Iceberg prediction model to reduce navigation hazards: Columbia Glacier, Alaska

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ABSTRACT: After centuries of relative stability Columbia Glacier began to disintegrate in the 1970s and went into a drastic retreat about 1980. With a 500 percent increase in the volume of icebergs calved from the glacier terminus since retreat began, the potential for an iceberg/oil tanker collision has risen. Since July 1996, monitoring of the glacier and the icebergs it produces has been underway. Observations using time-lapse photography, high-altitude aerial photography, and bathymetry of the recently opened fjord have been made. A mass balance model of the glacier was developed to reconstruct its balance history and relate mass change and runoff to iceberg calving. Using local tide and weather observations, an iceberg prediction model is under development to reduce the hazard created by the hundreds of large icebergs that enter the shipping lanes each year. The model provides real-time forecasts of icebergs released from the glacier into Prince William Sound.

1 INTRODUCTION

The Iceberg Monitoring Project (IMP), funded by the Regional Citizens' Advisory Council of Anchorage and Valdez, Alaska has been underway since July, 1996 to analyze calving and drift of icebergs into the shipping lanes used by oil tankers. The basic goal of IMP is an improved understanding of the underlying causes and timing of iceberg calving and ice-drift processes in order to develop a prediction model that relates iceberg production and movement to ocean tides, glacier runoff and other phenomena. To accomplish this goal, a detailed study of all aspects of Columbia Glacier's current and historic regime was undertaken. A mass balance model of the glacier was developed from meteorological observations collected at nearby weather stations. The model calculates snow accumulation, snow and ice ablation and runoff rates for the past 50 years and relates these variables to the current production of icebergs.

The ultimate purpose of IMP is to minimize the navigational hazard in Prince William Sound caused by icebergs that are produced by the drastic retreat of Columbia Glacier. Large icebergs pose a threat to oil tankers in particular. A large number (700) of these ships move through Prince William Sound each year, often at night and frequently under reduced visibility due to fog and stormy weather. Large masses of icebergs continually drift from Columbia Fjord (the newly developed forebay below the glacier terminus) into the traffic lanes and will do so for several decades to come. Thus, there is an ever-present danger of an oil spill caused by a collision between an iceberg and a loaded tanker. The Exxon Valdez had turned to avoid a large field of these icebergs when it grounded on Bligh Reef in March 1989. In January 1994 an iceberg that had drifted into the traffic lanes gouged a 20-foot hole in the bow of the tanker Overseas Ohio (which was empty). A determination of the mass of this iceberg is underway (Tangborn, A. et al, 1998). Together with a count and size distribution of a typical outbreak of icebergs from Columbia Fjord, the size of this iceberg will provide needed information for a tanker/iceberg risk assessment.

Columbia Glacier began a rapid retreat in 1980 after at least 2000 years of slow advance and has remained in a stable position for the past several hundred years. It is the last large tidewater glacier in Alaska to retreat during the previous 200 years (Viens, 1995). In the early 1970s, US Geological Survey glaciologist Austin Post, who had been observing this and other Alaskan glaciers since 1949, predicted that Columbia Glacier was on the verge of retreating. (Post, 1975, 1977) Break-up of the terminus began in the late 1970s and full-scale retreat was underway in 1980. (Krimmel, 1996, 1997; van der Veen, 1995)

2 DATA COLLECTION PROGRAM

The rapid and unpredictable changes that Columbia Glacier is undergoing, plus the large number of fast-moving icebergs calved from the glacier that have drifted into Prince William Sound, require a data collection technique with a short time interval between observations. Time-lapse photography was the best means to achieve this goal. The primary data collection program consisted of three Automax pulse cine 35-mm cameras programmed to photograph at 10-minute intervals during daylight hours: 1) the glacier terminus, 2) the shoal moraine at the outlet of the Columbia Bay fjord, and 3) a 50 square kilometer area of Prince William Sound through which the icebergs pass (Figure 1).

Approximately 70,000 photographs were collected at the three sites between June 1996 to October 1997. About 30 percent of these images are obscured because of fog, rain or snow, but the remainder are high quality, color photographs that provide a unique record of Columbia Glacier's historic retreat. The photographic sequences are placed on a laser disk and analyzed by documenting frame-by-frame changes in the glacier terminus caused by calving and changes in the heading and speed of floating icebergs. These observed changes are synchronized with two other measured variables: ocean tide levels observed at Valdez and runoff from Columbia Glacier simulated by the mass balance model. The calving rate of the glacier, tidal fluctuations and runoff are thought to be the main controlling forces for moving glacier ice into Prince William Sound. A time-lapse video has been created from the photographs, displaying a dynamic sequence of iceberg calving and drift

