The Sulu Sea

Overview

The Sulu Sea is located in the western Pacific Ocean along the west side of the Philippines (between approximately 5^o and 11^o N. latitude and 117^o and 123^o E. longitude). It is a deep-water sea, roughly circular with several exits to the Celebes Sea (to the south), the South China Sea (to the west), and the Pacific Ocean (to the east). It is a maritime regime that contains some of the oceans largest solitary waves with observed amplitudes up to 90 m, wavelengths between 5 to 16 km, speeds in excess of 2.0 m/s and lifetimes exceeding 2½ days.

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 up to 5 packets or groups of quasi-periodic waves apparently radiating from a small source at the southern boundary of the sea, then spreading cylindrically and propagating NNW toward the island of Palawan (Figure 5). This imagery lead to an experiment in the Sulu Sea carried out during April and May 1980, when the NOAA research vessel *Oceanographer* spent 22 days collecting a variety of in-situ measurements of the region and its internal wave activity.

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, returning to over 4000 m in the Celebes Sea. These bathymetric changes take place over approximately 150-km 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.

Table 1 presents a summary of internal wave characteristics from the Sulu Sea. The values have been reported in the literature and derived from both in-situ and remote sensing data sources. Internal wave activity in the Sulu Sea occurs year round.

Table 1. Characteristic Scales for Sulu Sea Solitons

Packet Length L (km)	Along Crest Length C_r (km)	Maximum Wavelength λ_{MAX} (km)	Internal Packet Distance D (km)
25 - 35	20 - 170	5 - 16	70-110
Amplitude $2h_0$ (m)	Long Wave Speed c_0 (m/s)	Wave Period (min)	Surface Width l_1(m)
-10 to -90	1.8 - 2.6	14 - 110	1000

