International Council for the Exploration of the Sea
C.M.1974/C:35
Hydrography Committee

Wind-driven Circulation in a Spanish Estuary

Joseph Chase
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts 02543

Abstract

The Ría de Arosa, located on the Atlantic coast of northwest Spain (Galicia), is highly productive of mussels. The nutrients required to support this fishery apparently are supplied to the estuary by an inflow of oceanic water ($S \approx 35.6$ ‰) along the bottom while surface waters are being blown out to sea by northeasterly winds. Salinity, which has been observed to correlate positively with the abundance of nutrients within the estuary, is used as a tracer. The salinities observed in two seasons at various locations in the estuary are shown to vary with the wind flow as indicated by weather maps and by an assessment of topographical influences.

Introduction

The rías of the Atlantic coast of Galicia have been known for their shellfish for centuries. Shortly after World War II the cultivation of mussels by the Japanese raft method was begun. The mussels are grown on ropes 10 m long suspended below the rafts. The system has proved to be highly successful and the number of rafts in the various estuaries is in the thousands. The most successful of the estuaries thus far is the Ría de Arosa. It is a matter of scientific interest and probably one of commercial importance to understand why the Ría de Arosa is so productive and why it compares so favorably with three neighboring rías, named for their principal municipalities Muros y Moya, Pontevedra and Vigo (fig. 1). Among the elements considered as possibilities for explaining the abundance are shelter from waves, bottom configuration and nutrient supply. Since the nutrients necessary for the growth of the phytoplankton upon which the mussels graze are believed not to come from the land, in this region, it has been presumed that they come instead from the sea and that wind may cause upwelling and an indraft of nutrient-laden water near the bottom (Cadee 1968, Gallego 1971).

The few observations of nutrients which have been made in the Ría de Arosa to date indicate a distribution with depth similar to that of salinity and both distributions indicate the presence at depth of oceanic water (K. R. Tenore personal communication and Fuglister 1960). Salinity has been observed at several locations in the estuary in two seasons (Gallego 1971 and personal communication) and these data are used here to indicate current flow and to compare with wind.

Wind observations in the rías are scarce so that it became necessary to resort to the reading of surface weather maps (U. S. Dept. of Comm., 1968 and 1969) for an indication of general air flow in the area. Plotted observations from Spain and Portugal and from ships along the coast were helpful in interpreting the isobaric patterns. To understand better the funneling of wind by mountains a survey of Galicia was made by automobile and various relief maps of the area were consulted.

The essence of the study of terrain is depicted in Figure 1 which shows the four principal estuaries, the watersheds of their rivers and the 400 m contour and gives an indication of where the higher elevations lie.

It is clear from the study that northerly winds can progress southward about as far as the watersheds of the Ulla and the Umia which empty into the Ría de Arosa, without much hindrance from terrain but that then much of the air must be deflected westward by the abrupt rise of the mountains in the western part of the Provincia de Pontevedra. Thus northerly winds which occur in all seasons but which predominate in summer can easily traverse the watershed of the Río Tambre, which empties into the Ría de Muros y Moya, but most likely become northeasterlies in the valley of the Ulla and follow that valley to its mouth in the Ría de Arosa and thence blow out to sea. Some of this air may detour through the valley of the Umia, which also enters the Ría de Arosa. The valleys of the Lérez, which flows into the Ría de Pontevedra, and those of the Oitaben and Verdugo, which flow into the Ría de Viga, would be somewhat sheltered from this kind of flow. Katabatic effects, so important in mountainous regions when the nights are clear, calm and cool should be much favored by the large low-lying valley of the Ulla.

Since the process of wind determination was somewhat subjective it was carried out without reference to the salinity data. Wind was read from surface weather maps for 000, 0600, 1200 and 1800 GMT for each day of July 1968, January 1969 and February 1969 to cover the periods of the two cruises reported by Gallego.

In summary, these show for the area as a whole

July 1968

1 - 5	northerly 5 - 15 kts
6 - 13	various directions and speeds
14 - 17	northerly 5 - 15 kts
18 - 27	northeasterly 15 - 20 kts diminishing to 10 - 15 kts
28 - 31	northerly 10 - 15 kts

Favorable dates for northeasterly katabatic winds: 6th and the 12th

January 1969

1 - 4	easterly 5 - 15 kts
5 - 18	mostly southwesterly 10 - 20 kts
19 - 21	southerly 15 kts
22 - 25	light southerlies and calms
26 - 28	southwesterly 10 kts
29 - 31	light variable or calm

Favorable dates for northeasterly katabatic winds: 5th, 22nd, 23rd, 24th, 25th, 29th, 30th and 31st.

February 1969

1 - 2	light variable or calm
3 - 10	easterly 15 kts diminishing to calm on the 7th then increasing to 20 - 25 kts by the 10th
11 - 15	northerlies 20 - 30 kts
16 - 21	southerlies 5 - 15 kts
22 - 24	westerlies 10 kts
25 - 26	light variable or calm
26 - 28	easterlies 5 kts

Favorable dates for northeasterly katabatic winds: 1st, 2nd, 11th, 25th, 26th, 27th and 28th.

