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Results from the Gibraltar Experiment on the Exchange between the Mediterranean and Atlantic Basins

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A major field program was carried out in the Strait of Gibraltar from October 1985 to October 1986, involving approximately 20 research groups from the United States, Spain, Morocco, Great Britain, France and Canada. The goal of the Gibraltar Experiment is to understand how the dynamics of two-layer flow through the narrow and shallow Strait controls the amount of exchange between the Atlantic and Mediterranean basins. Here, we present a brief summary of the research projects carried out as part of the Gibraltar Experiment. Next, we show that the estimate of the outflow of Mediterranean water through the Strait depends on a definition of the characteristics of the outflowing water. Finally, we discuss the investigations of the hydraulic control conditions for the two-layer flow through the Strait.

The research projects consisted of synoptic shipboard surveys, moored time series measurements and modeling studies. Five hydrographic cruises were carried out over the year-long experiment including CTD stations and water sample analyses for salinity, freons and trace elements in order to examine the hydrographic structure and the heat and salt transport of the flow through the Strait. Two cruises measured turbulence and dissipation and one examined the internal hydraulics at critical regions in the Strait. There were shore-based radar and airborne synthetic aperture radar measurements of the solitary waves propagating eastward into the Mediterranean. Finally, there was a study of the funneling effect of the atmospheric flow due to the Strait orography during high wind events. The moored time series measurements consisted of 30 moorings measuring currents, pressure, sea level, temperature and salinity throughout the year-long period at critical locations (Figure 1). Modeling studies emphasized the problem of hydraulic control of the two-layer flow by the combination of sills and narrows present in the Strait.

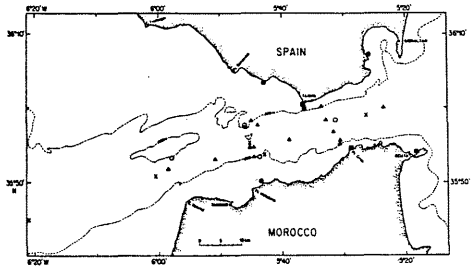

Figure 1. Gibraltar Experiment mooring array. Not all locations were occupied for the duration of the experiment. The mooring array was designed to provide intensive coverage at one across-strait section (Camarinal sill, northeast of Tangier), good along-strait coverage, and less intense coverage at a second across-strait section (in the narrowest part of the strait, east of Tarifa). The along-strait moorings generally follow the deep outflow path, which is south of the centerline west of the sill. Solid circles indicate sea level gages, open circles are bottom pressure gages, solid squares are meteorological stations, open triangles are doppler acoustic profilers, closed triangles are current meter moorings, and crosses are thermistor chain moorings (the four crosses in the along-strait alignment included current meters).

On the first hydrographic cruise, observations were made of western Mediterranean deep water exiting directly over the sill confirming a long-standing hypothesis. The moored current meter measurements show that the time-averaged Eulerian outflow over the sill is only 0.4 Sv. However, the interface between Atlantic and Mediterranean waters moves up and down over the tidal cycle and when the interface is shallow there is strong outflow of Mediterranean water. The current and salinity time series show that the strong correlation between the outflow velocity and the depth of the Mediterranean water yields a net outflow salinity transport (above a base Atlantic water salinity of 36.2 ppt) of 1.5 Sv ppt. Thus, the outflow can be considered to be either a 0.7 Sv outflow of pure (S = 38.4 ppt) Mediterranean water or a 1.1 Sv outflow of mixed (S = 37.5 ppt) Mediterranean-Atlantic water.

Many of the measurement programs were designed to investigate the hydraulic control conditions of the flow through the Strait. The flow at the sill exceeds a critical Froude number of one for short periods during nearly every semidiurnal tidal cycle. Critical Froude number flow was also observed at certain times in the narrowest part of the Strait just east of Tarifa. Also, the outflow over the westernmost sill north of Cape Spartel was always observed to be close to critical Froude number. Thus, the flow does appear to be hydraulically controlled at certain places and times. A remaining issue is to determine whether the two-layer exchange through the Strait is maximal or submaximal. Both hypotheses have been put forward and a close examination of the time series of the eastern parts of the Strait is being carried out to distinguish between the two.

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Resonant generation of nonlinear internal waves in a channel

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Satellite remote sensing and field experiments have shown that regions of abrupt topographic change can be the sites of significant internal wave activity in the coastal oceans. In Gibraltar Strait the exchange flow over bottom topography and past lateral constrictions gives rise to periodic generation of internal waves that propagate into the Alboran Sea. In the Gulf of California, tidal flows in the channels and past islands generate internal waves which propagate into the northern regions of the Gulf. If the waves were linear and dispersive they would decay in amplitude and not be of significance far from the generation site. The observation that the flows which generate the waves may be near a critical Froude number makes resonance and finite amplitude effects of interest. The balance between nonlinearity and dispersion then makes waves of (almost) permanent form which can propagate to great distances from the generation site.

There has been a great deal of interest in the resonant generation of nonlinear waves by moving disturbances in nonrotating systems (see WU (1987) for a review), and some work on the forcing of nonlinear Rossby waves ; however, little has been done on the generation of nonlinear Kelvin waves. Indeed, the subject of nonlinear Kelvin waves is one of some controversy (MAXWORTHY, 1983 ; GRIMSHAW, 1985 ; RENOUARD et al., 1987 ; KATSIS & AKYLAS, 1987). The primary result in the nonrotating case is that three-dimensional forcing may lead to two-dimensional solitary waves upstream. This result is unlikely to hold in rotating systems in which rotation influences the reflection process that permits the transition to two-dimensional waves upstream. Further, the presence of other modes, most notably Poincare waves, leads to a more complicated picture.

Experiments were conducted, at the Coriolis Laboratory, I.M.G., to investigate the generation of nonlinear waves upstream of a transcritical disturbance in a rotating channel. A channel 10 m long and 2 m wide was placed on the large rotating platform. The channel was stratified with layers of fresh and salt water. A "ship-shaped" body was suspended from a motorized carriage and towed at constant speed along the channel. Internal waves were measured with a set of interface followers.

The measurements show that nonlinear waves are generated upstream. The leading wave profile at the wall has a sech^2 shape, similar to a KdV solitary wave (cf. RENOUARD et al., 1987). The nonlinear correction to the wave speed is proportional to the amplitude at the wall, which increased with increasing Froude number in the transcritical regime ; although some experiments showed a local maximum at supercritical Fr (cf. MELVILLE & HELFRICH, 1987). The decay of the wave across the channel was approximately exponential (scaling on the Rossby radius), with a tendency to be a little slower at the larger Froude numbers. The waves showed a clear change in phase across the channel, consistent with the curvature observed in earlier related experiments (MAXWORTHY, 1983 ; RENOUARD et al., 1987).

The results are discussed in the light of the recent controversy regarding the existence of solitary Kelvin waves. In particular, attention is drawn to the fact that for some parameter ranges transcritical forcing of Kelvin waves is not separable from transcritical forcing of Poincare waves ; in consequence of which the presence of both modes may be anticipated.