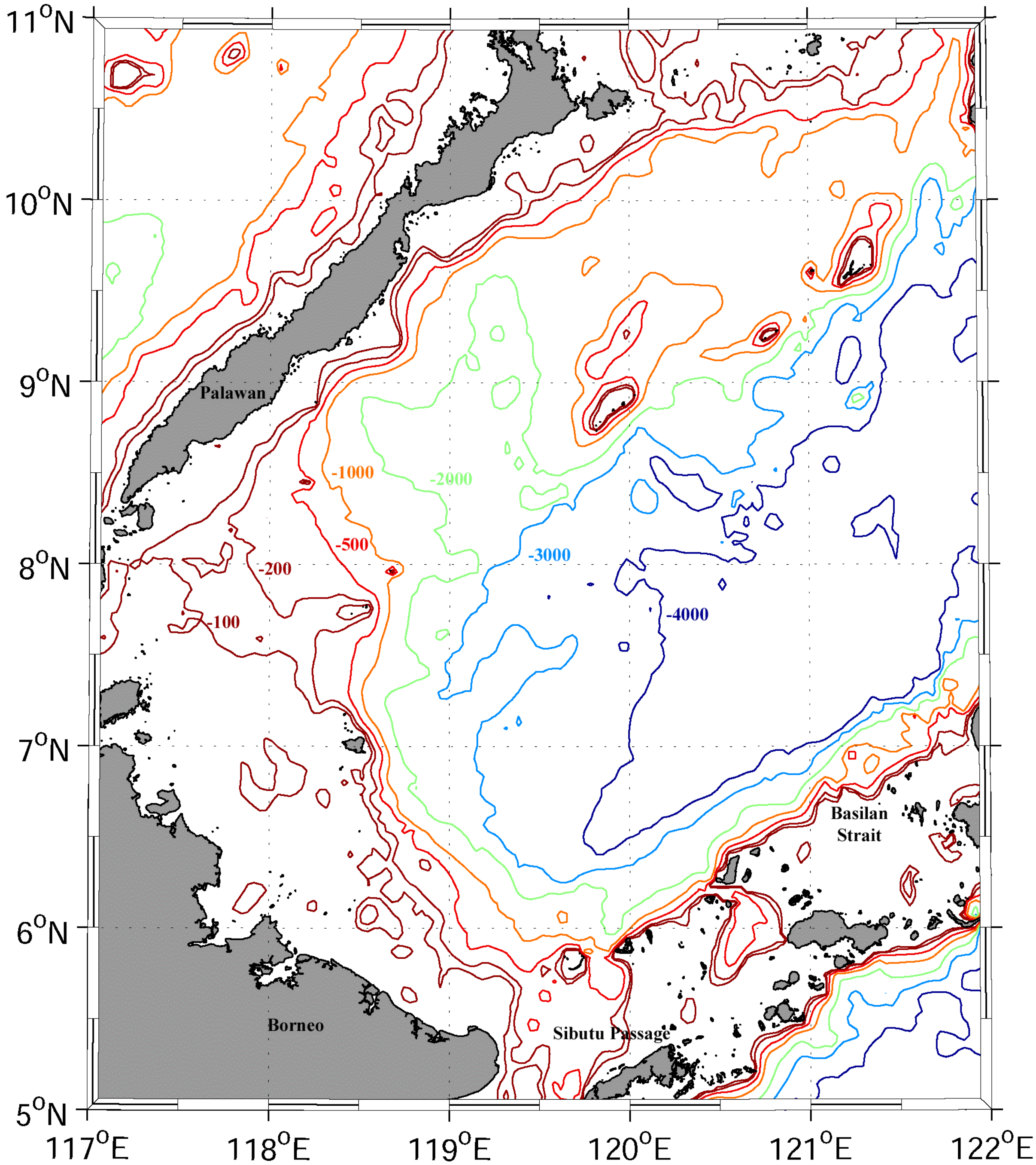

Figure 1: Bathymetry map of the Sulu Sea. Bathymetry derived from Smith and Sandwell version 8.2

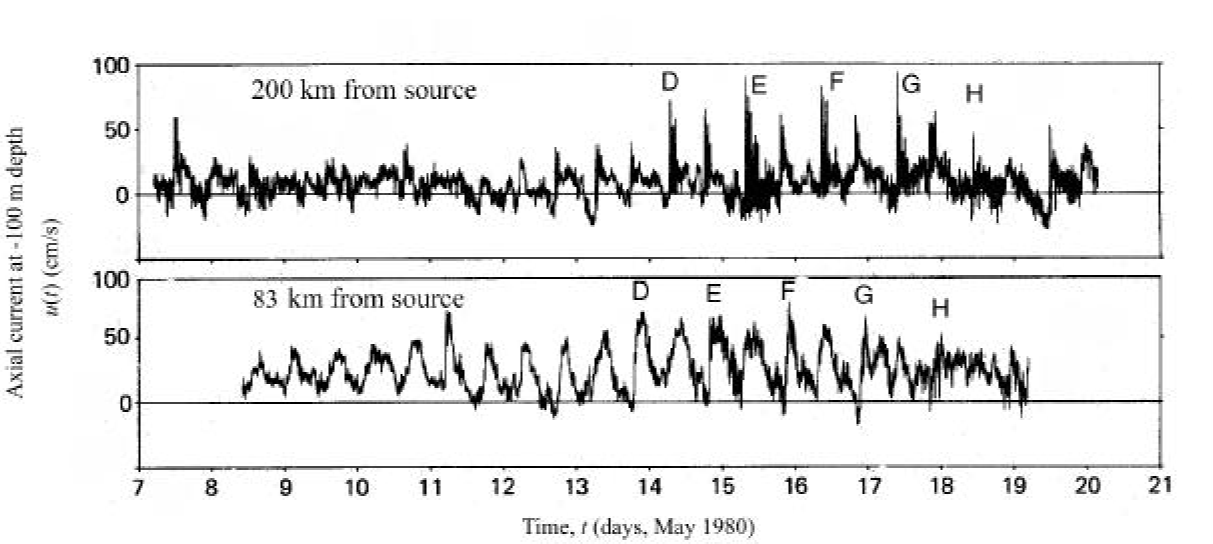

Figure 2. Current meter observations in the Sulu Sea over 11 days, spanning neap (early times) and spring (later times) tides. Solitons appear at D through H. Asymmetry between adjacent packets is due to semi-diurnal and diurnal differences, while the longer-term modulation is due to the fortnightly tides (Apel et al., 1985).