Salinity

The grid of observation sites planned by Gallego for the Ría de Arosa is shown in Figure 2. In the program of July 1968 he occupied positions 20, 21, 26 through 31 and 33 through 44 and in the winter of 1969 positions 18, 20, 21 23 through 32 and 34 through 44. The data of principal interest here are the salinities obtained in hydrographic stations extending to the bottom. Some use has been made of the temperature data from the stations, the air temperature observations and the current meter data.

As Gallego pointed out, salinity generally increases with depth and increases seaward at any one level the lowest values being found, of course, at the river mouths. To establish a tentative normal curve of salinity vs. depth for each program, the salinities have been averaged by depth and season regardless of position in the ría.

The "normal" curve for the July program appears in Figure 3 for comparison with the curves of soundings taken at various positions in the ría. The soundings at positions 33 and 29 were taken on 19 and 20 July in a well established period of northeasterly winds. Whereas both positions are out of the main channel one might expect to find salinity below average. That these soundings were more saline supports the hypothesis of wind-driven upwelling.

Positions 34 through 37 are in a line in the main channel. The data lie on both sides of the normal curve but the dates on which they were taken fall within two different regimes of wind. The observations at position 36 (high salinity) were made on 24 July in the long period of northeasterlies whereas the other positions(low salinity) were occupied on 11 - 13 July when the winds were variable. On 13 July the observers noted strong southerly winds for a few hours. The salinity curve for position 37 shows mixing in the upper 10 meters and thus a surface salinity which was higher than had been observed on the two previous days when the wind was light. This salinity was, however, less than average for the middle section of the estuary (positions 20 - 37).

Although tidal currents are important to changes in salinity Gallego's data show that salinities at position 36 were higher, depth for depth regardless of tidal phase. This leaves wind as the only apparent cause of the difference between stations.

The two layer water column at position 33 further supports the hypothesis of upwelling. The current should have been ebbing at the time of the observations yet at 20 meters four of nine current measurements showed northerly components while at 5 meters eight of nine observations showed southerly components. Currents into the Ensenada at depth and outward at the surface should produce the salinity profile observed.

The weather maps of this period, of which the one for 1200 GMT 19 July (fig. 4) is typical, clearly indicate the prevalence of northeasterly winds in the area.

Without weather maps and without round-the-clock wind observations an investigator would be hard put to understand the coupling of water and wind because of wind aberations of a local or of a temporary nature. On 19 July the wind observed on board the research vessel was a dying northerly which was followed by a calm. The northerly direction instead of northeast is attributable to terrain near the mouth of the Ensenada de Cariminãl and the dying speeds by a sea-breeze effect in opposition to the areal wind.

Gallego recognized the seeming incongruity between the low water column temperatures and high air temperatures at position 33 and on the following day at position 29. Upwelling in response to northeasterly winds (even those interrupted briefly by a sea breeze) provides both the colder water - since it comes from greater depths in the off-shore waters - and the warmer air - since it comes from the hot interior of Spain. For consistency then warmer water and cooler air should be observed with southwesterly winds. As a simple test for such an inverse relationship a plot was made of bottom water temperature vs. air temperature (fig. 5). The data from the very shallow upper part of the ría were omitted. The correlation coefficient for the 13 points is -0.676 which is significant at the 1% level. Without the data for shallow water positions 30 and 31 the coefficient becomes -0.813.

Winter 1969

The greater range of salinity in the normal curve for winter (fig. 6) reflects the heavier rainfall and runoff. The water of the estuary was less saline on the average at each depth than in summer.

The longest period of easterly winds was 3 - 10 February. This was followed for five days by strong northerlies some of which must have been steered by terrain to pass over the Ría de Arosa as northeasterlies although the question as to whether the effective wind action during 11 - 15 February took place within the estuary or by Ekman transport out on the shelf is moot. In any case, the observations of the first half of February whether the wind was easterly or northerly, reveal that salinity was above normal, depth for depth, at various places halfway up the ría. Curves of average salinity vs. depth for 8 - 14 February are illustrated in Figure 6. A curve for position 26 on 15 February shows similar high salinities but has been omitted to avoid confusion. The remarkable curve for position 35 indicates upwelling to within 5 meters of the surface but above that the salinities have been lowered by heavy rains. The two-layer distribution at positions 31 and 32 at the entrance to the Ensenada de Caraminal implies rainfall not apparent on the weather maps except through possible orographic showers on the east side of the Montes de Barbanza which dominate the land immediately north-northwest of the Ensenada.

In late January, when the winds were southwesterly, salinity was below normal at positions 34, 30 and 29 (fig. 7).

