Tidal Currents and Glacial Discharge, Laguna San Rafael, Southern Chile

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ABSTRACT


The interaction between meltwater from a tidewater glacier, San Rafael Glacier, and tidal currents in the the Laguna San Rafael, southern Chile, were monitored during January 1986. Current measurements were taken adjacent to the glacier snout in the laguna and indicated localised influence of glacial meltwater on velocities. The laguna has one tidal input/output channel and detailed measurements of water level and velocities indicated a clear discharge asymmetry. Estimates of glacial discharge and iceberg melt account for this asymmetry and show that the glacier exerts a strong influence on tidal flows through the tidal channel connecting the laguna with the adjacent fjord.

Additional Index Words: Discharge asymmetry, tidewater glacier, tidal currents, Chile.

INTRODUCTION

The San Rafael Glacier in southern Chile is the northernmost tidewater glacier in the southern hemisphere and discharges directly into Laguna San Rafael. The laguna itself discharges to the ocean via a narrow tidal inlet, the Rio Tempano, which shows flood and ebb current reversal on a semi-diurnal basis. The freshwater inputs to this estuary and the laguna are dominated by the glacier. Although the Laguna San Rafael area is noted for its wet climate, with annual precipitation totalling more than 4000 mm, there is no regular seasonal variation (ENOMOTO & NAKAJIMA, 1985). However, the discharge from the glacier into the laguna varies both seasonally and diurnally, its melt regime being controlled by temperature rather than precipitation. This study examines the interaction between this glacial meltwater, iceberg melt, and the tidal currents in the laguna and their discharge through the Rio Tempano.

STUDY AREA

Laguna San Rafael lies at the base of the Andes in southern Chile at approximately 46°40'S, 74°00'W. It is accessible by boat from Puerto Aisen, 100 km to the north and lies at the head of a long, possibly fault controlled, fjord system. The laguna is separated from the Golfo Elefantes, the southernmost part of this fjord system, by a tidal channel, the Rio Tempano (Figure 1). The Tempano is approximately 500 m wide for most of its length, widening to over 1 km near the mouth of the Rio Dorotea, and approximately 30 m deep in the center of the channel. The tides are semi-diurnal and the range in the Tempano is approximately 2 m.

The San Rafael Glacier descends from the Hielo Patagonico Norte (North Patagonian Icefield) and enters the laguna from the east. It was classified by LLIBOUTRY (1956) as the fifth largest glacier in Chile. Despite observations suggesting advance in the winter or spring of 1958 (HEUSSER, 1960) more recent observations suggest a net retreat of 2600 m between 1944 and 1983 (ANIYA & ENOMOTO, 1986). Recent retreat is confirmed by aerial photography from 1974 which shows the glacier terminus extending out from the constraints of the valley walls, whereas in 1986 the glacier did not protrude into the laguna, the terminus showing a similar profile to its 1984 position (Figure 1).

The glacier terminates in an ice cliff, measured at 60 m high in 1983 (NARUSE, 1985). As the depth of the laguna is approximately 100 m the terminus of the glacier is grounded on the
bed. The glacier snout is highly crevassed and seracced, and near its terminus moves rapidly, velocities of up to 17 m per day having been measured in 1983-84 (NAKAJIMA, 1985). The glacier calves in to the laguna (Plate 1) producing ice blocks of irregular shape and size. The distribution of the larger of these across the laguna is strongly influenced by wind, but eventually the bergs either melt within the laguna or are discharged via the Rio Tempano.

TIDEWATER GLACIERS AND DISCHARGE

The interaction between meltwater from tidewater glaciers and the surrounding tidal waters has been described by WALTERS et al. (1985) in Columbia Bay, Alaska. They describe the situation as being like an 'upside-down' estuary. Usually in an estuary the freshwater remains on top of the saltwater due to its lower density, and mixing takes place between the two water layers dependent upon local conditions. A tidewater glacier, like that at San Rafael, contributes fresh meltwater to the tidal zone but from below the water surface, discharge usually occurring at or near the point of grounding. This results in a buoyant freshwater plume adjacent to the glacier snout, and mixing takes place rapidly as the freshwater rises. This freshwater input affects both the salinity and the temperature structure of the adjacent water, the combined influence of glacier discharge and melt from calved icebergs producing particularly complicated temperature structures in many Chilean fjords (PICKARD, 1971).

Work by Japanese scientists in the area, as part of the Glaciological Research Project in Patagonia, 1983-84 (GRPP), had indicated that the influence of floating ice on the Laguna San Rafael was to decrease surface temperatures (NAKAJIMA et al., 1985). Measurements of salinity with depth showed a slight decrease in salinity near the surface but the general range was 15 to 17 ppt. However, NAKAJIMA et al. took no measurements of current velocity in the laguna. They attempted to calculate the contribution of meltwater discharge to flow through the Rio Tempano but were unable to obtain reliable measurements due to problems with floating ice and irregular eddies.