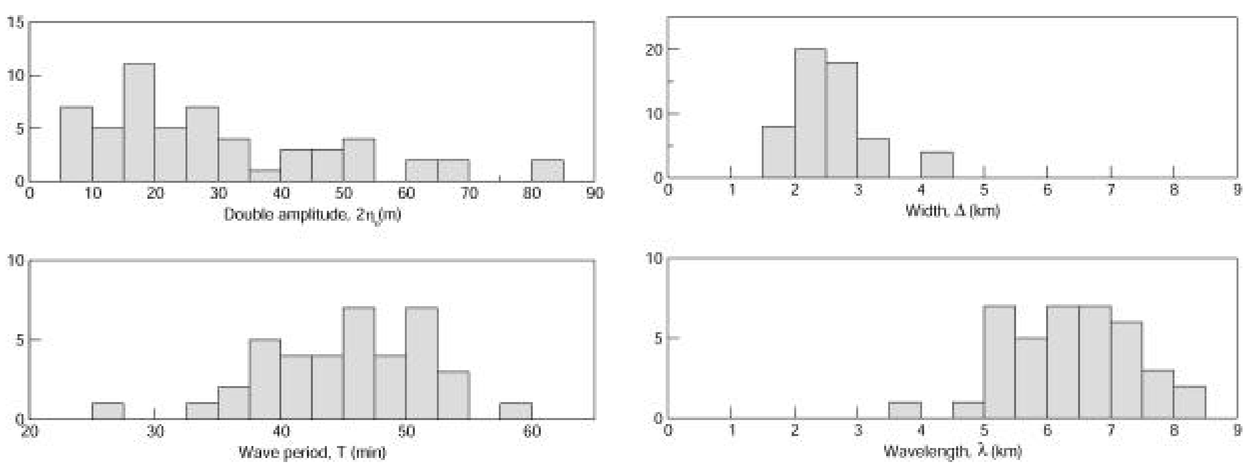

Figure 3a - 3d Histograms showing the distribution of Amplitude ($2h_o$), Period (T), Full Width at Half Amplitude (Δ) and Wavelength (λ) for 56 well developed solitions in 17 packets observed at mooring SS3.

Observations - Sulu Sea Experiment 1980

The experiment conducted during April and May 1980 collected, along with other data, in-situ data from three morrings each with a phased arrary of current meters and thermistors located 1) near the wave source (SS1 near 5^{o}48' N., 119^{o}49' E.), 2) 82 km distant from the source (SS2 - near 6^{o}36' N., 119^{o}36' E.) and 3) 200 km distant from the source (SS3 - near 7^{o}45' N. 119^{o}0' E.)

Figure 2 shows the axial currents for the instruments at a depth of 100 m for moorings SS2 and SS3. The data show that semidurnal 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 solitions. In contrast, 12 to 18 May showed intense internal wave activity. All totaled, the moorings yeiled data on 56 well developed solitons distributed over 17 packets. Characteristics of the solitons observed at SS3 are presented in figure 3a-d.

Imagery

Defense Meteorological Satellite Program (DMSP)

In connection with the Sulu Sea experiment, Apel et al. [1985] performed analyses of DMSP visible satellite imagery collected during March, April and May of both 1979 and 1980. Detailed examination of these data revealed 41 clear scenes capable in principle of showing internal waves, 19 of which actually exhibit a number of individual crests and packets. The internal waves in DMSP images are observed in the sunglint region as stripes of rough (i.e. dark) water. The 1979-1980 imagery show interpacket distances ranging from 56 to 98 km, depending on azimuth and fortnightly tidal phase. Intersoliton distances ranged from 5 to 16 km. A scene from April 1973 is presented in figure 5. The image clearly shows five wave packets propagating toward the island of Palawan at the top of the image. Even at 1-km resolution, individual solitons can be distinguished. The image shows the increases in crest length, wavelength, number of solitons per packet and modifications to the propagation by the bathymetry.

ERS

SAR data from the Sulu Sea collected by ERS 1/2 and Radarsat during the 1990's show the same internal wave patterns and features of the DMSP data. The strong agreement in wave signatures between the radar images and the DMSP data, taken over more than two decades apart, shows the coherency and reproducibility of the generation process. Figure 6 is a composite of 7 ERS scenes taken during three overflights in April 1996, July 1996 and January 1998. Lead soliton wavelengths vary between 2 km, shortly after formation to approximately 14 km as the waves approach at Palawan Island. Interpacket separations, are approximately 100 km for the three packets visible in the April 1996 image. The January 1998 image of Pearl Bank shows that 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. The ERS data, like the DMSP images shows the increases in crest length, wavelength, number of solitons per packet and modifications to wavefronts from the bathymetry. Wavefront variation can be most clearly seen on the west side of the July 1996 image and the lower most packet of the April 1996 image. The April 1996 image shows refraction effects around the San Miguel Islands were small solitons appear to be radiating away nearly orthogonal to the main wave. Finally, a very faint wavefront appears to be propagating southward from Palawan Island, most likely because of some reflection of the incident solitons.