Katabatic Effects

A period of slack pressure gradients began late on 29 January as a ridge of high pressure entered Galicia. The resulting light winds and clear skies must have been conducive to the formation of katabatic winds in the region. There are no known observations of wind on the Ría de Arosa during this period but if katabatic winds reached there they probably were from the northeast quadrant. The rise in salinity at positions 40, 39 and 38 at the mouth of the Ensenada de Rianjo suggest that upwelling can occur even in the shallow upper reaches of the estuary and the only apparent way this could have been caused by wind was through katabatic northeasterlies. The advance of salinity at the surface and at 5 m is seen in Table 1.

Several other situations suitable for katabatic winds were observed but the hydrographic data were insufficient for demonstrating changes in the water column.

Presumably katabatic effects are strongest in winter.

The hydrographic data which have been discussed thus far illustrate in the two seasons some of the clearest cases in support of the model of upwelling. All of the remaining data and associated winds fit the model also.

Summary and Conclusions

1. In the Ría de Arosa in periods of northeasterly winds there is an apparent upwelling of bottom water which is balanced by an outflow of water at the surface and an inflow of highly saline oceanic water along the bottom.

2. Northerly winds can be turned by the terrain to become northeasterlies over the ría and produce similar upwelling.

3. In regimes of wind from other directions the salinities in the ría tend to fall below average particularly if there is plentiful rainfall and runoff.

4. The theory that the abundant supply of nutrients and therefore the success of the mussel raft fishery is the result of frequent wind-induced inflow of water along the bottom is supported by the study.

Acknowledgments

The author wishes to thank Sr. Gallego for the use of his data for the winter program before the publication of his paper.

References

Cadee, G. C. Molluscan biocoenoses and thanatocoenoses in the Ría de Arosa, Galicia, Spain. Zoologische Verhandelingen Uitgegeven door het Rijksmuseum von Natuurlijke Historie te Leiden No. 95 121 pp E. of Brill Leiden 1968.

Fuglister, F. C. Atlantic Ocean Atlas. International Geophysical Year of 1957 - 1958 Woods Hole Oceanographic Institution, Woods Hole, Mass. 209 pp 1960.

Gallego, J. G. Estudio de las condiciones oceanográficas en la Ría de Arosa en verano. Boletin del Instituto Español de Oceanografia 39 pp 1971.