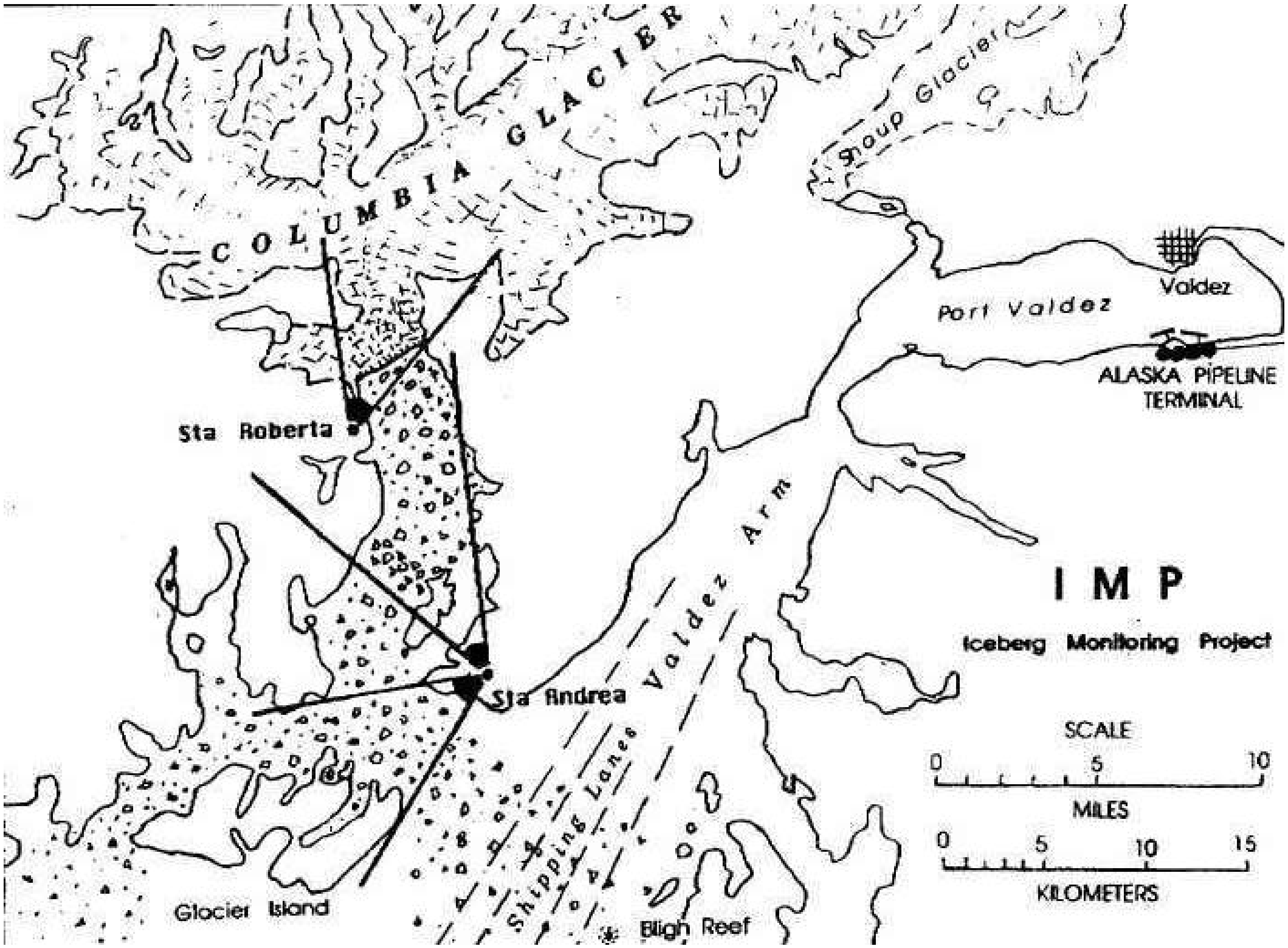

Figure 1. Location map showing the lower part of the glacier, the three camera sites with their approximate views, and the shipping lanes used by oil tankers traveling to and from the Alaska Pipeline Terminal and the Pacific Ocean. Most of this paper concerns the results obtained from the time-lapse photographic sequence collected at Station Andrea of the moraine shoal (camera with the view facing northwest).

trajectories

Other data collection activities for IMP are periodic aerial photography of the lower glacier (used to measure glacier flow and elevation changes) and bathymetry of the deep, 56 square kilometer fjord that has formed since 1980 as a result of Columbia Glacier's retreat.

3 CALVING PREDICTION

Prediction of the calving rate of Columbia Glacier on a daily basis is still not possible. Monthly and annual calving estimates based mass losses determined by aerial photography and mapping are more reliable, it is known that maximum calving occurs in mid-September and the minimum in mid-March. The rate is highly dependent on water depth at the terminus and partially controlled by runoff intensity (Brown, et.al,1983). A method of calculating the retreat rate using the photographic record of daily terminus changes is under development and appears to be a promising way of estimating daily or weekly calving rates. The glacier is now calving at an annual maximum rate of approximately 100 tons of ice per second. Columbia Glacier has lost over 40 cubic kilometers of ice since 1980 and will lose another 80 cubic kilometers or more before it becomes grounded after retreating another 20 kilometers.

4 GLACIER MASS BALANCE AND ICEBERG PRODUCTION

The mass balance of Columbia Glacier is primarily the difference between the accumulation of snow at high altitudes and the melting and calving of ice at low altitudes. The mass balance for many centuries was likely near zero so that melting and calving just equaled snow accumulation, and the glacier maintained a nearly constant size and shape. Then, probably around the mid-1930s, the balance became slightly negative, likely due to an increase in ablation. Its steady-state condition ended and the glacier began losing mass. The lower part of the glacier thinned and embayments began forming at the terminus causing minor retreats each year. Full-scale retreat was underway in the early 1980s, once the terminus had retreated from the moraine shoal into deeper water.

