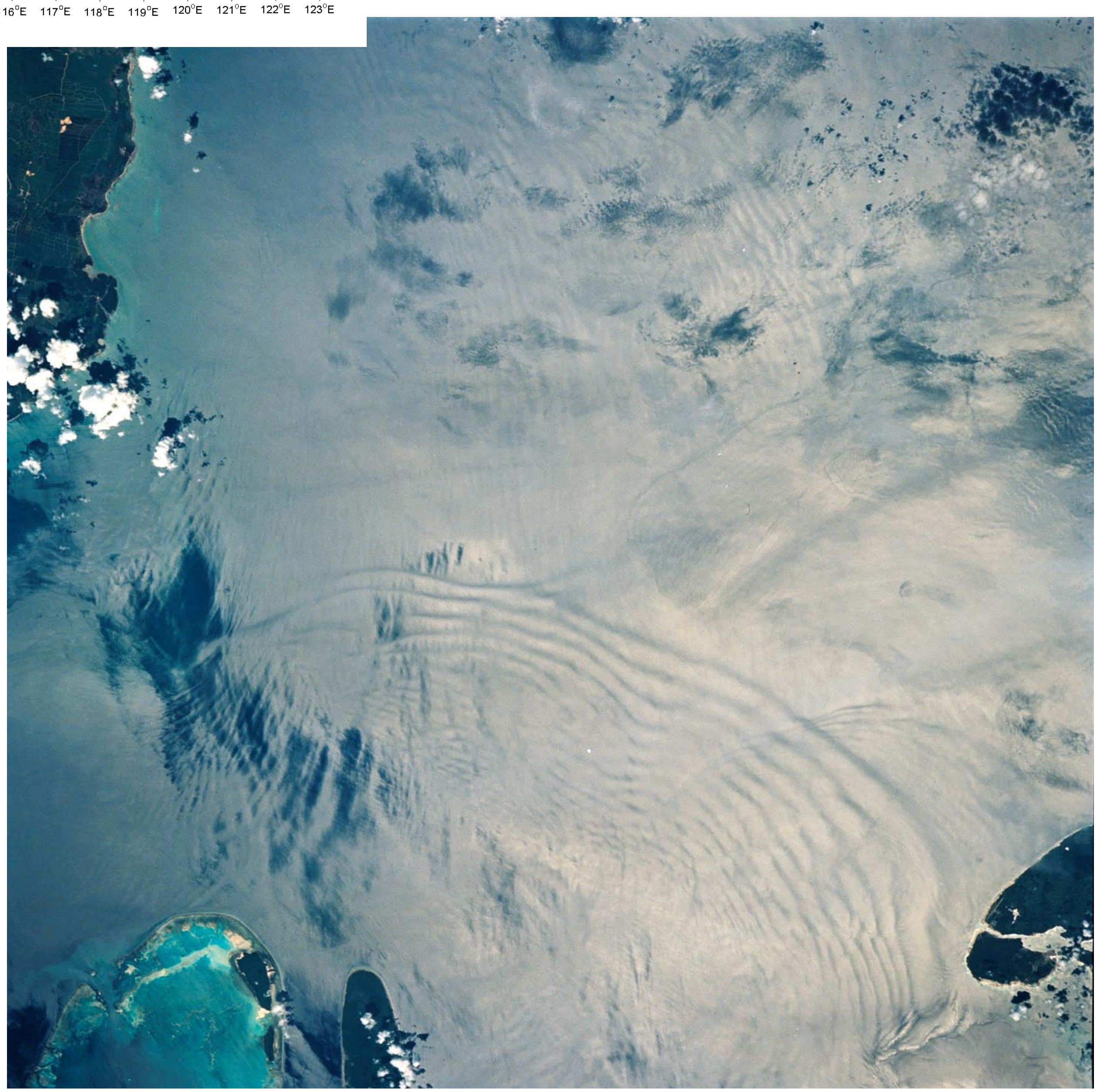


Figure 14. Astronaut photograph (STS038-086-081) over the western end of the Sulu Archipelago acquired on 19 November 1990 at 0334 UTC. Imaged area is approximately 60 km x 60 km. [Image Courtesy of Earth Sciences and Image Analysis Laboratory, NASA Johnson Space Center (http://eol.jsc.nasa.gov)]



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