U. S. Department of Commerce, Weather Bureau, Northern Hemisphere Weather Maps 1968 - 1969.

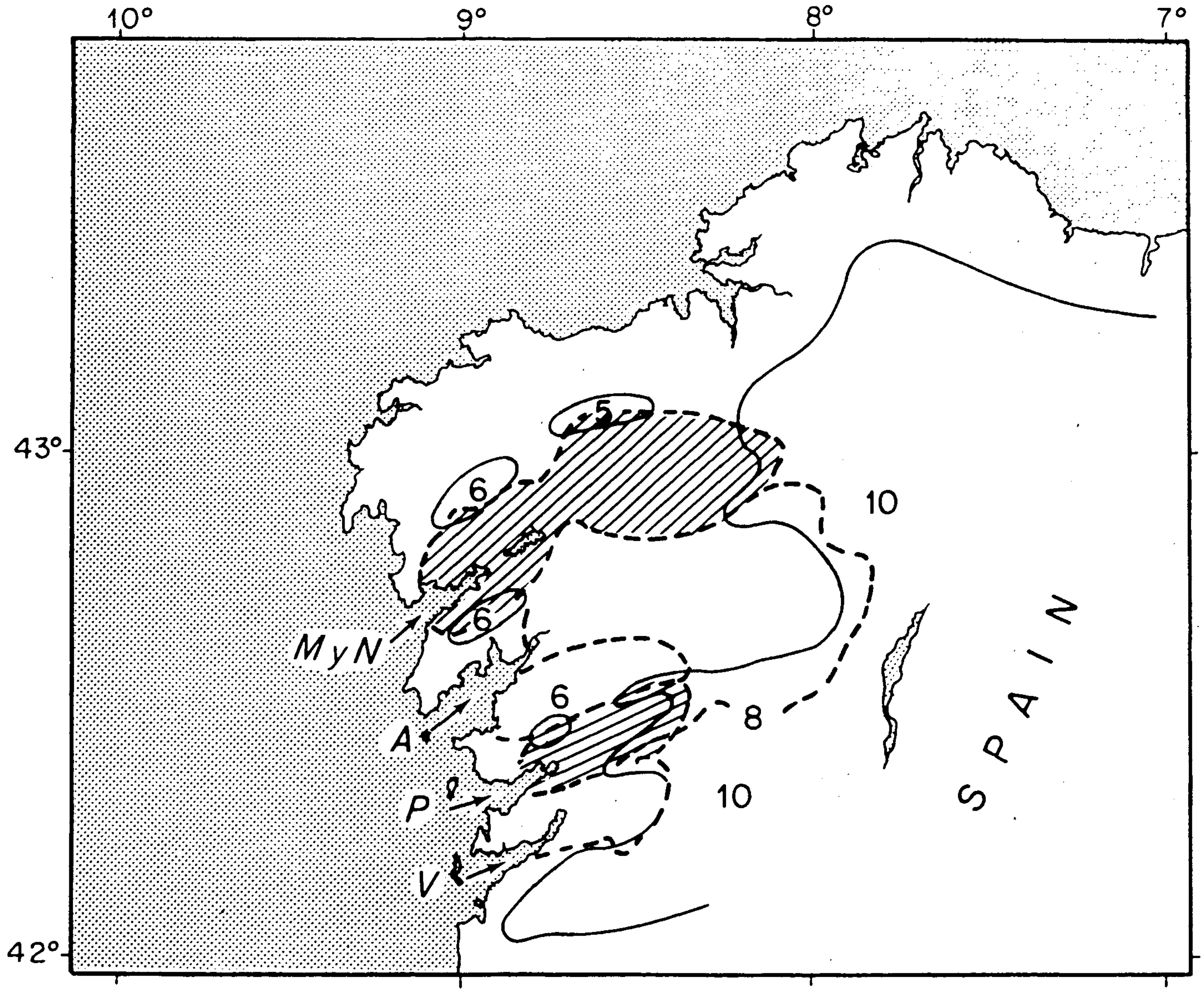

Figure 1. The Rías Bajas. The dashed lines deliniate the watersheds of the principal rivers which flow into the rías. The solid lines show the approximate position of the 400 meter contour and the numbers indicate higher elevation in hundreds of meters.