In order to relate iceberg production at the Columbia Glacier terminus to the climate, a glacier balance model was developed that uses long-term meteorological observations at Valdez, Cordova and Seward (Tangborn, 1997). The model converts observed precipitation and temperature at these weather stations to snow accumulation and snow and ice melt on the glacier. The reliability of the balance model was verified by field measurements of snow accumulation at higher elevations of the glacier. Successful field measurements were made on August 3, 1997 by US Geological survey glaciologists Bob Krimmel and Dennis Trabant by measuring the depth to the ash layer deposited by the 1992 eruption of Mt. Spurr (Krimmel, personal communication, 1997). Figure 2 shows these measured balances at several altitudes and the modeled balance distribution averaged for the 1993-97 period.

It is puzzling that the modeled mass balance (disregarding calving) has been positive nearly every year since retreat began, however the

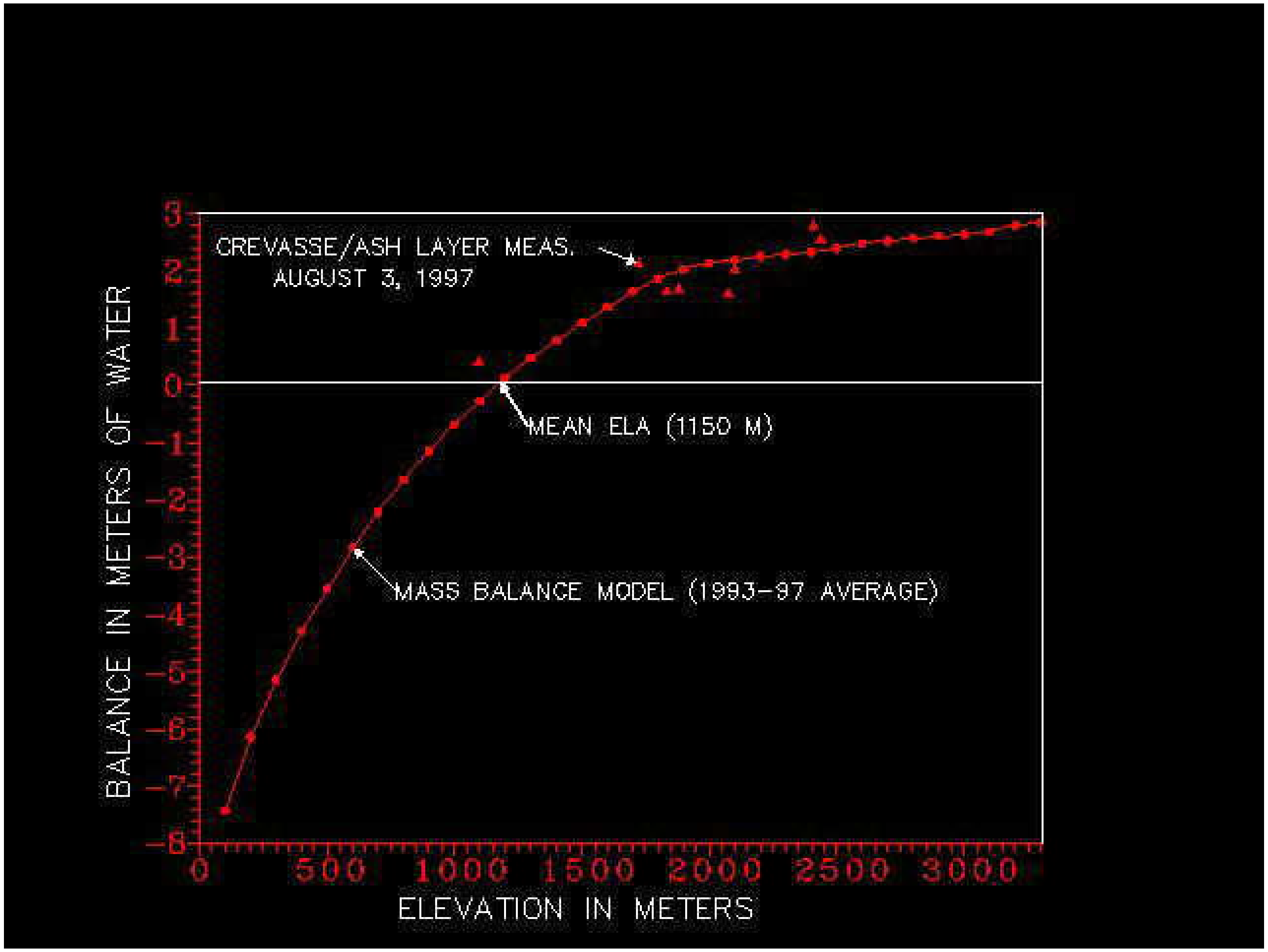

Figure 2. The authenticity of the modeled mass balance results is verified by field measurements of the snow balance at higher altitudes of Columbia Glacier. Eight measurements were made on August 3, 1997 of the snow depth along crevasse walls to the ash layer deposited by the eruption of Mt Spurr in September 1992, thus providing a 5-year total water balance at each site. The modeled balance is based on the simulation of snow accumulation and snow and ice ablation derived from daily meteorological records at three nearby weather stations for the previous 50 years. The balance distribution shown here is the 1993-1997 average. The root-mean-square-error of measured versus modeled balance is 0.15 meters (water equivalent).

resulting increase in mass has not been nearly enough to compensate for the enormous losses due to calving. Much of the large increase in mass above the equilibrium line and from over the upper glacier (approximately 20 cubic kilometers) will ultimately end up as icebergs in Prince William Sound.

