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THE CIRCULATION OF PRINCE WILLIAM SOUND

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16. Abstract

This project was intended to determine the feasibility of studying water circulation in Prince William Sound, Alaska using satellite imagery from ERTS-1 and, in the event that this proved feasible, to study the regional circulation using ERTS-1 data. This was carried out by coordinating visual analyses of the satellite data with existing oceanographic information on the study region.

A combination of heavy cloud cover, darkness and the 18-day overpass period of the satellite prevented acquisition of sufficient data for effectively studying the circulation of the study region. It is concluded that ERTS-1 data are insufficient for studying circulation in an area having the climatic character of Prince William Sound. As a consequence of this, no new oceanographic information was obtained for the Prince William Sound region from the satellite data.

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PREFACE

The objectives of this project were to determine the feasibility of using ERTS-1 satellite data for studying the water circulation in Prince William Sound, Alaska and, in the event that this proved possible, to obtain information on this circulation. Sufficient background information was available on the oceanography of the Prince William Sound region to serve as baseline material for the study.

The data analysis consisted solely of visual inspection of the satellite images. Experimentation with color coding revealed no new information which could not be obtained by visual inspection of the black and white images.

Due to a combination of excessive daylight cloud cover, winter darkness and the 18 day cycle of satellite overpasses, it was impossible to obtain any new information on circulation in the study region. An additional drawback was imposed by theoretical considerations involving viewing of a three-dimensional distribution in only two dimensions. It was concluded that ERTS-1 data are at present not useful for studying the water circulation in a region having climatic characteristics and time scales similar to those in the study region.

Limitations of the ERTS-1 satellite which hampered this study were the lack of a thermal IR band and the 18 day periodicity of the coverage. It seems unlikely that these could be remedied using this same satellite; the solution would therefore be to modify the orbits of succeeding satellites and add thermal IR to their sensor complements.

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1. INTRODUCTION

The original purposes of this project were: (1) to determine, using ERTS-1 imagery, the feasibility of detecting circulation in near-shore and estuarine waters with satellite data; and, (2) in the event that this proved feasible, to study the circulation in the Prince William Sound, Alaska region. The geographical location of this region is indicated on Figure 1.

The Prince William Sound region was chosen, from among numerous possible sites along the Alaskan coastal zone, as the study area because: (1) it is about to undergo industrial development as part of the oil shipping route from the Trans-Alaska Pipeline terminal in Port Valdez; (2) it is becoming increasingly desireable as a recreational area and also more subject to commercial fishing pressure (in light of the obvious potential conflict areas, any new information on the region will be of use.) and, (3) there is a backlog of oceanographic information from the region sufficient to serve as ground truth for the ERTS data. This last point has proven to be essential, as it has not been possible to obtain adequate ground truth observations during the course of this study.

This final report presents the conclusions drawn concerning the project purposes. In light of the prevailing conditions, peculiar to this geographical region and which posed problems for the study from the outset, it is not intended that all of the conclusions below be extrapolated to other regions.