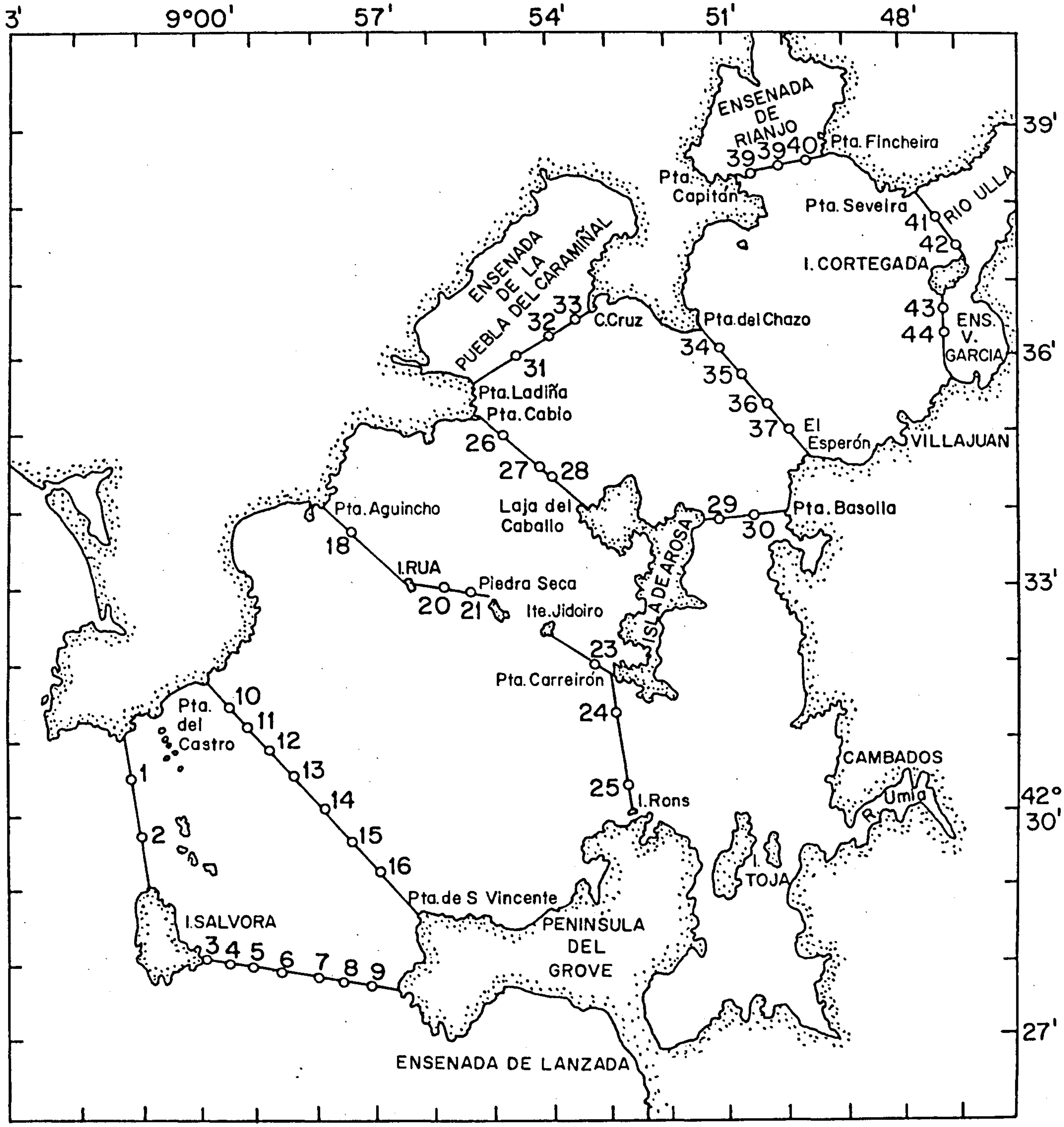

Figure 2. The grid of station positions in the Ría de Arosa

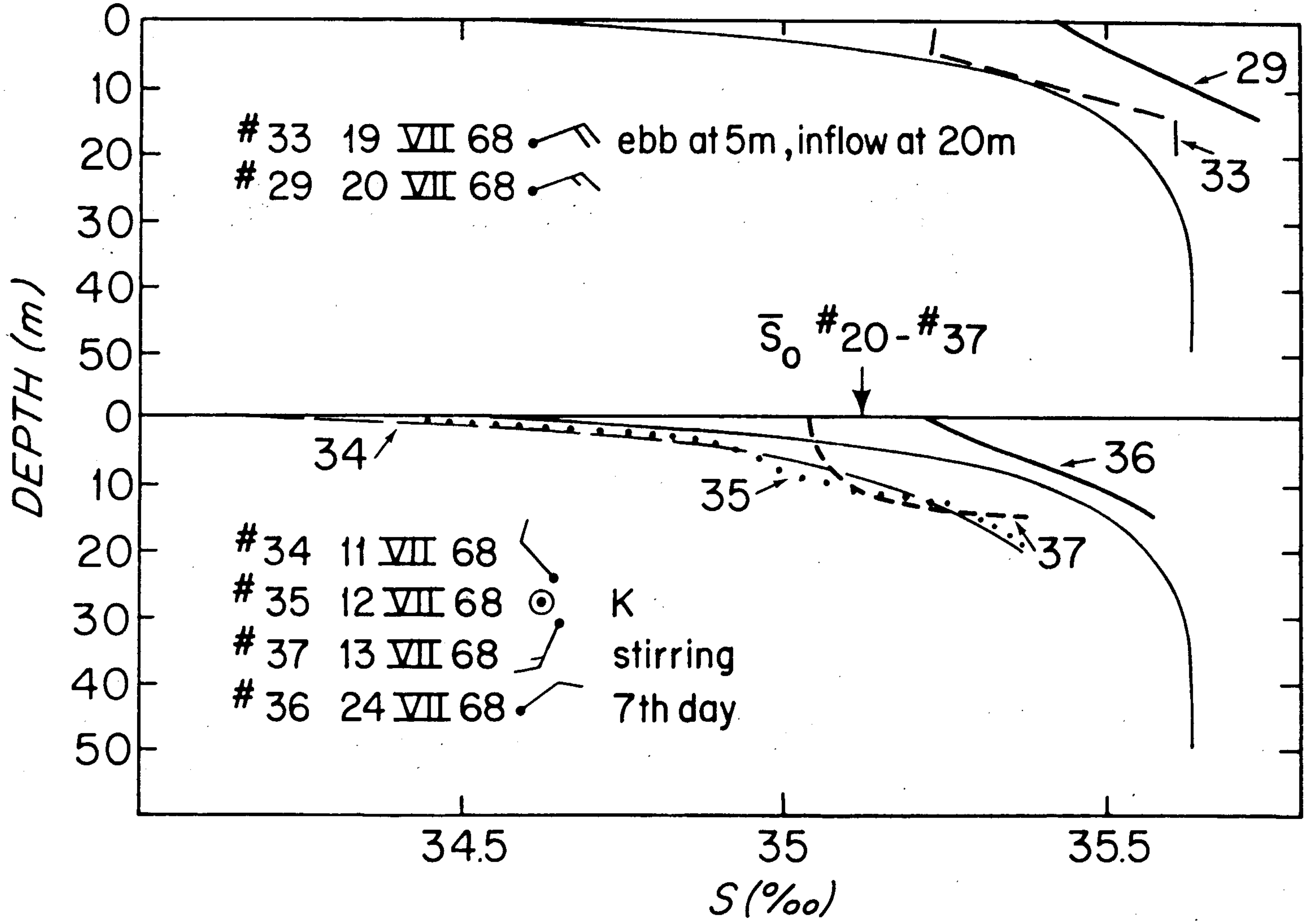

Figure 3. Salinity vs. depth at certain positions (numbered curves) in comparison with the seasonal average (unnumbered curves) Summer 1968.