Runoff (equal to precipitation as rain plus ice and snowmelt simulated by the balance model) influences the speed at which the glacier moves and transports ice from higher elevations to the terminus. Runoff from Columbia Glacier reaches discharge peaks of over 2800 cubic meters per seconds (100,000 cfs) during the summer months. Both water storage at the bed of the glacier and glacier speed reaches a maximum in March and a minimum in September. In addition, large influxes of surface water into the glacier are believed to be related to the high calving rates that occur in early autumn. However, Columbia Glacier terminates in extremely deep water (more than 300 meters), therefore the high calving rate of this glacier is due primarily to a great instability that exists at the terminus because of the deep water.

5 ICEBERG DRIFT PREDICTION

Forecasting the presence of icebergs in the shipping lanes in Prince William Sound using easily obtained synoptic observations of tide levels and meteorological parameters such as precipitation and temperature is the major goal of this project. The ability to make these forecasts on a daily or more frequent schedule would reduce the probability of a tanker / iceberg collision. To develop such a forecasting model, the movement of icebergs from the fjord over the moraine shoal was analyzed by documenting the direction, intensity and time duration for each event of ice motion in the time-lapse photographs. The date and hour were first added to each frame and the entire sequence transferred to laser disk so that frame-by-frame changes could be detected and recorded. Each event was assigned an index number from -9 to + 9, based on the direction and relative amount of ice noted. A positive value indicates movement away from the glacier and into Prince William Sound; a negative value indicates movement toward the moraine and glacier. Over 1000 major event-hours were noted during the July 26 to December 31 period (the only time-segment analyzed thus far), and compared with tidal fluctuations and simulated runoff from the glacier.

Both tidal fluctuations and runoff from the glacier were found to control ice drift over the moraine and into Prince William Sound. The maximum tidal range in Prince William Sound is 5 meters, and tidal currents are thought to be small because of the great water depth and small tidal prism (Walters, et. al., 1988, 1989). The iceberg speeds that were determined from the time-lapse sequences agree with this assessment. The average speed below the moraine shoal of clusters of several bergs was 0.40 kilometer per hour (215 observations), and 0.90 kilometer per hour (293 observations) in Columbia Bay (Figure 3).

The currents generated by tidal action move icebergs both away from and toward the moraine, while glacier runoff moves them outward only. Figure 4 is an example of the tidal cycle for one 36-hour period and its relation to the three drift observations that occurred during the period. A regression of the observed drift index against the tide level and runoff suggests that periods of high tides together with high runoff from the glacier cause the greatest outflow of icebergs into Prince William Sound. (Figure 5) The large amount of scatter is likely due to the lack of correlation between tides and runoff, so that high runoff can coincide with low tides and vice versa. Other factors that decrease correlation between ice drift and tide are wind effects on ocean currents, changes in freshwater/salinity interfaces, and changes in water temperature.