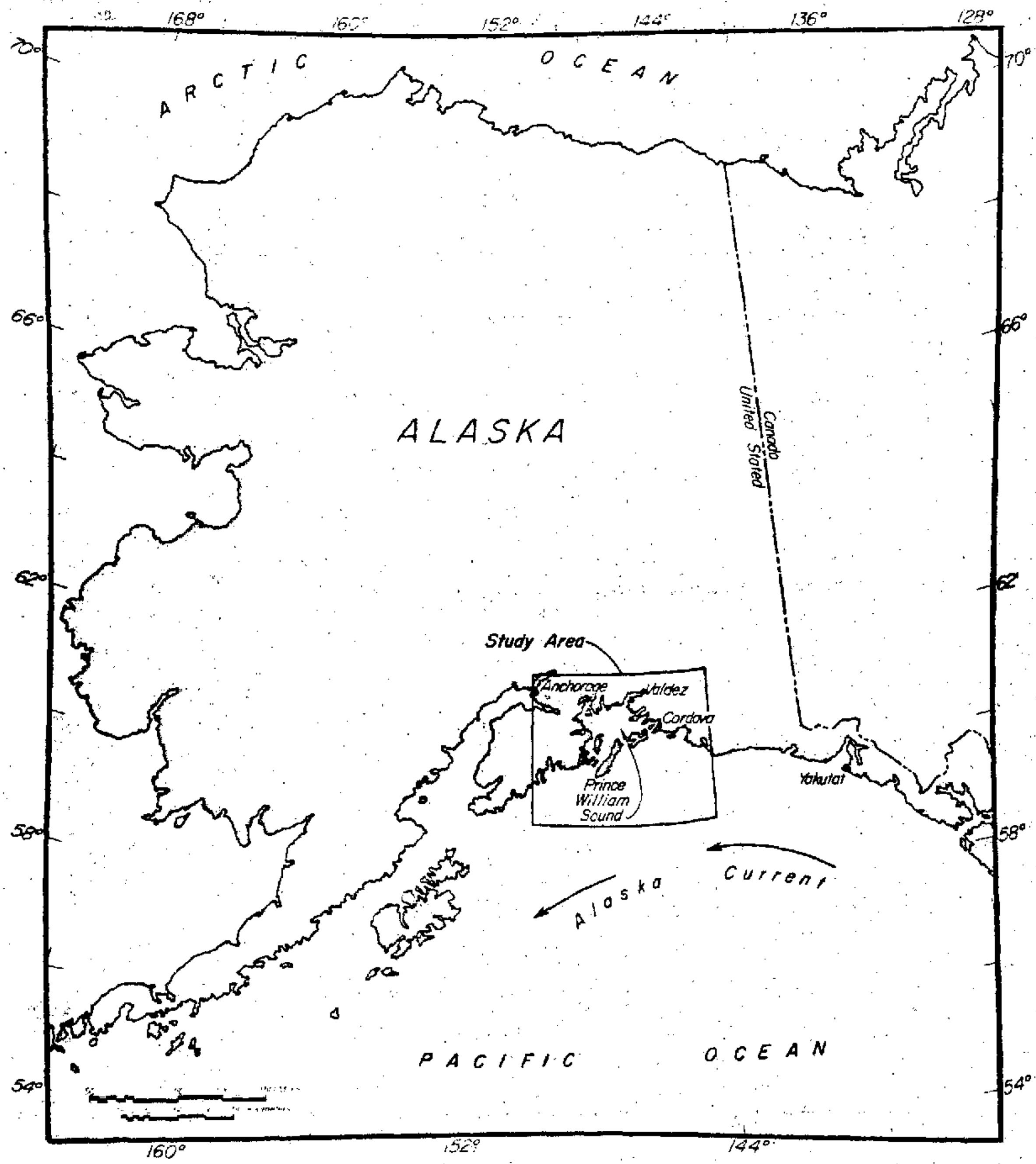

Figure 1. Geographical location of the Prince William Sound, Alaska region.

The degree to which the conclusions may be assumed to apply to other situations is left up to individual investigators having specific problems.

The research performed consisted of acquisition and visual inspection of ERTS MSS data (bands 4-7) obtained from the Prince William Sound, Alaska region. It was determined early in the study that suspended sediment plumes from rivers provided some indication of the path of surface water, as these sediment plumes were clearly visible on MSS band 4 and, occasionally, on bands 5 or 6. It was possible to use the Copper River sediment plume to trace the westerly path of the Alaska Current along the continental shelf south of Prince William Sound. It was also possible to detect, via the sediment plumes from the Lowe and Valdez rivers, the cyclonic circulation within Port Valdez.

Within Prince William Sound proper, there was insufficient visible structure in the suspended sediments to allow detection of any particular pattern. It was possible to detect inflow and outflow into the Gulf of Alaska on the flood and ebb tides, respectively, using the Copper River sediments as a tracer.

The project was plagued from its inception by three major problems: (1) the weather in the study area is typically heavily overcast for a large percentage of the year, which has reduced greatly the quantity of useful satellite data; (2) darkness during the winter prevented acquisition of satellite data during late October through late February, creating a hiatus in year-round data coverage; and

(3) the orbital period of the satellite, yielding a set of passes once every 18 days, was long relative to the time scale over which changes have been observed to occur in the study area, which precluded any attempt to study such variations. These three problems, which seriously impeded the progress of the project, are construed as a practical example of factors which should be considered in undertaking such a study. Taken in this light, they do not carry necessarily negative implications vis-a-vis the results of the study.

2. MAIN TEXT

2.1. *Oceanographic Background*

Prior to attempting use of a satellite in studying a marine system, it is necessary to consider the oceanographic nature of the system. This will facilitate early determination of features which might profitably be examined using the satellite information.

