news and views

The oceanography of fjords

from David M. Farmer and Herbert E. Huppert.

FJORDS, inlets or sea lochs are deep, twisting arms of the world's oceans, generally formed by glacial erosion. In sharp contrast to the depth of the main basin — up to 1700 m — most fjords have a shallow sill at their mouth, of between 1 and 10^2 m, and sometimes with second, third and further sills. All fjords are influenced by the tides, the prevailing winds and fresh water input from rivers. Some, particularly those in the Artic, are covered with ice for part of the year. Many people live along their shores, especially in Scandinavia, and have come to rely on the fjords for water, food, the disposal of waste and recreation. All these demands are interconnected, so that the ill-considered construction of a hydroelectric scheme, for example, will modify the water circulation, which in turn can decrease the production of herring in the fjord and of codling on the continental shelf. Man's intervention can also seriously disturb the millions of juvenile salmon which use fjords as highways on their seaward migration and depend throughout their journey on food produced in the fjords.

Scientifically, fjords provide a relatively simple system for investigations which can also contribute to knowledge of the open ocean. All these aspects were borne in mind at a recent NATO Advanced Research Institute on the physical, biological and chemical oceanography of fjords.*

G.L. Pickard (University of British Columbia) and B.R. Stanton (New Zealand Oceanographic Institute) have compiled a detailed description of the water characteristics in Pacific fjords. In contrast to the open ocean, their density structure is controlled almost entirely by salinity (rather than temperature). In Pacific fjords the salinity almost always increases with depth, whereas the temperature and dissolved oxygen generally decrease slightly. The river run-off near the head of each fjord, although very variable, can make an important contribution to the circulation. Fjords with high river run-off have well-mixed layers up to 10 m in depth, and there tends to be some movement in the deep water. The Alaskan and Chilean fjords with glaciers flowing into them, in contrast to those without, tend to have a positive dissolved oxygen anomaly at depth and a stepped salinity structure. This can be explained in terms of the predominantly horizontal flow, in a series of layers, of the glacier melt water and the extra oxygen contained in the ice as suggested recently (Huppert & Turner *Nature,* **271,** 46; 1978). Although morphologically similar to Pacific fjords, Scandinavian fjords typically experience smaller tides and this may have important consequences for the types of mixing process which dominate. A further distinction is that New Zealand fjords are short, have relatively deep sills and their circulation, in contrast to other fjords, tends to be set by the oceanographic conditions along the coast.

R.R. Long (Johns Hopkins University, Baltimore) felt that rare but severe disturbances, such as bad storms, could be responsible for a considerable amount of the vertical mixing and affect the circulation in fjords and in the deep ocean. The concept that rare, large, inputs might be considerably more influential than the inputs usually observed, was much discussed, but the final consensus was that the available data from all sources were not sufficient to make a definitive statement.

The renewal of deep water, due to the occasional flow of relatively heavy water over the sill into a fjord may occur over a range of time-scales — as infrequently as only once every 7 years in one case — in response to a combination of tidal range, strength of the off-shore winds, amount of river run-off and interaction of the flow produced by these effects with the major sills (A. Edwards, Dunstaffnage Marine Research Laboratory, Scotland). In between renewal, diffusion and mixing slowly decrease the salinity at depth, thus helping to promote the next renewal. Mixing may be the result of the breaking of internal waves and of turbulence generated by the tidal flow past the boundaries, although the magnitude of both these mechanisms is uncertain. D. Dyrssen (Göteborg University, Sweden) drew attention to the practical importance of deep-water mixing in connection with pollution. Deep water exchange is also crucial in determining the amount of available oxygen, which in turn produces changes in the distribution of species and alterations in feeding behaviour.