In view of this, the present study set out to monitor flows in the laguna adjacent to the glacier front to assess the role of buoyant freshwater flow and surface ice on current velocities. A detailed study of currents and tides in the Rio Tempano was undertaken to allow a more accurate calculation of inputs and outputs from the laguna than had been possible in the past.

LAGUNA SAN RAFAEL

Methods and Results

Observations of the laguna near the glacier snout suggested that a major meltwater stream discharged towards the northern side. However, the area up to 500 m from the front of the glacier was generally clear of floating ice, except immediately after an ice fall, indicating some flow away from the glacier along most of its terminus. Four monitoring sites were established in the area of the laguna adjacent to the glacier (Figure 1) and Braystoke current meters (12.5 cm impellor) were used to monitor flow velocities at depths of 1, 5 and 20 m below the surface. Although the laguna is over 100 m deep in many areas, measurements were limited to the surface layers by the available instrumentation. The results are not considered representative of the whole water column but indicate the influence of buoyant freshwater from the glacier on the surface layers of the laguna.

Results from Station 1, in the midst of the floating ice in front of the glacier, show velocities in the range 0.05 to 0.25 m s\(^{-1}\) (Figure 2). Velocities on almost all the profiles are lowest at the surface. This is due to the floating ice fragments both damping any movement in the surface water layers and producing some density stratification. NAKAJIMA et al. (1985) note that within the area of floating ice surface water temperatures and salinities are lowered by melting ice. In general velocities increase with depth, especially so in the late afternoon (17.1.86 and pm 18.1.86). Glacial discharge usually increases to a maximum in the late afternoon and early evening in response to maximum incoming solar radiation in the middle of the day (PATERSON, 1981). In the laguna, this increase in discharge is reflected in these increased currents below the surface, as
the fresh meltwater rises through the water column.

In contrast, velocity measurements from Station 2, to the south of the glacier snout and away from the immediate influence of the meltwater, show much lower velocities (Figure 2). Velocities are highly variable near the surface and often decrease to zero at 20 m. The results show a lower velocity range, generally lower than 0.15 ms\(^{-1}\), while almost all the measurements at Station 1 (16.1.86 and 17.1.86) show both higher velocities and increases at depth.

Attempts to monitor velocities in the area of major meltwater discharge were hampered by the difficulty of anchoring a small boat in 100 m of water with a strong current. Some results were obtained at Station 3 (Figure 2) and clearly indicate much greater velocities in this area, up to 0.38 ms\(^{-1}\). There is no floating ice in this zone as it is quickly carried out into the laguna by the current, and this is reflected in the much higher surface velocities at this Station. There is no clear pattern of velocity increase or decrease with depth and velocities.
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are still high at 20 m below the surface. However, these results must be treated with some caution due to the need for frequent repositioning of the boat and the possibility of drift during monitoring.

Monitoring further out into the laguna, in the midst of the main stream of floating ice moving from the ice cliff to the Rio Tempano, at Station 4, again indicated the importance of surface ice in decreasing velocity (Figure 2). There is a clear pattern of increased velocity at 5 m below the surface, with decreases at 20 m. At this position in the laguna, currents either from meltwater discharge or tidal circulation are concentrated just below the surface, and although velocities are not high they appear stable during the monitoring period.

Discussion

The velocity measurements taken in the laguna show the diurnal influence of the glacial meltwater in determining currents. Adjacent to the glacier and between its snout and the Rio Tempano, strong near-surface currents are observed. Away from the influence of the glacier e.g. at Station 2, currents are very low and water movement is largely associated with tidal circulation.

Velocity measurements were taken between 16 and 19 January which included some very warm weather (daily maximum 19.2°C on 16.1.86) and a wet day (16.8 mm of rain on 17.1.86). However, these are not extreme conditions at Laguna San Rafael, and the weather has no clear influence on flow patterns during this period. During exceptionally cold weather, even in the summer, discharge from the glacier would decrease and calving be reduced.

The influence of the San Rafael Glacier on currents within the laguna appears to be localised. Where the main meltwater channel enters the laguna currents are strong, but mixing is rapid and much of the laguna, towards the south and west, is unaffected. The most widespread influence of the glacier is in its discharge of floating ice. Its distribution by the wind across the laguna causes much of the surface water to be cooler, calmer and less saline than at depth (NAKAJIMA et al., 1985).