Prince William Sound may be classified as an estuarine system since it fits, insofar as available data indicate, Pritchard's (1967) definition of an estuary as a water body containing measurable quantities of water derived from land drainage and having a free connection with the open sea. Its relatively great depths and low fresh water input classify it, further, as a fjord type estuarine system.

Research carried out in Prince William Sound has been limited in scope, and has consisted to date primarily of work in peripheral fjord systems (Jones, 1960; Muench and Nebert, 1973). This work, in conjunction with information from more generalized fjord research (e.g. Rattray, 1967) has, however, established in qualitative fashion those parameters and processes which may significantly affect the circulation; fresh water runoff, winds, tides and the nature of the available marine source water (in this case, water from the Gulf of Alaska).

Fresh water runoff is typically one of the major driving forces for circulation in a fjord system, as it drives the near-surface estuarine entrainment flow (see Pritchard, 1967). Runoff in the Prince William Sound region appears to be relatively slight, and its effects have been observed to be confined to a shallow (5-10 m.) near-surface layer. This is typical of subarctic fjord systems which generally exhibit a pronounced vertical salinity (hence also density) stratification, which impedes vertical mass and momentum transfer. These are generally characterized, also, by a low fresh water input.

A second major factor in controlling water circulation is the surface wind field. It has been established (see, e.g., Rattray, 1967; Farmer, 1972; Heggie, 1973) that surface winds may affect both the circulation and the subsurface temperature-salinity structure within a fjord. The large horizontal extent of Prince William Sound suggests that winds may be particularly important there. The climate is such that severe storms occur frequently during the winter months and high wind speeds (up to 100 knots) are common. Ongoing research in a fjord slightly to the west of Prince William Sound has suggested, in addition, that there is a 4 day periodicity in weather patterns which may be reflected in the water circulation.

Tidal currents affect circulation by enhancing vertical mixing and by creating a nonlinear horizontal circulation which is cyclonic (counterclockwise) in the northern hemisphere. Presence of this cyclonic circulation has been qualitatively established within the Port Valdez system by surface observations of suspended sediments there (Sharma and Burbank, 1973), and by a numerical tidal model (Mungall, 1973). The tides in Prince William Sound are semidiurnal, and have a range on the order of 3-4 m. Little is known of the magnitudes of the tidal currents, due to a lack of measurements.

The Gulf of Alaska shelf region, which provides the marine source water for Prince William Sound, is characterized by a relatively slow (8-10 cm sec^{-1}) westerly current. This is the near-shore remnant of the westerly Alaska Current, which has its core farther south along the edge of the continental shelf (Fig. 1). While its existence has been documented since the 1920's (McEwen *et al.*, 1930), little new research has been carried out on it until recently (Royer, in prep.). Of significance to this project is the fact, known to ship operators in the region and based on ship drift, that the magnitude of the nearshore portion of the current may vary from day to day.

2.2 *Theory*

Satellite imagery showing distribution of suspended sediments is essentially a two-dimensional view of a three-dimensional field. Such a field is described by the oceanographic distribution of variables equation

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} + w \frac{\partial C}{\partial z} = K_h \left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2}\right) + K_v \frac{\partial^2 C}{\partial z^2} + R ,$$

where x, y, z are the easterly, northerly and vertical axes of a Cartesion coordinate system, u, v, w are the current speeds in the corresponding directions, K_h, K_v are the horizontal and vertical eddy diffusivities, R is a production-consumption term (which in this case would represent a settling out of sediments) and C is the sediment concentration.

This equation can be simplified only minimally for the case of a near-surface suspended sediment distribution. We can assume that w is zero at the surface, and we can measure C and its gradients in the x, y directions from the satellite data. None of the remaining terms can be assumed negligible, which leaves a single equation having as unknowns u, v, K_h, K_v and R. Clearly the system is underdetermined; there can be no solution for u and v without extensive assumptions or additional data input.

Consider the unknown terms. From information given above (section 2.1) it is clear that the time variations $\frac{\partial C}{\partial t}$ cannot be assumed negligible; they would be expected to be a function of tidal periodicity, of weather systems and of the seasons. Only the last of these three time variations can be detected using ERTS imagery, and it is possible that even this variation might be masked by shorter period variations. Wide ranges of values for the eddy diffusivities K_h and K_v have been obtained in the oceans, and there is no basis for choosing a specific value for this case. These must therefore be considered unknown yet appreciable. The settling out of sediments, represented by R, must be assumed to be appreciable;

it is, however, a function of sediment particle size and turbulence, both of which are unknown here. This leaves u and v, the variables which are to be determined.