Shuttle Photography

Astronauts photographed Internal waves in the Sibutu Passage south on November 19, 1990 from Space Shuttle Atlantis (STS038-086-081). The image is shown in Figure 7 overlaid with bathymetry and includes the ERS image from January 1998. 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 wavelength of around 1.6-km. These are first known imagery showing internal waves south of Pearl Bank, the source of the Sulu Sea Solitons.

KDV Parameters

Figure 8 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. latitude, 119.6^o E. longitude. The normalized Mode 1 and Mode 2 eignefunctions have been evaluated for $l = \frac{2}{pk_0} = 2120m$, 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 8e and 8f give the phase velocity and dispersion relations for the data. The red curve includes the effect of current. Table 2 presents the environmental coefficients and KDV parameters evaluated at k_0

Table 2. 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) h_0 (m)	Non-Linear Phase Velocity V (m/s) for (s^2=1)
2.04	-93.8	132.6	-21.8	2.36

Environmental Coefficients and KDV parameters (λ_0=2120) Sulu Sea Solitons (with Current)

Long Wave Speed c_0 (m/s)	Nonlinear coefficient $1/\alpha$ (m)	Dispersion Factor $\gamma^{1/2}$ (m)	Amplitude (KDV theory) h_0 (m)	Non-Linear Phase Velocity V (m/s) for (s^2=1)
2.09	-96.3	138.1	-24.2	2.43

References

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.

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.