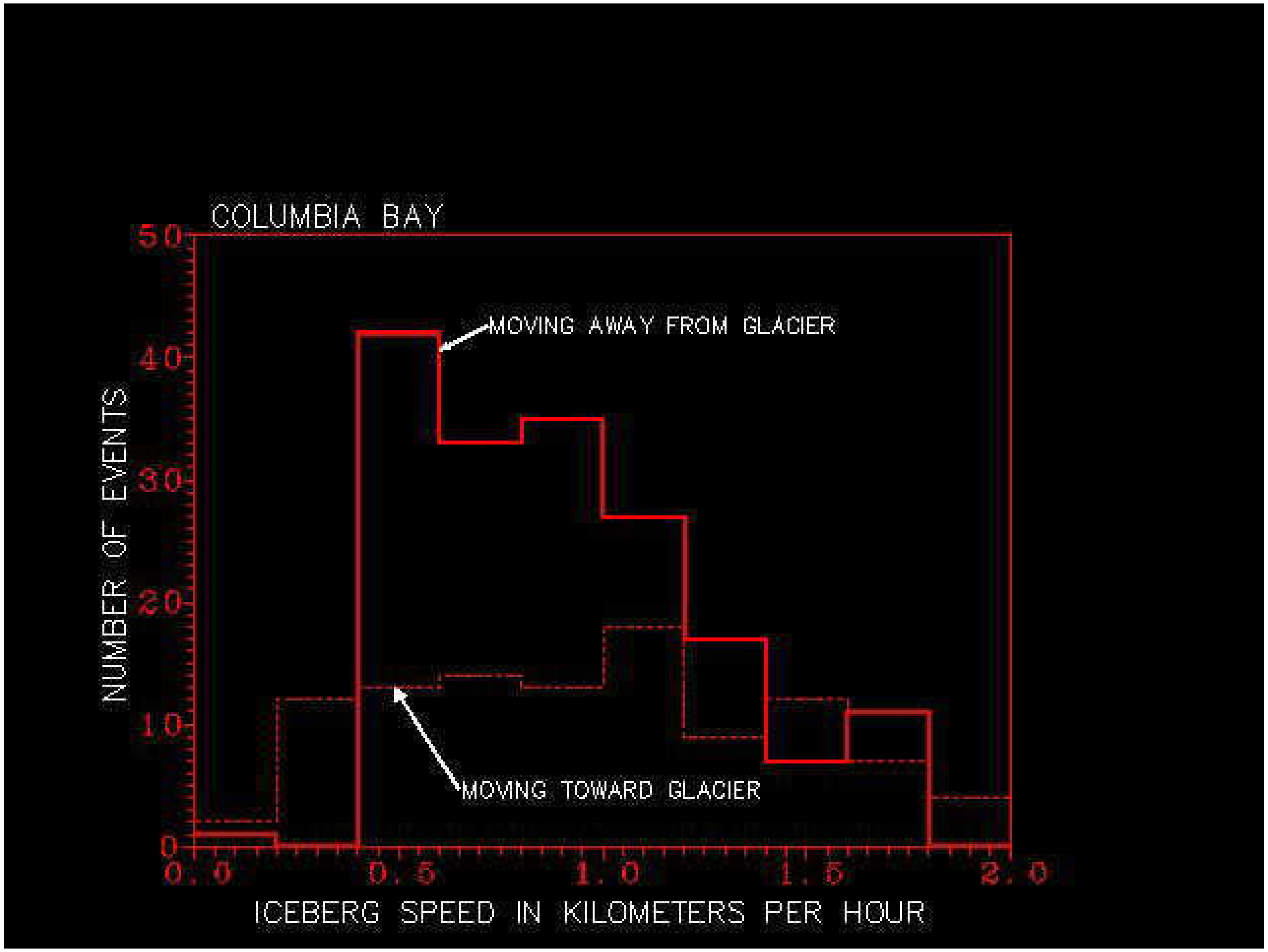
COLUMBIA BAY
MOVING AWAY FROM GLACIER
MOVING TOWARD GLACIER
NUMBER OF EVENTS
0
10
20
30
40
50
0.0
0.5
1.0
1.5
2.0
ICEBERG SPEED IN KILOMETERS PER HOUR

Figure 3. Iceberg drift speeds in Columbia Bay (top) were made for individual bergs by estimating travel distances on the monitor screen during the 10-minute interval between photo frames. The average speed for bergs traveling north, toward the glacier, is 0.83 km/hr and for bergs traveling south is 0.95 km/hr. Drift speeds just below the moraine shoal (bottom) are made usually for masses of ice (not individual bergs) and are also for travel distances during 10-minute interval frames. Drift speeds closer to the moraine shoal are about one-third those in more open water in Columbia Bay. Average speed toward the moraine is also slightly less than for outbound bergs - 0.34 km/hr inbound and 0.37 km/hr outbound. These results generally agree with current measurements made over the moraine in 1983 (Walters, 1989).