Clearly, these considerations place severe restrictions upon the information which can be obtained from the satellite data. In particular, it is impossible to obtain values for the surface currents as represented by u and v. It is possible, in fact, to use the satellite data only to broadly corroborate known surface circulation patterns, e.g., the Alaska Current. A more widely publicized example would be the tracking of the Gulf Stream "North Wall" via satellite data. Without prior oceanographic knowledge of this feature, it would have been impossible to determine from the satellite data whether this feature was in fact the boundary of a major current or a surface line of convergence. In carrying out any analysis of a marine system using satellite data, it is therefore necessary to be aware of these limitations.

2.3 *The Satellite Data*

ERTS-1 data from MSS bands 4-7 were acquired from the study area during the course of this project. It was estimated at the outset of the project that those images having less than 8-tenths cloud cover would be useful. Existing cloud cover proved, however, to occur primarily over the water areas, leaving the inland regions clear. A cloud cover of far less than 8-tenths was generally sufficient, therefore, to make the images useless.

The magnitude of this problem can be better appreciated by considering the historical cloud cover data for the southcentral

Alaskan coastal region. Annual mean data were obtained from the National Weather Records Center, Asheville, N.C. Over the past 14 years the mean sunrise-sunset cloud cover in Anchorage, about 150 km. west of Prince William Sound, was 7.3 tenths. The corresponding figure for Yakutat, about 400 km. to the ESE along the Gulf of Alaska, was 8.3 tenths. While no cloud cover figures are available for Valdez or Cordova, on Prince William Sound, the weather at both places is reputedly worse than at Anchorage. An annual mean daylight cloud cover of about 8 tenths is therefore judged reasonable for the Prince William Sound region.

In addition to the cloud cover limitations, winter darkness made the satellite data useless for this project from about late October until late February. No data were obtained, therefore, during these periods of 1972-73 and 1973-74. Those data which contained information useful to this project are listed in Table I.

TABLE I

ERTS-1 images used in the study of Prince William Sound

Image ID	Date
1063-20282	24 Sept. 1972
1081-20284	11 Oct. 1972
1333-20285	21 June 1973
1335-20402	23 June 1973
1352-20340	10 July 1973
1352-20342	10 July 1973
1387-20275	14 Aug. 1973
1387-20284	14 Aug. 1973
1388-20333	15 Aug. 1973
1388-20335	15 Aug. 1973
1389-20391	16 Aug. 1973
1389-20394	16 Aug. 1973
1390-20450	16 Aug. 1973

Of the ERTS images listed in Table I, the first two covered primarily the Gulf of Alaska shelf region. The series from August 1973 are included in the composite image (Fig. 2), and so all yield the same information. The data are clearly biased towards summer conditions, which includes the period when fresh water runoff - hence suspended sediments - are at a seasonal maximum.

A series of aircraft data gathering flights was made over the region by a NASA aircraft in July of 1972 (Mission 209; Test Site 314; Flight 4). Data collected included visible and near IR photographs and thermal IR scans.

2.4. *The Data Analysis*

Analysis of both the satellite and aircraft data consisted solely of visual inspection of photographic prints of the images. It was possible in this way to identify all features having any bearing on the investigation, i.e., suspended sediment plumes.

Color enhancing the imagery using both the 3-M color overlay method and a VP-8 image analyzer yielded no information which could not be obtained by simple visual inspection. Based on this experimentation, no attempt was made to utilize the color display unit (CDU). The quantity of imagery available, coupled with the qualitative nature of oceanographic information on the study region, made utilization of such methods as density slicing unjustifiable.

2.5. *Results of Investigation*

The satellite imagery proved to be useful primarily in corroborating information known from previous oceanographic research in the region.