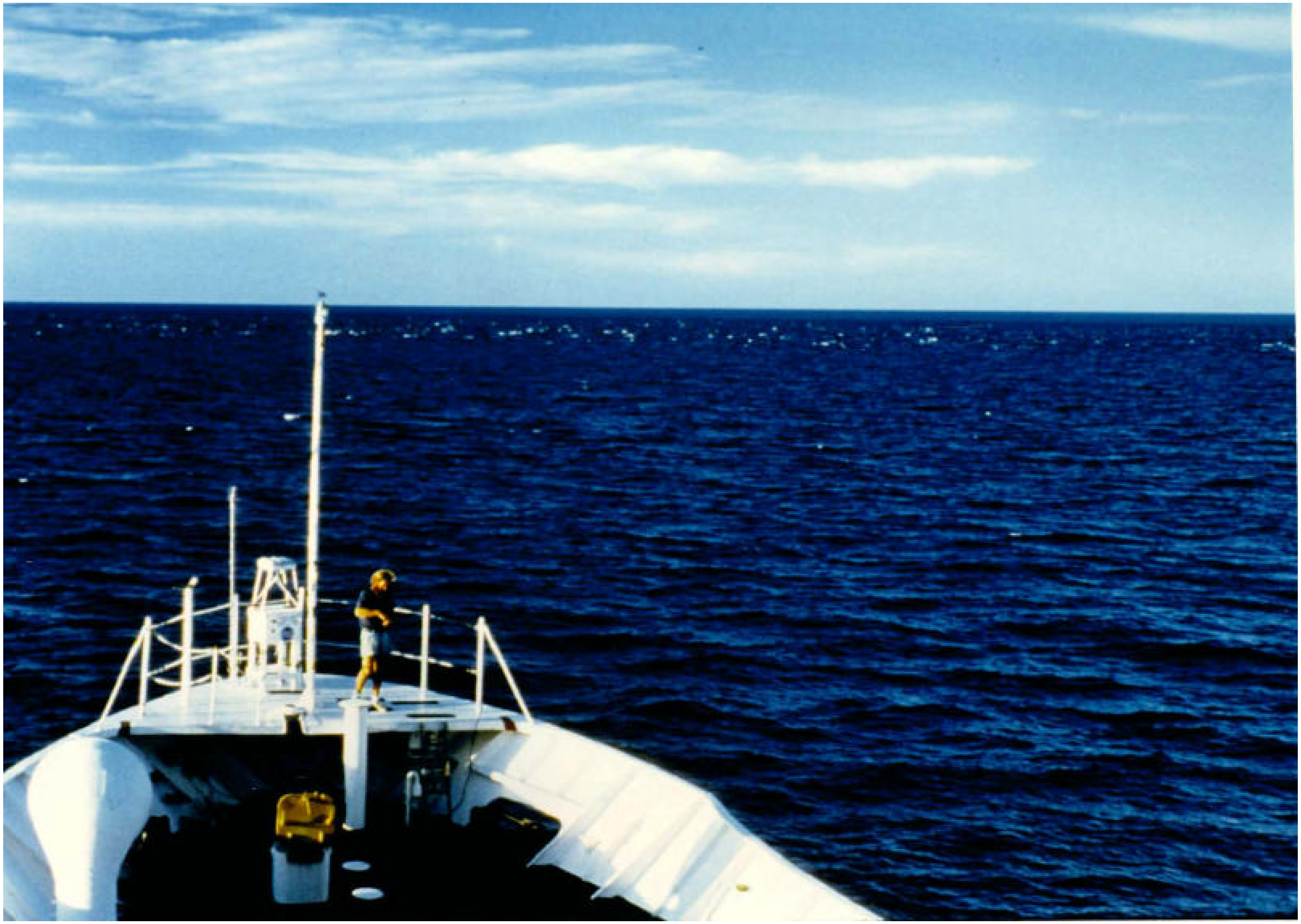

Figure 4: Photograph of the surface of the Sulu Sea surface taken as a soliton approaches the NOAA research vessel Oceanographer. The breaking surface waves had approximately 1-meter amplitude and were audible as they passed the ship. [Taken from Apel and Holbrook 1983]

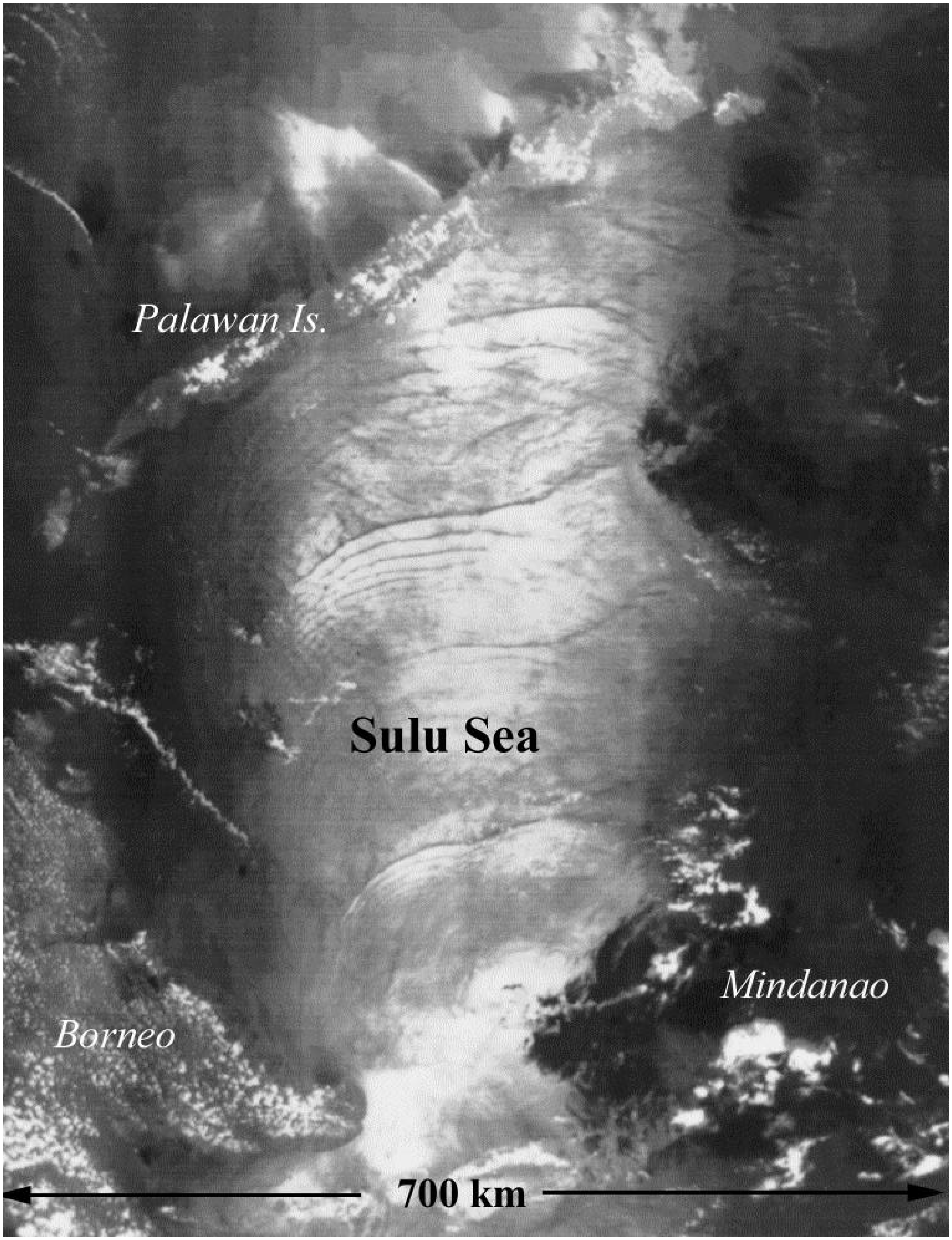

Figure 5 DMSP image of Sulu Sea, Philippine Islands, acquired in April 1973, made in visible light. Solar reflection shows roughness modulations from five groups of large internal solitons generated at a small sill between Mindanao and Borneo. Figure courtesy of U.S. Air Force.