From the results of the JASIN (Joint Air-Sea Interaction) experiment R. Pollard (Institute of Oceanographic Sciences, UK) pointed to three mixing processes believed to be relevant to the oceanic thermocline and possibly to the halocline in a fjord. First, there is the instability, wave breaking and mixing due to shear, which Pollard believed to be infrequent and unimportant in the oceanic thermocline. Second, there is the motion along isopycnals, as for example, across fronts. Third, there is the motion across isopycnals due to double-diffusive effects. The importance of the last effect is still controversial, but data from the open ocean continue to affirm its influence and Pollard discussed additional confirmation in data taken by M. Gregg (University of Washington, Seattle). Laboratory experiments by B.R. Ruddick and J.S. Turner (*Deep-Sea Res.*, in press) indicate that double-diffusive effects may also play a part in mixing across fronts. Pollard then pointed to processes believed to be relevant in the mixed layer: the generation of Kelvin-Helmholtz billows, with subsequent mixing, surface wave breaking and Langmuir circulation due to interactions between surface waves and shear in the water. Various theoretical models have been proposed to predict features of the upper mixed layer, but it seems that the models are more sophisticated, though less realistic, than warranted by the data.

One of the most comprehensively observed North American fjords is Knight Inlet in British Columbia and an impressive array of phenomena have been documented there. Acoustic soundings indicate that there is a large amplitude internal response to the tidally forced flow

* The Fjord Oceanographic Workshop was held at the Institute of Ocean Sciences Patricia Bay, British Columbia from 4 - 8 June, 1979. The proceedings are to be published by Plenum in their Marine Science Series, edited by D.M. Farmer and H.J. Freeland.

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over the sill. At the beginning of the ebb tide, the flow separates behind the inner sill and there is a large amplitude periodic disturbance on the shear layer emanating at the sill crest, at a depth of approximately 60 m. As the tidal flow increases, a large-amplitude, stationary lee-wave train, or more usually an internal hydraulic jump, is set up in the stratified layer in the lee of the sill. Such an event is shown in the illustration along with the laboratory simulation. The strong flow associated with the accelerated flow down the lee face of the sill suppresses the separation, in agreement with recent theoretical and laboratory experiments of P. W. M. Brighton (Ph.D. Thesis, University of Cambridge). As the tide slackens, waves propagate upstream, since their phase velocity is now larger than that of the opposing tidal flow. This is the same phenomenon as documented by acoustic measurements in the vicinity of Stellwagen Bank in Massachusets Bay (Haury, Brisco & Orr *Nature* **278**, 312; 1979), a model of which was investigated in the laboratory (Maxworthy *J. geophys. Res.* **84**, 338; 1979). From measurements taken by the small manned submersible Pisces IV, A. Gargett (IOS, British Columbia) found that the wave train in Knight Inlet has an amplitude of 10 m, is highly turbulent and has a very strong down-ward velocity at its front. The flood tide may set up a similar train of waves, which propagate downstream as the tide slackens, but they are of smaller amplitude and possibly of different character because of the asymmetric geometry of the sill.

Long discussed refinements of his two-layer frictional model for the circulation in a fjord, presenting an updated parameterisation of the friction to allow for a better comparison with data from Knight Inlet. Nevertheless, a consequence of the model, that the Froude number at the mouth be 1.0 (the critical value) is not reflected in recent data taken in Knight Inlet, which indicates that the value is close to 0.3.

Some of the many practical problems in fjords were skillfully described by Scandinavian workers. Careful consideration of the energy exchange between the barotropic and baroclinic tidal response over a sill indicates that some fjords have constrictions which make them close to resonant. This suggests that relatively small modifications of the constriction, such as altering the depth of the sill or placing a floating bridge or barrier over the sill, may bring the fjord closer to resonance. This would increase the tidally-generated internal response and lead to enhanced mixing.

The siting of hydropower installations and the depth of the fresh water discharge into a fjord can have enormous influence on the water characteristics; in particular, a fresh water layer, sufficiently deep and cold, on the top of a fjord can promote undesirable ice cover throughout the winter. T. Carstens (Norwegian Institute of Technology, Trondheim) explained that submerging the output and introducing compressed air into it enhances the mixing in the upper layers and increases the salinity at the surface, thereby inhibiting ice formation. T.A. McClimans (Norwegian Institute of Technology, Trondheim), described models for the point release of a fresh water supply into a fjord, incorporating tidal effects, which have been successfully used in a number of situations.