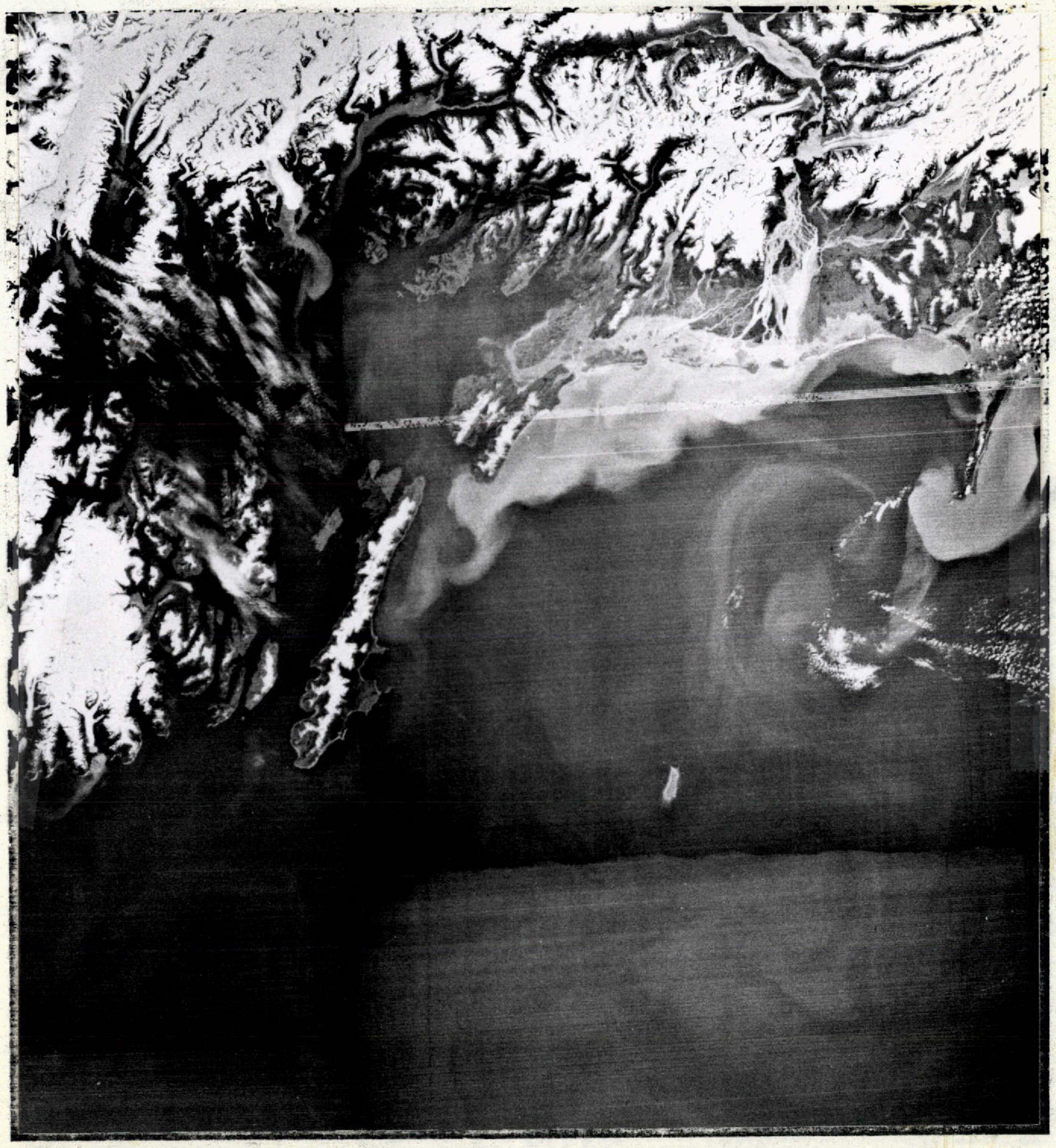

Figure 2. Composite of ERTS images 1387-20275, 1387-20281, 1387-20284, 1389-20391, 1389-20394 and 1390-20450 on 14-16 August 1973.