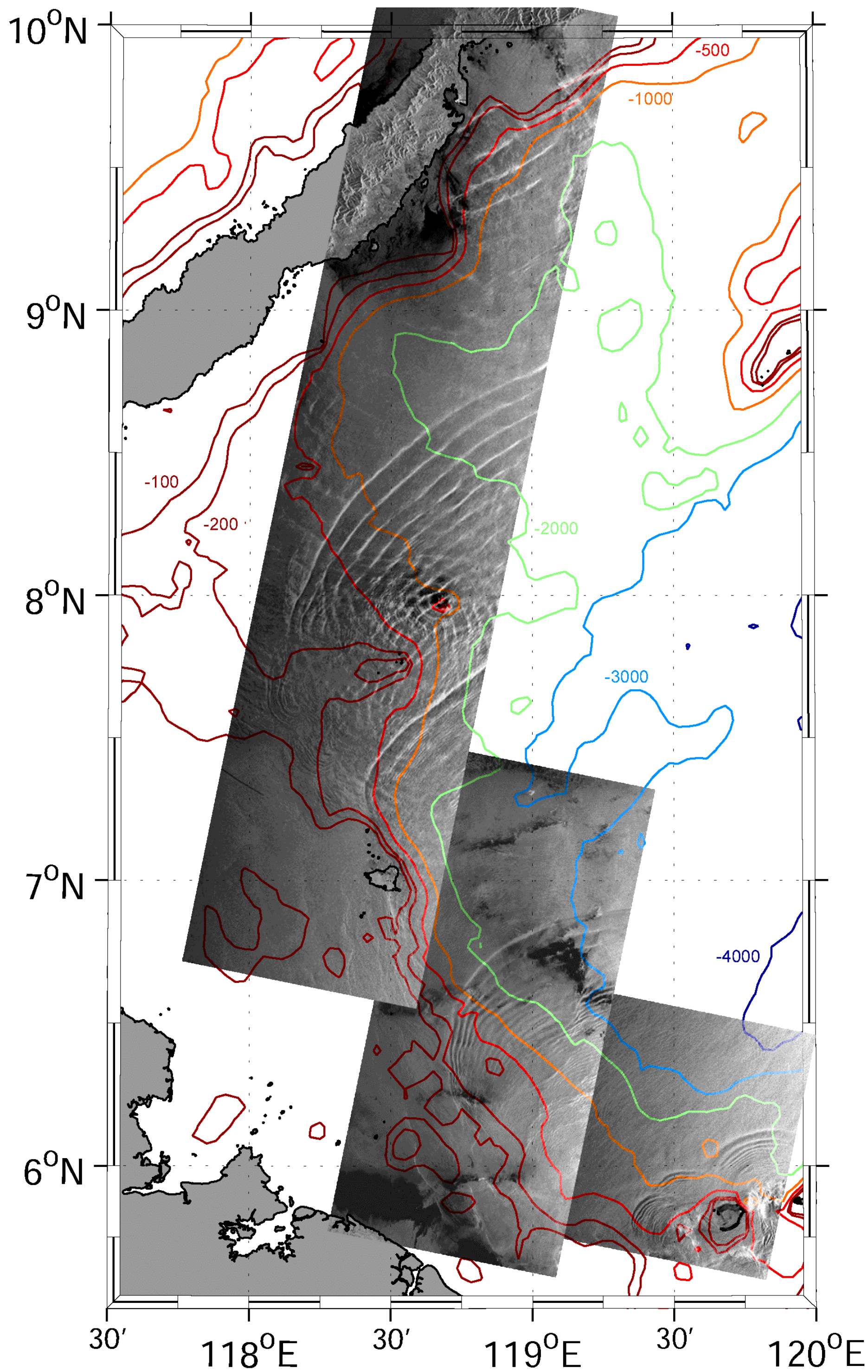

Figure 6. A composite image of ERS-1/2 data from three over passes. [ERS images ©ESA 1993, from The Tropical and Subtropical Ocean Viewed by ERS SAR http://www.ifm.uni-hamburg.de/ers-sar/]