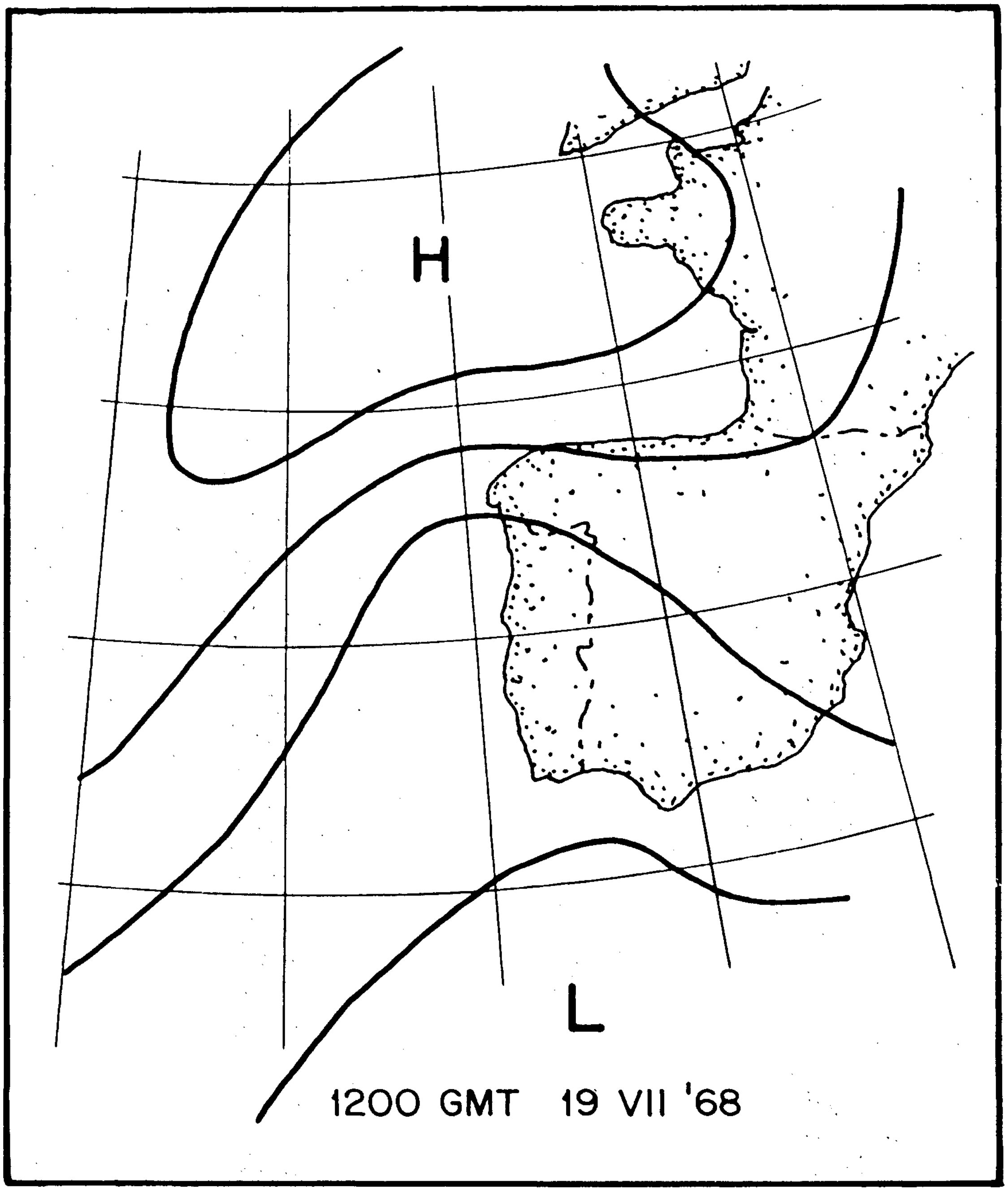

Figure 4. Sea-level pressures 19 July 1968.