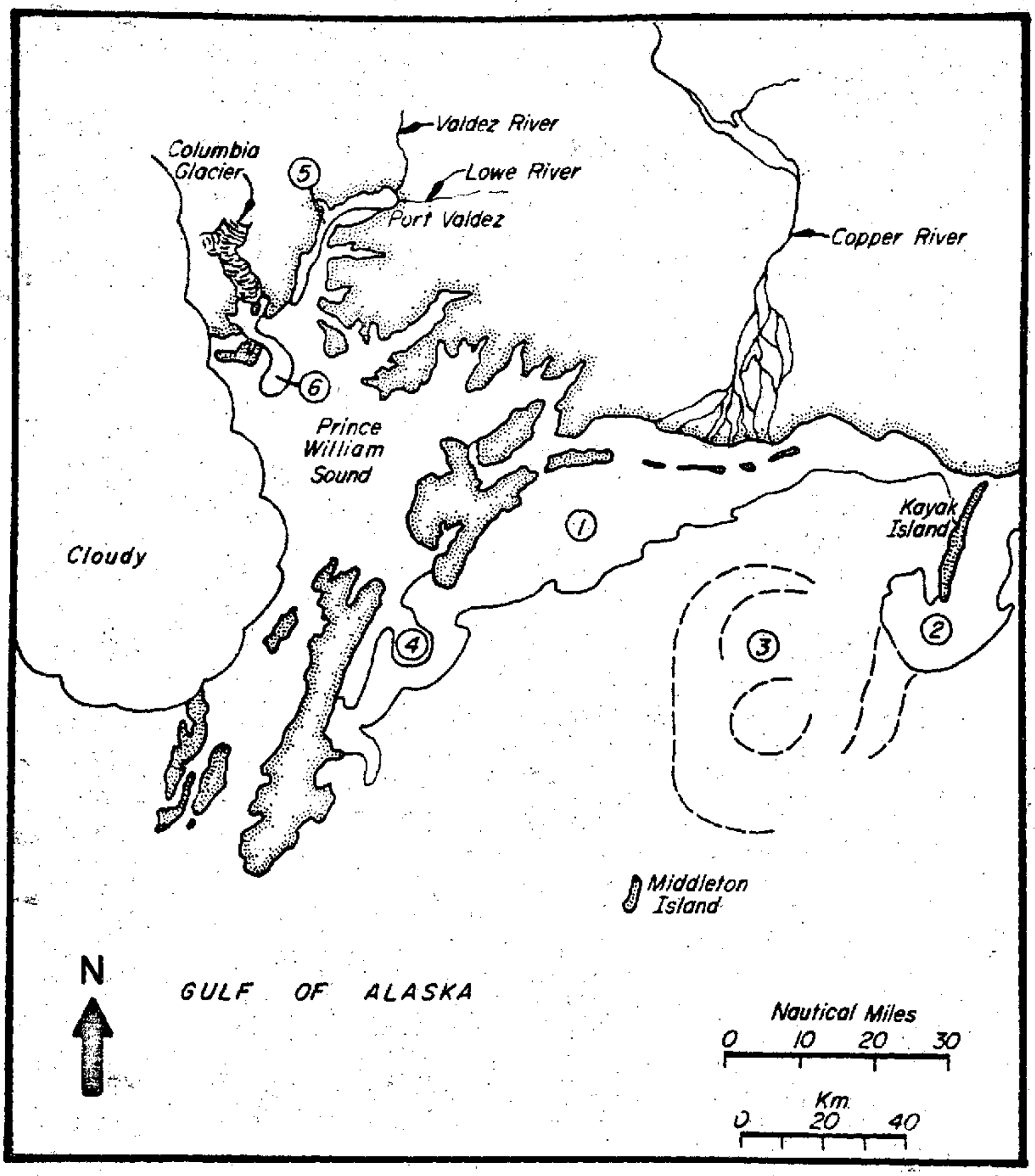

Figure 3. Legend for Figure 2. See text for discussion of numbered features.

The composite image reproduced here (Figs. 2 and 3) illustrates all of the features apparent on any of the satellite data obtained from the study region (Table I).

Referring now to Figures 2 and 3, the sediment plume (1) originated from the Copper River. Its westerly extension along the coastline was a consequence of advection by the easterly near-shore remnant of the Alaska Current. The irregular nature of the clearly defined outer (southern) edge of the plume may have been due to intermediate scale horizontal turbulence. It is impossible to say more about these irregularities without additional information on their spatial and temporal scales. As pointed out above (section 2.2), it is impossible to draw any conclusions concerning the current speed from the plume configuration.