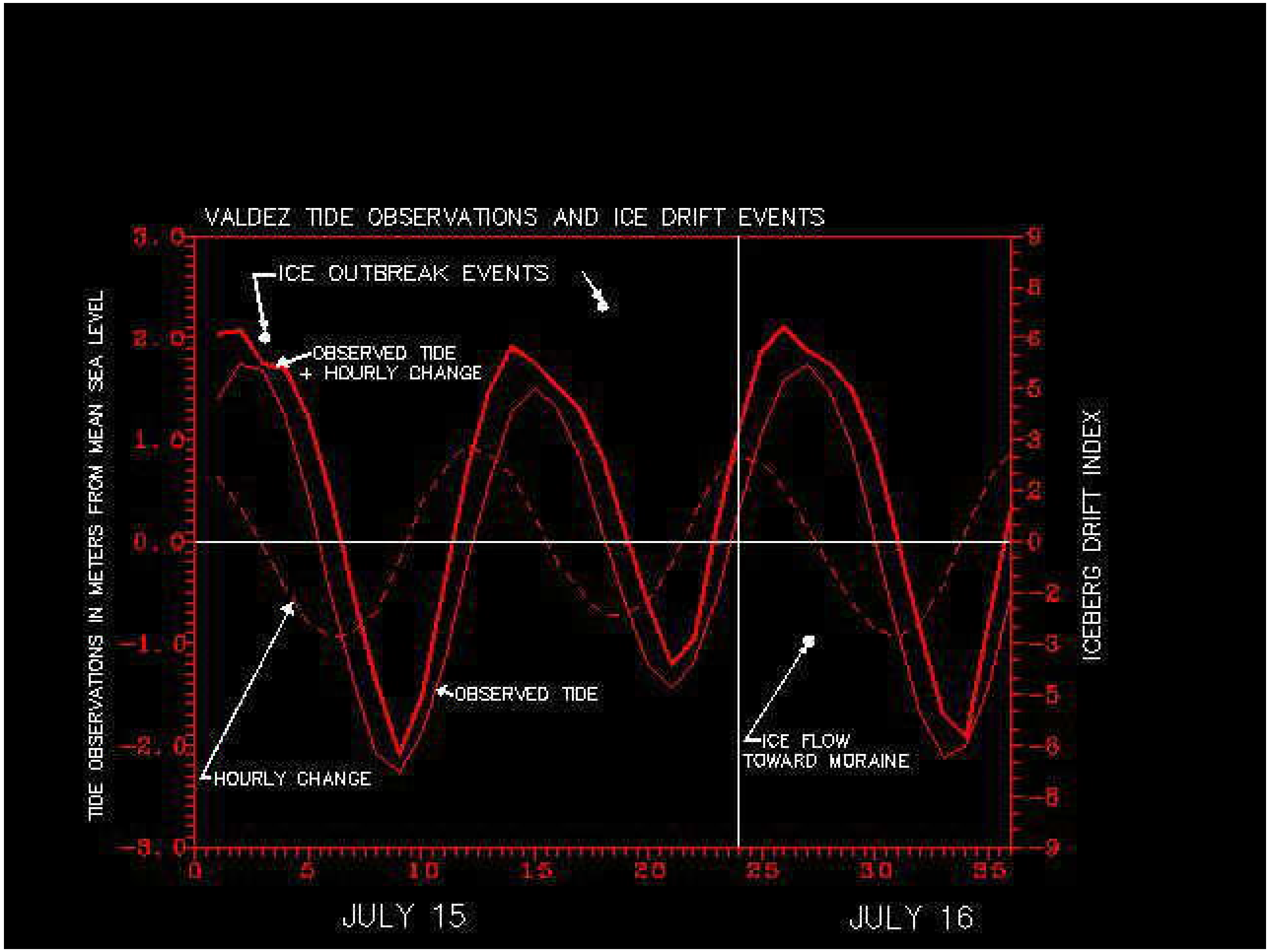

Figure 4. Example of tidal fluctuations and iceberg drift indices for a 36-hour period (July 15 and 16, 1996). Hourly ocean tide levels at Valdez are related to an iceberg drift index, three of which are shown for this day and a half period. The observed tide level (light solid line) is added to the absolute value of the hourly tidal change (dashed line) to form a composite tidal variable (heavy solid line), which is then regressed against drift indices recorded at the moraine shoal.