Methods and Results

Five monitoring stations were established on the eastern bank of the Rio Tempano (A-E in Figure 1). These consisted of a stage pole and a measured stretch of water, over which surface velocity readings were taken using timed floats. The five sites were manned for a 24 hour period, covering two spring tidal cycles on 26/27.1.86. In addition a boat monitoring position was maintained in the centre of the channel near the outlet to Laguna San Rafael and current meter measurements were obtained throughout the 24 hour period.

At each bank station water level was measured simultaneously at 15 minute intervals over two ebb-flood tidal cycles and during daylight hours floats were timed over a 100 m stretch of water close to the bank. It was not possible to establish a common datum for all the water level readings as dense undergrowth on the banks of the Tempano prohibited ground survey. However, readings were taken simultaneously at all stations in an attempt to identify the nature of tidal movement through the channel. Water level readings were also taken on the north shore of the laguna (L in Figure 1), close to base camp.

Plots of the stage-time curves reveal a progressive element to the tide in the Rio Tempano. The observed times of high water are not coincident at the five bank stations as they would be under standing wave conditions (DYER, 1973). A lagging E by approximately 2 hours on 27.1.86 (Figure 3). However, records from the station L within the laguna follow those of A closely, indicating almost simultaneous water level changes along the north shore of the laguna.

The velocity readings for A were taken from a small boat in mid-channel, position being maintained by running the engine against the tide and using fixed sites on both banks for alignment. The current meter was used with a 7 kg sinker weight which was inadequate for the current. Consequently the impellor was dragged to near the surface, whatever length of cable it was allowed. Thus most readings represent near surface velocities and are not representative of the water column. Measurements made by NAKAJIMA et al. (1985) suggest a
steep decline in velocity below the surface, decreasing from 1.15 ms\(^{-1}\) at the surface to 0.5 ms\(^{-1}\) at 2.4 m.

The velocity-time curves for the boat show maximum velocities reached at mid-tide level and mid-channel velocities on both flood and ebb of up to 2.5 ms\(^{-1}\) (Figure 4A). This relationship is confirmed in the surface velocities measured near the bank at D (Figure 4B) towards the northern end of the Rio Tempano, where maximum velocity occurs at around mid-tide level and reaches 1 ms\(^{-1}\). The effect of the diurnal variation in glacial discharge can be seen when comparing the magnitude of the flood flow between the two tides. At D the flood velocities are much higher in the early morning (26.1.86) than in the afternoon (27.1.86) when the flood tide is flowing against the discharge maximum from Laguna San Rafael. This is less clear at A as records are incomplete due to instrument failure on the afternoon of 27.1.86.

A cross-section of the Rio Tempano was taken at the boat monitoring station. The channel (Figure 5) has an area of approximately 10530 m\(^2\) and the channel at this point is 450 m wide. Unfortunately the velocity records at the boat are incomplete and so cannot be used in the calculation of flood and ebb discharge through the channel. However the records from the D are almost complete and these have been used to estimate the discharges. The method assumes that the surface velocities at the margin represent a mean velocity for the channel, and the cross-sectional area is the same at both D and A where channel widths are similar. Velocities have been interpolated where missing values occur. The resulting instantaneous discharges, using a surface velocity rather than a true mean, should overestimate discharge through the channel.

The flood-ebb cycle beginning in the early morning of 27.1.86 shows a clear asymmetry between flood and ebb discharge. Flood velocities are generally lower than those on the ebb and flood discharge is estimated at 5.63 \(\times\) 10\(^7\) m\(^3\) compared to 25.3 \(\times\) 10\(^7\) m\(^3\) on the ebb. Although they were unable to calculate discharges in the Rio Tempano, NAKAJIMA et al. (1985) made some estimates of the possible discharge based upon the tidal range in the laguna and its surface area. If the area of the laguna is 130 \(\times\) 10\(^6\) m\(^2\) and the tidal range is approximately 2 m then the amount of water leaving the laguna, including the contribution from the glacier, on each ebb tide should be approximately 2.6 \(\times\) 10\(^8\) m\(^3\). This agrees very well with the calculations made for the ebb tide on 27.1.86. The asymmetry between flood and ebb may be accounted for by the contribution of glacial meltwater to the laguna, and its inclusion in the estimate of ebb discharge. During flood tides this additional water cannot escape from the laguna and so contributes to the water level variations attributed to tidal action. The difference between flood and ebb discharge estimates is 19.7 \(\times\) 10\(^7\) m\(^3\). If the glacier is moving at its maximum velocity of 17 m/day, and its terminus area is about 3.5 km \(\times\) 160 m = 5.6 \(\times\) 10\(^5\) m\(^2\), and the position is assumed to be stable, then the daily discharge of ice into the laguna would be 9.5 \(\times\) 10\(^7\) m\(^3\). Assuming the amount of water mass draining through the glacier is about the same as the discharging ice mass, as NAKAJIMA et al. (1985) do, then the supply of water from the glacier to the lagoon would be 9.5 \(\times\) 10\(^7\) m\(^3\) /day, although not all of this would be discharged during one ebb tidal phase. The assumptions and estimates used in these calculations are many but the broad agreement in the figures indicates that the contribution of glacial ice and meltwater to the laguna can...
account for much of the asymmetry observed between flood and ebb discharges in Rio Tempano.