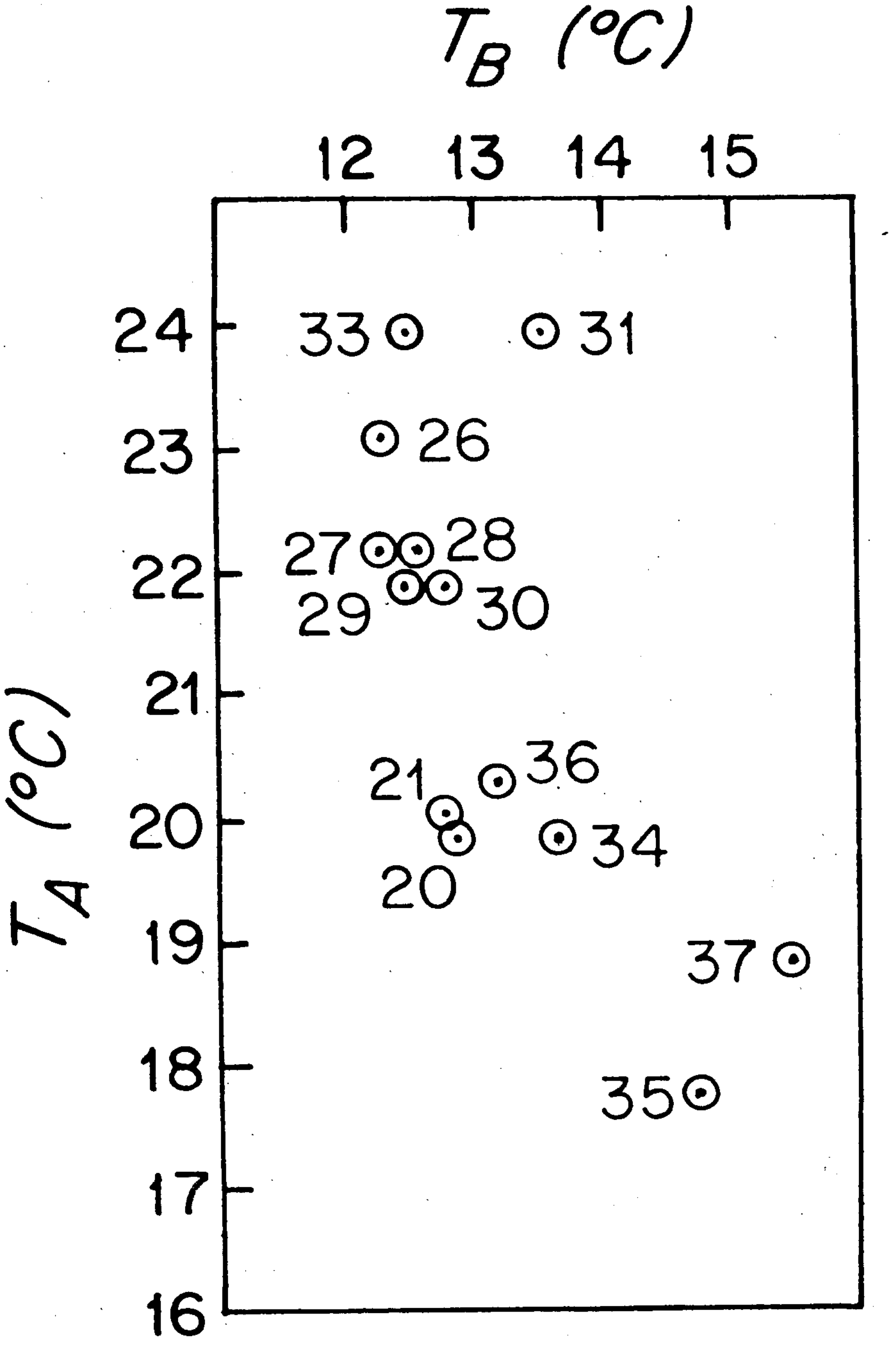

Figure 5. Bottom water temperature (T_B) vs. Air temperature (T_A) at numbered positions.