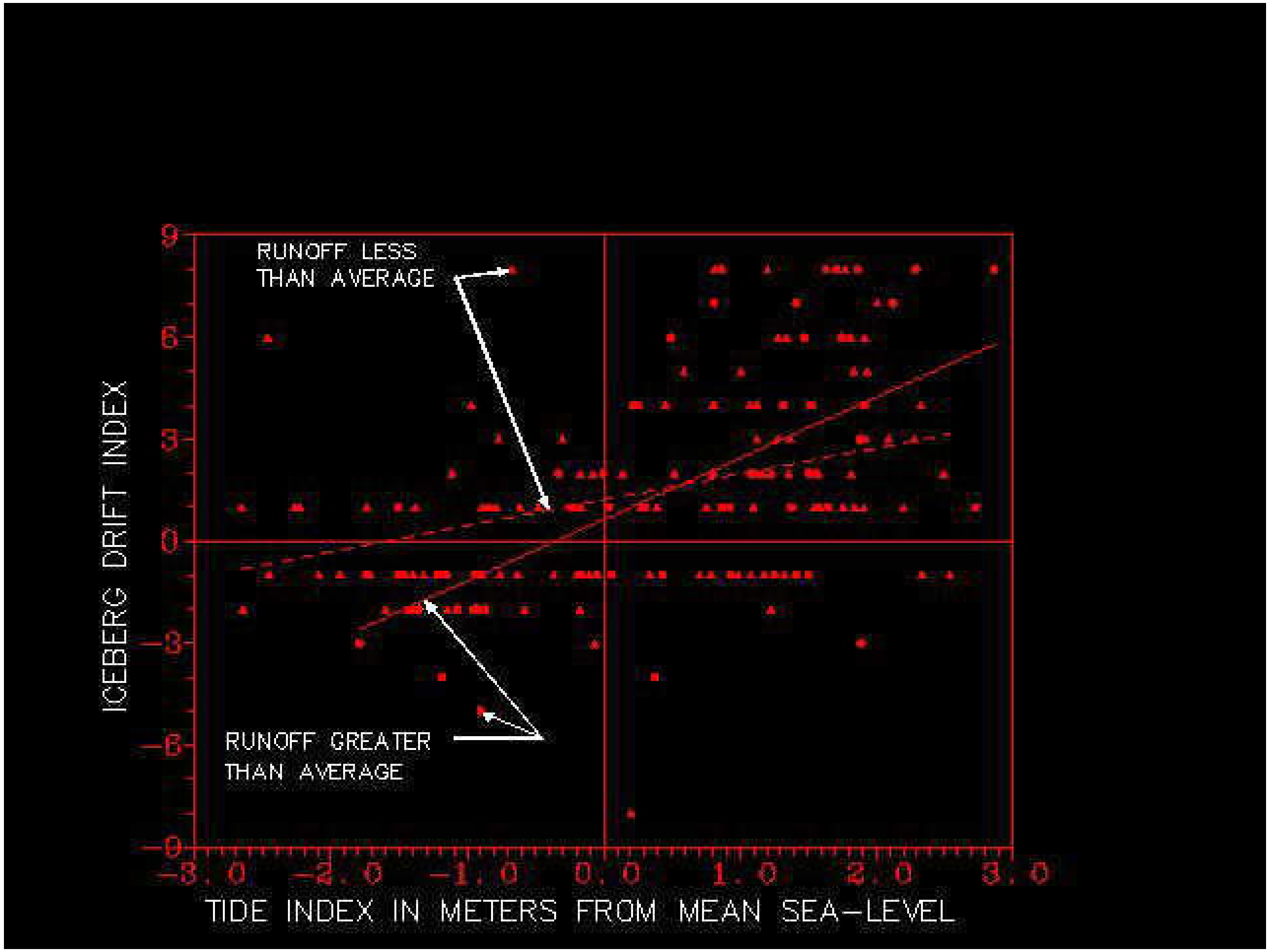

Figure 5. The relationship between the drift index recorded at the moraine shoal and the tidal index (tide height plus absolute value of hourly tidal change with a time-lag of 13 hours) for days when glacier runoff is greater than normal (solid dots) and days when glacier runoff is below normal (triangles). The R-squared for drift events occurring when runoff is high is 0.42 (solid regression line) and 0.15 when runoff is low. (dashed regression line). These results indicate that when the tide index is positive and runoff is higher than average, a significantly greater number of icebergs will be released from the forebay into Prince William Sound.

There are also unavoidable gaps in the data-when relying on photography because of darkness, fog, snow and rain.

A 13-hour lag-time exists between a tidal fluctuation and drift event, as suggested in Figure 6. The correlation between tide change and outbound iceberg drift is a maximum (+0.65) when runoff from the glacier is greater than normal, indicating a freshwater current component over the moraine shoal during the summer ablation season or heavy precipitation as rain.

6 ICEBERG COUNT AND SIZE DISTRIBUTION

A survey of icebergs was made on September 15, 1997 so that an accurate count and size distribution of icebergs for several outbreaks of ice can be determined. Measurements of berg dimensions and estimated mass were made by boat, and complete coverage of Columbia Bay and part of Prince William Sound by aerial photography was made on September 15 (about 60 more icebergs were not in range of the aerial photography but were near the shipping lanes). Approximately 100,000 icebergs with areas greater than 25 square meters (minimum size that could be detected on an aerial photograph) were counted. The size distribution is given in Table 1.

Table 1. Iceberg size distribution on September 15, 1997

Berg Area Sq Meters	**Prince Wm Sound** Total Berg Count	**Shipping Lanes** Count	**Shipping Lanes** Percent
<200	98,000	3200	3.3
200-400	490	35	7.1
400-600	55	5	9.1
600-800	21	4	19.0
800-100	34	0	--
>1000	80	4	5.0

Note: Approximately 1 percent of these icebergs had visible plumes, indicating the presence of soil and rocks embedded in them. These bergs pose an even greater danger to navigation because they are nearly submerged and extremely difficult to detect visually from a ship.