Orbit	Frame(s)	Satellite	Date	Time
14529	3483	ERS-2	30-Jan-1998	2:24
6284	3465-3483	ERS-2	03-July-1996	2:27
24726	3411-3429-3447-3465	ERS-1	07-Apr-1996	2:30

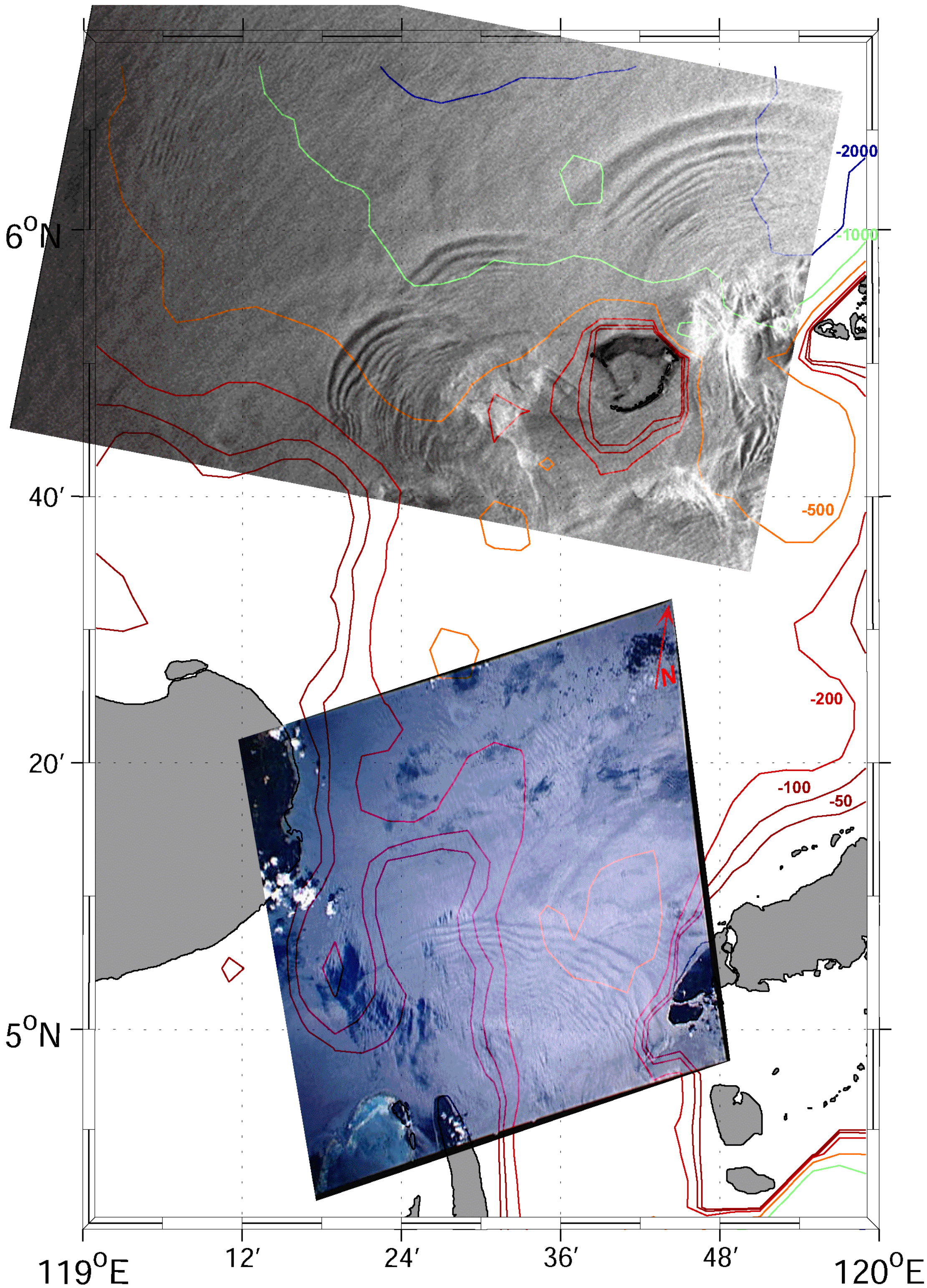

Figure 7. Space Shuttle Photograph (STS038-086-081) shown with ERS-2 SAR image from 1998 and local bathymetry. STS038-086-081 was acquired on November 19, 1990 03:34 GMT. Image dimensions of STS038-086-08 are approximately 61 x 61 km. Image Courtesy of Earth Sciences and Image Analysis Laboratory, NASA Johnson Space Center (http://eol.jsc.nasa.gov).