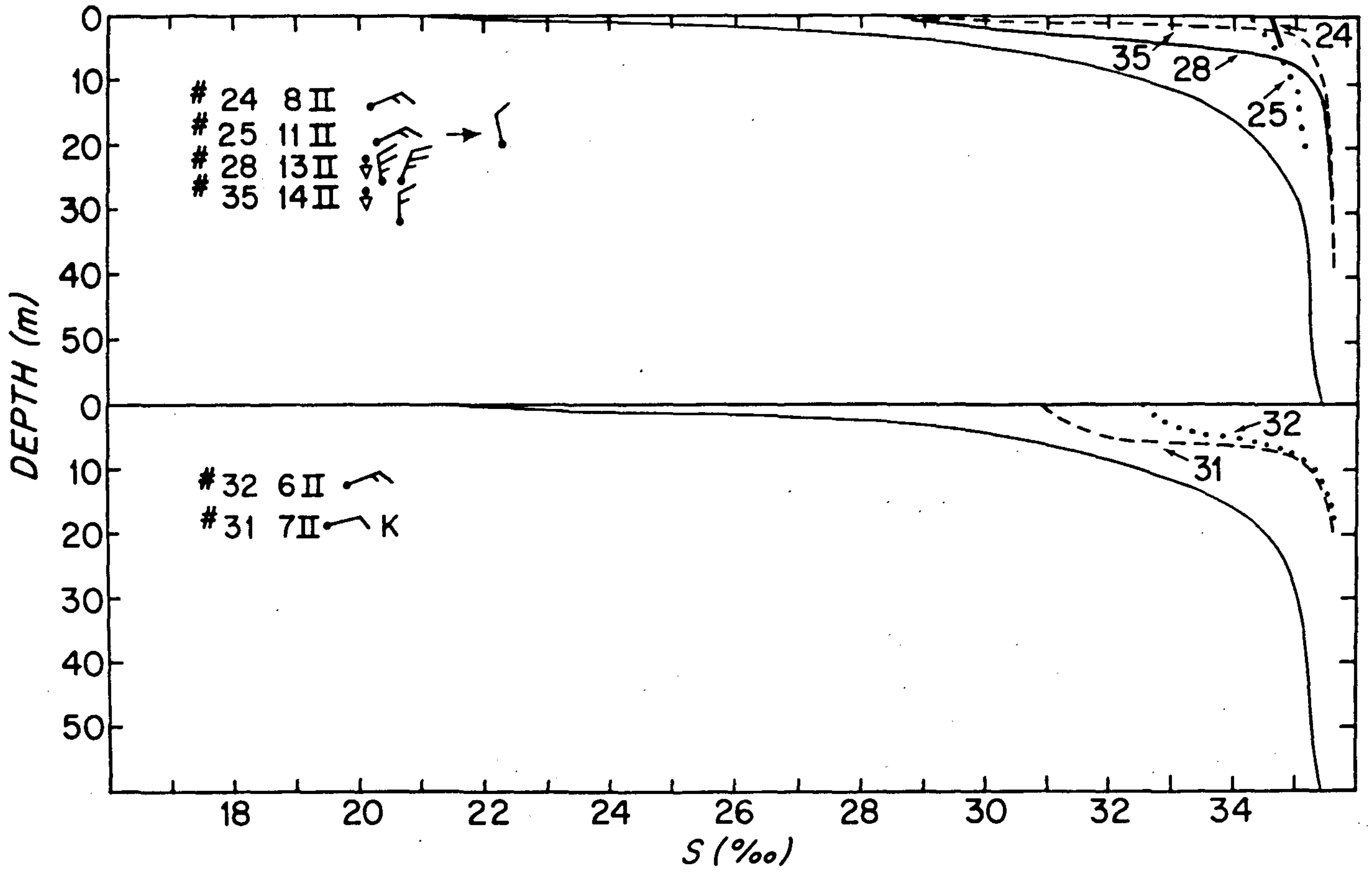

Figure 6. Salinity vs. depth at certain positions (numbered curves) in comparison with the seasonal average (unnumbered curves) Winter 1969.

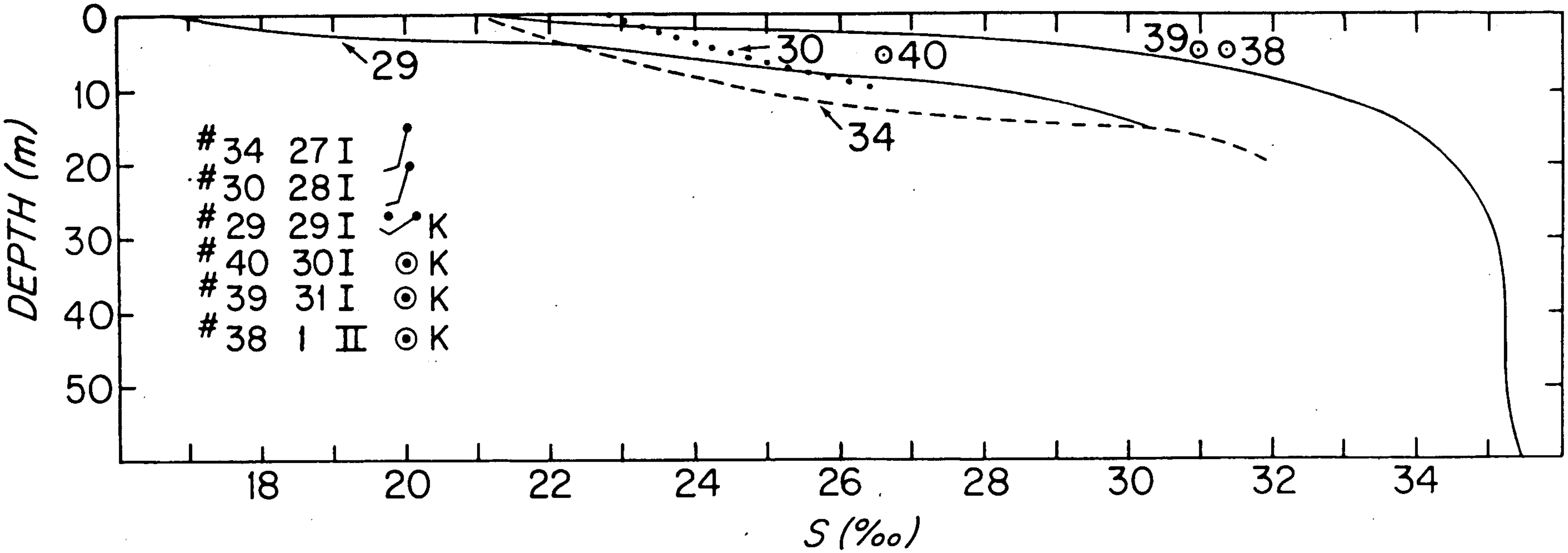

Figure 7. Salinity vs. depth at certain positions (numbered curves) in comparison with the seasonal average (unnumbered curve) Winter 1969.

position#	S_0	S_5
40	2.44	26.58
39	13.33	30.97
38	13.85	31.36
av. ria	21.14	30.35

Table 1. The rise in salinity at the surface and at 5 meters during a three-day katabatic situation.