8 CONCLUSIONS

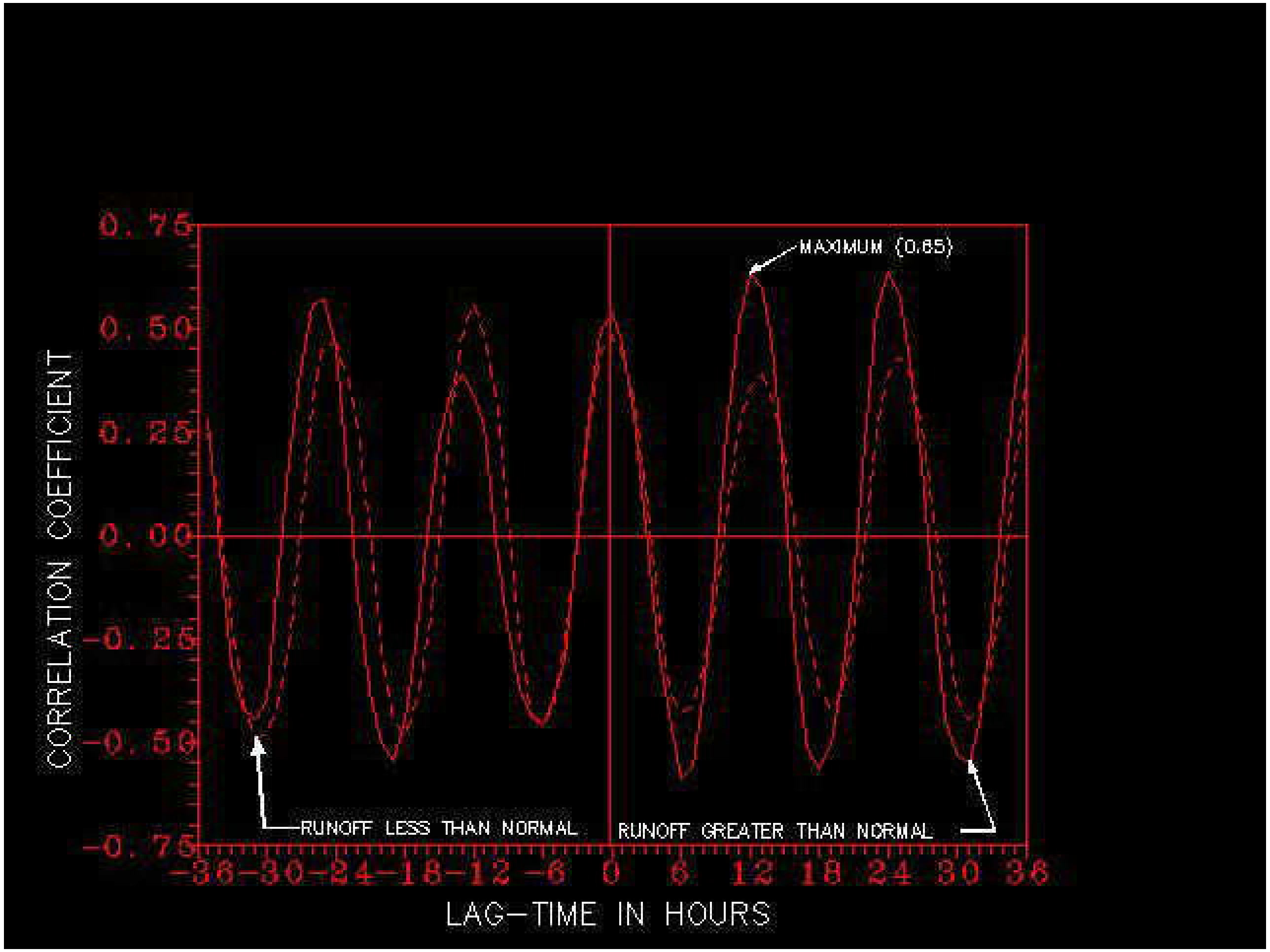

Figure 6. The correlation between drift indices and tide/runoff observations is affected by the lag-time between the index observation and the recorded tide. A positive lag-time of 13 hours (the drift event occurs 13 hours after the tidal fluctuation that caused the event) and when runoff was higher than average gave the highest correlation (0.65). This maximum corresponds to the scatter plot shown in Figure 5. Both positive and negative correlation suggest that tidal cycles in Columbia Bay produce a pumping action and that there is a continuous twice-daily flow reversal of currents over the moraine shoal.

Both ocean tides and runoff from the glacier are significant factors in moving icebergs out from the forebay into Prince William Sound. There is a fair correlation between tide level and the amount and timing of ice drift from the forebay into Prince William Sound. If high tides occur on a warm day with high melt rates or on a day with heavy rain, the rate of movement of ice from the forebay is a maximum. These results indicate that a real-time forecasting model that uses hourly observations of Valdez tide levels and daily observations of precipitation and temperature at Valdez, Cordova and Steward would provide an ice forecast with a fair degree of accuracy. Columbia Glacier is losing mass at a rate of 4 cubic kilometers (1 cubic mile) each year, even though snow accumulation currently exceeds the melting of ice and snow.

9 ACKNOWLEDGEMENTS

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10 REFERENCES

Brown, C.S. et al 1983. Calving speed of Alaska tidewater glaciers, with application to Columbia Glacier. US Geological Survey Professional Paper 1258-C, p. C1-C13.

Krimmel, R.M. 1996. Columbia Glacier, Alaska-Research on tidewater glaciers. US Geological Survey Fact Sheet FS-091-96, 4 p.

Krimmel, R.M. 1997. Documentation of the retreat of Columbia Glacier, Alaska. *Proceedings of Tidewater Glacier Workshop*, Byrd Polar Research Center. Feb 28-Mar 1.

Krimmel, R.M. 1997. Columbia accumulation, Personal communication, August 14, 1997.

Post, Austin 1975. Preliminary hydrography and historic terminal changes of Columbia Glacier, Alaska: US Geological Survey Hydrologic Investigations Atlas HA-559, 3 sheets [supersedes Open-File Report 75-491].

Post, Austin 1977. Reported observations of icebergs from Columbia Glacier in Valdez Arm and Columbia Bay, Alaska, during the summer of 1976: U.S. Geological Survey Open-File Report 77-235, 3 p.

Tangborn, A. et al 1998. Calculation of the size of the iceberf struck by the oil tanker Overseas Ohio, *Ice in Surface Waters*, Volume 1, Proceedings of the 14th International Symposium on Ice, Potsdam/New York/USA/27-31 July 1998. Ed. Hung Tao Shen. pp. 237-241.

Tangborn, W.V. 1997. Using low-altitude meteorological observations to calculate the mass balance of Alaska's Columbia Glacier and relate it to calving and speed, *Proceedings of Tidewater Glacier Workshop*, Byrd Polar Research Center. Feb 28-Mar 1.

Van der Veen, C.J. 1995. Controls on calving rate and basal sliding observations from Columbia Glacier, Alaska, prior to and during its rapid retreat, 1976-1993. Byrd Polar Research Center, Ohio State University.

Walters, R. 1988. Columbia Bay, Alaska: an 'upside down' estuary, *Estuarine, Coastal and Shelf Science*, 26, 607-617.

Walters, R. 1989. A tale of two estuaries: Columbia Bay, Alaska, and San Francisco Bay, California. *Estuarine Circulation*, Edited by Neilson et al, Humana Press, NJ.

Viens, R., 1995, Dynamics and mass balance of temperate tidewater calving glaciers of southern Alaska, MS Thesis, Geological Sciences, University of Washington.

This paper was published in *Ice in Surface Waters*, Volume 1, Proceedings of the 14th International Symposium on Ice, Potsdam/New York/USA/27-31 July 1998. Ed. Hung Tao Shen. pp. 231-236