Discussion

In contrast to the laguna, the contribution of glacial meltwater has a major impact on currents in the Rio Tempano. The diurnal variation is clearly shown at D where ebb velocities are higher in the late evening on 26.1.86, when they coincide with maximum glacial discharge, than the following morning. Similarly, flood velocities are lower in the late afternoon (27.1.86) than early morning, as the flow is against the increasing glacial discharge. The asymmetry in flood and ebb discharge as estimated from observations in Rio Tempano can be explained by the glacial contribution to the laguna.

The tide in the Rio Tempano is a combination of a progressive and a standing wave. The time
of high water is not coincident at the five stations but at any one location flow reversal and zero velocity are almost coincident with high and low water, characteristic of a standing tidal wave (DYER, 1973). There is a slight tendency for asymmetry shown in the stage-time curves towards the southern end of the Tempano (Figure 3). At A the rising limb of the curve is steeper and of shorter duration than the falling limb, whereas records from D and E are more symmetrical.

Thus the Rio Tempano behaves like an estuary with a strong seasonal freshwater inflow. Measurements for this study were taken during the summer when the diurnal variation in glacial discharge is at its maximum. Were records available over a complete year, then seasonal changes in meltwater and ice contribution would have a pronounced effect on tidal currents and discharge asymmetry.

CONCLUSIONS

The measurements of velocity within the laguna indicate spatial variability in the influence of meltwater from the San Rafael Glacier. Temporal variations appear to follow a pattern closely related to the diurnal glacial discharge. There are no other major freshwater inputs to the laguna, despite high levels of precipitation, as mountains rise steeply to the east and relief to the west is low. Glacial discharge and tidal input are therefore dominant within the laguna. The size of the laguna, and its exposed position to winds at the southern end of a long fjord, allows considerable wave action to develop during storms. The prevailing wind is from the north to north-northeast and surface waves of up to 0.5 m can develop during squalls. Prolonged northerly winds could cause exceptionally high water levels within the laguna and may alter the pattern of tidal currents in the Rio Tempano by increasing the magnitude of the flood flow.

This study has demonstrated that the Rio Tempano behaves as an estuary subjected to rapidly varying freshwater inputs. Such variations in the magnitude of freshwater rarely occur on such a regular basis due to fluvial inputs. In this case, however, the influence of the glacier allows studies to be made, in a short period, of fluctuations which in other environments would require continuous monitoring on a seasonal basis. This tidewater glacier has exceptionally high flow rates for a non-surgeing glacier, and thus provides an excellent context for further study of flow and discharge asymmetry in estuaries, as well as the interaction between tidal waters and glacial discharge.

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LITERATURE CITED


NARUSE, R., 1985. Flow of Soler Glacier and San Rafael Glacier. IN: C. NAKAJIMA, (Ed.), Glaciol-
Plate 1. Terminus of San Rafael Glacier viewed from the north, with ice block collapsing. The ice cliff is approximately 60 m high.

RESUME

A contrôlé en janvier 1986 les interactions entre les eaux de fusion glaciales et les courants de marée de la lagune de San Rafael. Les mesures de courant, prises à côté de la langue glaciaire dans la lagune, indiquent une influence locale des eaux de fusion sur la vitesse du courant. Les eaux de la lagune (mesures vitesses et du niveau de l’eau) circulent par un goulet où la décharge est nettement asymétrique. La décharge glaciaire et la fusion de l’iceberg participent à cette asymétrie et montrent que le glacier exerce une vigoureuse influence sur les courants de marée canalisés par le goulet connectant la lagune au fjord adjacent.
(Catherine Bressolier, EPHE, Montrouge, France)

RESUMEN

Se ha medido en el mes de enero de 1986 aspectos relacionados con la interacción entre las aguas de deshielo procedentes del glaciar San Rafael y las ondas de marea en la Laguna de San Rafael al Sur de Chile. Las medidas de la velocidad de la corriente y nivel medio del agua ponen de manifiesto la influencia de las aguas del deshielo, en particular en la asimetría del caudal de desagüe. Una valoración de los caudales de deshielo y de marea en el canal de maría, confirman los resueltados medios.
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