A novel technique for studying the circulation in the Clyde Sea Area fjord involving the use of radioactive pollutants from Windscale was presented by I.G. McKinley (University of Glasgow, Scotland). Caesium-134 and 137, which have different half lives (2 and 30 years), provide an ideal tracer pair for studying vertical diffusion, sedimentation rates and other exchange processes. The caesium was detectable as far away as off Northeast Scotland, suggesting that this procedure may be ideally suited for ocean circulation studies elsewhere. □

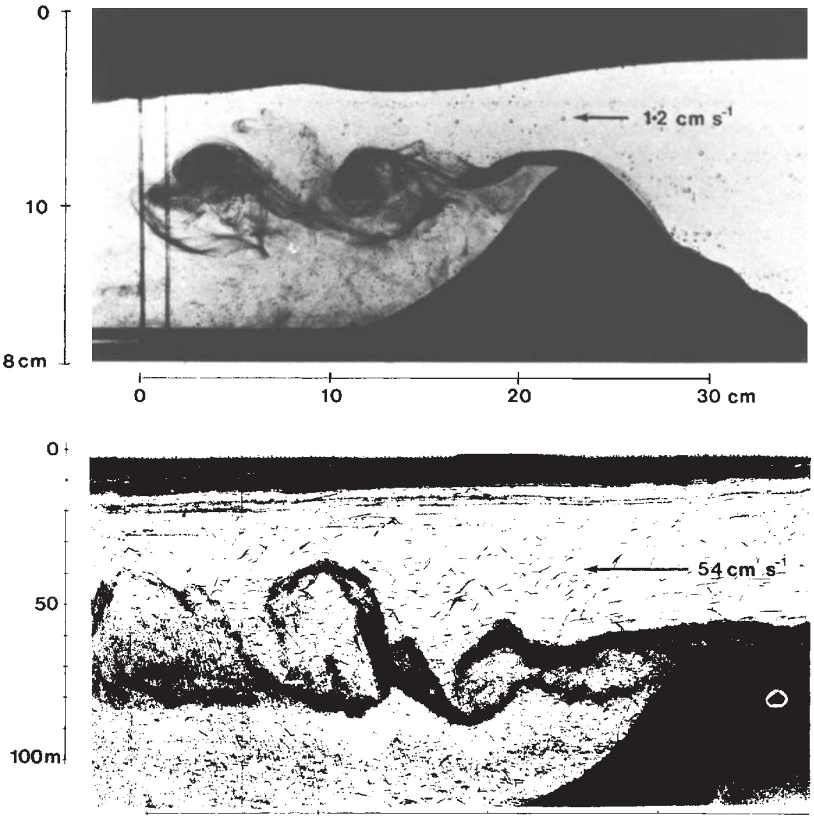

Fig.1. Tidally-generated flow in the laboratory (bottom) and Knight Inlet, British Columbia (top), showing the effects of flow separation and large-amplitude billows.

Changing cometary orbits

from David W. Hughes

TWO principal mechanisms are available for changing the orbit of a comet. The first is gravitational and relies on the proximity of a planet to perturb the comet's path. The change in the reciprocal of the semi-major axis of the orbit then suffers a random walk which is approximately proportional to the square root of the number of returns the comet makes to the inner Solar System. The second is non-gravitational and is due to the fact that gases given off by the cometary nucleus are not emitted symetrically in all directions. The importance of this second force was first realised in the early 1820s when Comet Encke consistently passed perihelion 2.5 h before the predicted time.

Imagine an icy conglomerate cometary nucleus which is not rotating. The maximum emission of the sublimating volatiles will occur on the sunward side, around the subsolar point. This jet of gas will effectively exert a force on the nucleus in the direction away from the Sun. Now if the nucleus rotates and if there is a time lag between the absorption of the solar radiation by the dusty surface of the nucleus and the sublimation of the cometary ices, then the effective force is not radial; this force will have a transverse component along the orbit of the comet and also a normal component perpendicular to this orbit. Marsden, Sekanina and Yeomans (*Astron. J.* **78**,

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