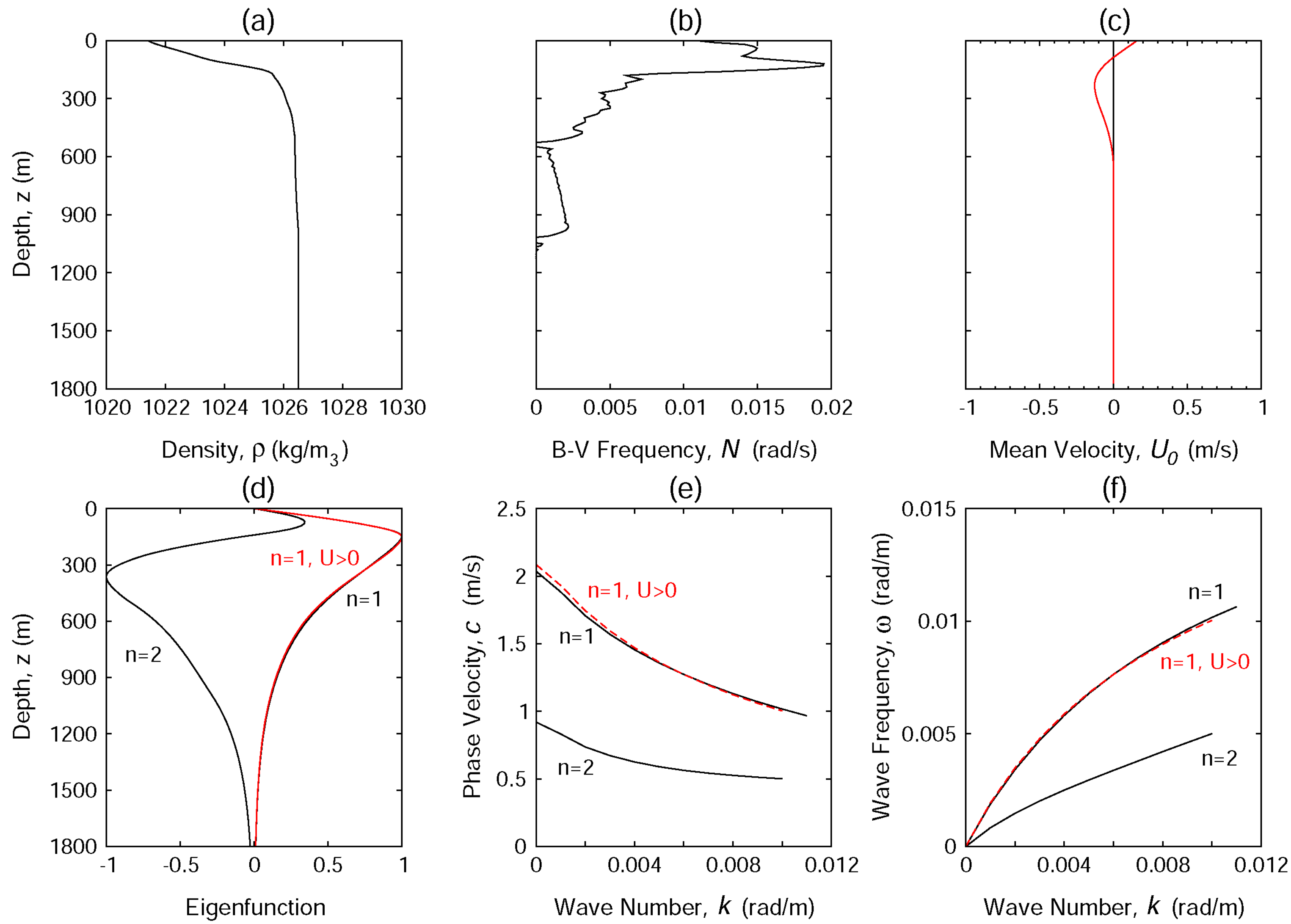

Figure 8. a) Density Profile derived from data collected at mooring SS2 (near 6.6°N. latitude, 119.6° E. longitude, depth ≈ 3500 m) during April and May 1980 b) derived Brunt-Väisälä frequency *N*(z) c) current flow profile d) Normalized vertical eigenfunctions (mode 1 & 2) for $2/\pi k_0$ = 2120 m, 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.