The clearly defined plume (2), which originated from glacial streams to the east, was suggestive of a lee vortex in the westerly current on the downstream side of Kayak Island. The similar feature (3) to the WSW appeared similar but perhaps older as it was considerably more diffuse. The features (2) and (3) may have been due to vortex shedding on the downstream side of Kayak Island. The eddy (3) may, on the other hand, represent a semi-permanent gyre being driven by the westerly current off Kayak Island. It is unlikely that the pattern represented an inertia current (i.e., one controlled by the earth's rotation). The radius of the circle of inertia at these latitudes is on the order of 1-2 km. for current speeds which might be reasonably expected here, while the radius of the observed eddy-like feature was on the order of 20 km., or an order of magnitude larger than would be expected if the motion were purely inertial.

The indentation (4) in the Copper River plume represented a bolus of water flowing outward from Prince William Sound on the tide, ebbing when this particular portion of the composite was obtained. All satellite images showed either this pattern, typical for an ebb tide, or an inward directed plume of sediment laden water on the flood tide. Once inside Prince William Sound, the flood tide plume always lost its identity too rapidly to be of any use in tracing water motions there.

The smaller sediment plume (5) in the Port Valdez region was evident both on the satellite images and on the aircraft imagery. Its presence has, in addition, been documented by oceanographic sampling within the Port Valdez region. It originates from the Lowe and Valdez rivers at the head of Port Valdez; these are the two largest rivers emptying into Prince William Sound, consequently, this sediment plume is the most prominent in the Sound. The distribution of the plume primarily along the N and NW shores of Port Valdez was due to a cyclonic circulation there which has been detected using both the suspended and bottom sediment distributions (Sharma and Burbank, 1973) and from a numerical model of tidal currents (Mungall, 1973). The cyclonic circulation is due to the tides, and is typical for a basin having the dimensions of Port Valdez. Since the sediment-laden layer is only a few meters thick, however, its configuration can be assumed to be a function only of the surface rather than the deeper water circulation. The extension of the plume to the southwest into Prince William Sound was due to the ebb tide.

A final feature of interest was the plume of ice (6) originating from the Columbia Glacier. Its extension into Prince William Sound was a function of the ebbing tide. This feature is not clearly defined at all times of year, based on ground observations, but fluctuates in extent depending upon the activity of the glacier.

The light clouds in the northwest portion of the composite image illustrate well the degree to which even a relatively light and discontinuous cloud cover can obscure the water surface and even the shorelines.

As a consequence of the factors which prevented the acquisition, on a regular basis, of useful ERTS data, it has been impossible to derive any new information on the water circulation in the Prince William Sound region from satellite data. While any new information obtained on circulation would be of use in routing shipping through the study region or in preparing contingency plans in the event of oil spills, it appears unlikely that future ERTS data will be able to provide significant new data. The same factors which hampered data acquisition during this project will continue to affect future data acquisition.

3. NEW TECHNOLOGY

No new technology has been derived from this project.

4. CONCLUSIONS

It is concluded, based on this study, that ERTS-1 satellite data are insufficient for studying circulation in the Prince William Sound, Alaska region. It has, in fact, been possible only to broadly verify the general, known circulation patterns in the Port Valdez region and in the near-shore portion of the Gulf of Alaska at a few isolated points in time. The reasons leading to these conclusions are:

1. An approximately 8-tenths daylight cloud cover over the study region reduced the number of useable images. Of those having little cloud cover, even a very light, discontinuous cloud cover was often sufficient to obscure features of interest;
2. Winter darkness prevented acquisition of useful data from about late October through late February of 1972-73 and 1973-74, thus biasing the data by providing information only during non-winter periods; and
3. A set of satellite images was obtained from the study region only once every 18 days. Changes in the system may occur, however, over periods as short as 6 hours (semidiurnal tides), and significant changes may occur over 3-4 day periods due to weather changes. It is impossible to use ERTS data to monitor these changes.

It is impossible to draw any conclusions, using the ERTS-1 data, concerning the circulation in Prince William Sound proper since the suspended sediments exhibited no pattern there.

5. RECOMMENDATIONS

Considering the limitations imposed by the ERTS-1 orbits and by the regional climate, it would be impossible to better the capability of the system using the existing satellite. A far more frequent coverage of the region would be needed; on the order of twice a day, as with the NOAA-2 satellite, would be near-ideal. In addition, sensors in the thermal IR bands would be highly desireable, as temperature is an important parameter in all marine systems and may be related to, e.g., upwelling and fog formation. Using thermal IR data in conjunction with visible imagery, it would be possible to better identify such features as cloud layers and regions of sea ice formation.

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